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The Marquette Range Supergroup in the Gogebic Iron District, Michigan and Wisconsin

GEOLOGICAL SURVEY BULLETIN 1460

Prepared in cooperation with the Geological Survey Division, Michigan Department of Natural Resources

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By ROBERT GORDON SCHMIDT

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Geologic description of the Precambrian X strata, particularly the Ironwood Iron-formation, and of the relationship between ore location and variations in sedimentary facies and metamorphic grade

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CONVERSION FACTORS

Metric unit		Inch-Pound equivalent
Length		
millimeter (mm)	= 0.03937	inch (in)
meter (m)	= 3.28	feet (ft)
kilometer (km)	= .62	mile (mi)
Area		
square meter (m^2)	= 10.76	square feet (ft^2)
square kilometer (km^2)	= .386	square mile (mi^2)
hectare (ha)	= 2.47	acres
Volume		
cubic centimeter (cm^3)	= 0.061	cubic inch (in^3)
liter (L)	= 61.03	cubic inches
cubic meter (m^3)	= 35.31	cubic feet (ft^3)
cubic meter	= .00081	acre-foot (acre-ft)
cubic hectometer (hm^3)	= 810.7	acre-feet
liter	= 2.113	pints (pt)
liter	= 1.06	quarts (qt)
liter	= .26	gallon (gal)
cubic meter	= .00026	million gallons (Mgal or 10^6 gal)
cubic meter	= 6.290	barrels (bbl) (1 bbl=42 gal)
Weight		
gram (g)	= 0.035	ounce, avoirdupois (oz avdp)
gram	= .0022	pound, avoirdupois (lb avdp)
metric tons (t)	= 1.102	tons, short (2,000 lb)
metric tons	= 0.9842	ton, long (2,240 lb)
Specific combinations		
kilogram per square centimeter (kg/cm^2)	= 0.96	atmosphere (atm)
kilogram per square centimeter	= .98	bar (0.9869 atm)
cubic meter per second (m^3/s)	= 35.3	cubic feet per second (ft^3/s)

Metric unit		Inch-Pound equivalent
Specific combinations—Continued		
liter per second (L/s)	= .0353	cubic foot per second
cubic meter per second per square kilometer [$(m^3/s)/km^2$]	= 91.47	cubic feet per second per square mile [$(ft^3/s)/mi^2$]
meter per day (m/d)	= 3.28	feet per day (hydraulic conductivity) (ft/d)
meter per kilometer (m/km)	= 5.28	feet per mile (ft/mi)
kilometer per hour (km/h)	= .9113	foot per second (ft/s)
meter per second (m/s)	= 3.28	feet per second
meter squared per day (m^2/d)	= 10.764	feet squared per day (ft^2/d) (transmissivity)
cubic meter per second (m^3/s)	= 22.826	million gallons per day (Mgal/d)
cubic meter per minute (m^3/min)	= 264.2	gallons per minute (gal/min)
liter per second (L/s)	= 15.85	gallons per minute
liter per second per meter [(L/s)/m]	= 4.83	gallons per minute per foot [(gal/min)/ft]
kilometer per hour (km/h)	= .62	mile per hour (mi/h)
meter per second (m/s)	= 2.237	miles per hour
gram per cubic centimeter (g/cm^3)	= 62.43	pounds per cubic foot (lb/ft^3)
gram per square centimeter (g/cm^2)	= 2.048	pounds per square foot (lb/ft^2)
gram per square centimeter	= .0142	pound per square inch (lb/in^2)
Temperature		
degree Celsius (°C)	= 1.8	degrees Fahrenheit (°F)
degrees Celsius (temperature)	= [(1.8 × °C) + 32]	degrees Fahrenheit

THE MARQUETTE RANGE SUPERGROUP IN THE GOGEBIC IRON DISTRICT, MICHIGAN AND WISCONSIN

By Robert Gordon Schmidt

ABSTRACT

The Gogebic district has been a major producer of high-grade iron ore, and the Ironwood Iron-formation, a ferruginous sedimentary unit, remains a major resource of concentrating ore.

The Marquette Range Supergroup in the Gogebic iron district consists of three groups of sedimentary formations. The oldest, the Chocolay Group, includes the Sunday Quartzite and the Bad River Dolomite; the next oldest, the Menominee Group, includes the Palms Formation and the Ironwood Iron-formation; and the youngest, the Baraga Group, includes the Tyler, the Copps, and the Michigamme Formations. The Copps and the Michigamme Formations are not discussed in this report. The formations are parallel or subparallel to one another in an east-trending narrow belt extending for 96 km (60 mi) in northeast Wisconsin and the western Upper Peninsula of Michigan. Radiometric dates and positive correlations are lacking, but the seven formations are believed to correlate with the Marquette Range

Supergroup in other parts of Michigan and with the Precambrian X rocks in the Mesabi and Cuyuna districts in Minnesota.

The Sunday Quartzite has been found only in limited outcrops east of Wakefield in Michigan. This formation is mainly white, gray, and red vitreous quartzite; contains conglomerate at the base; and is as much as 46 m (150 ft) thick.

The Bad River Dolomite consists of gray to buff dolomite and cherty dolomite, which is commonly stromatolitic. The unit is as much as 122 m (400 ft) thick. Tremolite is reportedly common in this formation, toward the western, highly metamorphosed end. The Bad River Dolomite is present at the east and west ends of the district but is absent in the middle because of nondeposition, erosion after deposition, or a combination of both.

The Palms Formation, unconformably overlying the Chocolay Group, is a uniform persistent unit that has little variation in thickness or lithology over a strike length of about 85 km (53 mi). Generally 122-150 m (400-500 ft) thick, the formation ranges from 109 m (360 ft) to 244 m (800 ft) in thickness. A layer of conglomerate is at the base of the Palms Formation in Wisconsin and also at the east end of the district east of Wakefield, Mich.; a little conglomeratic material is present in the central area between these locations, but only in thin small patches, especially in shallow depressions in the underlying surface.

About three-fourths of the Palms Formation is made up of gray thinly bedded argillite and fine siltstone, which are commonly red brown on surface outcrops. These argillaceous beds grade upward into a topmost facies of reddish-weathering gray quartzite, 15-32 m (50-105 ft) thick. The quartzite is fine to medium grained and well cemented; it is mostly thick bedded and blocky, although some is thin bedded.

The Ironwood Iron-formation is the major iron-bearing unit in the Gogebic district; almost all the high-grade iron ores formerly mined from the district were formed in this stratigraphic unit by secondary alteration. The formation is a complex succession divided into five members that persist for tens of kilometers of total strike length; dominantly thick-bedded cherty members alternate with dominantly thin-bedded members.

The members of the Ironwood Iron-formation are, from the oldest to youngest, the Plymouth, Yale, Norrie, Pence, and Anvil. The Plymouth, Norrie, and Anvil Members are, by definition, predominantly thick wavy-bedded chert; the Yale and Pence Members are mostly thin-bedded chert-carbonate-silicate rocks. The Plymouth Member has a bed of algal chert at the base and is made up of a main wavy-bedded part and an upper thin-bedded cherty part. The Yale Member contains a layer that is probably tuffaceous and some probably thin argillaceous layers, including a black argillite that is partly pyritiferous, but most of this unit is chert-carbonate-silicate iron-formation and is not argillaceous. A few granular wavy-bedded layers are included in the Yale Member. The Norrie Member is generally relatively thin bedded in the lower and upper parts of the member and thick bedded in the center; some is almost wholly wavy-bedded granular chert, and part is fine-grained ferruginous chert. The Pence Member is uniformly thin-bedded chert-carbonate-silicate iron-formation locally containing some thin layers of granular chert. The Anvil Member is locally the thickest member of the Ironwood Iron-formation and also may be locally absent, thus making it the most variable in thickness. It consists of granular wavy thick-bedded iron-formation containing chert layers several centimeters thick and in places, as much as 30 cm (12 in.) thick. A lens of Pence-like thin-bedded iron-formation as much as 7 m (23 ft) thick is present within the Anvil Member near Bessemer and Ramsay. The relationship of the Anvil Member to the overlying Tyler Formation is not known with certainty but is believed to be a normal sedimentary succession.

The Tyler Formation is a thick sequence of light- to dark-gray fine sandstone, argillaceous siltstone, and argillite; the lowermost 243 m (800 ft) contains local lenses of ferruginous chert and iron-formation.

Regional metamorphism of Penokean age has affected the end of the district eastward from Ramsay, and Keweenawan-age metamorphism has altered the Precambrian X rocks increasingly westward from Ironwood. The iron-formation and associated strata have been little affected by metamorphism between Ironwood and Ramsay, least of all at Ramsay.

Uplift after deposition of the Bad River Dolomite caused erosion of the Bad River Dolomite and Sunday Quartzite in the central part of the Gogebic district. East-trending block faults formed during the Penokean orogeny, and these faults, particularly those that became the loci of mafic dikes, were important controls in the later formation of high-grade ores. Plunging folds having the general form of drag folds formed at four localities at about the same time as the block faulting. Differential uplift, perhaps related to the Penokean block faulting, led to differential removal by erosion of the Tyler Formation and, in a small area near Wakefield, Mich., of a part of the Ironwood Iron-formation as well. The same faulting probably caused a 5° -15° southward tilt of the Precambrian X strata before the Keweenawan units were deposited on them.

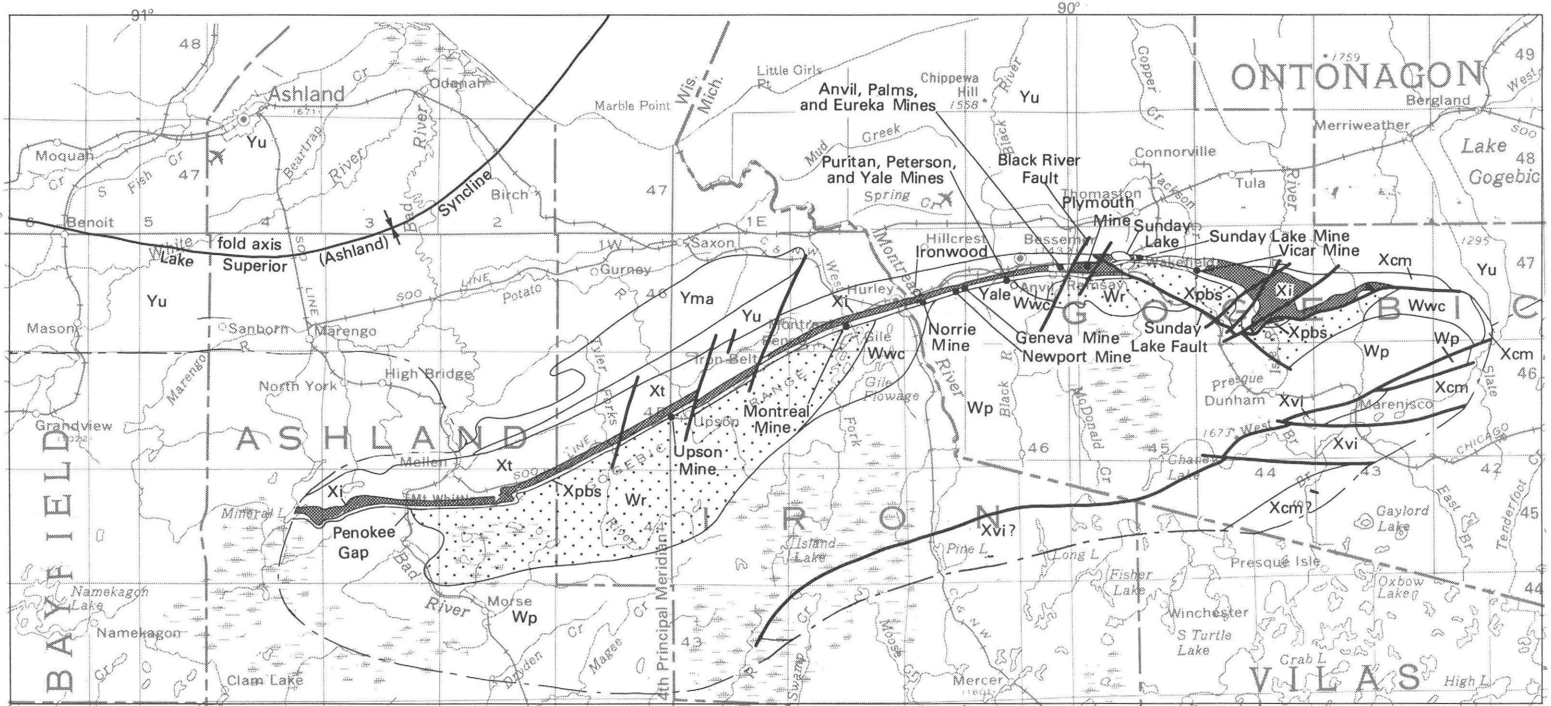
Intermediate in Keweenawan time, the Precambrian W crystalline block and its veneer of Precambrian X strata tilted northward to form the present north-dipping monoclinal structure on the south limb of the Lake Superior geosyncline. After early Keweenawan time, perhaps at the same time as the northward tilting, the Precambrian X and Y strata were cut by many near-vertical north-trending faults. The apparent displacement on most of these faults decreases downward toward the base of the Precambrian X strata, but several faults seem to be exceptions that offset the Precambrian W rocks as well.

The Gogebic district has been an important source of high-grade ore in the past, yielding 320,334,000 long tons in the period 1884-1967, but now and in the future, the important resource in the area is material containing 25-40 percent elemental iron, which can be used as concentrating ore. Properties of the iron-formation that affect its use as concentrating ore are mineralogy, grain size, and texture, which are functions of the original sedimentary facies and the degree of metamorphism. The detailed stratigraphy is very important in determining variations in characteristics at any one location on the range, but most of the variation along the length of the range has been produced by differences in the degree of metamorphism. Principal resources can be divided into the main categories: (1) oxidized and unoxidized little-metamorphosed iron-formation and (2) unoxidized metamorphosed iron-formation.

INTRODUCTION

The Gogebic district, one of the seven major iron-ore districts of the Lake Superior region, can be defined as the area of bedrock outcrop of the Ironwood Iron-formation. The outcrops, along with the water- and drift-covered iron-formation segments between them, form a gently curving narrow linear belt of northward-dipping iron-formation (fig. 1). This belt extends, with only local interruptions, 96 km (60 mi) eastward from Mineral Lake, sec. 14, T. 44 N., R. 4 W., in Wisconsin, through Hurley, Wis., and Ironwood, Bessemer, Ramsay, and Wakefield, Mich., to sec. 22, T. 47 N., R. 43 W., north of Marinesco, Mich. The district was formerly called the Penokee range; that name was later applied to only the Wisconsin part of the district, and more recently, the whole district has been called the Gogebic.

Iron-formation was discovered in the area in 1848 when A. Randall found low-grade magnetic ore during a survey of the fourth principal meridian (fig. 1) (Owen, 1852, p. 444), and the detailed geology of the iron-formation and ores of the Gogebic district has been studied intermittently by geologists for more than 100 years. The most important reports summarizing this work are those of Irving and Van Hise (1892), Van Hise and Leith (1911), Hotchkiss (1919), Aldrich (1929), and Huber (1959).



Adapted in part from Dutton and Bradley, 1970, Prinz and Hubbard, 1975, Prinz, 1967, Trent, 1973, and Fritts, 1969.

EXPLANATION

Contact—Approximately located

Fault—Approximately located

Syncline—Showing troughline

Limit of map area

6	5	4	3	2	1
7	8	9	10	11	12
18	17	16	15	14	13
19	20	21	22	23	24
30	29	28	27	26	25
31	32	33	34	35	36

Guides to section numbers in township and range grid. Each section is one mi^2

APPROXIMATE SCALE

0 10 20 MILES

0 10 20 30 KILOMETERS

Precambrian Y

- **Yu** — Sedimentary and volcanic strata of Keweenawan age, undifferentiated
- **Yma** — Anorthositic and gabbroic intrusive rock

UNCONFORMITY

Precambrian X — Marquette Range Supergroup

Baraga Group

- **Xt** — Tyler Formation—Slate and graywacke, may correlate with Xcm
- **Xcm** — Copps and Michigamme Formations, undivided—Mainly slate and graywacke, some low-grade iron-formation, includes Banner Lake and Paulding strata of Fritz (1969)

LOCAL UNCONFORMITY

Menominee Group

- **Xi** — Ironwood Iron-formation—Thick wavy bedded cherty iron-formation and thin-bedded cherty carbonate iron-formation. Amount of intercalated mafic flow rocks and pyroclastics increases eastward from Ramsay, Mich. Probably generally equivalent to Xvi
- **Xvi** — Metavolcanic and metasedimentary rocks—Mainly mafic flow and pyroclastic rocks with some interbedded low-grade iron-formation, graywacke, and quartzite and sparse felsic volcanic rocks. Includes Cup Lake and Blair Lake (in part) strata of Fritz (1969)
- **Xpbs** — Palms Formation—Argillite, siltstone, and quartzite; conglomerate at base in certain areas

UNCONFORMITY

Chocolay Group

- **Xpbs** (cont.) — Bad River Dolomite—Gray to buff dolomite and cherty dolomite, commonly stromatolitic
- Sunday Quartzite—White, gray, and red vitreous quartzite, conglomerate at the base

UNCONFORMITY

Precambrian W

- **Wp** — Puritan Quartz Monzonite and Van Buskirk Gneiss—Includes large areas of banded gneisses and migmatites as well as massive plutonic phases
- **Wwc** — Whiskers Creek Gneiss—Generally slightly foliated hornblende or biotite quartz diorite derived from Ramsay Formation by contact metamorphism
- **Wr** — Ramsay Formation—Stratified sequence of tuffaceous metasediments and some mafic flows

Figure 1.--Generalized geologic map of the Gogebic district in Michigan and Wisconsin. Geology modified from data of Dutton and Bradley (1970) and W. C. Prinz (unpub. data, 1975).

New data gathered on the Precambrian X strata have increased knowledge of the stratigraphy and metamorphic geology of the iron-formation and related stratigraphic units, but have added relatively little to what has been known about the areal distribution and structure of these rocks. Detailed field mapping of the rocks of the Ironwood-Ramsay area of Michigan was carried out by the U.S. Geological Survey from 1965 to 1970, and significant new data regarding lithology and mineralogy of the iron-formation were obtained for the eastern half of this area. To investigate lithology and mineralogy of the Ironwood Iron-formation outside the Ironwood-Ramsay area, brief examinations were made as far east as the Vicar mine, SW¼SW¼ sec. 12, T. 47 N., R. 45 W., Mich., and as far west as Mineral Lake, sec. 14, T. 44 N., R. 4 W., Wis. Stratigraphy, lithology, and mineralogy were studied at outcrops in Penokee Gap near Mellen, Wis., and by logging the cores of several drill holes near Upson, Wis., through the courtesy of the Inland Steel Company. Other sources of detailed stratigraphic and mineralogic data outside the Ironwood-Ramsay area were reports by Huber (1959) and Zinner and Holmberg (1947).

Much of the new information about the Precambrian X rocks in the Ironwood-Ramsay area was obtained by examining these rocks at two locations. The first location was a combination of an old open-pit mine and a line of shallow test pits, extending from the base of the Ironwood Iron-formation stratigraphically upward into the lower part of the Tyler Formation, near the center of sec. 17, T. 47 N., R. 46 W., east of the old Puritan mine, Mich. (After 1951, the Puritan mine was included in the Peterson mine.) The shallow test pits were filled in soon after I examined them. The second location was close to the Eureka mine, Mich., in the NW¼NW¼ and SW¼NW¼ sec. 13, T. 47 N., R. 46 W. The base of the Palms Formation is exposed in contact with Whiskers Creek Gneiss (Precambrian W), argillitic and quartzitic phases of the Palms Formation are exposed in scattered small outcrops, trenches expose part of the Plymouth and Yale Members of the Ironwood Iron-formation, the upper part of the Yale Member is extensively exposed, and several test pits have penetrated the Pence and Anvil Members of the Ironwood Iron-formation. Widely scattered outcrops provided most of the information regarding the Tyler Formation. Data on the basal iron-bearing beds were obtained from drill holes in the Peterson mine and outcrops in the bed of the Black River, both in Michigan.

The geology of the Keweenawan rocks in the Ironwood-Ramsay area was described by Hubbard (1975) and the geology of the Precambrian W rocks by Schmidt (1976). A geologic map of Precambrian W, X, and Y rocks in the Wakefield quadrangle to the east was prepared by Prinz and Hubbard (1975), and a recent map of the eastern end of the district was made by Trent (1973).

Metamorphism of the iron-formation has produced major changes in the mineralogy and mineral grain size, both of which affect the areas in which direct-shipping ores were formed and determine the success of concentration of the iron by industrial methods now in use. The leaching of carbon dioxide, silica, and alkalis from the iron-formation to produce high-grade hematitic ores was limited to essentially unmetamorphosed and relatively low metamorphic grade parts of the iron-formation; magnetite is uncommon at the lowest metamorphic grade but has increased in abundance and grain size as grade increased. The size of mineral grains determines the fineness to which the rock must be ground to obtain clean separations in a concentrating process; coarser grains tend to lower milling cost. The extent of mineral and grain-size changes differs in the different lithologic layers of the iron-formation. Planning for further use of the Ironwood Iron-formation as an iron resource requires knowledge of the detailed stratigraphy of the formation, the metamorphic gradients of the region, and the effects of the resulting grain and mineral changes on economic exploitation.

ACKNOWLEDGMENTS

Stratigraphic studies on diamond drill cores were made possible by the kind cooperation of the Keweenawan Land Association and Inland Steel Company, who made cores available for examination and sampling. Large quantities of subsurface data from the iron mines were provided by the Geological Survey Division of the Michigan Department of Natural Resources. The clarity of this report has been much improved by the painstaking critical reviews given by J. E. Gair and W. B. Myers of the U.S. Geological Survey.

