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2. Geology of the southern part of the Menominee District, Michigan and Wisconsin, by W. C. Prinz. 221 p., 6 figs., 27 pl. On file at the Geological Survey Library, 4 Homewood Place, Menlo Park, Calif.; 213 Science Hall, University of Wisconsin, Madison, Wis.; and Geological Survey Office, Iron Mountain, Mich.

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GEOLOGY OF THE SOUTHERN PART OF THE MENOMINEE DISTRICT

MICHIGAN AND WISCONSIN

by

William C. Prinz

1958

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ABSTRACT

The Menominee district, which is in the southern part of the Precambrian Canadian shield, consists essentially of an east-striking trough of metamorphosed Middle Precambrian sedimentary rocks bordered on the north and south mainly by Lower Precambrian igneous and metamorphic rocks. Lower Precambrian units in the southern part of the district are the Quinnesec formation, Marinette quartz diorite, and Hoskin Lake granite. Associated rocks include the Middle Precambrian Michigamme formation, intrusive metagabbro sills, and aplite dikes, and Upper Precambrian diabase dikes. The Lower and Middle Precambrian rocks have been tilted to a vertical position and have been regionally metamorphosed in the greenschist facies in the northern and eastern part of the area, in the epidote-amphibolite facies in the central part, and in the amphibolite facies in the southwestern part. In contrast, the Upper Precambrian rocks are unmetamorphosed.

The Quinnesec formation, the oldest rock in the area, consists mainly of metamorphosed mafic volcanic rocks, albite- and actinolite-bearing greenstone, oligoclase amphibolite, and andesine amphibolite, in order of increasing metamorphic grade.

Some of these rocks show original flow or pyroclastic structures or textures. Metamorphosed sedimentary rocks (iron-formation, arkose, quartzite, and chlorite-biotite schist) and schistose felsic flows (Pier Gorge schist) are interbedded locally with the mafic rocks. The Quinnesec strata have been intruded in turn by the Marinette quartz diorite and Hoskin Lake granite plutons. The diorite may be either massive or foliated and is variable in composition, in some places being rich in ferromagnesian minerals and poor in quartz. The granite is commonly coarse grained and porphyritic but locally is medium grained and non-porphyritic. It is in sharp contact with the Quinnesec formation but in gradational contact with the quartz diorite. Granitic dikes cut the Quinnesec strata and Marinette quartz diorite, and gneissic granite forms inclusions in the Middle Precambrian intrusive metagabbro sills.

The Middle Precambrian Michigamme formation consists of ferruginous or gray slate and chert-siderite iron-formation. The intrusive metagabbro is present in four large sill-like bodies that cut the Quinnesec formation and in several smaller intrusives that cut the Quinnesec formation and possibly the Michigamme strata. In most places the metagabbro has an original gabbroic texture but is composed of metamorphic minerals; actinolite, chlorite, albite, and saussurite in the greenschist facies; oligoclase, epidote, and hornblende in the epidote-amphibolite facies; and andesine and hornblende in the amphibolite facies. Relict original labradorite or pyroxene is locally abundant. In areas of low metamorphic grade, massive metagabbro may grade into chlorite schist, whereas in high grade areas, it may pass into foliated amphibolite. In places the metagabbro becomes porphyritic, pegmatitic, or rich in magnetite and contains segregations or anorthosite or granophyre. Pyroxenite and serpentinite are associated with metagabbro in the eastern part of the area.

It is postulated that the sills acted as bosses that resisted shearing stresses and without shearing stresses, metamorphism produced massive metagabbro with remnants of original textures and minerals. Where shearing stresses were operative, such as near the borders of the sills or along shear zones, metamorphic processes were accellerated and equilibrium rocks, schist and amphibolite, resulted. It is further concluded that the metamorphism was not progressive.

Foliation is the most prominent structural feature and it can be subdivided into four groups that appear to have genetic significance: (1) west-northwest striking parallel with the regional structural trend, (2) parallel with the borders of the Marinette or Hoskin Lake granitic plutons, (3) parallel with the borders of the metagabbro sills, and (4) irregular foliation in the inclusions in the metagabbro sills.

E. J. Lyons' (Emmons, et al., 1953, p. 107-110) conclusion that some of the mafic igneous rocks in the area are the result of the formation of a "basic front" along the border of the granite and quartz diorite batholith lying to the south is not upheld by my work.

INTRODUCTION

LOCATION AND ACCESSIBILITY

The Menominee district[1/] of the Northern Peninsula of Michigan and adjacent Wisconsin is part of the Lake Superior district of the Precambrian Canadian shield. It lies in southern Dickinson County, Mich. and eastern Florence County and northern Marinette County, Wis. It derives its name from the Menominee River, which here separates Michigan from Wisconsin. This report presents the results of a detailed study of the rocks in the southern part of the district.

The detailed mapping on which this report is based was confined to a roughly wedge shaped area of about 42 square miles in the southern part of the district (pls. 1 and 2). The western boundary of the area mapped in detail is 4½ miles long and lies along 88°07' 30" W. longitude. The southern boundary of the area mapped follows 45°45' N. latitude in the western part of the area but angles to the south in the eastern part, passing just south of the Sturgeon Falls. The northern

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1/ "Menominee district" is used in this report in a restricted sense. The name has been used to include the Iron River-Crystal Falls and Florence districts and, when used in this broad manner, the area here called the "Menominee district" is referred to as the "East Menominee" or the "Old Menominee" district.

boundary lies three-fourths of a mile south of Iron Mountain, half a mile south of Quinnesec, and one mile south of Norway, Mich. The area is 13½ miles long and its eastern edge is one mile east of the Sturgeon Falls. The towns of Aurora and Niagara, Wis. and Kingsford, Mich. lie within the area mapped in detail.

All points in the area are within 1¼ miles of good paved national, state, or county highways, graded gravel secondary roads, or dirt jeep trails. Fence lines and foot trails are common away from driveable roads, thereby making some of the remote areas more easily accessible.

TOPOGRAPHY, DRAINAGE AND VEGETATION

The area contains three types of topography: (1) rugged topography in the areas of extensive outcrop, (2) flat, high level plains, and (3) low terraces, locally present along the Menominee River. The topography of the outcrop areas is characterized by knobs or ridges of rock separated by low areas which commonly contain swamps. The sides of these outcrop hills vary from gentle slopes to precipitous cliffs as much as 200 feet high. The areas away from the river and not underlain by bed rock are generally flat plains whose surfaces range from 80 to 160 feet above the level of the Menominee River. In many places the edges of these plains are steep and highly dissected by small valleys and the plains themselves are pitted by kettle holes as much as 60 feet deep. Along the river, where it doesn't flow over rock, terraces as much as three-fourths of a mile wide may be present. These terraces are in no place more than 20 feet above the river and locally they contain numerous swampy areas. Where the Menominee River flows over bedrock, falls or gorges and rapids are present, and within this area, hydroelectric plants are located at the Big and Little Quinnesec Falls and at the Sturgeon Falls. The maximum elevation in the area is 1300 feet at the southwest corner of sec. 11, T. 38 N., R. 19 E.[2] The minimum elevation is about 800 feet at the Sturgeon Falls.

The major drainage feature of the district is the Menominee River which flows easterly through the area and which eventually empties into Lake Michigan. Within the area covered by this report, water is fed into the Menominee through ground water drainage and small surface streams; except for the Sturgeon River in the eastern part of the area, secondary surface streams of any consequence are lacking.

Poplar with low scrubby undergrowth is the most abundant vegetation in the open parts of the area, and cedar and balsam

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2/ To save repetition, the state name will not be used when giving locations by township and range. No confusion can result because all East ranges are in Wisconsin, whereas all West ranges are in Michigan.

are common in the swamps. Maple, oak, birch, Norway pine, and white pine are present locally but are nowhere abundant. In the past some land was cleared for farming, but a combination of a short growing season and poor soil is resulting in abandonment of much of the farmland.

FIELD AND LABORATORY METHODS

In the summers of 1954 and 1955 and during two weeks in the fall of 1956, all known outcrop areas within the map area were located by pace-and-compass traversing. During the summer of 1954, planimetric maps prepared from air photos at a scale of 1/20,000 were used as base maps. In 1955, topographic maps at a scale of 1/12,000 became available and were used for the completion of the mapping. All work was later compiled on a 1/20,000 planimetric base map, which is the scale of the final map presented in this report (pl. 2).

Inasmuch as magnetic rocks were encountered in the eastern part of the area, 19 magnetometer traverses were run during the spring of 1956. These traverses were made with an Askania vertical-intensity magnetometer having a sensitivity of 26.5 gammas per scale division. All readings were adjusted to an arbitrary zero base with a vertical intensity value of 58,400 gammas. The absolute value of the zero base was determined by "checking in" to U. S. Bureau of Mines station 5A of Crystal Falls, Michigan; the value of which had been determined by Bath (1951).

Laboratory study was started in the winter of 1954-55 and was completed in the winter of 1956-57. This work consisted mainly of the study of 300 thin sections cut from selected specimens from the area. Extinction angle charts presented by Tröger (1952) were used in determining the composition of the plagioclase feldspars, and index of refraction oils were used in the identification of some minerals. Magnetite was separated from 11 samples and was qualitatively tested for titanium by the hydrogen peroxide method. In addition, point count analyses were made on 14 thin sections; 1000 grains being counted in each slide. Chemical analyses of two specimens were prepared in the U. S. Geological Survey laboratory in Washington, D. C.

ACKNOWLEDGMENTS

I wish to thank Harold L. James and Carl A. Lamey for suggesting this problem and for their aid while work was in progress. Carl E. Dutton and Richard W. Bayley visited with the author in the field and many valuable ideas were obtained through discussions with them. Matt Walton, Bayley and James read parts of this manuscript and their aid is gratefully acknowledged. Thanks are also due to Kenneth L. Wier for suggestions dealing with the magnetic work and to Eloise I. Caldwell who helped with the many tedious magnetometer calculations.

SUMMARY OF THE GEOLOGY OF THE MENOMINEE DISTRICT AS A WHOLE

The district as a whole consists of a west-trending trough of metamorphosed Animikie (Middle Precambrian) sedimentary and volcanic rocks bordered on the north and the south by Lower Precambrian metamorphic complexes. The Animikie (Huronian) rocks were deposited unconformably on the older metamorphic rocks but they have been folded and faulted so that they now stand nearly vertical and form a belt paralleling the structural trough within the older rocks. Middle Precambrian (post-Animikie) metagabbro sills and dikes, granitic dikes, and Upper Precambrian (Keweenawan) diabase dikes intrude many of the rocks of the district. Patches of flat-lying and unmetamorphosed Cambrian sandstone overlie the Precambrian rocks in many places.

LOWER PRECAMBRIAN ROCKS

Large areas of Lower Precambrian rocks occur along both the northern and the southern edges of the Menominee district (pl. 1). The northern area has not been studied in detail so that the fine- to medium-grained pink and gray granites and gneisses present here have been mapped together and called simply the "Northern granite complex" (Table 1). As a result of the present investigation, however, more is known about these rocks in the southern part of the district where three Lower Precambrian units have been recognized. The oldest is

Table 1. Stratigraphic Seccession in the Menominee District

ERA-PERIOD-EPOCH				FORMATION		THICKNESS
CENOZOIC Cenozoic Pleistocene				Glacial till and outwash		
				unconformity		
PALEOZOIC Cambro-Ordovician				Hermansville limestone		100'
				Upper Cambrian sandstone		300'
				unconformity		
PRECAMBRIAN	UPPER			diabase dikes		
PRECAMBRIAN	MIDDLE			granitic intrusive rocks		
				metagabbro and metadiabase		
PRECAMBRIAN	MIDDLE	ANIMIKIE	Baraga group	Badwater greenstone		?
				Michigamme formation		?
				unconformity		
PRECAMBRIAN	MIDDLE	ANIMIKIE	Menominee group	Vulcan iron formation	Loretto slate	400'
					Curry member	100-200'
					Brier slate	80-300'
					Traders member	150'
				Felch formation		120'
				unconformity		
PRECAMBRIAN	MIDDLE	ANIMIKIE	Chocolay group	Randville dolomite		1000'
				Sturgeon quartzite		1250-1450'
				Fern Creek formation		0-250'
				unconformity		
PRECAMBRIAN	LOWER			Hoskin Lake granite	Northern granitic complex	
				Marinette quartz diorite		
				Quinnesec formation		

the Quinnesec formation, a series of metamorphosed mafic flows, with some interbedded pyroclastics, felsic flows, and sediments. In the eastern part of the district, these rocks have been metamorphosed in the greenschist facies and they pass into the amphibolite facies in the southwestern part of the district. The Quinnesec formation is in contact to the south with the northern edge of a large granitic area in northern Wisconsin which is commonly referred to as the "Wisconsin batholith". Two separate rock units in the southern part of the Menominee district belong to the so-called batholith. The older of the two is a large mass of foliated to massive quartz diorite, here called the Marinette quartz diorite, which crops out along the southern border of the district. The younger, known as the Hoskin Lake granite, forms an arcuate belt lying, in most places, between the Quinnesec formation and the Marinette quartz diorite. In the SW$\frac{1}{4}$ sec. 15 and the NW$\frac{1}{4}$ sec. 22, T. 38 N., R. 20 E. the Marinette quartz diorite is in contact with the Quinnesec formation. Here the granite belt is bordered on both sides by quartz diorite. These Lower Precambrian rocks will be described in detail in the main part of the report.

MIDDLE PRECAMBRIAN ROCKS

Animikie (Middle Precambrian) rocks occur in a west-northwest trending trough 18 miles long which attains a maximum breadth of about 9 miles at Iron Mountain, Mich. East of Iron

Mountain, the trough narrows rapidly, being only 4 miles wide at Norway, Mich. From Norway, outcrops of Animikie (Huronian) rocks continue eastward to Waucedah where they pass beneath Paleozoic sediments.

The Animikie rocks in the Menominee district have been divided into three groups, Chocolay, Menominee, and Baraga in stratigraphic order (James, 1958), with unconformities separating each group as well as separating the Animikie rocks from the Lower Precambrian rocks of the Northern granite complex. The Chocolay group consists of basal conglomerate and quartzite; the Menominee group of iron-formation, ferruginous slate, some sericitic slate, and some ferruginous quartzite; and the Baraga group of slate and greenstone. These formations have all undergone regional metamorphism in the greenschist facies.

The oldest Animikie formation of the Menominee district is the Fern Creek formation which crops out at several places along the contact between the sedimentary trough and the Northern granite complex. The basal unit of this formation is a massive, pink conglomerate with angular and subangular blocks of granite and gneiss set in an arkosic matrix. Most of the pebbles and boulders in this conglomerate have been derived from the older igneous complex adjacent to it. A thin, finely laminated phyllite lies stratigraphically above the pink conglomerate and is in turn overlain by another conglomerate. The upper conglomerate has a dark, very abundant matrix composed of fine-grained graywacke material. Pettijohn (1943) calls it a "graywacke conglomerate" and believes it may represent a tillite. The patchy distribution of this formation may be due to either (1) original deposition of the rocks in restricted areas or (2) erosion before deposition of the overlying quartzite.

The Sturgeon quartzite is stratigraphically above the Fern Creek formation and it crops out in a band around the southern border of the Northern granite complex. This formation is from 1250 to 1450 feet thick and in most places is a massive and vitreous white quartzite locally stained pink or green. Cross-bedding and ripple marks are common features of this unit. The upper part of the Sturgeon quartzite becomes very calcareous and finally grades into a quartzose dolomite. Some authors (Bayley, W. S., 1904; Van Hise and Leith, 1911) have used this fact as proof of a gradational relationship between the Sturgeon quartzite and the adjacent Randville dolomite, even though a contact between the two formations has not been found.

The Randville dolomite is the youngest formation of the Chocolay group and it crops out in the Menominee district in three distinct belts. The northern belt lies just south of the Sturgeon quartzite outcrops described above. The middle belt of Randville is much smaller and extends from north of Lake Antoine, 6½ miles east to a point 2 miles north of Norway. The southern, or main Randville belt crops out throughout the entire length of the Menominee district and lies just north of Iron Mountain, Norway and Waucedah.

The Randville dolomite is predominantly a fine-grained, almost massive, white, pink, blue, or buff dolomite with some beds containing numerous clastic quartz grains. Thin bands of gray or black slate are interstratified with the dolomite and these slate bands commonly show small drag folds or faults. The dolomite may contain algal structures, ripple marks, or mud cracks. Its maximum thickness is about 1,000 feet.

The oldest rocks of the Menominee group are sericitic slates which grade stratigraphically upward into ferruginous quartzite. These rocks, the Felch formation, are 120 feet thick and they crop out immediately south of the main Randville dolomite belt. In the early reports dealing with the district (Bayley, W. S., 1904, Van Hise and Leith, 1911) these rocks were called the "Footwall series" and were included with the Randville dolomite. However, more recent work has shown that an unconformity exists between these two units, thereby making the separation necessary. The relationship between the Felch strata and the younger Vulcan iron-formation is, however, conformable.

The largest belt of Vulcan iron-formation is immediately south of the main Randville and Felch outcrops and persists almost throughout the entire length of the Menominee district. Another belt, 5 miles long, is just north of Lakes Antoine and Fumee; and a third belt, possibly continuous with the second, crops out one mile north of Loretto and Waucedah.

The Vulcan iron-formation has been divided into four members; the oldest or Traders iron-bearing member, the Brier slate, the Curry iron-bearing member, and the Loretto slate. The Traders member is chiefly non-clastic and consists of 150 feet of fine-grained, banded hematite and maroon chert. Conformable with it is the clastic Brier slate, which is a banded ferruginous slate 80 to 300 feet thick. The Curry member is 100 to 200 feet thick and is very similar to the Traders; however, in places the Curry becomes somewhat quartzose and contains purplish rather than maroon chert. The youngest member of the Vulcan iron-formation is the Loretto slate. This ferruginous slate has a maximum thickness of 400 feet and is present only in structural troughs whereit was protected during the post-Menominee and pre-Baraga erosion cycle. In favorable structural sites, weathering and oxidation has converted the banded chert and hematite iron-formation of the Traders and Curry members to iron ore consisting almost entirely of hematite.

The youngest Precambrian sedimentary rock of the Menominee district is the Baraga group Michigamme formation which is separated from the underlying Vulcan iron-formation by an angular unconformity. In places, such as south of the northern Randville dolomite belt and east of Quinnesec, all of the Menominee group strata were eroded before deposition of the Michigamme strata. Michigamme strata crop out in three troughs: (1) between the central and northern Randville dolomite belts, (2) between the main or southern Randville belt and the Vulcan outcrops north of Lakes Antoine and Fumee, and (3) between the main belt of Vulcan iron-formation and the Lower Precambrian Quinnesec formation to the south. The Michigamme formation consists of a succession of gray to black slate, graywacke, calcareous slate, and some sideritic iron-formation. Folding and faulting have made it impossible to determine the thickness of this unit.

The Badwater greenstones occur in a synclinal trough above the Michigamme strata 2½ miles north of Iron Mountain. They are basalt flows which have been metamorphosed to the greenschist facies and which locally contain well defined pillow or ellipsoidal structures.

The youngest Middle Precambrian rocks of the district are intrusive. Dikes of metagabbro up to several hundred feet wide cut the Northern granite complex, Sturgeon quartzite, Vulcan iron-formation, and Michigamme formation, and large, sill-like bodies cut the Quinnesec formation in the southern part of the district. The petrography and petrology of the metagabbro sills cutting the Quinnesec formation will be described in detail in the main part of this report. Small aplite and granite pegmatite dikes are also common.

UPPER PRECAMBRIAN ROCKS

Upper Precambrian rocks in the Menominee district are found in scattered small unmetamorphosed diabase dikes. These rocks consist of primary labradorite, pyroxene, and olivine and are very fresh, which is in marked contrast with the highly altered middle Precambrian mafic intrusives.

PALEOZOIC ROCKS

Unconformably above the Precambrian rocks are unmetamorphosed Paleozoic breccia, sandstone, and limestone. These beds cap the ridges in many parts of the district (pl. 1) and are almost horizontal. The lowermost unit is a red sandstone or breccia whose basal portion contains material derived from the Precambrian immediately below. The red sandstone and breccia grade upward into a white calcareous sandstone which in turn grades upward into a sandy limestone. The sandstone is regarded as upper Cambrian in age and is generally referred to simply as the "upper Cambrian sandstone". The limestone has been dated as Cambro-ordovician and is called the Hermansville limestone. The maximum thickness of the upper Cambrian sandstone is 300 feet and of the Hermansville limestone, 100 feet.

STRUCTURE

On a broad scale, the district consists of three structural units; areas in the north and the south containing Lower Pre-cambrian rocks, and a synclinal area between them which is under-lain by Animikie sediments and volcanics. The Animikie formations strike slightly north of west and generally dip south at very high angles or north where overturned. Their tops generally face south and they crop out as long narrow bands and in places these bands are offset by small cross faults. The bands or belts can be divided into three groups with the major formations repeated in the following order, from north to south: Group 1, Sturgeon, Randville, Vulcan, and Michigamme; Group 2, Randville, Vulcan, and Michigamme; and Group 3, a repetition of the Group 2 sequence, Randville, Vulcan, and Michigamme. This relationship was explain-ed in Monographs 46 and 52 (Bayley, W. S., 1904; Van Hise and Leith, 1911) by a series of tight folds, with the Michigamme strata cropping out in the troughs of the synclines; the presence of the Michigamme strata adjacent to the Randville dolomite was explained by non-deposition of the Menominee strata. Lamey and Dutton (1939, 1941, 1942) studied the southern belt in detail and concluded that the three groups of sedimentary formations were large fault blocks with neither non-deposition nor unconformity being important. Current opinion[3/] is tending toward an hypothesis

[3/] Bayley, R. W., personal communication, 1956.

of unconformity modified by later faulting.

The nature of the contact between the Michigamme and the Quinnesec formations is a problem which will be dealt with later in this report.

PREVIOUS GEOLOGIC WORK

First mention of the geology of the southern part of the Menominee district was made by Foster (1849) in a report of his trip from the Keweenaw Peninsula to Escanaba, Mich. During this trip he came down the Menominee River and through the belt of Quinnesec formation outcrops. In this area he noted:

> "a series of igneous rocks, composed of porphyries and close grained basalts protruded among slate rocks" (Foster, 1849, p. 778),

and, in a later report, he and Whitney described rocks that

> "consist of black, compact masses of serpentine, exhibiting few signs of bedding" (Foster and Whitney, 1851, p. 24).

They evidently thought that both sedimentary and igneous rocks were present in the area.

Credner, a German geologist who worked for a short time in the Lake Superior district, described some of the rocks of the Quinnesec formation in more detail (Credner, 1869 and 1870). He thought that they were upper Huronian (Animikie) in age; were neither eruptives nor normal metamorphosed sediments, but were "crystalline sediments, thrown down from water of the pre-Silurian ocean" (Credner, 1870; translated by Bayley, W. S., 1904, p. 56).

Brooks (1873, 1876, 1880) was the first worker to do any systematic work in the southern part of the Menominee district, and from exposures along the Menominee River he (Brooks, 1873) described several layers of chloritic, hornblendic, and dioritic rocks which he believed represented metamorphosed sediments. Since these rocks dip south, he concluded that they must overlie the Animikian Michigamme strata. He also thought that the granite south of the Quinnesec formation was the youngest Animikie rock of the district (Brooks, 1876), and he concluded that it represented altered sediments (Brooks, 1880). Wright (1880), working with Brooks, presented brief microscopic descriptions of some of the rocks.

Rominger (1881) was also of the opinion that the Quinnesec rocks were originally sediments, but he disagreed with Brooks as to their age. Rominger considered them older than the Michigamme strata because of their lithologic similarity to diorites on the Marquette range and because of their higher degree of metamorphism. At first, Rominger interpreted massive diorites as sediments metamorphosed to such an extent as to obliterate all original structure, but he (Rominger, 1895) later changed his ideas and concluded that these rocks were probably eruptive. Like Brooks, he also thought that the granite south of the Quinnesec belt was the youngest Middle Precambrian rock of the district and that its "eruption" tilted all of the older formations to a vertical position.

Irving's (1885, 1890) interpretation of the rocks of the Quinnesec formation was very similar to the views held by Foster and Whitney in that he also believed that both igneous and sedimentary rocks were present. He thought that the diorites were altered diabases and gabbros in which the hornblende was secondary after augite and that the chlorite schists were in part flows and in part metamorphosed sediments. Irving further thought that the schistose structure present in many of the rocks had a secondary origin and was not due to original sedimentary bedding as had been argued by many of the earlier workers. Finally, Irving (1890) was of the opinion that the basic rocks and the granite which is intrusive into them were both pre-Animikie in age.

Williams (1890) studied the exposures at the major falls and rapids along the Menominee River in the southern part of the Menominee district and was the first to extensively use the petrographic microscope in the study of these rocks. He believed that the rocks of the Quinnesec formation were originally flows which had solidified under subaerial or subaqueous conditions and which had been tilted up on end; however, he presented no evidence or conclusions regarding their age. His main purpose was to prove that the schistose rocks had been derived from original massive igneous rocks by dynamic metamorphism and that the foliation was, therefore, not due to sedimentary processes.

He presented adequate proof for a secondary origin for this foliation and, in addition, was able to trace the results of the metamorphism of the mafic igneous rocks. The dike-like felsic rocks in part of the area were thought to be apophyses from the granitic area to the south. His petrographic descriptions and diagrams are very good, but he did, in my opinion, tend to overemphasize the effects of dynamic metamorphism and to attribute some low grade metamorphic minerals to weathering. Although, at the time of his study, many of the modern concepts of metamorphism were unknown, Williams seemed to be approaching some modern ideas when he wrote:

> "rocks fundamentally distinct in both origin and structure grow more and more alike when subject to metamorphism. They may finally become indistinguishable and thus their life histories may be lost, but so long as any trace of the original structure is recognizable it may be relied upon as a safe ground" (Williams, 1890, p. 195-196)

and later:

> "in exactly the same chemical compound, what may be a stable state under one set of conditions, may be an unstable state under another set. So delicate is this adjustment that the secondary minerals produced in a given case depend not merely upon the chemical composition of the original rock or of its constituents, but even to a greater degree upon the physical conditions obtaining at the time of their formation. Thus with every change of these, one generation of secondary minerals may give place to another." (Williams, 1890, p. 209).

Winchell (1893) thought that Williams had overestimated the value of the petrographic microscope and had thereby reached some false conclusions. Winchell contended that the rocks of the Quinnesec formation were for the most part pyroclastic with true lava flows being subordinate. Williams (1893) answered Winchell by reasserting his previous conclusions and Winchell followed (1895) with a more detailed criticism of Williams' work. Wadsworth (1893) noted several occurrences of tuffaceous rocks in the Quinnesec formation; information which was used by Winchell in his second paper.

W. S. Bayley (1904) wrote a monograph covering the whole Menominee district and gave the name "Quinnesec schists" to the altered basic igneous rocks along the southern edge of the district. He quoted quite freely from Williams' earlier report and presented few new conclusions. But Bayley did recognize more tuffaceous and more intrusive rocks than did Williams and noted several occurrences of acidic flows which Williams thought were specially altered basic flows. Bayley also recognized the intrusive relationship of the granite to the Quinnesec schists and considered them both Archean (pre-Animikie).

The monograph by Van Hise and Leith (1911) covering the whole Lake Superior district contains no new conclusions concerning the origin of the rocks along the southern edge of the Menominee district, but does contain a very brief description of these rocks south of the Florence, Wis. district to the west. Van Hise and Leith referred to some unpublished work by W. O.

Hotchkiss who reportedly found Quinnesec tuffs and flows interbedded with upper Animikie slates; therefore, all of the rocks in the southern part of the Menominee district were thought to be Middle and Upper Precambrian.

Leith, Lund, and Leith (1935) published a correlation chart for the Lake Superior region in which the rocks of the Quinnesec formation were placed in the lower part of the Baraga group below the "Hanbury" (Michigamme) slate. The granitic rocks to the south were considered Killarney (Upper Precambrian).

Lyons mapped the Wisconsin portion of the southern edge of the Menominee district and, in addition, included some areas to the west and south of that covered in the present report. The results of his work are in an unpublished Ph. D. thesis[4] and in summary form in Memoir 52 of the Geological Society of America (Emmons, et al, 1953, p. 107-110). Lyons attempted to relate almost all of the rocks of the area to one igneous or metamorphic cycle, coinciding with the formation of the batholithic area of northern Wisconsin. He thought that some of the basic rocks of the area were altered basalt flows; some other rocks were considered more basic. The more basic rocks were visualized as a "basic front" formed in front of the Wisconsin

[4] Lyons, E. J., 1947, Mafic and porphyritic rocks of the Niagara area; unpublished Ph. D. thesis, University of Wisconsin.

batholith. In a later section of the present report, Lyons' ideas will be presented in further detail and will be discussed at greater length.

Finally, Norman Shapiro, G. L. Thompson, A. J. Froelich and I mapped four small areas in sec. 12, T. 39 N., R. 31 W., sec. 7, T. 39 N., R. 30 W., sec. 12, T. 38 N., R. 19 E., and sec. 7, T. 38 N., R. 20 E. in the summers of 1951 and 1952. The results of these studies are in Ohio State University Master of Science theses which contain detailed maps and petrographic descriptions, but because of the limited size of the areas studied, no conclusions of a general nature were reached.

GENERAL GEOLOGY

The rocks in the area covered in detail by the present report are all Precambrian in age. Lower Precambrian rocks include the Quinnesec formation, Marinette quartz diorite, and Hoskin Lake granite; Middle Precambrian rocks include the Michigamme formation, intrusive metagabbro, and aplite; and Upper Precambrian, diabase dikes.

The Quinnesec formation consists mainly of mafic igneous rocks which have been metamorphosed to greenstones and aphibolites. Some of these rocks preserve igneous structures and textures and can be accurately classified as having originated from lava flows or pyroclastic material. Some metamorphosed sedimentary rocks are interbedded with the mafic igneous rocks, and in part of the area a distinctive calc schist has been mapped separately as the Pier Gorge schist member of the Quinnesec formation. The Quinnesec formation has been intruded in turn by the Marinette quartz diorite and the Hoskin Lake granite. The diorite may be either massive or foliated and is variable in composition, in some places being rich in ferromagnesium minerals and poor in quartz. The Hoskin Lake granite is intrusive into both the Quinnesec formation and the Marinette quartz diorite. It is commonly coarse grained and porphyritic but locally is medium grained and non-porphyritic. It is in sharp contact with the Quinnesec formation but in gradational contact with the quartz diorite, and it contains inclusions of both host formations. The granite also forms dikes which cut the Quinnesec formation and Marinette quartz diorite and which occur as inclusions in younger metagabbro sills.

The Middle Precambrian rocks of the area include two major units; the Michigamme formation and intrusive metagabbro. The Michigamme consists of ferruginous slate and gray slate and some chert-siderite iron-formation. The metagabbro is present in four large sill-like bodies cutting the Quinnesec formation and in several smaller intrusives which cut the Quinnesec formation and possibly the Michigamme strata. In most places the metagabbro has an original gabbroic texture but is composed of metamorphic minerals. In areas of low metamorphic grade, the massive metagabbro is chloritic or actinolitic and may grade into chlorite schist, whereas in the higher grades it is hornblendic and may pass into an amphibolite. In places the metagabbro is porphyritic or pegmatitic, or rich in magnetite and locally it contains segregations of anorthosite and granophyre. Pyroxenite and serpentinite are associated with the metagabbro in the eastern part of the area, and they are described with the metagabbro even though evidence relating the rock types is tenuous. Small metadiabase dikes cut the metagabbro and aplite dikes cut the Quinnesec formation, Marinette quartz diorite, and Hoskin Lake granite.

Upper Precambrian rocks are represented by diabase dikes that cut the Quinnesec formation and Hoskin Lake granite.

The Lower and Middle Precambrian rocks have been tilted to a vertical position and have been metamorphosed in the greenschist facies of regional metamorphism in the northern and eastern part of the area, in the epidote-amphibolite facies in the central part, and in the amphibolite facies in the southwestern part. This metamorphism occurred in two periods; (1) between the Lower and Middle Precambrian, and (2) between the Middle and Upper Precambrian. In contrast with the older rocks, the Upper Precambrian rocks are unmetamorphosed.

LOWER PRECAMBRIAN ROCKS

QUINNESEC FORMATION

Definition and Distribution

The name "Quinnesec schist" was proposed by W. S. Bayley (1904) for the altered mafic igneous rocks in the southern part of the Menominee district. My detailed investigation shows that the Quinnesec includes volcanic rocks, minor interbedded sediments, and younger metagabbro intrusives. Therefore, in this report the term "Quinnesec" will be restricted to the volcanic rocks and associated sediments, the younger intrusive metagabbro being excluded. Quinnesec formation will be used rather than the older designation, because, although schist is present, it is not the most abundant rock type within the formation. Where the schistose rocks do form extensive outcrop areas, they have been mapped separately and are here called the "Pier Gorge schist member", a name derived from Pier's Gorge southeast of Niagara, Wis. where schists are well exposed.

The Quinnesec formation forms a west-northwest trending belt through the center of the area which is bordered on the north by Michigamme strata, and on the south by the Hoskin Lake granite; and, in secs. 15 and 22, T. 38 N., R. 20 E., by the Marinette quartz diorite. Also it is interrupted by Middle Precambrian metagabbro sills.

Quinnesec strata are well exposed in the following places (pl. 2): (1) south and southwest of Aurora, Wis., (2) along part of the Horserace Rapids, (3) one-half mile south of the Horserace Rapids, (4) south, southwest, and west of Niagara, Wis., (5) at Pier's Gorge, and (6) east of U. S. Highway 8 near the southern edge of the area. Less extensive outcrops may be found elsewhere within the map limits of the formation. These rocks are also found as inclusions in the Hoskin Lake granite.

Description

The Quinnesec formation rocks can be divided into five groups: (1) greenstone and amphibolite, (2) metapyroclastic rocks, (3) metamorphosed sedimentary rocks, (4) Pier Gorge schist, and (5) miscellaneous rocks. Greenstone and amphibolite are the most abundant rocks in the formation and, in some places, they contain ellipsoidal and amygdaloidal structures indicating an extrusive origin. Metamorphosed pyroclastic and sedimentary rocks are not abundant but are present locally. Large areas of schistose rocks (Pier Gorge schist) are present in the central portion of the area and they probably represent highly altered flows. Finally, several rocks with unique mineralogies were found making a "miscellaneous rocks" subdivision necessary.

Greenstone and Amphibolite

Greenstone and amphibolite are the most abundant rocks in the Quinnesec formation and, excluding areas mapped as schist, may be found in almost every Quinnesec outcrop area. These rocks generally form small low outcrops, but some large exposures are found south of Niagara and southwest of Aurora, Wis. Most of the large outcrop areas shown on plate 2 are actually groups of small outcrops separated by soil-covered areas. The knobs of greenstone and amphibolite commonly have gentle slopes except where an outcrop ends along a schistose zone. Here, steep slopes as much as 20 feet high may be present.

