Geology of the Lake Mary Quadrangle Iron County, Michigan

GEOLOGICAL SURVEY BULLETIN 1077

Prepared in cooperation with the Geological Survey Division Michigan Department of Conservation

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By RICHARD W. BAYLEY

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GEOLOGY OF THE LAKE MARY QUADRANGLE, IRON COUNTY, MICHIGAN

By RICHARD W. BAYLEY

ABSTRACT

The Lake Mary quadrangle is in eastern Iron County, in the west part of the Upper Peninsula of Michigan. The quadrangle is underlain by Lower and Middle Precambrian rocks, formerly designated Archean and Algonkian rocks, and is extensively covered by Pleistocene glacial deposits. A few Upper Precambrian (Keweenawan) diabase dikes and two remnants of sandstone and dolomite of early Paleozoic age are also found in the area.

The major structural feature is the Holmes Lake anticline, the axis of which strikes northwest through the northeast part of the quadrangle. Most of the quadrangle, therefore, is underlain by rock of the west limb of the anticline. To the northwest along the fold axis, the Holmes Lake anticline is separated from the Amasa oval by a saddle of transverse folds in the vicinity of Michigamme Mountain in the Kiernan quadrangle.

The Lower Precambrian rocks are represented by the Dickinson group and by porphyritic red granite whose relation to the Dickinson group is uncertain, but which may be older. The rocks of the Dickinson group are chiefly green to black metavolcanic schist and red felsite, some of the latter metarhyolite. The dark schist is commonly magnetic. The Dickinson group underlies the core area of the Holmes Lake anticline, which is flanked by steeply dipping Middle Precambrian formations of the Animikie series.

A major unconformity separates the Lower Precambrian rocks from the overlying Middle Precambrian rocks. In ascending order the formations of the Middle Precambrian are the Randville dolomite, the Hemlock formation, which includes the Mansfield iron-bearing slate member, and the Michigamme slate. An unconformity occurs between the Hemlock formation and Michigamme slate. The post-Hemlock unconformity is thought to be represented in the Lake Mary quadrangle by the absence of iron-formation of the Amasa formation, which is known to lie between the Hemlock and the Michigamme to the northwest of the Lake Mary quadrangle in the Crystal Falls quadrangle. Post-Hemlock erosion may account also for the absence of iron-formation of the Fence River formation on the east limb of the Holmes Lake anticline within the Lake Mary quadrangle.

The Randville dolomite is not exposed and is known only from diamond drilling in the northeast part of the area where it occurs in the east and west limbs of the Holmes Lake anticline. The formation has a maximum thickness of about 2,100 feet; this includes a lower arkosic phase, some of which is quartz pebble conglomerate, a medial dolomitic phase, and an upper slate phase. The triad is gradational. Included within the formation are a few beds of chloritic schist thought to be of volcanic origin. An

unconformity between the Randville and the succeeding Hemlock is not indicated in the quadrangle, but is probably present.

The Hemlock formation is best exposed in the northwest and south-central parts of the area. The apparent thickness of the formation is 10,000–17,000 feet. It is composed mainly of mafic metavolcanic rocks and intercalated slate and iron-formation. In the north part of the quadrangle the volcanic rocks are greenstone, which includes altered basaltic flow rocks, volcanic breccia, tuff, and slate. Pillow structures are common in the metabasalt. It is not certain if any Hemlock rocks are present in the east limb of the Holmes Lake anticline. In the south part of the quadrangle, the rocks of the Hemlock are chiefly chlorite and hornblende schist and hornfels. Pyroxene hornfels is sparingly present.

At least two sedimentary slate belts are included in the Hemlock formation. One of these, the Mansfield iron-bearing slate member, includes in its upper part an altered chert-siderite iron-formation 30 to over 150 feet thick from which iron ore has been mined at the Mansfield location. The position of the iron-bearing rocks has been determined magnetically, and past explorations for iron ore are discussed.

Though probably unconformable, the contact between the Hemlock and the Michigamme formations appears conformable. The Michigamme slate consists of at least 4,000 feet of interbedded mica schist and granulite, the altered equivalents of the slate and graywacke characteristic of the Michigamme in adjacent areas. The Michigamme rocks are best exposed in the south part of the quadrangle in the vicinity of Peavy Pond.

Two periods of regional metamorphism have resulted in the alteration of almost all of the rocks of the quadrangle. The Lower Precambrian rocks underwent at least one period of metamorphism, uplift, and erosion before the deposition of the Randville dolomite. After the deposition of the Michigamme slate, a post–Middle Precambrian period of regional metamorphism occurred with attending deformation and igneous intrusion. The grade of metamorphism rises toward the south in the area. The rocks in the northern two-thirds of the quadrangle are representative of greenschist facies of regional metamorphism, whereas the rocks in the southern one-third of the quadrangle are representative of the albite-epidote-amphibolite, the amphibolite, and the pyroxene hornfels facies, the metamorphic node centering about the intrusive Peavy Pond complex in the Peavy Pond area.

The Precambrian sedimentary and volcanic rocks are cut by intrusive igneous rocks of different types and several different ages. Gabbroic sills and dikes invaded the Hemlock rocks at some time after the Hemlock was deposited and before the post–Middle Precambrian orogeny and metamorphism. Some contact metamorphism attended the intrusion of the major sills. One of the sills, the West Kiernan sill, is well differentiated. A syntectonic igneous body, composed of gabbro and minor ultramafic parts and fringed with intermediate and felsic differentiates and hybrids, the Peavy Pond complex, was intruded into the Hemlock and Michigamme formations during the post–Middle Precambrian orogeny. The complex is situated in the Peavy Pond area at the crest of the regional metamorphic node. Contact-altered sedimentary and volcanic rocks margin the complex.

The effects of regional metamorphism have been superposed on the contact metamorphic rocks peripheral to the complex and on the igneous rocks of the complex as well. The mafic augite-bearing rocks of the complex emplaced early in the orogeny were deformed by granulation at the peak of the deformation and subsequently metamorphosed to hornblende rocks. Some of the intermediate and felsic rocks of the complex were foliated by the deformation, while the more fluid, felsic parts of the complex were intruded under orogenic stress and crystallized after the peak of deformation. The deformation culminated in major faulting during which the formations were dislocated, and some of the granite of the complex was extremely brecciated.

A few diabase dikes, probably of Keweenawan age, have intruded the deformed and altered Animikie rocks.

The only known metallic resource is iron ore. The Mansfield mine produced 1½ million tons of high-grade iron ore between the years 1890 and 1913. Sporadic exploration since 1913 has failed to reveal other ore deposits of economic importance.

INTRODUCTION

LOCATION AND ACCESSIBILITY

The Lake Mary quadrangle is near the east edge of the Canadian Shield in eastern Iron County, Mich. (fig. 1). The quadrangle includes an area of about 51 square miles between 88°07′30″ and 88°15′00″ west longitude and 46°00′00″ and 46°07′30″ north latitude. It includes the south half of T. 43 N., R. 31 W., most of T. 42 N., R. 31 W., and narrow strips of adjoining townships on the west. Its position, relative to the major geologic features in the western part of the Upper Peninsula of Michigan, is shown in figure 2. The town of Crystal Falls and the east fringe of the Iron River–Crystal Falls iron-mining district are about 4 miles west of the quadrangle; the town of Iron Mountain is 12 miles to the southeast; and the old mining district at Florence, Wis., is 8 miles to the south.

The quadrangle is crossed by Michigan State Highway 69, which connects the towns of Sagola and Crystal Falls. From highway M-69 good secondary roads extend north and south, and few places in the area are more than a mile from passable roads, but some spots are more easily reached by boat from the Michigamme River. In winter, most of the area is not easily accessible.

CLIMATE AND VEGETATION

The mean average temperature of the region is 39.2° F; the average annual precipitation is 33.72 inches; and the average annual snowfall is 56.5 inches. Humidity, percentage of sunshine, wind movement, and rate of evaporation are low (Foster, Veach, and Schoenman, 1937).

Vegetation in the area is of three general types: deciduous hardwood forest, characteristic of drift areas and morainic uplands; pine forest, characteristic of glaciofluvial sand plains; and thick growths of alder, aspen, spruce, tamarack, and birch, characteristic of lowlands and swampy areas.

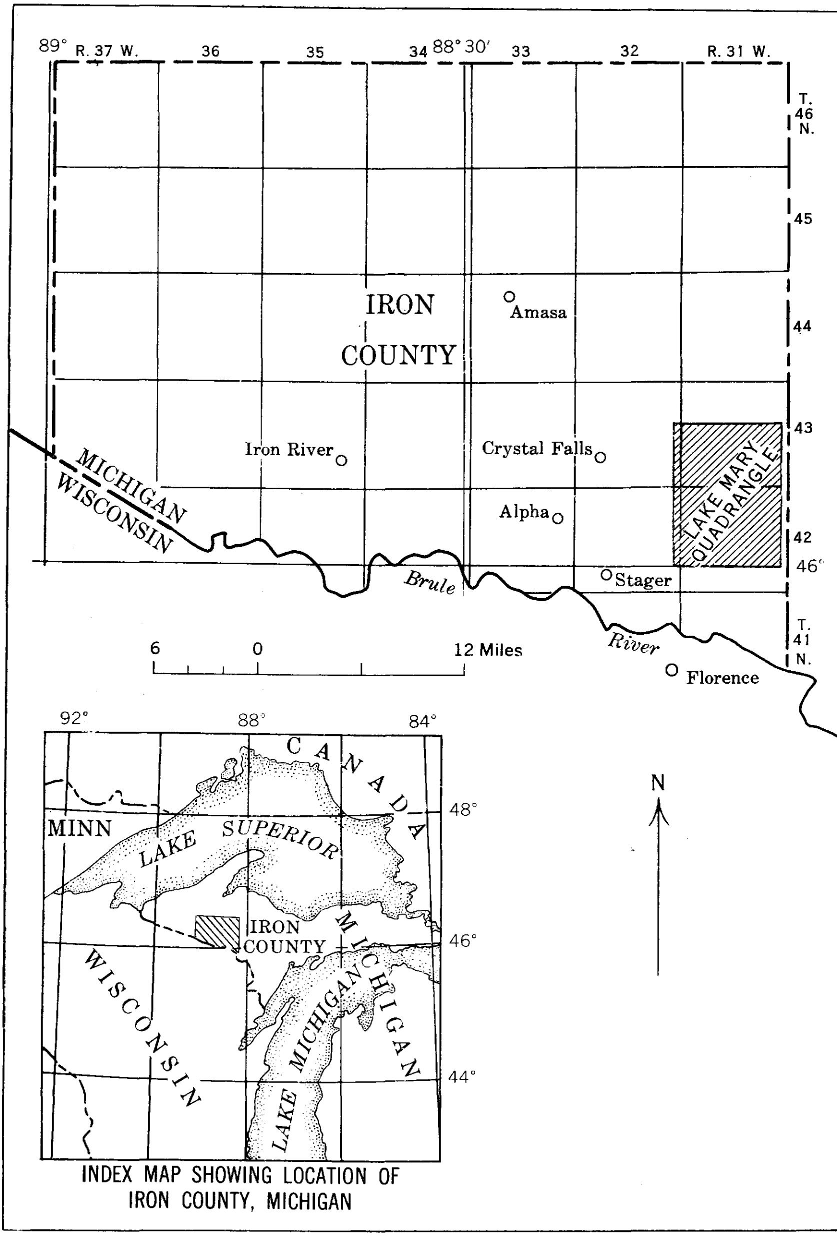

FIGURE 1.—Index map showing location of the Lake Mary quadrangle, Iron County, Michigan.

TOPOGRAPHY AND DRAINAGE

The topography is typical of the glaciated Lake Superior upland. Low, swampy areas alternate with undulating plains, knob and kettle terrain, steep rock hills, and rocky uplands. The maximum relief of the area is 230 feet and the high and low points

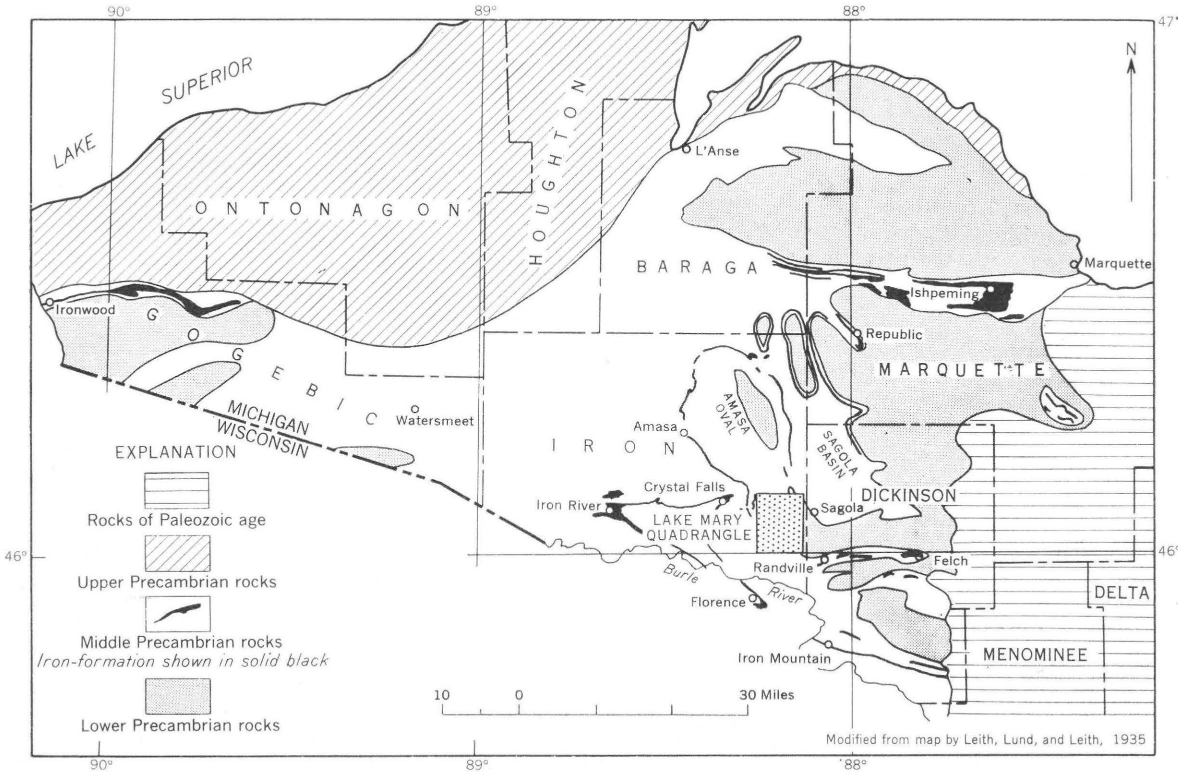

FIGURE 2.—Map of the western part of the Upper Peninsula of Michigan showing location of the Lake Mary quadrangle with respect to the principal geologic features.

are, respectively, in the northwest and the southeast corners of the quadrangle.

In part, the topography is controlled by the bedrock. The uplands are predominantly massive igneous and volcanic rocks or siliceous facies among the sedimentary rocks; the low, swampy tracts generally are underlain by slates and schists. Chiefly, however, the topography is controlled by Pleistocene glacial deposits, which cover most of the area (fig. 3).

The maximum thickness of the glacial deposits, known from drillings, is 170 feet. In the area west of the recessional moraine on the east border of the quadrangle, the constructional surface of the deposits is 1,360–1,380 feet above sea level. Hills rising above 1,380 feet are generally bare rock or rock thinly veneered with till and many are marked with glacial striae that indicate a S. 70°–80° W. direction of the last ice movement.

The quadrangle lies entirely within the drainage system of the Michigamme River, one of the major rivers in the region. In a few places the river crosses bedrock, but for the most part it is entrenched in glacial deposits. Many small tributaries, often blocked by beaver dams, drain the swampy tracts. Only part of the drainage is integrated; swampy areas are abundant in lowlands and uplands alike. Some large morainic areas drain internally.

FIELDWORK AND ACKNOWLEDGMENTS

This report on the geology of the Lake Mary quadrangle represents part of an investigation of the Iron River–Crystal Falls, and Menominee iron-bearing districts of Michigan by the U.S. Geological Survey in cooperation with the Geological Survey Division of the Michigan Department of Conservation. Most of the fieldwork was done between April 1952 and September 1953. The area was mapped on topographic sheets enlarged to 1:12,000 from the standard 7½ minute (1:24,000) topographic map of the Lake Mary quadrangle published by the U. S. Geological Survey (pl. 1).

Outcrops were located by pace-and-compass traverses from known locations and, whenever possible, by direct reference to prominent topographic features. Three small areas, totaling about 10 square miles, were surveyed with magnetometers to aid in tracing magnetic formations under the glacial cover. (The results are shown on plates 2, 3, 4, and 6.) The methods of collecting and interpreting magnetic data are discussed in the section "Magnetic surveys." One small area joining sec. 32, T. 43 N., R. 31 W., and sec. 5, T. 42 N., R. 31 W., on the west bank of the Michigamme River was mapped by plane-table methods.

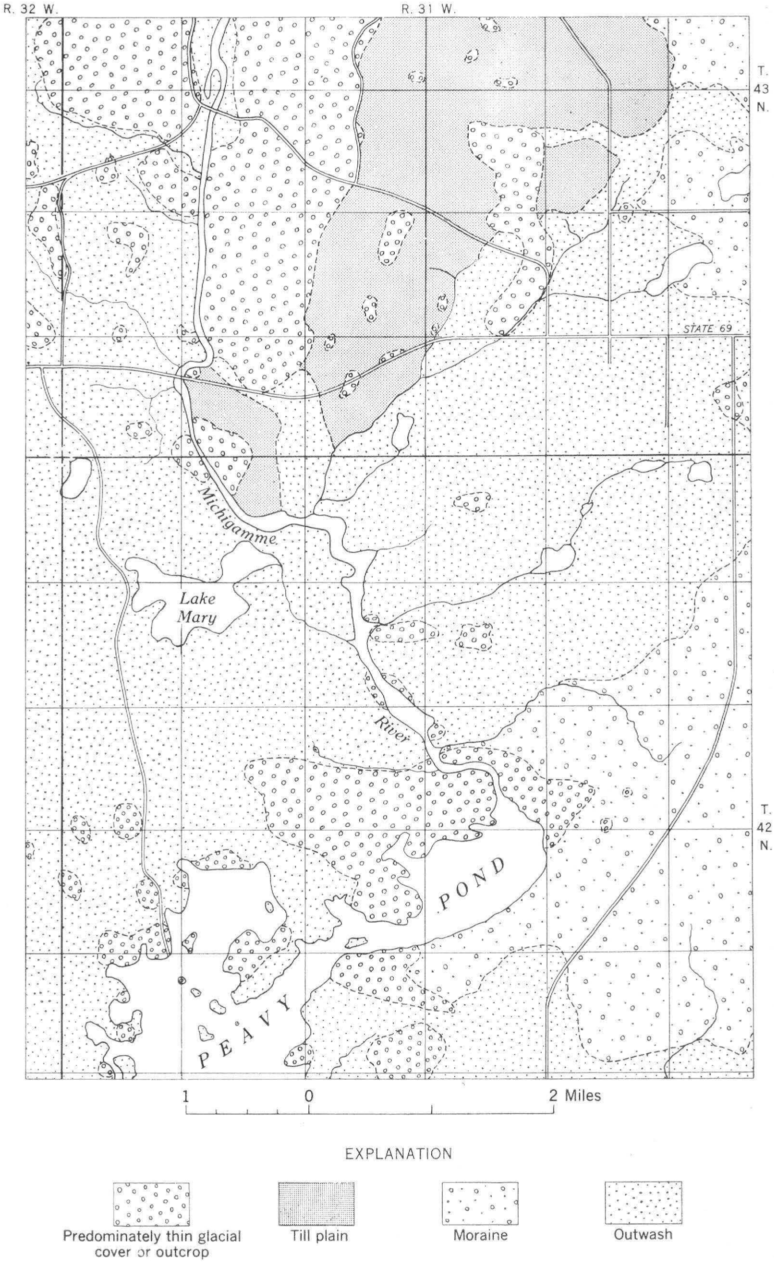

FIGURE 3.—A sketch map showing the distribution of glacial deposits in Lake Mary quadrangle. Modified from Bergquist's map (1932).

PREVIOUS WORK

The first detailed account of the rocks of the Lake Mary quadrangle appeared in a monograph by Clements and Smyth (1899), which treated the geology of the Crystal Falls district.

In that report a comprehensive description of the rocks was given and the principal stratigraphic units were defined. That part of the early monograph map covering the area of the Lake Mary quadrangle is reproduced here as figure 4*A*. More recent data bearing on the age and distribution of the rocks in the Lake Mary quadrangle are contained in the maps and reports of Van Hise and Leith (1911) ; Allen and Barrett (1915) ; Barrett, Pardee, and Osgood (1929) ; Stratton and Joyce (1932) ; Leith, Lund, and Leith (1935) ; Martin (1936) ; Gair and Weir (1956) ; James (1958) ; and in a report in preparation by James and others. The geologic map of Iron County by Barrett, Pardee, and Osgood (1929) represents a considerable advance in geologic knowledge over previous maps and is reproduced in part here as figure 4*B*. The map accompanying the present report, reduced to the same scale, is shown for comparison as figure 4*C*.

GENERAL GEOLOGY

The Lake Mary quadrangle is underlain chiefly by Lower and Middle Precambrian rocks. Upper Precambrian rocks are represented by a few diabase dikes considered to be of Keweenawan age. Two small outliers of sandstone and dolomite, probably of Late Cambrian age, are present in the northeast part of the quadrangle, but are not mapped. Most of the bedrock is covered by Pleistocene glacial deposits. The stratigraphic sequence is shown in table on page 10.

The Lower Precambrian rocks are represented by porphyritic red granite, which crops out in a small isolated area in sec. 24, T. 42 N., R. 31 W., and by the Dickinson group, an unknown thickness of metavolcanic rocks that lies unconformably beneath the Middle Precambrian Randville dolomite in the northeast part of the quadrangle. The Middle Precambrian formations that make up the Animikie series (James, 1958) are, from oldest to youngest, the Randville dolomite, the Hemlock formation, and the Michigamme slate. The latter two formations are assigned to the Baraga group (James, 1958). The Animikie formations are apparently conformable within the quadrangle area, but unconformities are probably present between each of the several formations.

Igneous rocks representing three periods of intrusion cut the Animikie rocks. Small dikes and two large sills of gabbro invaded the rocks of the Hemlock formation prior to the post–Middle Precambrian folding and metamorphism. The two sills are mappable units in the north part of the quadrangle and in the Kiernan quadrangle where they have been named East and West Kiernan sills by Gair and Wier (1956). The West Kiernan sill

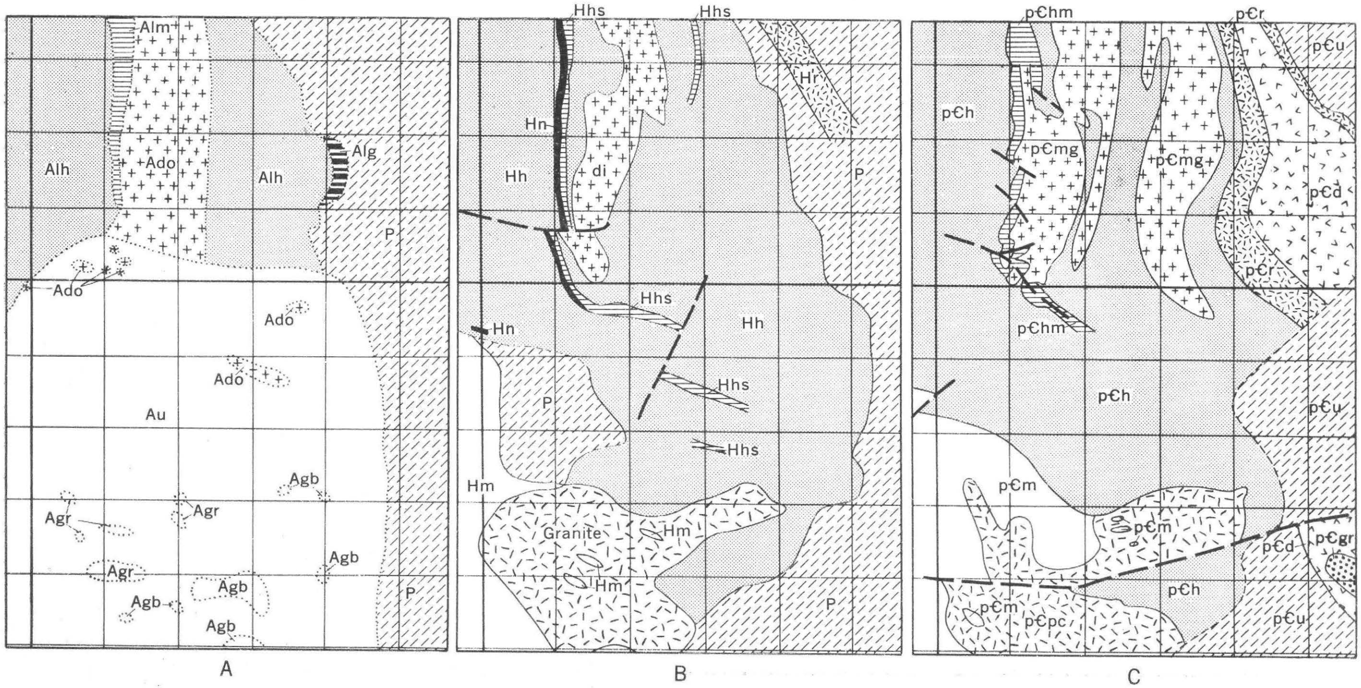

FIGURE 4.—Maps showing three stages of geologic interpretation of the rocks of the Lake Mary quadrangle. *A*, After Clements and Smyth, U. S. Geol. Survey Mon. 36, 1899, pl. 3; *B*, After Barrett, Pardee, and Osgood, Geologic Map of Iron County, Michigan, 1929; *C*, Reduced and generalized from plate 1 of this report. *P*, Pleistocene deposits; *p€pc*, Peavy Pond complex; *Au-Hm-p€m*, Michigamme slate; *Alh-Hh-p€h*, Hemlock formation; *Hhs*, slate in Hemlock formation; *Alm-p€hm*, Mansfield iron-bearing slate member of the Hemlock formation; *Alg*, Groveland formation; *Hn*, Negaunee iron-formation; *Ado-di-p€mg*, metagabbro; *Hr-p€r*, Randville dolomite; *Agr-p€gr*, granite; *Agb*, gabbro; *p€d*, Dickinson group; *p€u*, Precambrian rocks undifferentiated. Dashed line, inferred, probable, or approximately located fault.

Quaternary	Pleistocene		Glacial deposits
			Unconformity
Cambrian	Upper Cambrian		Sandstone and dolomite
			Unconformity
Upper Precambrian	Keweenawan series		Diabase dikes
			Unconformity
Middle Precambrian			Peavy Pond complex
			Metagabbro (East and West Kiernan sills)
	Animikie series (Huronian)	Baraga group	Michigamme slate 4,000–5,000 feet
			Unconformity
			Hemlock formation with Mansfield iron-bearing slate member 10,000–17,000 feet
			Unconformity (?)
			Randville dolomite 800–2,100 feet
			Unconformity
Lower Precambrian		Dickinson group	Undifferentiated metavolcanic rocks
			Porphyritic red granite (age and relations uncertain)

is differentiated. A syntectonic complex of igneous rocks, here called the Peavy Pond complex, cuts the Hemlock and Michigamme formations in the south part of the quadrangle. Posttectonic dikes of fresh diabase, presumably Upper Precambrian (Keweenawan), cut the West Kierwan sill and altered and deformed rocks of the Hemlock formation in a few places.

The major structure is the Holmes Lake anticline, the crest of which strikes northwest through the northeast quarter of the quadrangle (pl. 1). Most of the rocks in the area lie west of the crest of the anticline and make up the west limb, which locally exhibits faults and transverse folds of lesser orders.

All the Precambrian rocks except the late diabase dikes have been metamorphosed. A pre-Animikie period of folding and metamorphism affecting only the rocks of the Dickinson group is implicit in the correlation of these rocks with the type rocks a few miles to the southeast, and is petrographically explicit. Both

Lower and Middle Precambrian formations and included intrusive rocks were deformed and metamorphosed regionally during the post–Middle Precambrian orogeny (James, 1955).

SEDIMENTARY AND VOLCANIC ROCKS

LOWER PRECAMBRIAN ROCKS

DICKINSON GROUP

DEFINITION, DISTRIBUTION, AND THICKNESS

The Dickinson group is a thick sequence of metasedimentary and metavolcanic rocks that underlies the Middle Precambrian rocks in north-central Dickinson County, and eastern Iron County, Mich. (James, 1958; Gair and Wier, 1956). The group was defined from exposures in north-central Dickinson County to consist of the arkose and arkosic conglomerate of that part of the Sturgeon River tongue area (Bayley, 1899) referred to as the Sturgeon quartzite, and the metavolcanic and metasedimentary schist and gneiss south of the latter and north of the Felch trough formerly referred to the Archean (James, 1958). The principal occurrence of the group is in a broad eastward-striking belt that crosses Rs. 28–30 W., T. 42 N., in central Dickinson County. Exposures are plentiful in the eastern part of the belt and the group has been divided into formations, but to the west of R. 29 W., exposures are scarce and the group cannot be divided. From the vicinity of Sagola, Mich., in west-central Dickinson County the rocks of the group have been traced magnetically northwestward into the northeast part of the Lake Mary quadrangle and the southeast part of the Kiernan quadrangle, Iron County, Mich. (Gair and Wier, 1956).

In the type area in Dickinson County the Dickinson group rests unconformably on a gneissic granite (James, 1958), with which the porphyritic red granite of Lake Mary quadrangle is correlated. The group has been intruded and metamorphosed by batholithic granite of Lower Precambrian (pre-Animikie) age (James, 1958). The group is overlain unconformably by the Sturgeon quartzite or by younger Animikie formations. In north-central Dickinson County, especially in secs. 31 and 36, T. 43 N., R. 29 W., and near Turner, Mich., in the northeast part of the same township, the Randville dolomite is the oldest Animikie formation present.

In the Lake Mary quadrangle the rocks of the Dickinson group occupy the core of the Holmes Lake anticline and are flanked to the east and west by the Randville dolomite and succeeding younger formations (pl. 1). The area underlain by rocks assigned to the Dickinson group is almost completely covered by glacial deposits. One small "grass-roots" outcrop occurs along the road near the center of sec. 36, T. 43 N., R. 31 W., but other than that, information regarding the nature of these rocks has been derived from the examination of core from 7 diamond-drill holes.

The thickness of the Dickinson group can not be determined in the Lake Mary quadrangle. In the type area the thickness is approximately 7,000 feet (James, 1958).

DESCRIPTION

The rocks are dominantly schists of varying composition. The most characteristic rock types are greenish-gray quartz-sericite-magnetite schist, which contains scattered eyes of opalescent quartz, dense red felsite, which often contains opalescent quartz eyes, and green to blackish-green biotite-chlorite-magnetite schist (greenschist).

QUARTZ-SERICITE-MAGNETITE SCHIST

Quartz-sericite-magnetite schist occurs at bedrock surface in 2 diamond-drill holes in sec. 23, T. 43 N., R 31 W., and immediately below the basal arkose of the Randville dolomite in 2 drill holes in the NW¼ sec. 26, T. 43 N., R. 31 W. The only outcrop of Dickinson rocks is of this type.

The schist is buff to greenish gray where fresh, and mottled red where oxidized. It is medium to fine grained and well foliated. The cleavage surfaces have a bright sericitic sheen and are dotted with visible euhedral crystals of magnetite or martite. Eye-shaped spots of opalescent quartz are common. Some of the schist is finely laminated with thin alternating light and dark layers less than a centimeter thick. The groundmass of the schist is composed of granular quartz, subparallel plates of pale-green sericite, occasional small dusty-red grains of altered feldspar, and crystals of euhedral magnetite. Scattered through the groundmass are larger quartz grains and pods of granular quartz. The larger quartz individuals are strained and show undulatory extinction, which accounts perhaps for their opalescent character. Some of the quartz occurs in the strain shadows of magnetite crystals (fig. 5).