STRATA OF MARQUETTE RANGE SUPERGROUP

The Precambrian X (Middle Precambrian) stratified rocks of the Gogebic district rest with profound unconformity on Precambrian W (lower Precambrian) metasedimentary and plutonic rocks. The designation Marquette Range Supergroup is applied here as a result of long-range correlations and is equivalent to "Animikie" age as used by James (1958) and Huber (1959). However, this age assignment of the Precambrian X strata of the Gogebic district is made without specific radiometric ages of rocks within the district. The geochronologic work in the nearby Lake Superior region, such as that of Banks and Cain (1969), on the "Amberg Granite," "Newingham Granodiorite," Hoskin Lake Granite, and "Dunbar Gneiss," bears indirectly on the age of Gogebic rocks by helping to define the times of orogenic events, but none of the work applies directly by dating either rocks or events in the area of this report. The present study has provided neither new radiometric ages nor new correlative interpretation. The Precambrian X rocks of the Gogebic district presumably belong to the "Late Aphebian" (2.0 to 1.6 b.y.) of Stockwell (1964).

The oldest Precambrian X formation, the Sunday Quartzite, has been found only in limited outcrops at the eastern end of the Gogebic district, and the succeeding Bad River Dolomite is found at both east and west ends; both formations are probably absent in the middle of the district. Whether this absence is due exclusively to erosion after deposition, to nondeposition, or to a combination of both, is not clear. Certainly some erosion of the Bad River Dolomite took place, as indicated by its abundance in the basal conglomerate where the Palms Formation rests on the dolomite. Where the Palms rests on granite, the most common pebbles at the base are granite, and the Bad River Dolomite may never have covered the Precambrian W rocks in the central Gogebic district. The attitudes of the Sunday Quartzite and the Bad River Dolomite are generally similar to those of the younger Precambrian X strata, but Prinz (1967) noted some angular discordance probably related to pre-Palms deformation.

The Palms Formation and the Ironwood Iron-formation are coextensive for the entire length of the district. From the west end at Mineral Lake, Wis., the Tyler Formation is continuous eastward to Ramsay, Mich.; beyond that, it and part of the Ironwood Iron-formation were removed by erosion in pre-Keweenawan time, and these strata are missing for about 9.5 km (6 mi), or roughly the width of R. 45 W. Eastward beyond R. 45 W., to the limit of the Ironwood Iron-formation and Palms Formation, the Copps Formation succeeds the Ironwood Iron-formation. The Copps Formation was correlated with the Tyler Formation by Atwater (1938) and Trent (1973). The Copps Formation was not examined in this study and is not discussed further in this report.

Westward from Mineral Lake, Wis., are four outcrop areas of metasedimentary rocks; three include highly magnetic iron-formation. Little is known about the geology of these locations. Outcrops of cherty as well as thin-bedded iron-formation and quartzite are in secs. 14 and 23, crystalline marble and siliceous and tremolitic dolomite crop out in secs. 15 and 22, and amphibolitic siliceous iron-formation and quartzite crop out in secs. 16, 17, 20, and 21, all in T. 44 N., R. 5 W. (Aldrich, 1929, p. 261-266). Amphibolitic iron-formation and one outcrop of rock interpreted to be Tyler Formation are found in sec. 26, T. 44 N., R. 6 W. (Aldrich, 1929, p. 270-273). I have not visited these localities and think that the existing geologic descriptions and the magnetic survey data are insufficient for reasonable correlations with the rocks of the Marquette Range Supergroup in the main Gogebic district. Consequently, I do not consider these isolated outcrops to be part of the Gogebic district and do not describe them further in this report.

CHOCOLAY GROUP

SUNDAY QUARTZITE

The Sunday Quartzite is the oldest Precambrian X sedimentary unit in the main Gogebic district; it was named and assigned an early Huronian age by Van Hise and Leith (1911, p. 227-228) and is known only in a small area east of Wakefield, Mich., in T. 47 N., Rs. 44 and 45 W.

The formation is mainly white, gray, and red vitreous quartzite and has conglomerate at the base; it is as much as 30 m (100 ft) thick (Prinz, 1967). According to Van Hise and Leith (1911, p. 227), the basal conglomerate is made up of fragments "largely derived from the immediately underlying Keewatin schists." These investigators stated that the conglomerate is "for most part--but a few inches thick, but in places it has a thickness of 10 feet." Exposures and attitudes of this formation were given by Prinz (1967). The unconformable relationship of the basal conglomerate and underlying Archean rocks is well exposed in SE¼ sec. 18, T. 47 N., R. 44 W.

A probably erroneous interpretation of a small occurrence of conglomerate near the Newport mine has led to a very confusing entry among type localities for the Sunday Quartzite. Van Hise and Leith (1911, p. 227-228) described small lenses of conglomerate "clinging to the face of the granite" at the Archean-Animikie unconformity in the vicinity of the Newport mine. They said: "This conglomerate contains different kinds of granite, porphyry, and various basic rocks. From the relations of this conglomerate to the Palms Formation it is believed to be the equivalent of the conglomerate east of

Presque Isle River." (The Presque Isle River is now Jackson Creek; it was also called the East Branch of the Black River in earlier reports.) The location of this outcrop is not certain. The only conglomerate that I found in the old Newport mine area I interpreted to be part of the basal Palms Formation. Presumably the same outcrop as that cited by Van Hise and Leith (1911) was described in field notes of C. K. Leith as follows:

> With Seaman walked out toward the Newport mine. On the last hill before reaching the Newport overlooking toward the east a great cross valley is a ledge of massive granite on the west face of which there is a considerable amount of conglomerate clinging in a thin film to the surface of the granite. The pebbles are as much as 4 inches in diameter and one large greenstone boulder 8 inches in diameter was seen. The pebbles contain two or three kinds of granites and porphyries and several kinds of basic rocks. Seaman says that he has also seen vein quartz pebbles in this place which have now been blasted out.

From Leith's description, I think the outcrop may have been near the center of the S½ sec. 23, T. 47 N., R. 46 W., or more probably in the SW¼NE¼ sec. 24, T. 47 N., R. 46 W. It would have been the outcrop that is now on the side of the abandoned railroad cut near the "new shaft." If viewed before the artificial exposures of the railroad cut were made, this outcrop might have been interpreted by Leith as having an attitude inconsistent with the Palms Formation. Whether Leith made this erroneous interpretation or whether a real outcrop of Sunday Quartzite was missed in this study or was later obscured by human activity is not known; unfortunately, this site has been included in the type localities of the Sunday Quartzite in the "Lexicon of Geologic Names of the United States" (Wilmarth, 1938, p. 2087).

BAD RIVER DOLOMITE

The Bad River Dolomite is present at both the east and west ends of the district but is probably totally absent in the central part of the district, where, in many good exposures, the base of the Palms Formation is in direct sedimentary contact with Precambrian W crystalline rocks. The Bad River Dolomite is exposed east of Wakefield in Michigan (locations are shown best by Prinz, 1967) and at the west end of the district in Wisconsin, westward from near Ballou Creek (not shown in fig. 1), in the NE¼ sec. 11, T. 44 N., R. 2 W. (Aldrich, 1929, p. 80). Irving and Van Hise (1892, pl. 8) and Van Hise and Leith (1911, pl. 16) also reported outcrops 19 km (12 mi) farther east in NE¼NW¼ sec. 15, T. 45 N., R. 1 E., near Iron Belt, Wis. Irving and Van Hise (1892, p. 129) mentioned that two outcrops of "cherty limestone" were in T. 47 N., R. 46 W., Mich., but showed none on their detailed outcrop maps (pl. 12).

The formation was probably first noted by Sweet (1876). The name "Bad Limestone" was first assigned to the formation by Van Hise (1901, p. 338) for exposures on the Bad River at Penokee Gap near Mellen, Wis. Leith, Lund, and Leith (1935, insert, p. 10) adopted the name Bad River Dolomite.

The formation consists of gray to buff dolomite and cherty dolomite. Van Hise and Leith (1911, p. 228) emphasized the siliceous nature of the unit and said that quartz is, in places, closely intermingled with dolomite but elsewhere is present as separate intercalations ranging from a fraction of an inch (<1 cm) to 50 feet (15 m) in thickness. Stromatolitic structures are common in the Michigan localities according to Prinz (1967). Van Hise and Leith (1911, p. 228) described the relationship of the Bad River to the Sunday Quartzite as gradational. The maximum known thickness is 400 feet (122 m) in the eastern area (Prinz, 1967). The thickness of 300 feet (91 m) given by Hotchkiss (1919, p. 444) for the western area at the Marengo River, secs. 15 and 22, T. 44 N., R. 5 W., southeast of Grandview, Wis., was measured on siliceous and tremolitic dolomite that I regard as of undetermined age. Part of the dolomite has been metamorphosed; tremolite is reported to be a common constituent in T. 44 N., Rs. 3 and 4 W., Wis., toward the western highly metamorphosed end of the district as far east as Penokee Gap on the Bad River, and a little is also present in sec. 18, T. 47 N., R. 44 W., Mich. (Irving and Van Hise, 1892, p. 135, 137).

MENOMINEE GROUP

PALMS FORMATION

The Palms Formation persists throughout the Gogebic district, being coextensive with the succeeding iron-formation. It is a very uniform argillite, siltstone, and quartzite unit, showing only slight changes in thickness and lithologic character over approximately 85 km (53 mi) from Mineral Lake in Wisconsin to the Little Presque Isle River in Michigan. According to Van Hise and Leith (1911, p. 230), the lateral persistence of this unit suggested that it was deposited on a relatively uniform surface. About three-fourths of the formation is gray thinly bedded argillite and fine siltstone, and the uppermost one-fourth is gray quartzite. Both facies weather to red brown on the outcrop surface and at depth where exposed to circulating solutions near oxidized iron-formation. In part of the area, conglomerate and laminated cherty rock are present at the base of the formation.

The Palms Formation was described by Irving and Van Hise (1892) as the "quartz-slate member"; it was named by Van Hise (1901, p. 338) for a partial but typical section of the unit south of the site of the old Palms mine in the NW¼ sec. 14, T. 47 N., R. 46 W., Mich., where natural and artificial exposures of the unit are found. Leith, Lund, and Leith (1935) used the name Palms Quartzite. The predominance of argillaceous beds in all except the uppermost part of the unit makes the original formal name more appropriate. Nowhere did I see continuous exposures of the whole unit, and good exposures of the middle of the unit are especially meager. Many development mine workings transected the Palms Formation underground after it became customary to place mine shafts in the older granitic rocks, but none of these is accessible now.

According to Van Hise and Leith (1911, p. 229), the formation is 400-500 ft (122-154 m) thick for most of the known strike length, but the maximum thickness, which is east of Sunday Lake, Mich., is 800 ft (244 m). Aldrich (1929, p. 82) gave an average thickness of 450 ft (137 m) for the formation in Wisconsin. Thicknesses between Ironwood and Ramsay range from 109 to 171 m (360 to 562 ft).

In the Ironwood-Ramsay area, the lower beds of the Palms rest directly on granitic rock; however, the base of the Palms was not exposed west of the Newport mine. The pre-Palms bedrock surface was generally planar but locally had many closely spaced basins 0.5-4 m (1.6-13 ft) in diameter and as much as 1.5 m (5 ft) deep. Within these depressions, a rock distinctly different from typical Palms Formation was deposited, as first noted by Irving and Van Hise (1892, pl. 17). This rock is mostly thinly laminated and generally siliceous; some of it is granular chert, and some of the depressions contain fragments of the underlying rock, as large as 30 cm (1 ft) in diameter, and also well-rounded pebbles of quartz, jasper, and chert. Such pebbles are also commonly found in small crevices or cracks in the granitic rock, as noted by Irving and Van Hise (1892, p. 174).

Crevices and sheltered depressions in the underlying rock surface are identical with the protected sites at the base of the Pokegama Quartzite in Minnesota where Cloud and Licari (1972) found well-preserved Gunflintia minuta Barghoorn and other nannofossils. Two thin sections were cut from sheltered crevice material collected underground in the Peterson mine, Mich., and neither of them contains algal filaments.

Some of the laminated rock at the base of the Palms has distinct thin layers of light-gray to greenish-gray chert, and perhaps some of the rock is more nearly siliceous argillite. At an abandoned railway cut at the old Newport mine, some of the cherty rock is granular and somewhat resembles iron-formation. The granules are mostly 0.5-1.0 mm (0.02-0.04 in.) in diameter, 5 to 10 times the size of the associated clastic material. Most of the granules are mixtures of chlorite and chert or chlorite and calcite, but a few are all chlorite and some are all chert or red-dusted jasper. Some granules and also other grains are mostly apatite (W. F. Cannon, oral commun., 1977). Granules composed either entirely or partly of stilpnomelane are very sparse, but several were seen. A few flakes 10-20 μm long were tentatively identified as minnesotaite. In hand specimens, the cherty granules are light gray, buff, and pink; those that are largely or entirely chlorite are dark green to black. Matrix material is mostly chert, some having a grain size of 1-2 μm; in other specimens, grain size is 5-10 μm, and rare grains are as large as 20 μm.

An abundance of angular granitic blocks near the base of the Palms Formation in the Yale mine "shaft crosscut" (NW¼ sec. 16, T. 47 N., R. 46 W., Mich.) was described by Hotchkiss (1919, p. 444). Previous investigators had emphasized the presence of a basal conglomerate at the bottom of the Palms Formation. Van Hise and Leith (1911, p. 229) regarded the conglomerate as an informal member, 1-10 ft (0.3-3 m) thick. They described this part of the formation mostly at localities in Wisconsin and cited a substantial layer of conglomerate at exposures along the Potato River at Upson and West Fork of the Montreal River at Gile, both in Wisconsin.

Irving and Van Hise (1892, p. 172, 173, and 176) described conglomerate exposed at these rivers and also at Bad River, southwest of Mellen, Wis. They found that the matrix of the rock at Bad River and Potato River contained abundant magnetite (p. 157-159), and they also described (p. 165) a breccia having a cherty matrix "composed chiefly of white, gray, black, and red chert, but containing also fragments of other minerals and of granite, and resting directly upon the granite," in the SE¼NE¼ sec. 15, T. 47 N., R. 46 W., Mich., near the Palms mine. In outcrops near the Palms mine, polymictic conglomerate in a laminated chert matrix fills discontinuous depressions in the older rock.

Although a conglomeratic layer is present at the base of the Palms Formation farther west in Wisconsin, and also east of Wakefield, Mich. (Prinz, 1967), I have not seen evidence either in the field or in published descriptions to suggest that more than small discontinuous lenses, found especially in pockets and depressions in the pre-Palms surface, are present between Ironwood and Ramsay, Mich.

The main part of the Palms Formation is a light-gray and greenish-gray laminated argillite and silty argillite containing much interbedded fine quartzitic siltstone and a little quartzite. Specific layers and sequences of argillite, siltstone, and quartzite in the few rather extensive exposures, such as that in an abandoned railway cut at the old Newport mine (SW¼NE¼ sec. 24, T. 47 N., R. 47 W., Mich.), seem to be lenticular and discontinuous, for they cannot be identified in more than one exposure.

At the abandoned railway cut at the Newport mine, the lowermost 3.5 m (12 ft) of the main Palms section is a laminated fine quartzite and very finely laminated hard siliceous argillite. In scattered layers as much as 3 cm (1 in.) thick, medium-grained quartz sand is abundant, and appreciable calcite is present, probably as cementing material. The overlying 23 m (75 ft) of the Palms Formation is very thinly bedded silty argillite and siltstone and a few fine-grained hard quartzitic siltstone beds as thick as 15 cm (6 in.). The next 26 m (85 ft) consists of predominant quartzitic siltstone in blocky beds 2-15 cm (1-6 in.) thick, along with silty argillite and siltstone. About 4.5 m (15 ft) of stratigraphic section is exposed above these beds; the section consists of very thinly bedded silty argillite and siltstone and some hard fine-grained quartzitic siltstone beds. All the rocks in the exposure are mixed red brown and gray to greenish gray; the red brown is believed to be due to surface-related oxidation of iron, and the formation is probably gray at depth.

Some relatively extensive flat outcrops of the lower part of the Palms Formation are found at the site of the old Puritan mine (SE¼SW¼ sec. 17, T. 47 N., R. 46 W., Mich.). The lowermost 2 m (6 ft) is laminated gray and red-brown argillite, including several beds of red-brown, quartzitic siltstone 5-15 cm (2-6 in.) thick. The next 15 m (50 ft) is red-brown and sparse gray laminated argillite and a few thin siltstone layers. Stratigraphically above this interval is 5 m (17 ft) of mostly red-brown laminated argillite containing beds of quartzitic siltstone 5-15 cm (2-6 in.) thick. Beyond this argillite, the bedrock is covered by glacial drift.

Within the Ironwood-Ramsay area, there is a gap in significant outcrops of the Palms Formation between 52 m (172 ft) above the base and the quartzite unit at the top of the formation. Information obtained from the sporadic small outcrops only indicates that the strata are mostly laminated argillite and some interbedded siltstone.

A detailed description of the Palms Formation, which contains a particularly good depiction of the middle part of the formation as it is found east of Wakefield, Mich., was given by Tyler and Twenhofel (1952, p. 124-125).

Straight smooth bedding lamination is common in the Palms Formation, more so in the lower part than in the quartzite at the top. Hotchkiss (1919, p. 444) described the lower part of the Palms as ripple marked, but these features were rarely seen in this study. Aldrich (1929, p. 85-86) found common ripple marks and crossbedding in Wisconsin and made 53 studies of current direction along the Potato River 21 km (13 mi) southwest of Ironwood.

The microscopic character of the fine-grained strata of the Palms Formation was well described by Irving and Van Hise (1892, p. 149-151). The argillite is more than half muscovite in silty laminae and mostly muscovite in the finest layers. The coarser grains, 0.1-0.2 mm (0.004-0.008 in.) in longest dimension, are rather sharp angular fragments in which feldspar exceeds quartz by two to four times in some specimens. Some of the feldspar is microcline, but much of it is difficult to identify specifically. Chlorite and a little biotite are lesser constituents in the finer grained material. The angularity of the silty and fine sand grains and the abundance of feldspar, chlorite, and biotite suggest that the material had undergone little weathering before deposition. Argillite from the Peterson mine, Mich., contains relatively less feldspar and 1-3 percent opaque grains.

The upper quartzitic layer is 25-32 m (80-105 ft) thick in mine workings in the Ironton-Peterson mine vicinity, where a minimum of structural disturbance was noted by mining company geologists and engineers. Van Hise and Leith (1911, p. 229) gave a thickness of 50 ft (15 m) for the layer, and the quartzitic layer is 50-60 ft (15-18 m) thick in Wisconsin (Aldrich, 1929, p. 82).

The quartzitic layer is nowhere entirely exposed at the surface in the Ironwood-Ramsay area; extensive outcrops are in the Black River and in the SW¼NW¼ sec. 14, T. 47 N., R. 46 W., Mich., close to the old Palms mine (perhaps the outcrops for which the formation was named). I have not seen the lower boundary of the quartzitic layer, but from the downward diminution in bedding thickness and grain size in the Black River outcrop at Ramsay, Mich., I presume it is gradational. The top of the formation and beds rather close to the top are visible at many places in both natural and manmade exposures.

In the E½ sec. 23 and W½ sec. 24, T. 47 N., R. 47 W., Mich., bedding surfaces are exposed on the sides of the caved mined areas, and these surfaces are regularly corrugated. These structures in section 23 are probably valid ripple marks, but I could not decide whether the ridging in section 24 was a type of ripple or, at least partly, the result of tectonic deformation. Crossbedding and graded bedding were not noted.

The quartzite is gray and greenish gray to dull red brown or pink, and is a fine- to medium -grained well-cemented rock. Irving and Van Hise (1892) designated some less well-indurated specimens as sandstones, but I observed only quartzitic material. The quartzite is mostly thick bedded and blocky, but some is thin bedded. It is somewhat ferruginous and locally very iron stained near the base of the overlying iron-formation, but presumably this staining is entirely from the secondary introduction of iron oxide from above.

The quartzite is made up of well-sorted, well-rounded fine grains of quartz and lesser amounts of chert, feldspar, and iron silicate; most grains are 0.1-0.3 mm (0.004-0.012 in.), but rare grains are as large as 0.8 mm (0.03 in.). Cementation has been predominantly by grain enlargement of quartz. Some quartz grains show strongly undulatory extinction; others show none. The feldspar content is low, a few percent at the most. Cherty grains are more abundant than feldspar; locally, patches of iron silicate may represent original ferruginous pellets or granules or possibly original chert grains that have been replaced. The ferruginous material is mostly a dark-brown strongly pleochroic material, probably ferristilpnomelane, and some is a dull-brown chloritic mineral; both are abundant in certain patches 1-2 mm (0.04-0.08 in.) in cross section. Hematite is found in grains and as part of the interstitial material, and I believe it to be the product of oxidation of some of the iron silicate.

IRONWOOD IRON-FORMATION

The Ironwood Iron-formation is the major iron-bearing unit in the Gogebic district, and almost all the high-grade iron ores have been derived from it by secondary alteration. A product of mostly chemical sedimentation, the unit has a rather complex internal stratigraphic sequence, much of which is persistent for tens of kilometers. The name "Ironwood Formation" was applied by Van Hise in 1901 (p. 338) to deposits in and near the city of Ironwood, Mich. The name was changed to Ironwood Iron-formation by Leith, Lund, and Leith (1935, insert, p. 10).

The Ironwood Iron-formation is probably correlative with the Negaunee Iron-formation of the Marquette district and the Vulcan Iron-formation of the Menominee district (James, 1966, p. W34-W35); correlations with the Biwabic Iron-formation of the Mesabi district and the Trommald Formation of the Cuyuna district are more speculative but are accepted by many geologists (Marsden, 1968, p. 497 and 499). The age of the Ironwood Iron-formation has not been closely delimited by isotopic determinations.

The Ironwood Iron-formation was divided into five distinctive members by Hotchkiss (1919), and little refinement has been made in subsequent studies. Each member is defined by the predominance of one of two general types of iron-formation: thick wavy-bedded cherty iron-formation and thin straight-bedded iron-formation. These types correspond generally to the types that make up the cherty and slaty members of the Biwabic Iron-formation; however, the terms "cherty" and "slaty" are not used in this report.