Quinnesec strata included in the Hoskin Lake granite consist mainly of amphibolite. These inclusions range from a few feet to 3,000 feet in length and most are cut by dikes and stringers of granite.

The Mineral composition of the greenstone and amphibolite indicates that they have been derived from mafic igneous rocks. Moreover, the local presence of ellipsoidal (pillow) and amygdaloidal structures shows that they were, in part, flows. The least deformed pillows are 1 to 2 feet long and 6 to 12 inches wide (fig. 1), but in most places they are deformed so that their length may be as much as ten times their width. These pillow structures may be observed in the NW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 18, T. 38 N., R. 20 E., the NE$\frac{1}{4}$ sec. 8, the SW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 14, and in sec. 15, T. 39 N., R. 30 W., and in the NE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 19, T. 38 N., R. 21 E. Only those in sec. 18, T. 38 N., R. 20 E. are well enough preserved to determine top directions and here the lava flows stand nearly vertical with their tops facing southeast. Vesicular flows with

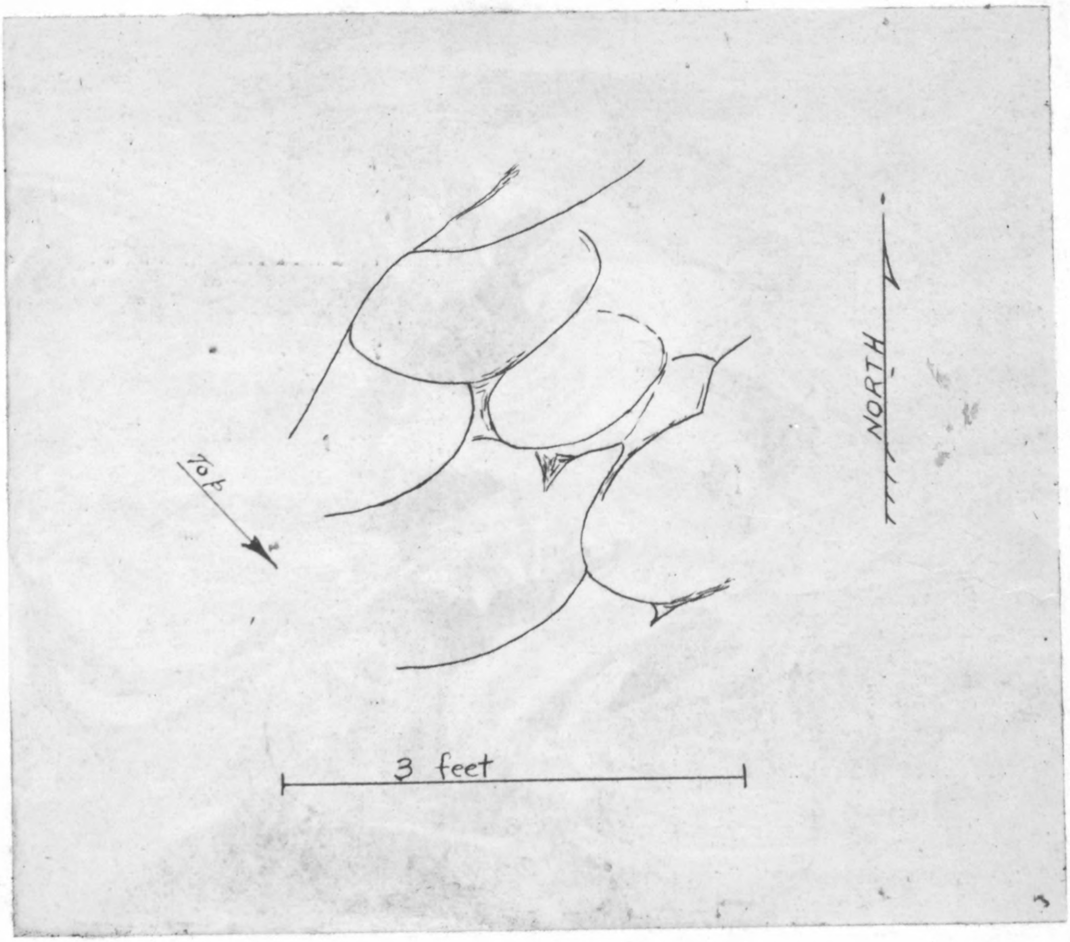


Figure 1. Sketch map of ellipsoidal structures in amphibolite. NW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 18, T. 38 N., R. 20 E.

calcite- or quartz-filled amydales occur in the $NW\frac{1}{4}SE\frac{1}{4}$ sec. 14, T. 38 N., R. 20 E. and along the north edge of sec. 3, T. 39 N., R. 31 W.

The greenstones are commonly light to dark green or gray-green, or locally they may be mottled gray-green and rusty brown. They are massive or slightly foliated and are fine to medium grained, usually too fine to permit identification of individual minerals in hand specimen. Seams of green chloritic schist as much as 1 inch wide and parallel with the regional structural trend, are with the greenstone in many places. Porphyritic greenstone with phenocrysts of altered tan feldspar, glassy quartz, or black amphibole in a fine-grained green matrix are exposed locally. The greenstones are cut in places by veins of quartz or calcite and in a few places they contain grains of pyrite. On a weathered surface, these rocks are dark brown, dark brownish gray, reddish brown, or dark gray, and a thin film of limonite or hematite commonly coats foliation or joint planes.

In the amphibolites the individual grains are slightly larger than in the greenstones and, in some hand specimens, black hornblende can be identified. These rocks are darker than the greenstones; their color varies from dark green to greenish black to black. They are either massive or foliated and, in some places, lineated. Like the greenstones, they include porphyritic varieties which consist of light to greenish-gray altered plagioclase phenocrysts in a medium-grained, greenish-black groundmass. Quartz veins cut many of these rocks but calcite veins are rare. The amphibolites commonly weather brown or brownish black, and in the porphyritic varieties, the phenocrysts commonly stand up in relief on weathered surfaces. In some foliated varieties, resistant bands form minute "ridges" separated by lower less resistant bands.

The varied mineralogies of these rocks as determined in thin section may be divided into the following assemblages:

(1) actinolite and/or chlorite-albite-quartz (-epidote)

(2) hornblende-oligoclase-quartz-epidote (-chlorite-biotite)

(2a) hornblende-oligoclase-quartz

(3) hornblende-andesine-quartz

(3a) hornblende-andesine-quartz-epidote

(3b) hornblende-andesine-quartz-chlorite

(4) hornblende-diopside-andesine-quartz

Assemblage (1) includes rocks called greenstone in hand specimen and assemblages (2), (2a), (3), (3a), and (3b) comprise rocks commonly called amphibolite. The amphibolite is further subdivided into oligoclase amphibolite (assemblages 2 and 2a) and andesine amphibolite (assemblages 3, 3a, and 3b). Assemblage (4) rocks are not abundant and they are pyroxene-bearing amphibolites. The distribution of the various assemblages is shown on plate 3.

As will be discussed in detail later, the transition from greenstone to oligoclase amphibolite to andesine amphibolite to pyroxene-bearing amphibolite represents increasing metamorphic grade. The greenstones were probably metamorphosed in the greenschist facies, the oligoclase amphibolites in the epidote-amphibolite facies, and the andesine amphibolites and pyroxene-bearing amphibolites in the amphibolite facies.

Greenstones, or rocks with assemblage (1) mineralogy, are exposed in the northern and eastern parts of the Quinnesec formation belt, north of the isograd separating the greenschist from the epidote-amphibolite facies (pl. 3). These rocks are massive or slightly foliated, and are fine to medium grained and in some places porphyritic. Remnants of a diabasic texture are visible in some specimens; others have an irregular texture consisting of a mat of fine-grained alteration minerals. Plate 4 is a photomicrograph of well preserved, but abnormally coarse, diabasic texture in greenstone.

The greenstones consist mainly of actinolite or chlorite or both, albite, and in most specimens, epidote. Small amounts of quartz and leucoxene are in all of the thin sections studied, and minerals present in minor amounts include pyrite, calcite, hematite, aircon, magnetite, biotite, muscovite, and sericite. The estimated modes of eight typical greenstones are shown in Table 2. In general, where the actinolite and epidote content is high, the chlorite and albite content is low, and excluding samples 3 and 8, the sum of actinolite and chlorite, and of albite and epidote is about the same in all specimens.

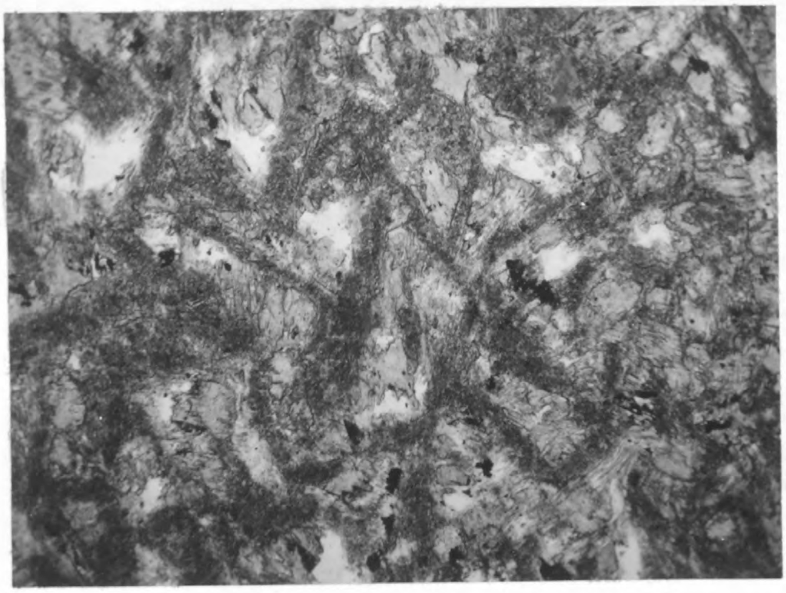


Plate 4. Photomicrograph of diabasic texture in greenstone. Mainly reddish-brown albite (dark gray) and pale green chlorite (light gray). Black areas are leucoxene and magnetite and white areas are holes in the slide. Plane polarized light. x40.

Table 2. Estimated modes of typical greenstones.

	1	2	3	4	5	6	7	8
Albite 1/	25	15	10	40	45	50	45	35
Actinolite	45	40	35	30	15	10	0	30
Epidote minerals 2/	25	40	20	15	tr	0	0	0
Chlorite	tr	tr	25	10	25	35	40	5
Calcite	tr	0	0	tr	tr	tr	5	20
Other	5	5	10	5	15	5	10	10

tr - trace

1/ includes some quartz

2/ includes epidote, clinzoisite, zoisite, and saussurite

1 - SW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 21, T. 38 N., R. 21 E.

2 - SE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 14, T. 39 N., R. 30 W.

3 - NE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 15, T. 38 N., R. 20 E.

4 - SW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 24, T. 39 N., R. 30 W.

5 - NW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 20, T. 38 N., R. 21 E.

6 - SW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 24, T. 39 N., R. 30 W.

7 - NW$\frac{1}{4}$SE$\frac{1}{4}$ sec. 14, T. 38 N., R. 20 E.

8 - SW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 24, T. 39 N., R. 30 W.

The common amphibole in the greenstones is actinolite which forms either stout fibers or bundles of thin fibers averaging 0.25 mm long with a maximum length of 0.7 mm. Actinolite is generally colorless or pale green and has an extinction angle ($Z \wedge c$) of 16 to 19°. Pseudomorphs after original igneous minerals were not observed. Specimens rich in chlorite and poor in epidote contain a slightly different amphibole. In these specimens the amphibole is mottled; part is pleochroic with X = colorless, Y = olive green, and Z = bluish green and the other part is either colorless or pleochroic with X = brown, Y and Z = reddish brown.

Plagioclase is commonly altered, but in some places, crude lath-shaped plagioclase crystals arranged to suggest a diabasic texture may be seen (pl. 4). These laths are either colorless or reddish brown and they have an average length of 0.5 mm with the maximum observed being 0.9 mm. In most places, however, plagioclase forms very small colorless grains within a mat of chlorite, epidote, or sericite. Because of their small size, extinction angle determinations could be made on plagioclase grains from only two specimens. One specimen contains albite (An_{10}), the other, sodic oligoclase (An_{11}). In other greenstone thin sections, the plagioclase has an index of refraction lower than balsam; therefore, albite or sodic oligoclase are the only plagioclase feldspars present. In prophyritic greenstones, the phenocrysts generally are altered plagioclase containing many inclusions of sericite, actinolite, and epidote. These phenocrysts have a maximum diameter of 2.5 mm.

Minerals of the epidote group vary from fine-grained, brown, aggregates of saussurite in which individual minerals are practically indistinguishable to anhedral crystals of epidote, clinozoisite, or zoisite. The crystals are as much as 0.2 mm across and some are zoned with epidote centers and clinozoisite borders. Laths of plagioclase are commonly interrupted by masses of epidote minerals, thus indicating that the epidote formed from plagioclase. In places, plagioclase phenocrysts have been completely replaced by fine-grained epidote and clinozoisite; the rocks now consist of large areas of epidote and clinozoisite in a fine-grained matrix. Coarse grains of epidote and clinozoisite as much as 0.5 mm long also occur with quartz in veins.

Small fibers of chlorite are scattered throughout many specimens and this mineral shows no relationship to original minerals. The chlorite is commonly pale to moderate green with anomalous olive-drab interference colors, but in one specimen it is gray green with deep blue interference colors. Amygdales in some specimens are composed of bundles of chlorite fibers and calcite.

All of the specimens studied contain a small amount of quartz which may be found in one of three environments. In most specimens it forms small clear grains (0.1 mm) in a mat of chlorite or epidote minerals. In one specimen, it forms irregular phenocrysts, and finally, coarse-grained quartz is commonly associated with epidote and calcite in small veins.

Leucoxene is a common accessory mineral in the greenstones and in one place it comprises 10 percent of the rock. It forms irregular masses which average 0.2 mm across, and, in some places, is associated with tiny, brown grains of sphene.

Calcite is commonly associated with quartz in veins but is rare elsewhere in the rocks. A few small calcite grains are scattered throughout some of the specimens and it forms 20 percent of one specimen.

Some epidote-poor greenstones contain muscovite or sericite as an alteration product of plagioclase. Here, the plagioclase is commonly crowded with sericite or muscovite inclusions.

Several specimens of greenstone contain irregular grains of pyrite and its weathering products, hematite and limonite. One specimen studied contained a few grains of magnetite, probably remnants which escaped alteration to leucoxene. Biotite was also detected in one specimen associated with amphibole, and a few zircon crystals were found in another.

A specimen collected from the SE$\frac{1}{4}$NW$\frac{1}{4}$ sec. 21, T. 38 N., R. 21 E. appears in thin section to be intermediate between assemblage (1) and assemblage (2). This rock consists of poikiloblastic plates of amphibole as much as 0.7 mm long in a groundmass of fibrous amphibole and equant albite grains averaging 0.2 mm across. The large amphibole plates are moderately pleochroic with X = pale straw, Y = olive green, and Z = bluish green. In part of the specimen, the amphibole is mottled with patches which show X = pale straw, Y and Z = greensih brown. The fibrous amphibole in the groundmass is pale green. The plagioclase forms more regular and more discrete grains than in a typical assemblage (1) rock and it contains tiny inclusions of its alteration product, epidote. Leucoxene is rather abundant in this specimen and small amounts of calcite, chlorite, and pyrite are also present. Unfortunately, this rock is not proved to be transitional between assemblages (1) and (2) by field facts, and its variation from a typical assemblage (1) rock is probably due to its proximity to a metagabbro sill.

Assemblage (2), hornblende-oligoclase-quartz-epidote (-chlorite-biotite), is the most common assemblage of the oligoclase amphibolites. Rocks of this type are found mainly in the central and western portions of the belt of Quinnesec formation rocks, within the isograds delimiting the epidote-amphibolite facies (pl. 3). Two exceptions, however, are found; one in the NW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 16, T. 38 N., R. 20 E., and one in the SE$\frac{1}{4}$NE$\frac{1}{4}$ sec.

11, T. 38 N., R. 19 E. Both are found within the amphibolite facies isograd.

Nine thin sections of oligoclase amphibolite were studied. Because of alteration, plagioclase determinations could not be made on three of the specimens but since their mineralogy and texture are similar to the other oligoclase amphibolite specimens, these three rocks are included here. The oligoclase amphibolites consist predominantly of hornblende, oligoclase, and epidote with a small amount of quartz. Sphene, chlorite, biotite, and calcite are common accessory or alteration minerals, and sericite, zircon, pyrite, hematite, magnetite, apatite, and tourmaline are present locally in small amounts. Table 3 gives the estimated modes of seven typical rocks of this assemblage.

Texturally, the oligoclase amphibolites are somewhat variable. Some specimens are rather fine grained and preserve traces of a diabasic texture, and are thus texturally similar to some of the assemblage (1) rocks, whereas other specimens are crystalloblastic and owe their textures wholly to metamorphic processes. Hornblende prisms in these rocks are roughly oriented to one plane, thus giving the rock a crude to well-developed foliation. The plagioclase and quartz grains are small and interstitial to the hornblende prisms. Altered plagioclase and hornblende phenocrysts are found in some of the specimens with diabasic texture, and small veins of epidote and quartz are present in a few.

Table 3. Estimated modes of typical oligoclase amphibolites.

	1	2	3	4	5	6	7	8
Hornblende	50	35	40	40	45	30	30	50
Oligoclase-quartz	10	30	35	40	30	40	45	45
Epidote-zoisite	40	25	25	20	15	$12\frac{1}{2}$	tr	tr
Biotite	0	10	0	tr	10	5	0	5
Chlorite	0	0	0	tr	tr	$12\frac{1}{2}$	15	0
Calcite	tr	0	tr	tr	0	tr	5	0
Sphene-leucoxene	0	tr	tr	0	tr	tr	5	tr
Plagioclase composition % anorthite	--	27	26	--	26	16	26	18-24

tr - trace

1 - NE$\frac{1}{4}$NW$\frac{1}{4}$ sec. 16, T. 38 N., R. 20 E.

2 - SE$\frac{1}{4}$SW$\frac{1}{4}$ sec. 7, T. 39 N., R. 30 W.

3 - NW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 16, T. 38 N., R. 20 E.

4 - NW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 8, T. 39 N., R. 30 W.

5 - NW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 8, T. 39 N., R. 30 W.

6 - SW$\frac{1}{4}$SE$\frac{1}{4}$ sec. 7, T. 38 N., R. 20 E.

7 - SW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 3, T. 38 N., R. 19 E.

8 - Average of 3 specimens of oligoclase amphibolites with 2a mineralogy.

The hornblende in the oligoclase amphibolites is generally darker colored than that in assemblage (1) rocks with X = straw to yellow, Y = olive-green, and Z = bluish green. The colors vary from pale to very dark and in some specimens individual grains may have deeply colored cores with pale mantles. Extinction angles ($Z \wedge c$) vary from 17° to 19°. It is apparently an aluminous hornblende. In the specimens showing crude diabasic textures, the hornblende is somewhat fibrous with individual grains varying from 0.1 to 0.2 mm long. In the specimens showing crystalloblastic textures, the hornblende forms subhedral prisms which are diamond shaped in sections perpendicular to the c-axis and lath shaped in longitudinal sections. These hornblende grains are generally between 0.2 and 0.4 mm long; however, prisms as much as 0.8 mm long were observed. One specimen contained a few phenocrysts of twinned hornblende 1.4 mm across.

The plagioclase in the oligoclase amphibolites is oligoclase (An_{16} to An_{27}), and it is zoned normally in a few places. In the diabasic amphibolites it is clear and is found in laths from 0.25 to 0.4 mm long. These laths are interrupted by epidote alteration or by inclusions of fibrous amphibole. The plagioclase in the crystalloblastic oligoclase amphibolites is associated with quartz in a mosaic of anhedral grains which vary from 0.07 to 0.4 mm across. The plagioclase grains are smaller than the hornblende prisms and in specimens where this difference is great, the plagioclase-quartz mosaic appears interstitial to the hornblende prisms.

The plagioclase of these mosaics is usually clear, but in some places, it is slightly altered to sericite. Twinned plagioclase is only rarely present. Phenocrysts of plagioclase as much as 1.5 mm across are found in the porphyritic varieties of these rocks, and here the plagioclase is highly altered to epidote and contains numerous inclusions of fibrous hornblende.

Quartz is universally associated with plagioclase in the crystalloblastic specimens and is identical to plagioclase in its habit and grain size. An exact evaluation of the quartz-plagioclase ratio cannot be made because these two minerals are so similar in thin section; however, quartz appears subordinate to plagioclase in all but one specimen. This specimen is from along a contact with a granite dike and it appears likely that silica was introduced from the granite. Quartz with epidote also forms small veinlets in many specimens.

Minerals of the epidote group in the oligoclase amphibolites are generally different from those found in the assemblage (1) rocks. Epidote is the commonest member of this group present, zoisite and clinozoisite are only locally present and "saussurite" is absent. The epidote minerals vary from masses of fine-grained anhedral crystals to euhedral crystals as much as 0.4 mm long. They are generally coarser where they are associated with plagioclase phenocrysts than where associated with plagioclase in the groundmass. In one specimen where the plagioclase is almost entirely altered, zoisite and clinozoisite aggregates form perfect pseudomorphs after original plagioclase laths. Epidote minerals, in grains as much as 0.7 mm long, are also found in vein quartz.

Small amounts of sphene are present in almost all of the oligoclase amphibolite specimens studied. It is brown and is found either as masses of small grains or as wedge-shaped euhedral crystals as much as 0.2 mm long. One specimen contained an exceptional euhedral porphyroblast 1.5 mm across.

Chlorite is found in many of the oligoclase-amphibolite specimens, but in most it is not abundant. It is colorless to pale green and has brownish gray or anomalous blue interference colors. Chlorite forms plates as much as 0.2 mm long and in some places is intergrown with biotite.

Biotite is found in half of the oligoclase amphibolite specimens studied. Its color varies from X = colorless and Y = Z = pale brown to X = pale brown and Y = Z = dark brown, and it forms plates which reach a maximum size of 0.5 mm. The plates generally lie parallel to the foliation of the rock, but in one specimen they show no preferred orientation and lie athwart the main foliation of the rock as imparted by hornblende prisms.

Sericite is found as a plagioclase alteration product, but it is usually only a minor constituent. In one place, poikiloblastic plates of muscovite are associated with zoisite in altered plagioclase laths. Small amounts of calcite are also found in some specimens, but it is nowhere an important constituent as it is in some of the assemblage (1) rocks.

Magnetite, pyrite, hematite, zircon, euhedral gray-green tourmaline, and apatite are accessory minerals which are present in some of the oligoclase amphibolites.

Assemblage (2a), hornblende-oligoclase-quartz, is a special variety of assemblage (2) containing no chlorite and practically no epidote. Rocks with this mineralogy are found near metagabbro intrusions in the SW$\frac{1}{4}$ sec. 7, T. 39 N., R. 30 W. and in the NE$\frac{1}{4}$ NW$\frac{1}{4}$ sec. 10, T. 38 N., R. 19 E., and within the amphibolite isograde in the SE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 11, T. 38 N., R. 19 E. Thus, it appears that assemblage (2a) rocks may represent rocks intermediate between assemblage (2) and assemblage (3) rocks.

Four thin sections of assemblage (2a) rocks were studied and except for the almost complete absence of epidote and chlorite, these rocks are identical with the assemblage (2) rocks having a crystalloblastic texture. They consist predominantly of subhedral, pleochroic hornblende and a mosaic of oligoclase (An_{18} to An_{24}) and quartz, with minor biotite, sphene, magnetite, pyrite, hematite, zircon, apatite, sericite, epidote, and clinzoisite. The average of the estimated modes of three of these specimens is given in Table 3, column 8.

The andesine amphibolites have been subdivided into three assemblages: assemblage (3), hornblende-andesine-quartz; assemblage

(3a), hornblende-andesine-quartz-epidote; and assemblage (3b), hornblende-andesine-quartz-chlorite. Rocks showing these mineral assemblages are all essentially the same except for the presence of a little epidote in (3a) and a little chlorite in (3b) so they will be described together. Andesine amphibolites are found in the south-central and southwestern portions of the belt of Quinnesec formation rocks, south of the isograd separating the epidote-amphibolite from the amphibolite facies (pl. 3). Andesine amphibolites without epidote or chlorite (assemblage 3) are found in the western part of the area, south of the Horse-race Rapids, and south and southwest of Aurora, Wis. Epidote bearing andesine amphibolites (assemblage 3a) are also widely distributed and are found south of Niagara, Wis. and south of the Horserace Rapids. In the latter area, they are associated with non-epidotic amphibolites. Chloritic andesine amphibolites (assemblage 3b) are rare and are found in only two places: (1) south of Niagara, Wis. and (2) south of Aurora, Wis. In addition, a specimen collected from the large inclusion in the Hoskin Lake granite in the $W\frac{1}{2}$ sec. 18, T. 38 N., R. 20 E. proved to be an andesine amphibolite with assemblage (3) mineralogy.

Twenty-five thin sections of andesine amphibolites were studied; six are not shown on plate 3 because some of the specimens were borrowed and their exact location is not known. Except for the presence of a more calcic plagioclase and for the scarcity of epidote and chlorite, these rocks are almost identical with the crystalloblastic oligoclase amphibolites. They consist predominantly of aluminous hornblende and a mosaic of andesine and quartz with minor amounts of epidote, chlorite, sericite, muscovite, magnetite, pyrite, sphene, biotite, zircon, hematite, calcite, apatite, tourmaline, and garnet.

Texturally, many of these rocks are similar to the crystalloblastic oligoclase amphibolites and show a rough parallelism of hornblende prisms. Other specimens are granoblastic with practically no foliation; still others show a crude banding. Plate 5 is a photomicrograph of the pillow amphibolite illustrated in figure 1; it shows the typical, non-foliated granoblastic texture. In most of the andesine amphibolite specimens, hornblende forms grains which are larger than the plagioclase and quartz grains; thus, the latter two minerals appear interstitial to the hornblende. However, in some of the granoblastic specimens, the hornblende is smaller and forms tiny grains set in a plagioclase-quartz mosaic. One specimen showing a relict porphyritic texture consisted of altered plagioclase phenocrysts set in a crystalloblastic groundmass. Small veinlets of quartz, plagioclase, sericite, and zoisite or of epidote and quartz cut some of the epidotic specimens; and quartz, calcite, and chlorite veinlets cut one of the chloritic varieties.

The mode of chloritic andesine amphibolite is given in table 4.

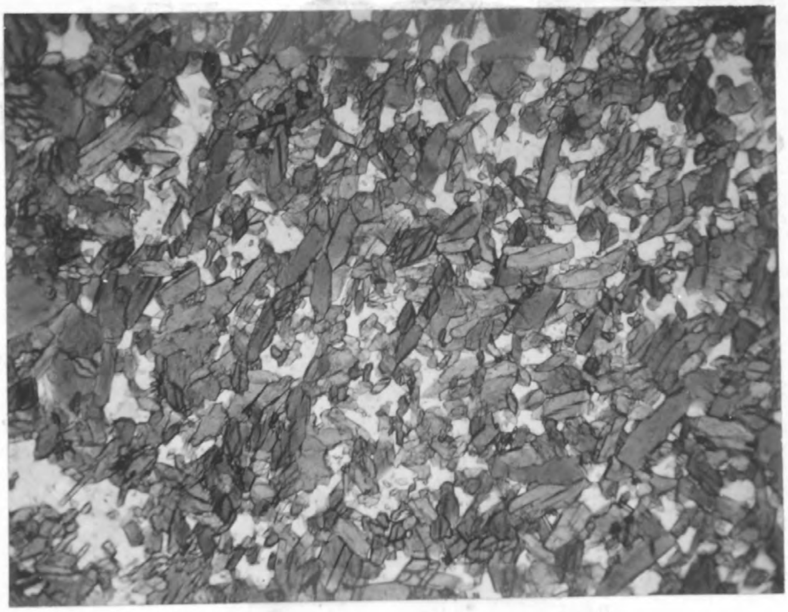


Plate 5. Photomicrograph of granoblastic texture in andesine amphibolite. Hornblende (gray) and andesine-quartz mosaic (white). Plane polarized light. x40.

Table 4. Point count mode of chloritic andesine amphibolite.

	1
Hornblende	51.7
Quartz-andesine (An_{35})	43.2
Chlorite	2.9
Magnetite	1.6
Biotite	.4
Apatite	.2
Tourmaline	tr

tr - trace

1 - SE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 11, T. 38 N., R. 19 E.

The hornblende in the andesine amphibolites is much like that in the oligoclase amphibolites except that it is commonly a little darker in color, but some very pale hornblende is also present. Hornblende forms from 35 to 55 percent of the andesine amphibolites. It is moderate to deeply colored. Pleochroic variations in color are X = straw, Y = olive green to bright green, and Z = blue green to brownish blue green; $Z \wedge c$ 16 to 24 degrees. It commonly forms anhedral to subhedral prismatic crystals which range from 0.05 to 0.5 mm long, but anhedral poikiloblastic plates as much as 1.5 mm across were observed. Some grains show a basal parting, and a few are twinned.

Plagioclase and quartz form from 40 to 60 percent of the andesine amphibolites and generally form a mosaic of clear, irregular or equant grains averaging from 0.05 to 0.2 mm across. Quartz, which is also found in small veinlets, is subordinate to the plagioclase in all but two of the specimens studied. The plagioclase is andesine (An_{30} to An_{50}) and commonly shows polysynthetic albite twinning. In many specimens, the plagioclase is partly altered to sericite and in one porphyritic specimen, the plagioclase phenocrysts are altered to zoisite, clinozoisite, and muscovite, whereas the groundmass plagioclase is clear and unaltered.

Epidote minerals are absent in many andesine amphibolites but in some they form as much as 10 percent of the rock so the separation of the epidote-rich rocks as a subassemblage, assemblage

(3a), is warranted. In the epidote-rich specimens, the epidote minerals are generally restricted to: (1) veins, (2) plagioclase phenocrysts, or (3) irregular patches. Zoisite, clinozoisite, and epidote were all observed in veins where they form coarse grains as much as 0.7 mm long. They are found in the veins either without other minerals or associated with quartz or quartz and muscovite. In a porphyritic specimen studied, plagioclase phenocrysts are altered to fine- to medium-grained clinozoisite and some muscovite. Other specimens may contain irregular shaped patches rich in epidote minerals; these may represent either irregular veinlets or highly altered phenocrysts. Small amounts of subhedral epidote grains from 0.05 to 0.15 mm across are scattered throughout the groundmass of some of the specimens with assemblage (3) mineralogy, but the amounts are not sufficiently large to warrant classifying the rocks with the epidotic amphibolites.

Chlorite in the chloritic andesine amphibolites may be: (1) restricted to veins, or (2) restricted to irregular patches or streaks. The chlorite is pale green with either blue or gray interference colors, and it may be intergrown with biotite. In the veins, it is associated with quartz and calcite. Traces of chlorite are also found in some of the assemblage (3) or (3a) andesine amphibolites, but nowhere in amounts sufficient to warrant classifying the specimens as chloritic.

Sericite has formed as an alteration of plagioclase, but it is not abundant. Some specimens contain muscovite with quartz and epidote in veins or with epidote or clinozoisite in altered plagioclase phenocrysts. Magnetite is present in 75 percent of the specimens studied and in one place it comprises 10 percent of the rock. It forms irregular grains which are from 0.05 to 0.075 mm across and which in some places are rimmed by a narrow zone of sphene. In addition to rimming magnetite, sphene also forms anhedral to subhedral grains 0.1 to 0.2 mm across. In one specimen, euhedral sphene crystals as much as 0.4 mm across are found in a vein with epidote, and are pleochroic in pale brown to red-brown. Small irregular grains of pyrite are present in some of these rocks but are nowhere abundant. In a few places, brown biotite in flakes as much as 0.3 mm long are associated with either chlorite or hornblende. Calcite is commonly found in veins but is rare in the main part of the rock. Euhedral, colorless garnet crystals, 0.2 mm across, were observed in one specimen and euhedral, blue-green tourmaline in another. Apatite and zircon are locally present as accessory minerals and hematite as a minor secondary product.

Two specimens collected from a mafic inclusion, probably related to the Quinnesec formation, in the Hoskin Lake porphyritic granite in the NW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 16, T. 38 N., R. 20 E. contained pyroxene and are here separated as assemblage (4), hornblende-diopside-andesine-quartz. These rocks consist mainly of hornblende, diopsidic pyroxene, and andesine (An_{34}) with minor amounts of quartz, epidote-clinozoisite, sphene, sericite, pyrite, magnetite, and calcite.

One of the two specimens is mainly an amphibolite with assemblage (3) mineralogy; pyroxene is absent in this specimen except in one small patch at one end of the thin section. Here, the pyroxene forms either poikiloblastic plates 0.6 mm across or tiny granules 0.05 mm across. Epidote and clinozoisite with the same habit are associated with the pyroxene; no other minerals are found in the pyroxene-rich area.

The second specimen from the pyroxene-bearing inclusion is quite different. It consists of large subhedral plagioclase plates, possibly porphyroblasts, 2.5 mm long set in a fine-grained mosaic of pyroxene, plagioclase, and quartz. Some grains of pyroxene as much as 1.5 mm across are also present. The pyroxene is colorless to very pale green, monoclinic, with $Z \wedge c$ 40 degrees, and a moderate 2V. It is probably diopsidic. Some subhedral grains of epidote and clinozoisite are distributed sporadically through the specimen and they are often zoned with clinozoisite centers and epidote borders. Green hornblende grains from 0.2 to 0.6 mm long are locally present, and in some places sericite formed from the alteration of plagioclase.

Rocks from the outcrops in the western part of the area near the Michigamme contact along the north edge of sec. 3, T. 39 N., R. 31 W. contain some features similar to those found in rocks described in this section, but mineralogically it is impossible to classify them according to the assemblages as set forth in preceding pages. These rocks are hornblende schists which in hand specimen appear fine grained, green, and strongly foliated and lineated. Some specimens contain tubular-shaped streaks which average 4.0 mm long of colorless quartz or brown calcite or both. These streaks probably represent stretched amygdales, and the rock therefore, is probably a metamorphosed flow.

Two specimens from this outcrop area were collected for microscopic study, one with and one without amygdales. The non-amygdaloidal specimen consists of parallel-oriented slender blue-green hornblende prisms and brown biotite flakes in a matrix of clear untwinned albite (An_3) and some clear quartz. The blue-green hornblende is typical of assemblage (2) or (3) rocks, whereas the albite is typical of assemblage (1) rocks. The hornblende prisms and the biotite flakes average 0.15 mm long but some are as much as 0.4 mm long. The average size of the grains in the albite-quartz groundmass is 0.1 mm. Clusters of strongly pleochroic yellow-green epidote grains as much as 0.7 mm across are scattered throughout the slide. The clusters are circular- or lens-shaped with their long axes parallel with the foliation of the rock. Pyrite, magnetite, hematite, and sphene are also present.