FELSITE

Dense red felsite is interbedded with schist in 3 diamond-drill holes in sec. 23, T. 43 N., R. 31 W., and at bedrock surface in 1 drill hole located south of Mitchell Lake in sec. 25, T. 43 N., R. 31 W. In sec. 23, 2 of the holes cut a single layer of felsite not over 5 feet thick. The third hole cuts over 100 feet of felsite that has numerous schist partings. The hole in sec. 25 entered

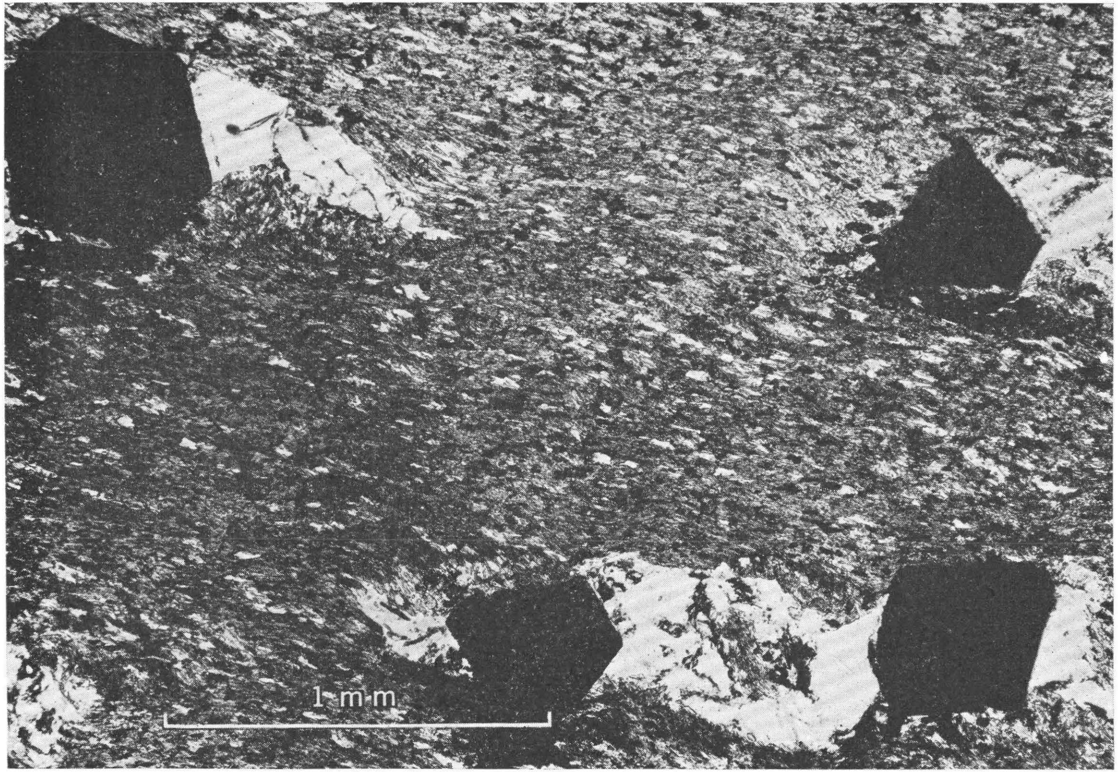

FIGURE 5.—Photomicrograph of quartz-sericite-magnetite schist. ×50, ordinary light. Showing elongate pods of quartz and euhedral metacrysts of magnetite. Specimen RB–72–52.

the felsite at bedrock and continued in it for 20 feet before the hole was abandoned.

The felsite is usually red, aphanitic, and cherty in appearance, and often contains scattered eye-shaped phenocrysts of bluish-white opalescent quartz and white microcline. Many of the phenocrysts have been granulated and form intermittent streaks across the core parallel to the foliation of the enclosing schist.

The groundmass minerals of the porphyritic rock are quartz, pale-green sericite, potash feldspar, and magnetite. The texture is mylonitic blastoporphyritic, the groundmass minerals being somewhat differentiated into subparallel laminae that bend around the phenocrysts and pods of quartz and microcline (figs. 6 and 7). Quartz phenocrysts show undulated extinction and a few of them appear corroded. The few scattered crystals of magnetite present cut across the laminae and thus may have formed later than the deformation of the rock.

Although no complete chemical analysis is available for these rocks, their general appearance and mineralogy indicate that they are probably metarhyolite. The mineralogically related quartz-sericite-magnetite schist associated with the felsite and described above, is probably metarhyolite tuff or ash, but its fragmental character has not been determined.

The red felsite from sec. 25, T. 43 N., R. 31 W., though otherwise similar in appearance to the felsite described above, is very poor in quartz and is probably metatrachyte. It is an aphanitic rock of rather uniform texture, liberally spotted by infiltrated secondary quartz and pink dolomitic carbonate. The rock is composed chiefly of potash feldspar with only a trace of quartz. One specimen more schistose than the rest is probably a crystal tuff. The groundmass is composed of dusty-red microperthite and microcline, pale-green sericite, chlorite, and calcite. Larger crystals and crystal fragments of twinned albite oligoclase occur as "phenocrysts" in the groundmass. A dense aphanitic variety of felsite from the same drill hole is composed completely of subhedral crystals of microperthite and microcline in a matrix of carbonate.

GREENSCHIST

The rocks referred to as greenschist include a variety of rock types that characteristically are green to blackish green and are often moderately magnetic. The greenschist is interbedded with the light-colored schist and felsite, but in no regular sequence. This schist has been penetrated by drilling near the centers of secs. 23 and 26, T. 43 N., R. 31 W., and in the SE¼NE¼ sec. 25, T. 43 N., R. 31 W. east of the quadrangle border. Magnetic

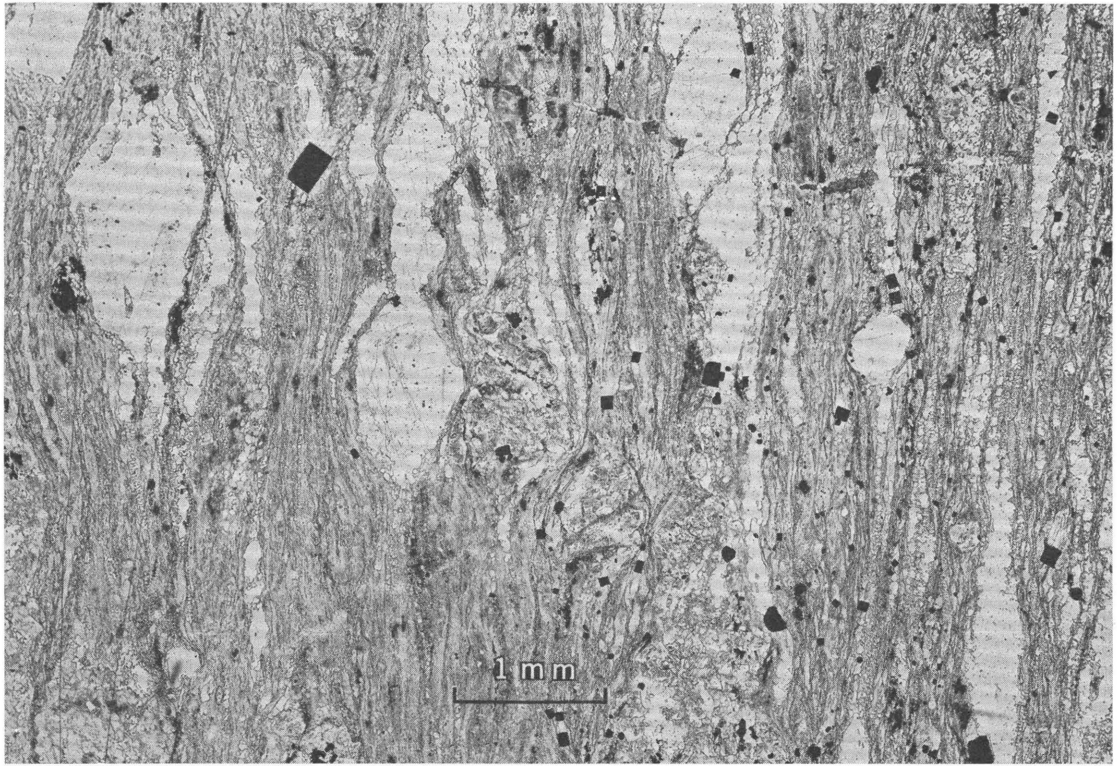

FIGURE 6.—Photomicrograph of a mylonitic felsite (metarhyolite). ×20, ordinary light. Composed of strained and partly granulated individuals of quartz and microcline in a sheared groundmass of quartz, sericite, and feldspar. The opaque mineral is magnetite. Specimen RB–244–52.

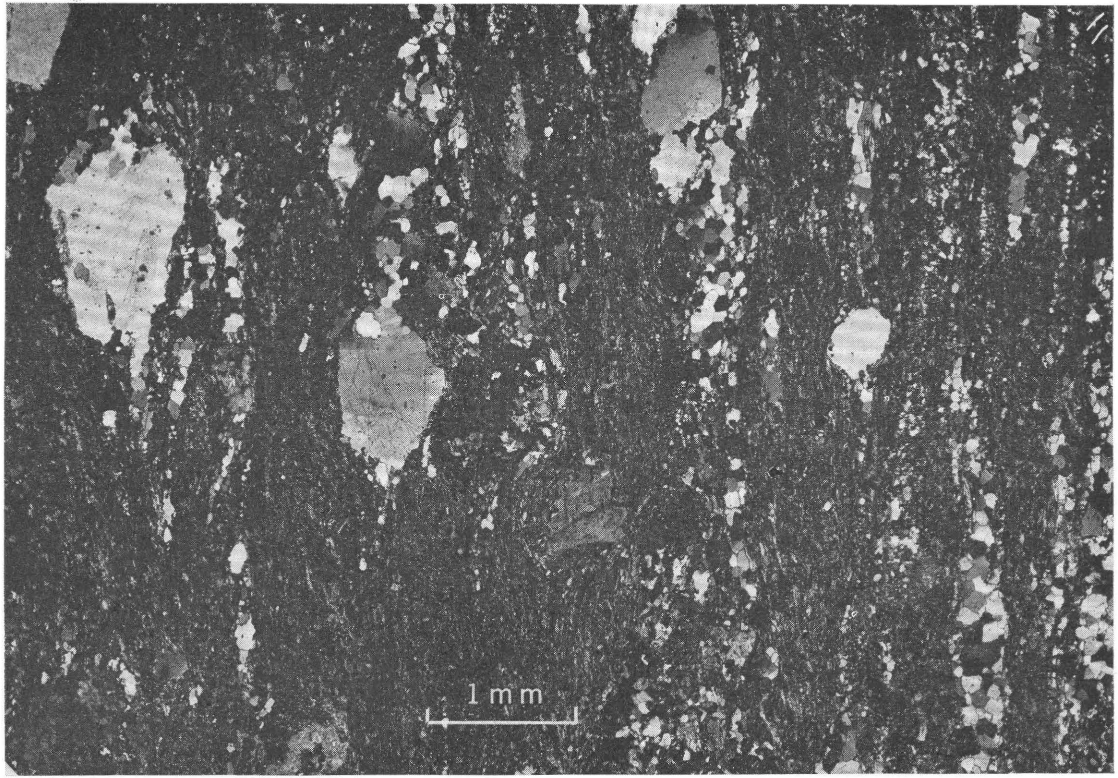

FIGURE 7.—Photomicrograph of mylonitic felsite (metarhyolite). ×20, crossed nicols. Composed of strained and partly granulated individuals of quartz and microcline in a sheared groundmass of quartz, sericite, and feldspar. The opaque mineral is magnetite. Specimen RB–244–52.

data and information from borings indicate that broad areas of anomalous positive magnetism within the core of the Holmes Lake anticline roughly outline the distribution of the magnetic greenschist (pl. 2).

Most of the rocks are schistose, but some are massive and poorly foliated. Some of the least deformed rocks retain their original volcanic characteristics, such as agglomeratic structure with discrete fragments of varying character, and amygdaloidal structure with elongate pods of quartz or calcite that represent original vesicle fillings. Some tuffaceous beds, though strongly sheared, still show their fragmental nature, but finer tuffs and ash have generally been totally recrystallized and their volcanic origin can only be inferred from association and mineral composition. All the greenschists are fine grained and composed of pale-green sericite, greenish-brown biotite, chlorite, quartz, and magnetite. Some of the schists contain an undetermined feldspar that has a dusty-red appearance, and some contain a chloritized plagioclase, probably albite. Sphene was found in traces in some of the specimens. One specimen of laminated schist contains thin layers of pale-yellow carbonate in which tiny garnets are embedded. In all of the greenschist, chlorite is more or less abundant as an alteration mineral replacing biotite and plagioclase.

CONDITIONS OF DEPOSITION

The rocks of the Dickinson group, as nearly as can be determined from the meager sampling in the Lake Mary quadrangle, represent the metamorphic equivalents of acidic and intermediate lava flows and associated pyroclastics. The assemblage includes porphyritic and nonporphyritic felsite, amygdaloidal, agglomeratic, and tuffaceous greenstone, and rudely bedded tuff. Only the laminated rocks (tuff) suggest deposition in water.

RELATION TO OTHER FORMATIONS

Four diamond-drill holes in the Lake Mary quadrangle have crossed the contact between the Randville and the rocks of the Dickinson group. Three of the holes are in sec. 23, and the other in sec. 26, T. 43 N., R. 31 W. The contact is believed to be unconformable for the following reasons:

(1) Throughout the region, exposures show that a profound unconformity separates the Middle Precambrian (Animikie) rocks from the older Lower Precambrian rocks. The Randville dolomite is the oldest recognized Middle Precambrian formation in the quadrangle and in the adjacent areas to the north and east. Therefore, even in the absence of additional data, the unconformity could be safely inferred.

(2) The basal Randville is composed of arkose and arkosic conglomerate that is in sharp contrast with the dark volcanic schist of the underlying Dickinson group. Schist fragments apparently derived from the underlying rock have been seen in two specimens of the arkose.

(3) The arkose grades upward into the dolomite but never downward into the schist, nor is the schist dolomitic.

(4) In contrast to the mildly deformed Middle Precambrian rocks, the Dickinson rocks generally show the results of very strong internal deformation.

(5) The Holmes Lake anticline is in the chlorite zone of regional metamorphism as shown by the mineralogy of the Randville and Hemlock rocks. The mineralogy of most of the Dickinson group rocks is consistent with this level of metamorphism, but the local presence of relict minerals such as garnet shows that these rocks had attained a higher metamorphic rank in a previous period of metamorphism.

MIDDLE PRECAMBRIAN ROCKS (ANIMIKIE SERIES)

RANDVILLE DOLOMITE

DEFINITION AND DISTRIBUTION

The Randville dolomite was named for the town of Randville, Mich., in sec. 33, T. 42 N., R. 30 W. by Clements and Smyth (1899, p. 406). As originally defined, the formation included about 700 feet of dolomite marble and some interbedded schist and quartzite conformably overlying the Sturgeon quartzite and underlying the Mansfield slate. The Randville was correlated with dolomite in the lower iron-bearing sequence exposed near the town of Iron Mountain, Mich.; with the Kona dolomite of the Marquette district; and with dolomite bounding the Archean (Amasa) oval (Clements and Smyth, 1899, p. 384 and 457). The Mansfield slate thought to be correlative with the Mansfield iron-bearing slate member of the Hemlock formation by Smyth (Clements and Smyth, 1899) was redesignated Felch schist in the type area of the Randville by Van Hise and Leith (1911) who regarded the Felch schist older than the Mansfield iron-bearing slate member.

In the Lake Mary quadrangle the Randville dolomite is known only from diamond drilling, and its distribution on plate 1 is partly inferred from magnetic trends in the adjacent, older, magnetic schist of the Dickinson group. The formation makes two belts bounding the Lower Precambrian core rocks of the Holmes Lake anticline (pl. 1). The western belt of dolomite is believed to dip 60°–80° west and southwest. Its extension from the north border of the map to the center of sec. 26, T. 43 N., R. 31 W., is fairly well controlled by drill holes, but to the south and southeast of sec. 26 the position of the belt is almost entirely inferred from magnetic data. The east belt of dolomite has been penetrated by drilling in sec. 14, T. 43 N., R. 31 W., where it is separated from the west belt by a narrow zone of magnetic schist of the Dickinson group. The northwest and southeast extensions of the east belt of dolomite are inferred to bound, on the east, a nearly continuous, broadening belt of positive magnetic disturbance probably associated with this magnetic schist (see pl. 2). Recent (1955) drilling east of the Lake Mary quadrangle in sec. 30, T. 43 N., R. 30 W., has penetrated rocks similar in part to the iron-rich quartzites exposed at Michigamme Mountain in the adjacent Kiernan quadrangle to the north. Because the iron-rich quartzite is known to lie above the Randville dolomite at Michigamme Mountain, the occurrence in sec. 30 is interpreted as a favorable indication that the previously inferred position of the eastern belt of dolomite is approximately correct.

DESCRIPTION

The lithology of the Randville has been determined by the examination of core and thin sections of core from 28 diamond-drill holes. The formation appears to consist essentially of a basal arkose, a medial phase of crystalline and slaty dolomite, and an upper slate, with an aggregate thickness of 800–2,100 feet. The three distinct lithologies intergrade. The thickness of the dolomite where drilled is quite uniform about 500 feet. The arkose is about 900 feet thick in secs. 23 and 26, on the west limb of the Holmes Lake anticline, but may be absent on the east limb. The upper slate is 400 and 700 feet thick in secs. 26 and 23, respectively. The presence of the slate on the east limb is uncertain, because the age of the slate lying above (east of) the dolomite in sec. 14, T. 43 N., R. 31 W. is not known. The slate drilled in sec. 14 is much weathered and oxidized, and is not distinctive of any formation. Conceivably the slate in sec. 14 could represent part of either the Randville, the Hemlock, or the Michigamme formations. This slate above the Randville on the east limb of the Holmes Lake anticline is shown as undifferentiated Middle Precambrian on plate 1.

On the west limb of the anticline, the upper part of the slate sequence is black pyritic slate containing layers of chloritic schist, probably of volcanic origin. Although there is no apparent break between this black slate and the underlying dolomitic slate, which is distinctly a part of the Randville, the interbeds of volcanic rock are incongruous in the regional picture of Randville sedimentation, and for that reason the black slate and chlorite schist are placed in the overlying Hemlock formation, which is chiefly composed of volcanic material. The west limb of the Randville dolomite thins to the north, particularly at the expense of the upper slate.[1]

ARKOSE

Arkose, arkosic conglomerate, sericitic-feldspathic schist, and dolomitic arkose form a distinct basal member of the Randville, although these rock types are not confined to this stratigraphic position and are known to occur higher in the formation. Arkose was found by borings in secs. 23 and 26, T. 43 N., R. 31 W., chiefly below (east of) the slate and dolomite phases of the formation. The arkose belt, thus defined by drilling, is believed to extend northwest into the Kiernan quadrangle where it is known from a single outcrop and several drill holes in sec. 10, T. 43 N., R. 31 W. No arkose was found below the dolomite on the east limb of the Holmes Lake anticline in sec. 14. Because the drill holes are rather closely spaced in sec. 14, the arkose is believed to be absent or very meagerly represented. There the dolomite probably rests on oxidized sericite-martite schist of the Dickinson group.

The arkose is generally pink or light gray and fine to coarse grained. It may be either massive or schistose. The massive rock is usually devoid of foliation or bedding planes and is granitelike in appearance—in fact, in a number of the older drill holes the arkose was logged as granite, and the associated carbonate rock was logged as quartzite. The important minerals are quartz, microcline, perthite, and sericite. The accessory minerals are dolomitic carbonate, magnetite, zircon, and sericite. Figure 8 illustrates a typical arkose from NW¼ sec. 23, T. 43 N., R. 31 W.

Quartz, which makes up 70–75 percent of the rock, occurs as clear subangular grains 0.1–0.5 mm in diameter in closely fitted mosaics without any visible cement, or with a minor amount of intergranular sericite; and as subangular to well-rounded grains as much as 5 mm in diameter. The larger quartz grains, many of which show marked undulatory extinction, are crossed by many chains of tiny gas or liquid inclusions typical of the quartz in many igneous rocks.

The microcline and perthite, which account for 25–30 percent of the arkose, are present as small subangular grains, 0.1–0.5 mm in diameter, that are dispersed among the quartz grains of the

[1] The thinning of the west limb of Randville to the north of sec. 23, T. 43 N., R 31 W., may or may not be real. On plate 1 the upper contact of the Randville has been depressed to accommodate about 1,000 feet of quartzose sericite slate and schist lying above the dolomite member of the Randville in secs. 9 and 10, T. 43 N., R. 31 W., in the Kiernan quadrangle, which has been interpreted to be a part of the Hemlock formation by Gair and Wier (1956).

groundmass, and as larger scattered grains as much as 5 mm in diameter.

Sericite occurs as an alteration product of some of the feldspar, and as small lenses and discrete plates and needles intergranular to the quartz and feldspar. In the schistose arkose the sericite is a prominent constituent; it occurs as parallel plates and as sheaths around grains of quartz and feldspar. Much of the sericite appears to have formed from the alteration of clastic feldspar.

DOLOMITE

The medial, dolomitic part of the Randville has been cut by diamond drilling in secs. 14, 23, and 26, T. 43 N., R. 31 W. The occurrences in secs. 14 and 23 in the Lake Mary quadrangle and in sec. 10, T. 43 N., R. 31 W., in the Kiernan quadrangle define the structure of the Holmes Lake anticline. The northwestward-trending belts of dolomite on the limbs of the anticline are believed to extend northward into the area of recognized Randville dolomite west of Michigamme Mountain in Kiernan quadrangle (Clements and Smyth, 1899).

The dolomite is generally light colored, commonly pink or white, or mottled purple and white. It may be thick or thin bedded. Interlayers of arkose are present and much of the dolomite is arkosic. Interbeds of slate are also present, as are thin-layered rocks composed of carbonate layers alternating with layers of slaty material. The slaty dolomite and intercalated slate beds are generally schistose in the plane of the bedding.

Many of the rocks are true dolomite containing more than 50 percent dolomitic carbonate. The accessory minerals are quartz, microcline, perthite, sericite, magnetite, and pyrite. The carbonate of most of these rocks is generally fine grained, but inclined to be patchy and somewhat coarser along bedding planes, in shear zones, and in the strain shadows of the clastic grains of quartz and feldspar. In the arkosic dolomite, the clastic grains are widely spaced in the carbonate matrix as in calcarenite (fig. 9). Index determinations on carbonate from three core specimens gives an N_0 of about 1.681, which is approximately the index of pure dolomite.

SLATE

The upper member of the Randville triad consists of slate and schist, at least in the west limb of the Holmes Lake anticline. As noted previously, the presence of the member in the east limb is not certainly known. Twenty drill holes penetrate these slates in secs. 23 and 26, T. 43 N., R. 31 W. In the lower part of the se-

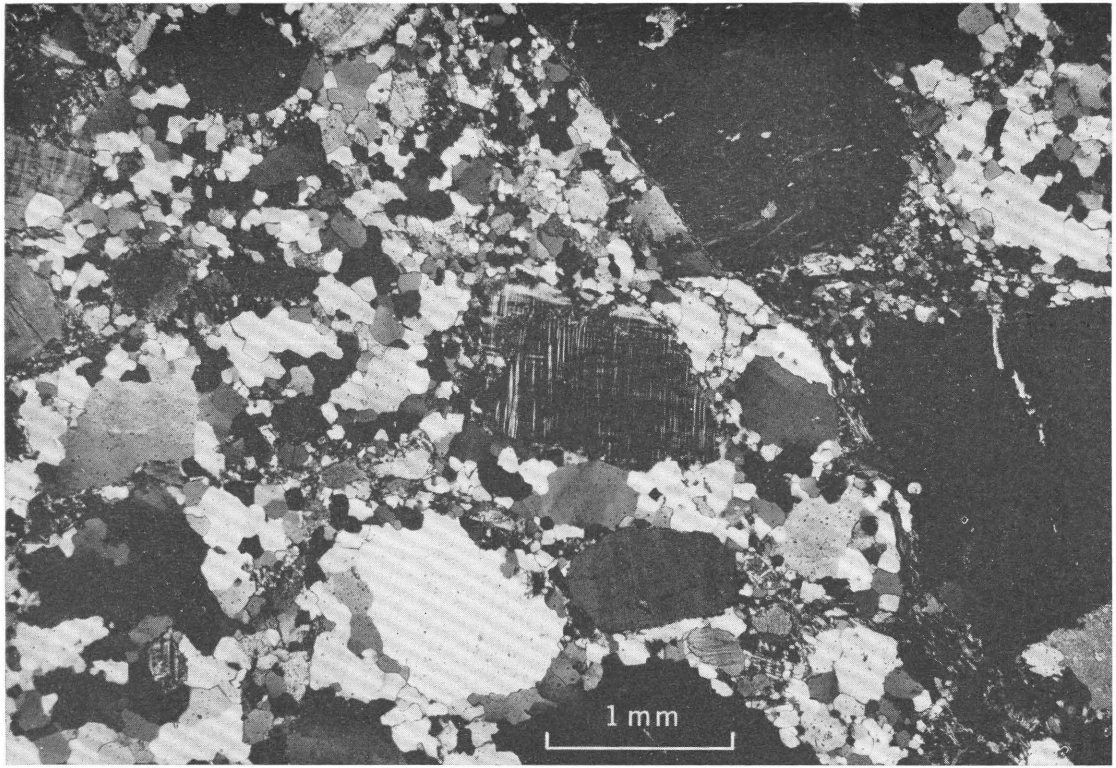

FIGURE 8.—Photomicrograph of arkose composed chiefly of quartz and microcline. ×25, crossed nicols. From near the base of the Randville dolomite in the NW¼ sec. 23, T. 43 N., R. 31 W. Specimen HJ–207b–51.

FIGURE 9.—Photomicrograph of arkosic dolomite. ×25, crossed nicols. Showing grains of clastic quartz (*q*) and microcline and perthite (*pf*) in a matrix of dolomitic carbonate. A little clear secondary quartz fringes some of the feldspar grains. The rock has been deformed. Note especially the crystalline carbonate protected in the strain shadows of the clastic grains. From sec. 23, T. 43 N., R. 31 W. Specimen RB–68–52.

quence the slates are interbedded with the dolomite, and therefore constitute a definite part of the Randville.

Two slate types are prevalent: light-colored dolomitic and sericitic slate, and nondolomitic sericitic slate. The slate is fine to very-fine grained, and most of it is laminated or thin bedded, with alternating light and dark layers, which reflects either slight variations in grain size or the occurrence of light-colored carbonate-rich layers alternating with darker slate layers. Chloritic greenschist, possibly of volcanic origin, occurs in the lower part of the slate sequence in sec. 26, T. 43 N., R. 31 W.

The minerals of the slate are sericite, chlorite, quartz, feldspar, dolomitic carbonate, magnetite, hematite, biotite, sphene, pyrite, and tourmaline.

Parallel microscopic plates of pale-green sericite and minor chlorite intimately interlaced with finely comminuted quartz and feldspar make up the bulk of the slates. In schistose rocks, particularly, the quartz has recrystallized in elongate grains parallel to the foliation. Dolomitic carbonate is often present either in discrete layers or disseminated intergranularly among the other components. Magnetite is often present as small euhedral crystals partially surrounded by plates of bright-green chlorite. Where abundant, magnetite peppers the sides of core specimens in crystals usually less than 0.5 mm in size, rendering the total specimen magnetic. Fine-grained needles of dark tourmaline occur as an accessory mineral in gray sericitic slates.

Rocks in the lower part of the slate sequence, logged as greenschist of possible volcanic origin, are dark-greenish-gray rocks, and are rather massive in appearance. The groundmass is composed of pale-green chlorite, finely disseminated carbonate, and limpid grains of albite. "Phenocrysts" in the groundmass include 1 or 2 percent of medium-grained quartz in irregular grains that are penetrated by the chlorite, mottled and partially chloritized albite, and granular sphene in widely spaced, regularly shaped aggregates probably derived from ilmenite. The texture of the rocks is unsystematic, and the minerals are clumped into irregular aggregates in a manner suggestive of volcanic tuff.

CONDITIONS OF DEPOSITION

The dolomite and slate of the Randville are stable shelf deposits which characterize the Randville wherever it is known in the district. The arkose is regarded as an anomalous phase probably derived from a granitic island source. It is assumed that during the time of Sturgeon-Randville sedimentation the Lake Mary quadrangle lay near the distal edge of the Sturgeon clastics, but the paleotectonics for this period are not known with any certainty.

AGE AND CORRELATION

The dolomite and interbedded arkose and slate of the Lake Mary quadrangle are correlated with the Randville dolomite, which crops out in the adjacent Kiernan quadrangle to the north. If the rocks were more favorably exposed, the Randville undoubtedly would have been divided into three formations including a lower arkose formation, the stratigraphic but not the lithologic equivalent of the Sturgeon quartzite; a medial dolomite formation, both stratigraphically and lithologically equivalent to the Randville dolomite elsewhere; and an upper slate formation which is probably the stratigraphic equivalent of slate in sec. 32, T. 44 N., R. 31 W., considered a part of the Randville (Van Hise and Leith, 1911, p. 295–296; Gair and Wier, 1956), and possible equivalent to the Wewe slate of the Marquette area (Van Hise, 1899, p. xxv).

BARAGA GROUP

HEMLOCK FORMATION

DEFINITION, DISTRIBUTION, AND THICKNESS

The Hemlock formation was named by Clements and Smyth (1899, p. 73) for exposures along the Hemlock River on the west side of the Amasa oval, northeast of the town of Amasa, Mich. The name Hemlock greenstone was used for these rocks by Leith, Lund and Leith (1935), and the name Hemlock formation has been reinstated by Gair and Wier (1956), who consider the term greenstone too restricted to include all of the various lithologies now included in this formation.

The Hemlock formation is composed chiefly of altered basaltic flows and pyroclastic rocks and a small percentage of metarhyolite disposed in an asymmetrical belt about the Amasa oval, and extending south into the Lake Mary quadrangle in the west limb of the Holmes Lake anticline. A few isolated exposures of altered rhyolite in the vicinity of Sagola, Mich., suggest that the Hemlock formation may also be present in the east limb of the Holmes Lake anticline. The maximum known thickness of the Hemlock occurs near the town of Amasa, where the apparent thickness is 25,000–30,000 feet. From Amasa eastward the formation thins rapidly so that it is less than 2,500 feet thick on the east side of the Amasa oval. Southward from Amasa the Hemlock wedge also thins. The formation probably does not exceed 17,000 feet in thickness where it enters the Lake Mary quadrangle on the north (see pl. 1), 3,000 feet or more of which lie outside the quadrangle to the west, and probably does not exceed 10,000 feet in thickness in the southern part of the Lake Mary quadrangle. All known outcrops of Hemlock formation have been mapped and are shown on plate 1. Symbols denoting lithologic types have been used, and no further discussion of the distribution seems warranted here. The locations of the upper and lower formation boundaries are, for the most part, inferred from airborne magnetometer data or data derived from magnetometer surveying on the ground. Positive magnetic crests as located by the airborne magnetometer are shown on plate 1 as red circles.

RELATION TO OTHER FORMATIONS

Black pyritic slate and chlorite schist have been interpreted as being the lowermost rocks of the Hemlock formation. These rocks lie with apparent conformity on the upper slate of the Randville dolomite. According to Gair and Wier (1956), the stratigraphic position of the Menominee group (middle Animikie of James, 1958) is between the Randville and Hemlock formations. Accordingly a disconformity of considerable magnitude may be present though not detected in the diamond drilling.

How the Hemlock is related to the overlying Michigamme slate in the Lake Mary quadrangle is not certain. A natural division between the two formations may be seen in the SW¼ sec. 15, and the NE¼ sec. 21, T. 42 N., R. 31 W., north of Peavy Pond. There, the Hemlock is represented by dark hornblende schist derived from mafic volcanic rocks. The dark schist forms prominent east-west striking ridges that give way abruptly to the south to irregular terrain and exposures of the Peavy Pond complex, which contain abundant xenoliths and pendants of siliceous schist and granulite derived from slates and graywackes and which probably represent the Michigamme slate. At two places in the NE¼ sec. 21, T. 42 N., R. 31 W. the two formations are found separated only by a narrow zone of gneiss ordinarily less than 50 feet in breadth. At these two places the formations appear structurally conformable. At other places in secs. 15 and 21, T. 42 N., R. 31 W., the gneiss occurs between the metagabbro of the complex and the schist formation of the Hemlock, and the Michigamme is represented by xenoliths deep within the metagabbro. These xenoliths appear not to have been greatly disturbed by the intrusion of the metagabbro. Iron-formation of the Amasa formation (James, 1958) that is present between the Hemlock and the Michigamme formations on the west side of the Amasa oval in the Crystal Falls quadrangle does not appear to enter the Lake Mary quadrangle. No rocks resembling iron-formation are known from the Peavy Pond area, nor is there any positive magnetic anomaly in the area comparable in intensity to the anomaly present where the iron-formation is positively known to occur. The absence of the Amasa formation suggests that the Hemlock and Michigamme formations are unconformable.

It was hoped to determine the position of the Amasa formation and the Hemlock-Michigamme contact under the cover of glacial deposits in the area between the Crystal Falls and the Lake Mary quadrangles by using a magnetometer (see pl. 3), but the results are not at all clean cut.

Anomaly *A* (pl. 3), is thought to continue to the northwest, where it is caused by iron-formation or associated rocks in the upper part of the Hemlock formation. In sec. 1, T. 42 N., R. 32 W., the anomaly lies within the volcanic terrain of the Hemlock. The abrupt termination of anomaly *A* at the quadrangle border in sec. 1 may indicate either lensing-out, nondeposition, erosion, or faulting of the magnetic rocks. It is possible that anomaly B^1 is the faulted extension of anomaly *A*. However, anomaly B^1 is tentatively correlated with anomaly B^2, which is probably attributable to magnetic schist in the lower part of the Michigamme slate—schist lying stratigraphically well above the Hemlock volcanic rocks in about the position of the post-Hemlock Amasa iron-formation to the northwest.

Allen and Barrett (1915) report that the post-Hemlock Amasa formation, which they considered equivalent to the Negaunee iron-formation, has been locally truncated by erosion and is overlain by conglomerate in the vicinity of Amasa, Mich., 12½ miles northwest of the Lake Mary quadrangle. Leith, Lund, and Leith (1935) state that this conglomerate has now been demonstrated by intermittent exploration along a belt nearly 10 miles in extent. An unconformity between the Hemlock and Michigamme formations is also postulated by Gair and Wier (1956) for the north adjacent Kiernan quadrangle. It is considered probable, therefore, that an unconformity of undetermined magnitude does exist at the Hemlock-Michigamme contact and that the post-Hemlock Amasa formation is absent, but there is no positive evidence in the Lake Mary quadrangle to support this view. The sparse scattering of outcrop in the critical area leaves ample room for a number of sizable rock units.

Anomalies *C* and *D* (pl. 3) lie in the upper part of the Hemlock formation and either might represent the extension of anomaly *A*, or they may be entirely different anomalies.

DESCRIPTION

In the Lake Mary quadrangle the Hemlock formation consists of 10,000–14,000 feet of altered basaltic lava flows, tuffs, agglomerates, and laminated slates of volcanic origin. In addition to the volcanic slates, which form thin, discontinuous lenses particularly associated with the ellipsoidal metabasalts, there are at least three rather persistent sedimentary slate belts of variable character within the formation. One of these, the Mansfield iron-bear-

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ing slate member (Van Hise and Leith, 1911, p. 295), contains a banded, cherty-siderite iron-formation from which ore has been mined at Mansfield location in sec. 20, T. 43 N., R. 31 W.