The minerals present in the Ironwood Iron-formation in the area of detailed study include only those found in unmetamorphosed iron-formation and in the lowest grade metamorphic zones: quartz, siderite (including some magnesium-, manganese-, and calcium-bearing siderite), hematite, magnetite, chamosite, and stilpnomelane. Aphrosiderite and greenalite are probably also present. Huber (1959, p. 92) and Mann (1953, p. 261) identified minnesotaite from the Gogebic district, but I did not find any between Ironwood and Ramsay. I believe that stilpnomelane and minnesotaite are both mostly metamorphic minerals in this district because their areal distribution is so closely related to metamorphic gradients in the area.

The term "chert," as used in this report, always refers to fine-grained quartz, mostly present as an interlocking mosaic of grains of about equal size; the minimum size is approximately 2 μm where least metamorphosed. Especially in the vicinity of Ramsay, some of the chert is found in minute spherulites that extinguish as a cross under crossed prisms. In zones of higher metamorphic grade, the grain size of the chert is larger; this increase in grain size has been used as an index of the degree of metamorphism (James, 1955).

The iron-formation almost certainly originated as a chemically precipitated subaqueous sediment, but workers still disagree on many details of the sedimentary environment. Important recent reviews and discussions of origin were presented by Percival (1955), Gross (1970), LaBerge (1973), Cloud (1973), Eugster and Chou (1973), and Garrels, Perry, and Mackenzie (1973).

Much of the following stratigraphic information about the Ironwood Iron-formation was derived by examining a series of outcrops and exploratory trenches in Michigan at the old Eureka mine at Ramsay and a series of small test pits near the old Puritan mine. The first locality contains information about the Plymouth, Yale, and Norrie Members; at the second locality, the entire iron formation and the base of the Tyler Formation were exposed at closely spaced intervals. Most of the pits at the Puritan mine have been filled since I examined them. In addition, good stratigraphic sections were obtained from the cores of a few drill holes identified in this report. A complete, probably composite, stratigraphic diagram, assembled by unidentified mining company geologists from data obtained from the underground workings of the Eureka mine, is referred to in this report as the "Eureka mine stratigraphic diagram" (unpub. data, 1918) and was useful in my studies of the district.

THIN-BEDDED IRON-FORMATION

The thin-bedded iron-formation consists of finely laminated sideritic rock, intercalated sideritic and cherty rock, and, to a lesser extent, sideritic chert. Most of this type of iron-formation is characterized by bedding laminae less than 1 cm (0.4 in.) thick; most laminae are less than 5 mm (0.2 in.) thick, and many are too thin to be seen with the unaided eye. Uncommon chert layers more than 1 cm (0.4 in.) thick, and some especially large blebs and short fat lenses of thick-bedded-type chert are probably normal constituents of the thin-bedded phase itself. Some intervals of thin-bedded iron-formation in the Ironwood contain many granule-bearing layers 3-10 mm (0.12-0.4 in.) thick (as described in the following section on thick wavy-bedded cherty iron-formation); perhaps these intervals are best considered as being transitional between the thin-bedded and thick wavy-bedded types.

The primary mineral suite of the thin-bedded iron-formation is siderite, chamosite, chlorite, and chert, and perhaps some stilpnomelane, and is characteristic of the silicate-carbonate facies (James, 1966, p. W21-W24). Although some thin layers within the Yale Member of the Ironwood Iron-formation are carbon and pyrite bearing, no appreciable or continuous part of the iron-formation is representative of the sulfide facies.

THICK WAVY-BEDDED CHERTY IRON-FORMATION

The wavy-bedded iron-formation consists of interbedded layers of thick chert and "separators" of more ferruginous thinly laminated material. The thick chert beds are largely made up of granules of various iron minerals in a chert matrix. Use of the term "separator," introduced by Aldrich (1929, p. 140-143) for the thinly laminated material between the thick cherty beds, greatly simplifies description of this rock.

Granules are a common feature of many of the cherty iron-formations of the world. They were well illustrated by Irving and Van Hise (1892, pls. 22, 23), and the term was probably first applied in essentially the same usage as at present by Spurr (1894, p. 49). Van Hise and Leith (1911, p. 169) described the great variety of mineral variations that make up the granules and their matrices.

Granules are mostly rounded equidimensional to somewhat flattened grains, embedded in a matrix of contrasting or similar mineral composition. The granules tend to be rather uniform in size, suggesting that they may have been subjected to a normal water-transport sorting process; 0.5 mm (0.02 in.) is a good average size for them (fig. 2). Chert is a common mineral constituent of granules

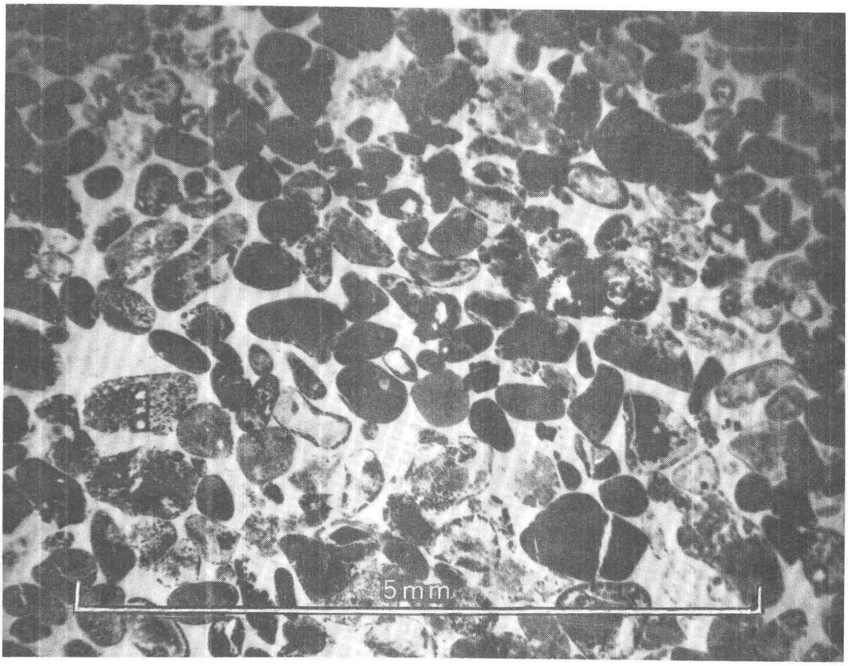


Figure 2.--Photomicrograph showing hematitic granular cherty iron-formation from Anvil Member, Ironwood Iron-formation; NW¼NW¼ sec. 13, T. 47 N., R. 46 W., near Ramsay, Mich.; plane-polarized light.

and matrix. Chert granules in a chert matrix are not uncommon; these structures may be visible only under crossed prisms when a contrast in grain size reveals the outline of the granule. Minerals present in unmetamorphosed granular iron-formation are commonly chert, siderite, hematite, pyrite, chamosite, aphrosiderite, greenalite, and various other chloritic minerals, and minor stilpnomelane. In slightly metamorphosed iron-formation, minnesotaite, stilpnomelane, and magnetite are common, and many more mineral changes have taken place in that part of the iron-formation where metamorphism has been greater.

Granules may be well-rounded spheres or ellipsoids, but they are often irregular, rodlike, or banana shaped, and some "have small 'tails' or comma-like appendages" (White, 1954, p. 7, and Leith, 1903, pl. 9). Internal textures very suggestive of organic forms are common in some of the granules (figs. 3 and 4).

The internal structures of many granules are complex. Some seem to have a core grain or a nucleus, perhaps of clastic origin, overgrown by another material. Rims or overgrowths of fine concentric layers are rather common, and a few oolitic grains are mostly made up this way (fig. 5). Some granules contain chert-filled spaces that suggest contraction cracks (fig. 6). In most iron-formation that has undergone very limited metamorphism, the cherty granules are a very fine mosaic of quartz in the 2- to 10-μm-size range, but in some iron-formation in the Gogebic district, a few

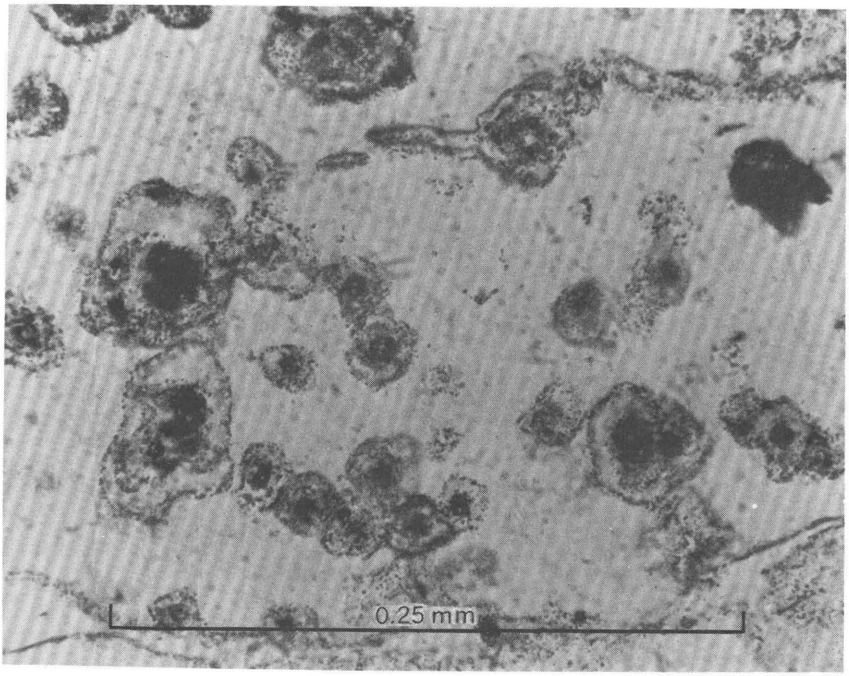


Figure 3.--Photomicrograph showing forms of possibly organic origin within chert granules, base of Anvil Member, Ironwood Iron-formation, drill hole 540, 47 m (155 ft) from hole collar, Peterson mine, Yale, Mich.; plane-polarized light.

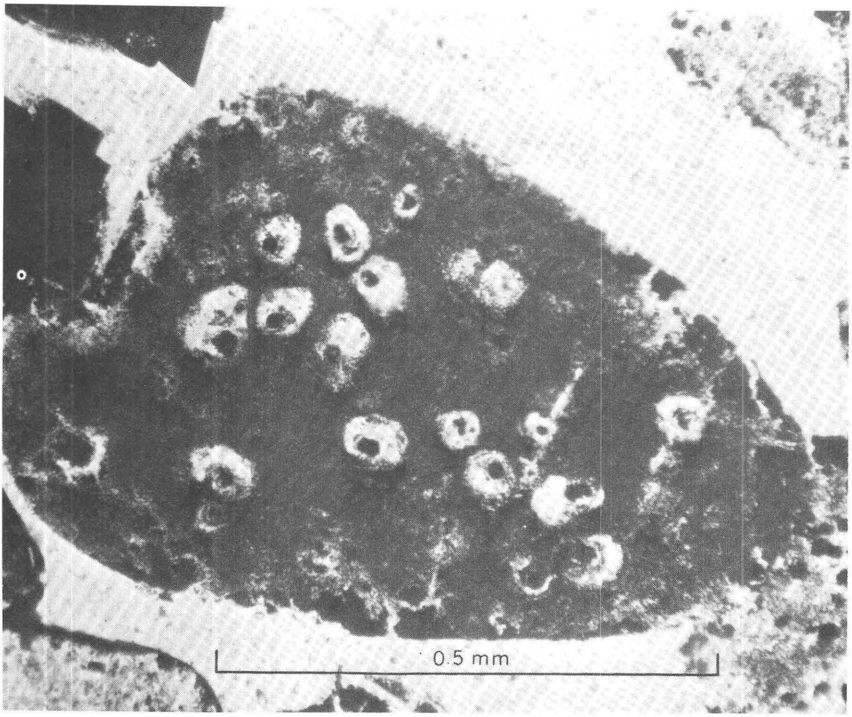


Figure 4.--Photomicrograph showing chert granule (dark gray) containing transparent structures, each having an opaque "nucleus." The darkest material is mostly hematite. Hematitic granular cherty iron-formation from Anvil Member, Ironwood Iron-formation; NW¼NW¼ sec. 13, T. 47 N., R. 46 W., near Ramsay, Mich.; plane-polarized light.

quartzose granules are mostly made up of a single quartz crystal fringed by small euhedral-subhedral grainlets (fig. 7). These single crystal granules are believed to have grown diagenetically rather than to have had a clastic origin.

In unoxidized iron-formation, the wavy chert beds contain much less iron than the separators, possibly as little as 10-20 percent, though little analytical work seems to have been done on the individual layers. The unoxidized wavy chert beds contain, in addition to the chert, mainly siderite and sparse hematite where the beds have been only slightly metamorphosed; very sparse green chlorite

Figure 5.--Photomicrograph showing cross section of chert granules with dark concentric layers of hematite; plane-polarized light. Wavy-bedded iron-formation from Plymouth Member, Ironwood Iron-formation, NW¼NW¼ sec. 13, T. 47 N., R. 46 W., near Ramsay, Mich.

is the only accompanying silicate I recognized. Where the beds have been more metamorphosed, magnetite has taken the place of siderite as the major mineral, and stilpnomelane has replaced the chlorite. It is not possible to estimate how much the content of hematite has changed.

The individual cherty layers pinch and swell and are commonly lenticular, giving the characteristic wavy-bedded appearance. In places, the wavy

Figure 6.--Photomicrograph showing chert granules in the Anvil Member, Ironwood Iron-formation; plane-polarized light. Some granules contain chert-filled spaces (c) that may be contraction cracks. The dark material is hematite. Drill hole 540, 47 m (155 ft) from hole collar, Peterson mine, Yale, Mich.

beds are no more than 3 cm (1.2 in.) thick, but at other places they are commonly as much as 30 cm (1 ft) thick. The bedding undulations do not appear to be oriented along any direction; and such orientation has not been observed in other districts. Distinct graded bedding of granules was not observed here, but a suggestion of grading exists in some samples. Undoubted crossbedding was observed in only one specimen, but it may be commoner than this single observation would indicate; surficial alteration would probably make crossbedding hard to see on outcrops, and it is too large a feature to recognize easily in drill cores.

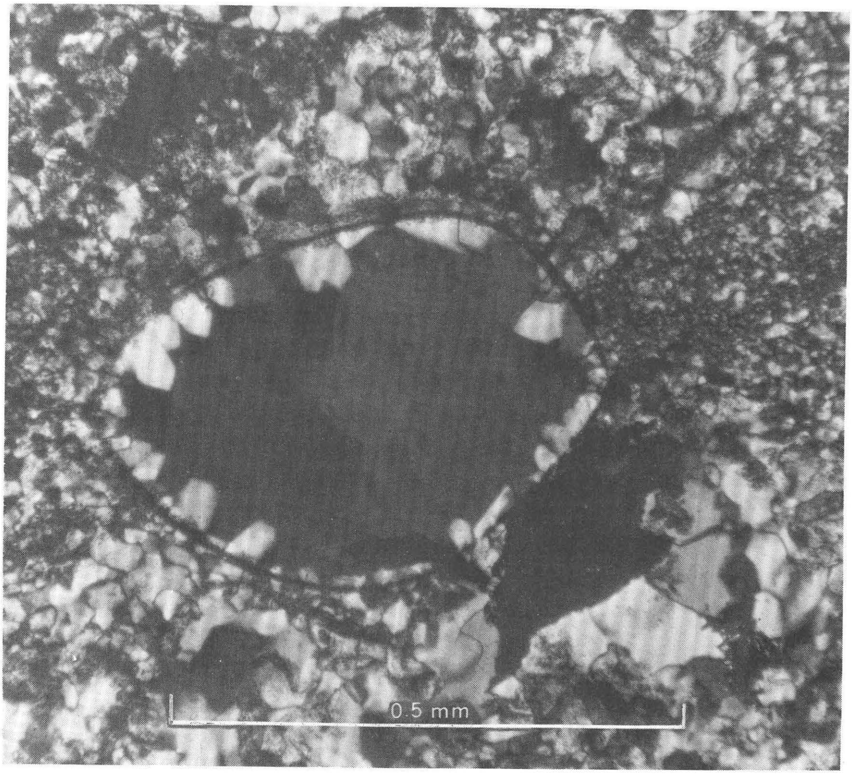


Figure 7.--Photomicrograph showing "chert" granule consisting of one large single quartz crystal fringed by inward-facing prismatic grainlets; cross-polarized light. Base of Anvil Member, Ironwood Iron-formation, drill hole 540, 47 m (155 ft) from hole collar, Peterson mine, Yale, Mich.

Small fragments of chert and jaspery chert are common in the wavy-bedded chert, and locally they are abundant. The origin of the fragments is not clear, but where they are coarse and abundant, they have been interpreted as conglomerates resulting from erosion. Although most of the fragmental layers almost certainly do not represent significant erosional intervals, some of the most persistent layers, which seem associated with anomalous thinning of the strata beneath, may have had such an origin. Some of the fragmental layers may be the result of the breaking up of newly deposited layers by storm waves.

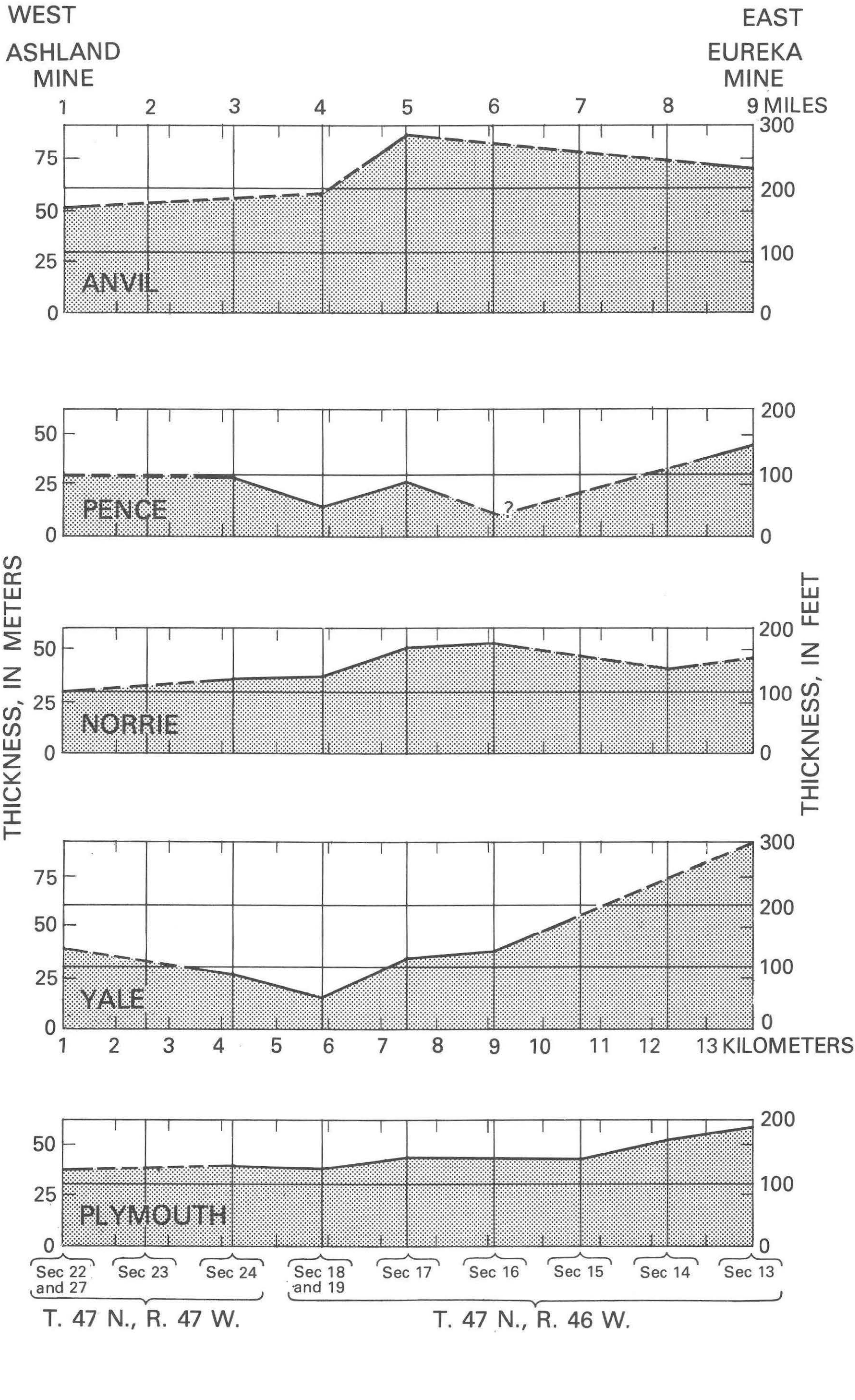
The fragments themselves range from oversized granules to rounded or angular pieces several centimeters (about an inch) across. Many are of thinly laminated iron-formation, and some are flat plates made up of several laminae of that type of rock. Layers containing rounded chert fragments as much as 1 cm (0.4 in.) long are common. Only material that seems to have been derived from the iron-formation is found in the pebbles.

Description of the separators is based on sparse data because the separators tend to oxidize and alter much more readily than the thick chert layers, and it is very difficult to get fresh rock to study. The separators are more ferruginous than the thick cherts, and their composition is probably similar to that of the thinly laminated iron-formation, which they resemble, though there are not enough analytical data to prove this hypothesis. The separators are mostly 3 cm (1.2 in.) or less thick and are very unevenly lenticular, splitting around chert lenses, swelling where the chert layers thin, and joining similar layers from above or below where the intercalated granular chert layers pinch out. Although I have not seen unoxidized separator material in the Ironwood-Ramsay area, but only in the much more metamorphosed rock in Wisconsin, I think that siderite was the dominant primary mineral of the separators in the less metamorphosed part of the district in Michigan.