In the amygdaloidal specimen, the hornblende is more fibrous, biotite is less abundant, and the albite-quartz groundmass is less abundant and finer grained than in the non-amygdaloidal variety. The striking feature of this specimen is the amygdales which appear in thin section as coarse-grained streaks of calcite with some quartz, or of clear quartz with some brown biotite oriented across the foliation of the rock (pl. 6).

The greenstones and amphibolites have mineral assemblages suggesting that they were derived from mafic igneous rocks. Flow structures are found in a few places, but commonly the structures and textures of the rocks are secondary. It is concluded that many of the greenstones and amphibolites originated from basalt flows; others undoubtedly represent altered pyroclastic rocks, fine grained dikes or sills, and so forth, indistinguishable in their present recrystallized state.

Metapyroclastic rocks

Metamorphosed mafic rocks which are of unmistakable pyroclastic origin are not abundant in the Quinnesec formation, but volcanic breccia and possibly tuff are well-exposed in sec. 15, T. 39 N., R. 30 W. A less well-preserved crystal tuff or fine volcanic breccia crops out in the SE$\frac{1}{4}$SW$\frac{1}{4}$ sec. 7 and NW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 8, T. 39 N., R. 30 W.

The best volcanic breccia exposures in sec. 15 are along the Michigan bank of the Menominee River, 500 feet south of the Kimberly-Clark Paper Company power dam at the Little Quinnesec Falls. The most striking part of this outcrop consists of breccia showing large, subangular slaty fragments set in a fine-

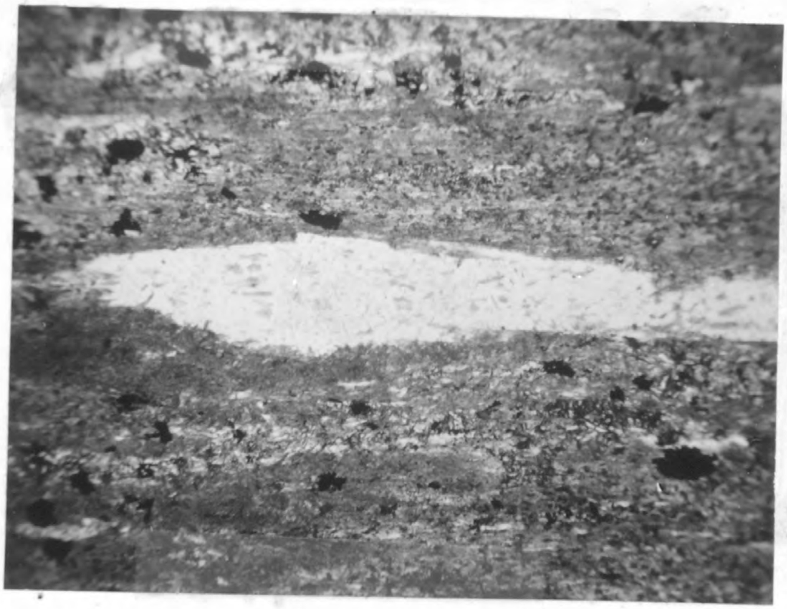


Plate 6. Photomicrograph of stretched amygdale in hornblende schist. White lens at center is stretched amygdale consisting of quartz (white) and biotite (light gray). Groundmass is mainly hornblende (gray) with some albite and quartz (white), and magnetite and pyrite (black). Plane polarized light. x23.

grained phyllitic matrix (pl. 7, A & B). The slaty fragments are as much as ten feet across and consist of very fine grained, greenish black material with a slaty cleavage or foliation. In some fragments, the formation of the foliation or cleavage predated the incorporation of the fragment into the breccia (pl. 7, A). The matrix of the breccia is greenish black, strongly foliated and lineated phyllite (pl. 7, C) containing numerous quartz-rich pods ranging from 1/8 to 2 inches across. The quartz-rich pods weather gray and stand out as tiny knobs on the weathered outcrop surfaces surrounded by the less resistant light-brown phyllitic matrix. A few tiny clear quartz grains are also scattered throughout the matrix. This coarse breccia is exposed for a distance of about 65 feet along the river bank. Southward, the large fragments become less abundant and the rock grades into a coarse tuff or fine-grained volcanic breccia which is identical to the matrix of the coarse breccia. To the north, the volcanic breccia outcrop area is covered by sand. Late quartz veins cut the breccia, passing indiscriminantely from matrix into fragment.

In thin section, the phyllitic matrix can be seen to consist of rounded, in some cases broken or embayed, clear quartz grains ranging from 0.3 to 1.5 mm in diameter set in a fine-grained chloritic groundmass with an average grain size of 0.05 mm. The quartz-rich pods which are so striking on a weathered surface

A.

B.

C.

Plate 7. Photographs of metamorphosed volcanic breccia. A. Note folded banding in large slate fragment in center of picture. B. Irregular slate fragments in phyllitic matrix. C. End view of volcanic breccia boulder. Note strong foliation and stretched fragments.

are less conspicuous in thin section. They are actually areas richer in fine-grained quartz than the rest of the matrix and they consist predominantly of quartz grains 0.05 mm in diameter with some pale green chlorite (penninite) and calcite. Most of the groundmass away from the quartz-rich pods consists of quartz and penninite with lesser amounts of muscovite and calcite. In addition, there are several chlorite-rich patches in the specimen studied. These chlorite-rich areas form either streaks across the slide or masses "interstitial" to the quartzose pods. Some pyrite, magnetite, hematite, and limonite grains are scattered throughout the specimen except in the quartzose pods. Some leucoxene and plagioclase were also noted.

In thin section, the slaty fragments appear very fine grained with an average grain size of 0.025 mm. The rock is mostly quartz and pale green chlorite with gray birefringence. Foliation is imparted by parallel-oriented chlorite flakes. Some fine-grained muscovite is also present and hematite and limonite pods 0.2 to 0.6 mm long are scattered throughout the specimen. These pods are elongated parallel with the foliation, but the chlorite flakes imparting the foliation do not bend around the pods; instead, the flakes terminate against the pods. Some leucoxene is also found in the specimen.

Along the Menominee River, 350 feet southeast of the volcanic breccia exposure and southeast of a younger metagabbro dike is an outcrop of a fine-grained, dark greenish gray rock which appears in thin section to be an altered tuff. It consists of angular fragments of albite which average 0.2 mm in diameter set in a fine-grained matrix of quartz and possibly albite. The average grain size of the matrix is 0.03 mm. The albite fragments are found either as scattered isolated grains or in clusters. Pale green penninite is scattered throughout the specimen or more rarely it forms clusters. A few clusters of epidote grains 0.15 mm across are also present. Leucoxene, pyrite, and limonite occur as minor accessories. A second specimen of this rock contains albite fragments set in a foliated groundmass.

A rock probably derived from coarse-grained crystal tuff or fine-grained volcanic breccia crops out along the Menominee River in the SE$\frac{1}{4}$SW$\frac{1}{4}$ sec. 7, T. 39 N., R. 30 W. associated with an oligoclase amphibolite with assemblage (2b) mineralogy. In the field, the rock looks like a porphyritic amphibolite with dull-gray altered feldspar set in a fine-grained greenish black matrix. In thin section, the feldspar (plagioclase) grains look fragmental and are set in a matrix of finer grained plagioclase, quartz, hornblende, biotite, and other minor constituents. The plagioclase fragments (An_{27}) are as much as 5.0 mm long, are angular, and show no crystal outlines. The edges of these fragments are very irregular and grade into the surrounding material which has also invaded them in the form of small quartz or quartz-hornblende-biotite veinlets. Biotite and hornblende are included in the plagioclase fragments, but the main alteration product of this mineral is a granular aggregation of small epidote and clinozoisite grains. Hornblende is usually the predominant mineral in the groundmass and it forms anhedral grains as much as 0.5 mm long. It is moderately pleochroic with X = light tan, Y = green, and Z = bluish green and in some places, it is associated with biotite. Smaller grains of quartz, clinozoisite, epidote, and some feldspar are mixed with the hornblende. The relative abundance of these minerals varies greatly; some portions of the groundmass are almost all hornblende with a little biotite, whereas other portions may be almost all quartz, clinozoisite, and epidote.

The only other known exposure of a metapyroclastic rock in the area is along the Menominee River in the NW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 8, T. 39 N., R. 30 W. The rock here is fine-grained volcanic breccia or coarse tuff similar to the matrix material of the exposure south of the Little Quinnesec Falls dam. The maximum size of the fragments here is 1.0 cm. No thin section of this specimen was studied.

Metamorphosed Sedimentary Rocks

Rocks believed to represent metamorphosed sediments are found in several places in the Quinnesec formation, but they are nowhere abundant and form only small outcrops associated with the more common greenstone and amphibolite. These metasediments can be divided into four groups: (1) iron-formation, (2) biotite schist, (3) quartzite, and (4) arkose.

Metamorphosed iron-formation was found in the Quinnesec formation in two places south of the Horserace Rapids; in the NE$\frac{1}{4}$SW$\frac{1}{4}$ sec. 12, T. 38 N., R. 19 E. and along the western edge of the NW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 7, T. 38 N., R. 20 E. It is a layered rock consisting of layers of quartz and some magnetite alternating with layers of green to greenish black amphibole. The individual layers vary from a fraction of an inch to an inch in thickness and are quite regular along strike, but because the outcrops are small, they cannot be traced very far. These rocks weather brownish black and limonite commonly coats joints. Andesine amphibolites are found in the outcrops adjacent to the iron-formation exposures, indicating that the iron-formation is in a zone of relatively high metamorphic grade for the area.

In thin section, the layered character of the rock is well displayed by alternating amphibole-rich and quartz-rich bands (pl. 8). The amphibole-rich bands consist mainly of anhedral hornblende grains averaging 0.5 mm long. The hornblende is

A.

B.

Plate 8. Photomicrographs of metamorphosed iron-formation. A. Quartz (white), hornblende (gray), and magnetite (black). Plane polarized light. x23. B. Same as A. Crossed nicols.

strongly pleochroic with X = pale yellow, Y = green, and Z = blue-green, and its index of refraction is N_y = 1.667 with Z∧c 17 to 19 degrees. Some grains show a well-developed basal parting. Subhedral grains of magnetite averaging 0.5 mm long are interstitial to the hornblende and in some places they are altered to hematite and limonite. Quartz grains are found in the hornblende-rich bands, but they are nowhere abundant.

The quartz-rich bands, which probably represent recrystallized chert, consist predominantly of clear quartz grains which average 0.2 to 0.4 mm in diameter. The quartz is thus a little larger than is common for recrystallized chert in the amphibolite facies (James, 1955, table 2). Magnetite forms inclusions in the quartz and is generally in smaller grains than the magnetite in the amphibole-rich bands. Some hornblende is also associated with the quartz and it is also smaller than the hornblende in the amphibole-rich bands.

One specimen of a wide quartz-rich band contained streaks of amphibole of a different composition than the hornblende in the other specimens. Here the amphibole has a high birefringence, Z∧c 16 degrees, and a large 2V. It is faintly pleochroic with X = pale yellow, Y = pale yellowish green, and Z = pale bluish green. It is probably an iron-rich gruneritic amphibole. Some muscovite is associated with the grunerite and some pyrite, magnetite, hematite, and limonite are also present. This quartz-rich band is bordered by bands rich in normal green hornblende.

Magnetite was separated from this specimen and yielded negative results to the hydrogen peroxide test for titanium.

The second group of rocks within the Quinnesec formation believed to be of sedimentary origin are biotite or chlorite-biotite schists. These schists are found in the SE$\frac{1}{4}$SW$\frac{1}{4}$ and the NE$\frac{1}{4}$SW$\frac{1}{4}$, sec. 7, T. 39 N., R. 30 W.; the S$\frac{1}{2}$NW$\frac{1}{4}$, sec. 12, T. 39 N., R. 31 W.; the SW$\frac{1}{4}$NW$\frac{1}{4}$, sec. 3, T. 38 N., R. 19 E.; and the NE$\frac{1}{4}$SE$\frac{1}{4}$, sec. 12, T. 38 N., R. 19 E. One specimen of a hornblende-biotite schist was found in the NE$\frac{1}{4}$SE$\frac{1}{4}$, sec. 12, T. 38 N., R. 19 E., 100 feet north of the place where a chlorite-biotite schist specimen was collected. These rocks are well foliated and in some places the foliation is crumpled. Biotite and chlorite can be identified in hand specimen and the color of the rocks varies from black in biotite-rich varieties to greenish black in chloritic ones. Some specimens rich in fine-grained quartz are gray. In some places, the rock is distinctly layered with thin calcite-, quartz-, chlorite-, or biotite-rich layers a fraction of an inch thick alternating with each other. These schists form small outcrop areas associated with amphibolite and later granitic dikes. In a few places, quartz-tourmaline veins cut the schists.

In thin section, these rocks are seen to be rather variable. They consist mainly of biotite and chlorite flakes in a granoblastic mosaic of quartz and minor plagioclase. The schistosity of the rocks is imparted by parallel-oriented chlorite and biotite flakes, and the foliation is not as distinct in the specimens from along the granite contact in sec. 12, T. 38 N., R. 19 E. where the rocks are more hornfelsic. Biotite forms flakes, commonly intergrown with chlorite (pl. 9), which vary from 0.1 mm to 0.7 mm long. They are brown with X = pale brown to colorless and Y = Z = deep reddish brown to brown to pale brown. Pleochroic haloes around zircon inclusions are present but are rare. Chlorite commonly forms flakes which are about the same size as the biotite flakes, but in some specimens, they are slightly smaller. The chlorite is pale to moderate green with interference colors ranging from gray to brown to blue or purple. In many specimens, chlorite appears to have formed later than biotite because: (1) chlorite flakes commonly penetrate biotite flakes, (2) remnants of biotite are found completely surrounded by chlorite, and (3) in some places, chlorite flakes are not as well oriented as biotite flakes, In the specimen from sec. 3, T. 38 N., R. 19 E., however, biotite flakes are oriented across the foliation of the rock as imparted by chlorite flakes, indicating that here the biotite was probably later.

The quartz and plagioclase grains in the groundmass are everywhere finer grained than the biotite flakes and are commonly finer grained than the chlorite. They average from 0.05 to 0.2 mm in diameter but are coarser in the exposures in sec. 12, T. 38 N., R. 19 E. where the metamorphic grade is higher. The quartz is clear and is more abundant than the plagioclase which is untwinned and either clear or partly altered to sericite. The plagioclase

Plate 9. Photomicrograph of banded chlorite-biotite schist. The central part consists of quartz (white), chlorite (light gray), biotite (medium gray), and leucoxene (dark gray). The band at the left side of the photograph is mainly calcite (gray). Note the banding and the chlorite-biotite intergrowths near the center. x23.

is albite (An_3) in sec. 3, T. 38 N., R. 19 E., and oligoclase (An_{29}) in sec. 12, T. 38 N., R. 19 E.; the only two specimens in which plagioclase determinations were possible in thin section.

Calcite is found in some specimens either in separate layers with quartz, in veins, or scattered throughout the specimen. A specimen from sec. 12, T. 38 N., R. 19 E. contained no chlorite but did contain a little blue-green hornblende. This specimen also contains several anhedral poikiloblastic grains of garnet as much as 0.4 mm across. Blue-green to brownish green, anhedral to subhedral tourmaline grains from 0.1 to 0.4 mm long were found in several specimens. Other accessory minerals commonly present include magnetite, pyrite, hematite, zircon, and epidote.

The amounts of the major minerals vary considerably. In the layered specimens, some layers are mostly chlorite with some biotite and quartz, others are mostly biotite with minor amounts of chlorite and quartz, whereas still others are calcite and quartz with few or no micaceous minerals (pl. 9). Unlayered specimens show similar variations in composition. The specimens from sec. 12, T. 38 N., R. 19 E. are in a higher metamorphic zone and are different in that they are rich in quartz and feldspar, which combined form from 65 to 80 percent of the rock.

The fact that the biotite schists are found primarily in areas cut by numerous granite dikes or adjacent to the contact with the Hoskin Lake granite suggests that these rocks may be genetically related to the granite. The presence of tourmaline in some may suggest that metasomatic alteration has occurred. The argument could be advanced that the biotite schists are greenstones or amphibolites metasomatically altered during emplacement of the Hoskin Lake granite. I do not believe that this is the case, but believe that the schists are metamorphosed sediments for the following reasons: (1) Not all rocks in the areas intruded by numerous granitic dikes are biotitic; most are normal greenstones or amphibolites with only a trace of biotite. (2) Biotite schists do not form an aureole around the Hoskin Lake granite pluton; specimens from the contact south and southwest of Niagara, Wis. contain no biotite. (3) Inclusions of Quinnesec formation rocks within the granite are not biotitic. And (4), the layering in some of the biotite-chlorite schists is suggestive of original bedding, but this, of course, has been selectively replaced.

Quartzite has been found in the SE$\frac{1}{4}$ and the NE$\frac{1}{4}$ of the SW$\frac{1}{4}$ sec. 7, T. 39 N., R. 30 W. where it is associated with amphibolite, biotite schist, arkose, and granite. It is a massive, fine-grained gray to brownish gray rock which weathers dark brown. One specimen of this rock contained some chalcopyrite, and a second, flakes of biotite.

The quartzite consists mainly of clear quartz grains which average 0.05 to 0.1 mm in diameter, but tiny flakes of brown biotite are scattered through one specimen and comprise about 10 percent of the rock. Coarse-grained quartz veins traverse the quartzite, and minor accessory minerals include green hornblende, magnetite, pyrite, chalcopyrite, hematite, zircon, epidote, sericite, muscovite, and feldspar.

Arkose is associated with biotite schist, quartzite, amphibolite, and granite in the NE$\frac{1}{4}$SW$\frac{1}{4}$ sec. 7, T. 39 N., R. 30 W. The arkose is very difficult to distinguish from granite in dikes because of poor exposures and because deformation and metamorphism has produced a gneissic rock, identical in appearance, from both. Many of the granitic dikes shown on plate 2 may actually be arkose altered to such an extent as to obliterate all trace of sedimentary origin. The arkose specimen collected for microscopic study is relatively undeformed and contains numerous rounded clear quartz grains believed to be of sedimentary origin. Large grains of red feldspar, flakes of black biotite, a few grains of pyrite, and some limonite are also visible in hand specimen.

In thin section, rounded to angular, clear, and in some places recrystallized and embayed, quartz grains as much as 0.1 mm in diameter, angular albite (An_9) grains as much as 3.4 mm across and loaded with inclusions of muscovite, and plates of biotite up to 1.0 mm long or nests of smaller biotite plates, are all set in a finer grained matrix. The biotite is strongly pleochroic with X = pale brown and Y = Z = deep reddish brown and pleochroic haloes are common. The matrix of the rock is extremely variable in grain size and consists mainly of quartz with some muscovite, plagioclase, microcline, and biotite. Minor accessory minerals include apatite, calcite, pyrite, and leucoxene.

Pier Gorge Schist

Pier Gorge schists are quite abundant in parts of the area; abundant enough to warrant their separation as a distinct member of the Quinnesec formation. The best schist exposures are along the Menominee River in a section known as Pier's Gorge in sec. 24, T. 39 N., R. 30 W. and secs. 13 and 14, T. 38 N., R. 20 E. Other exposures are found in the NW$\frac{1}{4}$ sec. 14, T. 38 N., R. 20 E., along some of the streets in the village of Niagara, Wis., at the Little Quinnesec Falls dam, along the north side of the railroad siding 900 feet west-southwest of this dam, and just north of the Big Quinnesec Falls dam in sec. 8, T. 39 N., R. 30 W. The schists do not form large outcrops except along Pier's Gorge where cliffs as much as 40 feet high face the river. Elsewhere, these rocks form low rounded knobs. In some of the greenstone outcrop areas, bands of green schist too small to be shown at the map scale are present. This schist is identical to some of the Pier Gorge schist and is included in the following description.

The Pier Gorge schist consists predominantly of fine-grained, brownish-gray, greenish-gray, green, or less commonly red schist or phyllite which weathers brown. In some places, massive and highly altered greenstone is associated with, and grades into, the green schist. These massive rocks are also green and in some places they are porphyritic showing white saussuritized feldspars set in a fine-grained green matrix. In most places, the schist contains calcite and some specimens are almost all calcite. Pink calcite veinlets are common and in many places they cut across the foliation of the schist. Some of the schist contains cubes of pyrite, or limonite-lined cubic voids as much as 0.8 cm across. Many of the specimens are lineated due to either a slight crumpling of the foliation or the intersection of two foliation planes. In some places, the schist contains "eyes" of clear quartz or of quartz and red feldspar in a greenish-gray or green matrix. These are the "schistose porphyries" of some of the earlier workers in the area (Williams, 1890, p. 119-122). In a few places, specimens contain cavities suggestive of original vesicles, and structures suggestive of highly deformed pillow structures are found near the center of sec. 13, T. 38 N., R. 20 E.

A gradational contact between Pier Gorge schist and Quinnesec greenstone can be seen in the SW$\frac{1}{4}$ sec. 24, T. 39 N., R. 30 W. To the north, the greenstone is highly altered and its plagioclase feldspars are bright red. To the south, schistose bands alternate with bands of altered massive greenstone. The contact between the Pier Gorge schist and metagabbro, 900 feet west-southwest of the Little Quinnesec Falls power dam, is sheared.

The Pier Gorge schist consists predominantly of parallel oriented plates of muscovite and chlorite as much as 0.1 mm long in a groundmass of quartz grains averaging 0.05 to 0.1 mm in diameter. The chlorite is colorless to pale green with birefringence colors varying from brown to greenish brown to gray. The micaceous mineral in some specimens is muscovite whereas in others it is chlorite; in many places, both are present. Some of the chloritic schist contains roughly lath-shaped albite grains with a maximum length of 0.2 mm. The albite is commonly altered to sericite or paragonite and in some places is rust-red in color. All of the muscovite-rich schist and some of the chloritic schist contain calcite grains as much as 0.3 mm across scattered throughout the specimens. Some specimens are extremely rich in calcite; one specimen contains 65 percent of this mineral. These calcitic rocks are nearly massive as they contain only a small percentage of the micaceous minerals. Accessory minerals found in the Pier Gorge schist include leucoxene, hematite and limonite, pyrite, and zircon.

Good explosures of Pier Gorge schist containing quartz "eyes" are found in a road cut 700 feet north of the Big

Quinnesec Falls dam. The rock here contains subangular and embayed clear quartz grains or "eyes" up to 3.0 mm across in a groundmass similar to the normal muscovite-rich schists (pl. 10). The foliation in these rocks wraps around the quartz "eyes". An analysis of a "schistose porphyry" from this area is given by Williams (1890, p. 121) and is repeated in Table 5 along with an analysis of average calc-alkali rhyolite for comparison. The two analyses are almost identical.

An exposure along the Menominee River in the NW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 14, T. 38 N., R. 20 E. contains, in addition to normal Pier Gorge schist, a variety of rock rich in pink feldspar. This rock consists of altered and broken albite (An_3) and orthoclase grains and quartz "eyes" in a foliated, muscovite- and quartz-rich groundmass. The feldspar is rusty colored in thin section and is loaded with muscovite inclusions. The specimen of this rock studied is cut by a quartz-calcite-penninite veinlet and some penninite and calcite are also found in the groundmass.

Of the massive altered greenstones found within the Pier Gorge schist area, a porphyritic variety from along the Menominee River near the center of sec. 13, T. 38 N., R. 20 E. was selected for microscopic study. This rock is similar to the assemblage (1) greenstones and would have been included there except for its occurrence within the schists. It consists of phenocrysts

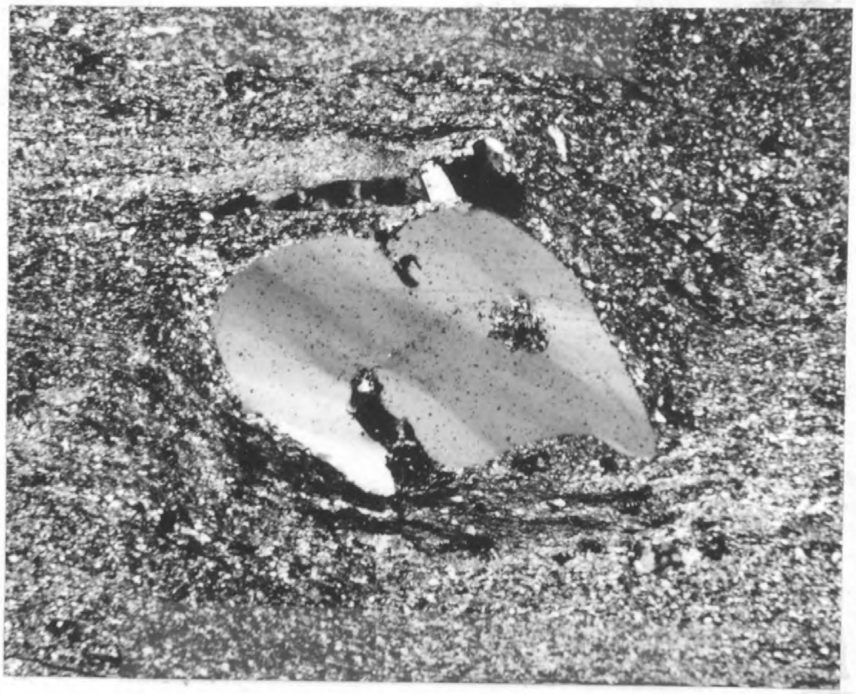


Plate 10. Photomicrograph of Pier Gorge schist showing quartz eye. Note embayed strained quartz grain in center of picture. Remainder of specimen is predominantly fine-grained quartz and muscovite. Crossed nicols. x30.

Table 5. Chemical analyses and norms of Pier Gorge schist porphyry and average calc-alkali rhyolite.

	1	2
SiO_2	66.69	73.66
TiO_2	n.d.	0.22
Al_2O_3	16.69	13.45
Fe_2O_3	2.06	1.25
FeO	0.93	0.75
MnO	n.d.	0.03
MgO	1.15	0.32
CaO	1.40	1.13
Na_2O	2.46	2.99
K_2O	5.23	5.35
H_2O	1.70	0.78
P_2O_5	n.d.	0.07
CO_2	1.42	n.d.
Total	99.73	

	1	2
qz	30.8	33.2
or	30.6	31.7
ab	21.0	25.1
an	0.0	5.0
C	7.0	0.9
$MgSiO_3$	3.8	0.8
mt	3.0	1.9
il	--	0.5
ap	--	0.2
cc	2.5 1/	--

n.d. - not determined

1/ some excess CO_2 not included

1. "schistose porphyry" from Big Quinnesec Falls. Williams (1890, p. 121).

2. Average calc-alkali rhyolite. Nockolds (1954, table 1, anal. II).

of plagioclase 0.3 mm long, almost completely altered to saussurite, in a fine-grained groundmass of epidote and saussurite, chlorite, calcite, and quartz. Some remnants of original plagioclase laths are found in the groundmass, but they now consist of albite and alteration minerals. Pyrite and zircon are also present.

The origin of the Pier Gorge schists is a problem which cannot be solved completely. The composition of a porphyritic variety with quartz "eyes" and the lack of field evidence for crosscutting or dike-like relations indicate that they are probably altered felsic lava flows. The chloritic rocks, the rocks with pillow structures, and the porphyritic greenstone, are believed to be altered mafic flows, probably basalts. I conclude that the Pier Gorge schists consist of intercalated altered felsic and mafic flows some of which have undergone carbonate alteration.

The chlorite schist bands associated with massive greenstone away from the main Pier Gorge schist area appear to be the result of metamorphism under local conditions of shearing.

Miscellaneous Rocks

Within the Quinnesec formation, three rocks with unique mineralogy or texture were found: (1) chlorite-hornblende schist, (2) chlorite hornfels, and (3) epidosite.

The chlorite-hornblende schist was found near the contact between the Quinnesec formation and the Hoskin Lake granite in the $SW\frac{1}{4}SE\frac{1}{4}$ sec. 7, T. 38 N., R. 20 E. where it is associated with a chloritic oligoclase amphibolite (see "Greenstone and Amphibolite", assemblage 2). This rock consists of parallel plates of pale green penninite in a groundmass of sericitized plagioclase and clear quartz. Some blue-green hornblende is associated with the chlorite. Calcite and sphene are scattered throughout the groundmass and some zircon, magnetite, pyrite, and tourmaline are also present.

The chlorite hornfels was collected $1\frac{1}{2}$ feet south of the metagabbro-Quinnesec formation contact 2,400 feet north and 1,150 feet west of the southeast corner of sec. 12, T. 38 N., R. 19 E. The rock is fine grained, massive, and green in hand specimen and looks much like a normal amphibolite. However, thin section study shows that it is lacking in amphibole. It consists of small unoriented plates of pale green chlorite set in a matrix of clear andesine (An_{35}) and quartz. Calcite and sphene are scattered throughout the specimen but are not abundant, and a few grains of epidote were seen.

An entire small outcrop, 5 feet wide and 10 feet long, just west of the Chicago, Milwaukee, St. Paul and Pacific railroad, 250 feet north of the Menominee River in sec. 7, T. 39 N., R. 30 W. is composed of an epidote-rich rock, epidosite. Ninety percent of this rock is subhedral epidote grains which average about 0.1 mm in diameter. Fragments of a non-pleochroic amphibole and quartz and minor amounts of calcite and sphene are the only other constituents of the rock. This is believed to be a mafic igneous rock which has undergone epidote metasomatism or which had an abnormal initial composition.

Age and Correlation

Early workers in the district thought that the Quinnesec formation was either Lower Precambrian (Archean) or Middle Precambrian (Animikie) and post-Michigamme in age; except Leith, Lund, and Leith (1935) who believed that the formation was Middle Precambrian but pre-Michigamme in age. The arguments for a Lower Precambrian age are summed up by W. S. Bayley who states:

> "They (Quinnesec schists) have all the complex lithological and structural features that are recognized as characteristic of typical Archean greenstone-schists . . . the schists are in every respect identical with similar schists in the Marquette district of Michigan that have been demonstrated to be unconformably beneath the Lower Huronian sediments . . ." (Bayley, 1904, p. 131).

Seven years later, Van Hise and Leith advocated an Animikie (Middle Precambrian) and post-Michigamme age for these rocks because:

> ". . . the Wisconsin . . . Survey, under the direction of W. O. Hotchkiss, mapped what is probably the continuation of the Quinnesec schist to the northwest along the south side of the Florence district of Wisconsin, and determined the green schists there clearly to overlie the upper Huronian (Animikie) sediments to the north of them and to be locally interbedded with upper Huronian (Animikie) sediments." (Van Hise and Leith, 1911, p. 345).

Hotchkiss' work was never published so his evidence could not be properly evaluated, but I have studied Hotchkiss' unpublished maps and examined several outcrops in the field and I found no evidence to support his findings. Likewise, there is no evidence in the district to support the Leith, Lund, and Leith proposal that the Quinnesec formation is Animikie but pre-Michigamme in age.

I agree with W. S. Bayley that the Quinnesec rocks are Lower Precambrian for the reasons listed by him and because the Quinnesec formation rocks have undergone too complex a history to be Animikie. They have been intruded by granite dikes which were deformed into gneisses and then taken up as inclusions in later gabbro sills. As will be shown later, the gabbro sills were metamorphosed. Elsewhere in the region, there is no evidence of post-Animikie periods of deformation and metamorphism separated by gabbro intrusion. Therefore, it appears more likely that the Quinnesec formation rocks are Lower Precambrian and were deformed and probably metamorphosed in pre-Animikie time, and again in post-Animikie time. Metagabbro, here considered Middle Precambrian, was included in the Quinnesec formation by previous geologists working in the area.

The closest possible correlative unit of the Quinnesec formation is the Lower Precambrian Dickinson group of the Felch district, 15 miles to the north. These two groups of rocks are alike in that they are mainly metamorphosed mafic igneous rocks with associated iron-formation and other meta-sediments. They differ in that the Dickinson group rocks are of higher metamorphic grade, amphibolite facies. Also the meta-sediments of the Dickinson group are more common and form distinct bands which can be mapped as separate units.

Origin and Metamorphism

As has been shown, the Quinnesec formation consists of basaltic flows, pyroclastics, felsitic flows, and sediments which have been metamorphosed under a range of conditions from low to moderate grade. If my dating of the Quinnesec formation as Lower Precambrian is correct, the regional history indicates that the rocks of the Quinnesec formation must have undergone at least two periods of regional metamorphism, one between Lower and Middle Precambrian and a second between Middle and Upper Precambrian. However, the effects of these two periods of metamorphism cannot be separated. Also, on a limited scale the Quinnesec strata adjacent to the granite and metagabbro intrusions may have undergone contact metamorphism but the effects of the contact metamorphism also are not evident.

The basaltic rocks are the most widespread and afford the best basis for subdividing the formation into metamorphic facies. The greenstones (assemblage 1) and Pier Gorge schists are typical greenschist facies rocks (Turner, 1948; Turner and Verhoogen, 1951) whereas the andesine amphibolites (assemblages 3, 3a, and 3b) are typical amphibolite facies rocks. Therefore, the oligoclase amphibolites (assemblages 2 and 2a) which lie between, may represent the pressure-temperature conditions of the epidote-amphibolite facies. The pyroxene bearing rocks (assemblage 4) are somewhat higher amphibolite facies rocks.

The presence of calcic oligoclase (An_{16} - An_{27}) rather than albite or sodic oligoclase in the rocks from the epidote amphibolite facies is puzzling as James (1955) did not find any plagioclase with a composition from An_{20} to An_{30} in his regional study of metamorphism in Northern Michigan. This may be due to (1) possible anomalous conditions prevailing in the area during metamorphism, (2) abnormalities in the original composition of the rock, or (3) the rock having undergone two periods of metamorphism; i.e., rocks that are believed to have been metamorphosed in the epidote-amphibolite facies, may have been amphibolite facies rocks after the first period of metamorphism with the second period being less intense and not changing older metamorphic calcic oligoclase to a more sodic plagioclase.

In determining the position of the isofacies lines, the greenstone-oligoclase amphibolite and oligoclase amphibolite-andesine amphibolite boundaries were used. The isofacies lines determined in this manner fit the isofacies lines as determined from the study of the Middle Precambrian metagabbro sills. Also, this subdivision gives more uniform results than isofacies lines based on either the presence or absence of epidote, or on the pleochroism of the amphibole.