As noted previously, the Hemlock rocks have been altered by regional metamorphism, and locally by contact metamorphism. Four metamorphic facies are recognized: the greenschist facies, the albite-epidote-amphibolite facies, the amphibolite facies, and the pyroxene hornfels facies. Metamorphic facies used are those of Eskola as modified by Turner and Verhoogen (1951). Most of the Hemlock rocks are greenstones corresponding to the greenschist facies, but south of sec. 9, T. 42 N., R. 31 W., the regional metamorphic grade rises abruptly, and the Hemlock rocks south of that point are chiefly amphibole schist. Accordingly, the following brief description of the Hemlock rocks deals first with a variety of volcanic rock types conveniently lumped under the term "greenstone"; secondly, with the related slates and iron-formation; and finally, with the amphibolite schists and related rock types.

GREENSTONE

The distribution of greenstone outcrops is shown on plate 1. The outcrops are differentiated as to type wherever possible by map notations.

Flow rocks are chiefly metabasalt, including both nonamygdaloidal and amygdaloidal varieties, which have ellipsoidal phases. The mafic pyroclastic rocks are divided into tuff, volcanic breccia, volcanic conglomerate, and slate.

METABASALT

General features.—Approximately one-half of the Hemlock formation in the northern part of the Lake Mary quadrangle is made up of metabasaltic lava flows of varying character. Individual flows range from 10 to about 400 feet in thickness. Vesicular and ellipsoidal tops are common. A few flows seem to be ellipsoidal from top to bottom. In general the very dense or finely amygdaloidal metabasalt forms rather small pillows 1–2 feet in breadth, whereas in the coarsely amygdaloidal metabasalt pillows 5–6 feet in breadth are common. The larger pillows are invariably rather dense at the cores, and show a definite increase in the number of amygdales per unit volume of rock toward the outside border. Because of steep dips, many excellent exposures of pillow lavas in cross section may be seen in the north part of the quadrangle. Particularly good exposures occur both on the east and west sides of the Michigamme River at Mansfield location, and near the north quarter corner of sec. 19, T. 43 N., R. 31 W. The Hemlock pillow lavas are associated with laminated slate, slate, and banded chert-siderite, and are probably submarine in origin.

Description.—Outcrops of metabasalt are generally in shades of green or gray. Most of the rock is massive, and outcrops have glacially smoothed surfaces. Loose pillows and other fragmental material accumulate at the bases of many outcrop slopes. Fresh rock is ordinarily green or greenish gray, very hard, and generally aphanitic. Some of the metabasalt, however, show a very fine diabasic texture. Amygdaloidal varieties commonly have a dull greenish-brown aphanitic matrix. The vesicle fillings are white and reddish white if composed of quartz and calcite, and dark greenish brown if the filling is dominantly chlorite.

Texturally the metabasalt may be divided into two groups: the amygdaloidal rocks with a devitrified glass matrix, and the non-amygdaloidal rocks with basaltic textures. The minerals present, in decreasing order of abundance, are: actinolitic hornblende, sodic plagioclase, chlorite, clinozoisite, epidote, sphene, leucoxene, magnetite, stilpnomelane, quartz, apatite, and hematite.

Estimated modes of three specimens of metabasalt from the greenschist metamorphic facies of the Hemlock formation

	A (Specimen 173–52)	*B* (Specimen 27–51)	*C* (Specimen 69–52)
Actinolitic hornblende	46	41	45
Chlorite	2	2	Trace
Feldspar (albite)	3	38	30
Quartz	Trace	----	1
Epidote-clinozoisite	49	17	22
Biotite	----	Trace	----
Sphene	Trace	2	2
Total	100	100	100

Sodic plagioclase (An_5–An_{20}) forms microlites and laths with the growth habits typical of calcic plagioclase as exemplified by the diabasic and ophitic textures in the rocks. The feldspar ranges in amounts from mere traces to over 50 percent of the rock. Disregarding minor constituents, the original ratio of plagioclase to pyroxene was probably 50 : 50 in these rocks. The low albite count in some of the rocks as illustrated by mode *A* above is reflected in the high count of the chief alteration product, clinozoisite. Feldspar laths are considerably replaced by clinozoisite, epidote, and some chlorite; and some of the feldspar is deeply penetrated by adjacent fiibrous hornblende.

In view of the diabasic texture of the rocks and the nature of the feldspar alteration, it is probable that the albite was derive by metamorphic processes from a more calcic plagioclase, probably

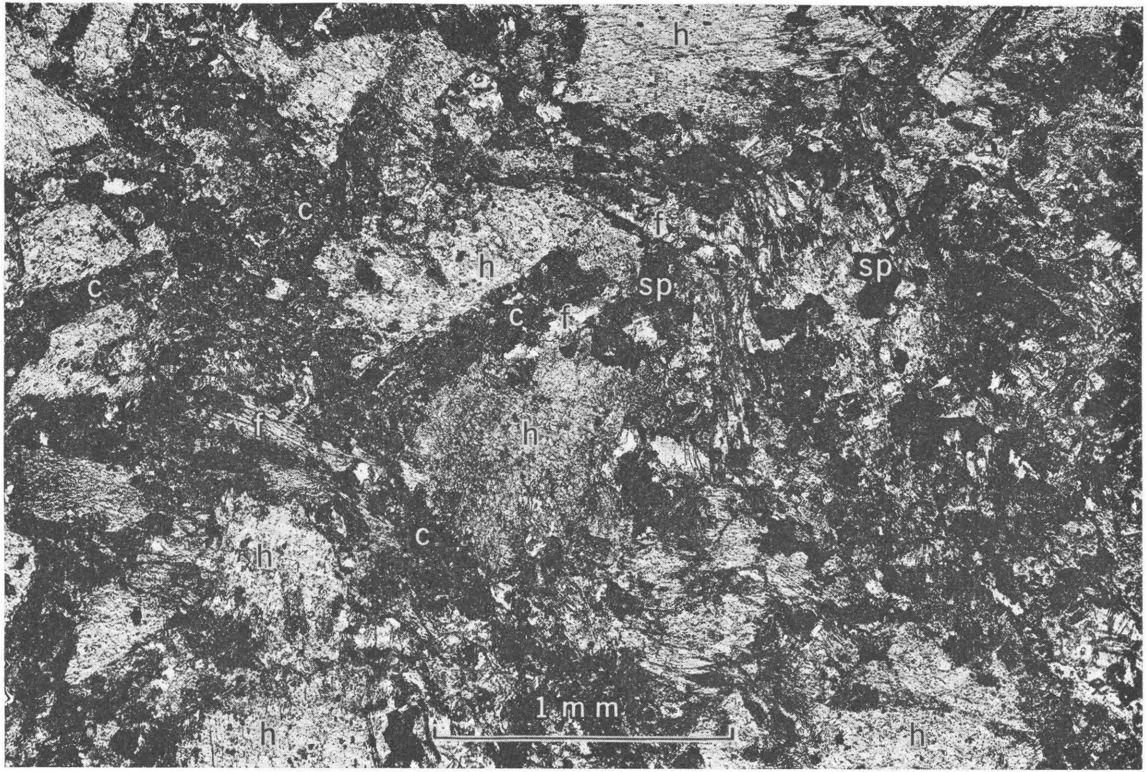

FIGURE 10.—Photomicrograph of micro-ophitic metabasalt. ×40, ordinary light. Composed chiefly of pale-green hornblende (*h*) in a matrix of clinzoisite (*c*), chlorite ,sphene (*sp*), and feldspar remnants (*f*). Specimen RB–172–52.

labradorite. The rocks are not spilitic. Twenty-three specimens of Hemlock and younger greenstones from areas adjacent to the Lake Mary quadrangle analyzed by J. M. Dowd of the U. S. Geological Survey for CaO, Na_2O, and K_2O have an average ratio of CaO to Na_2O of approximately 3 : 1, and an average of 0.836 percent K_2O by weight (Gair and Wier, 1956). Insofar as the partial analyses are indicative, they compare best with the analyses of tholeiitic basalts given by Turner and Verhoogen (1951, p. 180). The near 50 : 50 feldspar to mafic ratio, the diabasic and ophitic textures, and the lack of any discernible olivine, also indicate tholeiitic kindred.

Nonamygdaloidal varieties predominantly show distinguishable primary ophitic, diabasic, or microporphyritic textures. A typical specimen of this phase of the Hemlock is shown in figure 10. Modes for three specimens of metabasalt are given above.

The hornblende is very pale green. It forms anhedral individuals that fill voids around the feldspar laths, as in the diabases, or forms larger individuals that include feldspar laths, as in the ophitic rocks. The birefringence of the hornblende is moderate; pleochroism is weak in pale green and pale yellowish green, $Z>Y>X$. The maximum extinction angle $Z \wedge c$ equals 20°, the sign is negative, and $N_y < 1.642$. Simple twins, perhaps inherited from the original augite, are quite common.

Euhedral and anhedral clinozoisite is abundant in some specimens as an alteration mineral of the plagioclase. The clinozoisite is associated with lesser amounts of common epidote, chlorite, and acicular hornblende in the regular spaces originally containing the feldspar. Many clinozoisite individuals are zoned with an outer ferruginous zone of epidote; others show the interference colors of both epidote and clinozoisite on different parts of the crystal, probably representing a mixture of the two minerals. At the junction between plagioclase and hornblende crystals, epidote rather than clinozoisite commonly is present. Granular epidote also forms within the hornblende along with sphene, leucoxene, and some chlorite.

Chlorite is generally not an abundant constituent of the metabasalt, but is chiefly confined to the schistose pyroclastic rocks and devitrified glasses. A small to moderate amount of chlorite does occur in the metabasalt, developing concomitantly with hornblende as an apparent alteration mineral of the original pyroxene and calcic plagioclase. Some of the chlorite appears to have formed as an alteration mineral from the secondary hornblende. The chlorite is very pale green to green with variable birefringence. Anomalous brown as well as the ultrablue interference colors of penninite are common.

Sphene and leucoxene are generally present in small amounts. Rarely the original titaniferous iron ore occurs as a core surrounded by granular sphene, but more commonly the reaction has been completed. Some crystals are made up of laminations of fine granular sphene alternating with laminations of fine granular opaque iron ore, and the pattern produced by the laminae is rhombohedral, similar to the exsolution pattern of magnetite in ilmenite.

The minerals quartz, biotite, apatite, and stilpnomelane are present in most of the rocks, but only in accessory amounts. Olivine or alteration minerals indicative of olivine have not been identified in any of the metabasalt examined.

The amygdaloidal metabasalt differs from the nonamygdaloidal variety in that it contains abundant megascopic amygdales. Most of these lie in a very fine microlitic or devitrified glassy matrix. Mineralogically these rocks are the same as the nonamygdaloidal types with the exceptions that they generally contain some quartz, chlorite, carbonate, magnetite, and stilpnomelane. The groundmass texture is quite variable. Relatively coarse-grained varieties have intersertal or felty texture, whereas the very fine grained varieties are slightly devitrified glassy rocks with no obvious crystalline character, but some show perlitic structure. The general character of these rocks is illustrated in figure 11.

The specimen illustrated in figure 11 was collected from an ellipsoidal flow in the NW¼ sec. 28, T. 43 N., R. 31 W. The groundmass is devitrified perlitic glass composed chiefly of chlorite and fine-grained epidote. The vesicle fillings are concentrically zoned with quartz, and quartz and albite, and contain minor amounts of chlorite, epidote, clinozoisite, and stilpnomelane. Dark needles of stilpnomelane show plainly against the white of the central amygdale in figure 11. In some thoroughly recrystallized amygdaloidal rocks the original glassy matrix has recrystallized into a felty mat of feathery albite microlites with intergranular magnetite, sphene, chlorite, epidote, and stilpnomelane, but it still retains remnants of an original perlitic structure. The alteration minerals of the amygdales in descending order of abundance are pale-green chlorite, drab biotite, pale-green epidote (pistacite), sphene, and stilpnomelane. No two amygdales are alike; each may contain one or more of the above minerals in any combination. Some vesicles contain a core of euhedral epidote enveloped in a mantle of chlorite, perhaps indicating an original concentric structure of the vesicle filling, as illustrated in figure 11.

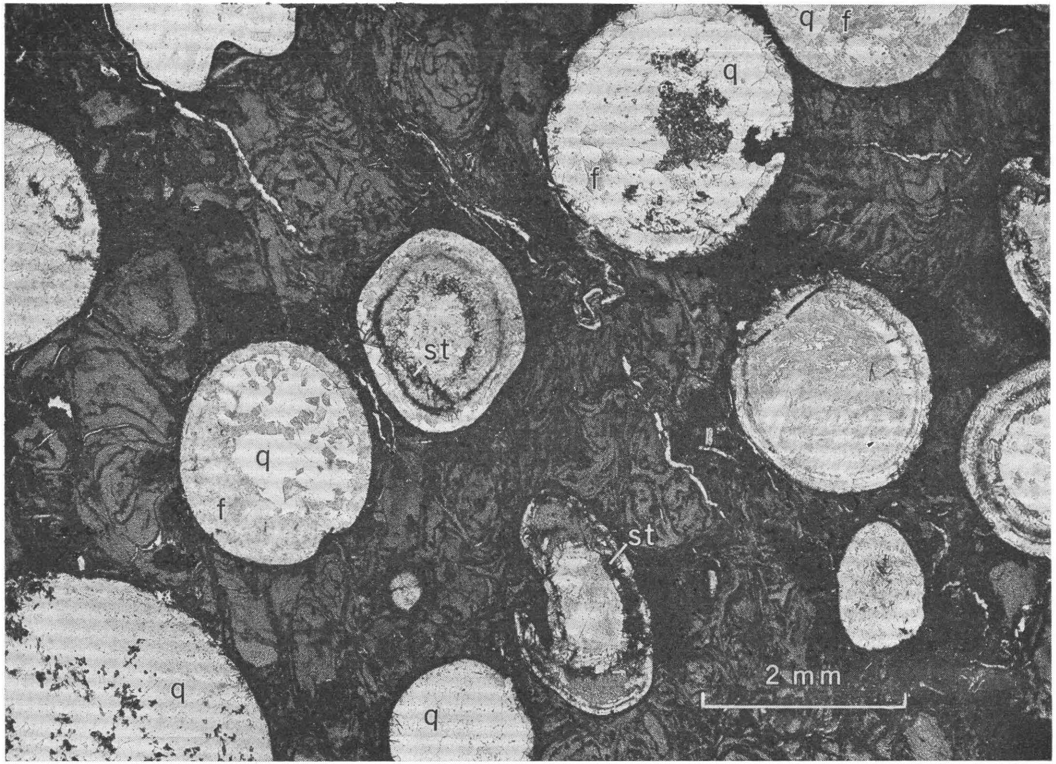

FIGURE 11.—Photomicrograph of amygdaloidal metabasalt. ×15, ordinary light. Showing devitrified perlitic groundmass and concentrically formed amygdales of quartz (*q*) and feldspar (*f*). Minute needles and plates of stilpnomelane (*st*) are visible in a few of the amygdales. Specimen RB–139–52.

An interesting mineral of secondary importance in these rocks is ferric stilpnomelane. The stilpnomelane forms very small needles and plates, pleochroic in golden yellow and brown and usually closely associated with chlorite. It is present in small amounts in most of the greenstone, especially the amygdaloidal variety, in the volcanic slate, in the intrusive sills, and in the iron-formation.

In the groundmass of the amygdaloidal rocks stilpnomelane forms discrete needles and plates that penetrate the other minerals. Its position relative to the amygdales is quite consistently at the outer borders penetrating in part the amygdale and in part the groundmass. Occasionally it forms concentric zones and streaks within the amygdales.

Magnetite is a constant companion mineral of stilpnomelane, but is noticeably diminished in quantity immediately adjacent to the stilpnomelane.

MAFIC PYROCLASTIC ROCKS

A major part of the Hemlock formation in the north of the Lake Mary quadrangle is composed of volcanic breccia and tuff, but thin beds of laminated, dark-colored slate, which are composed chiefly of detrital volcanic material, and a few beds of volcanic conglomerate are also present.

Volcanic breccia

The volcanic breccia forms a belt about 3,500 feet wide near the northwest border of the map area (pl. 1). The breccia belt extends from beyond the north border of the map southward to the NE$\frac{1}{4}$ sec. 36, T. 43 N., R. 32 W., where it is apparently offset to the west along a fault. In the adjacent Crystal Falls quadrangle, the breccia belt is warped toward the east and re-enters the Lake Mary quadrangle approximately at the center of sec. 1, T. 42 N., R. 32 W. From sec. 1 the belt extends southeast to the area of outcrop north of Peavy Pond, where it is represented by hornblende schist, which still retains outcrop characteristics of the breccia in the westernmost exposures. East and south of these exposures most of the original volcanic features of the rocks have been obliterated by metamorphism, and the rocks cannot be differentiated as to type.

The breccia is green to greenish gray to almost black. Outcrops are massive, rounded, and smooth; with "porphyritic" texture, if the rock is unsheared, or with slaty structure with a pitted surface, if sheared. The breccias are composed of dense angular to subangular greenstone fragments, which are microscopic in size in the pulverized chloritic matrix of the rock and as much as one-half meter in diameter in the coarser breccias. Accessible outcrops of the breccia occur along the north-south road on the west side of sec. 30, T. 43 N., R. 31 W., and at the inverted-Y trail junction in the center of the NW¼ sec. 19, T. 43 N., R. 31 W.

Tuff

Tuff beds occur at many places within the Hemlock formation, but they account for only a small percentage of the total thickness. The tuff is generally foliated rock, forming schistose and slaty greenstone, in contrast to the massive enclosing metabasalt, and is therefore easily distinguished in the field. Generally, the fragmental character of these rocks has been more or less obliterated by shearing. Mineralogically it differs from the metabasalt in that chlorite is abundantly present and hornblende is generally absent. Tuff of mixed felsic and mafic volcanic rock fragments, mineral grains, and sedimentary rock fragments, is particularly characteristic rock above the Mansfield iron-bearing slate member of the Hemlock formation at Mansfield location. Some of this rock is very coarse grained, and is described below as volcanic conglomerate. The mixed tuff occurs interbedded with ellipsoidal metabasalt and dark-colored slate. Accessible exposures are along the west edge of the north-south road in the SW¼ sec. 17, T. 43 N., R. 31 W. A specimen from these outcrops is illustrated in figure 12.

The rock is dark bluish gray and fine to rather coarse grained; it contains widely separated flat chips of black slate as much as 8 inches long, and occasional light-colored chert pebbles. The volcanic rock fragments vary in shape from sharp angular shards to well-rounded pebbles, and range in composition from metabasalt to metarhyolite. Slate and chert fragments and possibly graywacke fragments are present, as well as grains of quartz, feldspar, hornblende, epidote, and sphene. Many of the quartz grains are deeply embayed and probably originated in a rhyolitic rock. The specimen shown in figure 12 contains fragments of the following rock types:

Black slate, chert, graywacke(?)
Microporphyritic amygdaloidal metabasalt
Microlitic metabasalt
Melaphyre
Mafic glass
Diabasic metabasalt
Metarhyolite poryphyry
Perlitic felsic glass
Granophyre

The rounding of many of the rock fragments, the heterogeneous assortment, and the interbedding of slate and tuff, indicate that these tuff beds were probably water transported and deposited.

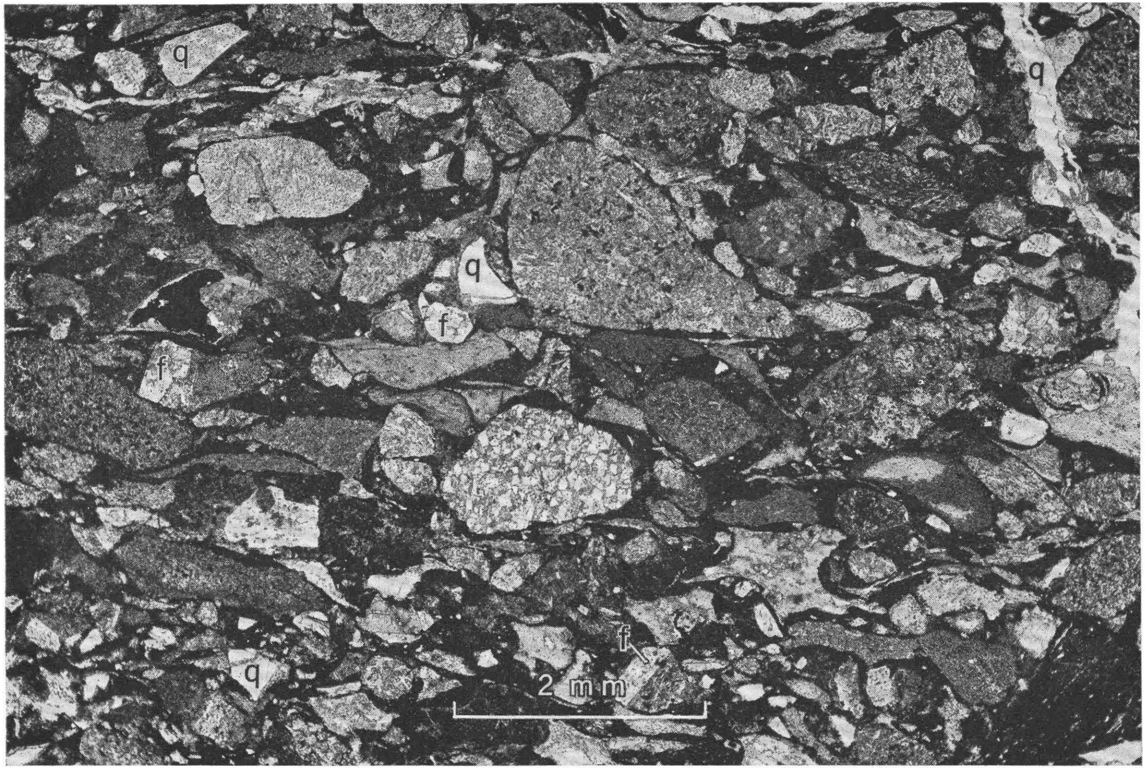

FIGURE 12.—Photomicrograph of greenstone tuff. ×17, ordinary light. Showing rounded fragments of a variety of volcanic rock types and grains of quartz (*q*) and feldspar (*f*) in a chlorite matrix. Specimen RB–81–52.

Volcanic conglomerate

Conglomerate composed of both volcanic and sedimentary rock types lies above the iron-formation of the Mansfield iron-bearing slate member of the Hemlock formation. The conglomerate is as much as 250 feet thick and has been traced along the strike from the north border of the map 3 miles south to the SE¼ sec. 31, T. 43 N., R. 31 W. The conglomerate is exposed and accessible at Mansfield location west of the road near the north border of the map, and on the dump surrounding the old main shaft of the Mansfield mine. This rock is also exposed on the east bank of the Michigamme River in the NW¼SW¼ sec. 29, and the SW¼SW¼ sec. 32, T. 43 N., R. 31 W., and on the west bank of the river in the NW¼ sec. 32, T. 43 N., R. 31 W. Most commonly, the conglomerate lies immediately above the iron-formation, though in some places it is separated from the iron-formation by chloritic greenschist or by gray or black pyritic slate. Dark quartzose graywackelike rocks are interbedded with the conglomerate and occur also as fragments within the conglomerate in the northern part of the belt.

The conglomerate is commonly gray green to blue green and is composed chiefly of moderately rounded greenstone fragments, which are under 1 inch in diameter, in a chloritic matrix. Subangular blocks of light-colored platy chert are dispersed throughout the greenstone matrix. The chert fragments are as much as 1 foot in length, and some of them are layered with hematite. A few larger blocks of contorted, interbedded green slate and graywacke occur. Thin interbeds of slate and graywacke similar to the included blocks are interlayered with the conglomerate.

The chert fragments were undoubtedly derived from the underlying iron-formation. The slate and graywacke beds appear to have been deposited at intervals within the conglomerate, and some of the early formed beds were apparently dismembered and contorted by slumping of the conglomerate.

The green slate and graywacke included in the conglomerate are composed predominantly of quartz and chlorite. Layers are from a few millimeters to 2–3 centimeters thick; the slaty layers contain finely comminuted quartz in a chlorite matrix and the coarser graywackelike layers contain well-rounded metamorphic quartz with undulatory extinction lying in a sparse matrix of chlorite and calcite. A few quartz aggregates probably representing rock fragments are also present, as well as a few rounded grains of perthitic feldspar and zircon.

The conglomerate in the northern part of the quadrangle is composed chiefly of volcanic rock types and is gradually replaced by quartzose, slaty sedimentary rocks toward the south. In the area about the Scadden exploration, including the SE¼ sec. 31, the SW¼ sec. 32, T. 43 N., R. 31 W., and the NW¼ sec. 5, T. 42 N., R. 31 W., the lithologic change in the conglomerate and associated rocks is so abrupt along the strike of the formation that only by reference to the iron-formation and a key rock type below the iron-formation, can the proper relation of the overlying rocks tc the iron-formation be determined.

In the SE¼ sec. 31, the first 250 feet of rock above the iron-formation includes oxidized and unoxidized chloritic schist, sheared green conglomerate, massive greenstone, and laminated quartzose gray slate. The greenschist is in the lower part of the section near the iron-formation; the gray slate forms thin breaks in the conglomerate. The conglomerate is green to gray, and is composed of platy and lenticular fragments an inch or less in length lying parallel to a bedding-plane foliation. The rock fragments are all very fine grained, composed chiefly of granoblastic quartz, biotite, and chlorite. The conglomerate matrix is chiefly chlorite. A quarter of a mile to the south in the NW¼ sec. 5 the conglomerate is absent. Gray pyritic slate similar to that interbedded with the conglomerate to the north is present, but in sec. 5 this slate is interbedded with a variety of slate not present with the conglomerate to the north. This rock is light-colored quartzitic, sericitic, and pyritic clay slate. Much of this slate is ferruginous throughout, but some of it contains alternating red ferruginous layers and light-gray nonferruginous layers. The rocks below the iron-formation in both sec. 31 and sec. 5 are distinctive quartz-chlorite schist with metacrysts that are now kaolin or muscovite. This schist is limited to a position immediately below the iron-formation. The schist and the iron-formation in conjunction form the basis for correlating the partly unlike rocks lying above the iron-formation of sec. 31 and sec. 5. There are no exposures of these upper rocks, natural or otherwise, between the two locations cited, and the relation of the slate to the conglomerate that apparently replaces it along the strike is unknown.

It is difficult to evaluate the erosion of the iron-formation of the iron-bearing slate member of the Hemlock formation in terms of time or tectonic significance. The former of these is most uncertain, but some facts concerning the latter can be deduced from the nature of rocks that overlie the iron-formation. First, the clastic rocks immediately above the iron-formation are slate, graywacke, tuff, and volcanic conglomerate, none of which show structures that would be expected in fluviatile or shallow marine sediments.

On the other hand, these rocks are interbedded with ellipsoidal metabasalt, probably of submarine origin. Some of the tuff and graywacke beds show graded bedding, and the volcanic conglomerates show contorted slump structures—structures generally associated with submarine sedimentation; second, both the tuff and the volcanic conglomerate are composed of fragments of volcanic rock types foreign to the Lake Mary quadrangle and, as far as known, the adjacent areas, indicating transport over a considerable distance; and third, the angularity of the iron-formation and slate fragments and the small amount of such fragments in the rocks overlying the iron-formation indicates probably minor erosion of the iron-formation and short transport of the eroded material.

The facts cited suggest strongly that both the erosion of the iron-formation and the deposition of the overlying clastic rocks are the product of submarine agencies—that is, slides of unconsolidated materials and turbidity currents (Kuenen, 1950).

The remarkably rapid lateral change from conglomerate to slate in the rocks above the iron-formation in sec. 32, T. 43 N., R. 31 W., and sec. 5, T. 42 N., R. 31 W. (see p. 38), is an understandable phenomenon if it is assumed that the conglomerate was emplaced by submarine sliding. However formed, the conglomerate cannot be demonstrated to have more than very local significance.

Volcanic slate

Although dark-colored banded slate composed of mafic volcanic material has been mapped at a number of places within the area of greenstone of the Hemlock formation, it is best exposed in the greenstone ridges east of the Michigamme River at Mansfield location in sec. 20, T. 43 N., R. 31 W. The slate forms beds that are from a few feet to over 100 feet thick and are interlayered with flows of ellipsoidal metabasalt (see pl. 1). An exceptionally thick slate bed has been traced for over 1,000 feet along the strike, but this is unusual, for most of the slate beds are lenticular and generally persist for less than a few hundred feet along the strike. The slate was apparently deposited in low spots on the irregular flow surfaces.

The slate is greenish gray to black, dense, very hard, and laminated, with alternating light and dark layers 1–2 cm thick. It is composed chiefly of chlorite. In the chlorite are scattered microlites of brown biotite, silt-size quartz and albite, and numerous tiny flecks of leucoxene. The layering is caused by very slight changes in grain size within the rock.

SLATE AND IRON-FORMATION

EAST SLATE BELT

There are at least three sedimentary slate members within the Hemlock formation in the Lake Mary quadrangle. A slate member east of the West Kiernan sill forms a belt 1,200–1,500 feet wide that trends approximately south through secs. 16, 21, 28, and 33, T. 43 N., R. 31 W. The ground underlain by the slate is typically low and swampy, but there are three equally spaced, till-veneered bedrock highs along the belt where the slate crops out or has been reached in shallow test pits. A variety of slate types are represented in the belt. Gray, red, and gray-banded clay slate and graphitic and pyritic dark slate crops out at the edge of Highway 69; gritty quartzose slate, colored red by iron oxide, occurs on test pit dumps in the SE¼ sec. 28, T. 43 N., R. 31 W.; partly oxidized platy red and gray clay slate was penetrated in a pump-house excavation in sec. 16, T. 43 N., R. 31 W.; a thoroughly oxidized pyritic slate was found in the dump of a deep test pit in the SE¼ sec. 21, T. 43 N., R. 31 W. According to Dwight M. Lemmon (U. S. Geol. Survey, written communication)—

> The test shaft (in sec. 21) was sunk by Nestor Hill and E. J. Dundon sometime between 1940 and 1944. Mr Hill reported that the shaft was 85 feet deep, with about 145 feet of workings from the bottom. The dump is composed of well-oxidized, earthy red slate with a few bands of quartz which probably represent recrystallized chert. The slate contains abundant hematite pseudomorphs after pyrite. * * * Red and gray slates are exposed on the dumps of many small pits dug at short intevals to 750 feet west of the main shaft. Greenstone tuff is exposed on the dump of a pit a short distance southwest of the main shaft. About 650 feet east of the shaft, red slates were found in a well dug beneath the cow barn at the Hill farm.

The area of test pits mentioned above is now under cultivation, and only material from the main shaft was examined by the writer.

MANSFIELD IRON-BEARING SLATE MEMBER OF THE HEMLOCK FORMATION

Distribution.—The Mansfield iron-bearing slate member of the Hemlock formation lies west of the West Kiernan sill, and is more or less confined to the valley of the Michigamme River. As interpreted here, this member includes two distinct units: a thick-bedded pyritic gray slate that makes up the lower part of the member, and an altered chert-siderite iron-formation that makes up the upper part of the member. Volcanic conglomerate, tuff, and associated slate overlying the Mansfield are included in the upper member of the Hemlock formation.

The distribution of the Mansfield iron-bearing slate member, as deduced from available exploration data and some new data from magnetic surveying, is shown on plate 1. Clements (Clements and Smyth, 1899, p. 65) estimated the maximum thickness to be about 1,900 feet, but diamond drilling completed since the publication of the early monograph indicates that the maximum thickness may be closer to 500 feet, and the average thickness only about 200 feet. The maximum known thickness is at Mansfield location, where 200 feet of gray pyritic slate has been separated from the lower part of the member by a tongue of the West Kiernan sill. From Mansfield location southward, the lower slate unit of the member is progressively cut out by the West Kiernan sill and disappears completely in the NW¼ sec. 29, T. 43 N., R. 31 W. (pl. 1). In the same region, the iron-formation that is 20–30 feet thick in the vicinity of Mansfield location thickens to about 100 feet. From the NW¼ sec. 29 south to the vicinity of the SW¼ sec. 32, T. 43 N., R. 31 W., the iron-formation rests on, or is intruded and split by the West Kiernan sill (pl. 4). In the latter area the iron-formation continues to increase in thickness, reaching a maximum of about 150 feet in the NE¼SE¼ sec. 31. From the point of maximum thickness, the iron-formation dwindles sharply to the south along the strike, and is only about 30 feet thick where it is last seen in the NW¼ sec. 5, T. 42 N., R. 31 W. (pls. 5 and 6). The lower slate is exposed again in the SW¼ sec. 32, separated from the iron-formation by about 100 feet of greenstone and tuffaceous greenschist. The total thickness of the Mansfield iron-bearing slate member in its southernmost exposures in sec. 5 is probably near 500 feet. No information now available would justify extending this member to the southeast beyond sec. 5, T. 42 N., R. 31 W.