The primary mineral suite of the thick-bedded iron-formation--chert, siderite, and sparse hematite and silicate--indicates that most deposition took place within the silicate-carbonate facies and locally in the oxide facies.

DESCRIPTIONS OF THE FIVE MEMBERS

The members of the Ironwood Iron-formation are, from oldest to youngest: Plymouth, Yale, Norrie, Pence, and Anvil, the names having been taken from mines that were important in the early history of


WEST
ASHLAND MINE
EAST
EUREKA MINE
1 2 3 4 5 6 7 8 9 MILES
ANVIL
PENCE
NORRIE
YALE
PLYMOUTH
THICKNESS, IN METERS
THICKNESS, IN FEET
1 2 3 4 5 6 7 8 9 10 11 12 13 KILOMETERS
Sec 22 and 27
Sec 23
Sec 24
Sec 18 and 19
Sec 17
Sec 16
Sec 15
Sec 14
Sec 13
T. 47 N., R. 47 W.
T. 47 N., R. 46 W.

the district. The variation in thickness of the members is shown in figure 8.

The Plymouth, Norrie, and Anvil Members are defined as being predominantly thick wavy-bedded chert; the Yale and Pence Members are mostly thin bedded. One layer in the Yale Member is probably tuffaceous; some layers are argillaceous, but chemical analyses of that member indicate that much of the unit is not. In this study, no argillaceous layers were noted in other parts of the iron-formation. The widespread use of the term "slaty" for both thin-bedded iron-formation and ferruginous argillite makes it difficult to identify real argillaceous layers in old descriptions of the rock units.

Although no one before Hotchkiss (1919) attempted systematic subdivision of thick- and thin-bedded iron-formation, many early observers had noted the two general types. Rominger (1895, p. 49-50), describing work done in 1881-84, fairly well defined the two in the area between Sunday Lake and the Black River in Michigan, but that area would have been a very difficult one in which to work out a stratigraphic succession. The lack of good surface exposures delayed subdivision until many underground mines were open and complete cross sections of the iron-formation could be observed.

The types of iron-formation that characterize each of the five members tend to be remarkably persistent along strike from Ramsay, Mich., westward at least as far as Upson, Wis. Beyond Upson, pertinent detail is not available to me. The detailed

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◁Figure 8.--Graphs showing thicknesses of the five members of the Ironwood Iron-formation between Ironwood and Ramsay, Mich. Thicknesses plotted on the vertical lines are averages of all data in a 1.6-km (1-mi) distance along strike. Thickness line is dashed where approximate. Numbers at the top are distances from the Michigan State line in miles and kilometers. (Thicknesses in the ninth column are average data from only 0.8 km (0.5 mi) of strike distance.)

stratigraphy east of Wakefield, Mich., does not correspond to the stratigraphic section at Ramsay, and correlations between the two areas are difficult to make. The problems involved in making correlations eastward from the Ramsay area, and the most reasonable alternate interpretations thereof, were described by Huber (1959, p. 87-89).

Plymouth Member

Hotchkiss named the lowermost member for the Plymouth open-pit mine between Ramsay and Wakefield, Mich. The Plymouth mine exposures are now mostly inaccessible. A large part of the ore mined in the district came from this member, especially in the early years of mining. This member is predominantly thick wavy-bedded and mostly granular chert. In the Ironwood-Ramsay area, the thickness ranges from about 34 to 55 m (110-180 ft), except near Ramsay where the thickness is somewhat greater in the Anvil mine and at the Eureka No. 2 shaft, where it may be about 55 m (180 ft) or 72 m (236 ft), depending on how the available information is interpreted. Hotchkiss (1919) has given the most complete stratigraphic description of the unit.

The Plymouth Member is here divided into five parts, from bottom to top: thin cherty quartzite, algal chert bed, "footwall slate," main wavy-bedded part, and upper thin-bedded cherty part. The main wavy-bedded part of the Plymouth Member is 43 m (140 ft) thick, or about three-fourths of the whole member at the Eureka mine; it probably makes up about the same proportion of the member westward to Ironwood.

The following description of the first part of the member is from Hotchkiss (1919, p. 502):

> The lowest part of the member is a thin cherty quartzite, which is sometimes present at the base. It is occasionally as thick as five feet, and rarely reaches a thickness of ten feet. Like the true foot-wall quartzite [Palms Formation],it

> is chiefly composed of rounded sand grains, but it differs in being cemented with chert, rather than with the crystalline silica, which is the characteristic cement in the true Palms quartzite foot wall. Wherever it is present, this cherty quartzite makes the southernmost [lowermost] bed of the Ironwood formation. Its contact with the quartzite below is abrupt * * *. The character of this thin introductory bed varies from quartzite in which the chert is present only as the filling of the spaces between the sand grains to a clear fine-grained chert in which there are only a few quartz grains.

Hotchkiss pointed out that the cherty quartzite was usually lumped with the Palms Formation by mine geologists. Its general resemblance to the Palms Formation may have caused it to be overlooked elsewhere. Hotchkiss did not cite specific localities for this bed. Although Aldrich (1929, p. 156) discussed "a zone of 5-10 feet comprising a mixture of chert and sand grains," it is not clear whether he was referring to the same stratum. Huber (1959) did not mention the cherty quartzite in his study; it was not recognized in the present work, although in the SW¼NW¼ sec. 24, T. 47 N., R. 47 W., Mich., I saw a few separate cherty layers in the Palms Formation quartzite close to the granular cherty iron-formation.

Unlike the cherty quartzite, the algal chert is easy to recognize in surface exposures and in drill cores. Called variously the jasper conglomerate, foot conglomerate, and gnarled chert, this layer has been described as being very persistent. Hotchkiss (1919, p. 502) said, "This bed is present in all places where the footwall of the formation is seen." I was not able to confirm its continuity, but the algal chert is certainly present at several widely spaced locations in Michigan and Wisconsin.

This bed is cherty to jaspery, is generally characterized by textures and structures attributed to organic forms, presumably algae, and locally is characterized by conglomeratic or conglomeratelike texture. The algal chert bed is 0.3-1.5 m (1-5 ft) thick in the central part of the district (Hotchkiss, 1919, p. 503), is 2.2-4.3 m (9-14 ft) thick near Ramsay, Mich., and seems to increase in thickness eastward toward Wakefield. The bed can be seen at several places in old mine workings; the best exposure is in an old railroad cut in the SW¼NW¼ sec. 15, T. 47 N., R. 46 W., Mich., near Bessemer, and the best algal material is in an old railroad cut in the SE¼NW¼ sec. 14, T. 47 N., R. 46 W., Mich., near Anvil.

The general stromatolitic character of the organic forms is very convincing. Structures of this type from the Mesabi district were specifically described as algal by Grout and Broderick (1919), and Hotchkiss (1933, p. 53-55) said that the layer in the Ironwood is "almost undoubtedly of algal origin."

The stromatolitic structures are small and rather irregular, mostly 1-3 cm (0.4-1.2 in.) in diameter and 2-10 cm (0.8-4 in.) high. Each structure is made up of very fine laminae, each lamina being crudely cup shaped, concave downward, the "stack of cups" forming the whole structure. The rock exposures I have seen in the Gogebic district are not good enough to show the relationship between the separate structures, though the relationship can be seen in the Mesabi district (Grout and Broderick, 1919, p. 18-19, 21-22, pl. 17). Where they are abundant, the structures probably make up only about one-tenth of the rock.

The structures seem to be found only in rock that is dominantly chert, and they are themselves chert containing only sparse hematite. The stromatoliths and the enclosing rock are either white, gray, or red and jaspery; mottling of the various colors is common. Magnetite is a constituent where the metamorphic grade approaches the biotite zone. The laminae are very thin and are formed by hematite dust. Certain lenses or "stratigraphic zones" in the algal laminae contain sparse to abundant granules of an unusually small size (0.05-0.06 mm long). Peculiar spherical forms, probably of organic origin (LaBerge, 1967), are common in the granules. Scattered sand grains are sometimes present in the algal chert bed, especially near the base, as in the old open pit near the NE cor. SE¼SW¼ sec. 17, T. 47 N., R. 46 W., Mich.

The stromatolitic layer is succeeded by a persistent thin-bedded unit that has been called the "footwall slate," although it is not clear how argillaceous the unit really is. It seems to have oxidized with unusual ease; therefore, unaltered samples are very difficult to obtain.

Where fresh, the "footwall slate" is a light-greenish-gray laminated iron-formation, in part without any distinct chert layers. In a fresh sample from Upson, Wis., 19 km (12 mi) southwest of Ironwood, fine clastic fragments make up perhaps 10-30 percent of the rock; a chloritelike mineral is abundant, magnetite is common, and carbonate material is less so. Studies of oxidized material from the Ironwood-Ramsay area identified it as a rather ordinary thin-bedded iron-formation, red brown and hard to soft. Hotchkiss (1919) gave a thickness for this unit of nearly 30 ft (9 m) at the Mikado mine, just east of Ramsay, Mich., but said (p. 503): "In most of the mines the slate has a maximum thickness of only two or three feet, and in some cases it becomes so thin that it practically disappears. In almost all cases, however, a thin soft seam is present, which can be correlated with the footwall slate." Thicknesses of 4-8.5 m (13-28 ft) were recorded in drill records from various mines from the Geneva to the Eureka. The "footwall slate" perhaps forms a plane of structural weakness relative to beds immediately above and below, for at places it appears to have been thinned and deformed by differential bed movement.

The softness of this unit results in a lack of good exposures, though the adjacent units are visible. In the old open pit near the NE cor. SE¼SW¼ sec. 17, T. 47 N., R. 46 W., Mich., the "footwall slate" is about 38 cm (15 in.) of soft hematitic laminated rock, much of which has been eroded out to leave an open slot.

A chemical analysis of the fresh sample obtained from Upson, Wis., is given in table 1. The relatively high content of Al_2O_3 (10.3 percent) indicates that the sample contains appreciable argillaceous material.

The main wavy-bedded part of the Plymouth Member.--The main wavy-bedded part of the Plymouth Member constitutes one-half to three-fourths of the Plymouth Member and has been perhaps the most important ore-bearing interval in the Ironwood Iron-formation. Relatively thin blankets of ore at the base of this part occupy more area on the former bedding surface than do ores at any higher horizon. These strata are made up of wavy-bedded and lenticular layers of granular chert ranging from less than 1 cm (0.4 in.) to 30 cm (12 in.) in thickness and separated by uneven thin-bedded ferruginous layers as much as 5 cm (2 in.) thick. A few granular chert layers are as much as 60 cm (24 in.) thick, and a few separators are as much as 20 cm (8 in.) thick.

TABLE 1.—*Chemical analysis, in weight percent, of a sample from the Plymouth Member, Ironwood Iron-formation*

[Field no. UP-196A-FW; lab. no. W-173-417; light-greenish-gray laminated iron-formation without distinct chert layers from "footwall slate," 4 cm (1.6 in.) of drill core from Upson, Wis. Analysts: Leonard Shapiro, P. L. D. Elmore, G. Chloe, L. Artis, J. Glenn, J. Kelsey, and Hezekiah Smith, U.S. Geol. Survey. Analysis done by rapid rock methods of Shapiro (1967)]

SiO_2	50.7	K_2O	0.27
Al_2O_3	10.3	H_2O^+	4.7
Fe_2O_3	10.1	H_2O^-	.09
FeO	14.6	TiO_2	.40
MgO	5.8	P_2O_5	.11
CaO	.74	MnO	.18
Na_2O	.08	CO_2	1.2
Total of both columns			99.3

Detailed stratigraphic study of relatively little altered material might reveal data for further dividing the main wavy-bedded part of the Plymouth Member into mappable layers.

Hotchkiss (1919, p. 503) divided it to the following extent:

> Certain rather consistent general tendencies as to thickness of bedding characterize various parts of this granular chert portion of the Plymouth Member. The lower part of it, for distances varying from twenty to sixty feet from the foot-wall slates, is frequently characterized by beds one to five or six inches in thickness, with rather heavy beds of iron oxide separating them. North of this in many sections there is observed a tendency on the part of the chert beds to become much thicker and more massive, and the separating beds of iron oxide to become thinner. This massive phase of the chert is frequently also fine-grained chert rather than the distinctly granular variety. The thickness of this massive chert is exceedingly variable. In some cases the chert is entirely lacking, and again it has a thickness of fifty or sixty feet.

In the Eureka mine area, the whole main wavy-bedded part of the Plymouth Member is about 41 m (135 ft) thick; near the Puritan mine, it is perhaps 24 m (80 ft) thick. Zinner and Holmberg (1947, fig. 3) recognized a similar unit somewhat less than 24 m (80 ft) thick between Pence and Iron Belt, Wis.

The upper part of the Plymouth Member.--The upper part of the Plymouth Member is made up of relatively thin chert layers and was shown as 13 m (43 ft) thick on the "Eureka mine stratigraphic diagram" (unpub. data, 1918); in contrast, my estimate for the thickness of surface exposures in the same area is 23 m (75 ft).

The layers are more uniform in the upper part of the member than below, generally ranging from 1 to 3 cm (0.4-1.2 in.) in thickness. Some of the layers are made up of granular chert and some are plain chert. No unoxidized iron-formation from this interval was seen in this study, and it probably is present only in deep drill holes and mine workings. The unoxidized material can be presumed to be gray or greenish gray; the rock at the surface is dull red brown and brown except for some of the most siliceous cherty layers, which are dull gray. Chert layers and separators make up about equal parts of the strata. According to Hotchkiss (1919, p. 503), "This thin-bedded portion usually constitutes the uppermost part of the Plymouth member, but in some cases toward the top the chert beds again become thicker."

Outcrops and trench exposures at the Eureka mine do not expose a complete section of the upper part of the Plymouth Member, but a minimum of 6.4 m (21 ft) of wavy thick-bedded jaspery granular iron-formation is present there. Granules in the cherty beds are partly bright red jasper; some of the jaspery layers have many intermixed rounded and angular jaspery fragments, some as large as 1 cm (0.4 in.). These fragment-bearing layers are presumed to be the "conglomeratic zone" at the top of the Plymouth Member (Huber, 1959, p. 102).

Within the thinly laminated strata in the upper part of the Plymouth is a zone of thinly layered bright red jasper, perhaps ranging from 15 cm (0.5 ft) to 1.8 m (6 ft) in thickness; this zone may be a very persistent stratigraphic unit. Hotchkiss (1919, p. 503) mentioned the zone, which he described as "yellow flinty chert" in the Davis mine (NW¼ sec. 19, T. 47 N., R. 46 W., Mich.) and brilliant red jasper east of it.

The thin jaspery zone was seen in a drill core from near Upson, Wis., where it is less than 30 cm (1 ft) thick and is found in a thin succession of thin-bedded cherty iron-formation within dominantly thick wavy-bedded material, 16 m (53 ft) below the top of the Plymouth Member.

The bright-red jasper layers are mostly less than 1 cm (0.4 in.) thick. In some specimens, the layers are fairly uniform and parallel, but most have some laminae that pinch out, and in many samples, jasper is present only as short lenses or even bleblike bodies. Less commonly, some layers contain jasper that is in angular fragments. In the "typical" jaspery beds, the jasper makes up one-fourth to three-fourths of the total thickness. Most of the separating material is brown or red-brown oxidized siliceous thinly laminated iron-formation.

The central Gogebic jasper (including that from the Puritan, Eureka, and Vicar mines) is colored by red-reflecting particles on the order of 0.0005 mm in diameter, whereas jasper of similar appearance from Ispheming in the Marquette district, Mich., is colored by hematite in minute crystal platelets. The particles in Gogebic jasper tend to be aggregated into spheres 0.008-0.016 mm in diameter. These are similar to the "type E" structures of LaBerge (1967, p. 336-337), who believed them to be of organic origin.

The Plymouth-Yale contact zone was described by Hotchkiss (1919, p. 503) as a gradation generally less than 1 ft (30 cm) thick.

Yale Member

The Yale Member of the Ironwood Iron-formation was named by Hotchkiss (1919, p. 501) for the Yale mine in the NW¼ sec. 16, T. 47 N., R. 46 W., Mich. Many rock types are present in the Yale Member, and data are unfortunately scant regarding succession, extent, and thickness of the various types. Although Hotchkiss (1919, p. 504) mentioned that the member could be divided into three subunits in Wisconsin, the member is here described in three parts that do not correspond to those of Hotchkiss.

The Yale Member is mostly thin bedded iron-formation; it also contains a few granular wavy-bedded layers, black argillite that is partly pyritiferous, and, in the eastern end of the district, a tuffaceous bed. The lower two parts of the member are not present at Pence or west of Pence, in Wisconsin, and some parts of the succession may be missing in other places also. Hotchkiss (1919, fig. 17, p. 502, and p. 504) seemed to imply some cutting out and probably also duplicating of beds by the "great bedding fault." This rather elusive structure must have considerably modified the succession and thickness of the Yale Member, but the places where the modifications are significant are now difficult to recognize.

The most complete and detailed section of the Yale Member that I obtained was in the cores of drill hole 81 in the North Palms property. Hole 81 was drilled on the section line, 720 m (2,363 ft) east of the NW cor. sec. 14, T. 47 N., R. 46 W., Mich.; the hole was drilled underground from an altitude of 26 m (85 ft) below mean sea level. The total thickness was interpreted to be 63 m (206 ft), and the member can be divided into subunits by the presence of the tuffaceous layer. A relatively complete stratigraphic section was also found in old trenches and a railroad cut at the Eureka mine, Ramsay, Mich., where excellent exposures of much of the upper part of the member are present. The "Eureka mine stratigraphic diagram" (unpub. data, 1918) was used here as a third measured section. In addition, I saw what I believe to be a section of the Yale Member, there represented by only the upper part, in a drill core from west of Upson, Wis. The thickness of the three parts of the member at these localities is shown in table 2.

The smallest estimates of the thickness of the Yale Member in the central part of the district, 9-14 m (30-46 ft), are for the West Davis-Geneva mine area (NW¼ sec. 19, T. 47 N., R. 46 W., Mich.). From this locality, the member seems to thicken eastward, and at the Eureka Mine (NW¼ sec. 13, T. 47 N., R. 46 W., Mich.), it is perhaps more than 91 m (300 ft) thick (fig. 8). Westward, it thickens to 30-43 m (100-140 ft) near the State line but thins somewhat to 24-29 m (80-95 ft) near Gile, Wis., and to 13.1 m (43 ft) near Upson. These thickness variations are presumed to be mostly primary, but some may be the result of movement on the "great bedding fault," of Hotchkiss (1919).

The lowermost beds of the Yale Member from three localities in the district were examined as part of this study. In the North Palms drill hole 81, they are 4.3 m (14 ft) thick and are partly oxidized red-brown thin-bedded silicate iron-formation; they include a 30-cm (1-ft) interval of granular and pebbly chert, having rounded and angular pebbles as large as 1.2 cm (0.5 in.). Most granules are of jasper, and part of the granular chert is magnetic.

In a series of old test-pits at the Puritan mine, the lower part of the Yale Member is perhaps 9 m (30 ft) thick. Only oxidized material is present. The beds are thin-bedded iron-formation and have chert laminae as much as 5 mm (0.2 in.) thick; in part of the interval, the chert is sparse.

The lower part of the Yale Member in old trenches and a railroad cut at the Eureka mine is roughly 12.2 m (40 ft) thick. The beds are siliceous and thin-bedded iron-formation containing moderately abundant chert layers and lenses and probably some granular chert layers in the lower 4.6 m (15 ft), and a few chert layers and bleblike lenses and sparse jasper layers in the upper 7.6 m (25 ft).

TABLE 2.—*Thickness of the three parts of the Yale Member, Ironwood Iron-Formation*

[In meters, feet in parentheses]

			Eureka Mine, Ramsay, Mich.	
Yale Member	Drill core from west of Upson, Wis.	North Palms drill hole 81, Bessemer, Mich. (see p. 42 for location)	"Eureka Mine stratigraphic diagram" (unpub. data, 1918)	Old trenches and a railroad cut at the Eureka mine
Upper part -----	13.1 (43)	53.0 (174)	70.1 (230)	63.4 (208)
Tuffaceous layer --------	0 (0)	5.5 (18)	13.4 (44)	[1].9 (3)
Lower part -----	0 (0)	4.3 (14)	15.2 (50)	12.2 (40)
Total -----	13.1 (43)	62.8 (206)	98.7 (324)	76.5 (251)

[1]Tuffaceous layer thickness is roughly estimated from relative abundance of dump material.

The middle unit of the Yale Member is present only in and eastward from the Yale mine and is probably the westernmost extension of the Emperor Volcanic Complex interbedded within the Ironwood Iron-formation east of Wakefield (Trent, 1973). This layer was interpreted as a tuffaceous bed by S. A. Tyler (oral commun., 1950), and the present study supports that conclusion. In the North Palms drill hole 81, the tuffaceous layer is 5.5 m (18 ft) thick and is a dull gray nonbedded rock, dark gray on a polished surface, and contains subrounded to angular clasts as large as 4 mm (0.16 in.). The matrix is leucoxene rich, and leucoxene makes up 5-10 percent of the whole rock. Scattered pyrite grains appear lacy on the polished surface. A layer of dull light-gray unbedded material, probably the oxidized and weathered equivalent of the same rock, is present in the same stratigraphic position in a trench at the old Eureka mine. No similar unit was identified in the Puritan mine test pits in the Yale Member. The "Eureka mine stratigraphic diagram" (unpub. data, 1918) and also mine cross sections show a 13-m (44-ft) -thick unit at this horizon called the "interbedded dike." I think that this unit can reasonably be interpreted as the tuffaceous bed. I believe it to be the same unit shown by Hotchkiss (1919, sec. 22, fig. 17, p. 502) as a sill extending eastward from the Yale mine. Old mine maps and cross sections show additional conformable layers ("sills") of igneous rock somewhat above the Plymouth Member about 1.6 km (1 mi) east of Ramsay; these layers may be pyroclastic or flow rocks also.