The transition from greenstone to oligoclase amphibolite to andesine amphibolite represents increasing metamorphic grade in a uniform original rock type, and thus affords an opportunity to note the mineralogical and textural changes which have taken place. The most notable change is the increase in the anorthite content of the plagioclase, from albite in the greenschist facies to oligoclase in the epidote-amphibolite facies to andesine in the amphibolite facies. The mafic minerals also change, from chlorite or fibrous and colorless actinolite in the greenschist facies to stout prismatic and pleochroic hornblende in the epidote-amphibolite and amphibolite facies. The pleochroism of the amphibole in the epidote-amphibolite and amphibolite facies is quite variable and the variation has no clear-cut relationship to the grade of metamorphism, except that the amphibolite facies rocks may locally contain brownish or poikiloblastic hornblende which does not appear in the epidote-amphibolite facies rocks. The character of the epidote minerals also changes with metamorphic grade. They are fine grained or saussuritic in the greenschist facies, and coarser and better formed in the epidote-amphibolite facies, and are restricted to streaks or stringers (possible veins) in the amphibolite facies where they probably represent retrograde action. Also, clinozoisite and zoisite are common in the low grade rocks but rare in the high grade ones. The titanium-bearing mineral found in the greenschist facies is leucoxene; in the epidote-amphibolite facies, well crystallized sphene; and in the amphibolite facies, titaniferous magnetite rimmed by sphene. Chlorite, which is common in the greenschist facies rocks, is rare in the higher grades. In the greenschist facies, remnants of original diabasic textures are common; they are rare in the epidote-amphibolite facies rocks where a crystalloblastic texture is common and are entirely absent in the amphibolite facies rocks.

The estimated modes of the greenstones (table 2) bring out an interesting feature. Where the percentages of albite and chlorite are high, epidote and actinolite are rare or are absent. Thus, where epidote forms as a plagioclase alteration product, the mafic alteration product is more apt to be actinolite. In these chlorite-and albite-rich rocks, the question of what happened to the calcium arises. Wiseman (1934) noted that in the Scottish Highlands, the calcium in the epidote-poor rocks goes into amphibole and chlorite. Since chlorite contains only a small amount of calcium, in the Quinnesec formation rocks the calcium either was never present or has migrated away. The original rocks probably were not spilitic as James (1955) presents 20 partial analyses of similar rocks from elsewhere in Northern Michigan, none of which are spilitic. The calcium, therefore, has probably migrated; possibly as calcite into some of the Pier Gorge schist. Support for this idea comes from the fact that most of the albite-chlorite-rich greenstones are found near the Pier Gorge schist outcrop areas. The detailed study of hot springs activity in Iceland by Barth (1950), indicates that the alteration of the flows and the accompanying changes in composition may have been initiated quite early in the history of the rock.

Several peculiar varieties of the Quinnesec rocks need special mention. The oligoclase amphibolite from an inclusion in granite in sec. 16, T. 38 N., R. 20 E. does not fit the metamorphic grade for this area and may be the result of either local retrograde metamorphism or of slight abnormalities in the original composition of the rock. The hornblende schist specimens from sec. 3, T. 39 N., R. 31 W. have characteristics of both the greenschist and epidote-amphibolite facies. On the basis of their high sodic plagioclase content, they are placed with the greenschists; however, this interpretation is subject to some question because their pleochroic amphiboles suggest a higher grade rock.

The chloritic rocks from the amphibolite facies area south of the Horserace Rapids also need special mention. The chlorite in the andesine amphibolites (assemblage 3b) is restricted to seams or streaks and is thus probably the result of retrograde metamorphism. Retrograde action was also probably responsible for the formation of chlorite in the chlorite-hornblende schist from sec. 7, T. 38 N., R. 20 E., as the chlorite here appears to have replaced some of the hornblende. The chlorite hornfels from the metagabbro contact in sec. 12, T. 38 N., R. 19 E. may have had a different origin. This rock contains no hornblende and is not schistose like most of the retrograde rocks. Here, water vapor pressure and bulk composition may have been such that chlorite, rather than hornblende, was the stable mineral even under the pressure-temperature conditions of the amphibolite facies (Yoder, 1952).

The Pier Gorge schists surely formed in the greenschist facies and possibly they represent a lower metamorphic grade than the greenstones.

The biotitic schists, which are probably sedimentary in origin, are highly foliated in the low grade areas but tend toward massive hornfelses in the higher grade areas. The presence of garnet in one of the higher grade metamorphosed sedimentary rocks is to be expected, but the chlorite is out of place; perhaps it is retrograde.

The metamorphosed iron-formation from the amphibolite facies is a typical high metamorphic grade rock. The size of the quartz grains in its metachert bands are as large as, or larger than, those which James (1955) considers typical for iron-formation metamorphosed in the amphibolite facies.

MARINETTE QUARTZ DIORITE

Definition and Distribution

The name "Marinette quartz diorite" is proposed here for the quartz diorite intrusion in the southern part of the Menominee district. It is named for the excellent exposures of this rock which are found in Marinette county, Wis. This diorite was mapped by Lyons (Emmons, et al, 1953), who referred to it as "biotite-hornblende quartz diorite" and did not give it a formal name.

The Marinette quartz diorite forms the bedrock in about 3 square miles of the south-central part of the area covered by this report, and work by Lyons (Emmons, et al, 1953) has shown that it extends further to the south, occupying in all an area of about 11 square miles. Most of the exposures of this formation lie to the south of the Hoskin Lake granite pluton, but inclusions of it are common within the granite and, south of Niagara, it occurs between Quinnesec strata and granite. The best exposures of diorite in the area are found south and southwest of Niagara and along the railroad south of County Highway "N".

Description

The diorite forms rather large outcrops and although they are not too abundant, they are usually good. The larger outcrops form rocky knobs which rise as much as 40 feet above the surrounding country and the sides of these knobs are often steep.

The diorite is mainly a medium-grained, massive or slightly foliated rock which varies somewhat in composition. Dark-colored minerals form about 30 percent of the rock with black biotite and some black to greenish black hornblende visible in hand specimen. White, gray, or flesh colored feldspar grains, some of which are striated, and clear quartz grains make up the rest of the rock and are recognizable in hand specimen. In some places, the quartz diorite contains small inclusions of finer-grained and more mafic rocks which appear to contain the same mineral suite as the quartz diorite host. The contact between the inclusion and host rock is sharp. Near the Hoskin Lake granite pluton, the quartz diorite is commonly cut by narrow quartz-feldspathic streaks containing porphyroblasts of feldspar as much as half an inch long. The quartz diorite weathers dark gray or brownish black.

The contact between the Marinette quartz diorite and the Quinnesec formation is sharp, whereas the contact between the quartz diorite and the Hoskin Lake granite is generally gradational. The contact with the Quinnesec formation is exposed in several places in the SW$\frac{1}{4}$ sec. 15 and the N$\frac{1}{2}$ sec. 22, T. 38 N., R. 20 E. (pl. 2). The contact is sharp but is somewhat irregular, and near the contact, the quartz diorite becomes finer-grained and richer in feldspar. The contact with the

Hoskin Lake granite as shown on plate 2 is only an approximation as there is nowhere that it can be accurately located. The porphyritic granite near the contact is loaded with quartz diorite inclusions and the quartz diorite is cut by numerous stringers and dikes of porphyritic granite. In any one outcrop, it is often impossible to determine whether the rock is mainly granite containing numerous quartz diorite inclusions or whether it is mainly quartz diorite cut by many granite dikes. The contact as shown on the map is placed approximately at the center of this gradational zone which in some places may be as much as 1000 feet wide.

The mineral composition of quartz diorite specimens as determined in thin section is as follows: 40 to 50 percent oligoclase, 0 to 20 percent potash feldspar, 10 to 30 percent quartz, and 20 to 30 percent prochlorite, biotite, or hornblende. The texture of the rock is hypidiomorphic to allotrimorphic granular consisting of large subhedral to anhedral plagioclase plates and flakes of biotite and chlorite, and finer-grained, interstitial grains of quartz and potash feldspar.

The average length of the plagioclase plates is 2.0 mm with some exceptionally large ones being as much as 5.0 mm. They are, for the most part, oligoclase (An_{15} to An_{29}) and commonly show normal zoning, and, less commonly, oscillatory zoning. The cores of some of the zoned plagioclase grains may be as calcic as andesine (An_{40}). The plagioclase is twinned by the albite, albite-carlsbad, and less commonly by the pericline laws, and in some specimens, myrmekitic intergrowths with quartz are common. In a few places, the plagioclase is clear, but usually it is partly altered to sericite or epidote with the sericitic alteration commonly being confined to the central part of the grain.

The potash feldspar is clear and unaltered and is finer-grained than the plagioclase. In most specimens it is microcline, but some orthoclase is present. The quartz is also clear but it varies considerably in grain size. It commonly averages between 0.2 and 0.5 mm, but grains as much as 1.0 long have been found.

The major mafic constituent is either chlorite or biotite, both of which form flakes ranging from 0.1 to 1.5 mm long. Individual specimens contain either mostly chlorite with a trace of biotite or mostly biotite with a trace of chlorite. The chlorite and biotite are commonly intergrown parallel with their cleavages. Some of the biotitic specimens contain no chlorite and some of these non-chloritic specimens contain hornblende. The chlorite is strongly pleochroic with X = straw and Y = Z = bright green. It is optically negative with a small 2V and has anomalous blue interference colors. Its index of refraction, $N_{Y\&Z}$, is 1.646. These optical properties indicate an iron-rich chlorite; possibly prochlorite (Troger, 1952) or aphrosiderite (Winchell, 1932). The biotite is deeply colored with X = pale brown and Y = Z = brownish green, greenish brown, or brown. In some places, the biotite flakes are slightly bent. The small amount of hornblende associated with biotite in a few specimens is strongly pleochroic with X = straw, Y = olive green, and Z = blue green, and $Z \wedge c$ 15 to 19 degrees.

Epidote was found in all of the specimens studied and it forms anhedral grains averaging 0.2 mm in diameter. It may be present either as an alteration product of plagioclase or in the groundmass where it is associated with biotite or chlorite. Sphene was also found in all of the specimens studied and it occurs as rims around magnetite, in clusters of small grains, or in euhedral crystals as much as 2.0 mm long. Magnetite, zircon, and apatite are ubiquitous accessory minerals, and hematite, pyrite, calcite and deep-blue tourmaline are found locally.

A thin section showing the gradation to the finer-grained border phase of the quartz diorite was collected from the contact in the NW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 15, T. 38 N., R. 20 E. The coarser part of this rock is like the normal, prochlorite-bearing, quartz diorite and it grades into the finer-grained border phase consisting almost wholly of a mosaic of equant, sericitized oligoclase grains varying from 0.2 to 0.8 mm in diameter. Some prochlorite, epidote, magnetite, and sphene are also found in this fine-grained border phase.

A thin section from a fine-grained mafic inclusion in the quartz diorite in the NE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 20, T. 38 N., R. 20 E. has an average grain size of 0.6 mm and consists of 55 percent sericitized oligoclase, 5 percent quartz, 25 percent biotite, and 15 percent hornblende with minor amounts of epidote, apatite, magnetite, sphene, and zircon. It contains no potash feldspar and is poorer in quartz and richer in mafic minerals than the enclosing quartz diorite.

The quartzo-feldspathic stringers which cut some quartz diorite consist predominantly of large oligoclase plates and quartz grains with little or no mafic minerals.

Origin

A complete evaluation of the origin of the Marinette quartz diorite cannot be made here because only a small part of the unit was studied. South of the area covered by this report is a large area of leucocratic quartz diorite or granite (Emmons, et al, 1953, pl. 16) which is part of the massif commonly referred to as the "Wisconsin Batholith". The Marinette quartz diorite probably represents a mafic border phase of this larger intrusion so that a final evaluation of its origin must await a complete study of the whole "Wisconsin Batholith".

The non-homogeniety of the unit may be used by some geologists as an argument for a metasomatic origin, but this can also be explained by an hypothesis of magmatic injection and assimilation of basic material from the Quinnesec formation.

Age

As has been shown, the Marinette quartz diorite is younger than the Quinnesec formation and is intruded by the Hoskin Lake granite. Inasmuch as the Quinnesec formation and Hoskin Lake granite are Lower Precambrian, then the Marinette quartz diorite must also be Lower Precambrian. Correlation of this unit with Lower Precambrian igneous rocks elsewhere in Northern Michigan cannot be made at this time. Perhaps after more positive methods of absolute dating have been perfected, correlations will be possible.

HOSKIN LAKE GRANITE

Definition and Distribution

"Hoskin Lake granite" is a new name used here for the rocks of a large porphyritic granite intrusion in the south-central part of the Menominee district. The name is derived from Hoskin Lake in the southwestern part of the area. Previous workers had referred to this unit simply as porphyritic granite or granite porphyry and did not give it a formal name.

The granite forms an arcuate-shaped intrusion of about 6 square miles within the present map area and work by Lyons (Emmons, et al, 1953, pl. 16) has shown that it extends both to the southeast and southwest and covers an area of about 14 square miles. Rocks of this unit are very well exposed and, with the exception of the S$\frac{1}{2}$ sec. 13, the NE$\frac{1}{4}$ sec. 23, and the NW$\frac{1}{4}$ sec. 24, T. 38 N., R. 19 E., excellent outcrops may be found almost anywhere within the map limits of the unit. Dikes related to the granite cut the Marinette quartz diorite and Quinnesec formation, and inclusions of the granite are found in the younger metagabbro sills. The relationship between the main pluton and the small area of porphyritic granite along the south edge of the district in sec. 20, T. 38 N., R. 20 E. is not known. The granite there could be either a large dike in the quartz diorite or an identation in the border of the main pluton.

Description

For descriptive purposes, the Hoskin Lake granite is divided into two groups: (1) the main intrusion and (2) dikes and inclusions. The rock of the main intrusion ranges from coarse porphyritic granite to quartz monzonite, whereas that of the dikes and inclusions is medium- to fine-grained porphyritic quartz monzonite, locally gneissic.

Main Intrusion

The rocks of the main intrusion form large outcrop knobs as much as 60 feet high. The sides of these granite knobs are steep, at places sheer-faced cliffs. The area underlain by porphyritic granite is therefore characterized by a rugged topography on a small scale.

Large subhedral feldspar phenocrysts as much as $2\frac{1}{4}$ inches long are characteristic of much of the Hoskin Lake granite (pl. 11). The phenocrysts form as much as half of the rock and are commonly white, gray, or flesh colored, or, in a few places, bright red. They are commonly carlsbad twinned and are set in a matrix of finer grained quartz, biotite, and feldspar. In most places, the large feldspar tablets are crudely aligned, giving the rock a suggestion of a foliation; however, it is rarely developed well enough to permit measurement. In some places, the granite is coarse grained and almost non-porphyritic. The amount of biotite varies considerably, and in some places the granite contains small, fine-grained, biotite-rich inclusions.

Plate 11. Photograph of typical Hoskin Lake porphyritic granite. Note the large, euhedral feldspar phenocrysts (light gray).

Commonly these inclusions contain porphyroblasts of potash feldspar, have ragged edges, grade into the surrounding granite, and occur in granite abnormally rich in biotite. Granite with red feldspar is especially abundant to the fault in the S½ sec. 16 and the N½ sec. 21, T. 38 N., R. 20 E., and the development of these red feldspars is probably related to solutions passing along the fault. Red feldspars are also found adjacent to many of the steep cliff faces; suggesting that these steep cliffs are also controlled by faulting.

In some places, the porphyritic granite is crushed and mylonitized; such a rock can be seen 950 feet north and 1250 feet west of the southeast corner sec. 7, T. 38 N., R.20 E. where a prospector has blasted into mylonitic granite. The rock here grades from normal porphyritic granite to porphyritic granite containing crushed red feldspar in a fine-grained, greenish-black matrix to a fine-grained, greenish-black mylonite with splotches of red suggestive of original feldspar areas although no feldspar cleavage is visible. Some fluorite, pyrite, chalcopyrite, and arsenopyrite are associated with the mylonite. The width of the mylonitic zone is about 1 foot.

Small quartz veins commonly cut the porphyritic granite and in most places they are parallel with the crude alignment of the large feldspar phenocrysts. The veins are commonly rich in tiny anastomosing veinlets of fine-grained black tourmaline, and some also contain a little pyrite and arsenopyrite.

The porphyritic granite weathers gray to brownish gray with the large phenocrysts weathering to a lighter color than the groundmass. The red feldspar-rich granite weathers pink. The surface of the porphyritic granite outcrops often exfoliate to slabs varying from a fraction of an inch to 4 inches thick.

Porphyritic granite is in sharp contact with the Quinnesec formation to the north and with the Marinette quartz diorite in secs. 15 and 22, T. 38 N., R. 20 E., but is in gradational contact with the quartz diorite elsewhere. Toward the contact with the Quinnesec formation, a gradation from coarse-grained, porphyritic granite into medium-grained, non-porphyritic granite can be seen in many places. Where observed, the contact is sharp but numerous granite dikes cut the Quinnesec formation north of the contact and numerous amphibolite inclusions are found in the granite to the south. The inclusions are cut by small granite dikes and the boundary between the inclusion and the surrounding granite is sharp. In several places, the contact is sheared and the Quinnesec rocks immediately north of the contact are foliated or schistose and the contact itself is marked by a lens of vein quartz.

A sharp contact between granite and quartz diorite is exposed in the NW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 15, T. 38 N., R. 20 E. The contact is sharp but irregular, and the quartz diorite is cut by numerous small quartz veins originating at the contact. Within six inches of the contact the granite is finer grained.

The contact with quartz diorite elsewhere is different. As has been mentioned in the description of the quartz diorite, this contact is gradational with the porphyritic granite to the north being rich in vaguely delineated quartz diorite inclusions. In many places, these inclusions are loaded with porphyroblasts of feldspar, or with streaks and veins of granite. Granite dikes commonly cut the quartz diorite south of the contact, and in most places, it is impossible to see a sharp boundary at the edge of the dike because it simply grades into the quartz diorite; the amount of granitic material introduced into the quartz diorite apparently has been large. Some of the dikes cutting the quartz diorite are as much as 50 feet thick and they contain porphyritic granite identical with that found in the main pluton. The coarse-grained rocks from these larger dikes will therefore be described in this section.

In the NW$\frac{1}{4}$ sec. 22, T. 38 N., R. 20 E., a slump block was found showing part of a granite dike cutting quartz diorite and containing an inclusion of quartz diorite. The relationship between the two rock types is illustrated in figure 2. The contacts are sharp and the inclusion is offset in a way to suggest that it was broken while floating in viscous granite.

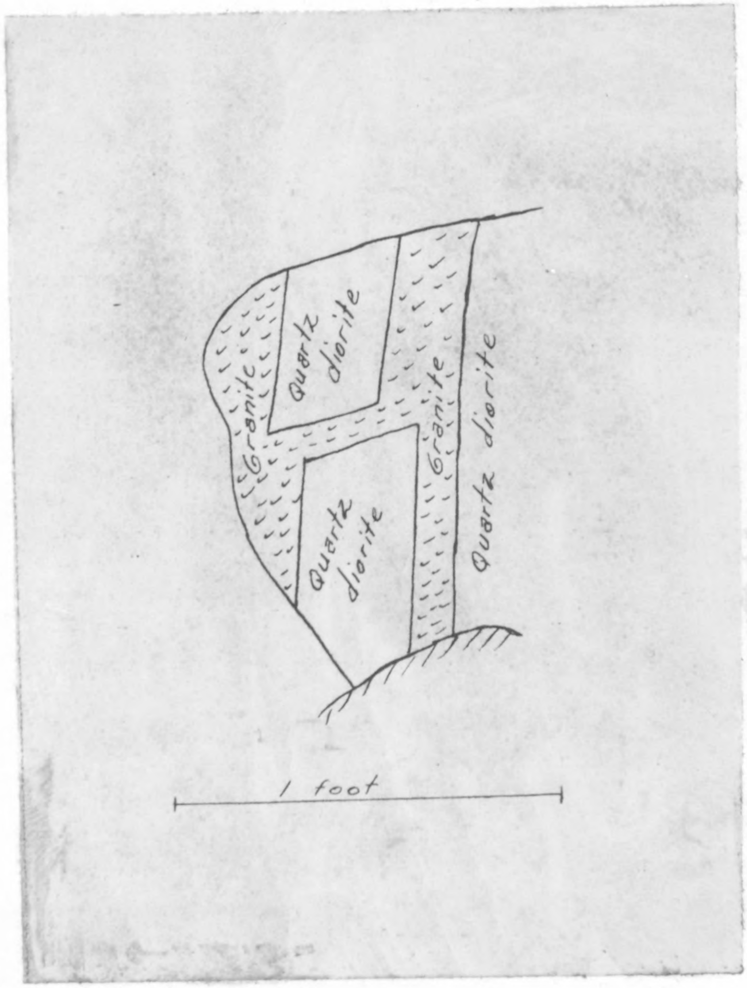
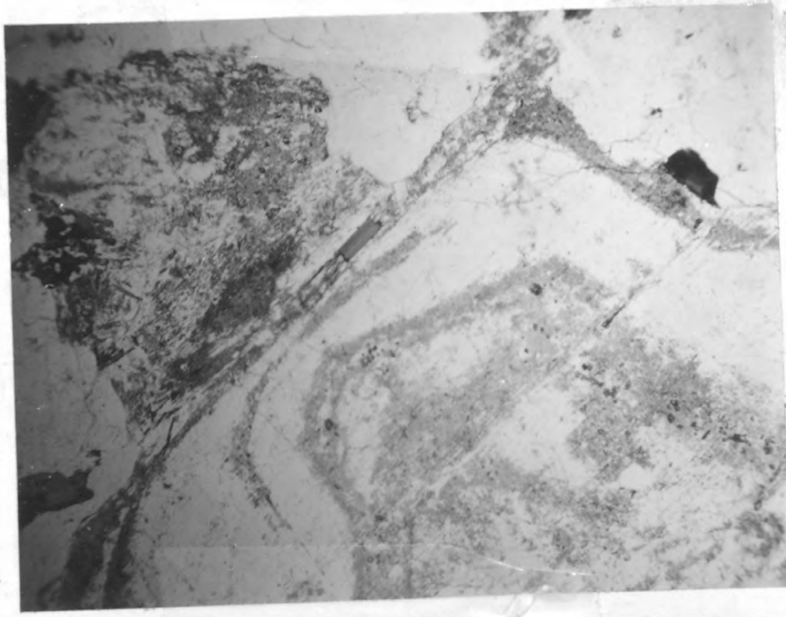
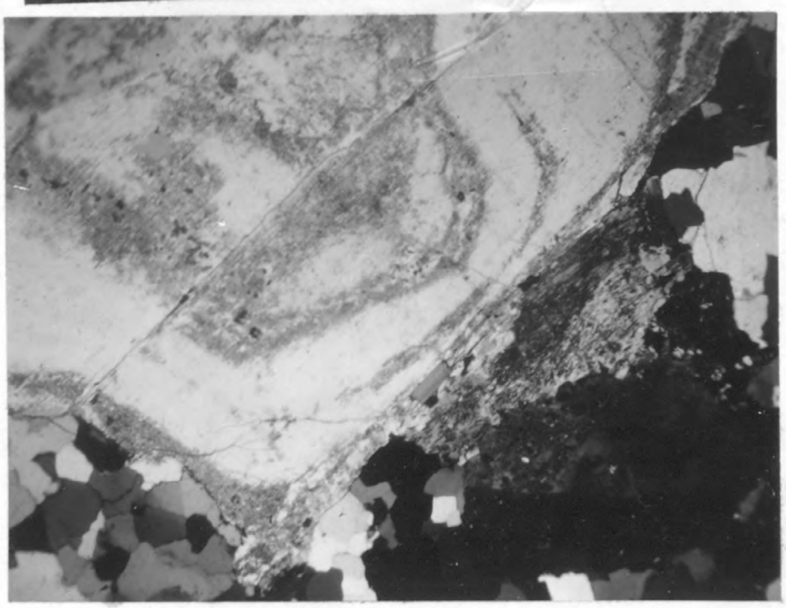


Figure 2. Sketch of quartz diorite inclusion in granite dike. NW$\frac{1}{4}$ sec. 22, T. 38 N., R. 20 E.

The texture of the granite as seen in thin section is hypidiomorphic to allotrimorphic granular, dominated by large anhedral to subhedral plates of microcline and oligoclase in a finer, but still coarse-grained, matrix of oligoclase, quartz, microcline, and biotite. The large carlsbad twinned phenocrysts seen in hand specimen are clear microcline with a well-developed grid twinning. Orthoclase is present but is rare. The oligoclase (An_{10} to An_{20}) generally shows combination albite and carlsbad twins and in most places is partially altered to sericite, or less commonly to epidote or muscovite. The completeness of this alteration varies in different parts of many of the oligoclase crystals, thereby giving the grain a zoned appearance (pl. 12). True compositional zoning is only rarely present, and in all cases is normal, with the borders of some grains being as sodic as An_3. In the red porphyritic granite, the plagioclase is rusty colored in plane polarized light. Myrmekitic intergrowths are commonly found along the edges of some of the larger oligoclase grains, or throughout some of the smaller grains. Perthitic intergrowths were also seen in several specimens and they were of two types: (1) small stringers of clear oligoclase traversing larger clear grains of microcline (pl. 13), or (2) irregular masses of clear microcline in altered oligoclase grains. Also, in many specimens, clear microcline may contain inclusions of smaller grains of



A.



B.

Plate 12. Photomicrographs of oligoclase phenocryst in Hoskin Lake granite. A. Note zonal arrangement of fine-grained sericite (gray) in subhedral oligoclase phenocryst (white). Quartz (white) and biotite (dark gray) are also present. Plane polarized light. x23. B. Same as A. Crossed nicols.

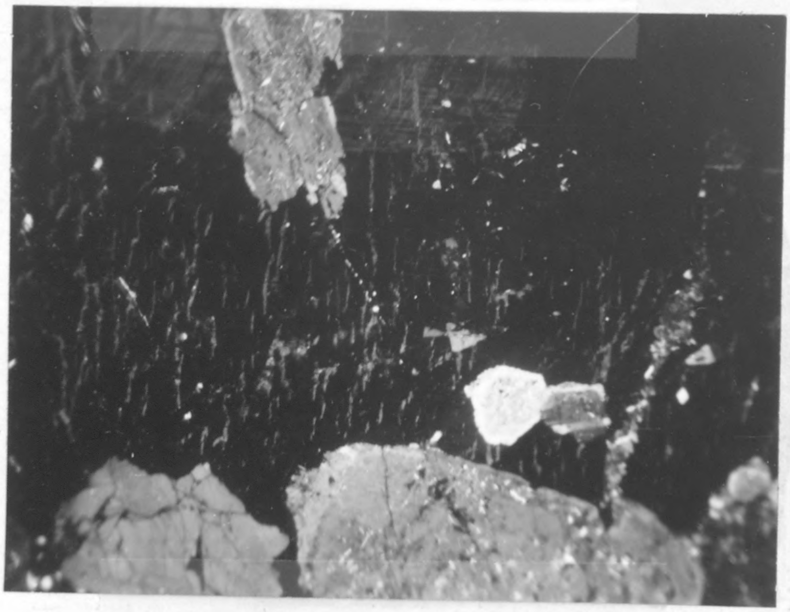


Plate 13. Photomicrograph of string perthite in Hoskin Lake granite. Note stringers of oligoclase (white) in larger microcline grain (black). Crossed nicols. x23.

altered plagioclase. In many of the thin sections studied, the oligoclase microcline ratio is near 1/1, approaching a quartz monzonite in composition. However, the bulk composition of the pluton is probably granitic. The specimens collected for thin section study are not actually typical, as samples with extremely large microcline phenocrysts were avoided, and it is these coarser-grained rocks which are more granitic in composition. As a whole, therefore, the unit is predominantly granite with microcline phenocrysts, grading locally into a coarse-grained, almost non-porphyritic quartz monzonite.

The quartz in the granite is clear and variable in size, and is interstitial to the feldspar grains. Biotite forms from 5 to 25 percent of the rock and is generally deep brown with dark pleochroic halos around zircon, monazite, or less commonly sphene grains. Some strongly pleochroic green chlorite, probably prochlorite, with anomalous blue interference colors is everywhere present with the biotite, the two being intergrown parallel with their cleavage direction. Blue-green hornblende is associated with the biotite in a few places. The biotite-rich areas noted in some hand specimens have the same mineral composition as the surrounding rock but are finer grained and richer in biotite. In the specimens containing red feldspar, the biotite is either greenish brown or it is almost entirely absent; its place being taken by prochlorite.

Epidote is present in most of the specimens studied and it is found in three forms: (1) as an alteration product of plagioclase, (2) in tiny grains in the groundmass, or (3) forming a narrow rim around allanite grains. The latter mineral is present in about half of the specimens and forms yellow brown, and nearly isotropic, subhedral crystals as much as 1.0 mm long. Sphene in subhedral to euhedral crystals, in many places altered to leucoxene, is found in all of the specimens studied as are zircon and apatite. Subhedral to euhedral monazite grains surrounded by pleochroic halos in biotite occur in about half of the specimens, and tourmaline, calcite, magnetite, and pyrite are found in a few specimens.

In order to study the transition from normal porphyritic granite to mylonitic granite, three specimens were collected from the prospect pit in the SE$\frac{1}{4}$ sec. 7, T. 38 N., R. 20 E. Away from the mylonite zone, the granite is normal except that it contains prochlorite rather than biotite. In the first stage of the transition to mylonite, most of the groundmass has been crushed to an irregular mat of finer-grained material with the chlorite drawn out somewhat into streaks. The large feldspar grains have irregular rather than sharp borders and they are either (1) microcline grains broken and invaded by the groundmass or (2) oligoclase recrystallized to an aggregate of small rusty grains. Some calcite and tourmaline have been introduced. In the last stage, the groundmass is even finer grained and the microcline is more broken and invaded by the groundmass material. The oligoclase is further recrystallized to a finer-grained mass with the outlines of original grains no longer being discernable.

A specimen of the finer-grained granite found locally along its contact with the Quinnesec formation was collected from the SE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 16, T. 38 N., R. 20 E. for microscopic study. This specimen is quartz monzonitic in composition and it consists of anhedral oligoclase plates, highly altered to muscovite, in a slightly finer-grained matrix of quartz, microcline, and oligoclase. Biotite and prochlorite are present but are not as abundant as in the main granite pluton. Minor accessory minerals are the same as those found in the normal granite.

Dikes and Inclusions

Granitic dikes are common in the Quinnesec formation near its contact with the porphyritic granite, in the Horserace Rapids area, and south and west of Aurora, Wis. Small dikes also cut the Marinette quartz diorite in the outcrop areas between porphyritic granite and Quinnesec formation south of Niagara, Wis. Inclusions of granitic rocks are found locally in the metagabbro sill in the Horserace Rapids area and in the sill south and southwest of Aurora.

The dikes near the granite contact are slightly to strongly foliated with feldspar phenocrysts in a medium-grained groundmass. Carlsbad or albite-carlsbad twinned feldspar, quartz, and biotite are visible in these rocks which may be red, flesh colored, or gray. In the dikes away from the contact and in the metagabbro inclusions, the rock is finer grained and, generally, strongly foliated. In some places, they are porphyritic showing streaks of biotite wrapping around phenocrysts of feldspar. In other places, they are non-porphyritic showing parallel oriented streaks of fine-grained biotite, giving them a gneissic appearance. In several of the larger inclusions in metagabbro, the rock near the center of the inclusion is massive, whereas that near the border is gneissic. In one place, a few flakes of graphite were found in a gneissic, porphyritic granite dike. The dikes and inclusions weather reddish-brown, brown, or brownish-black.

The dikes of granite vary from thin streaks resembling lit-par-lit injections to dikes and irregular masses 10 feet across. The contacts between the dikes and the Quinnesec strata are sharp, and in some places, the dikes are parallel with the foliation in the amphibolite or schist, in other places, they cut across the foliation. Where they transect the foliation, the foliation in the dike is not parallel with its borders, but is parallel with the foliation in the enclosing amphibolite or schist. This relationship is especially well exposed in a group of outcrops along the north side of the Horserace Rapids, 1200 feet west of the railroad bridge. Figure 3 is a sketch map of these outcrops.

The granitic inclusions in metagabbro vary from small, and in many places poorly exposed, patches to large masses. The largest of these inclusions is in the W$\frac{1}{2}$, NW$\frac{1}{4}$ sec. 7, T. 38 N., R. 20 E., and it is 25 feet wide and at least 200 feet long. The contact between the two units is sharp and previous workers called these inclusions, dikes. If dikes, then their foliation must be the result of either (1) flow structure formed during injection or (2) later deformation. Identical foliation is found in dikes cutting amphibolite where it can be clearly shown to be the result of deformation. Furthermore, in the SE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 12, T. 39 N., R. 31 W., the foliation in the gneiss inclusion strikes into its contact with massive metagabbro. The foliation in the inclusions therefore cannot be the result of primary igneous flow structures and must have resulted from deformation.

Near some of the gneiss inclusions the metagabbro is weakly foliated and the contact itself may be marked by a shear zone. Also, the foliation in many of the inclusions is parallel with the regional structural trend. These facts indicate a post-metagabbro deformational origin for the foliation in some of the inclusions. But in some places, foliated inclusions are found

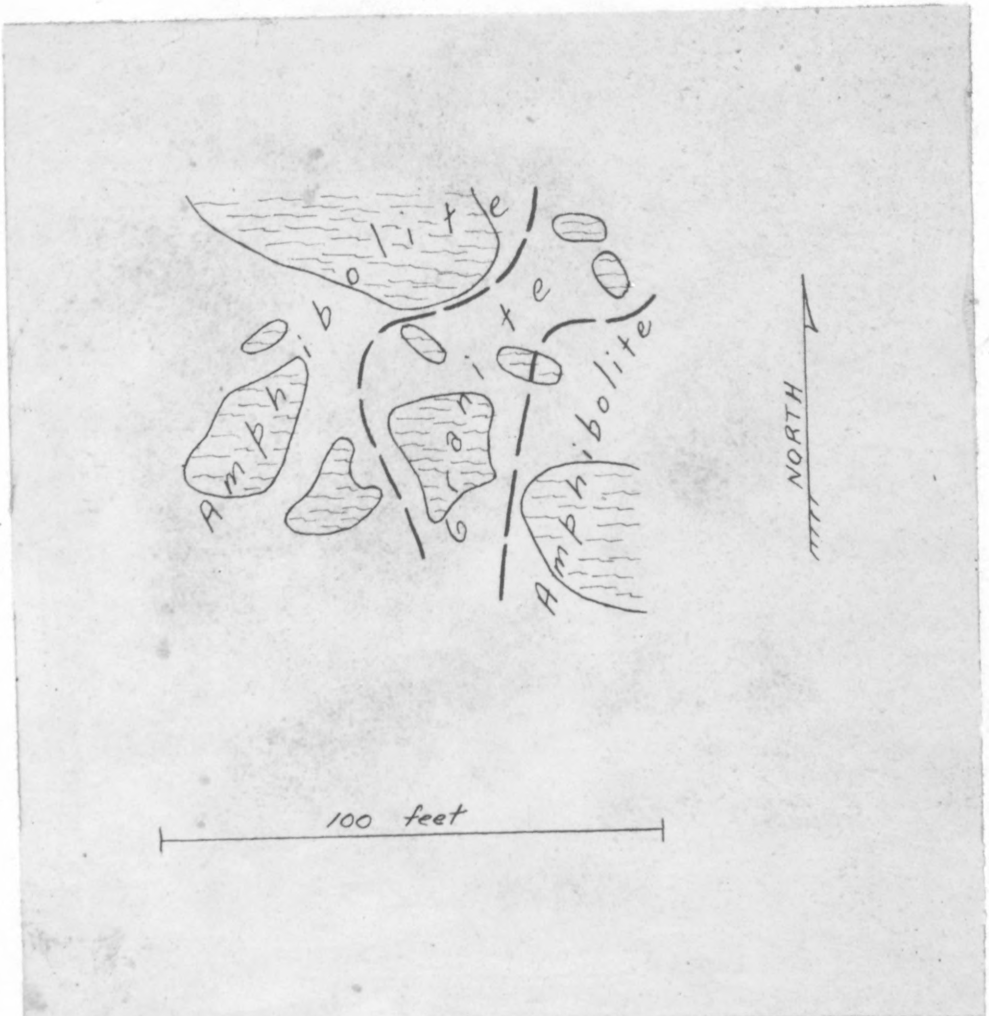
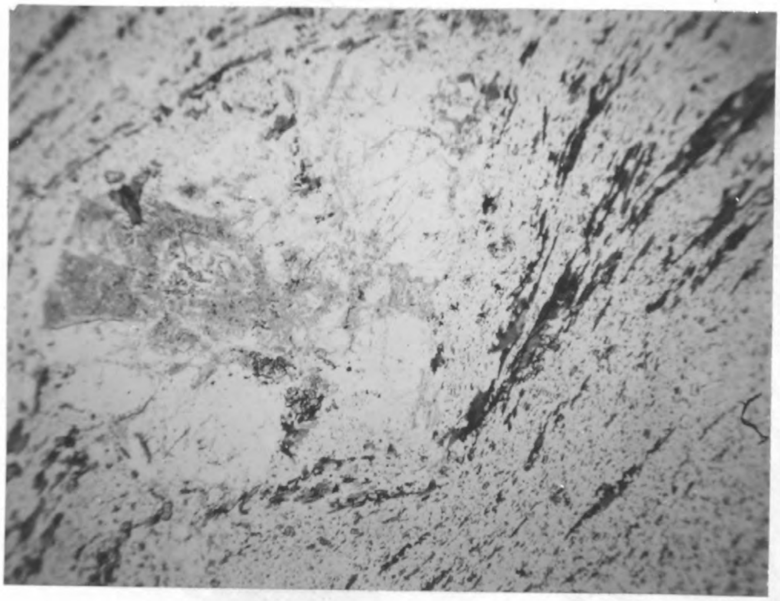


Figure 3. Sketch map of outcrops of porphyritic granite dike in Quinnesec formation oligoclase amphibolite. Note lack of relationship between foliation and dike contact. North side Horserace Rapids, 1200 feet west of C.M.St.P.&P. R.R. bridge.