Description.—Most of the slate of the iron-bearing slate member of the Hemlock formation is normal gray to black clay slate, thinly laminated to thickly bedded, and commonly megascopically pyritic. It is composed chiefly of very fine grained white mica and chlorite accompanied by quartz, pyrite, rutile, and a small proportion of ferruginous and carbonaceous material. The texture is generally microschistose. Spotted slate occurs 10–15 feet above the top of the West Kiernan sill in the NE¼SW¼ sec. 20, T. 43 N., R. 31 W. This slate is similar in structure to metamorphosed slate from secs. 7 and 8, T. 43 N., R. 31 W., referred to as "spilosite" by Clements (Clements and Smyth, 1899, p. 206). The spotted slate consists of alternating layers of chloritic green slate and carbonaceous black slate only a few inches thick. Locally the color is gradational between bands. Both black and green layers are speckled with white streaks and eye-shaped spots 1–6 mm long, which are roughly parallel and plunge about 10°–15° in the plane of foliation. Some undeformed spots retain sharp lath shapes, which probably represent the original shape of all of the deformed spots. The white spots in the dark matrix so distinctly defined megascopically, are much less distinct in thin section. The texture of the rock is microschistose, and there is a pronounced differentiation of the light and dark constituents into clumps that give the rock a very mottled appearance. The minerals are all very fine grained. The dark areas are composed chiefly of chlorite with minor amounts of quartz, white mica, and anhedral rutile; whereas the light-colored areas—the white spots in hand specimens—are composed chiefly of white mica and a scattering of chlorite and anhedral rutile. The white spots presumably represent porphyroblasts, probably sodic plagioclase originally, that were produced in the slate as contact effects of the West Kiernan sill. Subsequently they were deformed and altered to mica and chlorite during later regional metamorphism.

The upper iron-bearing strata of the Mansfield iron-bearing slate member of the Hemlock formation are quite variable in appearance and mineralogy, chiefly because of different degrees of metamorphism and weathering of a banded cherty or slaty, sideritic iron-formation. Ferruginous quartzite is present, but in a very subordinate amount. Unoxidized and relatively unmetamorphosed iron-formation is known only from diamond drilling. The unaltered formation is typically dark brown to brownish gray, finely laminated with alternating light- and dark-colored layers as much as 2 inches thick. The dark layers are composed of very fine, granular, iron-rich carbonate, commonly mixed either with tiny clear grains of quartz, representing recrystallized chert, or with clay minerals. The light-colored layers are predominantly fine, granular, recrystallized chert, but most contain a small amount of carbonate. With increase in the amount of clayey material the rocks become sideritic slate strictly analogous to similar facies in calcitic or dolomitic formations.

For most of its known length, the iron-formation lies close to, and has been variously metamorphosed by contact with, the West Kiernan sill. The degree of metamorphism is a function of the distance from the sill, though the breadth of the zone of affected rocks does not exceed a few hundred feet. Ferric stilpnomelane is one of the first minerals formed during the metamorphism. It occurs alone as metacrysts in some slightly altered rocks, but more commonly in association with magnetite, and these two minerals may make up 1–90 percent of the rock, depending on the completeness of the adjustment. A typical specimen of stilpnomelane-bearing iron-formation is shown in figure 13.

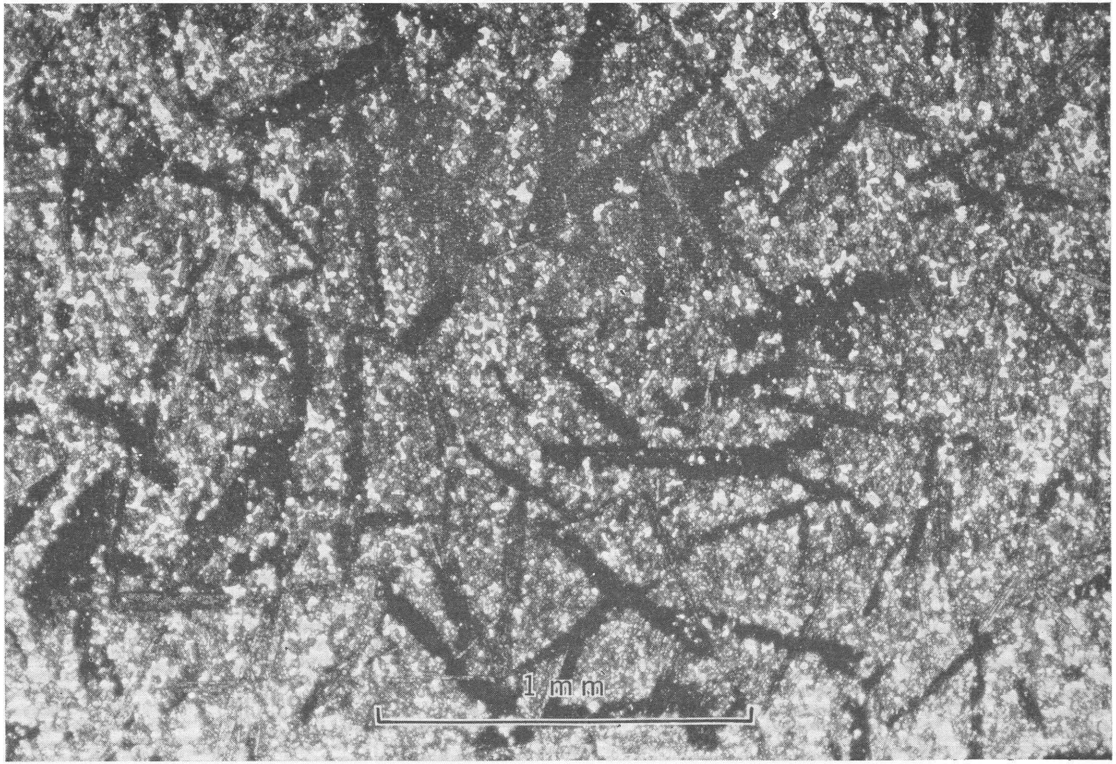

FIGURE 13.—Photomicrograph of chert-carbonate iron-formation with metacrysts of stilpnomelane. ×50, ordinary light. Specimen RB–44–52.

Iron-formation lying very close to the West Kiernan sill or included in the upper part of the sill differs from the moderately metamorphosed rocks described above in that grunerite is the prominent silicate mineral present rather than stilpnomelane. The associated minerals present are magnetite, stilpnomelane, and quartz. Estimated modes of two specimens of these rocks are as follows:

	Specimen	
	RB–102–52	*RB–102A–52*
Grunerite	69–80	87–90
Magnetite	18–28 (0.08–0.13 mm)	2–5
Stilpnomelane	1	2–5
Quartz	1–2	6

The two specimens whose modes appear above, are illustrated in figures 14 and 15. The original layering of the rock is retained and emphasized by the alternation of layers rich in magnetite with layers rich in the light-colored grunerite.

Oxidation and iron enrichment concomitant with the leaching of silica in the zone of weathering have proceeded from the surface downward to variable depths all along the iron-formation belt. The resultant rocks are all hematite red or brownish red and include ferruginous chert, banded light-colored chert and hematite, hematitic iron ore, earthy ferruginous slate, and soapy ferruginous schist. Although the iron-bearing rocks have been quite extensively prospected, ore in commercial quantity has been found only at the Mansfield location, where 1,462,504 tons of high-grade ore was mined between the years 1890 and 1913 by the DeSoto Mining Co. and the Oliver Iron Mining Co. For a detailed description of the Mansfield mine, the reader is referred to the description given by Clements (Clements and Smyth, 1899, p. 65–73). According to Clements (Clements and Smyth, 1899, p. 69)—

The ore varies from soft limonitic hematite to a moderately hard hematite. It is for the most part opaque under the microscope, but in places shows bright-red to brownish-red color in transmitted light. In incident light the ore for the most part shows a dull-brown or reddish color, though in places it has a bright metallic reflection. In places in the ore are spots, in which is a large quantity of chert mixed with iron oxide. As such ferruginous-chert areas increase in quantity the ore grades into ferruginous chert and chert which is found associated with it in bands and lenticular areas.

The composition of the ore representing the average of a number of analyses is given by Clements (Clements and Smyth, 1899, p. 69.) as metallic iron, 64.80; phosphorus, 0.037; and silica, 3.70. Ore mined at Mansfield from the lower levels of the mine in the years after the publication of Monograph 36 (1899) contained a higher percentage of phosphorus.

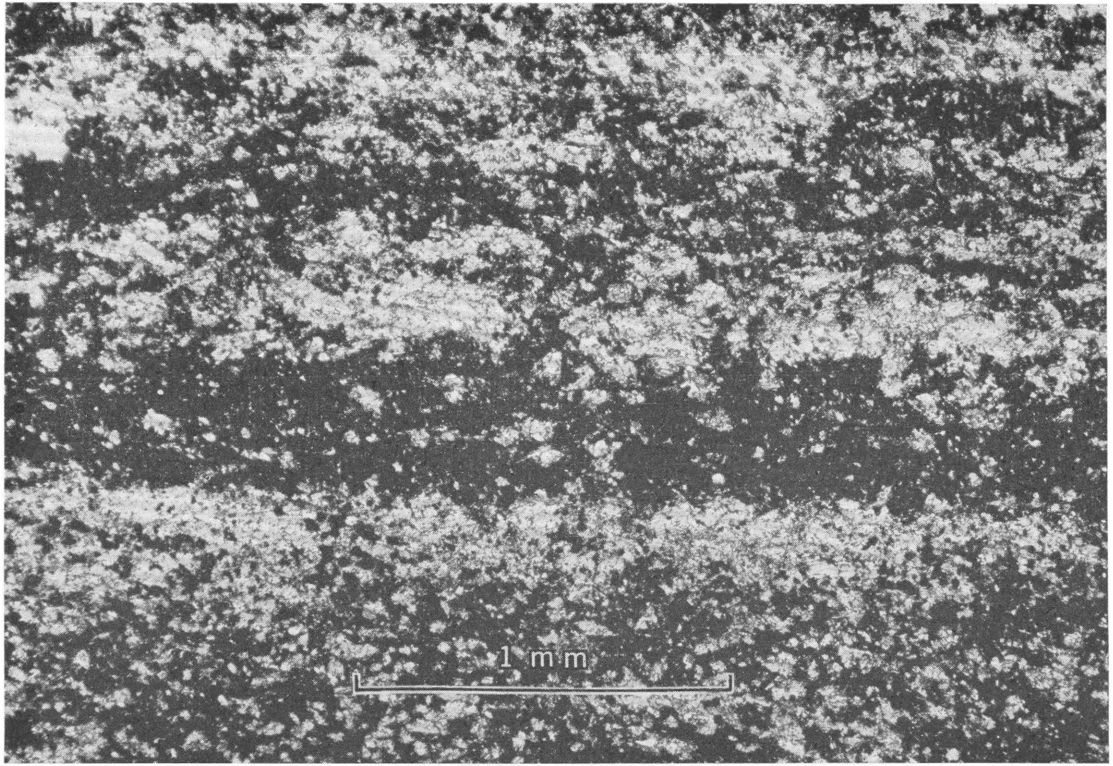

FIGURE 14.—Photomicrograph of magnetite-grunerite hornfels. ×50, ordinary light. Showing magnetite-rich layers (dark) containing minor amounts of grunerite and quartz, alternating with grunerite-rich layers (light). Specimen RB–102–52.

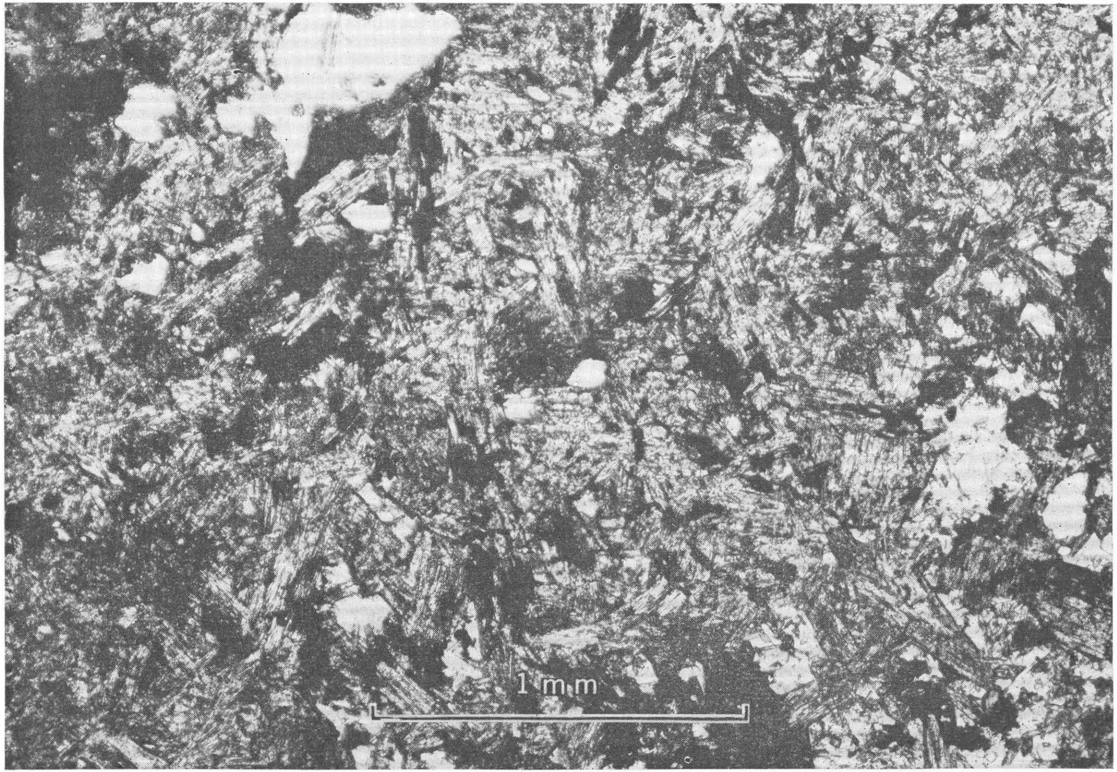

FIGURE 15.—Photomicrograph of grunerite-magnetite hornfels. ×50, ordinary light. Matted prismatic grunerite with a small amount of quartz and fine-grained euhedral magnetite. The grunerite is idiomorphic against the quartz which fills in around the prismatic crystals. Specimen RB–102a–52.

METAVOLCANIC ROCKS OF THE PEAVY POND AREA

South of sec. 9, T. 42 N., R. 31 W., the Hemlock formation is represented by hornblende schist, hornblende-garnet schist, and hornblende or pyroxene hornfels. These rocks crop out in prominent ridges north and east of Peavy Pond. The original rocks are believed to have been basic volcanic breccia and tuff for the most part, but include a minor quantity of associated basaltic flow rock.

Outcrop ridges are steep and rugged. The rocks are dark green to greenish black and fine grained; they are generally well foliated, and commonly show a distinct linear arrangement of the prismatic hornblende. The rocks may be divided into three metamorphic facies: albite-epidote-amphibolite, amphibolite, and pyroxene hornfels (Turner and Verhoogen, 1951). The two lower facies are regional and cover a broad area not confined to the Lake Mary quadrangle (James, 1955), but the hornfels fringes younger intrusive rocks and must be considered a product of contact metamorphism.

ALBITE-EPIDOTE-AMPHIBOLITE FACIES

In the albite-epidote-amphibolite facies are included rocks with mineral combinations as listed below:

Hornblende-albite-quartz-chlorite-magnetite-sphene
Hornblende-albite-quartz-magnetite-sphene
Hornblende-albite-quartz-chlorite-epidote-magnetite-leucoxene
Hornblende-sericite-epidote-clinozoisite

These rocks are all hornblende schist composed of fine-grained closely packed needles of blue-green hornblende and interlamellar, inclusion-loaded albite or oligoclase, and subordinate quartz. Accessory minerals are epidote, clinozoisite, calcite, sphene, sericite, chlorite, and magnetite.

The hornblende is pleochroic in blue green, pale green, and pale yellowish green, $Z > Y > X$. N_y for average of three specimens is 1.654 and $Z \quad c\ 16° - 17°$.

In some of the rocks assigned to the albite-epidote-amphibolite facies the albite has been slightly sericitized or chloritized, and it is possible that the albite may have been derived by retrograde metamorphism from a more calcic metamorphic plagioclase. Therefore, some of the rocks assigned to this facies on their present mineralogy may rightfully belong in the higher grade amphibolite facies.

AMPHIBOLITE FACIES

The transition from the albite-epidote-amphibolite facies to the amphibolite facies is most readily apparent in thin section, the general appearance of the rocks in the the outcrop being similar.

In thin section the general tendencies with increased metamorphic grade are toward the diminution of chlorite, and epidote, the development of twinned individuals of clear plagioclase (An_{12}–AN_{49}) and the development of clearer, darker colored, and more strongly pleochroic blue-green hornblende with higher indices of refraction. In one specimen included in this group, the plagioclase (An_{35}) shows continuous normal zoning. Two specimens contain garnet (fig. 16).

The hornblende is well crystallized. The pleochroism is in blue green, green, and greenish yellow, $Z>Y>X$, stronger than that of the hornblende of the epidote-amphibolites. The 2V is moderate, $Z \wedge c$ $16\frac{1}{2}°-20°$, and N_y average for three specimens is 1.677, representing a considerable increase over the 1.654 determined on the hornblende of the lower grade schist. According to Wiseman (1934), who studied the effects of metamorphism on the optical and chemical properties of hornblende, the increase in index is due chiefly to chemical changes that the hornblende undergoes concomitant with the disappearance of chlorite with increasing metamorphic grade. Also according to Wiseman, the chemical composition of hornblende from the garnet zone when compared to the composition of hornblende from the chlorite and biotite zones, shows an increase in Al (Al replaces Si and Mg), a higher ratio of FeO to MgO, and a decrease in Ca caused by an increase in alkali elements.

Hornfels

Hemlock mafic volcanic rocks intricately intruded by, or immediately adjacent to, gabbroic bodies of the Peavy Pond complex commonly are altered to hornblende-plagioclase hornfels, hornblende-pyroxene-plagioclase hornfels, and pyroxene-plagioclase hornfels. Within this group of rocks there is a transition from hornblende hornfels through hornblende-pyroxene hornfels to pyroxene hornfels. Some of the pyroxene hornfels has been altered again to hornblende hornfels.

The hornfels of the amphibolite facies is a fine-grained equigranular rock composed chiefly of hornblende, andesine, and a moderate amount of diopsidic pyroxene. Hornfels of this facies occurs in the NE¼SE¼SW¼ sec. 15, T. 42 N., R. 31 W., close to the gabbro of the Peavy Pond complex, and at several places in the NE¼ sec. 28, T. 42 N., R. 31 W., close to small bodies of intrusive gabbro. A typical hornblende-plagioclase hornfels is shown in figure 17. Well crystallized brownish-green hornblende in short prismatic individuals 0.2–0.3 mm long makes up 50–75 percent of the rock. In general, the colors of the hornblende are brighter and deeper than in the hornblende of the lower grade

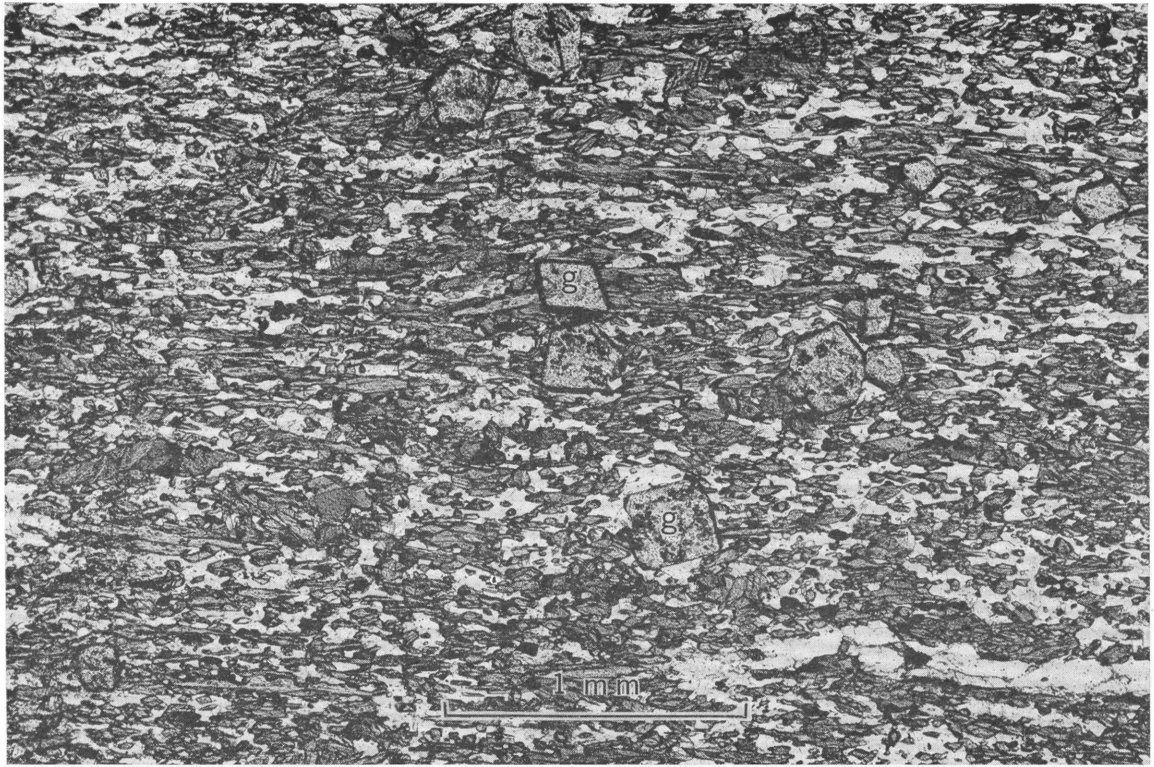

FIGURE 16.—Photomicrograph of hornblende-garnet schist. ×40, ordinary light. Minerals, blue-green hornblende (gray), plagioclase and quartz (white), and garnet (*g*). From NE¼SW¼ sec. 22, T. 42 N., R. 31 W. Specimen RB–65–51.

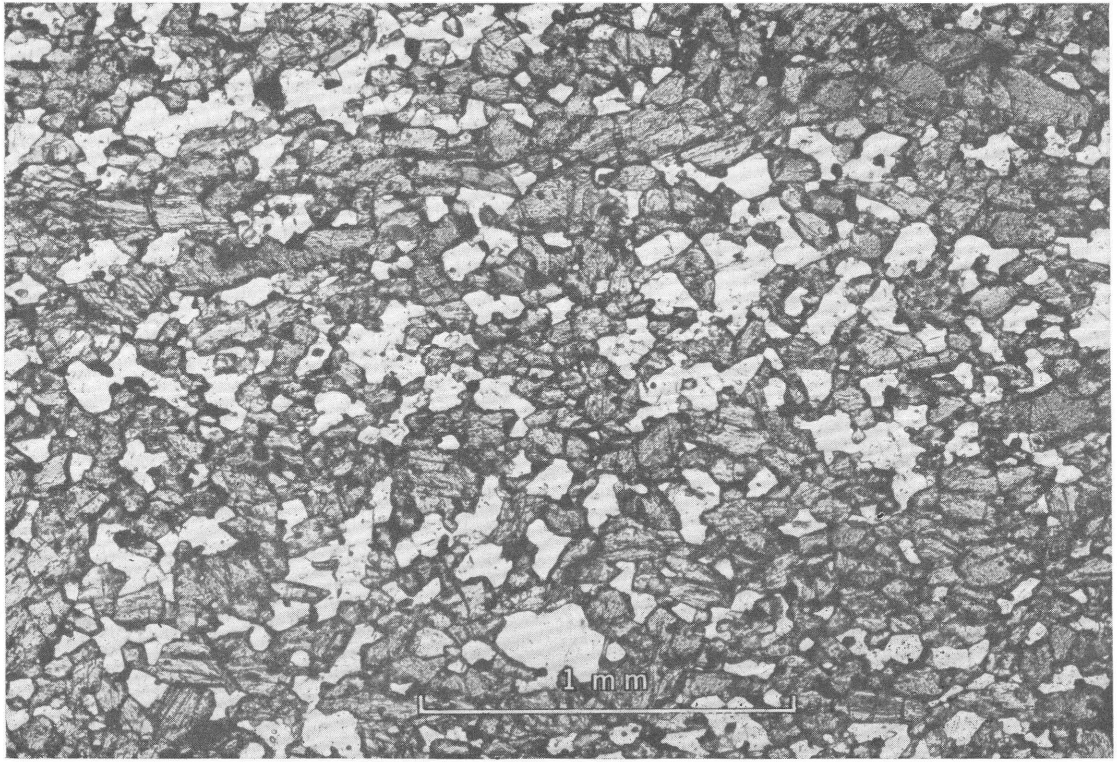

FIGURE 17.—Photomicrograph of hornblende-plagioclase hornfels. ×50, ordinary light. Composed of blue-green to brownish-green hornblende, andesine, and a little biotite. Specimen RB-219-52.

rocks, and are usually tinged with brown; $Z \wedge c$ is 15°–18°, and N_y is 1.675 for one specimen. Andesine (An_{30}–AN_{40}) forms irregularly shaped interlocking grains and blocky, equidimensional twinned crystals that commonly show continuous normal zoning. Some of the andesine grains show a discrete euhedral core zone of higher index than the mantling zones, but most grains extinguish in a continuous sweep to a dark central point.

Pyroxene, where present, is colorless diopside with a distinct basal parting. It may be present in small amounts in irregular grains or in larger individuals as metacrysts. The diopside invariably shows partial replacement by hornblende that is similar to the hornblende making up the bulk of the rock. For this reason it is usually impossible to tell how much pyroxene the rock may have contained. Accessory minerals present in the hornfels are chiefly magnetite and sphene.

PYROXENE HORNFELS FACIES

Included in the pyroxene hornfels facies are fine- to medium-grained rocks in SW¼ sec. 14 and NE¼ sec. 28, T. 42 N., R. 31 W., where the mafic volcanic rocks of the Hemlock have been intimately intruded by gabbro. The texture of the rocks is fine- to medium-grained hornfelsic, locally with metacrysts of plagioclase. The minerals present are diopsidic pyroxene, andesine (An_{40}–An_{50}), orthopyroxene, tremolite, hornblende, biotite, chlorite, epidote, sericite, and magnetite. Hornfels showing no traces of retrograde metamorphism contains only diopside, andesine, hypersthene or enstatite, and magnetite (fig. 18). Diopside and andesine are present in nearly equal amounts and together constitute over 90 percent of the rock. Pale-pink hypersthene is present in very small quantities, usually in anhedral individuals somewhat larger than the background minerals, and commonly situated close to the plagioclase metacrysts. In 1 or 2 specimens, rounded and colorless euhedral enstatite takes the place of the hypersthene.

All of the pyroxene hornfels shows some degree of replacement by hornblende. The alteration hornblende is pale green to drab brownish green or dark brown. Two distinct variations of the hornblende replacement occur: (1) pale-green to greenish-brown hornblende replaces the hornfelsic diopsidic pyroxene without disturbing or altering the adjacent andesine crystals, and (2) deep-brown hornblende forms large poikiloblastic metacrysts enclosing and partly or completely assimilating the andesine crystals. The hornblende metacrysts have irregular outlines and partly assimilated andesine within the metacrysts is charged with

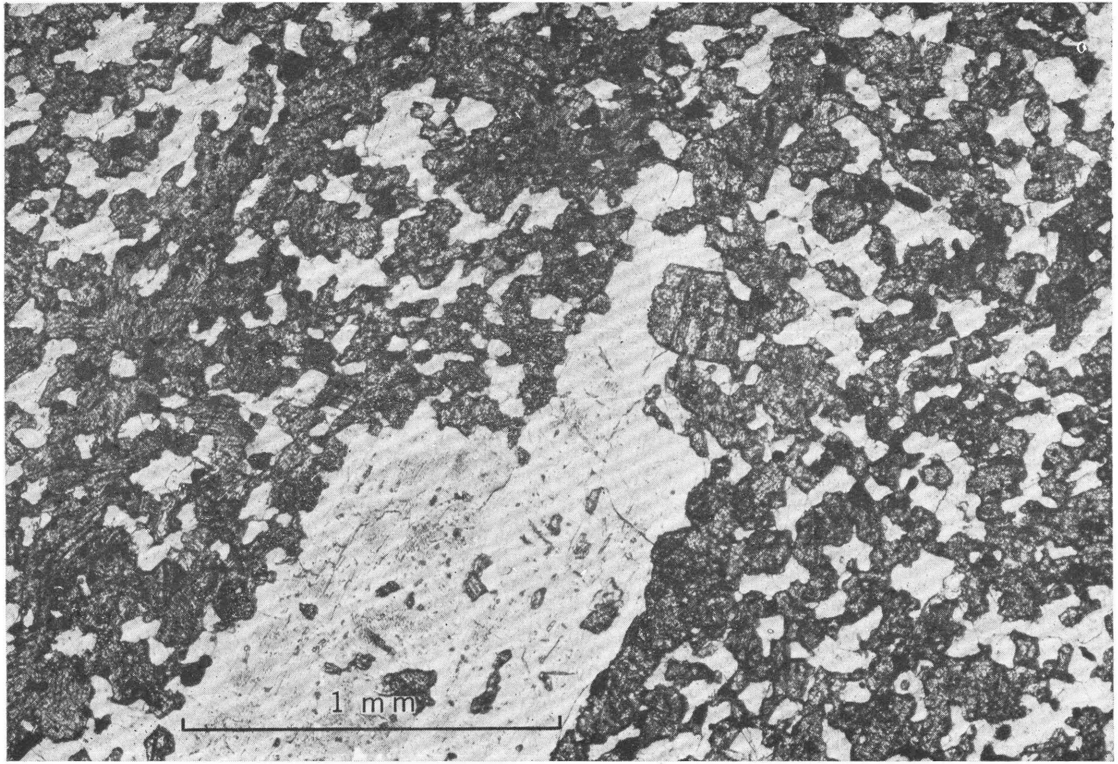

FIGURE 18.—Photomicrograph of a porphyroblastic pyroxene-plagioclase hornfels. ×50, ordinary light. Minerals, chiefly diopsidic pyroxene (dark gray), andesine (An_{45}), and magnetite. A small amount of hypersthene and alteration hornblende present. From the SW¼ sec. 14, T. 42 N., R. 31 W. Specimen RB–216–52.

fine sericite and surrounded by colored halos. In some hornblende metacrysts all of the included andesine has been assimilated and only the halos remain. In some specimens, deep-brown biotite, similar to the hornblende in habit and relations to the other minerals of the rock, forms metacrysts along with the brown hornblende. Both the biotite and the hornblende of the metacrysts are charged with abundant opaque oriented needles, some of which have been determined to be rutile.

Very small quantities of fibrous tremolite, actinolite, and possibly serpentine occur as alteration products of the orthopyroxene.

MICHIGAMME SLATE

The Michigamme slate consists characteristically of pelitic slate and graywacke. It was named Michigamme formation for island exposures of these rocks in Lake Michigamme of the Marquette district by Van Hise and Bayley (1897, p. 598). The formation was referred to as Michigamme slate by Van Hise and Leith (1911), and this has been its formal name since that time.

Outcrops other than inclusions in igneous rocks are generally low, broadly rounded, and difficult to see in the field. Accessible exposures occur along the road in the west part of sec. 19, T. 42 N., R. 31 W., along the north shore of Peavy Pond in the NE¼ sec. 30, T. 42 N., R. 31 W., and particularly at the Peavy dam just south of the quadrangle in sec. 32 T. 42 N., R. 31 W.

The thickness of the formation cannot be determined in this area, but it is probably 5,000 feet or more.

Within the quadrangle the rocks of the Michigamme slate are chiefly schist and granulite, the metamorphic equivalent of pelitic and quartzose slate and graywacke. Most of the rock is light colored, reddish buff to gray. Alternating relatively coarse and fine beds and graded beds are conspicuous features retained by these rocks. Composition differences between beds effectively controls the metamorphic mineral assemblages (fig. 19).

A short distance away from the immediate area of the Peavy Pond complex, the metasedimentary rocks of the Michigamme are chiefly schist, which is well foliated parallel to the bedding. Much of the foliated rock, especially in sec. 19, is also crinkled at varying angles to the foliation, probably due to secondary folding within the formation. Elongated calcareous concretions occur in certain beds (fig. 20). Irregular quartz bodies of various sizes and shapes are present in abundance. Most of these are small lentils, but some are veins. Some of the larger bodies have been dismembered, boudinage-fashion, parallel to the foliation of the

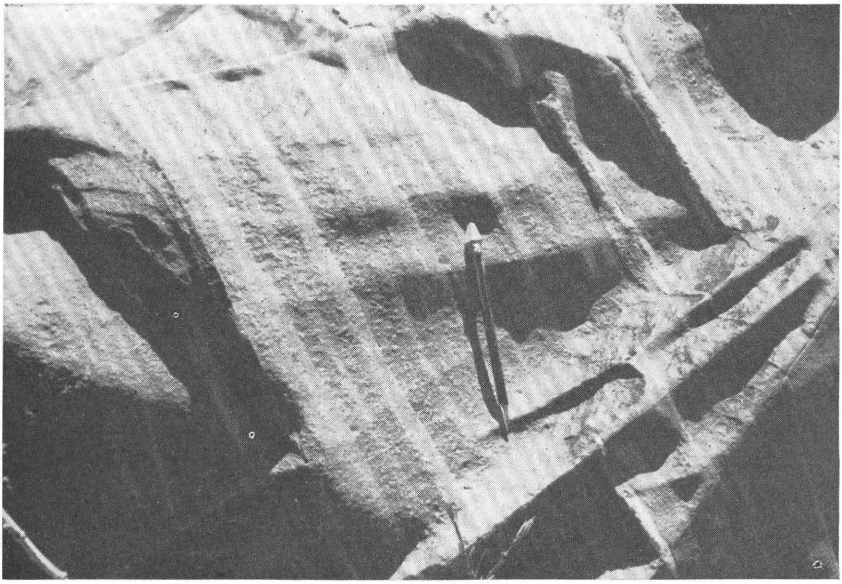

FIGURE 19.—Photograph of graded beds of graywacke in the sillimanite zone of regional metamorphism. Illustrating the rigid control of the original rock composition on the metamorphic mineral assemblage. The light-colored bands are the "coarse" quartzose bottoms of beds, and the darker colored bands are the "fine grained" tops of beds that have been rendered coarser than the bottoms by the growth of abundant staurolite and mica. From sec. 32, T. 42 N., R. 31 W.