The upper part of the Yale Member is the most extensively exposed unoxidized iron-formation in the Ironwood-Ramsay area. The best exposures are near Ramsay on the side of an old railroad cut in the NW¼NW¼ sec. 13, T. 47 N., R. 46 W., Mich., near the Eureka mine. Several good exposures in the nearby Anvil-Palms mine area probably represent most of the same section, but their relative stratigraphic positions are more difficult to determine.

In the Ironwood-Ramsay area, the Yale Member for about 13 m (43 ft) above the tuffaceous bed is dark gray or black, partly pyritic, possibly somewhat argillaceous iron-formation having almost no separate chert layers; it grades upward into about 21 m (70 ft) of gray argillaceous iron-formation containing less black carbon and pyrite and an increasing amount of chert. Scattered 1- to 3-cm (0.4- to 1.2-in.) -thick granular chert layers and lenticles, perhaps one or two per meter (3.3 ft), make up the cherty part of the remaining higher beds; more rarely, as in a drill hole at Pence (Huber, 1959, p. 104), the succession of thinly laminated beds is interrupted by short intervals of thick wavy-bedded granular iron-formation. The higher beds also contain many thin laminae and blebs of green nongranular chert.

According to Zinner and Holmberg (1947, fig. 3) and Huber (1959, p. 104-105), the lowermost beds of the Yale Member at two localities near Pence, Wis., are dark gray to black, carbonaceous, and locally pyritic and "slaty," and probably are argillaceous iron-formation. However, I interpret these beds to be the normal strata above the tuffaceous layer, the tuff and the lower part of the Yale being missing here. In drill holes 121 and 113 at Pence (Huber, 1959, p. 104-106), the black slate at the base is 3.7 and 4.0 m (12 and 13 ft) thick, and all the Yale present is 20.4 and 13.7 m (67.5 and 45.5 ft) thick. A chemical analysis of a sample (table 3, sample 121-715) of the lowest 6.4 m (21 ft) of the Yale Member (drill hole 121, 217.9-224.3 m (715-736 ft), SE¼SE¼ sec. 31, T. 46 N., R. 2 E., near Pence) examined by Huber indicates a moderately high amount of TiO_2 relative to Al_2O_3, a condition also found in the tuffaceous layer.

In a drill hole west of Upson, Wis., where I also believe only the upper part of the Yale Member is present, the member is dark-gray to black carbonaceous and pyritic argillaceous iron-formation, 8.8 m (29 ft) thick, overlain by 4.3 m (14 ft) of gray and dark-greenish-gray thinly laminated cherty iron-formation containing sparse intercalated dark chert layers as much as 3 cm (1.2 in.) thick. The whole upper interval is 13.1 m (43 ft) thick, whereas the thickness of "black slate" and the total thickness of the upper part of the Yale in the

TABLE 3.--*Chemical analyses, in weight percent, of samples from the Yale Member, Ironwood Iron-formation*

[Analyses in the first seven columns by P. L. D. Elmore, L. Artis, J. Kelsey, Leonard Shapiro, G. W. Chloe, J. Glenn, Hezekiah Smith, U.S. Geol. Survey, by rapid-rock-analysis methods of Shapiro (1967). Analyses of samples 9472, 12885, and 12887 are from Irving and Van Hise (1892, p. 191-192, cols. II, III, and IV). Analyses in the last two columns are from Huber (1959, p. 91, table 2, col. C and p. 101, table 8). Tr, trace; n.d., not determined]

Laboratory No. ------	W173 410	W173 411	W173 412	W173 413	W173 414	W173 415	W173 416				53-2107 CD	
Field No. ------	366-A	366-B	366-AO	368-C	368-S	372	P81-625	9472	12885	12887	NKH-104-53	121-715
SiO_2 -------	52.6	85.1	57.6	82.9	42.8	47.6	86.2	28.86	46.01	46.47	32.87	51.81
Al_2O_3 -------	.91	.30	1.8	.42	1.6	1.9	1.5	1.29	.83	.70	2.46	6.78
Fe_2O_3 ------	1.1	2.4	32.4	.58	1.0	.86	5.9	1.01	1.35	.86	4.78	3.44
FeO --------	24.4	7.6	.28	8.2	30.0	26.4	5.0	37.37	26.00	28.57	30.84	[1]19.83
MgO --------	2.1	.61	.25	.72	2.5	3.0	.10	3.64	2.86	2.30	3.58	3.46
CaO --------	.36	.17	.18	.19	.44	.75	.10	.74	.63	.49	.62	.37
Na_2O -------	.00	.00	.00	.04	.03	.03	.04	n.d.	n.d.	n.d.	.00	.00
K_2O --------	.00	.00	.00	.02	.00	.00	.04	n.d.	n.d.	n.d.	.00	.00
H_2O --------	([2])	([2])	([2])	([2])	([2])	([2])	([2])	.68	1.71	.60	([2])	([2])
H_2O^+ -------	.17	.54	4.5	.57	.53	.64	.76	n.d.	n.d.	n.d.	1.69	4.32
H_2O^- -------	.07	.03	.87	.04	.05	.08	.04	n.d.	n.d.	n.d.	.28	.33
TiO_2 -------	.03	.02	.06	.07	.16	.12	.02	.20	.12	.10	.27	.93
P_2O_5 -------	.12	.04	.16	.04	.16	.34	.05	Tr	.07	Tr	.09	.16
MnO --------	.75	.25	.81	.40	.92	.62	.04	.97	2.09	.40	1.33	.49

TABLE 3.—*Chemical analyses, in weight percent, of samples from the Yale Member, Ironwood Iron-formation*—Continued

Laboratory No.	W173 410	W173 411	W173 412	W173 413	W173 414	W173 415	W173 416				53-2107 CD	
Field No.	366-A	366-B	366-AO	368-C	368-S	372	P81-625	9472	12885	12887	NKH-104-53	121-715
CO_2	16.6	4.6	.15	5.6	19.8	17.6	.18	25.21	17.72	19.24	20.94	4.30
FeS_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	.11	n.d.	n.d.	n.d.
S	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	.09	1.94
V_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	.00	.04
C	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	.45	2.54
Total	99.2	101.7	99.1	99.8	100.0	99.9	100.0	99.97	99.50	99.73	100.29	100.74
Less O for S											.05	.49
Corrected total											100.24	100.25

[1]The acids used to dissolve the sample do not attack pyrite. Therefore, a calculated correction, based on the sulfur present, was made on the FeO to take care of the Fe in the pyrite. When this correction was made, it was assumed that all sulfur was present as pyrite.

[2]The H_2O^+ and H_2O^- were determined separately.

Descriptions of the sampled materials:

366-A, 366-B, 366-AO:

Thin-bedded granular or pelletal chert carbonate iron-formation. Analyses of: 1.0-cm (0.4-in.-) -thick unoxidized carbonate-rich-layer (366-A), readily susceptible to oxidation; unoxidized 0.3-cm (0.12-in.-) -thick chert-rich layer (366-B), less susceptible to oxidation; and oxidized part of the susceptible 1.0-cm (0.4-in.-) -thick carbonate-rich layer (366-AO). Surface outcrop, near middle of Yale Member and probably above tuffaceous layer. In SE part, NW¼NW¼ sec. 14, T. 47 N., R. 46 W., Mich.

368-C, 368-S:

Unoxidized laminated chert-carbonate iron-formation. Analyses of: 0.7-cm (0.28-in.-) -thick chert-rich layer (368-C) and 1.5-cm (0.6-in.-) -thick carbonate-rich layer (368-S). Old railroad cut, below center of Yale Member, probably above tuffaceous layer, along the south boundary of the NW¼NW¼ sec. 14, T. 47 N., R. 46 W., Mich.

TABLE 3.—*Chemical analyses, in weight percent, of samples from the Yale Member, Ironwood Iron-formation*—Continued

372:

Unoxidized thin-bedded chert-carbonate iron-formation. Analyses of: 1.3-cm (0.52-in.-) -thick layer of carbonate-rich iron-formation that includes one 0.3- to 0.5-cm (0.12- to 0.2-in.-) -thick chert layer. Below midpoint of Yale Member, probably above the tuffaceous layer. Surface outcrop in SE part, NE¼NW¼ sec. 14, T. 47 N., R. 46 W., Mich.

P81-625:

Coarsely granular magnetite-bearing chert from 30-cm (1-ft-) -thick layer within laminated carbonate-silicate iron-formation. Analyses are of 3.0-cm (1.2-in.-) -thick piece of drill core from about 3 m (10 ft) above base of Yale Member; North Palms drill hole 81, 190.5- to 192.0-m (625- to 630-ft) depth, drilled from 12th mine level (26 m (83 ft) below mean sea level) on the section line, 720 m (2,363 ft) east of the NW cor. sec. 14, T. 47 N., R. 46 W., Mich. (compare with 366-B).

9472:

From the "large precipitous exposure on the south side of the outlet of Sunday Lake" (Irving and Van Hise, 1892, p. 191) (original course of Little Black River, not shown in fig. 1), SE¼NE¼ sec. 13, T. 47 N., R. 46 W., Mich. Sideritic iron-formation, probably Yale Member (but could perhaps be Pence).

12885:

Cherty carbonate iron-formation "occurring near the base of the iron-bearing member on the Miner & Wells option, sec. 13, T. 47 N., R. 46 W.," Mich. (Irving and Van Hise, 1892, p. 191-192). The option was the N½NE¼, according to pre-1890 property maps, but the location "near the base" coupled with the outcrop map, plate 12 of Irving and Van Hise (1892), suggests the outcrop was near the east boundary of the SE¼NE¼ sec. 13. The sample is probably from the lower part of the Yale Member. The sample was described by Irving and Van Hise (1892, p. 236-237).

12887:

A specimen "representing a large natural exposure on the Palms property, sec. 14, T. 47 N., R. 46 W.," Mich. (Irving and Van Hise, 1892, p. 191-192). The specimen is almost certainly from the Yale Member and is probably from above the tuffaceous layer. The specimen does not seem to have been described by Irving and Van Hise (1892).

NKH-104-53:

Chert-carbonate iron-formation from middle of Yale Member present; however, the lower and middle divisions of the member are probably lacking at this place. From drill hole 121, 201.2-205.4 m (660-674 ft), SE¼SE¼ sec. 31, T. 46 N., R. 2 E., near Pence, Iron County, Wis.

121-715:

Pyritic ferruginous slate (siliceous argillaceous iron-formation) from lowermost part of Yale Member present; however, the lower and middle divisions of the member are probably lacking at this place. From drill hole 121, 217.9-224.3 m (715-736 ft), SE¼SE¼ sec. 31, T. 46 N., R. 2 E., near Pence, Iron County, Wis.

Eureka mine are 3-6 m (10-20 ft) and 70.1 m (230 ft), respectively.

I have not found carbonaceous argillaceous iron-formation within the Yale Member in Michigan, and I suspect there may not be any. However, very dark gray chamositic iron-formation is in the bottom of the upper part of the member near Ramsay, Mich., and this has been called "black slate" in old stratigraphic descriptions, giving the impression that the carbonaceous rock is present here also.

Chemical analyses of samples from the Yale Member are given in table 3. Samples 366-A, 366-B, 368-C, 368-S, 372, and NKH-104-53 are representative of the unoxidized chert carbonate or chert silicate iron-formation and are probably from the upper part of the Yale; 366-AO is from an oxidized part of the same layer as 366-A. Sample 121-715 is probably from the base of the upper part, and sample 12887 is probably also from the upper part of the member. Samples 12885 and P81-625 are probably from the lower part of the Yale, whereas the stratigraphic position of 9472 is not certain.

A chemical analysis for the lowermost part of the Yale Member present in drill hole 121 near Pence, Wis. (Huber, 1959, p. 104-105), is given in table 3 (sample 121-715). Though the alumina content is high for iron-formation, the analysis indicates that the rock is more appropriately called siliceous argillaceous iron-formation than slate.

According to Hotchkiss (1919, p. 504), "The relation of the Yale Member to the Norrie Member is such as to suggest continuous deposition and an entirely conformable relation."

Norrie Member

The middle member of the Ironwood Iron-formation was named by Hotchkiss (1919) for the Norrie mine, in the SE¼ sec. 22, T. 47 N., R. 47 W., Mich. Good natural or mine exposures of this member are unknown in the central Gogebic area, and the only good sections available were in the North Palms drill hole 81 near Bessemer, Mich., and in drill holes near Upson, Wis. The holes described by Huber

(1959, p. 104-106) from near Pence, Wis., penetrated oxidized material in this interval; because core recovery was poor, little information was obtained. The report by Hotchkiss and the North Palms hole were major sources of information on this member. Hotchkiss (1919, p. 504-505) described the Norrie Member as follows:

> The Norrie member is made up almost wholly of wavy-bedded granular and fine-grained ferruginous chert, with hematite in beds and grains exactly as in the Plymouth member. The thickness of the individual beds varies considerably from place to place in this member, but there is in general in the lower part of the Norrie a heavily ferruginous, moderately thin-bedded part, succeeded by rather massive, thick-bedded fine grained chert, which has low iron content. In most places where it is known, the upper part of the Norrie member is thin, wavy-bedded, heavily ferruginous chert. In places where the Norrie member is thicker than usual there is oftentimes found at the very top a massive, thick-bedded, fine-grained, green chert, which alters in spotted fashion, giving an appearance which has been described as 'worm-eaten chert.' These leached spots are usually a quarter to an eighth of an inch in diameter.
>
> East of the Davis mine the thin-bedded upper part of the Norrie contains numerous thin beds of ferruginous slate which vary from a few inches to one foot or two feet in thickness. The thickness of the Norrie member is as little as 30 ft. in the Windsor mine (Hurley, Wisconsin) and becomes as great as 230 ft. in the Yale mine. Fig. 17 shows that the Norrie member varies greatly in thickness in short distances. In some of the crosscuts across the formation the Pence member apparently cuts out the upper beds

of the Norrie member, leaving only a few feet of the lower portion.

Marking the top of the Norrie member in a pronounced fashion in the western end of the district, but somewhat less noticeable in the eastern part, is a thin conglomerate made up of flat pebbles of a considerable variety of phases of the iron-formation material. Associated with this conglomerate bed is often found several inches of granular red jasper having a decidedly fragmental appearance. This granular jasper rather than conglomerate, is the usual phase found east of the Ashland mine.

The considerable variation in thickness of the Norrie, the difference in the character of its uppermost beds, where it is thick, from those which make the top, where it is thin; the abrupt transition in character of beds from Norrie to Pence, and the occurrence of a conglomerate or of a fragmental appearing granular jasper, are all facts which indicate an erosion interval succeeding the deposition of the Norrie and preceding the deposition of the Pence. Though little can be said of the duration of this period, it was probably relatively short compared to the erosion period between the granite and the Palms, or that between the Anvil and the Pabst members.

Ferruginous strata at the base of the Tyler Formation have been designated as the "Pabst Member" by various investigators. These beds are not regarded as a separate unit in this report.

In the "Eureka mine stratigraphic diagram" (unpub. data, 1918), the Norrie Member is described as 24 m (80 ft) thick and consisting of a thin basal "conglomerate" followed by thin platy iron-formation containing interbedded granular chert and jasper. I was not able to separate the Norrie and Pence Members on the basis of test-pit spoil in the Eureka mine area. The thickness of the Norrie in the now-filled Puritan mine test pits could not be measured accurately, but abundant oxidized material in the spoil heaps retained textural details. This spoil material was hematitic granular wavy-bedded cherty iron-formation; it was mostly thick bedded but was thin bedded in an interval about one-third of the way up from the bottom and also near the top. The pit spacing did not permit reliable estimates of thicknesses of these subunits. Jaspery pebbles and thin jasper plates as much as 2 cm (0.8 in.) long were common in the uppermost pit in the Norrie Member. In this relatively small sampling of the uppermost Norrie, the fragmental jaspery material appears to contain intercalated normal thin undisturbed iron-formation layers, and, at least here, the "conglomerate" seems to be a normal part of the sedimentary sequence rather than the product of an erosional interval.

A chemical analysis of material from an outcrop east of Ramsay, probably from thin-bedded iron-formation in the middle or upper part of the Norrie

TABLE 4.—*Chemical analysis, in weight percent, of a sample from the Norrie Member, Ironwood Iron-formation*

[Sample no. 12543. Sample location: SE corner of NE¼ NW¼ sec. 18, T. 47 N., R. 45 W., Mich. Analysis from Irving and Van Hise (1892, p. 192, 237-238)]

SiO_2	36.73
Al_2O_3	.38
Fe_2O_3	.98
FeO	34.74
MgO	2.74
CaO	.48
H_2O^+	1.40
H_2O^-	.12
TiO_2	.19
P_2O_5	.009
MnO	.52
CO_2	22.44
FeS_2	.12
C	.00
Total	100.84

Member, was given by Irving and Van Hise (1892, p. 191-192) and is reproduced here in table 4.

A good stratigraphic section of the Norrie Member is provided by two diamond drill holes west of Upson, Wis., but the section there is probably somewhat different from that in the Ironwood-Ramsay area. Although the mineral-composition change related to metamorphism must be taken into account, the cores are particularly informative because they are mostly unoxidized and give indications of original composition not obtainable from oxidized material.

Measured section of probably all of the Norrie Member, Ironwood Iron-formation, penetrated by North Palms drill hole 81

	Stratigraphic thickness (meters)	Stratigraphic thickness (feet)
No core		
Precambrian X:		
Diabase dike (incomplete):		
Red-brown oxidized dike rock	8.9	29
Ironwood Iron-formation (incomplete):		
Breccia between Pence and Norrie Members:		
Hard gray-brown very dense cherty iron-formation (perhaps thin bedded), and brecciated material	1.2	4
Norrie Member:		
5. Hematitic oxidized granular cherty iron-formation. Seems locally brecciated. In interval 1.5-3.0 m (5-10 ft) above base as much as half the core is dark red-brown dense faintly laminated thin-bedded iron-formation. In the interval 16.8-25.9 m (55-85 ft) above base, red oxide locally makes a mottled pattern in the chert	29.9	98
4. Hematitic incompletely oxidized thinly laminated iron-formation without chert	12.8	42
3. Granular cherty iron-formation; oxidized and hematitic, containing irregular gray areas that are not oxidized	6.1	20
2. Partly oxidized thinly laminated iron-formation containing thin layers and perhaps lenticles of granular chert as much as 2 cm (0.8 in.) thick	2.4	8
1. Oxidized hematitic granular cherty iron-formation, containing irregular unoxidized patches. Granular layers also contain fragments and flakes 5-10 mm (0.2-0.4 in.) in size	6.4	21
Total thickness of Norrie Member	57.6	189
Yale Member (incomplete):		
Thinly laminated carbonate-silicate-magnetite iron-formation		

Measured section of the Norrie Member, Ironwood Iron-formation, prepared from a composite of two drill holes near Upson, Wis.

	Stratigraphic thickness (meters)	Stratigraphic thickness (feet)
Precambrian X:		
Ironwood Iron-formation (incomplete):		
Pence Member (incomplete):		
Thinly laminated iron-formation		
Breccia between Pence and Norrie Members:		
Shattered rock cemented by white quartz-------	1.2	4
Norrie Member:		
5. Wavy, irregular, and indistinctly bedded iron-formation; rather nondescript. Carbonate material in irregular patches; magnetite limited to a few thin zones. Carbonate material and probably rest of core somewhat granular. Granular layers siliceous but not distinctly cherty ------------------	11.0	36
4. Mixed thin-bedded and thick-bedded finely granular cherty iron-formation. Two chert beds 25 cm (10 in.) thick, but most are less than 5 cm (2 in.). Part of thin beds and separators between thick beds dark gray to black and magnetite rich; some layers rich in carbonate material ------------------	6.4	21
3. Thick-bedded granular chert; granules fine to very coarse. Lower half of interval distinctly hematitic containing bright-red individual granules. Separators thin and wispy; parts of core almost massive ------------------------	9.1	30
2. Magnetic, granular to pebbly wavy-bedded iron-formation. Some chert layers white to greenish gray, or dark gray containing granules, small "pebbles," and irregular blobs of magnetite; 1-6 cm (0.4-2.4 in.) thick. The separators are variously thinly laminated magnetite, wispy magnetite-rich zones, and thin layers of ordinary light-gray laminated iron-formation that may be somewhat argillaceous. Most all-magnetite separators are cut by minute veinlets that are perhaps stilpnomelane or other iron silicate. A 30-cm (12-in.-)-thick layer of chert breccia is present 8.5 m (28 ft) below the top of the interval ----------------	20.4	67
1. Cherty thick-bedded iron-formation, greenish gray partly mottled with light creamy yellow or buff. Beds as much as 20 cm (8 in.) thick, not conspicuously granular. The separators are laminated magnetite, and some black carbon on partings. Stylolites are abundant. Appears transitional to laminated ferruginous argillite(?) of Yale Member below. Bottom of Norrie Member ---------------------------------	4.0	13
Total thickness of Norrie Member------	50.9	167

Pence Member

No certain exposures of the Pence Member were seen anywhere in the district during this study; few good stratigraphic data were obtained from test pits near the Puritan or the Eureka mines; the North Palms drill hole 81 did not penetrate this member, and little other good drill-hole core was available. The description provided here is quoted directly from Hotchkiss (1919, p. 505):

> The Pence member is an even-bedded, thin-bedded ferruginous slate. Practically wherever seen the transition is abrupt from the wavy-bedded ferruginous cherts of the Norrie member, with its beds oftentimes as much as three or four inches in thickness, to the strikingly even-bedded, very thin-bedded Pence member. The conglomerate which marks this transition has been discussed under the Norrie member. * * *
>
> The chert present in the Pence member seems to vary considerably in moderately short distances. In some parts of a single mine this member is comparatively free from chert, and in other parts certain portions of the member will show an abundance of thin, continuous flinty chert plates an eighth to a quarter of an inch in thickness. These flinty chert plates or bands are usually of a clear greenish gray or light yellowish gray in color. Where the formation is altered to any extent, these clear flint bands easily disintegrate into a white chalky chert, which can be crumbled in the fingers like a soft blackboard crayon. * * *
>
> On the Wisconsin end of the range, the Pence member varies from 80 to 130 ft. in thickness. This thickness continues fairly uniform eastward to the Davis

> mine, where there is a rather sharp decrease to a thickness of twenty-five to forty feet. All through the eastern end of the range the member will average close to thirty feet in thickness. The top of this member grades within a comparatively small thickness of beds into the granular jasper and granular chert of the lower part of the Anvil member. The Pence member in many localities contains sufficient magnetite to give a magnetic line when tested with the dip needle.