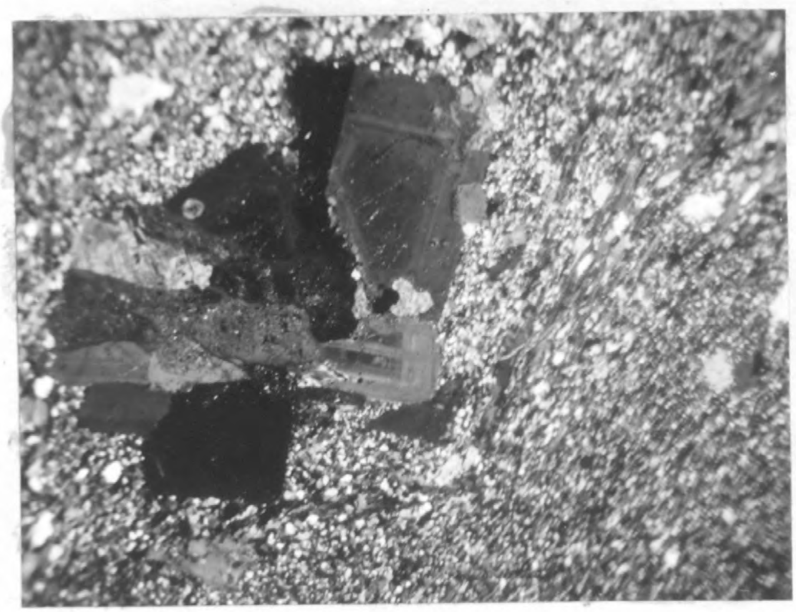
in massive metagabbro. Also, along the Menominee River in the SW$\frac{1}{4}$SE$\frac{1}{4}$ sec. 7, T. 39 N., R. 30 W., there is a gneiss inclusion with its foliation oblique to the regional trend. Thus, it seems unlikely that most of the inclusions became foliated while in the gabbro; but rather that the gabbro picked up inclusions which were already foliated. Other evidence to support this hypothesis may be found around the small inclusion located immediately north of the large inclusion in sec. 7, T. 38 N., R. 20 E. Here, laths of plagioclase in the metagabbro are aligned parallel with the contact of the included gneiss; indicating that gabbro magma flowed around this inclusion. Where not sheared, the metagabbro may be either finer or coarser grained near inclusions.

The medium-grained granitic dikes near the main body of the intrusion have essentially the same mineralogy as the granite except for a higher plagioclase content; they are quartz monzonites rather than true granites. They contain subhedral to anhedral clear microcline or orthoclase and altered plagioclase (An_5 to An_{23}) phenocrysts as much as 6.0 mm long in a finer-grained groundmass of quartz, plagioclase, and microcline or orthoclase. The plagioclase is slightly to moderately altered to sericite or epidote and commonly the centers of the grains are more altered than their edges. Some plagioclase grains are normally zoned and some myrmekite and perthite are also present. The grain size of the groundmass is quite variable, averaging between 0.1 to 0.5 mm. Brown or green biotite with some green prochlorite and clear muscovite are present, and in some places the micas exhibit a parallel orientation which gives the rock a crude foliation. Accessory minerals are zircon, monazite, allanite, and rarely sphene or leucoxene.

The porphyritic granitic rocks found in dikes away from the main granite pluton and in inclusions in the metagabbro are deficient in potash feldspar and are classified as leucocratic granodiorites. These rocks consist mainly of phenocrysts of plagioclase (An_6 to An_{30}) and, less commonly, quartz in a fine-grained groundmass of quartz and feldspar grains averaging 0.05 to 0.1 mm in diameter. The plagioclase phenocrysts are subhedral to anhedral and are as much as 10.0 mm in diameter. They are commonly altered to sericite or, less commonly, to epidote or muscovite, and in the more altered specimens, they are rust colored. In most places, the large plagioclase phenocrysts are actually composed of several diversely oriented grains which may represent either recrystallized larger phenocrysts or glomeroblastic texture (pl. 14). In a few places, the plagioclase phenocrysts are bent or broken and invaded by the groundmass material. In several specimens, embayed anhedral quartz phenocrysts as much as 3.0 mm in diameter are present. They are commonly recrystallized and in one place are drawn out into streaks. Microcline or orthoclase may be present as small phenocrysts or in the groundmass; in the latter occurrence, they are difficult to separate from albite.



A.



B.

Plate 14. Photomicrographs of glomeroblastic texture in granite porphyry. A. Note biotite (dark gray) bending around plagioclase phenocryst (white). Phenocryst is partially altered to sericite (medium gray); groundmass (white) is feldspar and quartz. Plane polarized light. x23. B. Same as A. Crossed nicols. Note that phenocryst is not a single grain.

Brown biotite, deep green prochlorite, or bright green penninite are present in small amounts in all of the specimens studied; the chlorite is restricted to the more altered specimens and biotite to the less altered ones. Flakes of these minerals commonly are arranged parallel and in streaks giving the rock a well-developed foliation, but they are not so oriented in all specimens. The biotite and chlorite flakes and streaks wrap around the feldspar phenocrysts (pl. 14). Muscovite is present in some places, and accessory minerals include zircon, apatite, monazite, allanite, and, less commonly, tourmaline, leucoxene, pyrite, and magnetite. One specimen contains considerable calcite, some of which occurs in veins. Williams (1890, p. 119) gives an analysis of a specimen of a porphyritic granitic rock with a fine-grained groundmass and this analysis is repeated in Table 6 along with Nockolds' average analyses of muscovite-biotite granodiorite and tonalite. The analyses confirm the previous statement that these rocks are more closely related to granodiorites than to granites.

Non-porphyritic granitic rocks which are found associated with Quinnesec amphibolite in a few places have the same mineral composition as the porphyritic granitic dikes. These rocks are actually slightly porphyritic, but their phenocrysts are more recrystallized, thereby giving the rock a non-porphyritic appearance in hand specimen. One specimen of this rock contained some blue-green hornblende associated with the biotite.

Table 6. Chemical analyses and norms of gneissic porphyritic "granite", average muscovite-biotite granodiorite, and muscovite-biotite tonalite.

	1	2	3
SiO_2	67.77	70.47	70.63
TiO_2	n.d.	0.30	0.37
Al_2O_3	16.61	15.50	15.69
Fe_2O_3	2.06	0.63	0.86
FeO	1.96	2.12	1.40
MnO	n.d.	0.03	0.04
MgO	1.26	0.65	0.83
CaO	1.87	1.91	2.82
Na_2O	4.35	4.12	4.91
K_2O	2.35	3.59	1.68
H_2O	1.69	0.52	0.62
P_2O_5	n.d.	0.16	0.15
CO_2	0.19	n.d.	n.d.
Total	100.11		

	1	2	3
qz	27.5	27.1	28.3
or	13.9	21.1	10.0
ab	36.7	34.6	41.4
an	8.1	8.6	13.1
C	4.0	1.7	1.0
$MgSiO_3$	3.2	1.6	2.1
$FeSiO_3$	1.8	2.8	1.1
mt	3.0	0.9	1.4
il	--	0.6	0.8
ap	--	0.3	0.3
cc	0.5	--	--

n.d. - not determined

1. "Biotite gneiss" from $SW\frac{1}{4}SW\frac{1}{4}$ sec. 7, T. 39 N., R. 30 W. Williams (1890, p. 119).

2. Average muscovite-biotite granodiorite. Nockolds (1954, table 2, anal. 5).

3. Average muscovite-biotite tonalite. Nockolds (1954, table 2, anal. 9).

In addition to the well defined dikes and inclusions just described, some granitic rocks are found associated with sheared and schistose Quinnesec rocks where the field relationships are not clear. The granitic rocks in these places consist of irregular, flesh, red, or gray feldspar grains and glassy quartz in a fine-grained dark gray matrix. These rocks are similar to the mylonitic granite from the main mass of porphyritic granite and they probably originated from granitic dikes by a similar process. However, the possibility that they are related to some of the porphyritic felsic flows of the Pier Gorge schist cannot be eliminated.

Two thin sections of granitic rocks associated with sheared and schistose greenschist facies rocks were studied. Both consist of broken and highly altered and recrystallized albite phenocrysts in a very fine-grained quartzose groundmass which commonly invades the broken phenocrysts. A strong foliation in these rocks is imparted by parallel-oriented streaks of muscovite or prochlorite. One specimen, from the NW$\frac{1}{4}$SE$\frac{1}{4}$ sec. 14, T. 39 N., R. 30 W., is prochlorite-rich and dike-like, whereas the second, from the SW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 12, T. 39 N., R. 31 W., is muscovite-rich and forms an irregular pod. The former is certainly related to the other porphyritic granitic dikes; the latter may be related to the Pier Gorge schist.

Origin

Before considering the origin of the Hoskin Lake granite, the relationships between the main granite pluton and the dikes and inclusions of granitic rock must be discussed. The medium-grained granitic dikes found near the main pluton offer no problem; they are obviously related to the main granite intrusion. But the relationships of the porphyritic dikes and inclusions found away from the contact are subject to interpretation. They are quartz monzonitic or granodioritic in composition and it could be argued that they are related to the Marinette quartz diorite rather than to the Hoskin Lake granite, but except for their being finer-grained and lacking in potash feldspar, they are essentially like the dikes found near the granite contact. Furthermore, their distribution around the Hoskin Lake porphyritic granite pluton also suggests that they are related to this unit.

Evidence has been presented to show that the Hoskin Lake granite has undergone at least two periods of deformation. The first period produced gneissic granitic dikes which were later taken up as inclusions in the Middle Precambrian metagabbro sills. The sills have also been deformed and metamorphosed; thus, the granite underwent both pre- and post-metagabbro deformation, and at least post-metagabbro metamorphism.

Since the granite has been metamorphosed and deformed, the question as to whether the granite originally formed through igneous or metamorphic processes is difficult to answer. I believe that both agencies were responsible. The sharply bordered amphibolite inclusions in the granite and the sharply defined granitic dikes away from the main pluton indicate a magmatic origin. However, these dikes are quartz monzonitic or granodioritic in composition, as is the chilled border phase of the main intrusions; whereas, the main Hoskin Lake pluton is granitic in composition. The main potash-bearing mineral in the granite, microcline, is patchy in its distribution, and it may contain inclusions of altered plagioclase and in some places appears to have replaced plagioclase. These facts suggest that the microcline was introduced late in the history of the rock and indicate the following origin for the porphyritic granite. First, intrusion of granodioritic or quartz monzonitic magma and its subsequent solidification. Inasmuch as the porphyritic granite with the microcline removed is, in some ways, similar to the Marinette quartz diorite, this pluton may have been continuous with the quartz diorite intrusion to the south. Later, potash rich solutions invaded the area resulting in the formation of microcline porphyroblasts in most of the portions of the original monzonitic intrusion now occupied by the Hoskin Lake pluton. At the same time, some of the rocks in the granite area became remobilized and invaded the earlier Marinette quartz diorite intrusion and possibly formed some of the more potash-rich dikes in the Quinnesec formation. This postulated potash metasomatism may have taken place: (1) late in the history of the initial injection, (2) during the pre-gabbro metamorphism, or (3) during the post-metagabbro metamorphism; probably late in the history of the initial injection.

The biotite-rich areas in the granite need special mention. It appears that they are partially digested inclusions or mafic segregations as they grade into normal but biotite-rich porphyritic granite. They probably do not represent Quinnesec formation inclusions as inclusions of rocks from this formation generally show sharp contacts with the granite and show few signs of reaction with the granite. Also, Quinnesec formation inclusions are not biotitic. Perhaps these biotite-rich areas were derived from mafic inclusions similar to those found in the Marinette quartz diorite.

Age

It has been shown that the Hoskin Lake granite has undergone at least two periods of deformation and, inasmuch as there is no record of two post-Animikie (late-Middle Precambrian) periods of deformation, the granite must, therefore, be older. The initial granitic intrusion is thus probably Lower Precambrian in age.

LOWER PRECAMBRIAN(?) ROCKS

DACITE PORPHYRY

Dikes of fine-grained porphyry cut the Hoskin Lake granite in the NE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 21, T. 38 N., R. 20 E. and in the SE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 16, T. 38 N., R. 20 E. These dikes are from 1 to 3 feet wide and strike north-northeast. In hand specimen, light gray plagioclase phenocrysts and a few flakes of black biotite are visible in a fine-grained, medium- to dark-gray groundmass. Near the edges of the dikes, the rock becomes finer grained, and the contact with the granite is sharp. The rock weathers gray, like the granite.

Thin section study shows that the rock is dacitic in composition. It consists of euhedral plagioclase phenocrysts as much as 3.3 mm across in a fine-grained groundmass of clear plagioclase and quartz grains which average 0.1 mm in diameter in the central portions of the dike and 0.02 mm in diameter near the edges of the dike. The plagioclase phenocrysts show a strong normal or oscillatory zoning with a composition ranging from An_{63} to An_{16}. Most of the phenocrysts are partly altered to muscovite with some sericite and epidote. The centers of some grains are highly altered but their edges are clear; others are so highly altered throughout that their original composition cannot be determined in thin section. Rarely, myrmekitic intergrowths with quartz are found in some of the phenocrysts. The groundmass consists mainly of clear quartz and plagioclase that is commonly zoned like the phenocrysts. Some microcline was also detected in the groundmass. Brown or greenish-brown biotite is an abundant accessory mineral and it may be either scattered throughout the specimen or included in the plagioclase phenocrysts. Some muscovite and chlorite are also found in the dacite specimens studied, and in one, moderately pleochroic green chlorite with pale blue interference colors is rather abundant. Epidote is a rare to common accessory mineral in the groundmass as well as being an alteration product of plagioclase phenocrysts. Sphene, partly altered to leucoxene, apatite, zircon, and calcite are also present.

The age of these dikes is in doubt. They definitely post date the Hoskin Lake granite, and the altered state of the feldspar phenocrysts suggests that they are pre-Upper Precambrian as Upper Precambrian (Keweenawan) rocks in Northern Michigan and Wisconsin are everywhere rather fresh. The dacite is here considered Lower Precambrian, but a Middle Precambrian age cannot be eliminated.

MIDDLE PRECAMBRIAN ROCKS

MICHIGAMME FORMATION

Michigamme formation is the name used here for the gray slate, gray calcareous slate, graphitic slate, graywacke, quartzite, and iron-formation found stratigraphically above the Vulcan iron-formation in the Menominee district. These rocks had been called "Hanbury slate" by Bayley (1904, p. 40), but later work showed that they correlated with the Michigamme strata in the districts to the north (Van Hise and Leith, 1911, p. 340). These rocks form a belt 3/4 to 2 miles wide between the Quinnesec formation rocks to the south and the Vulcan iron-formation to the north (pl. 1), but this does not appear to represent the true thickness of the formation as complex folds are visible in many places. The southern edge of this belt is included in the area covered by this report.

Outcrops of Michigamme strata are not abundant and within the area covered by this report, they are found only in the NW$\frac{1}{4}$ sec. 4, the NE$\frac{1}{4}$ sec. 5, and the SE$\frac{1}{4}$NW$\frac{1}{4}$ sec. 11, T. 39 N., R. 30 W., in the NE$\frac{1}{4}$ sec. 20, the NE$\frac{1}{4}$ sec. 21, and in the SW$\frac{1}{4}$NW$\frac{1}{4}$ and the SW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 26, T. 39 N., R. 29 W. The outcrops are small and the rocks poorly exposed.

The Michigamme strata in the area are mainly fine-grained, medium to dark gray dolomitic slate or slaty dolomite. The former are well foliated with the foliation commonly being crumpled, whereas the latter are only crudely foliated. Black, hematite-stained graphitic slate and tan, well-foliated sericitic slate are also common, and fine-grained gray silicified dolomite, quartzite, and sideritic iron-formation are found locally.

In thin section, the slaty dolomite is a crudely foliated rock consisting almost wholly of dolomite. Some quartz grains are scattered throughout the specimen and a few muscovite flakes parallel the foliation. A trace of chlorite and streaks of a fine-grained, opaque and black-reflecting mineral, possibly graphite, are also present. The average grainsize of this rock is .05 mm. Rounded glassy quartz grains are abundant in some specimens of the dolomitic slate and the rock grades into an impure, dark gray quartzite.

In the eastern part of the area in sec. 26, T. 39 N., R. 29 W. some sideritic iron-formation is associated with red, hematite-stained black slate. The iron-formation is thin bedded and light to medium gray, but is commonly stained red-brown or brown by secondary hematite or goethite formed from the oxidation of siderite. This secondary stain may either parallel the bedding or cut obliquely across it (pl. 15). The beds in the iron-formation commonly show small folds. The rock weathers reddish brown or dark gray.

In thin section, the iron-formation is a well-banded rock consisting of quartz, siderite, and hematite with an average

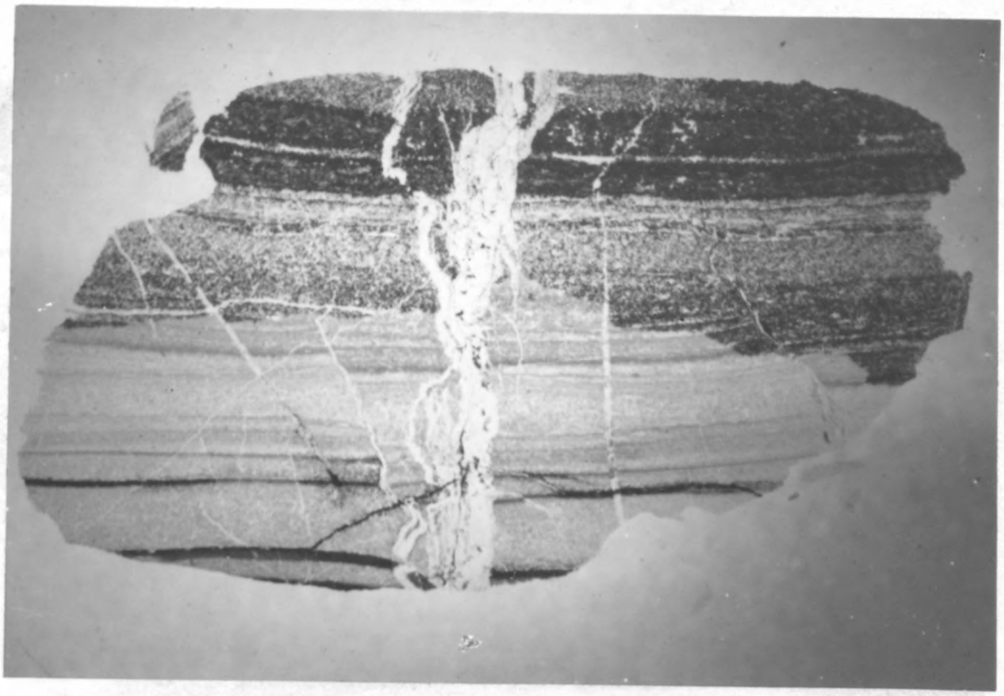


Plate 15. Photograph of thin section of partially oxidized Michigamme iron-formation. Layered chert and siderite (light gray) and hematite (dark gray) cut by quartz veinlet (white). x4.

grainsize of .02 mm. The banding in the rock is due to alternations in the relative percentage of quartz and siderite and/or hematite. Hematite apparently formed from the alteration of siderite as a complete transition can be seen from pale brown siderite to deep yellow brown siderite to deep red, semi-opaque material (probably a mixture of siderite and hematite), to almost completely opaque hematite. The quartz was probably derived from original chert although no chert is now visible. Quartz veins with some hematite and coarse-grained carbonate traverse the specimen.

The slate, dolomite, and iron-formation appear to be marine sediments which have undergone regional metamorphism in the greenschist facies. Work to the north has shown that they correlate with the Michigamme formation, a member of the Middle Precambrian Baraga group.

METAGABBRO

Definition and Distribution

Metagabbro is present in the area in four large sill-like bodies which are intrusive into the Quinnesec formation, in four smaller sills, three of which cut the Quinnesec formation and one which probably cuts the Michigamme formation, and in several dikes associated with the larger sills. In keeping with the precedent set by U. S. Geological Survey geologists working in Northern Michigan (Gair and Wier, 1957; and Bayley, R. W., 1958), the metagabbro will not be given a formal stratigraphic name, but for convenience, each of the four major sills will be given an informal name. The sill in the extreme eastern part of the area will be called the "Sturgeon Falls sill". The long sill extending from U. S. highway 8 at the Menominee River westward to the Big Quinnesec Falls will be called the "Niagara sill". "Horserace sill" will be used for the one extending eastward from the Horserace Rapids, and finally, the sill in the western part of the area will be called simply the "Western sill".

The Sturgeon Falls sill is exposed for two miles within the area covered by this report and has a maximum width of about 2,600 feet. The Niagara sill is about 6½ miles long and is variable in thickness, the maximum being about 3,200 feet. The Horserace sill is only two miles long and 2,000 feet wide, whereas the Western sill is at least 2½ miles long and may be as much as

3,400 feet wide. One of the several smaller metagabbro sills just north of the Western sill in the N½ sec. 10, T. 38 N., R. 19 E. is about 1,400 feet long and 300 feet wide. The largest of the smaller sills is south of Niagara, Wis. in the N½ sec. 15, T. 38 N., R. 20 E. It is about 4,000 feet long and has a maximum width of 800 feet. The third is north of the Niagara sill in the NE¼ sec. 14, T. 39 N., R. 30 W. and is only 1,200 feet long and 200 feet or less wide. The last of the smaller sills is represented by only one small outcrop in the SE¼SW¼ sec. 12, T. 39 N., R. 30 W. This metagabbro is highly magnetic and airborne magnetometer data show that it is at least 2,000 feet long. Its width is unknown.

Metagabbro is very well exposed and good outcrops of this unit can be found almost anywhere within the limits of the sills (pl. 2).

Description

The rocks of the metagabbro sills can be divided into six groups: (1) normal metagabbro, (2) schist and amphibolite, (3) magnetite-rich metagabbro, (4) pegmatitic metagabbro, (5) meta-anorthosite, and (6) granophyre. Normal metagabbro is the most abundant rock type in the sills and is found in all except the small intrusion in the Michigamme formation in the S½ sec. 12, T. 39 N., R. 30 W. Locally normal metagabbro grades into a mafic schist or amphibolite or into magnetite-rich metagabbro, or contains dikes or pods of pegmatitic metagabbro, meta-anorthosite, or granophyre. Serpentinite and pyroxenite are present along the northern edge of the Sturgeon Falls sill, and although the relationship of these rocks to the metagabbro is uncertain, they are described in this section because a discussion of their origin must be correlated with a discussion of the origin of the metagabbro.

The bodies formed by these rocks are referred to as "sills" because they are tabular with borders roughly parallel to the foliation in the enclosing Quinnesec formation rocks. They now stand nearly vertical, but evidence will be presented in a later section to show that they were probably intruded as horizontal sheets. The sills have been regionally metamorphosed; the Sturgeon Falls and Niagara sills in the greenschist facies, the Horserace sill mainly in the epidote-amphibolite facies, and the Western sill in the amphibolite facies.

Normal Metagabbro

Normal metagabbro consisting of about equal parts of ferromagnesian and feldspathic minerals, or their alteration products, is the most common rock encountered in the sills. This rock is resistant to erosion and forms relatively rugged topography with hills as high as 100 feet being common. At the Horserace Rapids, the Menominee River has excavated a steep walled gorge 100 feet deep in the metagabbro, and downstream from Niagara, Wis., cliffs of metagabbro as high as 200 feet face the river.

The appearance of the metagabbro in hand specimen varies with metamorphic grade. In the Niagara and Sturgeon Falls sills, which are in the greenschist facies, the metagabbro is commonly medium grained and consists of dull white, gray, or rarely greenish gray or flesh-colored, altered feldspar and pale green to greenish black amphibole. Cleavage surfaces in the altered feldspar are only rarely visible. Where present, the amphibole forms blades or masses of fine grains, but in some greenschist facies metagabbro no amphibole is visible. This rock is fine to medium grained, gray or greenish gray, and looks much like some Quinnesec formation greenstones. As will be noted later, thin sections show that this rock is chloritic and related to the normal metagabbro group.

The metagabbro in the Horserace sill, metamorphosed in the epidote-amphibolite facies, is medium to coarse grained. Cleavage surfaces in the feldspar grains are more common and the feldspar is more lustrous. The amphibole is darker colored and the grains are generally larger. In the Western sill, which is mainly within the amphibolite facies, the metagabbro appears even less altered. The feldspars generally show good cleavage surfaces and a vitreous or pearly luster and only rarely appear dull and altered. The amphibole is much like that found in the Horserace sill but may be slightly darker colored.

Small grains of pyrite and chalcopyrite are present in many metagabbro specimens except those from the Sturgeon Falls sill, but they are nowhere abundant. Barren quartz veins are found locally, and in the northeastern part of the Horserace sill some veins contain scattered pyrite crystals. Calcite veinlets are also present but are rare.

Porphyritic metagabbro is exposed in the Niagara sill just east of the Little Quinnesec Falls (pl. 2). This rock consists of euhedral phenocrysts of dull white altered plagioclase in a ground mass of normal metagabbro (pl. 16A). The phenocrysts are as much as $1\frac{1}{4}$ inches across and are commonly aligned in streaks (pl. 16B) paralleling the border of the sill, which here strikes slightly west of north. A similar fine-grained porphyritic metagabbro is present in a dike cutting the Quinnesec strata along the north shore of the Menominee River 850 feet southeast of the Little Quinnesec Falls, and in a dike cutting serpentinite in the northern part of the Sturgeon Falls sill in the SW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 26, T. 39 N., R. 29 W.

Metagabbro commonly weathers to a smooth brown, greenish black, or mottled white and green surface. However, in some places in the greenschist facies where the amphibole is fine grained, this mineral is less resistant and the feldspars stand up in relief. In places in the higher grades, the reverse is true and the amphibole may stand up in relief. Weathering also tends to emphasize the diabasic or ophitic texture which is present in many specimens.

A.

B.

Plate 16. Photographs of outcrop of porphyritic metagabbro. A. Euhedral altered plagioclase phenocrysts (white) in a normal metagabbro matrix (gray). B. Concentrations of plagioclase phenocrysts aligned in streaks.

The contact between metagabbro and Quinnesec strata is poorly exposed and even where exposed is difficult to study because the two rock types weather much the same and because metamorphism has produced almost identical appearing rocks from both units. As has already been noted, in areas of low metamorphic grade, some metagabbro hand specimens may look like Quinnesec greenstone. In the higher grade areas, metagabbro may grade into amphibolite, especially along the sill contacts, which is identical with Quinnesec amphibolites. Thus, due to metamorphism, many of the exposed contacts are gradational and location of the position of the boundaries of the sills in many places is somewhat subjective. On the other hand, some of the exposed contacts are sheared and are marked by a narrow schist zone, and are located easily.

In many places, fine-grained rocks suggestive of a chilled border are present near the edges of the sills; however, one can not be certain whether this is due to magmatic or to later metamorphic processes. Similar finer-grained streaks are also found in several places within the sills, but whether they represent chilled zones, and thus indicate multiple injection, or whether they are due to metamorphic processes cannot be answered.

The best exposed, apparently true chilled border, is found along the edge of the porphyritic metagabbro dike 850 feet southeast of the Little Quinnesec Falls. Here, fine-grained massive metagabbro is in sharp contact with foliated Quinnesec formation rocks and the contact truncates the foliation at an angle of 70 degrees.

In thin section, normal metagabbro can be subdivided into the following mineral assemblages (underlined names indicate probable relict primary minerals):

(1) pyroxene-actinolite-saussurite-quartz

(2) actinolite-chlorite-saussurite-quartz

(3) albite(-labradorite)-chlorite-calcite(-quartz)

(4) albite(-labradorite)-actinolite-epidote(-quartz-chlorite)

(5) oligoclase and/or labradorite-hornblende-epidote(-quartz)

(6) labradorite or bytownite(-andesine)-hornblende(-quartz)

Assemblage (1) represents the lowest metamorphic grade (greenschist facies) and rocks with this mineralogy are exposed immediately west of Sturgeon Falls (pl. 17). Assemblages (2), (3), and (4) also formed within the greenschist facies and are associated with each other in the Niagara sill and without assemblage (3) in the Sturgeon Falls sill. Assemblage (4) appears in this section, but not in the field, to grade into assemblage (5). Assemblage (5) rocks are found within the epidote-amphibolite facies isograds except for one specimen from the Niagara sill which is within the greenschist facies isograd. These rocks are found mainly in the Horserace sill and in the small sills west of Aurora and south of Niagara, Wis. Rocks with assemblage (6) mineralogy represent the highest metamorphic grade in the area (amphibolite facies), and they are found in the Western sill, along the southwestern edge of the Horserace sill, and in one place in the northwestern part of the Horserace sill outside of the amphibolite facies isograd.

The microscopic features of the assemblages will be described together because all are essentially the same with similar textures but slightly different mineral compositions. Also, the mineral changes in the various metamorphic grades can be best described in this manner. Point count modes of typical metagabbro specimens from all assemblages except (1) and (3) are in table 7. Rocks from assemblage (1) are identical to those from assemblage (2) except for the presence of relict pyroxene in the former. Assemblage (3) rocks are fine grained and difficult to count, but they consist of approximately 40 percent chlorite, 35 to 45 percent plagioclase, 5 to 25 percent calcite, and 0 to 10 percent saussurite.

The metagabbro is medium to coarse grained and is characterized by an ophitic or diabasic texture in various stages of preservation. Where original textures are best preserved, the rock consists of euhedral laths of plagioclase, or its alteration products, surrounded by anhedral grains of ferromagnesian minerals, in most places, an amphibole (pls. 18, 19, 20, and 21). Metagabbro of low metamorphic grade, assemblages (1), (2), (3), and (4), commonly consists of feldspar, or aggregates of its alteration products, which are only crudely suggestive of laths, in a mat of actinolite or chlorite. In the higher grade rocks, assemblages

Table 7. Point count modes of typical normal metagabbro.

Specimen No.	1	2	3	4	5	6	7	8	9
Assemblage	2	2	4	4	5	5	6	6	6
Amphibole	48.5	49.3	51.4	36.4	66.9	46.2	43.3	43.6	58.3
Chlorite	0.0	4.2	2.4	6.0	0.0	tr	1.9	tr	0.0
Plagioclase	6.5	6.5	18.6	25.6	23.0	27.8	53.4	55.8	38.4
Epidote group	43.8	37.1	20.0	28.8	4.6	23.4	0.0	0.4	0.5
Quartz	0.7	1.2	1.7	2.3	0.0	0.0	1.1	0.0	0.5
Magnetite	0.0	0.0	1.3	0.4	0.1	0.0	0.0	0.0	0.3
Sphene	0.0	0.0	tr	0.0	0.1	0.0	0.0	0.0	0.0
Leucoxene	0.3	tr	4.6	0.0	2.4	0.0	0.0	0.0	0.0
Pyrite	tr	tr	0.0	tr	tr	0.3	0.0	tr	tr
Biotite	0.0	0.0	0.0	0.0	2.9	0.0	0.0	0.0	0.2
Sericite	0.1	0.8	0.0	tr	0.0	1.8	0.3	0.1	1.8
Calcite	0.1	0.9	0.0	0.5	0.0	0.5	tr	0.1	0.0
Plagioclase composition	Albite	?	An_8	Albite & An_{44}	An_{53}	An_{67}	?	An_{48} & An_{83}	An_{66}

Tr - trace

1 - NW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 21, T. 38 N., R. 21 E.

2 - NW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 9, T. 38 N., R. 20 E.

3 - SW$\frac{1}{4}$SE$\frac{1}{4}$ sec. 14, T. 39 N., R. 30 W.

4 - NW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 14, T. 39 N., R. 30 W.

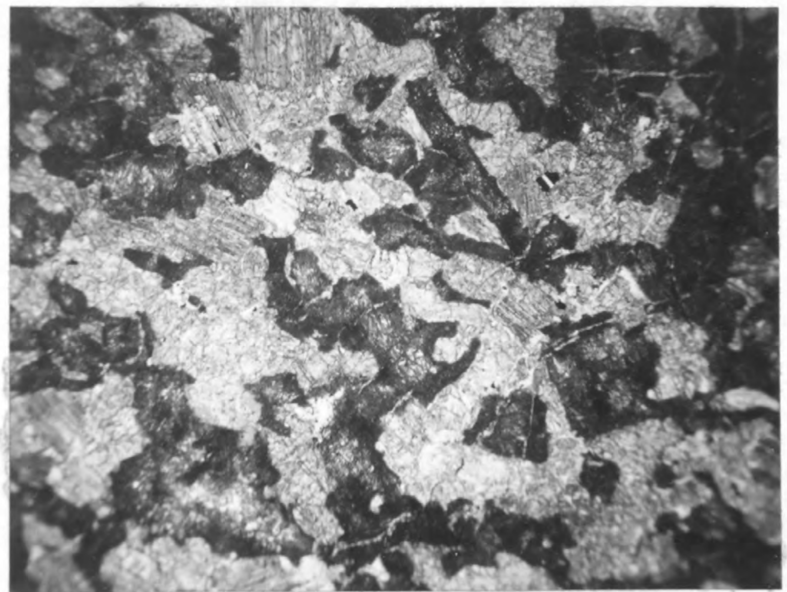
5 - SW$\frac{1}{4}$ SE$\frac{1}{4}$ sec. 7, T. 39 N., R. 30 W.