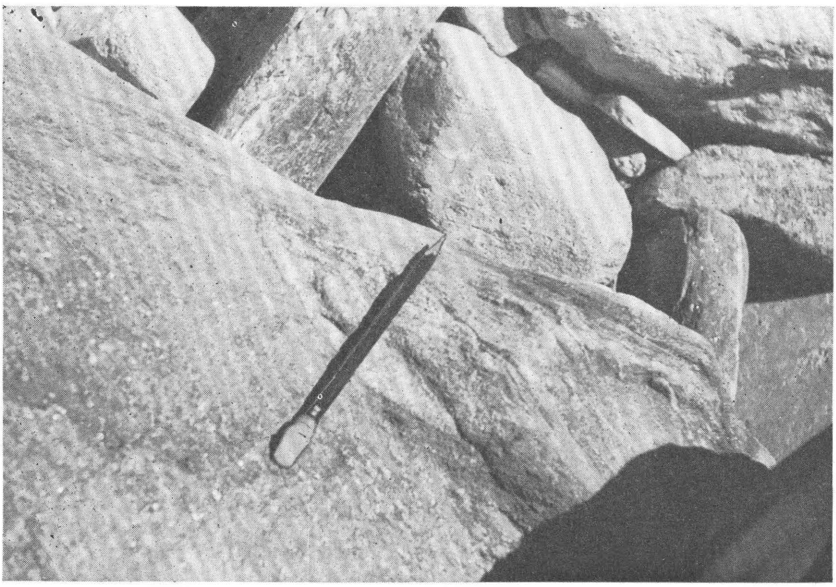

FIGURE 20.—Photograph of an elongated calcareous concretion in a micaceous granulite. From sec. 32, T. 42 N., R. 31 W.

enclosing rocks. A pink potasic feldspar commonly occurs with the quartz.

Metasedimentary rocks lying very close to the intrusive rocks of the Peavy Pond complex, or included within them, are chiefly hornfelsic and somewhat coarser grained than the lower grade schist of the outer aureole. The contact of the metasedimentary rocks with the igneous rocks is exceedingly variable and often perplexing, and will be discussed when the igneous rocks are considered.

Three metamorphic facies and a number of subfacies are recognized in the Michigamme terrain, but the scarcity of outcrop and the retrograde metamorphism of some of the rocks examined do not permit the proper placing of isofacies.

ALBITE-EPIDOTE-AMPHIBOLITE FACIES

The Michigamme rocks in sec. 24, T. 42 N., R. 32 W. and the NW¼ and SW¼ of sec. 19, T. 42 N., R. 31 W. are characterized by the mineral assemblage quartz-albite-biotite-muscovite-garnet. They are fine- to coarse-grained mica schist, micaceous graywacke, and schistose, micaceous conglomerate. The fine-grained rocks show granoblastic textures, whereas the medium- to coarse-grained rocks are incompletely adjusted and contain unaltered pebbles and grains of clastic quartz and feldspar. Most of the larger grains have been strained or partly granulated.

The mica schist is composed chiefly of fine-grained parallel plates of biotite and muscovite with a moderate amount of clear quartz in irregular grains, but a small amount of pink ferruginous albite and euhedral garnet is present intergranularly to the quartz.

The micaceous graywacke is a more massive rock, thick bedded, and only slightly affected by the stresses that have produced the foliation in the schist. It is generally granoblastic, poorly foliated to hornfelsic, composed of about equal amounts of quartz and limpid untwinned albite in a generous matrix of biotite, muscovite, and chlorite. Garnet is sparingly present in small euhedral crystals. Clastic grains of quartz and feldspar, and quartz-feldspar aggregates probably representing rock fragments are present in moderate amounts, although they have usually lost their original outlines due to the encroachment of the granoblastic quartz-albite matrix material. Chlorite is present in medium-sized plates as metacrysts, but is considered an alteration mineral of biotite.

Recrystallization has been least effective in the conglomerate. Quartz grains and pebbles of quartzite as much as 1 cm long, and rounded grains of sodic plagioclase, orthoclase, and perthite make up the bulk of the rock. The grains have been elongated and partly granulated, and a sparse matrix composed of biotite, secondary chlorite and hematite, forms around the augen-shaped pods. Garnet is present in the matrix in euhedral crystals as much as 1 mm wide. Recrystallization of the granulated material has progressed to varying degrees, and has produced a small amount of granoblastic quartz and albite.

The chloritization of biotite and the alteration of the metamorphic plagioclase in some of these rocks tends to obscure their proper metamorphic rank. The majority of the rocks are thought equivalent in rank to rocks of the Hemlock formation, similarly situated geologically, that are placed in the albite-epidote-amphibolite facies, but some of them may belong in the higher amphibolite facies.

AMPHIBOLITE FACIES

The rocks in the NW¼ and SW¼ sec. 20, T. 42 N., R. 31 W. and the SE¼ sec. 25, T. 42 N., R. 32 W. are characterized by the mineral suite quartz-plagioclase-biotite-muscovite-staurolite-garnet. The plagioclase ranges from An_{10} to An_{35} in composition. Accessory minerals are apatite, spene, zircon, and magnetite. Chlorite and sericite occur as retrograde minerals. Unfortunately, the rocks of this zone are almost completely covered, either by glacial deposits, or by the water of Peavy Pond. In sec. 20 the only rocks available for examination occur in outcrops where over half of the rock present is tonalite or granodiorite. The included metasedimentary rocks are usually gray, fine-grained, and have schistose or hornfelsic textures. They are commonly porphyroblastic with poikioblastic metacrysts of chlorite and muscovite in broad plates 0.5–3.0 mm long. Staurolite was not seen in these rocks, but its probable former presence is indicated by augen-shaped pods of sericite and quartz found in a specimen collected in the NE¼ sec. 19. A specimen from island exposures in the SW¼ sec. 20 is illustrated in figure 21. The figured rock is composed chiefly of biotite and muscovite plates in a background of interlocking quartz and plagioclase grains of about equal relief. The metacrysts are chlorite, probably formed at the expense of biotite.

Mica schist containing staurolite occurs in the southwest corner of the quadrangle. These rocks crop out in low patches on the hillsides. Outcrops are gray, broadly rounded, and have rough hobnail-like surfaces where the staurolite has been etched into relief by surface weathering. The staurolite-bearing beds are rather massive, 1–3 feet thick, interlayered with beds of fine-grained

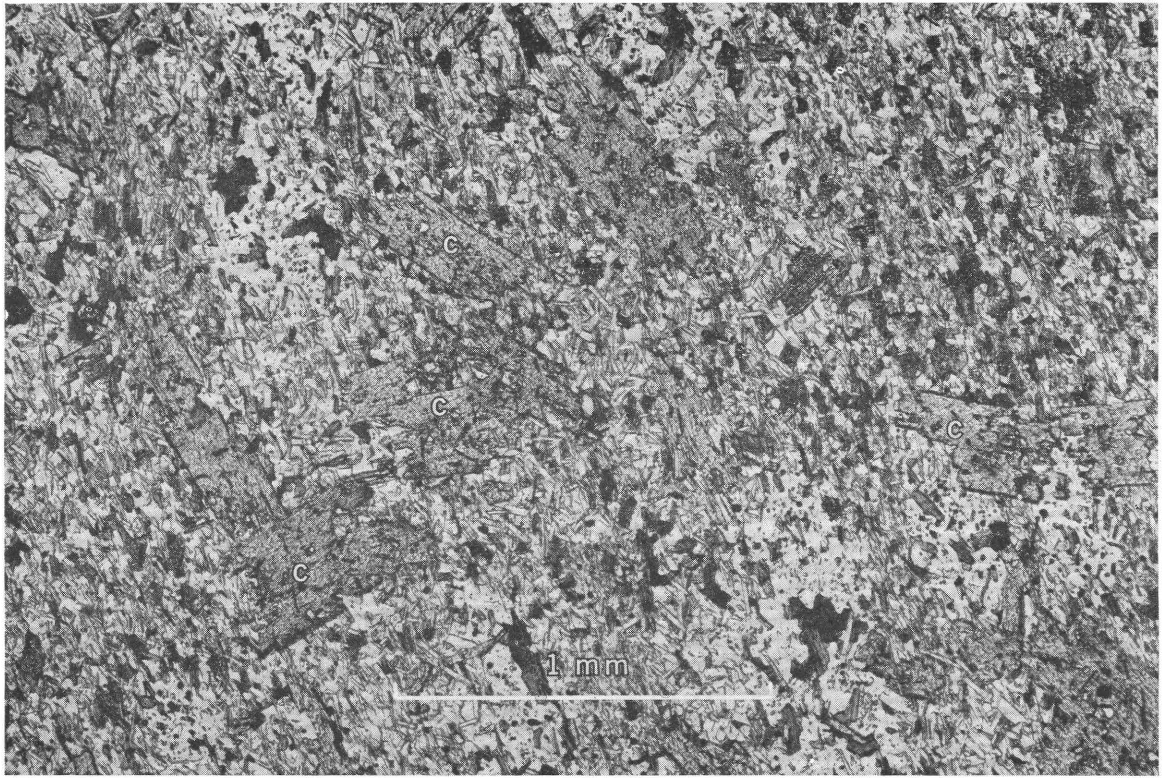

FIGURE 21.—Photomicrograph of a porphyroblastic biotite-muscovite schist. ×50, plane light. Showing metacrysts of chlorite (*c*) in a fine-grained groundmass of muscovite, biotite, plagioclase, and quartz. Specimen RB–135–52.

mica schist. Many of the staurolite beds are well graded with the greater staurolite and mica growth near the tops. In thin section, the staurolite beds are strongly foliated and partly differentiated biotite-muscovite-plagioclase-quartz schist, with preferentially oriented diamond-shaped staurolite in pods. The biotite and muscovite are present in about equal amounts, and form thin layers alternating with layers composed chiefly of quartz and plagioclase (An_{35}). The staurolite is 1–10 mm in its longest dimension, often twinned, and often replaced by cryptocrystalline pseudomorphs of sericite. The podded and oriented staurolite crystals indicate the deformation stresses continued after their formation. This is not the case where staurolite has formed in hornfelsic-textured rocks close to the competent igneous rocks of the complex. An additional interesting point in regard to these rocks is that the plagioclase usually shows zoning. The zoned plagioclase crystals are especially well developed in the rocks with hornfels texture, but they have been observed in the schist as well. It was noted previously that the plagioclase in some of the hornblende schist and pyroxene hornfels is also zoned. The zoning appears to be normal. Two to five zones have been seen on a single crystal. Zoned crystals, twinned subsequent to the zoning, still show their zoned character well (fig. 22).

Mineralogically these rocks belong in the amphibolite facies. Some of the rocks are hornfelsic contact rocks bearing the critical assemblage quartz-plagioclase-biotite-muscovite-garnet, and are best considered as belonging to the cordierite-anthophyllite sub-

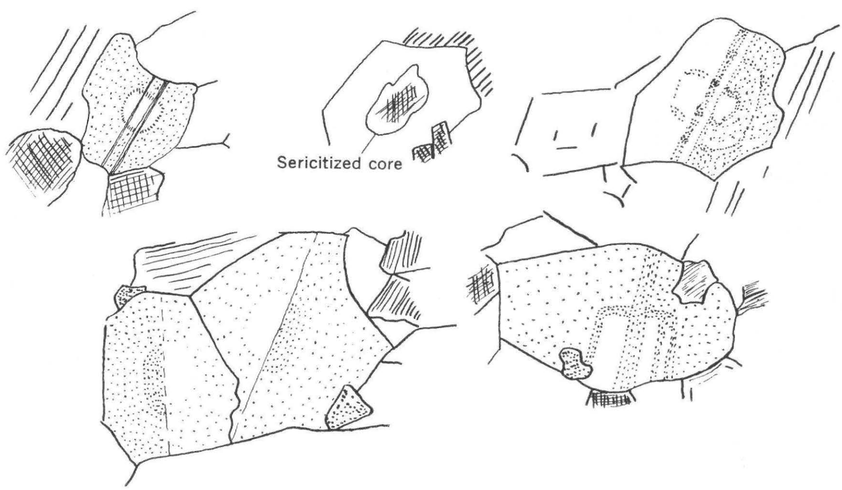

FIGURE 22.—Sketches from thin section of zoned and twinned metamorphic plagioclase. The containing rock is a biotite-quartz-plagioclase-magnetite hornfels from an island outcrop in the SW¼ sec. 20, T. 42 N., R. 31 W. Size of crystals about 0.1 mm.

facies, whereas some of the rocks are schist lying at least 1,000 feet from any intrusive rock and contain staurolite in addition to the minerals above, and therefore are best considered as belonging to the staurolite-kyanite subfacies of the amphibolite facies of regional metamorphism (Turner and Verhoogen, 1951).

AMPHIBOLITE AND PYROXENE HORNFELS FACIES

The Michigamme rocks in the SE¼ sec. 20, T. 42 N., R. 31 W. are characterized by the presence of sillimanite and, in some cases, andalusite, although in general appearance they are much like the rocks to the west and northwest. These rocks occur in the inner fringe of metasediments that lies adjacent to the intrusive rocks of the complex, and as pendants and xenoliths within the complex. The discordant contact rocks and the xenoliths are usually granulites with hornfelsic texture, whereas the rocks concordant with the intrusive bodies, or lying some distance from them, show schistose structures. An area of foliated sillimanite-bearing schist lies just south of the south edge of the quadrangle.

The essential minerals in these rocks are quartz, plagioclase (An_{27}–An_{37}), and biotite, which together make up about 95 percent of all the rocks. Many of the rocks are porphyroblastic, and metacrysts include garnet, staurolite, andalusite, sillimanite, tourmaline, and muscovite. The accessory minerals are magnetite, apatite, zircon, epidote, sphene, and tourmaline. Retrograde minerals include muscovite, sericite, chlorite, and possibly albite. In addition to the above minerals, microcline is present as an essential mineral in one specimen, along with quartz, plagioclase, and biotite, and with epidote-mantled allanite as the only accessory.

The grain size of the essential minerals is somewhat greater in these rocks than in the rocks to the west and northwest. The usual size range for quartz and plagioclase is 0.1–0.3 mm. Relatively coarse-grained porphyroblastic rocks of this zone contain plagioclase crystals as much as 2.5 mm in length. The plagioclase is zoned, and the zones become more numerous as the intrusive rocks are approached. The quartz is generally clear, but some of it contains hairlike inclusions of sillimanite. The biotite is dark brown and contains abundant dark halos, which are due to included zircon. The garnets are pink or brownish red, usually small, 0.1–0.3 mm, but unusually large garnets an inch or more in diameter occur in some of the xenoliths. In rocks with hornfels texture, the garnets are poikilitic dodecahedrons idiomorphic

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against the other mineral grains. In the foliates, the garnets form augen-shaped pods around which the mica is displaced, but the garnets do not appear crushed or rotated.

The paragenesis of staurolite is similar to that of the garnet. Figure 23 illustrates the habit of the staurolite in the hornfelsic rocks. In the foliates the staurolite is usually partly altered to sericite.

Andalusite is known to occur only in the contact rocks cropping out in the SW¼SE¼ sec. 20, T. 42 N., R. 31 W. It forms poikiloblastic oval-shaped individuals as much as 1 cm in width, and these are associated with other metacrysts of euhedral poikiloblastic garnet of equal size, and somewhat smaller metacrysts of euhedral and anhedral staurolite. The staurolite is idiomorphic against the outer fringes of the poikiloblastic andalusite, and is included within the andalusite as sharp euhedral crystals. Some of the andalusite is partly replaced by parallel needles of colorless sillimanite. The sillimanite needles do not pass through the staurolite crystals included in the andalusite, but are interrupted by them. The sillimanite needles in some cases extend beyond the margins of the andalusite host, and apparently replace biotite. Sillimanite needles in an andalusite host are shown in figure 24. Most andalusite crystals show partial replacement by muscovite. The muscovite also replaces sillimanite, but the staurolite appears to be stable within the muscovite plates. Many of the muscovite metacrysts are poikiloblastic containing quartz, biotite, and staurolite, and although it is often clear that some muscovite has replaced andalusite, it is impossible to know how much of the muscovite present may have formed in that way.

Besides growing in andalusite, sillimanite in minute needles forms interstitially to the quartz and plagioclase in some of the rocks, and occasionally as hairlike growths in the quartz. In two schist specimens the sillimanite appears to have formed at the expense of biotite during deformation. In one of the two specimens the sillimanite occurs along with frayed and deformed biotite mantling augen-shaped pods containing garnet, and the sillimanite is most abundant in the high stress area of each pod, and is inconspicuous or absent in the strain shadows.

Two other minerals of little quantitative importance that form metacrysts in some of the xenoliths in gabbro are chlorite, and hornblende. The chlorite forms large poikiloblastic plates and radiating sheaves in hornfelsic rocks composed of quartz, plagioclase, biotite, and staurolite. Often the euhedral staurolite is included in the chlorite. The chlorite is thought to be retrograde after biotite or possibly chloritoid in some rocks; however, the

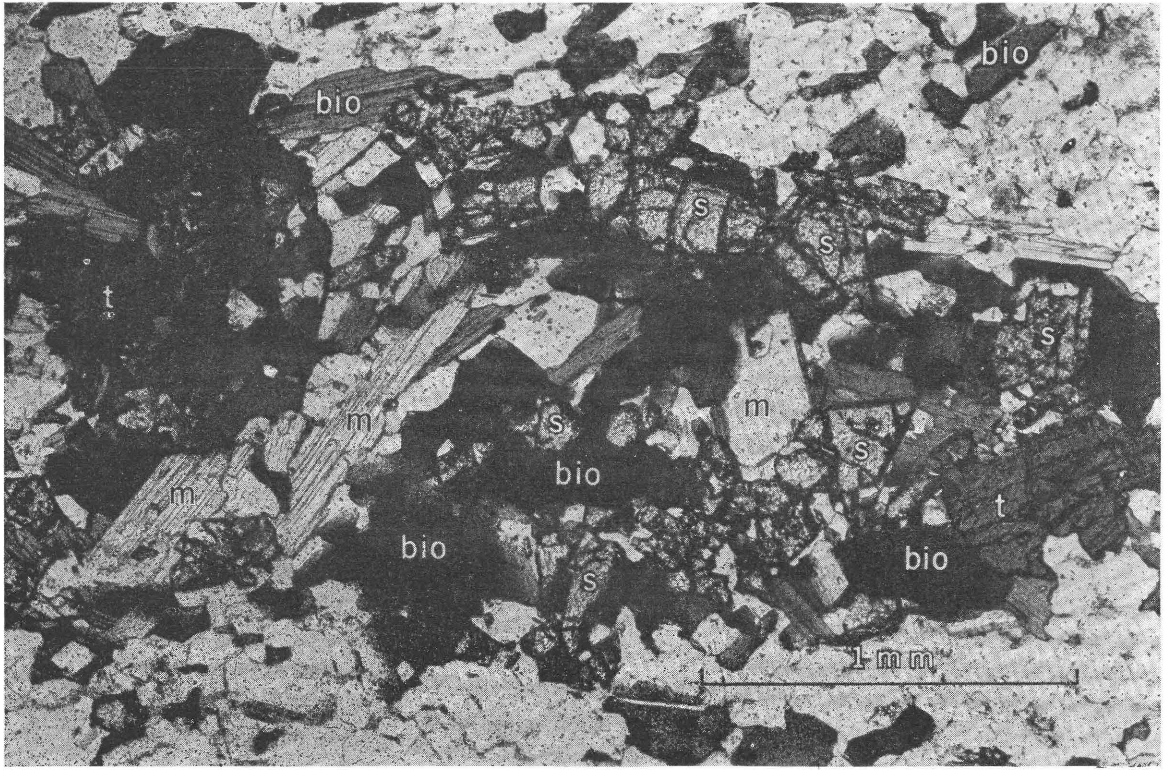

FIGURE 23.—Photomicrograph of staurolite granulite. ×50, ordinary light. Showing a small patch of staurolite (*s*) and tourmaline (*t*) crystals in a groundmass of biotite (*bio*), muscovite (*m*), plagioclase, and quartz. Specimen RB–81–51.

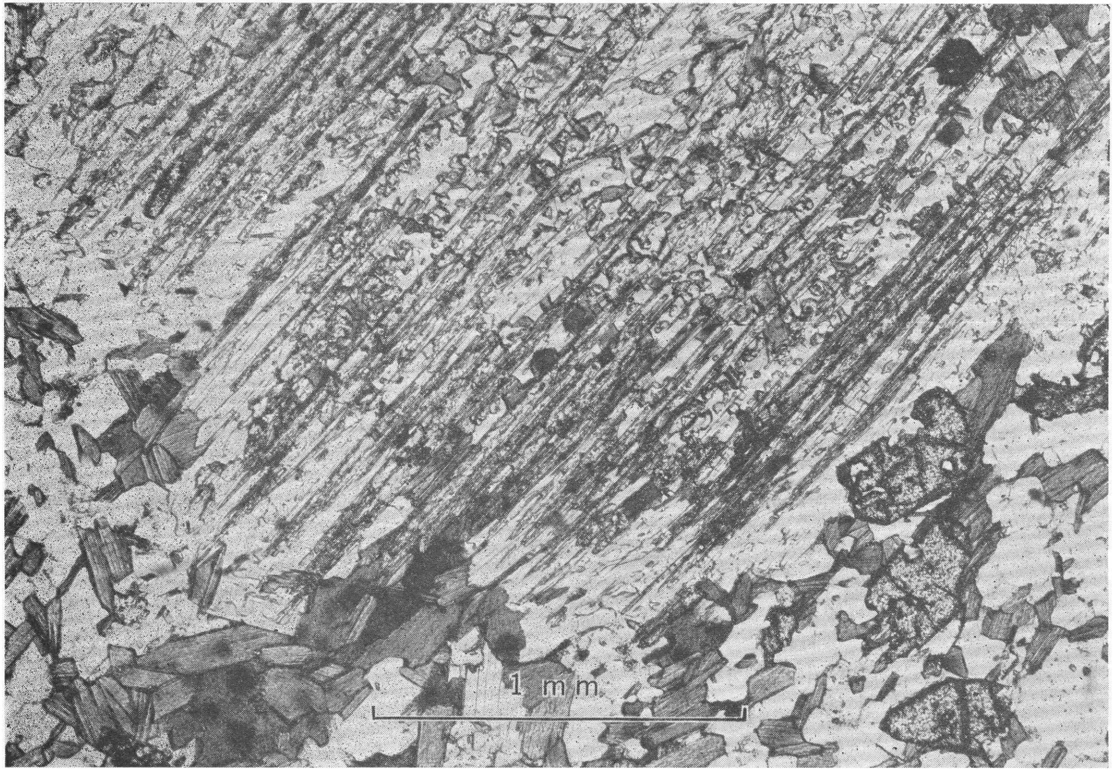

FIGURE 24.—Photomicrograph of a staurolite-andalusite granulite. ×50, ordinary light. Showing sillimanite needles in andalusite. Both the sillimanite and andalusite are partly replaced by muscovite. Unaltered staurolite is present (lower right). From NW¼SE¼ sec. 20, T. 42 N., R. 31 W. Specimen RB–81a–51.

alteration was selective, for the groundmass biotite is only slightly altered. The hornblende forms metacrysts in a slightly foliated xenolith collected from gabbro outcrops in the SE¼ sec. 28, T. 42 N., R. 31 W. The hornblende is brownish green, anhedral, 0.1–0.4 mm long in prismatic sections, and contains opaque inclusions. The groundmass minerals are quartz, andesine, and light-brown mica, all averaging about 0.1–0.2 mm in size. The andesine is sensibly zoned as in the other rocks described, and forms occasional metacrysts equal to the hornblende in size. Accessory minerals are sphene, apatite, and titaniferous magnetite.

The well-foliated sillimanite-bearing schist situated in the inner aureole of the Peavy Pond complex is best regarded as belonging to the sillimanite-almandine subfacies of the amphibolite facies, its position in the aureole being similar to that of the hornblende schist in the Hemlock formation of the same facies. The hornfelsic rocks bearing andalusite and sillimanite are similarly related to the igneous complex and comparable in metamorphic grade to the pyroxene hornfels in the Hemlock formation.

MIXED ROCKS

A special group of metasedimentary rocks yet to be considered are those interlayered with igneous rock in the NW¼ sec. 20 and the NW¼ sec. 21, T. 42 N., R. 31 W. The igneous parts of the resultant migmatite are granodiorite, tonalite, and diorite. The interlayering of the igneous and metasedimentary rocks is generally concordant, but locally it is discordant and extremely complicated. Both sharp and seemingly gradational contacts between the metasedimentary rocks and the several varieties of igneous rocks occur. In general, the metasedimentary rocks are porphyroblastic, with metacrysts of zoned plagioclase in a matrix of quartz and dark-brown biotite. In contrast with the weakly zoned plagioclase of the granulite and schist, the plagioclase metacrysts of these rocks are made up of tens of zones ranging in composition from about An_{20} to An_{28}. Reversal of the normal zoning are common features. Many of the larger metacrysts represent collections of smaller, zoned crystals, zoned identically within themselves, and bounded as a group by common zones, the first of which often penetrates between the small crystals. As a result of this glomeroporphyroblastic-type growth, many of the larger metacrysts have several cores that come to extinction at different times as the stage of the microscope is turned. This peculiar growth feature of the plagioclase in these metasedimentary rocks is also a common feature in the hybrid tonalite and granodiorite, some of which contain an abundance of partly assimilated metasedimentary material.

These metasedimentary rocks were deformed cataclastically, at which time many of the plagioclase metacrysts were crushed and partly granulated so as to give the rock a weak augen structure. Minor amounts of myrmekite and microcline are present in the granulated parts of the deformed rocks, and locally unaltered microcline partly replaces sericitized plagioclase.

ROCKS OF PALEOZOIC AGE—UPPER CAMBRIAN

Outliers of lower Paleozoic rocks, probably of Late Cambrian age, form the bedrock and are exposed at many places in the district west of the Paleozoic overlap boundary shown on geologic maps of regional scale (Leith, Lund, and Leith, 1935; Martin, 1936). One such outlier forms the bedrock below the glacial moraine situated just west of Sagola, Mich., and the west edge of the outlier probably is present below the glacial cover in the northeast part of the Lake Mary quadrangle, in secs. 14, 24, and 25, T. 43 N., R. 31 W. Diamond drilling near the crest of the moraine, east of the quadrangle, in sec. 31, T. 43 N., R. 30 W. penetrated 40–60 feet of clean buff medium-grained sandstone and a basal conglomerate composed of Precambrian ferruginous quartzite fragments in a buff sandstone matrix. The sandstone and conglomerate appear to rest horizontally on steeply dipping metavolcanic schist of the Lower Precambrian.

In the Lake Mary quadrangle, a 14-foot section of buff sandstone was penetrated by diamond drilling in the SE¼ sec. 14, T. 43 N., R. 31 W. The sandstone in sec. 14 overlies oxidized slate and schist of undetermined Precambrian position. The sandstone may be continuous, below the glacial deposits, with the sandstone west of Sagola. The lithology and stratigraphic position of the sandstone is similar to that of the Dresbach sandstone present to the east of the Lake Mary quadrangle.

Fine-grained buff dolomite of a type usually associated with Cambrian rocks at Iron Mountain, Mich., and in the Felch district, crops out in a narrow ledge on the north shore of Mitchell Lake near the north-south section line. The dolomite is nonfossiliferous, and its age has not been determined. East of the quadrangle, in Dickinson County, similar dolomite is present above a sandstone and grades into it. The dolomite may be Trempealeau formation (Late Cambrian) as indicated on the latest geologic map of northern Michigan (Martin, 1936), and it may be that the dolomite near Lake Mitchell in the Lake Mary quadrangle is also Trempealeau.

INTRUSIVE IGNEOUS ROCKS

LOWER PRECAMBRIAN ROCKS

PORPHYRITIC RED GRANITE

Coarse porphyritic granite crops out in one small area in sec. 24, T. 42 N., R. 31 W., about 5,000 feet west of similar granite in secs. 19 and 30, T. 42 N., R. 30 W., central Dickinson County, Mich.

The red porphyritic granite is a very massive rock, composed of lenticular and tabular crystals of pink microcline, typically about one-half inch in length, quartz, and biotite. Most of the microcline has been crushed and alined between folia of dark mica, giving a distinct gneissic structure to part of the exposed rock. The general homogeneity of the granite is interrupted in a few places by gradiation to minor quantities of aplite and pegmatite, and by dark schlieren.

The age of the porphyritic red granite has not been determined in the Lake Mary quadrangle. Structurally and lithologically it appears to be related to a domal area of similar granite that crops out to the east in central Dickinson County. The age of the latter granite is uncertain. Pettijohn (1951) considered it to be intrusive into the rocks of the Dickinson group, but James (1958, p. 31) considers it to be older than the Dickinson group.

MIDDLE PRECAMBRIAN ROCKS

METAGABBRO DIKES AND SILLS

Dikes and sills of metagabbro have intruded the rocks of the Hemlock formation in a number of places. Dikes in this category are few and scattered. Only one of these is large enough to be shown on the geologic map. It extends east from the center of sec. 17, T. 42 N., R. 31 W. into the adjacent section, where the exposures end. Similar dike rock crops out along the river near the center of sec. 15, suggesting a connection between the two segments. The dike rock is medium-grained amphibolite, generally sheared and moderately foliated, but retaining hypautomorphic texture locally. The rock is now composed of pale-blue-green hornblende, altered and broken grains of plagioclase, oligoclase-andesine, and accessory chlorite, titaniferous magnetite, sphene, apatite, quartz, epidote, and clinozoisite. The hornblende makes up 60–90 percent of the rock.

Two very thick sill-like bodies have intruded the greenstone of the Hemlock formation in the northern part of the quadrangle (see pl. 1). These sills have been named the East and the West Kiernan sills from their northward extensions in Kiernan quadrangle by Gair and Wier (1956). The sills strike approximately parallel to the enclosing greenstone and slate of the Hemlock formation, and appear to dip steeply to the west, roughly concordant with the enclosing beds. Tops determined from ellipsoidal structures in metabasalts adjacent to and within the sills are toward the west. The West Kiernan sill is differentiated, showing a mafic zone on the east side and a felsic zone on the west, which indicates that it was intruded as a nearly horizontal sheet and has since been folded into its present attitude.

EAST KIERNAN SILL

The inferred areal extent of the East Kiernan sill is shown on plate 1. It is quite possible that some of the area included within the sill boundaries may be underlain by easily eroded schist or slate of the Hemlock formation, but it is not here so interpreted. Although the quantity of metagabbro outcrop is small, it is the only rock type known to be present. The maximum thickness indicated by the map pattern is 4,200 feet.

The metagabbro is green to dark greenish gray, hypautomorphic granular, with conspicuous crystals of prismatic hornblende. The minerals present are hornblende, albite, chlorite, epidote, clinozoisite, quartz, sphene, rutile, magnetite, and apatite. Hornblende makes up 50–80 percent of the rock. It is pale green to brownish green or nearly colorless, blocky or fibrous or in clumps of fibers; commonly it shows a distinct basal parting presumably inherited from an original augite. Much of the hornblende has been partly chloritized, and most of the original plagioclase has been saussuritized or chloritized. The plagioclase present in the metagabbro is albite or albite-oligoclase, An_5–An_{15}. The albite is twinned with broad laminae and is not usually zoned. One of the seven thin sections of this rock examined contained chloritized, zoned plagioclase with an unaltered outer zone of albite. Free quartz amounting to less than 5 percent of the rock is present in all specimens. Sphene and rutile in amounts as much as 5 percent are present as alteration minerals of ilmenite or titaniferous magnetite. Euhedral apatite is a conspicuous accessory.

There is no petrographic evidence that the metagabbro of the East Kiernan sill has differentiated. Specimens from near the east side are little different from specimens collected near the west side. The body apparently crystallized in place. Fluxion structures, which indicate a high degree of crystallinity during intrusion, are lacking. Why only one of two essentially parallel sills of comparable thickness has differentiated is uncertain. It is possible that the East Kiernan sill, although apparently concordant, may be a dike.

WEST KIERNAN SILL

The areal distribution of the West Kiernan sill is shown on plate 1. The total length of the sill in the Lake Mary quadrangle is 3½–4 miles. It extends to the northwest beyond the north boundary of the quadrangle for at least 1½ miles, and perhaps in an interrupted fashion for another 8–9 miles. The average thickness in the quadrangle is about 5,700 feet. The maximum thickness occurs in secs. 28 and 29 where the sill is about 6,500 feet thick. In contrast with the East Kiernan sill, exposures are plentiful, and the mass forms a rugged, rocky upland of considerable relief.

The sill divides into two parts in the vicinity of the east-west road from the Mansfield location. At the time of emplacement the lens to the north of the road was intruded below the greenstone and slate that occur east of the river at Mansfield location, whereas, the lens south of the road penetrated partly below, but mainly above that greenstone and slate, and below the lower slate of the Mansfield iron-bearing slate member of the Hemlock formation. As a result, the iron-formation was raised in essentially a horizontal position, whereas the greenstone below was ruptured and offset upward (westward) about 3,000 feet. In the area where the two lenses join massive blocks of greenstone were engulfed by the gabbric magma.

The sill is in the low grade zone of regional metamorphism for its total length, and nearly all of the rocks conform mineralogically to the greenschist facies.

The sill may be divided megascopically and microscopically into 5 distinct zones: (1) a basal ultramafic zone composed chiefly of metaperidotite 400–1,200 feet thick; (2) a zone of normal diabasic or ophitic metagabbro 3,000–4,000 feet thick, which commonly shows rhythmic layering; (3) an iron-rich intermediate zone, between the normal diabase and the granophyre, 200–300 feet thick, present locally; (4) a zone of granophyre and granophyric granite 200–500 feet thick, present locally; and (5) a metadiabase cap rock, probably representing the upper chilled portion of the sill, 100–300 feet thick, present locally.