The "Eureka mine stratigraphic diagram" (unpub. data, 1918) described the Pence Member in two parts, a lower 14.3 m (47 ft) of thin platy magnetic iron-formation and an upper 8.5 m (28 ft) of blocky magnetic slates.

Drill hole 505, drilled from the 25th level about 363 m (1,192 ft) below sea level in the Ironton mine (362 m (1,187 ft) east and 280 m (920 ft) north of the center, sec. 17, T. 47 N., R. 46 W., Mich.), penetrated about 10.7 m (35 ft) of Pence Member; a description of the rather poor oxidized core is included here because better sections are not available from the Bessemer, Mich., area.

Measured section of Pence Member, Ironwood Iron-formation, from drill hole 505, Ironton mine

	Stratigraphic thickness (meters)	Stratigraphic thickness (feet)
Precambrian X:		
Ironwood Iron-formation (incomplete):		
Anvil Member (incomplete):		
Hematitic oxidized thick-bedded iron-formation		
Pence Member:		
3. Oxidized cherty iron-formation, probably thin bedded	3.0	10
2. Oxidized cherty thin-bedded iron-formation	1.8	6
1. Siliceous oxidized thin-bedded iron-formation	5.8	19
Total thickness of Pence Member	10.6	35
Norrie Member (incomplete):		
Oxidized thick-bedded granular cherty iron-formation		

Good stratigraphic sections are available from several cored drill holes in Wisconsin; some contain unoxidized iron-formation. The two that follow are from Pence, Wis., and were adapted from Huber (1959, p. 104-106). A third, even thicker section of the Pence Member, 45.7 m (150 ft), was penetrated by a drill hole west of Upson, Wis.

Measured section of Pence Member, Ironwood Iron-formation, drill hole 121, Pence, Wis.

[Drill hole 121, SE¼SE¼ sec. 31, T. 46 N., R. 2 E. Drilled from the surface just northwest of the town of Pence. Penetrated "Pabst Member" of Tyler Formation at bedrock surface, penetrated entire Ironwood Iron-formation, and ended in Palms Formation. Adapted from Huber (1959, p. 104-105)]

	Stratigraphic thickness (meters)	Stratigraphic thickness (feet)
Precambrian X:		
Ironwood Iron-formation (not completely described)		
Anvil Member:		
(Core lost) Even-bedded chert-carbonate rock containing some dense flinty chert layers and irregular layers of granular chert		
Pence Member:		
5. (Core lost) Even-bedded chert-carbonate rock containing minor magnetite; partly oxidized	7.9	26
4. Even-bedded chert-carbonate-silicate rock containing considerable magnetite. The chert is chiefly interstitial material, although scattered layers of granular chert are present. Carbonate material is generally dominant over silicate although the ratio varies greatly from layer to layer. Magnetite is disseminated throughout individual layers but varies greatly in percentage from layer to layer. Carbonaceous material is commonly present as thin irregular laminae. Table 5 gives the average chemical composition of 2.0 m (6.5 ft) of the lower part of this section	18.6	61
3. (Core lost) Even-bedded chert-carbonate rock containing occasional beds of conglomeratic granular chert	4.7	15.5
2. Even-bedded chert-carbonate-silicate rock similar to lithologic unit 4 above	4.3	14
1. Conglomerate. Angular fragments of green to gray chert in a granular and oolitic chert matrix. Also contains fragments of what appears to have been partly indurated even-bedded material	2.0	6.5
Total thickness of Pence Member	37.5	123
Norrie Member (incomplete):		
Wavy-bedded granular cherty rock		

Measured section of Pence Member, Ironwood Iron-formation, drill hole 113, Pence, Wis.

[Drill hole 113, NW¼NE¼ sec. 6, T. 45 N., R. 2 E. Drilled from the surface just west of the town of Pence. Penetrated Tyler Formation at bedrock surface, penetrated entire Ironwood Iron-formation, and ended in Palms Formation. Adapted from Huber (1959, p. 106)]

	Stratigraphic thickness (meters)	Stratigraphic thickness (feet)
Precambrian X:		
Ironwood Iron-formation (not completely described)		
Anvil Member (incomplete):		
Wavy-bedded granular cherty iron-formation		
Pence Member:		
2. Even-bedded chert-carbonate rock containing considerable silicate and magnetite. Many thin layers of irregular-bedded granular chert ----------------------------------	8.4	27.5
1. Even-bedded chert-hematite rock, extensively oxidized -------------------	22.7	74.5
Total thickness of Pence Member -----------------------------	31.1	102.0
Norrie Member		

Measured section of part of the Pence Member, Ironwood Iron-formation, from a drill hole west of Upson, Wis.

[Drill hole entered Pence Member at bedrock surface]

	Stratigraphic thickness (meters)	Stratigraphic thickness (feet)
Precambrian X:		
Ironwood Iron-formation (incomplete):		
Pence member (incomplete):		
4. Gray and greenish-gray magnetic laminated iron-formation; scattered short lenses, blebs, and layers of dark-gray chert (color on broken surface) as much as 8 cm (3.2 in.) thick, but mostly less than 5 cm (2 in.). The chert is partly or all granular; the thickness of layers and the granularity increase downward. Distorted beds near end of interval indicate folding or faulting	28.7	94
3. Magnetic laminated iron-formation as above; chert layers more abundant and as much as 25 cm (10 in.) thick	2.7	9
2. Dark-gray to almost black thinly laminated iron-formation, perhaps argillaceous. Mostly weakly magnetic to nonmagnetic; a few intervals magnetic. Scattered lenses and layers of gray granular chert as much as 6 cm (2.4 in.) thick, sparser toward bottom of interval	11.9	39
1. Gray thinly laminated iron-formation, weakly magnetic to nonmagnetic. No distinct granular chert layers, but fine-size granules present in some thin laminae	2.4	8
Thickness of Pence Member (incomplete)	45.7	150
Transitional layer between Pence and Norrie Members		
Pence strata are separated from underlying Norrie Member by 1.5 m (5 ft) of shattered iron-formation cemented by white quartz		
Norrie Member		

TABLE 5.—*Chemical analysis, in weight percent, of a sample from the Pence Member, Ironwood Iron-formation*

[Laboratory No. 53-2106CD, field No. NKH-103-53. Chert carbonate iron-formation from below the middle of the Pence Member, drill hole 121, 91.7-95.4 m (301-313 ft), SE¼SE¼ sec. 31, T. 47 N., R. 2 E., near Pence, Iron County, Wis. Analysis from Huber (1959, p. 91, table 2, col. B)]

SiO_2	40.09
Al_2O_3	2.23
Fe_2O_3	9.96
FeO	25.84
MgO	2.79
CaO	.50
Na_2O	.03
K_2O	.40
H_2O^+	1.80
H_2O^-	.56
TiO_2	.23
P_2O_5	.13
MnO	1.25
CO_2	14.38
S	.01
V_2O_5	.01
C	.05
Total	100.26
Less O for S	.01
Corrected total	100.25

Good exposures of partly unoxidized thin-bedded iron-formation in the NE¼SE¼ sec. 7, T. 47 N., R. 45 W., Mich., west of Sunday Lake, are probably of the Pence Member, though the rapid reconnaissance of these exposures did not permit determination of the probably complex structural geology and the stratigraphic position of the locality. The thin-bedded iron-formation exposed is dark gray and greenish gray and includes chlorite-carbonate, magnetite-chlorite-carbonate, and chert-carbonate iron-formation, most having thin bedding lamination. Chert layers and lenses are dark gray to black, and a few are 2-3 cm (0.8-1.2 in.) thick; one 10-cm (4-in.) -thick chert lens was seen. A small amount of chlorite is in bright-green granulelike grains, but most is found as dull-green to dull-brown aggregates that resemble the chamosite in the Yale Member near Ramsay. The magnetite is in 5-50 μm octahedra and is presumably the product of metamorphism.

Anvil Member

The Anvil Member, the thickest member of the Ironwood Iron-formation, can be seen in rather poor exposures in many areas in the district. There are fairly extensive outcrops in two places, near the old Geneva mine in the SE¼SE¼ sec. 18, and on Colby Hill in the SE¼NW¼ sec. 15, both in T. 47 N., R. 46 W., Mich. Some fairly good samples of the member were obtained from the Puritan mine test-pit section, including samples close to the upper contact. The core of drill hole 505, Ironton mine (location given in the section "Pence Member"), gives a good general section of the member, though the material is all thoroughly altered. No unoxidized material was found in any of the Anvil Member samples studied.

The Anvil Member is thickest in the Puritan mine area (fig. 8, col. 5) where it is nearly 90 m (300 ft) thick; from there it seems to thin both east and west. The Anvil Member is mostly made up of granular wavy thick-bedded iron-formation containing chert layers several centimeters (several inches) thick; in some places, very blocky chert beds are as much as 30 cm (1 ft) thick. The separators are generally less than 2 or 3 cm (0.8-1.2 in.) thick and are now mostly iron oxide in the central part of the district. No unoxidized separator material was seen, but some small samples of well-preserved granular chert within thick beds and lenses were found and have been examined in thin section.

Some of the material obtained from the northernmost test pits in the Eureka mine area in the lower part of the Anvil contains granular and oolitic chert that has remarkably well preserved textural detail. This material also includes feathery chalcedonic chert, delicate oolitic shells of powdery hematite that I believe to be primary hematite, and an impressive variety of 10- to 70-μm diameter structures of the general types described by LaBerge (1967). LaBerge thought that these structures, including some of the Eosphaera tyleri and other types (figs. 3 and 4, this paper), might be of organic origin. Material from this general area would seem to be excellent for a study like that by LaBerge.

Granular chert from the dump of an old test pit along the Black River, 61 m (200 ft) north and 67 m (220 ft) west of the SE cor. SE¼SW¼ sec. 12, T. 47 N., R. 46 W., Mich., is believed to be from the Anvil Member and includes silicate granules that are probably chamosite and some that may be greenalite (fig. 9).

Hotchkiss (1919, p. 505-506) described the stratigraphic sequence within the member as follows:

> The lower part of the Anvil member is everywhere composed of wavy-bedded granular chert and granular jasper, with frequent conglomeratic beds. The upper part of the Anvil is much less granular and conglomeratic, and contains more wavy-bedded flinty and fine-grained chert. This member is like the other chert members of the Ironwood formation in that granular jasper is more abundant toward the eastern end of the range. Toward the western end of the range the proportion of granular chert increases and the jasper is relatively insignificant in amount. * * * In Sections 18 to 22, 27, and 29 (T. 47 N., R. 46 W., Mich.) there appears a lens of slate * * * which is exactly similar in character to the Pence member in the same sections. Above this slate the formation is almost invariably possessed of a high iron content and of a porous character which makes it a favorable place for that extreme alteration of

the formation which results in ore-bodies. It is in this member that many of the large "hanging-wall" orebodies have been found in the last few years.

The stratigraphic section of the Anvil Member, as described on the "Eureka mine stratigraphic

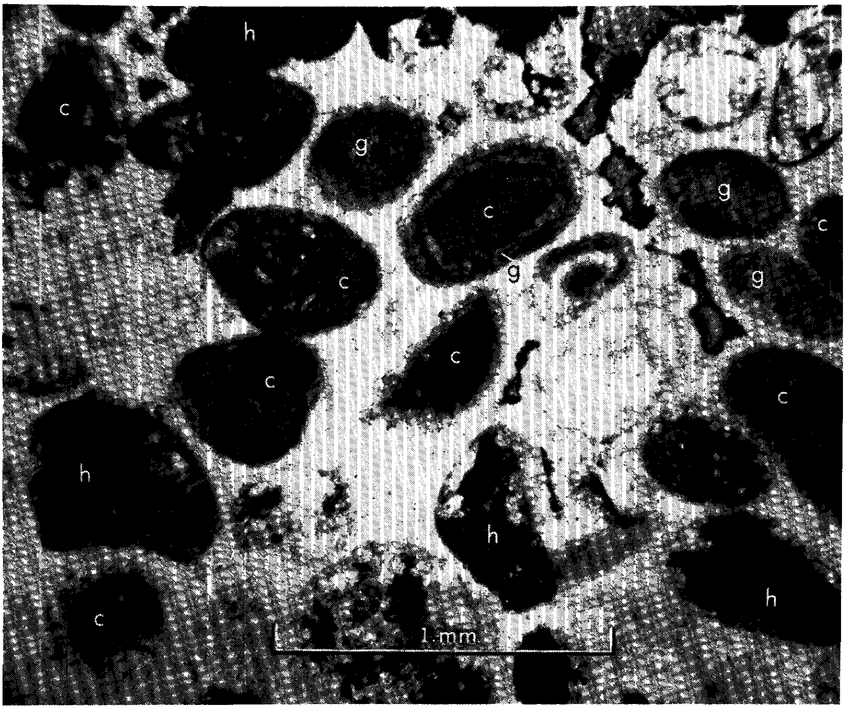

Figure 9.--Photomicrograph showing silicate granules in cherty iron-formation, probably from the Anvil Member of the Ironwood Iron-formation. Sample from a test pit dump 61 m (200 ft) north and 67 m (220 ft) west of the SE cor. SE¼SW¼ sec. 12, T. 47 N., R. 46 W., near Ramsay, Mich. Most silicate granules are probably chamosite (c); some may be greenalite (g); one granule seems to have a chamosite core and a greenalite margin. Opaque material is mostly hematite (h).

diagram" (unpub. data, 1918) is, from youngest to oldest:

	Stratigraphic thickness (meters)	(feet)
Thick and thin irregularly bedded cherty iron-formation....	47.1	155
Magnetic slate..................	7.0	23
Conglomeratic jasper interbedded with thin irregularly bedded iron-formation.............	26.5	87
Conglomeratic jasper...........	1.8	6

Figure 17 of Hotchkiss (1919, p. 502) suggests that he knew of the "magnetic slate" in the Eureka mine and correlated it with the lens of slate in secs. 18 to 22, 27, and 29, T. 47 N., R. 46 W., Mich.

Between the east edge of Ironwood (sec. 23) and Ramsay, the uppermost granular thick chert beds of the Anvil Member are said to be immediately overlain by thin-bedded "slaty" iron carbonate and sideritic chert (Hotchkiss, 1919, p. 506). However, over most of this distance I was unable to find exposures or drill-hole evidence for the iron carbonate and sideritic chert beds, nor did I identify them in Tyler-to-Anvil drill hole cores from the Peterson mine. Old mining company records for the Eureka mine area near Ramsay include a "magnetic soft red slate" at the base of the "Pabst Member" just above the Anvil, thus at the same sequential position described by Hotchkiss and presumably an oxidized form of the same beds. The large outcrops of dark-gray thin-bedded sideritic iron-formation in the bed of the Black River, 36 m (120 ft) east and about 213 m (700 ft) north of the SW cor. SW¼SE¼ sec. 12, T. 47 N., R. 46 W., Mich., if interpreted to be the "iron carbonate and sideritic chert," are the only good surface exposures of this unit. Although I interpret them to be near the top of the Anvil Formation, the stratigraphic position of the sideritic outcrops depends on rather tenuous interpretations of the geologic structure. The outcrops at this location, although about 122 m (400 ft) north of a normal projection along strike from the southwest, are explained in the mine cross sections by displacement on the Ayer fault. The composition of a representative grab sample from these outcrops of iron-formation in the bed of the Black River is given in table 6.

Atwater (1938, p. 164-165) described a drill hole from the Plymouth mine area, where the typical

TABLE 6.—*Chemical analysis, in weight percent, of a sample of thin-bedded sideritic iron-formation probably from the top of the Anvil Member, Ironwood Iron-formation*

[Laboratory No. W174214, field No. 4. Analysis by G. Chloe, Hezekiah Smith, P. L. D. Elmore, J. Glenn, and J. Kelsey, under Leonard Shapiro, U.S. Geol. Survey. Analytical methods used are those of Shapiro and Brannock (1962) supplemented by atomic absorption]

SiO_2	36.8
Al_2O_3	3.7
Fe_2O_3	1.5
FeO	33.7
MgO	2.5
CaO	.68
Na_2O	.06
K_2O	.09
H_2O^+	.21
H_2O^-	.25
TiO_2	.30
P_2O_5	.23
MnO	1.1
CO_2	18.8
Total	99.9

strata of the Anvil Member are transitional upward into thin-bedded iron carbonate strata (upper slate in fig. 10). Atwater differed from Hotchkiss (1919, p. 506) in that he interpreted at least part of the thin-bedded strata to be part of the Ironwood Iron-formation, rather than part of the Tyler Formation.

The exact nature of the top of the Anvil Member and its relationship to the overlying "Pabst Member" of the Tyler Formation are not very clear, and good descriptions of the contact are sparse. The only place where the vicinity of the contact is well exposed is in the bed of the Black River, and there outcrops are not complete at the contact zone. Although rocks on the dumps described below are near the contact zone, their exact stratigraphic position is not certain; I interpret them to be either completely, or at least partly, within the Anvil Member.

Iron-formation in the dumps of test pits, 283 m (930 ft) east and 43-67 m (140-220 ft) north of the SW cor. sec. 12, T. 47 N., R. 46 W., Mich., near Ramsay, is gray-green to red-brown partly granular chert and dark-gray-green to red-brown ferruginous argillite. Some of the gray granular chert contains pyrite in parts of the granules. The argillaceous material and the gray-green chert without granules look very much like iron-formation that is present 150 m (500 ft) above the base of the Tyler Formation, but the reddish granular chert is like that of the thick-bedded members of the Ironwood Iron-formation, the Anvil, Norrie, and Plymouth.

The dump of an exploratory shaft, 150 m (500 ft) north and 90 m (300 ft) west of the SE cor. SE¼SW¼ sec. 12, T. 47 N., R. 46 W., Mich., includes chamositic iron-formation, granular jasper, and thin-bedded sideritic iron-formation. The most common lithic type is a very dark gray-green ferruginous laminated argillaceous chamositic iron-formation. The microscopic texture is subgranular to minutely lenticular. All the silicate does not look the same. The most abundant silicate is dull very pale greenish gray to pale green, is only locally pleochroic, and has very low birefringence; it is almost certainly chamosite, the only silicate mineral identified by X-ray diffractometer analysis of the rock (J. W. Hosterman, U.S. Geol. Survey, analyst). Locally a little brightly birefringent pleochroic golden-brown silicate, presumably stilpnomelane, is present. Some of the opaque material is leucoxene, and some is probably magnetite or pyrite; the rock is very weakly magnetic.

Much less common on the dump, though conspicuous, is bright-red granular jasper that is mostly fragments of broken layers rather than pebbles. (Similar jasper from the Tyler Formation in the Puritan mine is mostly or all pebbles and cobbles.) This jasper consists of remarkably perfect, mostly dense and opaque jaspery granules 0.3-1.2 mm (0.01-0.05 in.) in diameter, set in a clear chalcedonic matrix. A few granules have complex internal textures, especially spherules 5-15 μm in diameter and also some larger 10- to 30-μm spherules. Green chlorite-type silicate is a sparse constituent of a very few granules. About 95 percent of the hematite is red in oblique reflected light and is probably primary; some of the remaining black-reflecting hematite is younger and has formed along cracks and across granule boundaries.

Sideritic iron-formation is only a minor rock type on the dump of this exploratory shaft, and the sequence cut by the workings is not like the rock in the sideritic iron-formation outcrop in the nearby Black River. If transverse faulting has not disrupted the succession, the shaft and crosscut are in rock lower in the stratigraphic sequence than the riverbed outcrops.

The dark chamositic iron-formation on this dump is not like any outcrops I have seen; it resembles rock from the Tyler Formation on the dump of the Puritan mine. The layers of jasper are probably more typical of the Anvil Member. Old maps show a crosscut southward from this exploration shaft, and this crosscut almost certainly penetrated strata that company geologists regarded as the Anvil Member. Perhaps the crosscut reached the thin-bedded "slaty" layer within the Anvil Member. The rocks of this dump are certainly of the Ironwood-Tyler gradation zone; my assignment of them to the top of the Anvil Member must be considered tentative.

Previous workers' conclusions regarding the relationship between the Ironwood Iron-formation and the Tyler Formation were based heavily on district-wide thickness data and interpretations of the significance of cherty fragments in the lower part of the Tyler Formation. Van Hise and Leith (1911), Hotchkiss (1919), Aldrich (1929), Atwater (1938), and Huber (1959) had widely divergent views on the nature of the Ironwood-Tyler contact.

Van Hise and Leith (1911, p. 232) described the contact as gradational, whereas Hotchkiss (1919, p. 506) believed it to represent "an erosion interval *** that probably was of considerable duration." Aldrich (1929, p. 101-102) felt that the "basal conglomerate" was local and not as significant as the continuity of iron deposition through Ironwood into the early part of Tyler time. By 1933, Hotchkiss (p. 56) regarded the unconformity as "a minor erosion interval." Atwater (1938, p. 162-167) revived the idea of major erosion of the Anvil Member and, locally, even of some of the Pence before deposition of the conglomeratic basal beds of the Tyler Formation. Huber (1959, p. 116) seems to have accepted Atwater's interpretation.