6 - SW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 7, T. 39 N., R. 30 W.

7 - NW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 15, T. 38 N., R. 19 E.

8 - SE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 9, T. 38 N., R. 19 E.

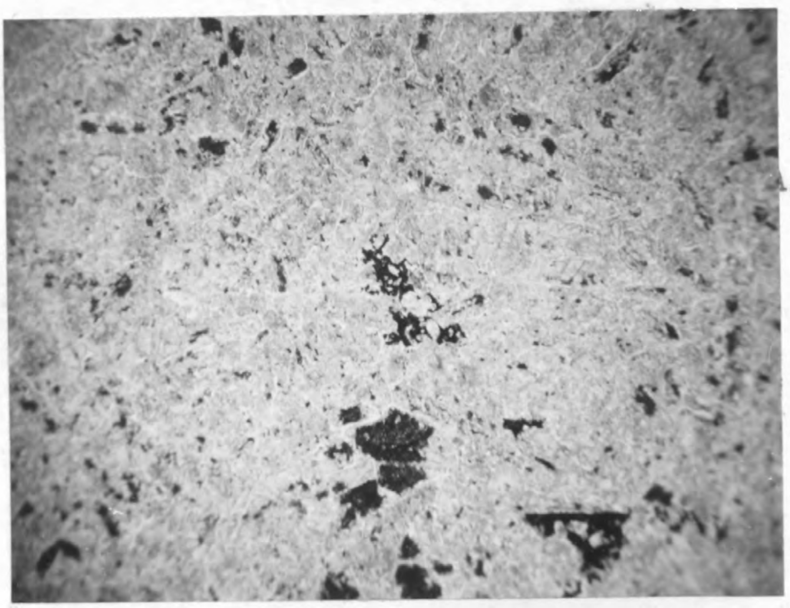
9 - SE$\frac{1}{4}$NW$\frac{1}{4}$ sec. 15, T. 38 N., R. 19 E.



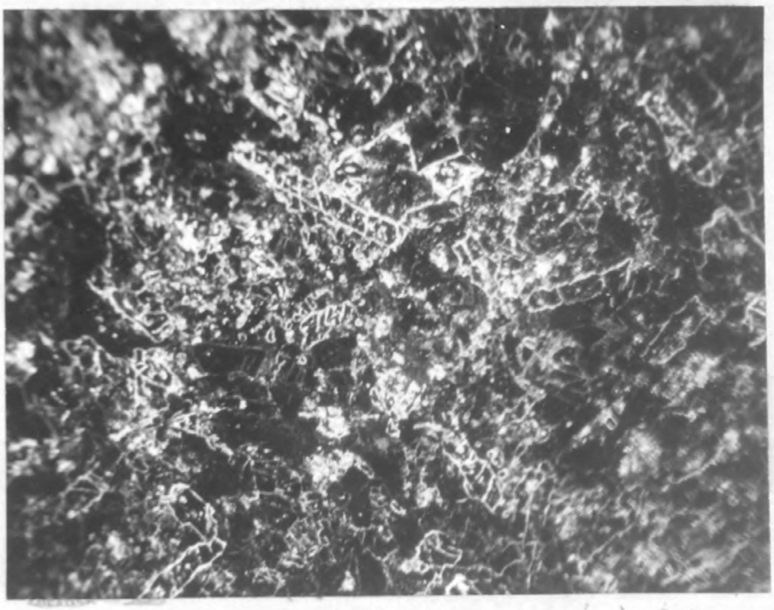
A.

B.

Plate 18. Photomicrographs of normal metagabbro. A. Assemblage (1). Note euhedral plagioclase laths, now mostly altered to dark gray saussurite, surrounded by actinolite (light gray) and pyroxene (medium gray). Plane polarized light. x23. B. Assemblage (4). Plagioclase laths, now albite and saussurite (mottled dark and light gray), and pale green amphibole (medium gray). Plane polarized light. x23.



A.



B.

Plate 19. Photomicrographs of assemblage (3) metagabbro. A. Medium gray is chlorite; lighter gray, albite; and dark gray, leucoxene. Plane polarized light. x23. B. Same as A., crossed nicols. Note original plagioclase laths now rimmed by albite (white).

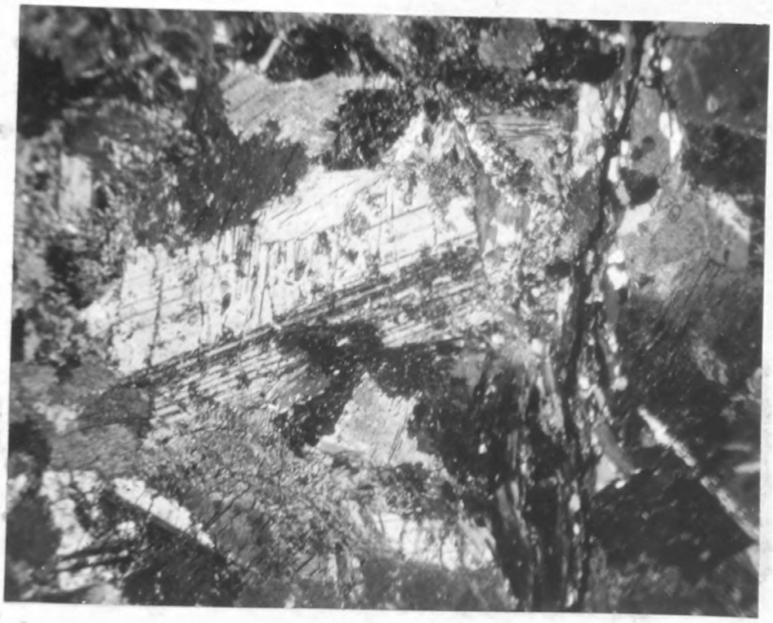
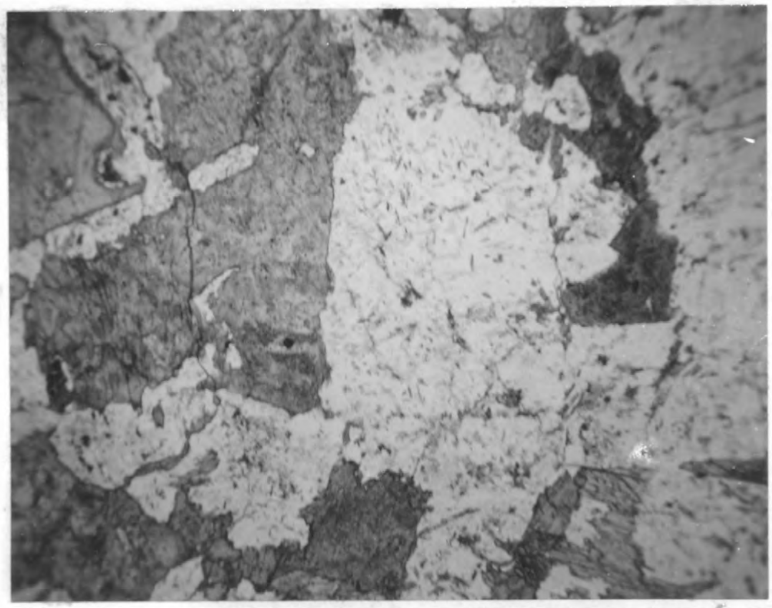
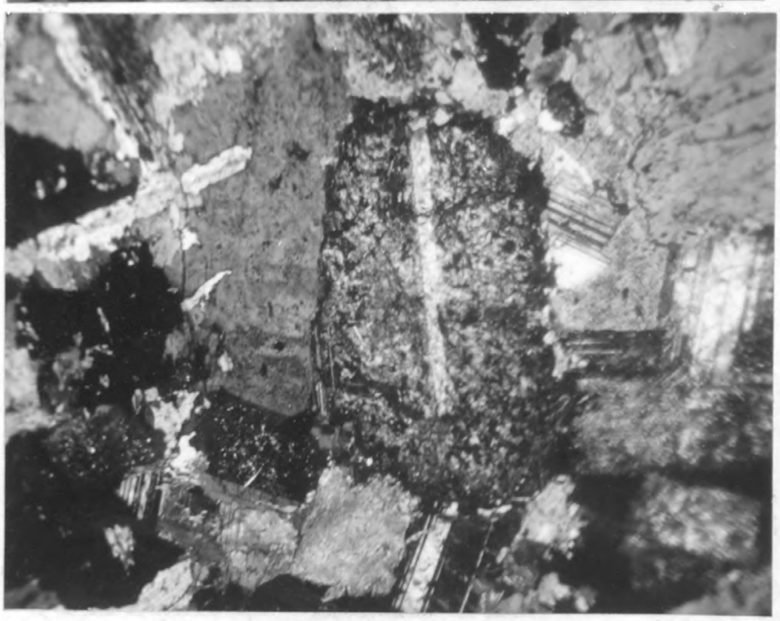


Plate 20. Photomicrograph of assemblage (5) metagabbro. Labradorite in center of picture partially altered to small epidote grains. Remainder of specimen is hornblende and plagioclase. Crossed nicols. x23.



A.



B.

Plate 21. Photomicrographs of assemblage (6) metagabbro. A. Note euhedral to subhedral plagioclase (light gray), surrounded by hornblende (medium gray). Inclusions in plagioclase are hornblende needles and sericite. Plane polarized light. x23. B. Same as A. Note plagioclase grain in center is actually made up of two plagioclases, andesine (An_{33}) at extinction and bytownite (An_{79}) white. Crossed nicols. x23.

(5) and (6), the original texture is better preserved and the plagioclase less altered. However, these rocks locally grade into rocks in which the original texture has been obliterated by the partial recrystallization of the constituents to a finer-grained mosaic. Chloritic metagabbro, assemblage (3), has a peculiar texture which needs special mention. In plane polarized light, the rock appears to consist mainly of an irregular mat of chlorite and albite. However, under crossed nicols, the albite grains formed from any one lath are in optical alignment, thereby outlining the original lath (pl. 19).

Amphibole is the most common mafic mineral in the normal metagabbro and it is found in a variety of forms. In most places it is clearly pseudomorphic after original pyroxene, preserving the original pyroxene habit of being molded around laths of feldspar (pls. 18 and 21). The amphibole commonly forms anhedral plates, in places twinned, which may be as much as 4.0 mm long and which in the higher grade rocks, tend to be poikiloblastic by including smaller grains of plagioclase and quartz. The edges of the plates may be ragged and fibrous and some of the ferromagnesian components have migrated and have formed fibrous amphibole inclusions in plagioclase or along grain boundaries and cleavage cracks of original plagioclase grains (pl. 21A). The amphibole inclusions are more common in the higher grade rocks [assemblages (5) and (6)]. The original pyroxene may also be replaced by a mat of amphibole fibers or by a mosaic of small, subequant amphibole grains. These latter two occurrences may be found in all of the assemblages, but in the higher metamorphic grades, the individual fibers or grains tend to be stouter and larger than in the lower grades. In contrast to the habit just described, amphibole in some of the more highly altered rocks from the greenschist facies forms irregular grains in a mat of alteration minerals with no apparent relationship to the original pyroxene.

The amphibole in the normal metagabbro is pleochroic with X = straw, Y = olive-green, and Z = bluish green. In assemblage (1) and (2) rocks it is generally pale and in places practically colorless, and is probably actinolitic. Some assemblage (2) rocks contain amphibole which is mottled with splotches of brownish amphibole showing X = straw, Y = greenish brown, and Z = brown in a normal actinolite. The amphibole in assemblage (4) rocks is pale to moderately pleochroic, tending toward an aluminous hornblende, whereas that in assemblage (5) and (6) rocks is moderately to deeply pleochroic and most of it appears to be aluminous hornblende. Some of the hornblende grains in assemblage (5) rocks have darker-colored borders than interiors. The extinction angle of the amphiboles is $Z \wedge c$ 13° to 20°, and there is no apparent relationship between this angle and geographic location of the sample, assemblage, or pleochroism.

Chlorite is common in the rocks from the greenschist facies but is rare in those from the epidote-amphibolite and amphibolite facies. It is green, weakly to moderately pleochroic with gray, or anomalous brown, blue, or violet interference colors. It is quite variable in its occurrence, but in the greenschist facies it is commonly found in irregular splotches in large amphibole grains or intergrown with fibrous amphibole. In this association it appears to be related to the original mafic minerals of the rock, but elsewhere it may be scattered throughout the slide where its relationship to original minerals is obscure. Chlorite also occurs as inclusions in plagioclase grains or along plagioclase cleavage cracks or it may be associated with plagioclase alteration products (pl. 19). In one specimen, it was found along the amphibole twin plane. In the higher grade rocks, the chlorite is generally restricted to streaks or stringers where it appears to be late, and is only rarely associated with the hornblende.

Pyroxene remnants surrounded by pale green or brown amphibole are characteristic of the assemblage (1) rocks (pl. 18A). The pyroxene is pale green, monoclinic, and has a moderately large 2V. Some grains show a well-developed basal parting. This pyroxene is probably augite and a relict of the primary mineral assemblage of the gabbro. Tiny pyroxene remnants were also found in one assemblage (2) specimen and in one assemblage (5) specimen, but they were too small to permit further identification. In general all primary pyroxene has been destroyed in the higher grade rocks.

One assemblage (2) specimen contained altered remnants of olivine. These olivine remnants now consist wholly of a fine-grained mat of serpentine and talc which shows the olivine outline and the pattern of cracks which characteristically traverse olivine grains.

The feldspathic minerals in normal metagabbro consist of plagioclase and/or its alteration products, epidote, clinozoisite, saussurite, and sericite, arranged in laths or stubby euhedral grains averaging from 1.0 to 7.0 mm long. The characteristics of these feldspathic minerals varies considerably and constitute the primary basic for the subdivision of the rocks into the various assemblages.

In assemblage (1) and (2) fine-grained, brown, aggregates of saussurite or subhedral to anhedral grains of epidote, zoisite, or clinozoisite as much as 0.5 mm across form pseudomorphs after original plagioclase laths (pl. 18A). Blue or yellow interference colors suggesting zoisite or epidote grains can be seen in some of the saussurite. The larger epidote grains are colorless and show the usual yellowish interference colors, whereas the zoisite has gray, rather than the more common blue, interference colors. Some clear, secondary albite, quartz, chlorite, calcite, and sericite are found in the laths in a few places.

Albite (An_2) rimming and traversing the sites of original feldspar laths is the common plagioclase in the assemblage (3) rocks (pl. 19). The albite is clear and that associated with any one lath is in optical continuity. The remainder of the original lath is now composed of chlorite or less commonly, saussurite. Some original labradorite (An_{56}) was found in one specimen of this assemblage.

Assemblage (4) rocks characteristically contain secondary albite (An_{1-8}) and in addition commonly contain original labradorite or calcic andesine (An_{44-62}). Where two plagioclase feldspars are present in the same specimen and their relationship can be observed, clear, untwinned albite rims or veins altered, twinned and in some places normally zoned labradorite. Saussurite or grains of epidote, zoisite, or clinozoisite as much as 0.5 mm long are alteration products found in all specimens with this mineralogy (pl. 18B). These alteration minerals commonly occur in patches in the original lath, or rarely along plagioclase cleavage cracks or as veinlets traversing the specimen. In the more altered specimens which contain no labradorite, the original laths are now mainly epidote-group minerals with scattered, clear, anhedral grains of albite. These last-described rocks thus appear transitional between assemblage (2) and assemblage (4) rocks. Sparse sericite and calcite grains are also found with the feldspathic minerals in rocks from this assemblage.

The porphyritic metagabbro specimens all consist of feldspar phenocrysts completely altered to saussurite or fine-grained epidote in a typical assemblage (4) groundmass.

Metagabbro metamorphosed in the epidote-amphibolite facies [assemblage (5) rocks] usually contains either oligoclase (An_{12-28}) or labradorite-calcic andesine (An_{43-67}), but in one specimen, two plagioclases (An_{19} and An_{45}) were found. In the specimen with two plagioclase feldspars, the oligoclase is clear, whereas the andesine is rusty colored. Elsewhere, the plagioclase may be either rusty-colored or clear, irrespective of its composition. The plagioclase is everywhere twinned by the albite law, but is rarely zoned. Epidotic alteration is found in all specimens studied, and epidote is the common mineral present. Zoisite and clinozoisite are rare. These minerals occur in subhedral or euhedral grains as much as 0.5 mm across. Fine-grained saussurite characteristic of the lower grade rocks is rare. Sericite is also a common alteration product of the feldspars in these rocks and calcite was found in a few places. In some specimens, especially those near the amphibolite facies, the borders of some of the plagioclase laths (oligoclase in these specimens) are recrystallized to a finer grained mosaic.

Most of the rocks with assemblage (6) mineralogy, which represent the highest metamorphic grade rocks in the area, contain two plagioclase feldspars, clear metamorphic andesine-sodic labradorite (An_{33}-$_{53}$) and relict calcic labradorite-bytownite-anorthite (An_{66-95}). Since they consist of an intergrowth of two feldspars, the laths in these specimens appear mottled in crossed nicols when one plagioclase is at extinction and the other is not (pl. 21). Albite twins are present in all of the specimens studied and pericline twins are also common. Some grains show normal zoning. Sericitic alteration is present but is not as common as in assemblage (5) rocks; epidotic alteration is almost entirely lacking. As in assemblage (5) rocks, the plagioclase grains locally have recrystallized borders.

Quartz is present in most of the specimens studied but it is nowhere abundant. It generally occurs as small, clear grains in a mosaic with secondary plagioclase and plagioclase alteration products. In a few places, however, it does form rather large, anhedral grains molded around plagioclase laths. Here it appears to be a primary mineral.

Calcite is found in some specimens from all of the assemblages except assemblage (6). It commonly occurs with chlorite or fibrous amphibole, or as inclusions in massive amphibole. Calcite is also found in small quartz veinlets.

Small, irregular grains of magnetite, or its alteration products, are found in most specimens. In the greenschist facies, assemblage (1), (2), and (3) rocks, the magnetite is rimmed or completely replaced by brown, opaque leucoxene. In assemblage (4) rocks, distinct grains are visible in the leucoxene which is tending toward crystallizing as sphene. Sphene rims magnetite in other assemblage (4) and most assemblage (5) rocks and occurs alone in one assemblage (2) specimen. Neither sphene nor leucoxene are found in the high grade assemblage (6) rocks.

Pyrite is found in some specimens and is locally weathered to hematite or limonite. Zircon is a common accessory mineral with apatite being found locally. Tourmaline was found in one assemblage (5) specimen and biotite is associated with the amphibole in some of the assemblage (5) and (6) rocks.

Chemical analyses and norms of four metagabbro specimens from the area are in Table 8. Three are old analyses (Williams, 1890) and one is new (anal. 4). Analysis 4 is the same specimen as mode 7, Table 7. In addition, Nockolds' (1954) analysis of average gabbro is given for comparison. All metagabbro specimens are fairly close to the average gabbro in composition except analysis 4 which is rich in Al_2O_3 and deficient in total iron. The high Al_2O_3 value is reflected by abnormally high normative feldspar, but this high feldspar percentage is not borne out by the mode (Table 7, specimen 7). Possibly the hornblende in this specimen is rich in alumina which would explain the anomalous relationship of the mode and the norm. The three old metagabbro analyses (specimen nos. 1, 2, and 3) show a low FeO/Fe_2O_3 ratio. This is probably due either to analytical errors or to metamorphism disturbing the ratio. As expected, the metagabbro specimens

Table 8. Chemical analyses and norms of normal metagabbro and of average gabbro.

Spec. No.	1	2	3	4 1/	5
Assemblage	1	2	4	6	-
SiO_2	51.46	47.96	48.35	47.6	48.36
TiO_2	n.d.	n.d.	n.d.	0.18	1.32
Al_2O_3	14.35	16.85	15.40	22.2	16.84
Fe_2O_3	3.90	4.33	4.04	1.1	2.55
FeO	5.28	4.17	4.63	4.4	7.92
MnO	n.d.	n.d.	n.d.	0.10	0.18
MgO	9.54	9.15	11.61	7.1	8.06
CaO	9.08	13.25	10.38	12.5	11.07
Na_2O	2.92	1.25	1.87	1.8	2.26
K_2O	0.24	0.30	0.35	0.50	0.56
H_2O	3.30	2.89	3.60	2.0	0.64
P_2O_5	n.d.	n.d.	n.d.	0.01	0.24
CO_2	0.20	0.08	0.08	0.18	n.d.
Total	100.27	100.23	100.31	99.75	

	1	2	3	4	5
qz	1.6	1.4	0.0	0.0	0.0
or	1.1	1.7	2.2	2.8	3.3
ab	24.6	10.5	15.7	15.2	18.9
an	25.3	39.7	32.5	51.1	34.2
$CaSiO_3$	7.8	10.7	7.8	3.9	8.0
$MgSiO_3$	23.8	22.9	24.1	11.0	14.0
$FeSiO_3$	6.6	4.1	4.2	4.2	7.4
Mg_2SiO_4	0.0	0.0	3.4	4.9	4.3
Fe_2SiO_4	0.0	0.0	0.7	2.0	2.5
mt	5.6	6.3	5.8	1.6	3.7
il	--	--	--	0.5	2.4
ap	--	--	--	0.0	0.6
cc	0.5	0.2	0.2	0.5	--

n.d. - not determined

1/ specimen also contains .0050% Cu, .0030% Co, .017% Ni, and .058 Cr.

1. "gabbro" from Sturgeon Falls. Williams (1890, p. 76, anal. I).

2. "gabbro-diorite" from Little Quinnesec Falls. Williams (1890, p. 89, anal. I).

3. "gabbro" from Big Quinnesec Falls. Williams (1890, p. 104, anal. I).

4. metagabbro. NW¼NW¼ sec. 15, T. 38 N., R. 19 E., Wis. Paul L. D. Elmore, Katrine E. White, Samuel D. Botts, and Harry J. Rose, U. S. G. S., analysts.

5. average gabbro. Nockolds (1954, table 7, anal. I).

contain more water than average gabbro. The close correspondence of the analyses shows that all the specimens were derived from rocks of essentially the same composition although now they differ greatly in mineralogy. The metagabbro mineral assemblages represented are shown on Table 8 below the specimen number. The assemblages of the old analyses were determined from Williams' (1890) published petrographic descriptions.

Schist and Amphibolite

Green schist or phyllite in the low metamorphic grades and amphibolite in the high are commonly associated with the normal metagabbro. In most places, the foliation in these rocks is parallel with the regional structural trend or with the border of the sill and the rock grades into normal metagabbro. Here, the schist and amphibolite appear to have been derived from normal metagabbro under the influence of shearing. In a few places, however, similar schist or amphibolite masses appear to be inclusions of Quinnesec formation rocks. Inasmuch as most of the schist and amphibolite derived from metagabbro is identical with that derived from Quinnesec formation rocks it is impossible to determine in many places whether one is dealing with an inclusion in the metagabbro or with metagabbro itself. Therefore, both will be described in this section.

Schists derived from metagabbro under greenschist facies conditions are found in many places in the Sturgeon Falls and Niagara sills. In these sills, normal massive metagabbro grades first into metagabbro traversed by occasional streaks of parallel-oriented, fine-grained chlorite flakes. The other minerals in the rock are slightly crushed. The rock gradually becomes finer grained and the foliation more pronounced until finally it grades into green phyllite or fine-grained schist. The phyllite or schist is less resistant to weathering than the metagabbro and commonly forms low areas in the outcrop. These transitions have been traced under the microscope by Williams (1890, p. 68-75, 81-95, and 102-106) and a description need not be repeated here.

A fine-grained black phyllite inclusion is found in the Niagara sill east of the Little Quinnesec Falls in the NW$\frac{1}{4}$SE$\frac{1}{4}$, sec. 14, T. 39 N., R. 30 W. This rock was probably derived from black slate of the Michigamme formation.

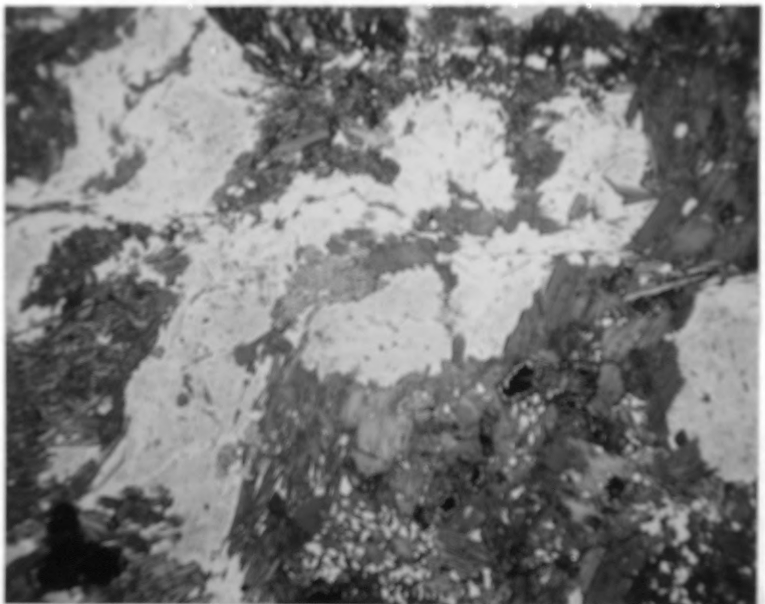
The metagabbro in the Horserace sill which has been metamorphosed in the epidote-amphibolite facies locally grades into chlorite or chlorite-biotite schists. The schists are coarser grained than those derived from metagabbro in the greenschist facies and in some places are associated with quartz veins. These veins may contain some pyrite and chalcopyrite. They have been prospected but nothing of economic importance has been found.

The rock which is transitional between massive metagabbro and schist is commonly pale to dark green and consists of streaks of sub-parallel chlorite flakes, and fragments of altered gray-green feldspar and green hornblende. Thin sections of the transitional rock show that the foliation is imparted either by chlorite flakes, or by hornblende prisms and biotite and chlorite flakes. The foliation is irregular in that it curves around remnants of plagioclase and hornblende. The plagioclase is everywhere altered; completely so in some places to sericite and muscovite. Locally it is recrystallized to a mosaic of secondary plagioclase and quartz. The chlorite is colorless to green with gray interference colors. The hornblende is also green to practically colorless. Magnetite surrounded by sphene, epidote, zoisite, and some calcite are also present.

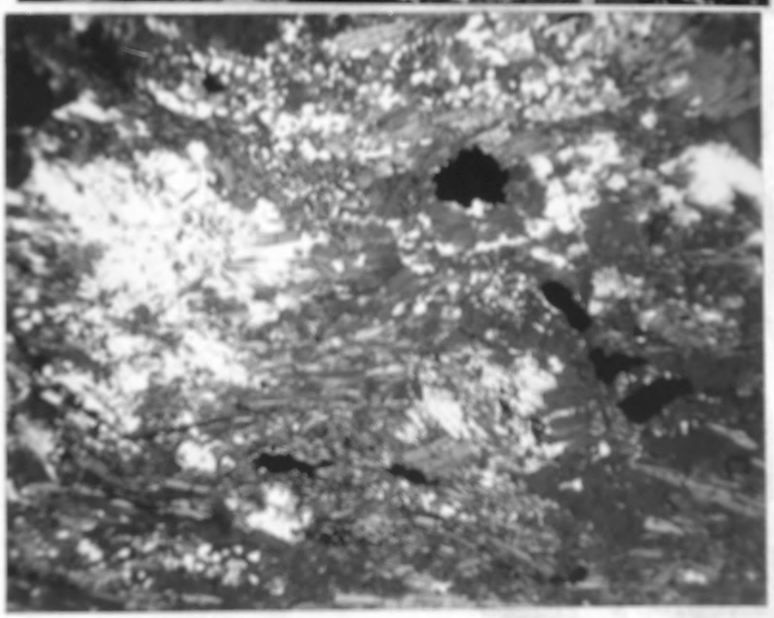
In the Western sill, patches or streaks of amphibolite are associated with the metagabbro in many places and in the north-western part of the sill, some whole outcrop areas are composed of coarse-grained amphibolite. As will be shown later, some of the amphibolite appears to have been derived from metagabbro through shearing, some apparently is inclusions of metamorphosed mafic igneous rocks (probably Quinnesec formation), and that occurring in whole outcrop areas is of doubtful origin.

An amphibolite border is found along the northern edge of the sill in sec. 11, T. 38 N., R. 19 E. and along the southern edge of the sill at the western edge of the map area. In addition, amphibolite streaks paralleling the regional structural trend and grading into normal metagabbro are found in several places within the sill. These amphibolite borders and streaks vary from one to 15 feet in width. Inasmuch as a complete gradation between amphibolite and massive metagabbro can be seen, it is postulated that the amphibolite in these occurrences was derived from metagabbro. In the first stage of the transition, some of the metagabbro components have recrystallized to a finer grain and hornblende needles show the beginnings of a crude preferred orientation. Through further recrystallization, the rock finally passes into a medium-grained amphibolite consisting of parallel-oriented needles of green or blackish green hornblende; gray, fine-grained feldspar; and some quartz.

In thin section, this transition is well illustrated (pl. 22). In the first stage, the hornblende is not in large plates pseudomorphic after pyroxene but has recrystallized to prisms or to poikiloblastic plates loaded with quartz inclusions (pl. 22A), and many of the prisms are showing some suggestion of a tendency toward parallelism. The plagioclase in this stage is only slightly recrystallized to a finer-grained mosaic with quartz (pl. 22A). In the final stage, the hornblende is mainly in parallel-oriented prisms averaging 0.5 mm long with only a few remnants of poililoblastic plates (pl. 22B). The hornblende is also more deeply pleochroic than in the original rock with X = straw, Y = green,



A.



B.

Plate 22. Photomicrographs of rocks transitional between metagabbro and amphibolite. A. First stage. Plagioclase plates (white) with slight recrystallization of borders and hornblende (gray) in prisms or poikloblastic plates. Note magnetite (black) surrounded by sphene in lower right. Plane polarized light. X23. B. Second stage. Andesine and quartz (white), hornblende prisms (gray), and some magnetite (black). Plane polarized light. x23.

and Z = blue-green. The plagioclase is almost completely recrystallized to a mosaic of andesine and quartz grains averaging 0.1 mm in cross section with only a few scattered large plates as much as 0.5 mm across remaining (pl. 22B). Some of the plagioclase is partially altered to sericite. Small magnetite grains form streaks parallel with the foliation of the rock and they are locally surrounded by rims of sphene. Some of the amphibolite contains a trace of zoisite, chlorite, or zircon, and one contains pyrite. The point count mode of a typical amphibolite believed to have been derived from metagabbro is in Table 9.

Amphibolite which contains chlorite and biotite associated with hornblende is found along the northern edge of the central part of the Western sill near the boundary between secs. 10 and 11, T. 38 N., R. 19 E. This amphibolite also contains some clinozoisite, epidote, tourmaline, and calcite, but is otherwise identical with the amphibolite just described. It appears to have been metamorphosed in the epidote-amphibolite rather than the amphibolite facies as shown on plate 2.

The second group of amphibolites found in the Western sill are those believed to represent inclusions of mafic Quinnesec formation rocks. These are considered inclusions rather than foliated metagabbro because: (1) their foliation is oblique to the regional trend, (2) they are finer grained than the just

Table 9. Point count mode of amphibolite derived from metagabbro.

	1
Hornblende	60.3
Andesine (An_{37})	30.7
Quartz	6.5
Magnetite	0.9
Sphene	1.6
Sericite	tr
Zircon	tr

tr - trace

1 - NE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 11, T. 38 N., R. 19 E.

described amphibolites, and (3) they are in sharp contact with the enclosing metagabbro. These inclusions vary from small, irregular masses to elongate sheets as much as 400 feet long. The largest and best exposed ones are found in the eastern part of the sill in the N$\frac{1}{2}$SE$\frac{1}{4}$ sec. 11, T. 38 N., R. 19 E. In hand specimen these rocks are fine to medium grained and are greenish black or black. Hornblende is the only identifiable mineral. In thin section they are like assemblage (3) or (3b) andesine amphibolites of the Quinnesec formation except they are slightly coarser grained.

The final group of amphibolites found in the Western sill are those which constitute whole or large parts of outcrop areas. They are found mainly in the northwestern part of the sill in the N$\frac{1}{2}$SW$\frac{1}{4}$ sec. 10, T. 38 N., R. 19 E. and in adjacent sec. 9. These rocks are moderately coarse grained, black, and slightly foliated. Prisms of black hornblende and, in a few places, plagioclase or quartz grains are visible under a hand lens. Pyrite is a common accessory mineral. These rocks are included with metagabbro rather than with Quinnesec formation amphibolite because they are coarser grained than the normal Quinnesec amphibolite and because, geographically, they appear to be closely related to the metagabbro.

In thin section, a crystalloblastic and slightly foliated texture is visible. The rock consists predominantly of hornblende, plagioclase, and quartz. The hornblende occurs in poikiloblastic plates sieved with quartz or in subparallel-oriented prisms. They average 2.0 mm long and are strongly pleochroic with X = light brown, Y = green, and Z = dark blue-green. The plagioclase is calcic oligoclase (An_{27-29}) which occurs in plates as much as 1.5 mm long or in a fine-grained mosaic with quartz. Irregular pyrite and magnetite grains are found molded around hornblende grains. Some epidote, zoisite, calcite, and chlorite are also present.

Magnetite-rich Metagabbro

Metagabbro abnormally rich in magnetite is found in the Niagara sill at its eastern end, near the Little Quinnesec Falls, and near the Big Quinnesec Falls, and in the small sill in the Michigamme formation in the S½ sec. 12, T. 39 N., R. 30 W. By a decrease in the amount of magnetite, this rock grades into normal metagabbro so the contact between the two units as shown on plate 2 is only approximate. In some places, the contact is marked by a shear zone. The magnetite-rich metagabbro is, of course, magnetic and on the basis of airborne magnetometer data, the Niagara sill has been extended west of known outcrops into the NE¼ sec. 7, T. 39 N., R. 30 W. and the small sill cutting the Michigamme formation has been extended both east and west of its only known outcrop (pl. 2).

Magnetite-rich metagabbro is heavier and darker colored than normal metagabbro and is medium to coarse grained. Black magnetite can be seen in all hand specimens of this rock, and pale green altered feldspar and greenish black hornblende in most. Pyrite is found locally. The rock weathers mottled white or light gray and dark green, or uniformly dark brown. In some places, magnetite stands out in relief on a weathered surface.