BASAL ULTRAMAFIC ZONE

The rocks of the basal zone are chiefly soft, serpentinized peridotites. They are green to greenish gray, medium grained, and generally porphyritic. In hand specimens they characteristically show dull-green spots representing altered phenocrysts of pyroxene in a darker, greenish-gray fine-grained matrix material. All of the specimens collected from this zone are moderately magnetic. The minerals present are serpentine, in a variety of forms; tremolite, talc, magnetite, carbonate, chlorite, and actinolite. All appear to be secondary minerals except perhaps some of the magnetite. Serpentine is present as pseudomorphs after pyroxene and as the chief mineral of the groundmass. In some rocks serpentine is present only in the groundmass, and the pyroxene pseudomorphs are composites of talc, tremolite, and carbonate.

The serpentine pseudomorphs are of two kinds: pale-green to pinkish-green pleochroic bastite, and cryptocrystalline clumps intergrown with tiny needles of colorless tremolite that are oriented parallel to the cleavage planes of the original pyroxene. Most of the bastite pseudomorphs contain ovoid inclusions of talc, tremolite, and fine granular magnetite that probably represents altered olivine. In rocks containing serpentine pseudomorphs, the groundmass is composed of a tangled mass of serpentine, talc, tremolite, and magnetite. A specimen containing tremolite-talc-carbonate aggregates as pseudomorphs after pyroxene in a serpentine and talc groundmass is illustrated in figure 25.

In all these rocks it seems likely that most of the original pyroxene present was orthorhombic. Direct evidence for the former presence of olivine is afforded only by the oval-shaped magnetite-tremolite inclusions in the bastite pseudomorphs.

The ultramafic character of these basal sill rocks is shown by chemical analysis *D* in the table below. The specimen analyzed is a medium-grained peridotite with bastite phenocrysts in a groundmass of serpentine, talc, tremolite, and magnetite. The mode was estimated as follows:

	Percent
Bastite pseudomorphs after orthopyroxene	20
Tremolite	30–40
Serpentine and talc	30–40
Magnetite	5
Apatite	Trace

Similar rocks have been described as picrite-porphyry (porphyritic limburgite) by Clements (Clements and Smyth, 1899, p. 212–220) from secs. 9, 22, and 27, T. 44 N., R. 32 W., Iron County, Mich.

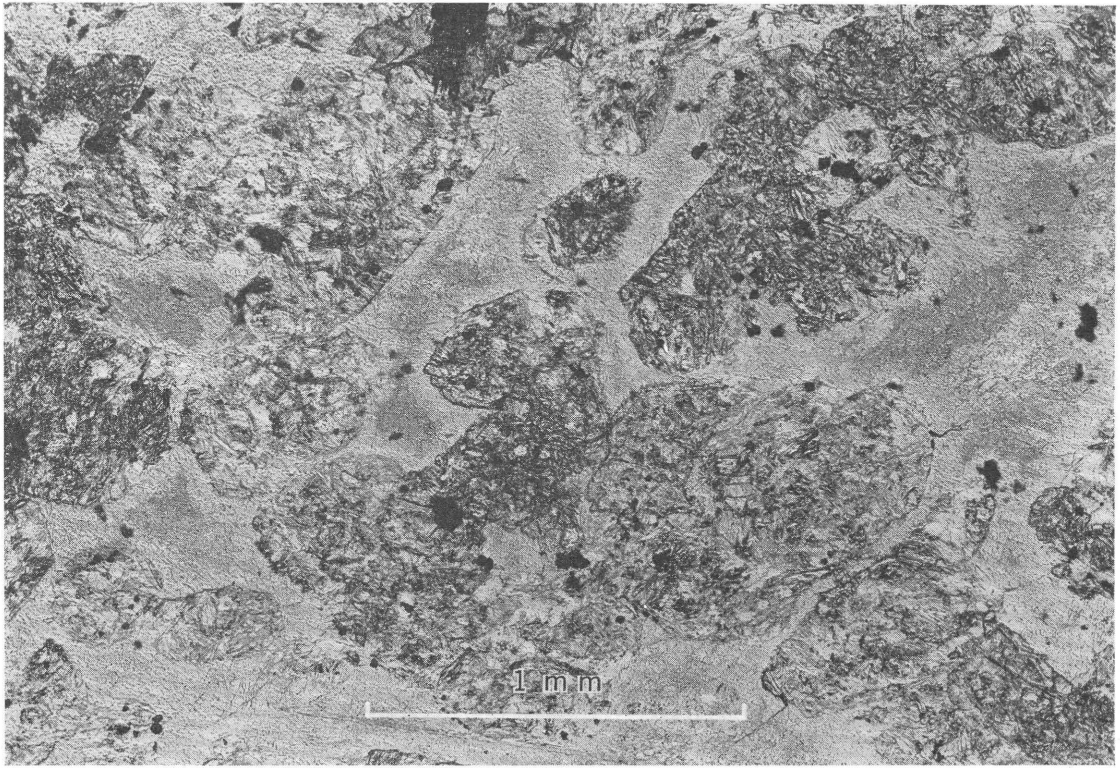

FIGURE 25.—Photomicrograph of a metaperidotite from the basal ultramafic zone of the West Kiernan sill. ×50, ordinary light. The groundmass is chiefly serpentine probably of the variety serpophite, and minor amounts of talc and chlorite. The phenocrysts are aggregates of tremolite, talc, and magnetite. From the NW¼ sec. 33, T. 43 N., R. 31 W. Specimen RB–166–52.

Chemical analyses of four sill rocks from the Lake Mary quadrangle, Iron County, Michigan

[Analysts: For *A*, *C*, and *D*, Lucille M. Kehl, U. S. Geol. Survey, 1954; for *B*, Paul L. D. Elmore and Katrine E. White, U. S. Geol. Survey, 1955]

	A	*B*	*C*	*D*
SiO_2	69.12	52.2	44.94	39.01
TiO_2	.73	2.9	.73	2.04
Al_2O_3	12.83	10.8	19.70	6.56
Fe_2O_3	.78	8.8	1.72	11.49
FeO	5.85	7.5	7.40	5.30
MgO	1.38	2.7	8.91	23.84
CaO	.70	4.8	9.22	3.57
Na_2O	1.72	2.8	1.94	.00
K_2O	3.44	1.1	.36	.02
H_2O	2.34	3.9	4.67	7.76
CO_2	.70	.37	.45	.08
P_2O_5	.11	.76	.09	.19
MnO	.05	.26	.13	.11
Total	99.75	98.89	100.26	99.97
Cu ppm	16	----------	23	125
Co ppm	0	----------	15	40
Ni ppm	0	----------	72	390

A. Specimens RB–15–53, sheared granophyric granite from 700 feet north and 750 feet east of the W¼ corner sec. 29, T. 43 N. R. 31 W.
B. Specimen RB–8–55, metagabbro from intermediate or transition zone SW¼NW¼ sec. 29, T. 43 N., R. 31 W.
C. Specimen RB–32–53, metagabbro, normal type, from 300 feet north and 400 feet east of the S¼ corner sec. 29, T. 43 N., R. 31 W.
D. Specimen RB–30–53, metaperidotite from 1,350 feet north of the S¼ corner sec. 21, T. 43 N. R. 31 W

NORMAL METAGABBRO ZONE

The central portion of the sill, 3,000–4,000 feet thick, is classed as normal metagabbro. Within this section a distinct transition may be seen between dark-colored rocks, which contain only a small amount of feldspar and are closely related mineralogically with the metaperidotites, and light-colored rocks, which contain abundant feldspar and are closely related to the upper transitional and granophyric rocks. Rhythmic layering is a common structure in this zone. The layers are generally less than 6 inches thick. Symbols indicating the attitude of the layers appear in the body of the sill on plate 1. Rare pegmatite stringers composed of plagioclase and blades of hornblende as much as 6 inches long occur near the top of the zone.

Nine specimens collected along an east-west traverse through the center of sec. 29, T. 43 N., R. 31 W., show an increase in the amount of plagioclase from about 12 percent at about 2,000 feet above the base of the sill to about 80 percent near the transition zone, at about 5,000 feet above the base of the sill. In the same group of specimens, the plagioclase shows a general increase in size from a maximum of about 2 mm in length in the lower part of the zone to a maximum of about 5 mm in length in the upper part of the zone.

Diabasic, ophitic, and parallel textures predominate in these rocks and are megascopically distinct. The ophitic rocks are particularly striking in appearance with flashing poikilitic hornblende individuals 1–2 inches in width.

The minerals present are chiefly secondary. They are albite and oligoclase (An_5–An_{16}), hornblende, chlorite, serpentine, epidote, zoisite, clinozoisite, calcite, stilpnomelane, ilmenite, magnetite, quartz, orthoclase, and andesine. Albite and hornblende make up about 90 percent of most of the rocks, but in some specimens others alteration minerals are dominant.

The original plagioclase calculated from analysis *C* (see p. 70) was An_{72}. A few specimens from the lower part of the zone contain relatively unaltered plagioclase (An_{32}–An_{50}), but in general the plagioclase has been replaced by granular aggregates of albite, clinozoisite or chlorite, and epidote. This is particularly true in the upper part of the zone. These lower rocks appear to have been highly magnesian pyroxene gabbros, and although the hydrous alteration has produced tremolite and serpentine from the original mafics, the plagioclase participated only slightly.

In addition to plagioclase, both perthite and granophyric intergrowths of quartz and potash feldspar occur sparingly in the higher rocks. These increase in amount upward (westward) to become the dominant minerals in the granophyre zone. The perthite ordinarily forms an outer zone on the plagioclase crystals, and the granophyric intergrowths occur interstitially among the plagioclase and hornblende individuals of the diabase as the last minerals to crystallize.

Hornblende is present in a variety of forms and colors, and is variously replaced by other minerals. It occurs chiefly as poikilitic individuals of large size in the ophitic rocks, and as anhedral crystals filling the angular spaces between the plagioclase laths in the diabasic rocks. In general it is colorless and tremolitic in the lower rocks, and becomes green and actinolitic toward the upper part of the zone, perhaps reflecting an increase in iron in the original pyroxene. Many characteristics of the original pyroxene are retained by the hornblende; these include stubby prismatic growth, simple and polysynthetic twinning, and a well developed basal parting. The hornblende is often partly replaced by some combination of the minerals chlorite, serpentine, epidote, clinozoisite, and stilpnomelane. Stilpnomelane alteration is particularly common in the upper part of the zone. Ilmenite or titaniferous magnetite occur as conspicuous accessories, comprising as much as 5 percent of some rocks in the upper part of the zone; it forms euhedral and anhedral crystals, poikilitic plates, and rods with rounded terminations. Most of these are completely altered to leucoxene or sphene. Rocks containing titaniferous magnetite as a principal accessory are moderately magnetic. A chemical analysis of a specimen collected near the center of the sill is shown in column *C* (p. 70). The specimen analyzed is composed chiefly of the alteration minerals, clinozoisite, albite, chlorite, sphene, and tremolite. The texture of the rock is ophitic with 15–20 percent of thinly spread, optically connected amphibole in broad patches. The plagioclase laths are almost completely replaced by clinozoisite, albite, and minor amounts of chlorite.

INTERMEDIATE OR TRANSITION ZONE

The intermediate zone includes a group of highly altered rocks that appear to be mineralogically and texturally transitional between the metagabbro and the granophyre. The rocks are generally dark brown and fine grained. They are soft and weather into coarse angular rubble. Tiny needles of apatite and grains of dark quartz are the only minerals visible in a hand specimen. These distinctive rocks form a fairly persistent belt of variable thickness below the granophyric rocks in the upper part of the sill. The transition rocks developed only where the sill is concordant with the overlying sediments. In the NE$\frac{1}{4}$ sec. 20, T. 43 N., R. 31 W., where discordant contacts prevail, neither granophyre nor transition rocks were detected.

The texture in these rocks varies from diabasic, which is most common, to hypautomorphic and xenomorphic granular. The minerals present are the same as in the metagabbro below, but with these exceptions: (1) stilpnomelane is abundant, which accounts for the brown color of the rocks; (2) apatite, a minor accessory mineral in the metagabbro below, is abundant in long, thin euhedral needles cutting all other minerals; (3) altered titaniferous ore minerals are present in amounts of as much as 5 percent; (4) the hornblende is darker, usually green, bluish green, or brownish green, but often mottled; (5) free quartz, granophyric intergrowths, and perthite are present in moderate amounts; and (6) euhedral blue-gray tourmaline is present in trace amounts. Tourmaline has not been observed in the metagabbro below the intermediate zone or in the granophyre or diabase above the intermediate zone.

Hornblende, where present, occurs only as remnants, partly replaced by cryptocrystalline stilpnomelane and small euhedral crystals of epidote and apatite. The stilpnomelane also replaces the outer perthite zones on the plagioclase crystals, and the feldspar fraction of the granophyric intergrowths. Chlorite selectively replaces the cores of many plagioclase crystals. In some specimens the plagioclase has been partly replaced by granular aggregates of epidote and zoisite or clinozoisite, and in such rocks the partly replaced laths are either albite or albite-oligoclase.

A chemical analysis of a typical rock specimen from the intermediate or transition zone is shown as analysis *B* on page 70.

GRANOPHYRIC ZONE

Granophyre is present near the top of the sill in secs. 17, 20, and 29, T. 43 N., R. 31 W., but the limits of the zone are not well established. The upper contact of the zone has not been observed, but an apparent gradation between the rocks of the normal gabbroic, transitional, and granophyric zones has been observed in nearly continuous exposures in the NW¼ sec. 29, T. 43 N., R. 31 W. The granophyric zone is discontinuous along the strike and is presumed to be lenticular. It is confined chiefly to areas where the upper contact of the sill is nearly accordant with the overlying country rock. In the SW¼ sec. 8, and the NE¼ sec. 20, T. 43 N., R. 31 W., there are large-scale discordances along the upper contact of this sill, and both transitional rocks and granophyre are absent.

The granophyre, as the name implies, is characterized by microgranophyric texture. It bears a close resemblance to granophyre described from other differentiated mafic sills. The appearance of the rock in thin section is most distinctive, but as Johannsen noted, it is easier to recognize than describe.

Two main varieties have been distinguished in the field, (1) dull greenish-gray fine- to medium-grained granophyre showing small grains of red feldspar and dark blebs of glassy quartz in a schistose base material, and (2) buff to reddish-brown medium-grained, granitic-appearing granophyre, either showing no mafic mineral, or showing abundant needle-shaped aggregates of magnetite or, if surficially altered, ocher-colored iron oxide.

The essential minerals of both varieties are albite or albite-oligoclase, potash feldspar (microcline and orthoclase), and micropegmatite. Nonimplicated quartz is an important constituent in some specimens. Secondary and accessory minerals are chlorite, sericite, biotite, epidote, calcite and a ferruginous carbonate, apatite, sphene, magnetite, and zircon.

The feldspar is generally clouded by fine-grained alteration minerals, chiefly chlorite and sericite, and an undetermined red dust, possibly hematite. Chlorite is the chief mineral of the schistose base which distinguishes one variety of granophyre.

In each variety the feldspars are similar, but relative quantities vary. The sodic plagioclase forms equidimensional to slightly elongate crystals commonly showing one large central zone, untwinned or twinned according to the albite and Carlsbad laws, and one outer zone or rim of outward radiating micropegmatite or microcline. The pericline twin of the microcline, in effect, gives the appearance of a radiating outer zone as does the micropegmatite. Many crystals show an irregular penetration of the microcline twinning into the central zone. Both orthoclase and microcline are abundant, but the relative amounts of these have not been determined. Both are intergrown with quartz and both form anhedral or subhedral crystals many of which show Carlsbad twinning.

Of the accessory and secondary minerals listed above, sphene, biotite, and apatite are virtually restricted to the first (schistose) variety of granophyre. The sphene forms skeletal pseudomorphs after ilmenite which are set in halos of fine-grained dirty-brown biotite. The apatite occurs as euhedral needles as in the transitional rocks.

Secondary calcite is pervasive. What appears to be a primary carbonate is the only important accessory mineral in the variety of granitic appearing granophyre which shows no mafic mineral in hand specimen. In all specimens examined the carbonate is partly replaced by hematite or limonite; it shows high indices relative to balsam, and therefore is presumed to be ferruginous. The granophyre which contains needle-shaped aggregates of magnetite is, in other respects, similar to the granophyre containing the carbonate. Also, the magnetite shows the same paragenetic relationships as the carbonate, indicating that either the magnetite replaced the primary carbonate or that the magnetite formed as a primary mineral under slightly different chemical conditions than those prevailing where the carbonate formed. Surficial oxidation has altered a considerable part of the magnetite in the exposed rocks to earthy iron oxide.

A chemical analysis of a chip sample representing the schistose variety of granophyre is given in column *A*, p. 70. Modes of other granophyre specimens are given below.

Modes of four specimens of granophyre from West Kiernan sill

	Specimen			
	114–52	115–52	109–52	109a–52
Potash feldspar (orthoclase or microcline)	37	10		9
Micropegmatite	57	80	[1] 62	75
Albite	Trace	7	33	8
Micas (chlorite-biotite-sericite)	Trace	1	3	Trace
Carbonate		2	.5	
Ore minerals	6	Trace	1.5	8
Apatite	Trace	Trace	Trace	

[1] Includes some free quartz and altered potash feldspar.

METADIABASE (CHILLED) ZONE

A zone of fine- to medium-grained metadiabase 100–200 feet thick is present between the granophyre zone and the intruded sedimentary rocks all along the top of the sill from the SW¼ sec. 20 through sec. 29, T. 43 N., R. 31 W. Texturally and mineralogically the metadiabase resembles the rocks of the normal metagabbro zone. The plagioclase laths are chloritized albite or albite-oligoclase with a maximum length of only about 2 mm as contrasted with laths 3–5 mm long common in the upper part of the sill below the granophyre. The metadiabase probably represents the upper chilled border phase of the sill. No chemical analysis is available for the metadiabase, but it compares so well in appearance and mineralogy with the metabasalt of the Hemlock, that they must be very closely related chemically.

The field relations indicate only that the West Kiernan sill is younger than the Hemlock and older than the post-Huronian folding and metamorphism. From a broader point of view, it is probably related to a pre-metamorphic diabase swarm that cuts all of the Middle Precambrian (Animikie) formations.

CHEMICAL DATA

Analyses *A–D,* which represent the four lower zones of the West Kiernan sill, are given on page 70. For easy comparison with chemical data from other areas, the oxide variations across the sill have been plotted on figure 26, and the proportional relationships between the oxides FeO, MgO, and $Na_2O + K_2O$ have been plotted on a triangular diagram (fig. 27). Thus plotted, the chemical data from the West Kiernan sill compares favorably with chemical data from other differentiated igneous bodies (Wager and Deer, 1939; Collins, 1934; Walker and Poldervaart, 1949; Cornwall, 1951; and Hotz, 1953). It appears that the present chemical character of the sill rocks was chiefly determined by differentiation of the gabbroic magma.

PEAVY POND COMPLEX

Definition.—The Peavy Pond complex as designated here includes all of the intrusive rocks exposed on the shores and islands of Peavy Pond in secs. 14–17, 19–22, and 27–30, T. 42 N., R. 31 W., Iron County, Mich. The areal distribution of the rocks of the complex is shown on plate 1. Although outcrops are scarce, there is, as indicated by the petrographic study of the rocks, a close genetic relationship between the rocks of the many isolated exposures, and it seems reasonable to conclude that many are physically con-

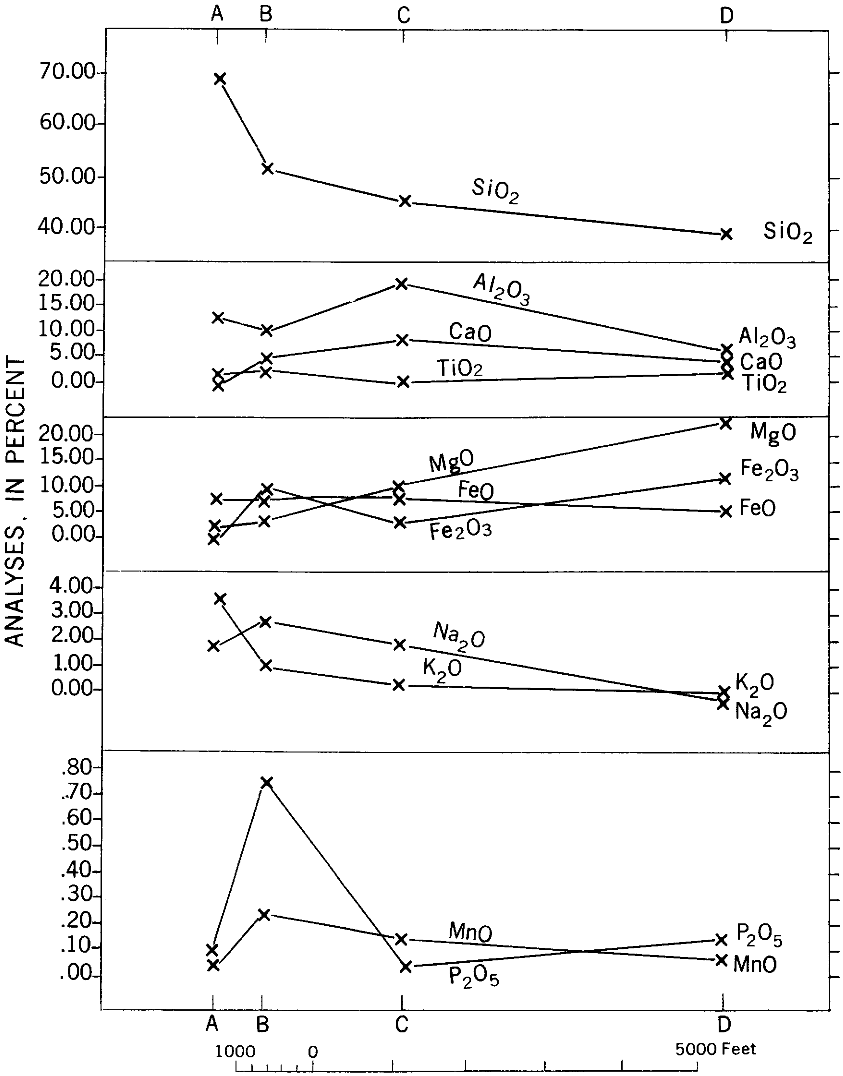

FIGURE 26.—A diagram showing variations in oxides across the West Kiernan sill. Letters *A–D* refer to the chemical analyses on page 70.

nected at depth. However, it is not known that the intrusive rocks constitute the bedrock between exposures, and the area shown on plate 1 as a single regularly shaped pluton might well have been shown as a series of apophyses in a background of metasedimentary rocks.

From structural and petrographic considerations, it appears that the complex was intruded syntectonically in the form of an elongate stocklike body, the base of which is roughly concordant with the top of the Hemlock formation, and the top being well up

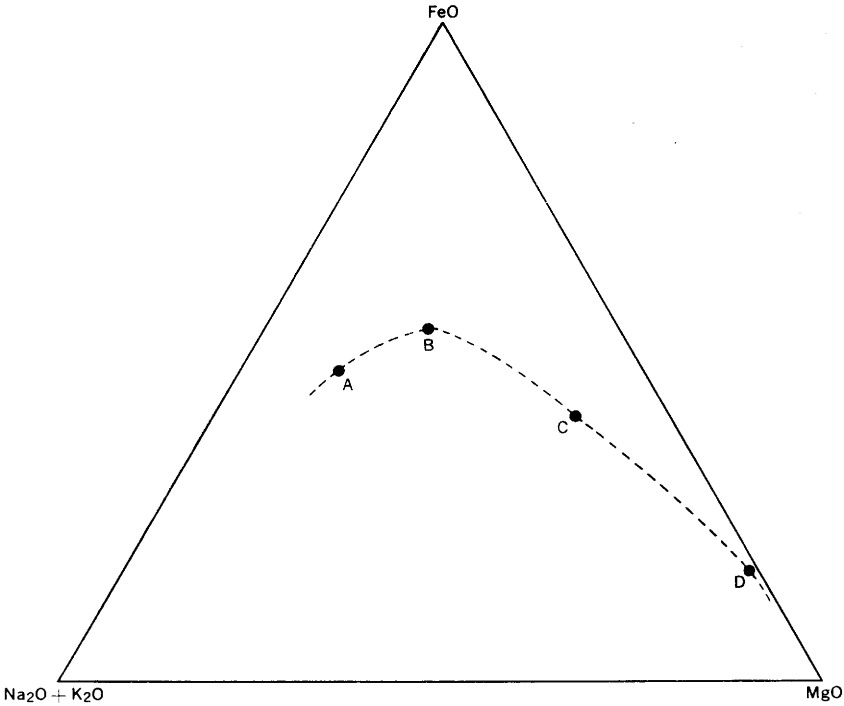

FIGURE 27.—A triangular diagram showing the proportional relationships between the oxides FeO, MgO, and Na_2O+K_2O for the four chemical analyses on page 70.

in the Michigamme slate, some of which it has assimilated, and some of which it has displaced.

Rock types and general distribution.—The intrusive rock types included in the complex are hornblende metagabbro, bronzite-hornblende metagabbro, bronzite metanorite, hornblende metadiorite, metatonalite, granodiorite, and granite.

Detailed petrographic descriptions of many of these rocks have been given by Clements (Clements and Smyth, 1899, p. 187–265), and therefore, only brief descriptions will be given here. The estimated modes of some of the rocks of the complex examined are summarized in the table below.

Of the parts of the complex now exposed, about 75 percent of the rock is hornblende metagabbro and hornblende metadiorite. Most of the igneous rocks south of and northeast of the fault in the Peavy Pond area are of these two types. The remaining 25 percent are felsic rocks, that is, tonalite, granodiorite, and granite, that are chiefly confined to the northwest edge of the complex where they are disposed roughly in bands according to decreasing basicity. Figure 28 illustrates the inferred distribution of these rocks.

Mineral modes of some rocks from the

[T, trace]

Minerals	Rock types and specimen numbers																					
		Meta-norite	Metagabbro															Metadiorite				
	Anorthosite (92)	Bronzite metanorite (23)	Bronzite-hornblende metagabbro (67)	Bronzite-hornblende metagabbro (108)	Bronzite-hornblende metagabbro (24)	Metagabbro (131)	Metagabbro (236)	Metagabbro (237)	Metagabbro (53)	Hornblende metagabbro (228)	Hornblende metagabbro (62)	Hornblende metagabbro (69)	Hornblende metagabbro (234)	Hornblende metagabbro (233)	Hornblende metagabbro (235)	Hornblende metagabbro (79)	Hornblende metagabbro (110)	Hornblende metadiorite (226)	Hornblende metadiorite (215)	Hornblende metadiorite (103)	Hornblende metadiorite (101)	Hornblende metadiorite (63)
Anorthite in plagioclase	52	---	55	57	50	65	58	57	---	58	58	56	57	67	63	63	65	45	35	---	35	43
Plagioclase	96	13	60	49	60	39	40	40	26	62	65	80	66	76	55	56	60	66	62	53	69	67
Potash feldspar	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Quartz	---	---	---	3	---	---	---	---	---	---	---	2	---	---	---	---	---	---	1	---	---	---
Augite	T	---	---	---	---	---	T	---	---	---	T	---	---	---	---	---	5	---	---	---	---	---
Enstatite	---	67	10	3	15	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Hornblende	4	17	30	33	24	60	60	55	73	37	35	16	34	22	45	40	35	21	35	43	13	33
Biotite	T	2	T	10	1	T	---	5	1	1	T	2	T	T	T	4	T	6	2	4	16	T
Muscovite	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Chlorite	---	T	---	---	---	---	---	---	---	---	T	---	---	---	---	---	---	1	T	T	---	T
Sericite	---	T	T	T	T	T	---	T	T	T	T	T	T	---	---	---	T	T	---	T	T	T
Serpentine	---	T	T	---	---	---	---	---	---	---	---	T	---	T	---	---	T	T	---	---	T	---
Epidote	---	---	---	---	---	---	T	T	---	---	T	T	---	---	---	---	---	---	---	T	---	T
Allanite	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	T	---	---	---
Apatite	---	---	T	---	---	---	---	---	---	---	T	T	---	---	T	---	---	T	---	T	T	T
Titanite	---	---	T	---	---	---	---	---	---	---	T	---	---	---	---	---	T	---	T	T	1	---
Iron ore	T	T	T	2	T	T	T	T	T	T	T	T	T	T	T	T	T	4	T	T	1	T
Rutile	T	---	---	---	---	T	---	T	---	---	---	---	---	T	T	T	---	---	---	T	---	---
Zircon	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Carbonate	---	---	---	---	---	---	T	---	---	---	---	---	---	---	T	---	---	---	T	---	---	---

MAFIC AND ULTRAMAFIC ROCKS

The hornblende metagabbro, bronzite-hornblende metagabbro, bronzite metanorite, and the hornblende metadiorite are all dark, holocrystalline, medium- to coarse-grained rocks, composed chiefly of hornblende and plagioclase. They generally have hypautomorphic textures, but porphyritic, diabasic, and parallel textures characterize some varieties.

HORNBLENDE METAGABBRO

The hornblende metagabbros form the bulk of the complex. They are gray, greenish-gray, or black rocks, composed almost entirely of labradorite (An_{50}–An_{70}) and hornblende. Variations in the amounts of the two main constituents lead to melagabbros containing over 60 percent of hornblende, and to anorthosites containing over 90 percent of labradorite. The melagabbros are common in some parts of the complex, but the anorthosites are rare.

Peavy Pond complex, Lake Mary quadrangle

[T, trace]

Rock types and specimen numbers—Continued																											
Metadiorite—Con.						Metatonalite							Granodiorite										Granite				
Hornblende metadiorite (76)	Hornblende metadiorite (77)	Hornblende metadiorite (220)	Hornblende metadiorite (78)	Hornblende metadiorite (104)	Hornblende metadiorite (208)	Biotite metatonalite (67a)	Biotite metatonalite (195)	Quartz metatonalite (102)	Hornblende metatonalite (82)	Quartz metatonalite (86)	Hornblende metatonalite (82a)	Hornblende metatonalite (83)	Biotite granodiorite (187)	Granodiorite (109a)	Granodiorite (dike) (70)	Granodiorite (175)	Quartz granodiorite (dike) (209)	Granodiorite (dike) (50)	Quartz granodiorite (90)	Quartz granodiorite (87)	Granodiorite (188)	Quartz granodiorite (dike) (174)	Granite (189)	Granite (dike) (51)	Granite (dike) (50a)	Aplite (dike) (177)	Granite (203)
48	45	41	35	36	40	33	25	32	32	28	27	38	29	28	22		10	15	10	23	15	5	28	10	10	10	
85	59	56	80	91	59	36	53	32	76	40	67	72	40	52	45	45	34	35	36	40	42	41	27	1	24	10	10
																25	20	32	15	10	23	15	46	80	48	45	70
T		1	2	2	1	13	15	33	11	50	19	11	45	32	30	25	39	26	44	45	27	42	19	17	28	44	15
	T		T	T					T																		
10	38	39	18	7	40	10	5	3	10	5	11	10															
3	3	4		T	T		26		3	5		7	15	12	4	5	3	3		5	4		8	1	T	1	5
													T	T		T	4	4	3	T	3		T	1	T		
			T	T	T	40		32		T	3			T	T				2		T	2	T		T		
T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
			T		T	T	T	T		T	T	T	T	1	T	T	T		T	T	T	T			T	T	
						T	T			T	T		T		T						T	T	T			T	
T		T	T	T	T	T	T	T	T	T	T	T	T	T		T	T		T		T						T
1			T		T		1		T			T	T	T			T			T							T
1			T	T		T	T	T	T			T							T								
T																	T										
		T				T	T	T					T	T				T	T				T				T
				T					T	T							T	T									

The metagabbro is not a foliated rock, but it has been extremely granulated in places. The chief textural variety is porphyritic. The porphyries contain about 65 percent labradorite, about 35 percent hornblende, a minor quantity of biotite, and accessory titaniferous iron ore and apatite. The labradorite forms laths and equidimensional anhedral crystals 1–6 mm long, most of which are strained or crushed. The crystals are usually slightly sericitized but rarely saussuritized. Secondary biotite and hornblende grows in the cracks of some crushed crystals.

Hornblende is present in the metagabbro in a variety of colors and shapes. The prevalent kinds are either pale green to nearly colorless, bluish green, or brown. In the common porphyry there are two hornblendes: a pale-green anhedral hornblende that occurs with labradorite in a hypautomorphic groundmass, and a dirty-brown hornblende that forms poikilitic metacrysts. Neither of the hornblendes is primary, and the pattern of their develop-

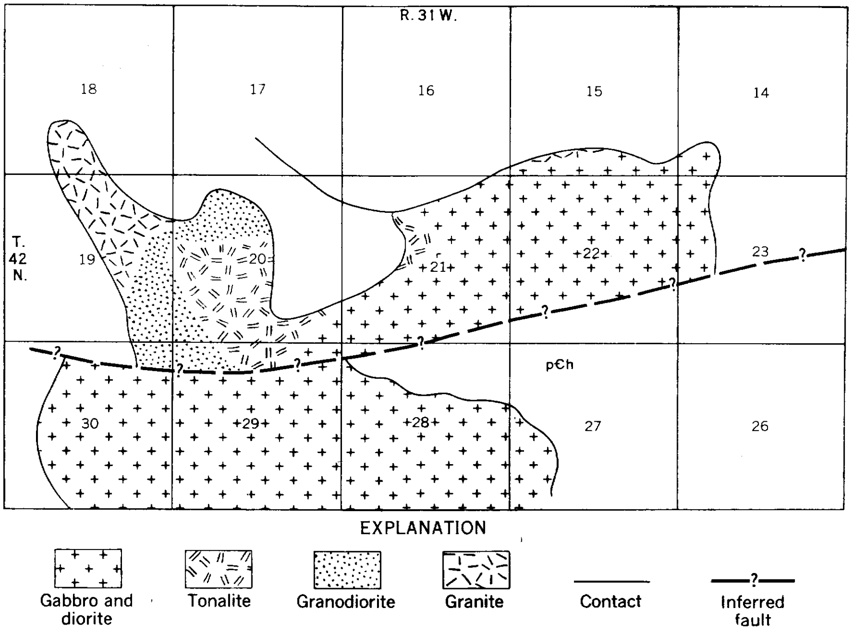

FIGURE 28.—Map showing the distribution of the igneous rock types in the Peavy Pond complex, T. 42 N., R. 31 W., the Lake Mary quadrangle, Iron County, Michigan.

ment in the gabbro is identical with the pattern of development of similar secondary hornblende in the pyroxene hornfels already described (p. 51).