Hotchkiss (1919, p. 502), Atwater (1938, p. 163), and Huber (1959, p. 104, 106, 116) stressed that the Anvil Member is thin and discontinuous in Wisconsin, as shown with great exaggeration in figure 10. All three investigators regarded the thinning as erosional rather than depositional; however, Atwater stressed evidence for subaqueous erosion and redeposition of some of the material to form the basal conglomeratic beds of the Tyler Formation. Nondeposition of the Anvil Member in parts of the area was probably not considered as an explanation for the local thinning of the member. However, uneven deposition can be an important cause of iron-formation thickness variation, as shown by the depositional thickness variations in the thick-bedded facies of the Trommald Formation, Cuyuna district, Minnesota, where the thinning exceeded 20 m per kilometer (100 ft per mile) in some places (Schmidt, 1963,, pl. 6).

Aldrich (1929, p. 100-102) regarded fragmental material in the "Pabst Member" as similar to "conglomerate" beds within the Ironwood Iron-formation and without great significance as an indicator of an unconformity; he placed "greater weight upon the gradation of the clastics with iron-formation in the west, and upon the high iron content of the base of the Tyler, apparently representing the gradation of carbonate deposition of the iron-forma-

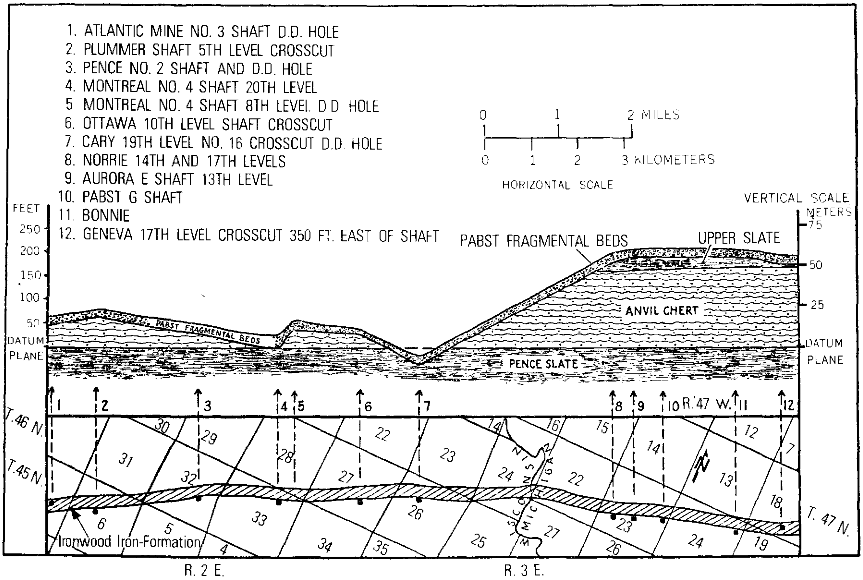

Figure 10.--Longitudinal section through part of the Gogebic district, showing one interpretation of relationship between the "Pabst Member" of the Tyler Formation and the Anvil and Pence Members of the Ironwood Iron-formation. The upper slate is a layer of thin-bedded carbonate iron-formation, at least partly within the Anvil Member. Compiled from measured sections in mines and drill holes. Location of sections given in map of Ironwood Iron-formation in lower part of diagram. Modified from Atwater (1938, p. 163, fig. 2).

tion with the clastics of the Tyler, than upon the conglomerate***."

The coarse fragments in the base of the Tyler Formation are of a typically intraformational type. None are of exotic material, and none seem to be of coarse granular chert of the type so common in the Anvil Member; this type should be present if the pebbles were derived by erosion of the Ironwood Iron-formation.

S. A. Tyler (oral commun., 1950) believed that the Ironwood-Tyler unconformity was extremely doubtful. Wolff (Grout and Wolff, 1955, pl. 6) showed a "probable unconformity" between the Tyler Formation and the Ironwood Iron-formation, but he placed the "Pabst Slate" at the top of the Ironwood.

The most likely interpretation is that the lateral thinning and local absence of the Anvil Member is a depositional feature and that the conglomeratic strata at the base of the Tyler Formation are are mostly intraformational. The ferruginous lowermost beds of the Tyler Formation resulted from the uninterrupted continuation of iron-rich sedimentation and a substantial dilution by clay, silt, and arkosic sand.

BARAGA GROUP

TYLER FORMATION

The Tyler Formation is a thick sequence of light- to dark-gray feldspar-rich fine-grained sandstone, argillaceous siltstone, and argillite. The formation can be regarded as a graywacke sequence in the nongenetic sense of Holmes (1965, p. 119). The lowermost 15 m (50 ft) of the formation is iron rich and was mined locally for iron ore. A layer of chert-carbonate iron-formation is known 137 m (450 ft) above the base in at least two places where exploration has tested that particular stratigraphic interval, and some iron-rich lenses may be present as much as 243 m (800 ft) above the base. The possible correlation of the Tyler Formation with the Copps Formation, which is found 9.5

km (6 mi) east of the easternmost Tyler near Ramsay, was discussed in detail by Atwater (1938).

The Tyler Slate was named by Van Hise (1901, p. 338) for the exposures along the Tyler Forks River. Tyler Formation, a more appropriate term because of the wide range of metamorphic grade in the outcrop area, was probably first used by Hotchkiss in 1919, and some workers have followed this usage. The basal ferruginous part of the formation was identified as a stratigraphic unit and named the "Pabst Member" by Hotchkiss (1919, p. 443), but the soundness of naming this member as a separate stratigraphic unit is questionable. The most comprehensive discussion of the "Pabst Member" as a separate unit was by Atwater (1938, p. 160-161). The low-grade cherty iron-formation about 137 m (450 ft) above the base of the Tyler was never included in the "Pabst Member."

The overall stratigraphic section of the Tyler Formation is fairly well known from many small exposures scattered from the base to the top. However, surprisingly little is known about the lowermost 180 m (600 ft), including the most ferruginous strata, because this interval is poorly exposed. The original thickness of the formation is unknown because the upper contact is an erosional surface, but a maximum thickness of 2,900 m (9,500 ft) is reported in Wisconsin (Atwater, 1938, p. 167), and about 2,070 m (6,800 ft) remains near Ironwood. The possibility that this thickness represents a lesser true thickness repeated by folding or faulting was also discussed by Atwater. No evidence for such structural complications within the Tyler was found in earlier studies or in outcrops examined during this investigation; however, some drag folding was mapped in Wisconsin by Felmlee (1970), some is indicated near Mellen, Wis., by the structure of the Ironwood Iron-formation, and some was seen by mine geologists in low-grade iron-formation about 150 m (500 ft) above the base of the Tyler in the Peterson mine, Mich. (fig. 11).

Three chemical analyses of samples of the Tyler Formation for which only the approximate stratigraphic positions are known are given in table 7.

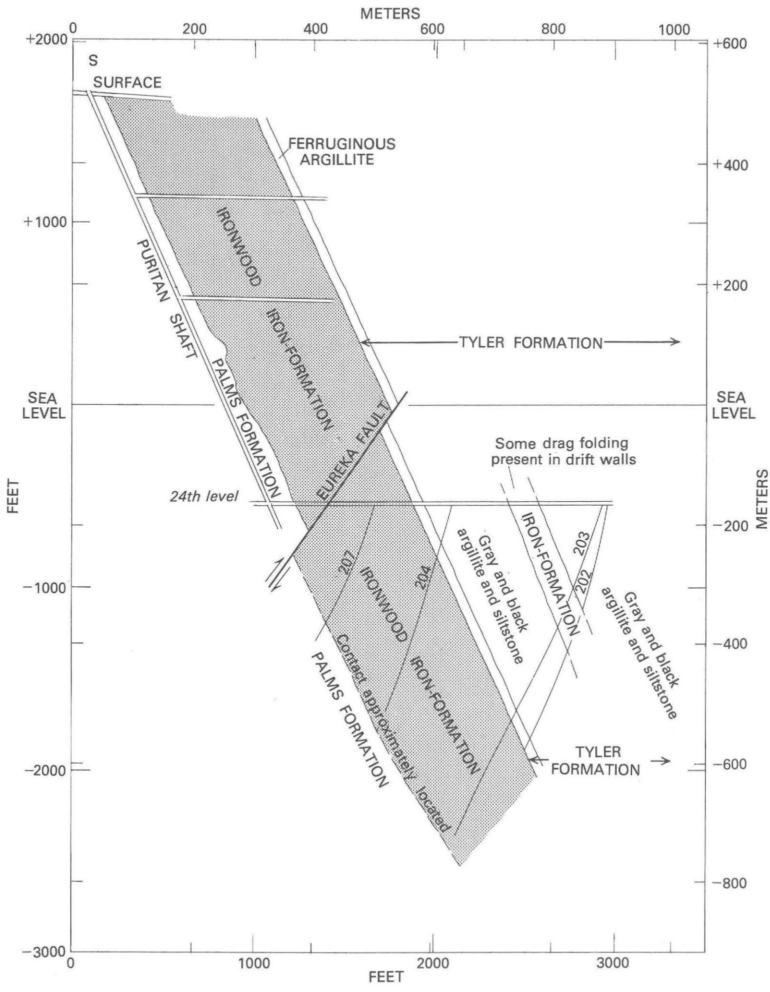

Figure 11.--Cross section of the Puritan mine workings in the Tyler Formation, Ironwood Iron-formation, and Palms Formation (after 1951 the Puritan mine was included in the Peterson mine). Drill holes are identified by number.

FERRUGINOUS STRATA NEAR THE BASE

Iron-rich beds at the base of the Tyler Formation and iron-formation intercalated in gray and dark-gray siltstone and argillite somewhat above the

Measured section of the basal part of the Tyler Formation from drill hole 202, Puritan mine

	Stratigraphic thickness (meters)	(feet)
Precambrian X:		
Tyler Formation (incomplete):		
16. Interbedded gray siltstone and gray to dark-gray fine-grained hard argillite. Some of the siltstone contains small black carbon flakes	95.1	312
15. Gray-black carbon-bearing argillite	11.9	39
14. Pyritic gray-black carbon-bearing argillite	1.8	6
13. Gray-black carbon-bearing argillite; 15-mm (0.6 in.-) -long pyrite nodules 10.7 m (35 ft) above base	17.1	56
12. Pyritic argillite	2.7	9
11. Faintly bedded gray carbonate iron-formation	6.1	20
10. Faintly bedded gray carbonate iron-formation, may be somewhat argillaceous	5.5	18
9. Iron-formation and ferruginous argillite	2.7	9
Unmetamorphosed diabase dike (14.4 m (46.2 ft) thick)		
8. Buff, gray, and black granular cherty iron-formation; partly oxidized carbonate material common; traces of stilpnomelane	2.4	8
7. Gray and greenish-gray ferruginous argillite and cherty iron-formation, partly oxidized to red brown	25.0	82
6. Thinly laminated dark-red-brown argillite and some silty laminae. A layer of lithic tuff containing fragments 2-3 mm (0.08-0.12 in.) in diameter at 15.5 m (51 ft) above base	23.2	76
5. Thinly laminated dark, dull-greenish-gray argillite	38.7	127
Unmetamorphosed diabase, containing grains 3 mm (0.12 in.) in diameter (15.8 m (51.8 ft) thick)		
4. Partly oxidized ferruginous hard gray argillite, siltstone, and sandy siltstone; partly magnetic	22.3	73
Unmetamorphosed diabase (3.3 m (10. 8 ft) thick)		
3. Gray and locally red-brown mostly only faintly laminated silty argillite and siltstone; somewhat ferruginous	11.9	39
2. Ferruginous siltstone and some argillite and sandy argillite; both unoxidized and oxidized. Sparse fragmental material	7.9	26
1. Mixed cherty conglomerate and dark-red-brown ferruginous argillite. Clasts are smaller than 2 cm (0.8 in.)	3.7	12
Bottom of drill hole and approximate top of Ironwood Iron-formation		
Total section of Tyler Formation described	278.0	912

base are known from spoil piles, drill holes, mine workings, and a few small exposures. Some very good exposures were found in the bed of the Black River near Ramsay, but the extent to which faulting may have shifted these beds from their true stratigraphic position is not known; this uncertainty diminishes their usefulness. An excellent section of the lowermost 311.5 m (1,022 ft) of the Tyler Formation was cut by an exploration crosscut on the 24th level of the Puritan mine (after 1951, the Puritan mine was included in the Peterson mine), in the W½ sec. 17, T. 47 N., R. 46 W., Mich., and drill holes 202 and 203 from the end of the crosscut were inclined southward to cut through the base of the Tyler Formation (fig. 11). The cores from these holes were examined by the author, and one of them is described in the following measured section. Data from these sources cannot be extrapolated very far because the facies present may change considerably along strike.

The lowermost 137 m (450 ft) of the Tyler Formation consists of argillite, siltstone, and arkosic quartzite, parts of which are very ferruginous. Some of the argillite is finely laminated. The quartzite, which is known to make up a major part of the section only in the exposures in the Black River, ranges from thinly to very thickly bedded and from greenish gray to almost black. In the quartzite, most of the feldspar is microcline, in contrast to the main part of the formation, where most of the feldspar is plagioclase.

Much of the lowermost 137 m (450 ft) seems to be ferruginous, but data are too sparse for a systematic study of the iron distribution (Hotchkiss, 1919, p. 506). In the quartzitic phases, the iron-bearing mineral is mainly chlorite; some fine-grained brown material of very low birefringence may be greenalite. The chlorite is too mixed with other material for identification, but some similar green chlorite from a small veinlet in the Tyler Formation, Puritan mine, was identified by X-ray diffraction as aphrosiderite (J. W. Hosterman, U.S. Geol. Survey, analyst). A sideritic carbonate mineral is probably a major mineral in the siltstone and argillite. The iron silicate and sideritic carbonate minerals are in the matrix of the siltstone and quartzite and also form irregular granules, the granule size corresponding roughly to that of the clastic quartz. The clastic quartz grains are very sharply angular in the siltstone and subrounded to angular in the quartzite (fig. 12). Feldspar, mostly potassium feldspar, and chert grains are common; some chert grains may be crude granules, and some are probably clastic.

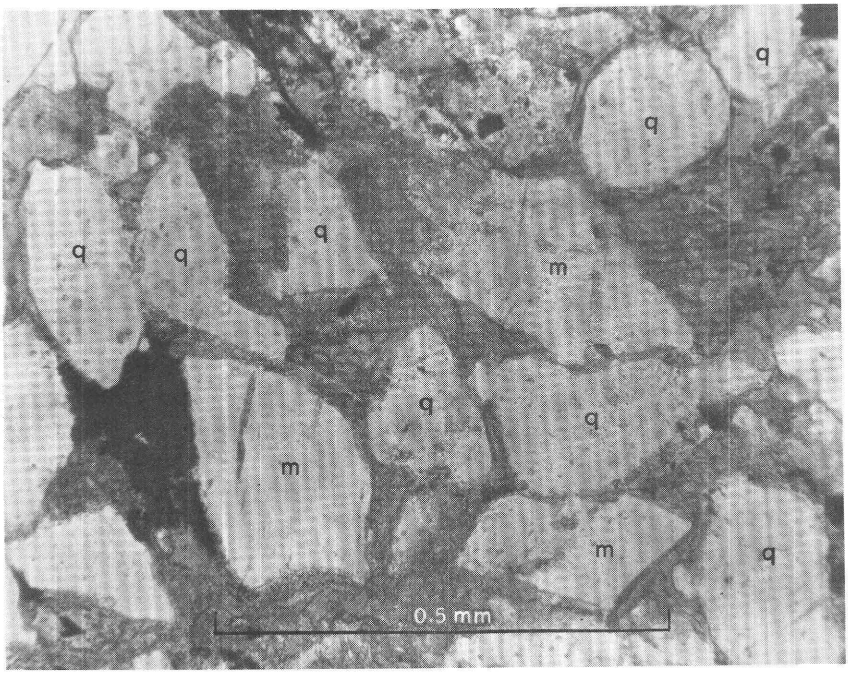

Figure 12.--Arkosic quartzite from the Tyler Formation consisting of angular and rounded grains of microcline (m) and quartz (q); plane-polarized light. The opaque material is pyrite; grains of hematite are common elsewhere in the thin section. Bed of Black River 298 m (980 ft) south of U.S. Highway 2 bridge, SW¼SE¼ sec. 12, T. 47 N., R. 46 W., Mich.

The "conglomeratic" beds (the type sometimes designated as the "Pabst Member") are fragment-bearing strata within this lowermost argillite-siltstone-quartzite section. The basal fragmental layer is 3-9 m (10-30 ft) thick in the few drill holes for which I have good records and is shown as 9-15 m (30-50 ft) thick on some of the best mine cross sections. Discontinuous fragment-bearing layers are also locally present at horizons above the base of the Tyler, as in the bed of the Black River, 219 m (720 ft) north and 45.6 m (150 ft) east of the SW cor. SW¼SE¼ sec. 12, T. 47 N., R. 46 W., Mich. The fragmental layers are present northward from this location for 91 m (300 ft) along the river. Elsewhere, the fragmental beds can now be seen in the Ironwood-Ramsay area only on mine and test-pit dumps and in a few drill cores. At the time of my fieldwork, the best test-pit dumps were near the center of sec. 17, T. 47 N., R. 46 W., Mich.; however, the pits have since been filled and the dump material has been spread. In dump specimens collected in secs. 16 and 17, T. 47 N., R. 46 W., most of the material is now oxidized, but enough unoxidized rock was seen for a description to be possible.

The clasts in the fragmental beds are flat pebbles as long as 10 cm (4 in.) but mostly shorter than 2 cm (0.8 in.); thicknesses of clasts are one-half to one-fifth the length. Many are rounded, but some have squared ends or angular outlines. The clasts are all fine-grained and ferruginous, quartz-rich to cherty rock. Some seem to contain more iron than others, especially in minute green chlorite granules less than 0.05 mm (0.002 in.) in size. Lamination is lacking or sparse in the clasts, and the few pebbles of coarse red granular chert that I have seen are probably unlike any granular chert in the Ironwood Iron-formation.

The irregular shapes, poor rounding, limited type of material, poor sorting, and random deposition of the fragmental material suggest that this conglomerate is intraformational in nature. It is not a basal conglomerate formed of material eroded from the Anvil Member of the Ironwood Iron-formation.

TABLE 7.—*Chemical analyses, in weight percent, of samples from the Tyler Formation*

[n.d., not determined]

	Slate of Tyler Formation[1]	Magnetite-rich Tyler Formation[2]	Magnetite-rich Tyler Formation[3]
SiO_2	51.38	53.44	52.58
Al_2O_3	23.89	19.62	20.76
Fe_2O_3	2.05	11.38	12.17
FeO	5.01	5.35	4.08
MgO	2.71	1.58	1.33
CaO	.24	.42	.30
Na_2O	.59	2.61	.37
K_2O	7.08	1.73	4.87
H_2O^-	.21	n.d.	n.d.
H_2O^+	4.66	n.d.	n.d.
H_2O	([4])	4.07	3.43
TiO_2	1.22	n.d.	n.d.
CO_2	.14	n.d.	n.d.
P_2O_5	.16	trace	n.d.
MnO	.02	trace	.21
C	.16	n.d.	n.d.
S	none	n.d.	n.d.
Li_2O	n.d.	trace	trace
Total	99.52	100.20	100.10

[1]Railroad cut of Soo Line, NE¼ sec. 31, T. 46 N., R. 2 E., Iron County, Wis. Chlorite zone of metamorphism. Analysis from Nanz (1953, p. 53-55, col. 5). Probably 300-460 m (1,000-1,500 ft) above base of Tyler Formation.

[2]NW¼ sec. 6, T. 45 N., R. 2 E., Iron County, Wis. Analysis from Irving and Van Hise (1892, p. 306, col. I). Probably from lowermost 300 m (1,000 ft) of Tyler Formation and may contain iron-formation.

[3]NE¼ sec. 1, T. 45 N., R. 1 E., Iron County, Wis. Analysis from Irving and Van Hise (1892, p. 306, col. II). Probably from lowermost 300 m (1,000 ft) of Tyler Formation and may contain iron-formation.

[4]The H_2O^+ and H_2O^- were determined separately.

Parts of the fragmental beds contain enough iron to have been of ore grade in the past, and a layer as much as 15 m (50 ft) thick was mined in parts of the Aurora and Pabst mines (Hotchkiss, 1919, p. 578). Ore was also mined from the fragmental beds above the 19th level in the Ironton mine (in the SW¼NE¼ sec. 17, T. 47 N., R. 46 W.), along the bedding for a strike length of 91 m (300 ft) and a depth as great as about 18 m (60 ft). Maximum thickness was probably about 9 m (30 ft).

IRON-FORMATION WITHIN THE TYLER FORMATION

Cherty low-grade iron-formation within the Tyler Formation was explored in the Puritan mine in

1942-43 (fig.11) and was penetrated by an old exploration shaft in the SW¼SW¼ sec. 18, T. 47 N., R. 46 W., Mich. A small amount also crops out in the bed of the Black River.

Exploration crosscuts and drill holes in the Puritan mine (later the Peterson mine) have provided most of the information about this iron-formation. There, it is 47 m (155 ft) thick, but drag folding noted in the mine crosscut indicates that the true thickness must be less than this measurement. Most of the material intersected by crosscuts and drill holes was unoxidized. Most is cherty, some is argillaceous, and part contains no chert. It ranges from almost massive, having only traces of bedding, to finely laminated. The dark-gray chert is partly massive and partly granular, having both thin laminae and layers as much as 5 cm (2 in.) thick. Pyrite or traces of magnetite are found locally, and sand grains are present in some layers. No chemical analyses were made of this material.

The dump of the old exploration shaft in sec. 18, T. 47 N., R. 46 W., Mich., contains much low-grade unoxidized iron-formation, including thick wavy-bedded granular carbonate-sulfide-bearing chert and thinly laminated chert-carbonate rock. Some pieces contain pebbles and cobbles of granular chert in a fine-grained matrix rich in carbonate material. The shaft is about 134 m (440 ft) stratigraphically above the base of the Tyler Formation and the iron-formation is probably from the same layer as that described in the measured section for drill hole 202, Puritan mine.