Except for the abundance of magnetite, the magnetite-rich metagabbro from the Niagara sill appears in thin section like normal chloritic metagabbro with assemblage (3) mineralogy or like normal amphibole-bearing metagabbro with assemblage (4) mineralogy. Magnetite-rich metagabbro similar to assemblage (3) normal metagabbro contains plagioclase laths outlined by albite as in the non-magnetic variety, but here the chlorite is darker green and has anomalous blue or maroon interference colors, properties which probably indicate a higher iron content. Magnetite-rich metagabbro similar to assemblage (4) normal metagabbro contains albite (An_{5-8}) and usually relict labradorite (An_{52-58}), and the relationship between the two plagioclases is more clearly shown here than in the normal metagabbro. The albite is clear and is definitely secondary as it rims and veins the labradorite which is partly altered to fine-grained epidote. Zoisite, clinozoisite, and saussurite are not present. The amphibole in the magnetite-rich metagabbro is rarely fibrous and is more deeply pleochroic than in the normal metagabbro showing X = brown, Y = olive-green to brownish green, and Z = bluish green, and $Z \wedge c = 18^\circ$. This amphibole is probably hornblende which contains more iron than the actinolitic amphibole in the normal metagabbro. In addition, some magnetite-rich metagabbro specimens have characteristics of both of the rocks just described. They have plagioclase laths outlined by albite with interiors of chlorite and epidote like the first described variety, but they also contain abundant brownish green hornblende like the second.

Magnetite forms as much as 10 percent of this rock and in many specimens, it forms irregular grains molded around the other constituents (pl. 23) and thus appears to have formed late. Elsewhere it forms subhedral to euhedral grains in which the relationship to the other minerals is not clear. Magnetite was separated from five specimens and it yielded positive results to the qualitative hydrogen peroxide test for titanium. In many places, the magnetite is rimmed by secondary dark brown leucoxene or fine-grained sphene, and in some places, these alteration minerals form a triangular grid pattern through the magnetite grain.

Other accessory and alteration minerals found in the magnetite rich metagabbro include quartz, pyrite, zircon, apatite, calcite, and hematite. The modes of two typical specimens of this rock type are in Table 10.

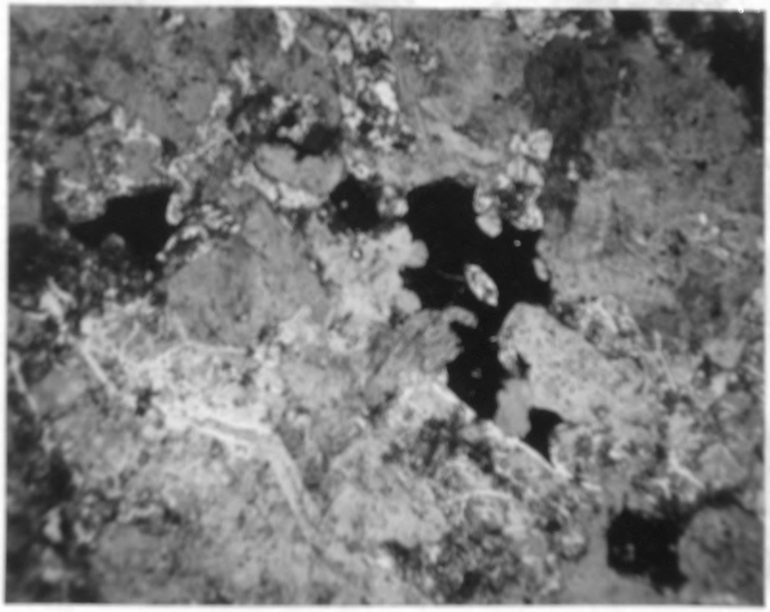


Plate 23. Photomicrograph of magnetite-rich metagabbro. Albite (white), chlorite (medium gray, clear), and epidote (dark gray) occupy original plagioclase laths. Also present, hornblende (medium gray with dark inclusions) and late magnetite and leucoxene (black). Plane polarized light. x23.

Table 10. Point count modes of magnetite-rich metagabbro.

	1	2
Hornblende	37.5	48.7
Chlorite	22.3	3.6
Plagioclase	15.1	17.8
Epidote	15.6	20.8
Quartz	0.4	0.0
Magnetite	6.1	9.1
Leucoxene	2.5	0.0
Pyrite	0.3	0.0
Apatite	0.2	tr

tr - trace

1 - SE$\frac{1}{4}$NW$\frac{1}{4}$ sec. 14, T. 39 N., R. 30 W.

2 - NW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 10, T. 38 N., R. 20 E.

A chemical analysis of magnetite-rich metagabbro is in Table 11. From the petrographic description of the analyzed specimen (Williams, 1890), it is certain that the rock is magnetite-rich metagabbro as defined in this report with a mineralogy intermediate between the chloritic and hornblendic varieties. As expected, the analysis is high in total iron, the other elements being present in amounts typical for a gabbroic rock.

The magnetic metagabbro from the small sill cutting the Michigamme formation in the $S\frac{1}{2}$ sec. 12, T. 39 N., R. 30 W. is different from that just described. It is highly altered and consists mainly of saussurite, sericite, pale chlorite with blue interference colors, subhedral brown sphene, euhedral to subhedral magnetite, and some colorless amphibole. These minerals form an irregular mat with only a faint suggestion of an original diabasic texture. Some calcite and apatite are also present.

Pegmatitic Metagabbro

Pegmatitic metagabbro is present in the Niagara sill near its eastern end and in the vicinity of the Little Quinnesec Falls. It occurs across the whole width of the sill and does not seem to be concentrated near either border. Especially good exposures of this rock are found in the eastern part of the sill in the small outcrop along the road in the $W\frac{1}{2}$ sec. 20, T. 39 N., R. 29 W., in

Table 11. Chemical analysis and norms of magnetite-rich metagabbro.

	1 1/
SiO_2	43.80
Al_2O_3	16.08
Fe_2O_3	9.47
FeO	10.50
MgO	6.54
CaO	7.81
Na_2O	1.96
K_2O	0.34
H_2O	3.99
CO_2	0.08
Total	100.57

	1
qz	0.5
or	1.7
ab	16.8
an	34.2
$CaSiO_3$	1.6
$MgSiO_3$	16.4
$FeSiO_3$	11.5
mt	13.7
cc	0.2

1/ TiO_2 not determined

1 - "dark massive greenstone" from Little Quinnesec Falls. Williams (1890, p. 91, anal. I).

the central part of the sill near its southern edge just east of the Little Quinnesec Falls, and near its northern edge in the NW$\frac{1}{4}$ sec. 10, T. 38 N., R. 20 E. The pegmatitic metagabbro forms dikes as much as 6 inches wide or irregular schlieren in either normal or magnetite-rich metagabbro. The dikes are in sharp contact with the enclosing metagabbro whereas the schlieren are in gradational contact. Where associated with magnetite-rich metagabbro, the pegmatitic phase is also rich in magnetite; where associated with normal metagabbro, the pegmatitic phase contains only a small amount of magnetite.

Green to greenish black hornblende or actinolite, white to green altered feldspar, and magnetite are visible in hand specimen. The amphibole commonly forms blades as much as 2$\frac{1}{2}$ inches long, but in some places these blades have recrystallized to a mass of finer amphibole grains. The feldspar is finer grained than the amphibole and, although it is altered, cleavage surfaces are visible in many places. The amphibole weathers dark green or black, the feldspar, light gray.

In thin section, the minerals in the pegmatitic metagabbro appear similar to those found in normal metagabbro with assemblage (4) mineralogy or to those in magnetite-rich metagabbro. Texturally, the rock is ophitic, but is very coarse grained. One specimen contained myrmekitic intergrowths of quartz and plagioclase.

The point count mode of pegmatitic metagabbro is shown in Table 12; 1000 grains were counted in a thin section of the finest grained specimen of this rock found in the area.

Meta-anorthosite

Metamorphosed anorthosite is of widespread occurrence in the metagabbro but it is nowhere abundant. It is most abundant in the Niagara sill where small patches of it are found both east and west of the Little Quinnesec Falls. It is also exposed in a few small patches near the western end of the Sturgeon Falls sill and in the south central part of the Western sill. None was found in the Horserace sill. The meta-anorthosite forms small patches or lenses as much as 20 feet wide and of undetermined length as the ends of the exposures are commonly covered. Its contacts with normal metagabbro may be gradational or sheared. Meta-anorthosite was not found in magnetite-rich metagabbro.

The meta-anorthosite is medium grained and in hand specimen is white to greenish gray. It consists mainly of feldspar or feldspar alteration products. In areas of low metamorphic grade in the Sturgeon Falls and Niagara sills, the feldspar is commonly altered and is white or greenish gray with only occasional cleavage surfaces visible. In the higher grade areas, in the Western sill, the plagioclase is light gray and lustrous with abundant cleavage faces. The meta-anorthosite also contains streaks or splotches of green hornblende or chlorite and in one place, sphene. By an increase in the amount of hornblende or chlorite, the rock grades

Table 12. Point count modes of pegmatitic metagabbro and of meta-anorthosite.

	1	2
Amphibole	47.8	12.0
Chlorite	4.3	1.6
Plagioclase	29.8	85.8
Epidote-clinozoisite	13.7	tr
Quartz	0.7	0.0
Magnetite	1.3	0.0
Sphene-leucoxene	1.8	0.0
Biotite	0.0	0.6
Sericite	0.0	tr
Apatite	0.2	0.0
Calcite	0.4	tr
Plagioclase composition	An_{13}	An_{34} & An_{70}

tr - trace

1 - pegmatitic metagabbro, sec. 15, T. 39 N., R. 30 W.

2 - meta-anorthosite, $SW\frac{1}{4}SE\frac{1}{4}$ sec. 10, T. 38 N., R. 19 E.

into normal metagabbro. Meta-anorthosite weathers gray, generally of a lighter shade than the normal metagabbro.

In thin section, the anorthosite is hypidiomorphic to allotrimorphic granular consisting mainly of plagioclase, or its alteration products, in subhedral or anhedral plates averaging 3.0 mm long (pl. 24). In the greenschist facies, the original plagioclase has been altered to albite or sodic oligoclase (An_{3-17}), zoisite, clinozoisite, saussurite, or more rarely sericite. In one specimen, clear albite was found rimming altered grains of oligoclase. In the amphibolite facies, the plagioclase in the meta-anorthosite is similar to that in the normal metagabbro. That is, it is mottled consisting of plagioclase of two different compositions, altered relict calcic plagioclase (An_{70}) and clear secondary andesine (An_{34}). In the higher grade rocks, the alteration is not as intense and is mainly sericite with only a trace of epidote.

Some mafic minerals are also found in the meta-anorthosite. In the greenschist facies, colorless chlorite was found in all of the specimens studied and some fibrous and colorless amphibole was found in one. In the specimen from the amphibolite facies, moderately pleochroic green hornblende and a trace of brown biotite and chlorite are present. A trace of quartz and calcite were found in most of the specimens studied and a few large subhedral grains of sphene with some leucoxene are in one from the greenschist facies. The mode of a typical meta-anorthosite from the amphibolite facies is in Table 12.

Plate 24. Photomicrograph of meta-anorthosite. Slide is mainly plagioclase (An_{34} and An_{70}) with some sericitic alteration. Crossed nicols. x23.

Granophyre

Quartz-rich feldspathic rocks are associated with metagabbro in many places in the northern part of the Horserace and Western sills. These rocks are similar to ones which have been called "granophyre" in the Dillsburg, Pa. sill (Hotz, 1954), "white veins" in the Palisades sill (Walker, 1940), "red acid segregations" in the Whin sill (Tomkieff, 1929), "sodic differentiates" in the Nördingrå-Rödö region (von Eckerman, 1938), and "red rock" in the Pigeon Point, Minn. sill (Grout, 1928). In the present report, they will be called granophyre in keeping with the terminology used by previous workers in Northern Michigan (Bayley, R. W., 1958).

In the area covered in the present report, granophyre is found in three environments. Dikes of granophyre ranging from one inch to six feet wide cut normal metagabbro in the northeastern and central parts of the Western sill in the SW$\frac{1}{4}$SE$\frac{1}{4}$ sec. 10, and the SE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 11, T. 38 N., R. 19 E., and in the western part of the Horserace sill in SE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 12, T. 39 N., R. 31 W. A small segregation of granophyre in gradational contact with normal metagabbro is found in the west-central part of the Horserace sill along the Menominee River in the SW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 7, T. 39 N., R. 30 W. Finally, granophyre forms large outcrop areas between metagabbro and amphibolite in the western part of the Horserace sill in the SE$\frac{1}{4}$ sec. 12, T. 39 N., R. 31 W. In the last-named occurrence, the metagabbro-granophyre contact is not exposed, whereas the amphibolite-granophyre contact is either gradational over a width of a few inches or it is sheared. The amphibolite adjacent to the granophyre has probably been derived from metagabbro rather than from mafic Quinnesec formation rocks. It should be noted, that except for the granophyre dikes in the central part of the Western sill, granophyre is everywhere at or near the northern edge of the sills. Perhaps the northern edge of the Western sill is near these dikes with the metagabbro outcrops to the north representing a separate intrusion. However, without more conclusive evidence, placing the contacts in this manner does not seem justified.

The granophyre is fine to medium grained with the fine-grained varieties being restricted to the small dikes. It is commonly gray or greenish gray but in one place is brown. Glassy quartz and striated plagioclase grains are visible in all specimens and dark green to black hornblende is found in most. Pyrite is also common in small amounts and one specimen contained some pink feldspar. Granophyre weathers gray to dark brown.

In thin section, the granophyre has an allotrimorphic, or more rarely a hypidiomorphic, granular texture and is commonly partially recrystallized. Feldspar and quartz are the predominant minerals in the rock with some hornblende, biotite, chlorite, and minor accessory minerals. The feldspar is generally plagioclase (An_{19-37}) in anhedral or rarely subhedral plates which average from 0.3 to 2.0 mm long. In some of the fine-grained varieties, the plagioclase grains tend to be equant. The plagioclase is commonly clear but in a few places is partly altered to sericite or less commonly to epidote or clinozoisite. In two specimens, orthoclase or microcline is the predominant feldspar rather than plagioclase. The habit of the potash feldspar is identical to that of the plagioclase.

Clear quartz grains averaging 0.1 to 0.3 mm in diameter are abundant in all granophyre specimens. They are generally interstitial to the feldspar but may also form myrmekitic, granophyric, or micrographic intergrowths in all but the fine-grained varieties. The intergrowths form a mantle around individual feldspar grains or occur throughout the whole grain.

Hornblende was found in all of the specimens studied except one. It forms ragged prisms or poikiloblastic plates and is moderately pleochroic with X = straw or tan, Y = olive-green, and Z = blue-green. Brown biotite is common in many places, and weakly to moderately pleochroic green chlorite is locally present. Other minor accessory minerals found in the granophyre include magnetite, commonly mantled by sphene, subhedral brown sphene without magnetite, pyrite, zircon, and apatite. Some calcite occurs in a few places.

Serpentinite and Pyroxenite

Serpentinite and pyroxenite are present in several places along the northern side of the Sturgeon Falls sill and magnetic data show that the serpentinite continues at depth to the west-northwest into secs. 21 and 20, T. 39 N., R. 29 W. The relationship of these rocks to the metagabbro is uncertain.

Serpentinite is exposed in three outcrop areas in the $NW\frac{1}{4}NE\frac{1}{4}$ sec. 21, T. 38 N., R. 21 E. and in the $SW\frac{1}{4}NW\frac{1}{4}$ sec. 26, T. 39 N., R. 29 W. The serpentinite in sec. 26 is cut by dikes of metagabbro as much as 90 feet wide (fig. 4). The serpentinite is fine grained, green to black, and contains splotches or veinlets of white, weakly effervescent carbonate, probably dolomite or magnesite. The serpentinite is traversed by sub-parallel planes of weakness which give the rock a crude foliation. The surfaces of these planes have a silky luster and are mottled yellow-green, black, and reddish brown. Some specimens are traversed by thin seams of asbestos as much as $\frac{1}{4}$ inch wide. The asbestos fibers are oriented perpendicular to the walls of the seam. Serpentinite weathers light to dark green or black.

In thin section 75 to 80 percent of the serpentinite is colorless antigorite with gray or bluish gray interference colors. The serpentine occurs in mats of fibers averaging 0.2 mm long and in one specimen fibers with approximately the same orientation extinguish together over a large area. This probably represents the space formerly occupied by a single original grain, but as these areas have an irregular outline, there is no indication as to the exact nature of the original mineral. Magnetite forms about 5 percent of the rock and occurs either as a fine dust or as subhedral grains as much as 0.7 mm long. In one specimen, small

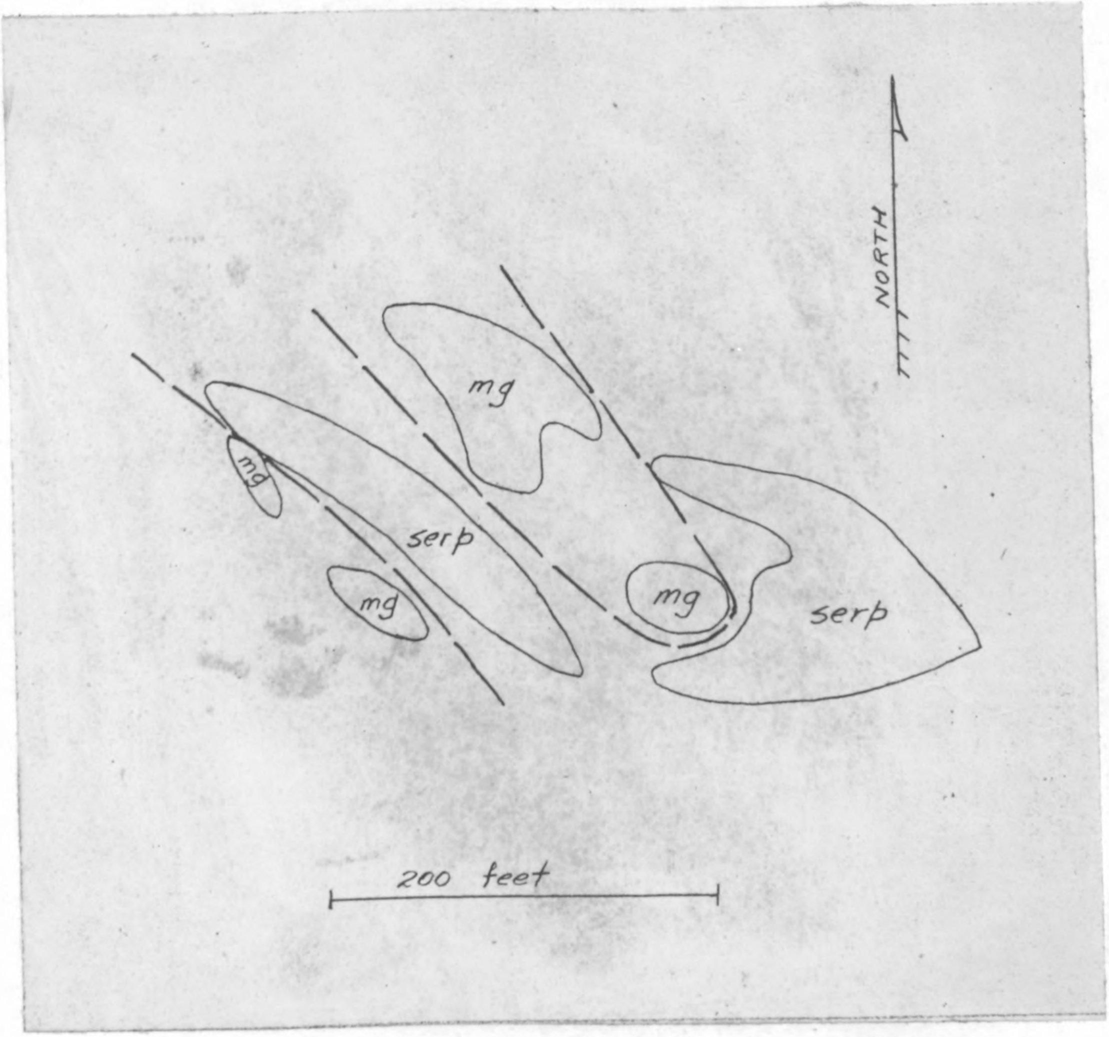
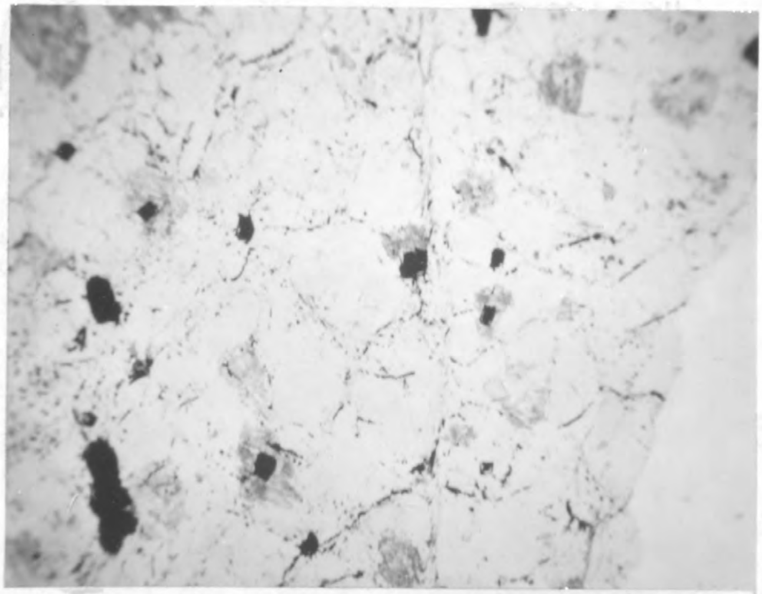


Figure 4. Sketch map of metagabbro and serpentinite outcrops in SW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 26, T. 39 N., R. 29 W. mg - metagabbro; serp - serpentinite.

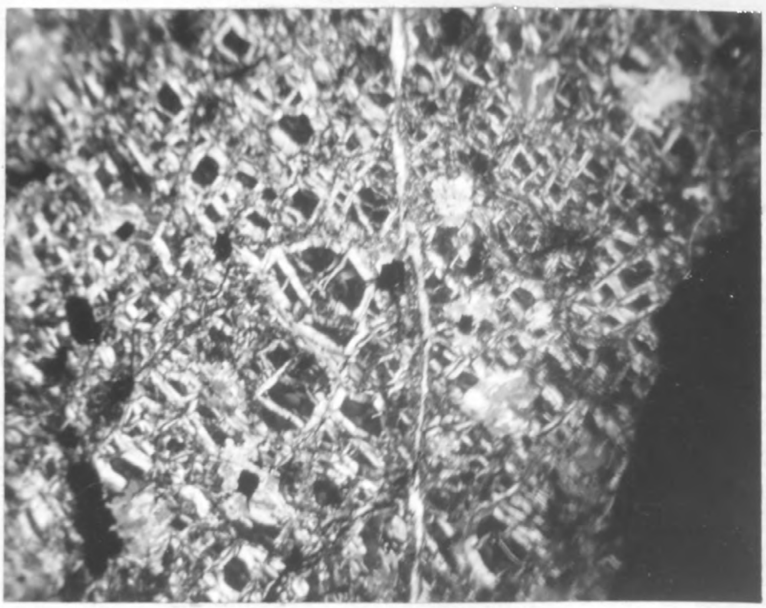
magnetite grains outline areas which were probably original olivine grains (pl. 25). The magnetite yielded negative results to the hydrogen peroxide test for titanium. Dark, reddish brown, nearly opaque, subhedral to euhedral grains of chromite are also found in some specimens. The chromite grains are commonly surrounded by a narrow rim of magnetite separated from the chromite by a narrow intermediate band of serpentine. Carbonate forms from 15 to 20 percent of the rock and occurs either in veins or in irregular blobs. The latter are 0.5 to 0.8 mm long and are composed of an aggregate of smaller grains.

In some places, antigorite streaks or veinlets cut calcite and earlier formed antigorite. The character of the antigorite of both ages is the same. Some pale yellow, moderately birefringent fibrous chrysotile forms veinlets in some of the specimens and a trace of colorless chlorite is present locally. The chlorite is associated with late carbonate veinlets. Hematite is present locally, probably as a magnetite alteration product, and a quartz veinlet was seen in one specimen.

The chemical analysis of a serpentinite specimen from the outcrop area just east of the Sturgeon Falls is given in Table 13. The table also shows the analysis recalculated to 100 percent less water and carbon dioxide, and the norm. The analysis is as would be expected from a rock composed almost wholly of serpentine, and it shows a slight concentration of nickel and chrome.



A.



B.

Plate 25. Photomicrographs of serpentinite. A. Serpentine (light gray), carbonate (medium gray), and magnetite (black). Plane polarized light. x23. B. Same as A. Crossed nicols. x23.

Table 13. Chemical analysis and norm of serpentinite.

	1	2
SiO_2	40.8	47.7
TiO_2	0.02	0.02
Al_2O_3	1/	--
Fe_2O_3	3.1	3.6
FeO	3.3	3.8
MnO	0.08	0.09
MgO	36.9	43.0
CaO	1.5	1.7
Na_2O	0.04	0.05
K_2O	0.04	0.05
H_2O	11.5	--
P_2O_5	0.01	0.01
CO_2	2.3	--
Cu	0.0020	--
Co	0.020	--
Ni	0.23	--
Cr	0.42	--
Totals	100.26	100.0

	2
$CaSiO_3$	3.5
$MgSiO_3$	40.2
$FeSiO_3$	1.6
Mg_2SiO_4	47.1
Fe_2SiO_4	1.9
mt	5.3

1/ less than 0.5 percent

1 - Serpentinite. SW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 26, T. 39 N., R. 29 W., Mich. Paul L. D. Elmore, Katrine E. White, Samuel D. Botts, and Harry J. Rose, U. S. G. S., analysts.

2 - same as 1. Recalculated to 100 percent less H_2O, CO_2, Cu, Co, Ni, and Cr.

Pyroxenite is found in the NE$\frac{1}{4}$ sec. 21, T. 38 N., R. 21 E. generally between serpentinite and metagabbro or as narrow bands within metagabbro. The contact between metagabbro and pyroxenite is sharp and the metagabbro is finer grained near this contact. This suggests a chilled border and intrusion of metagabbro into pyroxenite; however, the fine-grained metagabbro here may be due to metamorphic rather than igneous processes. The serpentinite-pyroxenite contact is not exposed.

The pyroxenite is a medium-grained, greenish black rock in which greenish black pyroxene is visible in hand specimen. The rock weathers gray.

Pyroxenite is made up almost wholly of practically colorless anhedral plates of pyroxene which average 3.0 mm in diameter and which reach a maximum of 10.0 mm. The pyroxene has a large 2V, an extinction angle $Z \wedge c = 38^{\circ}$, and $N_y = 1.678$. It is probably diopsidic. The only other minerals found in this rock are magnetite and serpentine which are along pyroxene grain boundaries or in small veinlets.

Origin

Metagabbro forms tabular sheets which are nearly parallel with the essentially vertical regional structural trend. The chemical and mineralogic composition and the texture of the metagabbro show clearly that the rock was originally a true gabbro, and the presence of associated rocks commonly found in horizontal sheets of gabbro: granophyre, pegmatite, anorthosite, etc., suggest that the metagabbro sheets were intruded in a horizontal position. It is therefore concluded that the tabular sheets of metagabbro are sills which have been subsequently tilted to a vertical position.

Before going further, it is necessary to establish the top direction of the sills. Pegmatitic gabbro is generally found in the upper half of gabbro sills (Walker and Poldervaart, 1949; Hotz, 1954; and Tomkeieff, 1929); however, Walker (1953) has noted that schlieren are usually in the top half but that dikes or veins may be at any position. In the area included in this report, pegmatitic metagabbro is found throughout the width of the sill, and therefore it cannot be used as a criteria for determining top direction. Late titaniferous magnetite commonly increases in the upper parts of gabbro sills; for example, Walker (1940) found that the magnetite content of the Palisade sill increases toward the top and Hotz (1954) found magnetite replacement bodies in the rock above the Dillsburg, Pa. sill. On the other hand, Holmes and Harwood (1928) note an apparent increase in the amount of "black ores" toward the base of the Whin sill, but they do not state whether it is early or late. Magnetite-rich metagabbro is found in the northern part of the Niagara sill in the vicinity of Niagara, Wis. and the Big Quinnesec Falls, thereby indicating that the top direction here is north. Anorthosite in gabbro sills apparently can be found at any position so the meta-anorthosite segregations in the sills from the Menominee district cannot be used to determine top directions. Segregations of granophyre or related felsic rocks are commonly found in the upper parts of gabbro sills (Holz, 1953; Grout, 1928; et al.), but dikes or veins of these rocks may be found in any position. In the Horserace and Western sills, granophyric rocks are found predominantly near the northern edge of the sills, thereby indicating a northerly top direction. Taken as a whole, the evidence indicates that the tops of the sills are to the north and structurally, a northerly top direction is also indicated. The Wisconsin batholith is a short distance south of the sills so that if we assume a southerly top direction, then at the time the sills were intruded, the batholith would have been above the sills. It seems improbable that there could have been a mass of rock of batholithic dimensions above the sills at the time of their intrusion.

The rocks in the metagabbro sills in the area included in this report appear to be metamorphosed equivalents of rocks which represent an association generally ascribed to fractional crystallization and gravity differentiation in gabbro sills. Inasmuch as metamorphism has obliterated much of the critical evidence relating to the origin of these various rock types, a genetic hypothesis for the metagabbro sills depends on analogies with better exposed and unmetamorphosed sills elsewhere.

Gabbro pegmatite is generally ascribed to the crystallization of late, volatile rich magma (Walker and Poldervaart, 1949; Walker, 1953; and Hotz, 1954) with the schlieren having crystallized from differentiated magma in place and the dikes from magma after it has migrated and been reinjected. Iron enrichment in the late stages of a gabbro intrusion undergoing fractional crystallization is well known (Tomkeieff, 1929; Fenner, 1937; Wager and Deer, 1939; and Walker and Poldervaart, 1949). Late felsic segregations, called variously "white veins" (Walker, 1940), "red acid segregations" (Tomkeief, 1929), "sodic differentiates" (von Eckerman, 1938), and "red rock" (Grout, 1928), are also thought to have crystallized from late differentiates although there is some variation in the intermediate steps postulated by these various workers. Hotz (1954) has related the late iron-rich and felsic rocks in the Dillsburg, Pa. sill as follows: He believes that during an intermediate stage in the crystallization, a volatile-rich fraction rich in iron and titanium, and in alkalis remained before solidification of the sill was complete. At this time, fracturing occurred and the iron- and titanium-rich volatiles escaped producing magnetite replacement deposits in the overlying rocks leaving the remaining alkali-rich liquid to crystallize as granophyre. Walker (1953) postulates a similar relationship but believes that the residual felsic liquid resulted from the crystallization of the iron-rich phase rather than its escape in a volatile fraction. Similar felsic or granophyric rocks have been ascribed to other causes such as: reaction with surrounding sediments (Walker and Poldervaart, 1941) or to later, unrelated intrusion (Leighton, 1954). Small anorthositic segregations in gabbro have been ascribed to the rising of early-formed plagioclase crystals in a more dense magma (Grout, 1928; and von Eckerman, 1938), but this idea has been questioned (Lodochnikow, 1925).

The pegmatitic dikes and schlieren in the sills in the southern part of the Menominee district can be explained by the prevailing hypothesis of crystallization from late volatile-rich magma. Similarly, the magnetite-rich metagabbro can be explained by the precipitation of magnetite from late iron-rich volatiles collecting in the upper and eastern parts of the Niagara sill before final solidification of the gabbro. The iron-rich volatiles presumably did not migrate out of the sill here as they did at Dillsburg, Pa. Inasmuch as dikes and schlieren of pegmatitic metagabbro with the same habit occur in both the normal and magnetite-rich metagabbro and are magnetite-poor in the normal metagabbro and magnetite-rich in the magnetite-rich metagabbro, it appears that the formation of the dikes and schlieren predates the introduction of the magnetite. The following history is postulated for the formation of these late-stage rocks: (1) accumulation of volatile-rich magma, (2) crystallization of pegmatitic gabbro from this magma with the remaining volatiles becoming further enriched in iron, (3) migration of these iron-rich volatiles into the upper and eastern parts of the Niagara sill, and (4) precipitation of late magnetite in already formed gabbro and gabbro pegmatite.

The hypothesis of crystallization from a late differentiate of the gabbro seems to apply best to the granophyre in the metagabbro sills under discussion here. It certainly cannot be ascribed to the reaction with enclosing sediments as postulated by Walker and Poldervaart (1941) for the Hangnest sill because metagabbro in the present area is intrusive into rock of essentially the same composition. Leighton's (1954) hypothesis of later, unrelated intrusion also cannot be applied because if this were the case, then one would expect to find similar felsic rocks elsewhere in the district away from the metagabbro sills. This is not the case. The relationship between the granophyre, and the pegmatitic and magnetite-rich metagabbro is unknown as they are not exposed in the same sills.

The anorthosite segregations appear to be the result of abnormally large local accumulations of plagioclase crystals; probably a larger scale of the phenomena which resulted in the streaks of porphyritic metagabbro in the area just east of the Little Quinnesec Falls (pl. 16). The porphyritic metagabbro and meta-anorthosite in the Niagara sill are found near a constriction in the sill in the vicinity of the Little Quinnesec Falls. Perhaps this constriction caused currents, or interference of currents, in the magma while it was cooling and this in turn was instrumental in the formation of plagioclase-rich accumulations.

The serpentinite and pyroxenite present special problems as the relationship of these two rocks to the metagabbro is uncertain. The serpentinite is definitely older than the metagabbro dikes cutting it, but it could still be an early stage of the same igneous cycle. The age of the pyroxenite is more of a problem. Field evidence indicates that it has probably been intruded by the metagabbro. The presence of fresh, unaltered pyroxene might suggest a much younger age, but it is quite unlikely that any igneous activity of sufficient intensity to produce pyroxenite intrusions took place after the metamorphism and deformation, so probably the pyroxenite was simply resistant to recrystallization at low levels of metamorphism because of its simple, almost monomineralic composition. An alternate explanation for the anomalous fresh-appearing pyroxenite has been suggested by Bowen and Tuttle (1949) who state that water vapor charged with silica streaming through peridotite can produce dike-like pyroxenite masses. It appears unlikely that the serpentinite and pyroxenite are the result of settling of early formed heavy crystals in the gabbro sill because the top of the sill is probably north rather than south. Therefore, it appears that these rocks are earlier and represent separate intrusions. Perhaps, they were derived from fractional crystallization in the magma chamber which supplied the gabbro magma; a fraction which was tapped and intruded before the normal gabbro. Or they could have been formed much earlier and thus be totally unrelated to the gabbro sills. Critical evidence is lacking.