Most of the pale-green hornblende is pseudomorphic, probably after a diopsidic augite, and still shows remarkably well the basal parting of the pyroxene (fig. 29). The brown hornblende metacrysts have formed at the expense of the pyroxene and labradorite of the groundmass, and probably also the titaniferous opaque mineral of the rock. The metacrysts are roughly oval-shaped, as much as 2 cm across. Commonly the brown hornblende of the metacrysts may be seen to grade into the pale-green hornblende of the groundmass. The brown hornblende contains laths and fragments of labradorite, and occasional remnant blebs of colorless clinopyroxene (fig. 30). It is generally heavily charged with opaque dust and needles. The metacrysts are not deformed, and since they now contain fragments of labradorite incorporated from the granulated groundmass, the time of hornblende development in the gabbros is dated as definitely postdeformation.

In other metagabbros, the hornblende may be green, brown, green and brown mottled or zoned. Small globular remnants of colorless to pale-green clinopyroxene are locally present within the hornblende. A green to dirty-brown hornblende in elongate prismatic crystals containing schiller inclusions usually characteristic

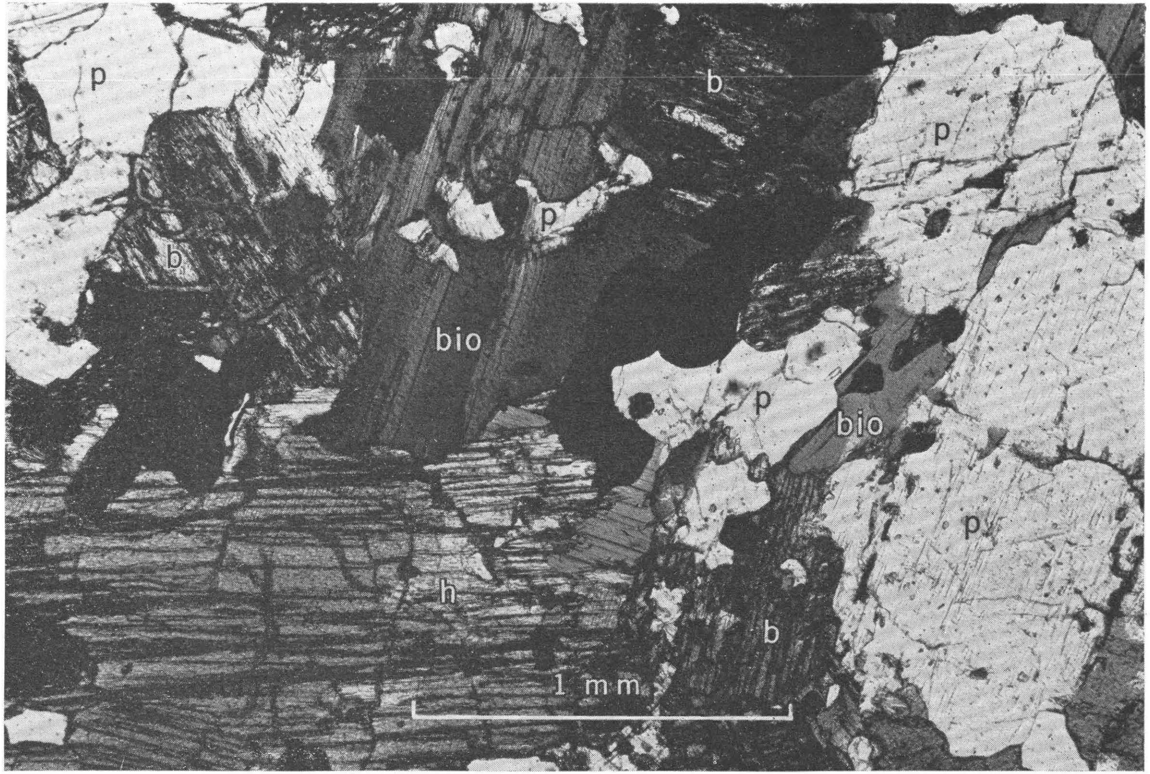

FIGURE 29.—Photomicrograph of bronzite-hornblende metagabbro. ×50, ordinary light. Showing hornblende (*h*) pseudomorphic after clinopyroxene with well formed basal parting, lower left. Biotite (*bio*) containing fragments of labradorite (*p*) and altered euhedral bronzite (*b*), upper central part. Specimen RB–108–51.

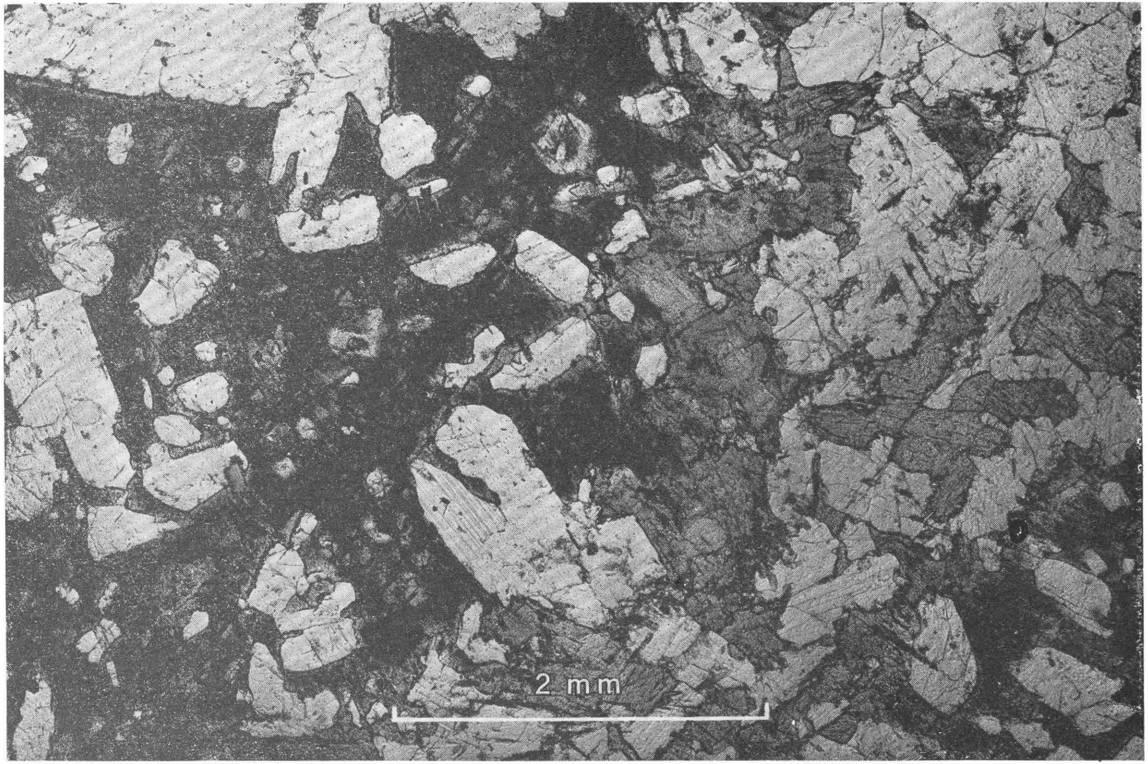

FIGURE 30.—Photomicrograph of poikilitic metacrysts of brown hornblende in metagabbro. ×25, ordinary light. Showing embayed laths and fragments of labradorite (white) in hornblende (dark). Color halos have formed around partly assimilated fragments. Specimen RB–235–52.

of hypersthene occurs in a few specimens. The opaque needle inclusions (some of which are rutile) are often oriented parallel to the 010 and the 001 planes of the replaced orthopyroxene and intersect at approximately 90°.

Pale-brown biotite is sparingly present in the gabbro. In some rocks the biotite appears to have formed concomitantly with the hornblende, but in others it has definitely formed at the expense of the secondary hornblende. In biotite formed from hornblende, the opaque dust and needles from the replaced brown hornblende are collected into globules of sphene, some of which have opaque cores. In a few specimens the alteration has progressed somewhat further than that already described, and minor quantities of chlorite, epidote, clinozoisite, sphene, and calcite have been formed. The low temperature alteration is local and spotty in the gabbros and diorites, and was probably contemporaneous with the local, hydrothermal, retrograde metamorphism that affected some of the metasedimentary rocks.

BRONZITE-HORNBLENDE METAGABBRO

The bronzite-hornblende metagabbro is similar to the hornblende metagabbro with the exception that the former contains as much as 15 percent of colorless euhedral bronzite. The modes of several specimens of bronzite-hornblende metagabbro are given on page 78. The bronzite-bearing rocks are holocrystalline, medium to coarse grained, and gray to black. The texture in general is hypautomorphic, modified somewhat by mild granulation and the growth of alteration minerals. The hornblende has been derived from a clinopyroxene (fig. 29) as in most of the metagabbro. Biotite, in amounts of as much as 10 percent, is present as a late alteration mineral partly replacing all the other minerals except perhaps the bronzite, which alters to serpentine and tremolite. Biotite containing fragments of labradorite and altered bronzite crystals is shown in figure 29.

BRONZITE METANORITE

A single specimen of bronzite metanorite was collected from a small isolated outcrop in the SE¼NE¼ sec. 21, T. 42 N., R. 31 W. The rock is dull greenish brown and fine to medium grained, and in addition to the usual minerals of the metagabbro it contains 67 percent of bronzite (p. 78). The original rock contained a pale-green clinopyroxene that is present now only as small remnants in pale-brown hornblende. The hornblende and the biotite together have replaced the clinopyroxene and some of the bronzite; however, both the hornblende and the biotite may contain euhedral crystals of bronzite that have partly altered to talc. The small amount of labradorite present is poikilitic with inclusions of bronzite (fig. 31).

This rock is similar to bronzite norite described by Clements (Clements and Smyth, 1899, p. 244–246) from exposures along the Michigamme River in sec. 29, T. 42 N., R. 31 W., now submerged in the waters of Peavy Pond. In the above locality, the norite occurs as dikes cutting the hornblende metagabbro of the complex.

METADIORITE

The close relationship of the metadiorite to the metagabbro is perhaps best illustrated by comparing the modes of these rocks. (See p. 78.) No determinable boundary exists between the metadiorite and the metagabbro in the field; they represent a single gradational unit. The plagioclase (An_{35}–An_{50}) of the metadiorite is slightly zoned, moderately sericitized, and commonly mildly granulated. Both green and brown hornblende may be present, the green variety being most abundant. The derivation of the hornblende from clinopyroxene is clearly indicated as in the metagabbro, and traces of the original pyroxene are present in some of the hornblende. Pale-brown biotite is present, and in one specimen exceeds the hornblende in amount. Much of the biotite appears to have formed by the replacement of the hornblende. Haloed inclusions of zircon, apatite, or epidote-mantled allanite are often present in the biotite. Quartz is present in traces.

INTERMEDIATE AND FELSIC ROCKS

METATONALITE

Mineralogically some of the metatonalite has much in common with the metadiorite of the complex and it appears to be gradational with it. In the field it can be distinguished from the metadiorite by its content of visible biotite and quartz, but it cannot readily be separated from the granodiorite. Most of the metatonalite is a gray rock, but some of it is reddish brown. Both massive and foliated types occur. The massive varieties are fine to medium grained, xenomorphic or hypautomorphic granular, and some are porphyritic. The foliated varieties are biotite-rich schist and gneiss. Both the massive and the foliated varieties of metatonalite have intimately intruded the metasidementary rocks of the Michigamme slate, and contain abundant xenoliths of mica schist and granulite. The mineral variations in some of the metatonalite examined are shown on page 78.

Plagioclase (An_{27}–An_{38}) is present in stubby anhedral and euhedral individuals as much as 5 mm in length. They are zoned,

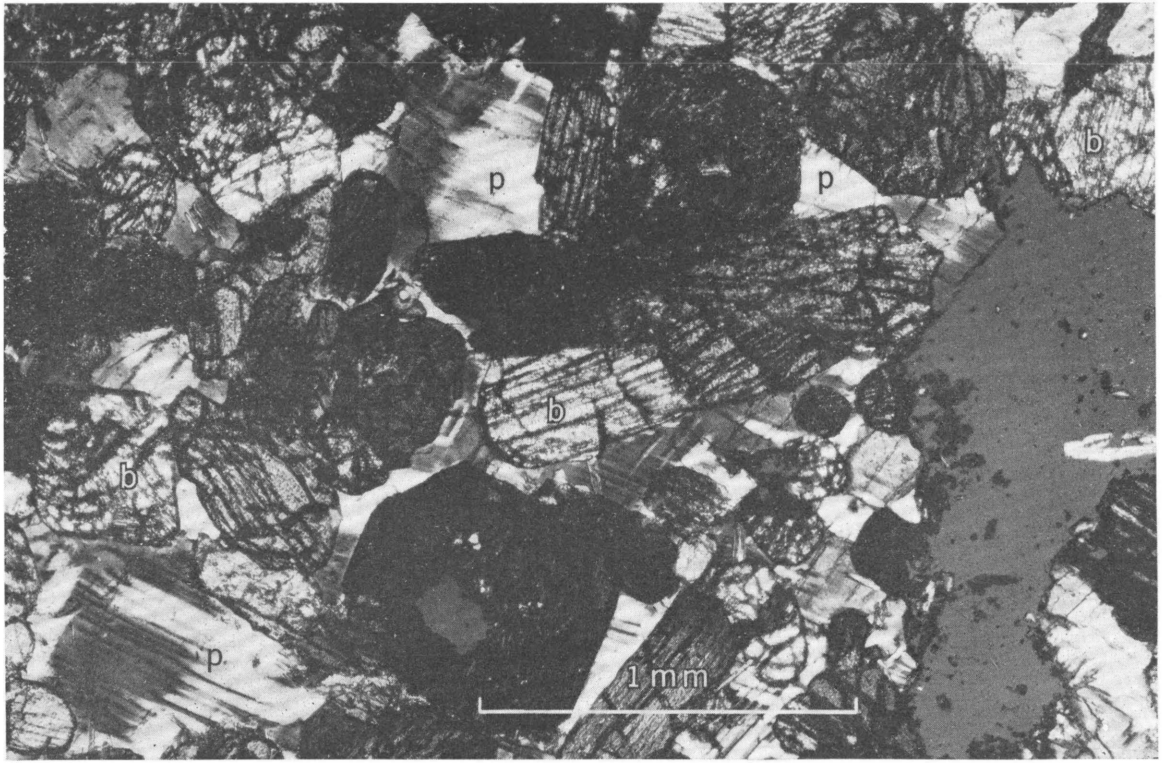

FIGURE 31.—Photomicrograph of bronzite metanorite. ×50, crossed nicols. Showing euhedral bronzite (*b*) contained in poikilitic labradorite (*p*). Specimen RB–23–53.

partly sericitized, and crushed. Characteristically there is considerable variation in the size of the plagioclase individuals present in any one specimen, which leads to a porphyritic texture. The plagioclase generally conforms to three habits in both the tonalite and granodiorite: (1) well-formed laths or anhedral crystals of equal size, probably of igneous origin; (2) tiny zoned crystals intergrown granoblastically with quartz, probably derived from the country rock; and (3) cloudy, irregular-shaped phenocrysts made up of a number of the smaller zoned crystals in (2) above.

Pale-green hornblende is present as a minor secondary mineral after clinopyroxene, and it has generally been partly replaced by biotite. Biotite is most abundant in the metatonalite. It is pale brown or dark brown, and forms anhedral plates and sheaves as much as 5 mm long. The biotite occurs alone apparently as a primary igneous mineral, as a replacement mineral with hornblende, and in granoblastic aggregates with quartz and plagioclase derived from the country rock. The biotite is poikilitic. It contains inclusions of one or more of the following minerals: Plagioclase, hornblende, sphene, magnetite, epidote, allanite, apatite, rutile, and zircon. Zircon, allanite, and apatite form haloed inclusions. In three specimens of tonalite the biotite has been totally chloritized.

GRANODIORITE

The granodiorite is generally a light-colored granitic rock closely associated with unfoliated granite in dikes, but small bodies of foliated rock of this composition occur intimately interfingered with mica schist of the Michigamme slate in the NW¼ sec. 20, T. 42 N., R. 31 W., and in sharp intrusive contact with mica schist and with metagabbro in the NW¼ sec. 21, T. 42 N., R. 31 W. The nonfoliated granodiorite is a fine- to medium-grained rock of granitic texture. It is composed chiefly of plagioclase (An_5—An_{28}), quartz, microcline, and biotite. Accessory and secondary minerals include magnetite, sphene, apatite, chlorite, epidote, allanite, rutile (rare), sericite, calcite, zircon, and muscovite. Hornblende is not present. The plagioclase is present in sericitized anhedral individuals of nearly equal size, many of them partly replaced by clear microcline or myrmekite. With an increase in the amount of late microcline the rocks become granite. Muscovite is present as a replacement mineral of the plagioclase. A small amount of biotite, or chlorite derived from biotite, is present in all specimens; commonly it contains one or more of the accessory minerals. The apatite, allanite, and zircon form haloed inclusions in the biotite.

The foliated granodiorite is porphyritic and somewhat gneissic, with augenlike pods of crushed plagioclase and quartz. A few percent of dark-brown biotite is present as wavy stringers about the large plagioclase crystals and dispersed between lenses of clear granular quartz and areas of granoblastic quartz, plagioclase, and biotite. The amount of microcline present is exceedingly variable. In similar appearing specimens from the same exposure it may be present in traces, replacing the granulated parts of some of the plagioclase, or it may be present as the dominant mineral of the rock as poikilitic phenocrysts containing sericitized plagioclase and quartz. Some of the microcline-poor foliates described here as granodiorites are petrographically identical with some of the porphyroblastic metasedimentary rocks of the Michigamme. Although they exist in intrusive relation with the metasedimentary rocks and with the gabbro of the complex, it is doubted that any considerable part of the rocks crystallized from a melt. They probably represent metasedimentary rocks that attained a measure of mobility by partial fusion and the introduction of small amounts of magmatic fluid from adjacent intrusive rocks, in this case highly contaminated tonalite and diorite.

GRANITE AND PEGMATITE

Foliated granite is closely associated with the granodiorite and is similar to the granodiorite except for the increased quantities of microcline. A small amount of relatively undeformed granite, pegmatite, and aplite occurs as late dikes. The granite is fine to medium grained and xenomorphic granular; it is composed of microcline, albite or sodic oligoclase, chloritized biotite, and quartz. The plagioclase is generally sericitized and colored pink with a ferruginous dust. Some of it is partly replaced by clear microcline or myrmekite, or included in poikilitic crystals of microcline along with quartz and biotite. The usual accessory minerals are epidote, epidote-mantled allanite, and zircon. The chemical analysis of a specimen of this granite collected from the SW¼NE¼ sec. 19 is given below.

Chemical analysis of a granite (specimen HJ–222–48) collected by H. L. James from the SW¼NE¼ sec. 19, T. 42 N., R. 31 W., the Lake Mary quadrangle, Iron County, Mich.

[Analysis by Leonard Shapiro, U. S. Geological Survey, 1949]

Constituent	Percent	Constituent	Percent
SiO_2	67.70	H_2O	.38
Al_2O_3	17.72	H_2O	0.08
Fe_2O_3	1.25	TiO_2	.34
FeO	2.61	P_2O_5	.13
MgO	.41	CO_2	.16
CaO	1.82	MnO	.03
Na_2O	3.16		
K_2O	4.12	Total	99.91

The pegmatite is a white coarse-grained rock, composed of potash feldspar, micropegmatite, quartz, sodic oligoclase, and mica. The potash feldspar individuals are most commonly 1–2 inches in length, but large crystals over 1 foot in length occur in some of the pegmatite bodies. Pegmatite dikes as much as 250 feet in length and 100 feet in width cut the rocks of the igneous complex and the adjacent metamorphic rocks in many places. Some of the pegmatite dikes cutting the metamorphic rocks have been mildly granulated since emplacement. A few small aplite dikes cut the granite.

INTERNAL AND EXTERNAL RELATIONSHIPS OF THE COMPLEX

The Peavy Pond complex is, in many ways, like the rocks of the West Kiernan sill already described. The initial magma of each of these intrusive rocks was gabbroic. But, whereas the Kiernan magma was emplaced chiefly by physical displacement of basaltic country rock, and whereas it differentiated normally, crystallizing chiefly to gabbro with a small percentage of granophyre in the upper part, the Peavy Pond gabbroic magma intruded siliceous graywacke and slate, much of which it assimilated, thus giving rise to various intermediate and felsic magma types.

The Peavy Pond gabbroic magma was intruded syntectonically as a sheetlike body roughly concordant in its major dimension with the layered rocks of the Hemlock and Michigamme formations. The magma was emplaced partly by physical displacement of the country rock, but chiefly by assimilation of the country rock, particularly the graywacke and slate of the Michigamme. Intrusion by displacement is particularly characteristic of the felsic parts of the complex, most of which occur as dikes that have sharp selvages and that have been intruded parallel to the bedding in the Michigamme slate or in fractures in the Hemlock formation and the mafic intrusive rocks of the complex. Displacement of the country rocks by the main mass of the complex may be indicated by the divergent strikes between the Michigamme rocks in sec. 20, and those in sec. 21, T. 42 N., R. 31 W. Evidence of emplacement by assimilation is most impressive. In the northwest part of the Peavy Pond area of the Michigamme rocks strike southeast into discordant contact with the intrusive rocks of the complex. In a few places, especially in the SE¼ sec. 20, T. 42 N., R. 31 W., the metasedimentary rocks may be seen to pass along the strike into a narrow, contorted migmatite zone, beyond which is igneous-looking metadiorite containing metasedimentary xenoliths. The mafic and intermediate intrusive rocks of the complex contain abundant pendants and xenoliths whose attitude and distribution suggest strongly that a large part of the Michigamme slate has been replaced in space by the intrusive rocks, probably by stopping and assimilation.

The decreasing basicity of the intrusive rocks of the complex toward the northwest in the Peavy Pond area (fig. 28) goes hand in hand with the increasing amount of undigested metasedimentary material contained in these rocks, clearly indicating that contamination by assimilation was a major factor in determining their present composition. Although assimilation of siliceous country rock by the gabbroic magma is probably the primary cause for the decreasing basicity in these rocks, it is thought probable too, that the siliceous and alkaline residuum from the cooling magma also collected in the northwest part of the complex.

Most of the Peavy Pond magma crystallized as gabbro. In the other rocks of the complex that can be definitely related petrographically to the original gabbroic magma, there appears to be a gradual transition to more felsic types as xenolithic metasedimentary material becomes more and more predominantly a part of the rocks. In this category are the metadiorite and some of the metatonalite, and although they have undoubtedly incorporated large quantities of sedimentary rock, petrographically they have an igneous aspect, and it is concluded that the assimilation was complete and that the foreign material was distributed in the melt. Associated with the latter rocks is another group of rocks, especially well exposed in the NW¼ secs. 20 and 21, T. 42 N., R. 31 W., which have developed marginal to the metagabbro, and which mineralogically have more in common with some of the porphyroblastic metasedimentary rocks. This group of rocks also includes tonalite (which is the approximate composition of the metasedimentary rocks involved), granodiorite, and granite. These rocks all contain more or less igneous material, and varying quantities of xenolithic material. The metasedimentary material is so prevalent in some of the rocks, that the igneous phase could not have amounted to more than a small fraction of the total composition. Such rocks appear to have developed by reaction of magmatically derived fluids on the metasedimentary rocks. The igneouslike granodiorite in the NW¼ sec. 20, T. 42 N., R. 31 W., may have formed in the above described manner.

On the east side of the large isolated hill in the center of the NW¼ sec. 21, T. 42 N., R. 31 W., light-colored igneouslike porphyritic rocks occur in sharp intrusive contact with fine-grained mica schist and metagabbro. The porphyry is foliated and uniform in appearance, yet varies in mineral composition from tonalite to granite. The tonalite contains phenocrysts of zoned plagioclase and is similar in mineral composition to porphyroblastic metasedimentary rocks intruded by metadiorite on the west side of the same hill. The tonalite grades into granodiorite where part of the plagioclase is replaced by microcline, and grades into granite at some points in the outcrop where microcline, as poikilitic phenocrysts including altered plagioclase and quartz, becomes prominent. These rocks, though igneouslike in appearance and in intrusive contact against the adjacent rocks, also may have evolved from the sediments. They were probably rendered porphyroblastic by action of heat and fluids from adjacent magma, and acquired a moderate degree of mobility under the late orogenic stresses.

The rocks thought to represent the siliceous and alkaline residual melt of the complex are generally even-grained granitic rocks with an igneous appearance. Mineralogically they are quartz tonalite, granodiorite, granite, and granite pegmatite. The first three are similar in character; they contain a red sericitized soda-rich plagioclase, and the only potash feldspar in microcline, which is present in varying amounts and has characteristically formed late along with small quantities of myrmekite replacing the plagioclase. The pegmatite is composed essentially of potash feldspar, quartz, and mica. These felsic rocks form dikes and stringers that cut all the rocks of the complex and the country rocks as well.

The times of intrusion of the rocks of the complex with reference to the intensity of deformation and regional metamorphism are shown diagrammatically in figure 32. With reference to the

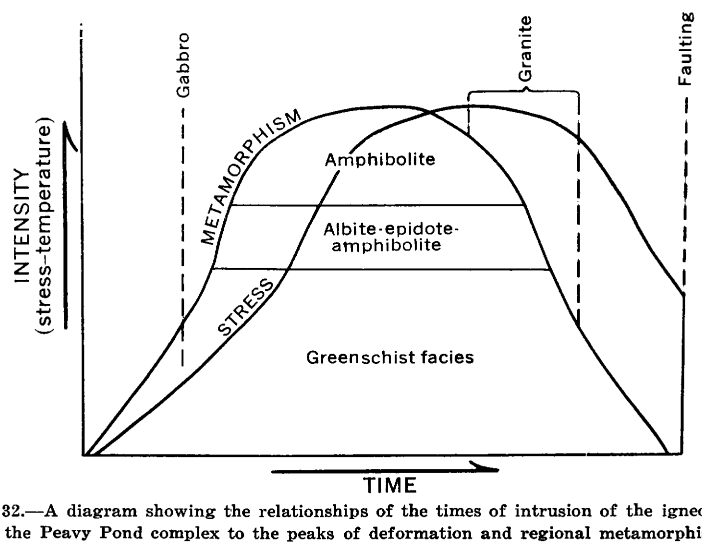

FIGURE 32.—A diagram showing the relationships of the times of intrusion of the igneous rocks of the Peavy Pond complex to the peaks of deformation and regional metamorphism.

deformation, it is known that the complex was present and influential in controlling the gross structure of the area. However, as will be discussed later, only the basic parts of the complex had crystallized before the peak of deformation.

The development of normally zoned plagioclase in the metasedimentary and metavolcanic rocks near the intrusive rocks of the complex is interpreted to mean that the complex was intruded rapidly, early in the period of deformation and metamorphism, in that calcic feldspar would be stable at high temperatures, and the normal zoning of the plagioclase would represent an adjustment to lower metamorphic temperatures as the igneous mass cooled. The cooling of the mass was undoubtedly slow, high temperatures being sustained longer than normal, because it was intruded into an area undergoing regional metamorphism (fig. 33). Since many of the metasedimentary rocks containing zoned plagioclase are schist, and since parts of the Peavy Pond complex are schistose, it seems reasonable to conclude that the formation of the tiny calcic cores of the plagioclase preceded the development of the schistosity, thus establishing a very early date for the intrusion of the complex with reference to the deformation.

With reference to the regional metamorphism, it is known that the intrusion of the complex preceded the peak of regional metamorphism, because the contact metamorphic pyroxene hornfels adjacent to the mafic rocks of the complex, and the mafic and in-

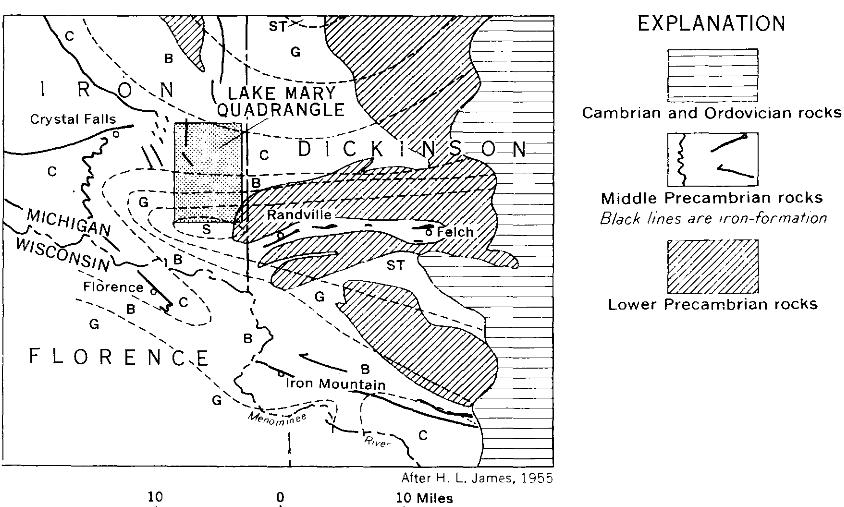

FIGURE 33.—A generalized geologic map of part of northern Michigan and adjacent parts of northern Wisconsin showing metamorphic zones in the Precambrian rocks. Symbols: *C*, chlorite; *B*, biotite; *G*, garnet; *ST*, staurolite; *S*, sillimanite. After H. L. James (1955).

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termediate rocks of the complex as well, have been altered by high grade regional metamorphism. It is known that the cataclastic deformation of the gabbro preceded its metamorphism, because some of the metamorphic hornblende has grown in the cracks of crushed labradorite crystals and because some of the hornblende contains fragments of such crystals. The cataclastic deformation of the gabbro is correlated with peak-of-stress conditions in the neighboring metasedimentary rocks, during which porphyroblastic minerals, such as staurolite and garnet, were alined and deformed. It is assumed that the porphyroblasts in the metasedimentary rocks attained their greatest size at the peak of regional metamorphism, and that the succeeding deformation of the porphyroblasts represents the peak of deformation. Actually the two may not be very far apart in time, because after the proposed peak of deformation the temperature in the metamorphic node was still high enough to facilitate the hornblendization of the mafic and intermediate rocks of the complex, and, perhaps even high enough to form sillimanite (p. 60).

East of the Peavy Pond, in the Felch district, in the same node of regional metamorphism, James (1955) has determined that the peak of metamorphism came later than the peak of the deformation. The difference between the two areas in this respect may be due to the intrusion of the Peavy Pond complex early in the orogeny in the Peavy Pond area.

At the peak of deformation (as defined) the solid body of mafic rocks deformed competently by fracturing and intense internal crushing. The granulated rocks were probably infiltrated by solutions at this time, and hornblendization was begun. At the same time, most of the marginal rocks, including metadiorite, metatonalite, and granodiorite, together with the adjacent metasedimentary rocks, became strongly foliated. The granitic residual magma in the northwest of the complex was still fluid however, and reacted to the deformation accordingly. The fluid magma, perhaps augmented by solutions pressed out of the marginal foliates, was injected under orogenic pressure as concordant dikes and lenses into the metasedimentary rocks, into fractures in the metavolcanic and igneous rocks, and into the "weak" contact zone between the complex and the Hemlock formation. Most of the granitic magma emplaced near the peak of deformation, crystallized after movement in the rocks had abated and does not show effects of the deformation. This is particularly true of the granodiorite and granite dike rocks that were intruded into the structurally competent mafic igneous rocks of the complex, but a number of granitic dikes cutting the metasedimentary and metavolcanic schists have been mildly granulated by later movements in the schist. Also, in the NE¼ sec. 30, T. 42 N., R. 31 W., where the bulk of the granite of the complex was intruded as a concordant fingerlike dike into the schist, and as minor lit-par-lit injections in the contorted schist, late movements in the schist culminating in major faulting caused extreme brecciation in the solid granite.

The effects of the gabbroic magma on the invaded metasedimentary rocks of the Michigamme slate are of three kinds: (1) much of the sedimentary rock was totally assimilated, especially by the distal parts of the sheet. This is indicated by the confused, intricately swirled, discordant contacts between the mafic intrusive rocks of the complex and the metasedimentary rocks, especially well exposed in the SE¼ sec. 20, T. 42 N., R. 31 W.; (2) some igneouslike rocks were formed metasomatically; and (3) fine- to medium-grained hornfels was produced from the sediments marginal to the gabbro and diorite, and in isolated rafts within the body of the intrusive rock. Some of the hornfels thus produced, lying within or close to the competent intrusive rock, was protected from the intense shearing that deformed the adjacent metasedimentary rocks at the peak of deformation.

The effects of the invading gabbroic magma on the basic volcanic rocks of the Hemlock formation is of two kinds: (1) concordant volcanic beds were altered chiefly to high-grade hornblende-plagioclase schist, although the schistosity may reflect deformational stresses that reached their peak long after the gabbro was emplaced. The hornblende schist that makes up the ridges north of Peavy Pond is rock of this type; and (2) volcanic rocks close to, and in discordant contact with the intrusive gabbro were altered to hornblende and pyroxene hornfels. The pyroxene hornfels approaches the composition of the gabbro, and included masses were probably stable in the cooling magma. The metagabbro contains pyroxene hornfels in the south-central part of sec. 15, the SW¼ sec. 14, the NE¼ sec. 28, and near the center of sec. 29, T. 42 N., R. 31 W. The hornfels has generally been protected from deformation in the body of the gabbro, but sheared hornfels occurs at the northeast margin of the gabbro in the SW¼ sec. 14, T. 42 N., R. 31 W.