Pyrite in two distinct forms is abundant in small exposures of iron-formation on the west bank of the Black River, about 60 m (200 ft) south of U.S. Highway 2, sec. 12, T. 47 N., R. 46 W., Mich. In one form, a granular chert-carbonate-pyrite rock, some granules are all pyrite, some are rimmed with pyrite, and some contain pyrite along chert-filled crosscutting fractures. The granular iron-formation is in thin to thick wavy beds separated by layers of iron carbonate rock. One layer 20-30 cm (8-12 in.) thick is a conglomerate made up of rounded granular cherty iron-formation pebbles as large as 15 cm (6 in.) in diameter.

In the second form of pyrite, lenses or disks, 5-30 cm (2-12 in.) in diameter and 1-3 cm (0.5-1.5 in.) thick, have a rather random orientation in a dark, perhaps argillaceous, matrix. The pyrite was observed only in small exposures and in loose blocks ripped from the bedrock during excavation work here. The lenses may be similar to the elongate pyrite structures described from massive sulfide deposits at the Kam Kotia mine, south of Timmons, Ontario, by Kalliokoski (1965, p. 487; fig. 1, p. 488). If the pyrite in this second form does resemble sulfide of volcanogenic origin in other districts, these poor outcrops may contain important information regarding the geologic history of the Tyler Formation and, perhaps, its economic potential.

The types of pyritic rocks appear to be 240 m (800 ft) above the base of the Tyler Formation, but faulting may have increased this apparent stratigraphic distance. Thus, this iron-formation containing pyrite may be at the same general position (134 m (440 ft) above the base) in the Tyler Formation as iron-formation farther west, or it may actually be at 240 m (800 ft) as it appears.

Several small masses and irregular veinlets as much as a few centimeters (a few inches) thick of brown pitchy anthraxalite are present here on the bank of the Black River but not in the other iron-formation in the Tyler.

THE MAIN PART OF THE TYLER FORMATION

The Tyler Formation above the interbedded iron-formation is a monotonous sequence of light- to dark-gray thinly bedded argillite, siltstone, and quartzite. Combined ferrous and ferric oxides probably make up less than 10 percent. The large roadcut at the intersection of U.S. Highways 2 and 51, north of Hurley, Wis., where quartzite beds constitute perhaps one-quarter of the strata, is probably typical of the whole unit above the basal iron-rich layers. Fine-grained quartzite is the most common rock in the natural outcrops because the argillite erodes more easily. The entire formation forms a wide topographic valley in which rock exposures are sparse although soil and glacial drift are thin. The best natural exposures of Tyler Formation in the area are along the creek in the SE¼SW¼ sec. 8, T. 47 N., R. 46 W., Mich.

The gray argillite is partly nonlaminated and partly strongly layered. Locally, certain layers a few meters (yards) thick weather brown and are probably somewhat pyritic. On weathering, the argillite breaks up into small hackly pieces or into fracture-cleavage platelets.

The fine-grained quartzite is in dull-gray beds 1 cm to 3 m (0.4 in. to 10 ft) thick, which are grouped in layers 3-6 m (10-20 ft) thick. Some individual beds are internally finely laminated and have a suggestion of crossbedding. The beds of finer quartzite are generally darker.

The arenaceous grains in the Tyler siltstone and quartzite are rounded to angular and poorly sorted. They are 55 percent quartz, 25 percent feldspar (mostly plagioclase), and 10 percent lithic fragments; the general grain composition is surprisingly uniform throughout the formation. Rounded black carbon-rich platelets or films as much as 1 cm (0.4 in.) in diameter are abundant on some surfaces in the strata. No penecontemporaneous deformation structures were seen in the Tyler Formation.

METAMORPHISM

Penokean and Keweenawan periods of metamorphism having different regional gradients have affected the Precambrian X rocks of the Gogebic range. The rather complex overall metamorphic history of the area has been delineated by examination of mafic dikes of several different ages (Schmidt, 1976, p. 29-36).

Regional metamorphism of Penokean age affected widely distributed mafic dikes, some of which are in the east-trending block faults that are associated here with the Penokean orogeny. The dikes cut the Palms-Ironwood-Tyler sequence and are probably all late Precambrian X in age; the metamorphism is probably also late Precambrian X (Penokean, but later than the block faulting and dike intrusion). The intensity of the Penokean metamorphism increased southward; the greenschist-amphibolite-facies isograd passes through McDonald Lake and trends about N. 60° E. (Schmidt, 1976, pl. 1). Penokean-age metamorphic effects on the Ironwood Iron-formation are probably very slight between Ironwood and Ramsay, because the iron-formation in the bed of the Black River at Ramsay is either unmetamorphosed or only slightly metamorphosed. Eastward from Ramsay, the iron-formation and mafic dikes and sills in the iron-formation were increasingly modified by Penokean metamorphism, and the economically significant mineral changes in the eastern end of the Gogebic range are related to the Penokean event. At Ironwood, and westward in Wisconsin, any Penokean-age mineral changes are probably obliterated by effects of the later Keweenawan metamorphic event.

The last thermal event to affect the Precambrian rocks of the Gogebic district produced the relatively broad contact-metamorphic aureole around the mafic intrusive body of Precambrian Y age between Hurley and Mellen, Wis. (fig. 1); other similar bodies (not shown) are present southwest of Mellen. The Ironwood Iron-formation and flows of the Powder Mill Group at Ironwood were weakly affected by this event (lower range of greenschist facies and equivalent), but there is no certain evidence of Precambrian Y metamorphism between Bessemer and Ramsay.

The westward-increasing Keweenawan-age metamorphism produced a succession of iron silicate minerals starting from chamosite and minor stilpnomelane in the essentially unaltered rock near Ramsay, through stilpnomelane, minnesotaite, and grunerite/cummingtonite, to iron pyroxene at the western end of the district in Wisconsin. These changes were accompanied by an increase in mineral grain size and by elimination of carbon dioxide, causing the conversion of carbonate minerals to other minerals, especially the conversion of siderite to magnetite. Magnetite is a rare mineral in the siderite-rich iron-formation at Ramsay but becomes increasingly common both east and west of Ramsay.

Minnesotaite is common near the Vicar mine in Michigan and near Pence, Wis., but I do not know how far it extends east and west from these localities; I have not identified it between Ramsay and Ironwood, Mich. Grunerite/cummingtonite is abundant in the iron-formation at Penokee Gap near Mellen, Wis.; and none was noted at Upson. The eastern limit of grunerite/cummingtonite between Penokee Gap and Upson is not known to me. Because the westward-increasing metamorphism is related to mafic bodies intruded stratigraphically above the iron-formation, higher members of the Ironwood Iron-formation in Wisconsin are slightly more metamorphosed than the strata below them at the same locality.

Greenschist-facies metamorphism of mafic flows in the Powder Mill Group 5-8 km (3-5 mi) east of Ramsay caused thorough albitization of plagioclase and converted most or all augite to chlorite and epidote. These mineralogic changes suggest that an eastward-increasing metamorphic gradient of Keweenawan or younger age also exists, but I have no information that suggests any changes related to this later event in the previously metamorphosed Precambrian X rocks.

Previous work on the mineralogy of the district (Mann, 1953; Huber, 1959) used sample material that was metamorphosed considerably more than the least metamorphosed rock at Ramsay; this work reported a mineral suite that is not representative of the parent rock of the high-grade ores from this area.

STRUCTURAL GEOLOGIC HISTORY

Successive periods of uplift and erosion, local folding, two widely separated periods of block faulting at approximately right angles, and the northward tilting of the 96-km (60-mi) -long iron range as a unit block, are the major events in the structural history of the Gogebic district.

Deep erosion of the Precambrian W metavolcanic and plutonic rocks to a surface of low relief produced the unconformity marking the Precambrian W-X boundary. Upon this platform surface was deposited a cratonic suite, the Sunday Quartzite and Bad River Dolomite. Only the Bad River Dolomite is preserved in the western part of the area in Wisconsin, and both formations remain east of Wakefield in Michigan. I have assumed but not proved that the Bad River Dolomite was originally continuous across the central part of the Gogebic district as well.

Differential upwarp and erosion of parts of the Sunday Quartzite and Bad River Dolomite were followed by deposition of the Palms Formation, Ironwood Iron-formation, and Tyler Formation. The map trace of the erosional unconformity at its base and the very uniform lithology of the thin shallow-water Palms Formation indicate an erosional surface of very low relief.

Folds, perhaps related to the vertical block faulting during the Penokean orogeny, formed at four places after Tyler time and before deposition of the first Keweenawan strata. On the basis of outcrop data from maps by Aldrich (1929), two folded areas were mapped using bedding attitudes in the Ironwood Iron-formation, general exposure patterns, and the extraordinary outcrop width of the iron-formation. These folded areas are 8-13 km (5-8 mi) southwest and 5 km (3 mi) southeast of Mellen, Wis. These folds were interpreted to be shaped like drag folds and to plunge gently northwestward.

The general drag-fold shape of the structure between Ramsay and Sunday Lake, Mich., is well established by formational contacts in records from exploration drilling and underground mining. The structure plunges northwestward, probably at a low angle. It is complex, and the folding that flattened the dip plus the offsets on east-trending block faults probably have been more important in causing the widened outcrop area of Ironwood Iron-formation and the offset in general trend than has displacement on the Sunday Lake fault.

The large complex structure east of the Presque Isle River, Mich., is an intricately faulted northeast-plunging fold, considerably generalized in figure 1. Measurements of bedding attitude (Trent, 1973) indicate that this fold may plunge at a high angle, unlike the first three folds described.

How much the Tyler Formation has been deformed internally by folding is not clear. Atwater (1938, p. 167) discussed the general lack of field evidence for folds, except for possible folding indicated by fracture cleavage in slate at two localities. Folding in the Tyler can be deduced from outcrop studies of the Tyler Formation east of Mellen, Wis., reported by Felmlee (1970) and from general outcrop patterns of the Ironwood Iron-formation near Mellen, Wis.; to my knowledge, folding in the Tyler has been observed underground only on the 24th level of the Puritan mine, Mich.

An important deformation in the Michigan end of the Gogebic district during the Penokean orogeny, at the end of Precambrian X time, was an east-trending system of nearly vertical block faults, mostly upthrown on the north side, from the east edge of Ironwood to the east end of the district. These faults may have had an important influence on the localization of high-grade ore. Ample subsurface data show that these faults are probably lacking westward near Hurley and Montreal, Wis., and that many parallel faults are present in the Bessemer-Wakefield area (mostly too small to show on the scale of fig. 1). Without much subsurface data east of the Little Presque Isle River, only a few major faults of this type can be identified in that area.

The "Sunday Lake fault" is part of a complex structure in which part or even most of the apparent offset may be due to displacement on several east-trending block faults and to a drag fold-related flattening of the dip; however, a well-developed northwest-trending fracture zone was found by Prinz and Hubbard (1975) along the line where the fault was shown by Hotchkiss (1919, fig. 24, p. 539). Eastward, beyond the Little Presque Isle River, fold and fault structures in the Precambrian X rocks are more complex (Trent, 1973) and include major northeast-trending faults, perhaps related to the folding. Early mapping west of Mineral Lake, Wis. (Aldrich, 1929, pls. 14, 15, 16), indicated complex pre-Keweenawan structures there also, but I am not aware of any new geologic mapping of Precambrian X rocks in that area.

About half of the east-trending block faults are occupied by dikes; additional dikes are several times more abundant than the faults, forming an impressive east-trending anastamosing dike swarm, as shown by diagrams of underground mines (unpub. data). The common trend of many dikes and block faults suggests that both may have formed during the same period of crustal extension.

Hotchkiss (1919, p. 504) described lateral displacement on a surface nearly parallel to the bedding and within the Yale Member of the Ironwood Iron-formation; he called the surface the "great bedding fault." The upper strata are believed to have slid eastward over the lower strata for 200-300 m (600-1,000 ft), offsetting the earlier dikes and faults. This study provided no new information regarding this major fault. The most convincing evidence for significant right-lateral displacement is the offset of most of the pre-Penokean mafic dikes where they cross the fault plane. The fault has been recognized from Wakefield, Mich., 30 km (19 mi) westward to Iron Belt, Wis. (Aldrich, 1929, p. 94-95, 174). Some of the old company mine cross sections show a thin sill in the position of the bedding fault. The apparent relationship of this displacement surface to later events indicates that it must have formed while the strata were still almost in a horizontal position, not in Keweenawan time as proposed by Aldrich (1929, p. 174).

A second group of east-trending faults formed after the "great bedding fault" and displaced it while the strata were still almost horizontal. The strikes of these faults are about the same as those of the beds, and the dips are at angles to the bedding greater than 45°. These faults are limited to the area between the old Peterson mine and Wakefield, both in Michigan, and are most abundant in an area just east of Ramsay where the underground geology was mapped in detail by the operating mining companies. There, the main faults of this group were given the names Ayer, Eureka, Mikado, Asteroid, and Wakefield. Both these faults and the "great bedding fault" are considered to have formed during the Penokean orogeny but are younger than the first group of block faults that were offset by the "great bedding fault" (these faults are not shown in fig. 1).

Differential uplift, perhaps accomplished entirely by the Penokean block faulting, caused partial erosion of the Precambrian X Tyler Formation over most of the area and complete removal of the Tyler and part of the Ironwood Iron-formation near Wakefield. The Penokean faulting probably also caused a 5°-15° southward tilt of the Precambrian X strata before the Precambrian Y beds were deposited unconformably on them.

The north-dipping monoclinal structure along the entire length of the Gogebic district in Wisconsin and Michigan (more than 100 km (62 mi)) is the south limb of a major fold, the Lake Superior geosyncline, that formed gradually during Precambrian Y time, but mostly at the time of the unconformity between lower and middle Keweenawan strata (as defined by Hubbard, 1968). The long rigid block of Precambrian W crystalline rock and the stratified veneer of Precambrian X and lower Precambrian Y layers appear to have tilted northward as a unit without much internal differential movement; however, the nature of the southern edge of the block is unknown.

After early Keweenawan time, perhaps at the same time as folding and northward tilting, the Precambrian X and Y strata were cut by a series of mainly north to northeast-trending faults along the entire length of the Gogebic range. Nine of these faults are shown in figure 1; many more could not be shown at this scale. The dip of the faults is now near vertical. Between Ironwood and Ramsay, Mich., the faults strike from N. to N. 60 E. but are mostly near N. 25 E. Inspection of topographic maps and aerial photographs of the area between Hurley and Mellen, Wis., indicates that the faults there trend generally north, not northwest as shown by Aldrich (1929, pl. 1). Both Gordon (1907, p. 464) and Hotchkiss (1919, p. 538) noted that the apparent displacement on these faults diminishes downward in the stratigraphic section. The deformation decreases from as much as hundreds of meters in the Keweenawan strata to only a few meters or tens of meters in the Ironwood Iron-formation, and most of the faults do not offset the Precambrian W-X contact at all. Important exceptions to this generalization are the Black River Fault at Ramsay, Mich., and probably several faults in Wisconsin. No evidence exists of structural changes in the Precambrian rocks after Keweenawan time.

Keweenawan stratigraphic studies by Hubbard (1968, p. 35; 1975) suggested that many of the major thrust faults shown by Dutton and Bradley (1970) are probably unconformities, and for this reason these thrusts are not shown in figure 1.

ECONOMIC GEOLOGY OF THE IRON-FORMATION

The Gogebic district was a major United States source of high-grade iron ore from 1884 to 1966, and its several types of iron-formation containing more than 25 percent metallic iron remain an important resource of iron. The high-grade ores were formed by the oxidation and leaching of unaltered iron-formation. Although some high-grade ores remain, the bulk of the iron resource of the district is in unaltered iron-formation and some oxidized but unleached iron-formation.

Production of high-grade iron ores from the last deep underground mine ended January 29, 1967, because the high mining costs could no longer be justified in competition with concentrating-type ores produced from open pits in other districts. Between 1884 and 1967, 320,334,000 long tons of iron ore was shipped from the Gogebic district (Frederick L. Klinger, U.S. Bureau of Mines, oral commun., 1975).

Extensive oxidation and the formation of high-grade ores were limited to a segment of the Ironwood Iron-formation in the center of the Gogebic district where the metamorphic grade is below a critical threshold. The metamorphic grade limit is approximately that found at the Vicar mine, a marginal operation east of Wakefield, Mich., at the east end of the former mining district, and at the small Upson mine at Upson, Wis., at the west end of the district. However, 3,000 long tons of concentrating ore was produced at the Berkshire mine, sec. 9, T. 44 N., R. 2 W., near Mellen, Wis. (Lake Superior Iron Ore Assoc., 1952, p. 53).

At the two ends of the high-grade ore district, inward from the limits near the Vicar and Upson mines, the bodies of high-grade ore were small; all the large ore bodies were found between the Sunday Lake mine at Wakefield, Mich., and the Montreal mine at Montreal, Wis. Within this central, most productive segment, however, no difference is obvious in the size of ore bodies between the essentially unmetamorphosed chamosite-siderite iron-formation near Ramsay, Mich., and the more metamorphosed adjacent areas to the east and west.

Conversion of the unoxidized primary iron-formation to ore took place as the result of oxidation of the iron carbonate and silicate and the removal of silica, carbon dioxide, magnesium, calcium, and sodium. This conversion is generally believed to have been accomplished by deeply circulating meteoric waters in structurally favorable zones after final tilting of the strata.

The underground ore mines of the Gogebic district made it possible to obtain a remarkable amount of three-dimensional information about the Gogebic ores, and a simple model for exploration based on a hypothetical ore-forming process was conceived early (Irving and Van Hise, 1892, p. 274-275, 285-290). Much work and discussion have centered on the processes by which ores formed from iron-formation and, in general, the ideas currently held in regard to the ores of the Gogebic district were mostly thought out 40-80 years ago. The most widely accepted interpretation of structural controls was described by Royce (1938, p. 41-45). The zones regarded as the most favorable loci are the bottoms of troughs formed by the intersections of south-dipping mafic dikes and less permeable strata, either within the iron-formation or immediately underlying it. A large proportion of the high-grade ore from the district seems to have been in masses within the thick-bedded layers of iron-formation above crosscutting dikes, and this distribution fits the model. This concept must have affected the planning of exploration drilling and thus, to some degree, tended to be self-proving.

Though small in total volume, some ore has been mined from locations that do not fit the simple "trough" model, such as the ore in layers of thick-bedded iron-formation beneath crosscutting dikes. These exceptional deposits may be evidence that part of the leaching to ore, or perhaps some type of incompletely understood preconditioning of the iron-formation that was favorable to later ore development, took place symmetrically to the dikes and without regard to the present inclination of strata and dikes--in other words, before the strata were tilted to their present positions (P. W. Zimmer, oral commun., 1973).

The present study has provided neither new data nor new insights regarding the ore-forming process, and, because the iron-ore industry is no longer based mostly on high-grade ores, a restudy of the origin of these ores was not given a high priority.

Major resources of oxidized and unoxidized little-metamorphosed iron-formation and unoxidized metamorphosed iron-formation are available in the Gogebic district. Most present methods of separating iron minerals from quartz are more efficient and less expensive when used on ore having a larger mineral grain size, and some processes require that most of the iron be present naturally in magnetite. Although the types of raw material that are most efficiently or economically used may vary, depending on the recovery techniques used, the types will almost certainly continue to be defined by minerals, grain sizes, and textures, all of which are functions of combinations of the original sedimentary facies and the degree of metamorphism. General stratigraphic and facies characteristics are believed to have been persistent from Ramsay, Mich., westward to Upson, Wis., and perhaps as far as Mellen, or beyond. Differences in grain size and mineral content at a particular locality are functions of the type of iron-formation originally deposited, and hence can be related to particular members. Within a member, primary mineral and grain-size characteristics are relatively persistent along strike, and the principal variable along the length of the range is the degree of metamorphism.

Within the Ironwood-Ramsay area, the iron-formation is all relatively unmetamorphosed, and outside the ore bodies, unenriched rock is present in both unoxidized and oxidized forms. Both eastward and westward from the Ironwood-Ramsay area, the grade of metamorphism increases, and a large volume of metamorphosed iron-formation is present, most of it unoxidized. The transition between low and high-grade metamorphosed iron-formation and to some extent between unoxidized and oxidized is very gradual so that sharp delineations between types are difficult to make.

The westward-increasing metamorphism of the iron-formation was described by Van Hise and Leith (1911, p. 231), who related it to the intrusion of the Keweenawan intrusive rocks and recognized that the more highly metamorphosed iron-formation was less susceptible to the ore-forming processes than were the less metamorphosed types. Aldrich (1929, p. 28), though referring to the metamorphism rather vaguely as "another process," understood that the western end of the range had been rendered unfavorable for the development of direct shipping ores, but that the iron-formation in it would eventually be more favorable for use as concentrating ore.

The important rock characteristics changed by the metamorphism have been mineral composition, chemical composition, and grain size. These characteristics have been affected unequally in the contrasting lithologic types of iron-formation generally represented by the three thick-bedded and two thin-bedded members. The most important compositional change during metamorphism has been expulsion of CO_2 from the carbonate minerals. Increase of grain size of iron oxide minerals and quartz as metamorphic grade increases has an important bearing on the size to which the rock must be ground to obtain clean separations in a concentrating process. The iron-mineral changes are from carbonate minerals to both oxide and silicate minerals, and from silicate minerals, especially primary chamosite (and perhaps some stilpnomelane) through metamorphic stilpnomelane, minnesotaite, grunerite/cummingtonite, to iron pyroxene at the western end of the district in Wisconsin. Exact locations where these mineral changes take place in the western Gogebic were not obtained in this study, but relatively simple mineralogical studies should make it possible to define the geographic limits of individual mineral species, such as grunerite/cummingtonite.

The narrow outcrop width and steep dip of the iron-formation over most of the length of the Gogebic district would necessitate removal of large quantities of adjacent strata during development of large open-pit mines. Four folded areas of wider bedrock exposures and flatter dips, two southwest and southeast of Mellen, Wis., one between Ramsay and Sunday Lake, Mich., and the large folded area east of the Presque Isle River, Mich., might be minable by open-pit methods and might have much lower waste rock ratios.

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