Metamorphism

As with the Quinnesec formation rocks, the composition of the secondary plagioclase feldspar formed during metamorphism or the character of feldspar alteration products were the main basis for locating the metamorphic isofacies lines in the metagabbro. The greenschist facies is represented by normal metagabbro in which the plagioclase is almost completely altered to saussurite [assemblages (1) and (2)] or normal metagabbro containing a significant amount of secondary albite [assemblages (3) and (4)]. Assemblage (1) rocks contain remnants of original pyroxene whereas assemblage (3) and (4) rocks may contain remnants of original labradorite. Assemblage (4) rocks are less altered than rocks from the other three greenschist facies assemblages and appear in thin section to be transitional between the greenschist and epidote-amphibolite facies. However, the distribution of these rocks (pl. 17) does not substantiate this conclusion. Foliated rocks associated with the greenschist facies metagabbro are typical greenschist facies chlorite schists. The epidote-amphibolite facies is represented by normal metagabbro containing an association of oligoclase or labradorite, or both, and epidote [assemblage (5)], whereas the amphibolite facies is represented by rocks containing one or two plagioclase feldspars at least as calcic as andesine and lacking anything more than a trace of epidote [assemblage (6)]. Foliated rocks associated with the amphibolite facies metagabbro are andesine amphibolites which are typical for this facies. Isofacies lines determined in this manner match those derived from study of the Quinnesec formation rocks.

The mineralogic differences in the normal metagabbro and foliated phases in the various facies have already been pointed out in the rock descriptions. Some of the other types of metagabbro need special mention. Magnetite-rich metagabbro is found only in the greenschist facies and contains felsic minerals similar to those found in the normal metagabbro. Its mafic mineral, however, is different. The amphibole is more deeply pleochroic and is probably hornblende rather than actinolite as is found in the normal gabbro. The chlorite is also more deeply colored and is probably an iron-rich variety. The pegmatitic metagabbro is also found only in the greenschist facies and it contains mineral assemblages identical with its finer grained counterparts. The meta-anorthosite is interesting because it is found in both the greenschist and amphibolite facies, and because it practically duplicates the plagioclase alteration noted for the normal metagabbro. In the greenschist facies, it is altered to albite or sodic oligoclase, zoisite, clinozoisite, or saussurite; all except the sodic oligoclase are typical of the plagioclase alteration in the greenschist facies normal metagabbro. In the amphibolite facies, it consists of mottled andesine and labradorite with only a trace of epidote, identical with that found in the amphibolite facies normal metagabbro. Granophyre cannot be compared because it is markedly different in composition.

Much of the metagabbro preserves remnants of an original gabbroic texture and some contains fragments of original gabbro minerals (calcic plagioclase and pyroxene). Metamorphism thus did not go to completion and these rocks commonly contain disequilibrium assemblages. Rocks associated with the metagabbro which apparently do contain equilibrium assemblages are the foliated varieties, schist and amphibolite. It is postulated that the sills acted as bosses which resisted shearing stresses and without the shearing stresses, metamorphism did not go to completion and the massive metagabbro with remnants of original textures and minerals resulted. Where shearing stresses were operative, such as near the borders of the sills or along shear zones, metamorphism went to completion and equilibrium rocks, schist and amphibolite, resulted. The shearing, directly or indirectly as passageways for water, apparently accelerated the metamorphic changes.

It is also concluded that the metamorphism was not progressive because: (1) on the whole, original textures are better preserved in the higher grade rocks, and (2) the transition from normal massive metagabbro with an ophitic texture to a foliated amphibolite can be traced without any evidence of an intervening schist phase which would have been necessary had the metamorphism been progressive.

Age and Correlation

Previous workers in the area included the metagabbro with the Quinnesec formation and were undecided as to its age. As has been shown in the discussion of the Quinnesec formation and the Hoskin Lake granite, metagabbro is younger than the Quinnesec formation and separated from it in time by a period of granite intrusion and of deformation. The metagabbro has been metamorphosed and inasmuch as the last period of metamorphism in the region is pre-Upper Precambrian, the metagabbro must also be pre-Upper Precambrian. The metagabbro is also probably post-Michigamme formation (Middle Precambrian) but positive evidence from the area included in this report is lacking except for the questionable magnetite-rich metagabbro sill in the northern part of the area. However, similar metagabbro sills in eastern Iron County, Mich. (Gair and Wier, 1957; and Bayley, R. W., 1958) have been shown to be late Middle Precambrian, and it is concluded that the sills in the southern part of the Menominee district correlate with those in eastern Iron County and are also late Middle Precambrian in age.

METADIABASE

Metamorphosed mafic stringers and dikes as much as one foot wide cut metagabbro in the Horserace sill in the SE$\frac{1}{4}$ sec. 7, T. 39 N., R. 31 W. These dikes are commonly parallel with the west-northwest regional structural trend and consist of massive or slightly foliated, fine-grained green or greenish black amphibolite. They weather gray and look much like some varieties of Quinnesec formation amphibolite in hand specimen.

The rock in these dikes is similar to Quinnesec formation oligoclase amphibolite in thin section. It consists mainly of hornblende and plagioclase with some quartz. The texture of the rock is crystalloblastic with occasional lath-shaped plagioclase grains which suggest that the rock may have originally been a diabase. The hornblende is moderately pleochroic with X = straw, Y = olive-green, and Z = bluish green, and it forms anhedral plates which show some tendency toward a poikiloblastic habit. The average size of the hornblende is 0.1 mm. The plagioclase is a sodic andesine (An_{32-34}) and where found as laths, it is commonly about the same size as the hornblende. Commonly, however, the plagioclase is finer grained than the hornblende and is interstitial to, or included in, the amphibole. Some quartz is associated with the plagioclase and fine-grained epidote or clinozoisite are scattered throughout the rock. One specimen was porphyritic with phenocrysts as much as 4.0 mm across of plagioclase now almost completely altered to clinozoisite. Sphene or magnetite surrounded by subhedral sphene are abundant accessory minerals. Some zircon and calcite are also present.

The metadiabase dikes are later than the metagabbro sills, but how much later is unknown. They could be a later stage of the same period of igneous activity or they could be much later, as Middle Precambrian mafic igneous rocks of several ages are found in Northern Michigan. However, it is known that they are Middle Precambrian because they have been metamorphosed; Upper Precambrian rocks have not.

APLITE

Fine-grained aplite dikes or pods cut the Quinnesec formation and magnetite-rich metagabbro in sec. 8, T. 39 N., R. 30 W., and the Marinette quartz diorite in the SW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 16, T. 38 N., R. 20 E. The dikes cutting quartz diorite are as much as three feet wide and they strike north-northeast. The aplite cutting the Quinnesec formation and metagabbro forms pods as much as two feet wide and ten feet long. These pods are elongated parallel with the foliation in the enclosing rock with the foliation bending around the pods. The contact between the aplite and enclosing rock is everywhere sharp.

The aplite is fine grained to aphanitic and in some places is porphyritic with visible phenocrysts of quartz and feldspar as much as 0.5 mm in diameter. It is gray to pink or red and it weathers reddish brown.

Thin section study shows that the aplite is a fine-grained rock with an average grain size of 0.02 to 0.04 mm. It consists mainly of feldspar and clear quartz. The feldspar is mainly orthoclase but some microcline and albite are also present. The feldspar is locally partially altered to rusty-colored sericite. Green-brown biotite, muscovite, and moderately pleochroic green chlorite form a few percent of this rock, and calcite, epidote, pyrite, and garnet are found in a few specimens.

The aplite dikes are probably related to the granitic rocks that mark the end of the Middle Precambrian.

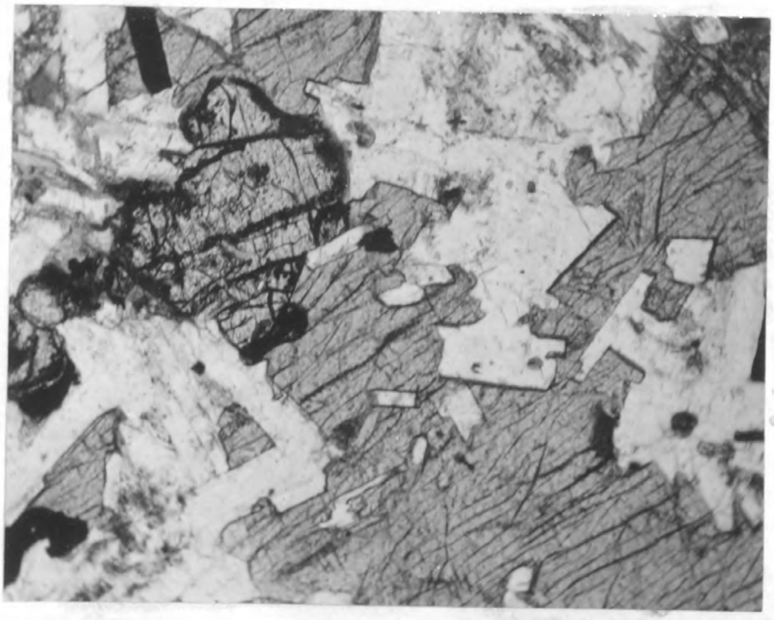
UPPER PRECAMBRIAN ROCKS

DIABASE

Diabase dikes cut the Hoskin Lake granite in the SW¼SE¼ sec. 12, T. 38 N., R. 19 E. and diabase is also in isolated outcrops associated with Quinnesec formation amphibolite in the NE¼SE¼ sec. 12, T. 38 N., R. 19 E. and with Hoskin Lake granite in SW¼SW¼sec. 12, T. 38 N., R. 19 E. These occurrences are restricted to a small area one-half mile south of the Horserace Rapids. The dikes are from two inches to one foot wide and have fine-grained, chilled borders.

The diabase is a fine- to medium-grained, dark greenish black rock in which laths of fresh plagioclase are visible in hand specimens of the coarser grained varieties. One of the dikes cutting the granite is porphyritic showing clear, unaltered plagioclase phenocrysts as much as one inch across. The diabase weathers greenish brown or brown.

In thin section, the characteristic feature of this rock, its diabasic texture, is striking (pl. 26). The diabase consists of euhedral laths of labradorite (An_{53-63}) from 0.1 to 1.5 mm long surrounded by anhedral plates of pyroxene or its alteration product. Albite and pericline twins are both common in the plagioclase and in some places this mineral shows normal zoning. It is very fresh, being only slightly altered to sericite in a few places. The pyroxene is pale brown pigeonite with a small 2V and it molds around the earlier formed plagioclase laths



A.

B.

Plate 26. Photomicrographs of diabase. A. Plagioclase (light gray), pyroxene (medium gray, moderate relief), olivine (medium gray, high relief), and magnetite (black). Plane polarized light. x40. B. Same as A. Crossed nicols. x40.

in the coarser grained specimens. In these coarser grained specimens, olivine anhedra are also common. The olivine, however, is partially altered to magnetite, green hornblende, and iddingsite, the latter two minerals form rims around the olivine grains. In the finer grained specimens, no pyroxene or olivine is visible. The mafic minerals consist mainly of fine-grained green hornblende with some reddish brown iddingsite, magnetite, in some places as skeletal crystals, and red-brown or brown biotite. Some calcite and pyrite are found in a few places.

The fresh, unmetamorphosed character of these rocks is in marked contrast with the highly altered and metamorphosed older mafic igneous rocks. Fresh diabase of this type is typical of the Upper Precambrian in Northern Michigan.

THE "BASIC FRONT" PROBLEM

The southwestern part of the area I mapped overlaps the northeastern part of an area that had previously been mapped by E. J. Lyons. This work is described in full in his doctoral dissertation[5/] and in condensed form in Memoir 52 of the Geological Society of America (Emmons, et al, 1953, p. 107-110). The northern boundary of his map in the area where our work overlaps is the Menominee River, and the eastern boundary is along the latitude of the east end of Pier's Gorge. The western and southern boundaries of the area he studied are about 5 miles west and south of these edges of my map.

In the area of overlap, our maps of the felsic units are essentially the same except that Lyons' map is more generalized. What I call "Hoskin Lake granite", he calls "porphyritic granite"; and my "Marinette quartz diorite" is referred to as "biotite-hornblende quartz diorite". Lyons also shows that the area south of my map area is underlain primarily by normal quartz diorite, a fact that I have verified by reconnaissance.

In the mafic units, the agreement disappears. Lyons subdivides these rocks into two units, a belt of "plagioclase hornblendite" along the northern and western porphyritic granite

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5/ Lyons, E. J., 1947, Mafic and porphyritic rocks of the Niagara area: unpublished Ph. D. thesis, University of Wisconsin.

contact, and "basalt" along the northern edge of the "plagioclase hornblendite" belt and along the eastern granite or quartz diorite contact. The contact between the "plagioclase hornblendite" to the north and the "basalt" to the south in the western part of my area is near what I show as the isograd separating the epidote-amphibolite and amphibolite facies. To the east, this contact crosses into Michigan north of Aurora, Wis. where it is not shown on Lyons' map. The contact re-enters Wisconsin south of the Big Quinnesec Falls and follows the isograd separating the epidote-amphibolite and greenschist facies for about 2½ miles. There, he shows the contact swinging to the southeast and south and butting into the porphyritic granite or quartz diorite contact about one mile south of Niagara.

According to Lyons, the "basalt", or "basaltic greenstone" as he sometimes calls it, characteristically contains actinolitic hornblende, chlorite, epidote, and zoisite. The "plagioclase hornblendite" is a "granitic-textured rock" containing 45 to 85 percent pleochroic hornblende, 10 to 55 percent plagioclase, and 0 to 10 percent epidote. His mapping is apparently based primarily on the color or nature of the contained amphibole rather than on textural features which I feel are much more significant. His "basalt" is equivalent to my greenschist and, in part, epidote-amphibolite facies Quinnesec strata and intrusive metagabbro, whereas his "plagioclase hornblendite" is equivalent to my amphibolite and, in part, epidote-amphibolite facies mafic igneous rocks.

Lyons believes that both the felsic and mafic rocks are related to one igneous cycle and that the normal quartz diorite to the south (i.e., south of the area covered by my mapping) "appears as an intrusive mass with border phases between it and the basaltic greenstones to the north. These border phases, hornblendite nearest the greenstone roof and mafic diorite (Marinette quartz diorite of my terminology) and porphyritic granite (Hoskin Lake granite) south of it, appear as textural and mineralogical modifications of the greenstone in its transition into granite." (Emmons, et al., 1953, p. 108). He concludes that "while regional metamorphism, in the broader sense, may not have been present in this area, the same minerals could form in a basalt under local processes of the regional metamorphic kind".[6/]

Lyons believes that the original rock in the whole area was basaltic and he visualizes the following history: (1) Formation of a "cupola" with "plagioclase hornblendite" developed around it. He believes that the magma advanced from the southeast and that the "plagioclase hornblendite represents an advancing wave of mafics being expelled from recrystallizing basaltic greenstone to leave behind the constituents required for granite." (Emmons, et al., 1953, p. 107). (2) Arcuate-shaped shearing developed

6/ Lyons, op. cit., 1947, p. 8.

above the "cupola" with shattering of the "plagioclase hornblendite" within the arc. (3) Magmatic solutions entered the arcuate shear zone and formed porphyritic granite (Hoskin Lake granite) from "plagioclase hornblendite" and similar solutions permeated the shattered "plagioclase hornblendite" zone to the south to form biotite-hornblende quartz diorite (Marinette quartz diorite). (4) Main body of magma advanced into the area. In his dissertation, Lyons does not refer to this as a "basic front", but does in the later condensation where he states "on the map the mafic rocks appear as a band or wave advancing before the granite into the greenstone. At the time of mapping in 1943, we referred to it as a 'bulldozer effect' to convey the working hypothesis. We regard this apparent basic front as a stage in the transition from greenstone to granite." (Emmons, et al., 1953, p. 107).

I cannot accept Lyons' concept of a basic front nor his postulated geologic history for the following reasons: (1) His subdivision of the mafic rocks is based on metamorphic rather than on more significant primary features which has resulted in the separating of similar and the combining of dissimilar rocks. (2) Most of Lyons' so-called mafic unit, "plagioclase hornblendite", contains features typical of intrusive gabbro sills which have been regionally metamorphosed. (3) Chemical analyses show that the compositions of metagabbro specimens from

Lyons' "basalt" unit and from his "plagioclase hornblendite" unit are essentially the same and show no increase in the mafic content in the latter although it does contain a more deeply pleochroic amphibole. And (4) field evidence shows that the age relationships of the porphyritic granite, quartz diorite, metagabbro, and Quinnesec amphibolite are such that they could not have been formed during the same igneous cycle.

MAGNETIC SURVEYS

The presence of magnetic formations, serpentinite, magnetite-rich metagabbro, and Michigamme and Quinnesec iron-formation, coupled with the fact that the rocks have been tilted to a near-vertical position, makes the area ideally suited for the use of magnetic surveys. The northern part of the area has been covered by an aeromagnetic survey and the results published by the U. S. Geological Survey (Wier, Balsley, and Pratt, 1953). Total intensity aeromagnetic crests taken both from this published data and from the authors' work sheets are plotted on plate 2 and, for the eastern portion of the area, are repeated on plate 27. In the eastern part of the area, 19 ground magnetometer traverses were run with an Askania vertical intensity magnetometer having a sensitivity of 26.5 gammas per scale division. Spacing of readings along the traverses varied from 25 to 200 feet. The positions of these traverses and the magnetic profiles adjusted to an arbitrary zero base of 58,400 gammas are shown on plate 27. Most of the profiles are oriented north-south across the regional structural trend and are grouped so that profiles across a given anomaly are adjacent. Crests of anomalies, derived both from airborne and ground data, are shown in red (pl. 27).

Near the eastern edge of the area, the sharp-crested anomaly found in profile R-R' (pl. 27) and in the northern part of Q-Q' is closely tied to outcrops of Michigamme iron-formation. The low, broad crest in the northeastern part of profile P-P' and a similar one in the eastern part of Z-Z' may represent the continuation of the iron-formation at depth to the west-northwest.

The sharp, multicrested anomaly on profile Q-Q' is tied to serpentinite outcrop, and the similar appearing anomaly in P-P' undoubtedly represents the extension of this unit. The sharp aeromagnetic crest at the southeastern corner of the map (pl. 27) probably represents the extension of this anomaly to the southeast; the intervening broad aeromagnetic crest appears to be off this trend but it may be misplaced as the location of aeromagnetic traverses is subject to some error. This anomaly is questionably extended to the northwest to connect with the one found in profiles M-M', L-L', K-K', J-J', and H-H'. Unfortunately, the aeromagnetic traverses did not extend south of the Menominee River in this area and swampy conditions made ground surveying impossible. The anomaly in profiles M-M' through H-H' reaches a maximum intensity along profile J-J'; the sharp drop in the intensity of the crest of this anomaly is illustrated in profile Y-Y' which, in part, follows this crest. The anomaly is broad which shows that the rock causing it is at depth rather than near the surface. Since Michigamme strata crop out on profile J-J', this anomaly does not appear to be due to Michigamme iron-formation. I believe that it is caused by serpentinite at depth as illustrated in figure 5.

The sharp crested anomaly in profile G-G' is due to magnetite-rich metagabbro and it can be traced to the west-northwest by a series of 3 aeromagnetic crests, 2 of which appear to be slightly mislocated.

Traverses F-F' and X-X' were run to determine whether the serpentinite or magnetite-rich metagabbro anomalies extended into this area. As can be seen (pl. 27), they do not. The small, broad aeromagnetic crest near the southwestern end of profile X-X' was not found in the ground survey; the reason is unknown.

The sharpest and largest anomaly found is associated with the small magnetite-rich metagabbro sill in the S$\frac{1}{2}$ sec. 12, T. 39 N., R. 30 W. This anomaly has a crest of at least 11,000 gammas along profile D-D' but drops off sharply both to the west-northwest and east-southeast as shown by the two, low aeromagnetic crests. Ground profiles one-half mile east, E-E' and one-half mile west, C-C' failed to find the extension of this anomaly.

The small anomaly along profile B-B' is probably due either to Michigamme iron-formation or to magnetite-rich metagabbro.

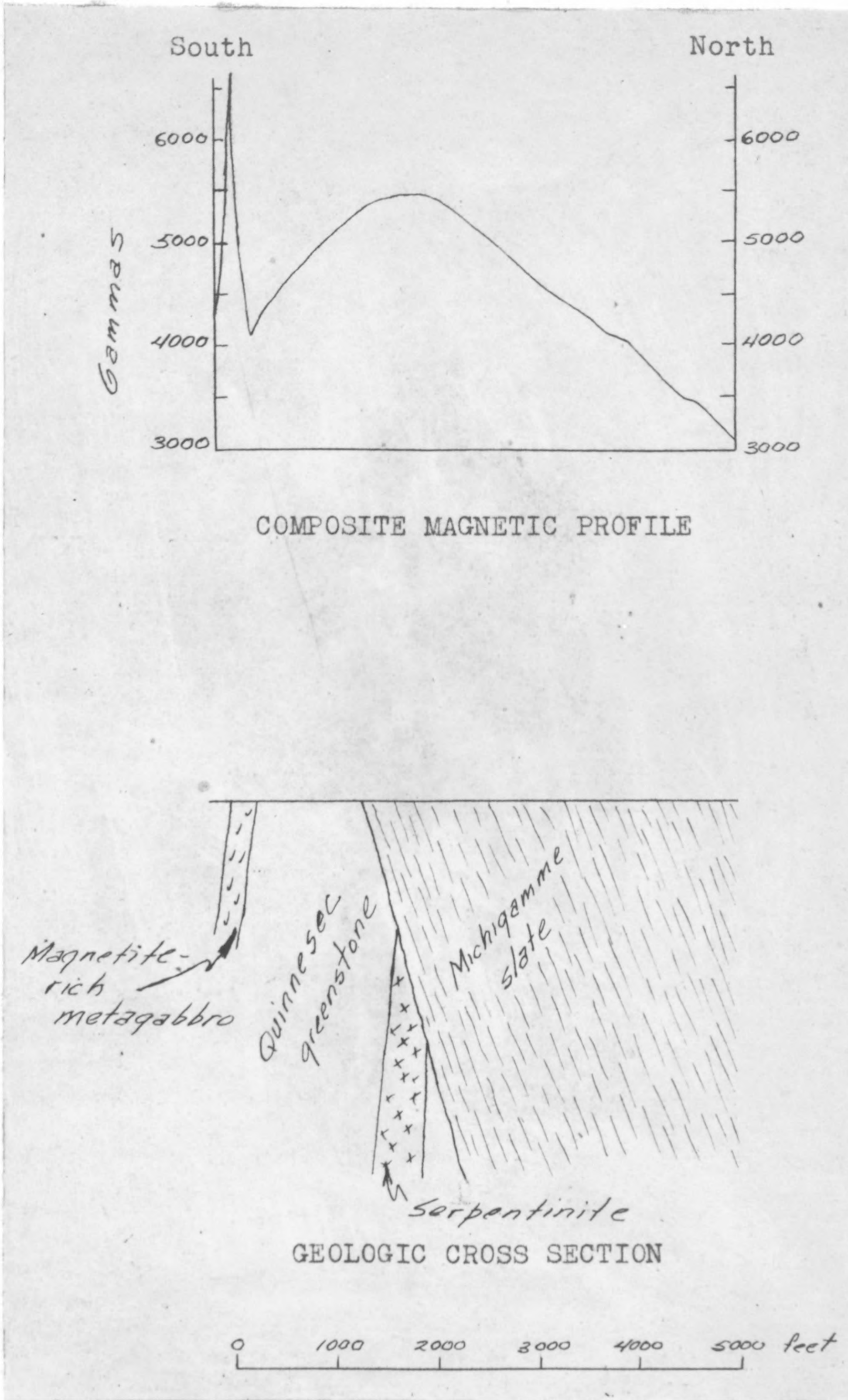

Figure 5. Magnetometer profile and geologic cross section along lines G-G' and H-H'. (see plate 27 for location).

The anomalies in profile A-A' along the road along the west edge of sec. 3, T. 38 N., R. 20 E. are of no significance. After the traverse was completed, I discovered that some of the road ballast is magnetite-rich metagabbro.

As would be expected, aeromagnetic crests are found over the magnetite-rich metagabbro in the vicinity of the Little Quinnesec Falls.

Numerous, irregularly distributed aeromagnetic crests are found in the western part of the area (pl. 2), but because of the lack of outcrops, the rock causing them is unknown except in the vicinity of the Big Quinnesec Falls where two aeromagnetic crests were used in tracing magnetite-rich metagabbro to the west-northwest into the NE$\frac{1}{4}$ sec. 7, T. 39 N., R. 30 W.

STRUCTURE

The most prominent structural feature in the area is foliation; the strike and dip of individual observations are posted on plate 2 and are summarized in rose diagrams in figure 6. Foliation is best developed in the Quinnesec formation rocks, especially the Pier Gorge schist member, and less so in the metagabbro and other units. The foliation is imparted by parallel-oriented flakes of a micaceous mineral, commonly chlorite in the mafic rocks or sericite in the felsic, or by parallel-oriented prisms of amphibole.

The foliation can be subdivided into four groups which appear to have genetic significance: (1) west-northwest strike parallel with the regional structural trend, (2) parallel with the borders of the Hoskin Lake granite or Marinette quartz diorite plutons, (3) parallel with the border of the metagabbro sills, and (4) irregular foliation in the inclusions in the metagabbro sills. Foliation parallel with the regional structural trend is the most common and is found in the Quinnesec and Michigamme formation strata and in the metagabbro and thus is post-metagabbro in age, probably late Middle Precambrian. It strikes west-northwest and dips nearly vertical or steeply south, and is thus parallel with the southern edge of the sedimentary trough which forms the main part of the Menominee District (pl. 1) and with most of the bedding within this trough. Foliation

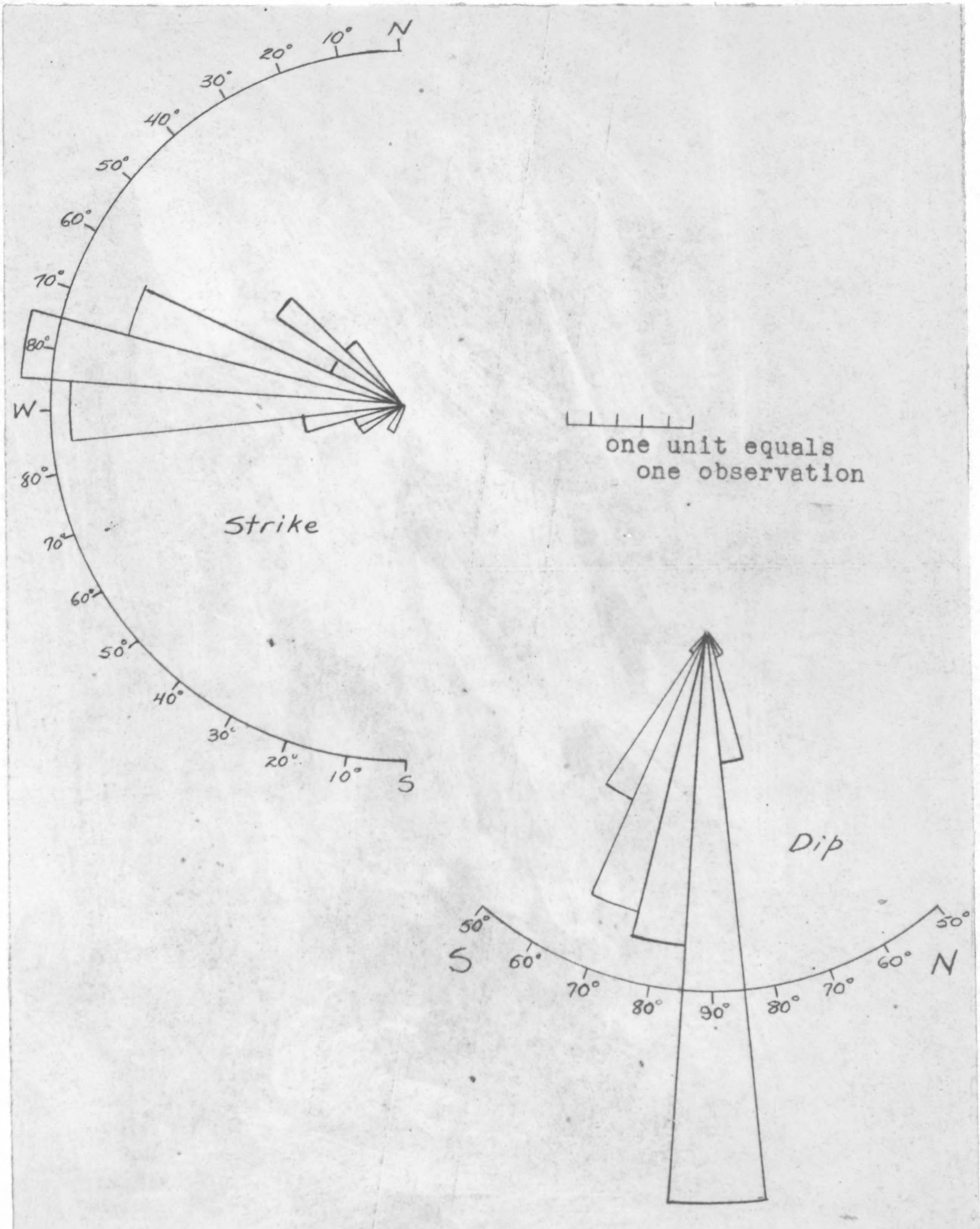

Figure 6. Rose diagrams showing strike and dip of foliation.

paralleling the borders of the granitic plutons is recognized in the Quinnesec strata south of Niagara, Wis. and further to the east in Pier's Gorge, but it has not been recognized in any of the Middle Precambrian rocks. The borders of the plutons south of Niagara strike northwesterly, as does the foliation. The lineation in some of the Pier Gorge schist is apparently a crinkling due to the intersection of northwest-striking foliation related to the borders of the plutons and west-striking foliation related to the regional trend. Foliation parallel with the borders of the metagabbro sills is found both in the Quinnesec strata and in the metagabbro. An example of the former is found near the northern edge of the Horserace sill in the SE$\frac{1}{4}$ sec. 7, T. 39 N., R. 30 W. An example of foliated metagabbro near the sill border is along the southern edge of the Western sill at the west edge of the map area. In places, the sills apparently acted as bosses which resisted the regional shearing stresses, thereby influencing the direction of the stresses around them. Finally, the direction of foliation in deformed Lower Precambrian rocks taken up as inclusions in the metagabbro sills is haphazard as is illustrated by the foliation in the amphibolite inclusion in the eastern part of the Western sill in the N$\frac{1}{2}$ sec. 11, T. 38 N., R. 19 E. which strikes N. 20° E. and by that in the gneiss inclusion along the north side of Horserace Rapids 400 feet east of the railroad which strikes N. 45° E.

Faults are common in the area but are difficult to interpret because of the lack of marker beds. The most distinct fault is in the southcentral part of the area in secs. 15, 16, and 21, T. 38 N., R. 20 E. This fault offsets the Quinnesec formation-Marinette quartz diorite and Marinette quartz diorite-Hoskin Lake granite contacts from 1200 to 1600 feet. The fault is nowhere exposed but is marked by a topographic depression. To the east, the fault apparently dies out in the Quinnesec formation outcrop areas in the S$\frac{1}{2}$ sec. 15. The Hoskin Lake granite adjacent to the fault generally contains bright red rather than gray feldspar grains, and the presence of similar red feldspar adjacent to low granite cliffs elsewhere in the area leads to the conclusion that faulting within the granite is more common than has been recognized.

Thin shear zones are found in some places along the edges of the Hoskin Lake granite pluton and along the borders of the metagabbro sills, but it is impossible to determine how much displacement has occurred.

The Michigamme-Quinnesec formation contact extends throughout the whole length of the area but is nowhere exposed. The most information concerning the configuration of this contact can be obtained from the area near U. S. Highway 8 in the eastern part of the area. There, correlation of magnetic and outcrop data yields a cross section as shown in figure 5. The contact depicted could be explained either by faulting the Michigamme strata against the serpentinite or by erosion truncating the serpentinite pluton before deposition of the Michigamme strata, or it could be a combination of the two.

GEOMORPHOLOGY AND GLACIAL GEOLOGY

The portions of the area which contain few or no outcrops are underlain predominantly by outwash. The surface of the outwash plain is from 60 to 180 feet above the Menominee River and it slopes gently to the east. It is relatively flat except where it is pitted by kettles. Kettles are especially well developed in the northwestern part of the map area, southeast of Kingsford, Mich., where they may be as much as 100 feet in diameter and 60 feet deep. A north-trending esker is present in the southwestern part of the area in the SE$\frac{1}{4}$ and NE$\frac{1}{4}$ sec. 23, T. 38 N., R. 19 E. It is about 4000 feet long and its crest is 20 to 40 feet high.

Terraces as much as three fourths of a mile wide and 20 feet high border the Menominee River in several places. Well-developed terraces are present southwest of the river half a mile to one mile southeast of the western edge of the map area (pl. 2), on both sides of the river between the Big and Little Quinnesec Falls, and north and south of the river between Pier's Gorge and the Sturgeon Falls. These terraces are probably related to temporary or local baselevels established in back of barriers of resistant rock at the various falls and rapids.

Inasmuch as the Menominee River is not adjusted to the structure or lithology of the bedrock, and the adjacent uplands are commonly underlain by outwash, it appears that the river may have been superposed from the surface of the outwash plain.

ECONOMIC CONSIDERATIONS

Several small quartz lenses or pods in the area have been prospected, but all proved barren. Under present conditions, the area contains nothing of economic importance. For possible use in the future, the following are the most promising: (1) titaniferous magnetite in the magnetite-rich metagabbro, (2) low-grade chrome and nickel in the serpentinite, (3) low-grade iron ore from the Michigamme iron-formation, and (4) chalcopyrite disseminated in the metagabbro sills. The metagabbro a short distance west of the map area has already been prospected for copper, but without success.

GEOLOGIC HISTORY

The geology of the southern part of the Menominee District can be summarized by the following geologic history:

(1) Formation of Lower Precambrian Quinnesec formation basalt flows and accompanying pyroclastic and sedimentary rocks and felsic flows.

(2) Intrusion of Lower Precambrian Marinette quartz diorite and possible related dike rocks.

(3) Intrusion of Lower Precambrian Hoskin Lake granite and related dike rocks. This may be related to the same igneous cycle which produced the Marinette quartz diorite.

(4) Deformation and metamorphism, probably in part contemporaneous with intrusion of the quartz diorite and granite.

(5) Erosion.

(6) Early Animikian hiatus; or deposition of Chocolay and Menominee sediments follows by pre-Baraga erosion.

(7) Deposition of marine Michigamme strata (Baraga).

(8) Intrusion of gabbro sills and minor mafic dikes.

(9) Metamorphism and deformation marking the end of the Middle Precambrian; rocks all tilted to a near vertical position.

(10) Intrusion of Upper Precambrian diabase dikes.

(11) Erosion, deposition of early Paleozoic sediments, and their subsequent removal.

(12) Glaciation.

(13) Erosion to present land surface.

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