Local retrograde hydrothermal alteration noted in some of the metasedimentary rocks of the Michigamme slate was probably caused by late emanations from the crystallizing granitic magma. Granitic dikes and small stringers cutting the metavolcanic rocks produced only retrograde metamorphic effects. Biotite, chlorite, and epidote minerals were produced from the hornblende schist at dike selvages and along small granitic stringers. From the structural relationship of the granitic dikes to the schist, and the nature of the contact alteration, it is reasonably certain that the peak of metamorphism had passed before intrusion, and that very little deformation took place after the intrusion.

The metamorphic effects at the selvages of granitic dikes cutting the basic igneous rocks of the complex are also low temperature hydrothermal. Usually chlorite and epidote have been formed at the expense of the hornblende, and the plagioclase has been saussuritized.

Where the granitic fluids were forced into the contact zone between the metagabbro of the complex and the hornblende schist of the Hemlock formation, the fluids reacted with the hornblende schist to form biotite gneiss. Usually no potasic feldspar is present in the gneiss, the potassium having been depleted by reaction with the hornblende to form biotite. The gneiss is generally dioritic or tonalitic, and locally it contains abundant black tourmaline, but rather pure granite in stringers and lenses occurs within the gneiss belt in a few places. Such a granite lens, containing a few large angular blocks of the metagabbro, occurs in the SW¼ sec. 14, T. 42 N., R. 31 W.

As a brief résumé, it appears from field relationships and petrographic data that the slate and graywacke of the Michigamme have reacted with a gabbroic magma to produce dioritic and tonalitic magma and an acidic residuum. Metasomatic reactions of the residuum with the graywacke and slate and with the tonalite produced some granodiorite and granite. Where siliceous and alkaline solutions permeated the hornblende schist of the Hemlock formation, dioritic or tonalitic biotite gneiss was formed, and it seems likely that similar solutions are chiefly responsible for the present metamorphic character of the metagabbro and related rocks of the complex.

The probable constituents of the solutions as deduced from the mineral changes involved and the material available for reaction within the rocks includes the following components: H_2O, CO_2, K_2O, Na_2O, SiO_2, Al_2O_3, B, and F.

UPPER PRECAMBRIAN ROCKS

DIABASE DIKES OF KEWEENAWAN AGE

Small diabase dikes cut the rocks of the Hemlock formation and the West Kiernan sill. Several of these dikes a few inches to 3 feet thick cut the hornblende schist of the Hemlock in the ridge north of Peavy Pond. A similar small dike cuts the metagabbro of the West Kiernan sill in the NW¼ sec. 21, T. 43 N., R. 31 W.

The dikes are fine grained, dense, and slightly iron stained on the exposed surface. They generally show chilled borders against the country rock. The dikes have intruded metamorphic rocks and have not been metamorphosed themselves, and therefore were intruded after the epoch of post-Animikie metamorphism. They are believed to be related to a swarm of diabasic dikes, most of which possess inverse magnetization, that invaded the region probably during Keweenawan time (Balsley, James, and Wier, 1949).

The dike rock from sec. 21 is fine grained and shows good diabasic texture. The primary minerals present are labradorite (An_{63}), pigeonitic pyroxene, and magnetite. A minor quantity of pale bluish-green uralite is present as an alteration product of the pyroxene. Very minor quantities of the alteration minerals chlorite and epidote also are present.

The dike rocks from the ridge of hornblende schist north of Peavy Pond are fine-grained olivine diabases. The primary minerals present are labradorite (An_{62}), diopsidic pyroxene, olivine, and magnetite. The labradorite forms tiny, twinned, and faintly zoned laths; some of the laths are altered in spots to sericite. The pyroxene is pale brown and is interstitial to the labradorite. A small amount of pale-green uralite, containing opaque dust, replaces some of the pyroxene. The olivine is in clumps of euhedral to anhedral crystals. Some of the crystals have been partly replaced by serpentine and magnetite.

STRUCTURE

The structural environment of the Lake Mary quadrangle is shown in figure 2. The southeastern extension of the general Amasa oval structure into the Lake Mary quadrangle, referred to by Gair and Wier (1956) as the greenschist uplift, and here called the Holmes Lake anticline, is the major structure involving all the rocks in the quadrangle (pls. 1 and 2). The crest of the Holmes Lake anticline strikes northwestward through the northeast quarter of the quadrangle. It is separated from the Amasa oval structure in the crest area by a saddle of eastward-trending cross folds in the vicinity of Michigamme Mountain. It is bounded on the east by a synclinorium called the Sagola basin (Pettijohn, 1951), and on the west by the Iron River–Crystal Falls synclinorium. To the southeast, the Holmes Lake anticline expands and probably includes the Lower Precambrian rocks of central Dickinson County in its core.

In the Lake Mary quadrangle, the core rocks of the anticline are magnetic volcanic schist of the Dickinson group. The schist is overlain by the Randville dolomite, which is in turn overlain by the Hemlock formation and the Michigamme slate, all of which dip steeply away from the anticlinal structure (see cross section *A–A′*, pl. 1). Consistent top directions in ellipsoidal basalts in the northern half of the quadrangle indicate that the west limb is probably not complicated by any significant folds.

The segment of the west limb of the Holmes Lake anticline in the north half of the quadrangle strikes nearly north and is crossed by many small secondary folds and several faults. The secondary folds may be best observed in the lower slate of the Mansfield iron-bearing slate member of the Hemlock formation exposed along the east side of the Michigamme River in sec. 20, T. 43 N., R. 31 W., where a series of westward-plunging minor folds have formed. The sill rocks and the volcanic flow rocks have generally reacted competently to these secondary stresses and have deformed by faulting or jointing, whereas the volcanic breccias that make up the western part of the Hemlock reacted incompetently; an axial plane foliation has been formed in these rocks transverse to the major structure, into which the elongate fragments of the rock have been rotated. The foliation in the breccia is thought to reflect a series of tight transverse folds and possibly fold-faults. Geologic work now in progress west of Lake Mary quadrangle may prove or disprove this interpretation. One of the largest of these faults shown on the geologic map of Iron County (Barrett, Pardee, and Osgood, 1929) in secs. 25 and 26, T. 43 N., R. 32 W. is thought to enter the Lake Mary quadrangle in sec. 36, T. 43 N., R. 32 W., and to cut diagonally across sec. 31, T. 43 N., R. 31 W., displacing the Hemlock and the included Mansfield iron-bearing slate member. The attitude of the fault plane is not known. The relative horizontal displacement is about 1,250 feet. This fault is believed to extend for some undeterminable distance to the southeast along the valley of the Michigamme River in sec. 5, T. 42 N., R. 31 W. (pls. 1 and 5).

Of the minor faults affecting the rocks of the West Kiernan sill and the rocks of the adjacent Hemlock formation, the fault shown in the center of sec. 20, T. 43 N., R. 31 W. is probably related to the intrusion of the sill rocks. The slate and greenstone north of the fault appear to have been displaced eastward as a tongue of the sill rock split the basal slate of the iron-bearing slate member. The next two faults to the south in secs. 29 and 32, T. 43 N., R. 31 W. are inferred from field mapping and magnetic surveying (pl. 4); they are roughly parallel to a prominent set of northwestward-striking shear joints in the southern part of the West Kiernan sill. If the attitude of the fault planes is similar to the attitude of the joint planes, they probably dip steeply to the northwest.

Strongly sheared sill rocks in the north block of the fault in the NW¼ sec. 29, T. 43 N., R. 31 W., indicate that the movement there may have been horizontal, the north side moving west relative to the south side. The apparent horizontal displacement is about 550 feet for the north fault and about 1,200 feet for the south fault.

Minor faults in the southern extremity of the West Kiernan sill in the SW¼ sec. 32, T. 43 N., R. 31 W. and NW¼ sec. 5, T. 42 N., R. 31 W. are based on detailed geologic mapping and magnetometer surveying (see pls. 5 and 6). Only the important faults are shown on the maps. The structure of that general area is complicated by many small faults, some of them very low-angle thrusts, and by the contorted condition of the sedimentary beds. The positions of the faults have generally been approximated. The three southernmost faults lying east of the river appear to be reverse faults developed under compression. The eastward-trending fault in sec. 5, T. 42 N., R. 31 W. is marked by a zone of extremely sheared slate and vein quartz dipping steeply north. The amount of displacement is uncertain. The two southernmost, east-trending faults in sec. 32, T. 43 N., R. 31 W., are apparently opposed reverse faults on either side of a graben block containing iron-formation. Evidence for faulting on the south side of the graben is a south-dipping shear zone in strongly lineated, cherty, iron-rich rocks. Also, and this is the case on the north side of the graben as well, the cherty, iron-rich rocks of the Mansfield, and the overlying volcanic conglomerate and schist are in contact, along the faults, with dark-colored slate that probably represents the lower part of the Mansfield member; a lateral offset of several hundred feet is indicated by the map pattern.

The northernmost fault in the SW¼ sec. 32, T. 43 N., R. 31 W., is inferred chiefly on magnetic data (see pl. 6). The magnetic anomaly north of the fault is caused by iron-formation. The magnetic influence of the iron-rich beds diminishes gradually over a broad fan-shaped area south and west of the proposed fault, perhaps indicating that the magnetic rocks abut the fault in a tight westward-plunging anticlinal structure, and that the fault plane dips south at a moderate angle. South of the fault the iron-rich rocks are interpreted to underlie a linear area of high anomalous magnetism that has apparently been offset to the east along the fault. The nature of the fault movement has not been determined.

Through the central part of the quadrangle, the rocks strike southeast and east and are foliated parallel to the trend of the major structure. The lineation, if any, is generally directly down the dip of the foliation. But in the southern part of the quadrangle the structures in the rocks chiefly reflect the secondary folds and undulations impressed on the limb of the major structure. The rocks have been metamorphosed, and are generally well foliated. The foliation is commonly parallel to the bedding or cuts the bedding at a slight angle. Lineation is a conspicuous feature in some of the metamorphic rocks; it is shown by foliation-bedding plane intersections, crinkles, elongated calcareous concretions, podded metamorphic minerals, and oriented prismatic minerals. The linear structures are best developed in the axial regions of folds in the metasedimentary rocks, and adjacent to the Peavy Pond complex in the metavolcanic rocks.

Secondary folding in the southern part of the quadrangle centers in the area of the Peavy Pond complex, which appears to have been present as a rigid competent body during most of the deformation. The broad convex-concave upper contact of the Hemlock formation is concordant with the igneous rocks of the complex around which the Hemlock rocks stretched during folding and metamorphism producing an anomalous east-plunging linear arrangement of hornblende in the schist of the Hemlock. The south contact of the complex, which is immediately south of the quadrangle border, as far as known, is roughly parallel to the north contact, arcuate south, and concordant with schist within the Michigamme slate. Relative to the Hemlock rocks, the Michigamme rocks reacted incompetently to the deformational stresses and whereas the Hemlock rocks warped into broad open structures, the Michigamme rocks folded tightly. Fold axes in the Michigamme slate also appear to be arcuate toward the south, parallel to the Hemlock–Peavy Pond complex contact.

In sec. 19, T. 42 N., R. 31 W. a synclinal axis and the trend of the Michigamme rocks is northwest. Through the central part of the Peavy Pond area the trend of the rocks and any fold axes present is nearly due east, and east of Peavy Pond particularly in the S½ sec. 15 and the SE¼, sec. 28, T. 42 N., R. 31 W., the trend of the Michigamme rocks is northeast. Folds within the Michigamme slate indicated by reversals in top directions of graded beds in the west and southwest parts of the quadrangle must therefore have arcuate axes. This point has been demonstrated to be correct by recent detailed mapping to the south in the Commonwealth quadrangle (H. L. James, oral communication, 1955).

The limb of Hemlock rocks north of Peavy Pond is twisted and overturned in places; the overturned portions were rotated approximately 145°. The folds in the Michigamme slate are also overturned, and apparently isoclinal, at least in sec. 19, T. 42 N., R. 31 W.

During the folding the solid basic parts of the Peavy Pond complex were granulated and not foliated. The parts of intermediate composition that were still in a semirigid state were strongly foliated; whereas, the still fluid acidic residual melt was pressed under the deformation stresses into the country rock and the fractured mafic rocks of the complex, where it solidified as granite or closely related rock.

Faulting took place in the Peavy Pond area sometime after the emplacement and solidification of the granite. Many minor dislocations are present in the area, but only the major fault is shown on plate 1. The trace of the fault is marked by breccia 100 feet or more in thickness, which crops out in the NW¼ sec. 29, the NE¼ sec. 30, and the SE¼ sec. 22, T. 42 N., R. 31 W. The direction of fault movement is not indicated by any lineation in the breccia, nor is the attitude known. Whether normal, longitudinal, or reverse, however, the apparent movement is right handed; the south block of Hemlock and older rocks having moved approximately 2 miles west. The linear magnetic anomaly in secs. 23 and 26, T. 42 N., R. 31 W., was apparently truncated by the faulting, but neither the source rock of the anomaly or the position of its counterpart in the block north of the fault are known.

It was noted earlier that the emplacement of the granite in the Peavy Pond complex came later than the peak of metamorphism. Since the faulting postdates the emplacement and solidification of the granite, it follows that any isograds or isofacies of regional metamorphism must also have been displaced. This point cannot be conclusively established in the Lake Mary quadrangle where outcrops are too few and scattered, but recent detailed mapping to the west in the Crystal Falls quadrangle lends support to this concept (K. L. Wier, oral communication, 1957). The trace of the major fault in the Peavy Pond area is coincident on the east border of the map with the Bush Lake fault (Pettijohn, 1951), which cuts diagonally across the north part of T. 42 N., R. 30 W., Dickinson County, and bounds the Sagola basin on the south.

SEQUENCE OF GEOLOGIC EVENTS

The earliest events in the history of Precambrian rocks of the Lake Mary quadrangle are cloaked with considerable uncertainty. The first clearly discernible event was the period of volcanism that gave vent to the thick series of volcanic deposits included in the Dickinson group. The extrusion of the volcanic rocks was followed by an orogeny, not conclusively identified in the Lake Mary quadrangle, but implicit in the correlation of these volcanic rocks with the Dickinson group to the southeast. During the orogeny the volcanic rocks were probably folded and moderately metamorphosed. The folded rocks were then beveled by erosion to a surface of low relief and inundated by the sea. During the early part of the Randville deposition at least the northern part of the quadrangle lay near the distal edge of clastic sedimentation from the mainland, and the material deposited was chiefly calcareous mud mixed with arkosic sand probably derived from nearby islands. Later in the epoch, in response to changing environmental conditions, carbonate deposition was gradually replaced by the deposition of mud and silt as the upper part of the Randville was deposited. There is no evidence in the Lake Mary quadrangle to indicate that a period of erosion separated the Randville and Hemlock sedimentation, but a post-Randville, pre-Hemlock period of erosion is postulated for the Kiernan quadrangle to the north (Gair and Wier, 1956).

During the deposition of the Hemlock formation basaltic lava and pyroclastic material were deposited. The periods of volcanism alternated with periods of relative quiet during which fine-grained clastic material, silica and iron-rich carbonate were deposited. Volcanism was temporarily suspended at the end of Hemlock time, and in the period of quiet that followed, mud and ferruginous material were deposited to form the slate and iron-formation at the base of the Michigamme slate to the northwest in the Amasa area. The southern part of the Lake Mary quadrangle may have been emergent and undergoing erosion during this time, but this point is uncertain. Since indications of post-Amasa formation pre-Michigamme formation emergence and erosion have been found in the vicinity of Amasa, Mich., and elsewhere in the region, it seems more probable that the Amasa formation was deposited in the south part of the quadrangle and removed by pre-Michigamme erosion. Deep erosion at this time is probably also responsible for the general absence of the Fence River formation of post-Hemlock age along the east limb of the Holmes Lake anticline.

The pre-Michigamme erosion was followed by resubmergence and inundation of the region generally. The deposition of ill-sorted mud and sand characteristic of the Michigamme slate immediately commenced and continued with only a few interruptions until the end of Animikie time. Volcanic activity occurred at intervals during late Animikie time, outside of the quadrangle area, and at least one period of iron-formation deposition occurred late in the epoch.

Between the time that the upper volcanic rocks of the Hemlock formation were deposited and the end of Animikie deposition, gabbroic magma invaded the Hemlock formation in the form of sills and minor dikes.

Animikie deposition was terminated by a period of intense deformation, widespread metamorphism, and local granite and gabbro intrusion in the western part of the northern peninsula of Michigan. In the Lake Mary quadrangle, the Holmes Lake anticline and the many secondary folds and faults date from this orogenic period. The syntectonic Peavy Pond complex was intruded early in the orogenic period. Faulting in the Peavy Pond area took place late in the period. At some time after the folding and before the deposition of the Upper Cambrian sandstone, the folded rocks were intruded by a few small dikes of fresh diabase usually considered to be Keweenawan in age.

During the long period of time following the post-Animikie orogeny the folded structures were eroded to their roots in a widespread peneplanation. Minor pockets of ore produced by the oxidation of the cherty iron carbonate rocks of the iron-bearing slate member of the Hemlock formation were probably formed during this erosion interval. Later, the quadrangle was inundated for a last time by the Upper Cambrian sea. Well-sorted quartz sand and limy mud, which now form sandstone and dolomite, were deposited. In the subsequent Cambrian to Pleistocene interval, the Cambrian rocks were almost completely removed by erosion leaving only two small outliers in the northeastern part of the quadrangle. There is no sedimentary record for the rest of the Paleozoic era, the Mesozoic era, or for most of the Cenozoic era. Quaternary (Pleistocene) glacial deposits overlie the rocks of the quadrangle in what may be safely considered a profound unconformity.

MAGNETIC SURVEYS

Data obtained from aeromagnetic and ground magnetic surveys have been a valuable aid to the interpretation of the geology of the Lake Mary quadrangle.

AEROMAGNETIC SURVEY

The Lake Mary quadrangle was included in an aeromagnetic survey of part of the northern peninsula of Michigan made in 1949 by the U. S. Geological Survey in cooperation with the Geological Survey Division, Michigan Department of Conservation.[2] A total intensity magnetometer (AN/ASQ–3A) installed in a DC–3 airplane was used. Traverses were flown east-west at quarter mile intervals at approximately 500 feet above the ground.

[2] Aeromagnetic survey directed by J. R. Balsley, U. S. Geological Survey.

The aeromagnetic data in the Lake Mary quadrangle are presented here as a series of total intensity profiles (pl. 7). Crests of positive anomalies are plotted on plates 1, 2, 3, 4, and 6 as circles sized in proportion to the intensity of the anomaly. Errors in crest positions may be 500 feet or more.

The dominant magnetic anomaly trends southeastward through the northeastern part of the quadrangle. It is known from diamond drilling to be chiefly caused by magnetite-bearing volcanic schist that underlies the Randville dolomite. The source rock of the linear anomaly which occurs near the top of the East Kiernan sill is not known. Magnetic anomalies caused by various source rocks occur near the upper and lower contacts of the West Kiernan sill. The northward-trending anomaly on the east side of the West Kiernan sill is caused by magnetic metaperidotite in secs. 16 and 21, T. 43 N., R. 31 W., by magnetic metabasalt and probably also metaperidotite in secs. 28 and 32, T. 43 N., R. 31 W., and by the metaperidotite in sec. 33, T. 43 N., R. 31 W. The upper (west) part of the West Kiernan sill is generally magnetic and is marked by several small anomalies. A well-defined anomaly trends northward along the strike of the iron-bearing rocks of the Mansfield iron-bearing slate member of the Hemlock formation. Although the crest of the anomaly is displaced as much as 500 feet in some places, there is no doubt that the iron-bearing rocks cause the anomaly (pls. 4 and 6). The extension of the anomaly to the southeast from the NW¼ sec. 5, T. 42 N., R. 31 W. has been determined by ground survey to crest about 600 feet above (west of) the iron-formation in an area underlain by slate and greenstone schist. The source rock of the linear anomaly in secs. 23 and 26, T. 42 N., R. 31 W., is unknown. It could represent magnetic iron-formation of either Hemlock or pre-Hemlock age, or any magnetic rock, not necessarily iron-formation. Magnetic anomalies within the Michigamme slate appear to be caused by magnetic mica schist. The major anomaly in the northwest corner of the quadrangle is caused by magnetic rocks in the adjacent Crystal Falls quadrangle.

Crests of anomalies in secs. 15, 16, 21, 22, 28 and 29, T. 42 N., R. 31 W. cannot be correlated directly from the aeromagnetic data because the strike of the rocks in this area parallels the flight lines.

GROUND MAGNETIC SURVEY

A magnetic survey of the northeastern part of the quadrangle, including parts of secs. 13, 14, 15, 23, 24, 25, and 26, T. 43 N., R. 31 W., was made to correlate the magnetic data with the bedrock geology as determined by diamond drilling (pl. 2). A temperaturecompensated vertical magnetometer with a sensitivity of about 29.5 gammas per scale division was used. Traverses were made with a magnetic compass from known locations. A diurnal correction was maintained by reading the magnetometer at a base station at least every 3 hours. Surveying was curtailed during periods of strong magnetic disturbance. All magnetic determinations are relative to an arbitrary zero base, which has an approximate absolute vertical intensity gamma value of 57,500 determined from magnetic base stations established in southeastern Iron County by the U. S. Bureau of Mines (Bath, 1951).

A single broad anomaly trends southeastward across the area surveyed. To the northwest the crest of the anomaly lies over a narrow zone of magnetite-bearing volcanic schist bounded on the east and west by limbs of younger dolomite, slate, and arkose. The anticlinal structure thus defined broadens toward the southeast where the major anomaly appears to favor the east side of the structure, whereas several anomalies of lesser intensity form west of it as the anticlinal structure broadens and more and more of the old volcanic terrain is laid bare in the core—bare except for the glacial cover, that is.

Detailed magnetic surveying in sec. 26, T. 43 N., R. 31 W. shows a relatively negative area of magnetism lying between two positive anomalies. Diamond drilling in that section indicates that the east positive anomaly is caused by magnetic schist of volcanic origin underlying the basal arkose of the Randville dolomite; the relatively negative area of magnetism marks the position of the dolomitic part of the Randville dolomite; and the west positive anomaly marks the position of the upper slate of the Randville dolomite. A somewhat analogous situation is represented by the detailed magnetics in sec. 25, T. 43 N., R. 31 W. and sec. 30, T. 43 N., R. 30 W. There again an area of relatively negative magnetism occurs between positive anomalies. A diamond-drill hole in sec. 25 near the crest of the west positive anomaly cut magnetic schist and greenstone thus indicating the continuation of the volcanic rocks from the north. Drill holes on the east positive anomaly cut ferruginous quartzite and cherty iron-formation in many respects similar to the iron-rich rocks overlying the Randville dolomite at Michigamme Mountain in sec. 4, T. 43 N., R. 31 W. Inasmuch as the dolomite lies below the iron-formation and above the volcanic schist to the north, and because its negative magnetic character relative to the other rocks of the area appears to be indicative, the dolomite is inferred to be present below the ferruginous quartzite in sec. 25, T. 43 N., R. 31 W.

Data from a magnetic survey along the strike of the iron-bearing rocks of the Mansfield iron-bearing slate member of the Hemlock formation are shown on plates 4 and 6. Two magnetometers were employed in this survey, one with a sensitivity of 29.5 gammas per scale division, and one with a sensitivity of about 44 gammas per scale division. On plate 4 the position of the positive anomaly coincides with the position of the iron-bearing rocks. No attempt to arrive at a detailed picture of the total magnetic setting was made. The magnetometer was used as a tool to find the iron-formation with reference to available outcrop and drill-hole data while occupying the least possible number of stations. As a result, the iron-formation is now properly mapped for the first time: two faults that displace the iron-formation have been found; the iron-formation heretofore shown on the west side of the Michigamme River between the NW¼ sec. 29 and SW¼ sec. 29, T. 43 N., R. 31 W. (Stratton and Joyce, 1932) is now known to be on the east side of the river where it crops out; the fault shown to displace the iron-formation in secs. 31 and 32, T. 43 N., R. 31 W. on the geologic map of Iron County (Barrett, Pardee, and Osgood, 1929) is now known not to exist—the crest of the magnetic anomaly indicates the presence of the iron-formation is continuous across the proposed fault. It has been determined that in general the iron-formation is highly magnetic only where it lies close to the intrusive West Kiernan sill. Where the formation is separated from the intrusive by a considerable thickness of slate, the magnetic intensity is less, and where the iron-formation is well oxidized as at Mansfield location, a pronounced magnetic depression occurs. Petrographic work indicates that the magnetism of the iron-formation is due to the formation of metamorphic magnetite in originally nonmagnetic cherty-carbonate rocks.

Plate 6 shows the southern continuation of the magnetic survey along the iron-bearing slate belt. The more detailed survey was dictated by the structural complication in the area. As on plate 4 the strong positive anomalies are caused by the iron-formation. From diamond drilling it is known that the source rock is over 100 feet thick in the SE¼NE¼ sec. 31, T. 43 N., R. 31 W. The structural interpretation of the rocks of the area, based partly on the magnetic data, is shown on plates 1 and 5. In the northern part of the area the iron-formation lies close to the intrusive metagabbro; it is poorly oxidized and highly magnetic. The magnetic pattern indicates that the source rocks are moderately contorted and probably displaced by a fault. The lobate nose of the anomaly in the NE¼SE¼ sec. 31 is interpreted to indicate a southwestward-plunging anticlinal structure lying north of a fault, the plane of which probably dips at a moderate angle to the southeast. Although there is no outcrop or exploration in the area of the high positive anomaly south of the inferred fault, the anomaly is interpreted to signify the position of a limb of iron-formation that has moved to the east relative to the north block of the fault. Elsewhere in the area of the survey, the iron-formation is only weakly magnetic, due in part to the low metamorphic grade and in part to deep oxidation. The limb of iron-formation proved by drilling in the SE¼ sec. 31 contains some magnetic material, but the anomaly, except near the curved south extremity of the limb, is overshadowed by the stronger anomaly to the east. Oxidized siliceous iron-formation found in pits on the east side of the river in sec. 32, T. 43 N., R. 31 W., is only faintly magnetic, but its position is roughly outlined by the survey. In the NW¼ of sec. 5, T. 42 N., R. 31 W., the iron-formation is not anomalously magnetic and can no longer be followed by magnetic surveying. The anomaly crests determined by the aeromagnetic survey reflect the position of the iron-formation in the northern part of the area, but to the south the anomaly shifts to the slate overlying the iron formation.

Inasmuch as the iron-bearing rocks dip steeply west and are deeply oxidized at the surface in sec. 5, T. 42 N., R. 31 W., the westward shift of the magnetic anomaly may reflect unoxidized magnetic iron-formation down the dip from the surface exposures.

Magnetic surveying in the southern part of the quadrangle is described on page 27. (See also plate 3.)

ECONOMIC GEOLOGY

Iron ore, sand and gravel, and road metal are the only economic products that have been mined in any quantity in the Lake Mary quadrangle up to the present time.

IRON

Although sporadic exploration for iron ore has been carried out in the quadrangle for more than 65 years, ore has been found in commercial quantities only in the Mansfield iron-bearing slate member of the Hemlock formation at Mansfield location. North of the Mansfield mine to the edge of the quadrangle, the iron-formation is only thinly veneered with overburden and has been tested by many surface pits, but no ore was found. A few holes were drilled north of the mine but with negative results. South of the Mansfield mine, in secs. 20 and 29, T. 43 N., R. 31 W., 16 exploratory holes were drilled by the Longyear Michigan Exploring Co.

in 1921 (pl. 1). Iron-formation was found in all the holes, but only two of them, located about 1,700 feet south of the mine, were in ore.

The Scadden and Glidden explorations include a number of test pits and shafts in the iron-formation and adjacent rocks in the SE¼ sec. 31, T. 43 N., R. 31 W., and the NW¼ sec. 5, T. 42 N., R. 31 W. Oxidized iron-formation was penetrated by many of these pits, but no ore was found. The iron-formation is very siliceous. Reported iron values for the Scadden exploration range from 38.64 to 41.53 percent.

In 1931 the M. A. Hanna Co. drilled 19 exploratory holes in the vicinity of the Glidden and Scadden explorations, 4 in sec. 5, T. 42 N., R. 31 W., and 15 in sec. 31, T. 43 N., R. 31 W. Of the 19 holes, 8 located iron-formation (pl. 5). Where drilled, the formation dips steeply west, and oxidation is chiefly confined to shallow depths on the west side of the belt. A large percentage of the drilling was in unoxidized chert-siderite iron-formation. The reported range in iron values for the 15 holes in sec. 31 is from 10.0 to 47.3 percent, and the average value is about 25 percent.

Diamond drilling in other parts of the area has particularly centered in the northeast quarter of the quadrangle. Some of the holes entered strongly magnetic volcanic schist of the Dickinson group; others were drilled to test for iron-formation erroneously shown on earlier monograph maps to underlie a part of the area (map A, fig. 4). Forty-seven diamond-drill holes have been put down in this northeast area, about half of them by the M. A. Hanna Co., and half of them by Virgil and Leonard Skewes; none found iron-formation (pl. 1). The many test pits scattered around the quadrangle not in iron-formation generally lie within the area of the Hemlock formation and have bottomed in greenstone or slate.

The generally unsuccessful exploration of the iron-bearing rocks of the iron-bearing slate member of the Hemlock formation thus far has considerably reduced the possibility of finding ore in commercial quantities in the remaining unexplored part of the known belt, but it has not eliminated the possibility. Some of the facts derived from the sum of the available data, relevant to further exploration along the iron-bearing slate member, are as follows:

1. The thickness of the iron-formation is 30–150 feet along the belt extending from the north border of the quadrangle to the NW¼ sec. 5, T. 42 N., R. 31 W. It is not known why the thickness of the formation varies. A volcanic conglomerate containing chert chips occurs above the iron-formation for most of its known

length, and it is possible that the variations are due chiefly to post–iron-formation erosion.

2. The Mansfield mine is located at one of the points of minimum thickness (30 feet), yet produced 1,462,500 tons of high grade ore from a single ore body.

3. The iron-formation is composed chiefly of chert and sideritic carbonate and is not believed to be primarily magnetic. It is magnetic where it lies adjacent to the West Kiernan sill.

4. For this quadrangle the position of ore as related to structure cannot be resolved into any simple generalization. The ore body at the Mansfield mine appears to have formed in a broad westward-plunging synclinal structure, but a small ore body to the south is near the crest of the adjacent anticlinal structure.

5. The metamorphosed parts of the iron-formation appear to be more resistant to oxidation by meteoric waters than the unmetamorphosed parts. This is perhaps chiefly due to the abundance of refractory silicate minerals in the metamorphosed parts.

The real and inferred distribution of the iron-bearing rocks is shown on plate 1, and the character of the rocks has been briefly described in the appropriate section, but a few additional points should be noted here. First, some of the magnetic iron-formation lying east of the Michigamme River at the top of the West Kiernan sill may be amenable to beneficiation. This could not be determined by the writer's meager sampling of the beds. Second, although the present knowledge does not justify the continuation of the iron-bearing slate member to the southeast from sec. 5, T. 42 N., R. 31 W., the lack of any sharp magnetic anomaly is not considered as evidence that the member is absent; because the formation is primarily nonmagnetic, it may be present. The small magnetic anomaly close to the iron-formation in the NW¼ sec. 5, T. 42 N., R. 31 W., has been determined on the ground to occur about 600–1,000 feet above (west of) the iron-bearing rocks which are thoroughly oxidized at the surface. From the aeromagnetic data, this anomaly appears to be linear and to strike southeast across the quadrangle. Third, it has not been conclusively established that the rocks of the iron-bearing slate member do not continue to the north of the Lake Mary quadrangle.

COPPER, COBALT, AND NICKEL

The differentiated character of the West Kiernan sill makes it a potential source of metallic segregations in the basal part. The four chemical analyses on page 27 indicate geochemical maxima of the elements Cu, Co, and Ni near the base of the sill. Theoretically, mineral segregations of economic value could be present in the lower sill rocks.

RADIOACTIVE MINERALS

Over 400 hand specimens representing almost all of the rock types present in the quadrangle have been tested by Geiger counter with negative results. The strongest radioactivity, though slight, was found in specimens of black pyritic slate from outcrops at the north edge of Highway 69 in the NW¼ sec. 33, T. 43 N., R. 31 W.

NONMETALS

The only nonmetallics utilized from the quadrangle to date are crushed rock, and sand and gravel.

Rock for crushing is accessible at many places within the quadrangle (pl. 1), but it has very little economic value at the present time. At some time in the past, a considerable amount of massive basalt was quarried in the SE¼ sec. 27, T. 43 N., R. 31 W.

Sand and gravel, used widely in the district for road material, is accessible at many places in the quadrangle. Although quite variable in character from place to place, the distribution of such deposits is roughly outlined by the pattern indicating glacial outwash on figure 3. In a very general way, the coarse gravel and sand appear to preponderate east of Parks Creek and west of the glacial moraine bounding the quadrangle on the east.

Very plastic, varved glacial clays of undetermined thickness and extent crop out along the west bank of the Michigamme River in the NE¼NW¼ sec. 9, T. 42 N., R. 31 W.

Igneous rocks suitable for dimension and ornamental stone are located at a number of accessible places in the quadrangle. The granite in secs. 18 and 19, T. 42 N., R. 31 W., is light colored and even grained, and has two well developed, widely spaced sets of joints that intersect at about 90°. Several varieties of gabbro (black granite) are available in the SE¼ sec. 28, T. 42 N., R. 31 W.

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