Geology and Ore Deposits of the Iron River-Crystal Falls District, Iron County Michigan

GEOLOGICAL SURVEY PROFESSIONAL PAPER 570

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

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By H. L. JAMES, C. E. DUTTON, F. J. PETTIJOHN, *and* K. L. WIER

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By H. L. James, C. E. Dutton, F. J. Pettijohn, and K. L. Wier

ABSTRACT

The Iron River-Crystal Falls district occupies about 300 square miles in the northern peninsula of Michigan. It is an area of low relief within the Lake Superior highland between Lake Superior and Lake Michigan. Glacial deposits mantle more than 99 percent of the bedrock surface, to known depths of as much as 488 feet. Outcrops are most abundant in the eastern part of the district; elsewhere much of the knowledge of the geology is from a study of mine workings and of core from many thousands of drill holes, coupled with detailed magnetic surveys.

Except for a small remnant or two of Cambrian(?) and Ordovician strata, the district is underlain by rock of Precambrian age. The district proper is a synclinorium of tightly folded strata of the Paint River Group, which forms the upper part of the Animikie Series (middle Precambrian). The Paint River Group is underlain by the Baraga Group, which in this area comprises four formations, from youngest to oldest: (1) Badwater Greenstone, 0–15,000 feet thick, (2) Michigamme Slate, 6,000 feet thick, (3) Amasa Formation, an iron-rich unit about 1,800 feet thick, and (4) Hemlock Formation, dominantly greenstone, more than 6,000 feet thick. The Baraga Group in turn is underlain by the Chocolay Group, represented in this area only by the Saunders Formation, which is mainly massive dolomite with a probable thickness of about 1,000 feet. The Saunders is assumed to be correlative with the Mesnard Quartzite and Kona Dolomite and the Sturgeon Quartzite and Randville Dolomite sequences in other parts of northern Michigan.

The Paint River Group underlying the district proper comprises five formations, from youngest to oldest: (1) Fortune Lakes Slate, (2) Stambaugh Formation, (3) Hiawatha Graywacke, (4) Riverton Iron-Formation, and (5) Dunn Creek Slate.

The Fortune Lakes Slate, confined to the central part of the Iron River-Crystal Falls basin, is probably more than 4,000 feet thick and is the thickest and least known formation of the group. Its known parts are chiefly slate and graywacke, but beds of siderite and sideritic slate are common near the base. The contact with the underlying Stambaugh Formation is gradational and conformable.

The Stambaugh Formation, generally less than 100 feet thick, is composed of laminated flinty magnetic slate, chlorite mudstone, pyrite-porcelanite beds, and minor graywacke. It is an iron-rich unit, in part of chemical and in part of clastic origin, and it gives rise to a strong magnetic anomaly in most places. Much of the knowledge of the geologic structure of the district is derived from the distribution pattern of the Stambaugh Formation, as determined by detailed magnetic surveys.

The Hiawatha Graywacke, which conformably underlies the Stambaugh Formation, ranges in thickness from 50 feet in the eastern part of the area to 500 feet in the western part and pinches out entirely near the extreme southeast end of the district. The lowest part of the formation commonly is a distinctive sedimentary breccia made up of angular fragments of chert in a graywacke matrix. The breccia, which grades vertically and laterally into massive graywacke, marks a widespread disconformity and local unconformity between the Hiawatha Graywacke and the underlying Riverton Iron-Formation.

The Riverton Iron-Formation is the host rock for the principal ore deposits of the district. The formation typically is about 600 feet thick in the eastern part of the district and about 150 feet thick in the western part. Where unoxidized, it consists chiefly of interbedded siderite and chert and has an iron content of about 25 percent. Locally, particularly in the eastern part of the district, the formation contains layers of stilpnomelane and layers rich in magnetite. Graphitic partings are common, and beds of graphitic sideritic slate are present in some places. A chaotic chert breccia intermixed with slate and graywacke occurs at the base of the formation in parts of the Iron River area; most commonly, chert breccia is found in the upper part of the formation, where it may grade into the basal breccia of the Hiawatha Graywacke.

The Dunn Creek Slate underlies the Riverton Iron-Formation with an abrupt but gradational contact. The Dunn Creek ranges in thickness from about 400 feet in the western part of the area to about 1,500 feet in the eastern part. The uppermost part of the formation is a graphitic pyritic slate, the Wauseca Pyritic Member, that contains 35–40 percent pyrite, which is visible only under high magnification. This pyritic member generally is about 50 feet thick. The lower half of the Wauseca is a highly distinctive breccia (the "speckled gray") consisting of slate fragments in a slate matrix and is a marker bed throughout the district. Below the Wauseca Pyritic Member, the formation consists of sericitic slate and fine-grained graywacke and contains, in the eastern part of the district, beds of cherty black slate and striped slate.

Igneous rocks are scarce in the district. The most common are metadiabase and metagabbro, which occur as dikes, particularly along faults, and as irregular bodies, the largest of which is less than half a mile across. Granite, which also has been sheared to some degree and metamorphosed, forms several dikelike or stocklike bodies in the eastern part of the district. The only unmetamorphosed igneous rock is a single diabase dike in the Iron River area; the rock is assumed to be comagmatic with the Duluth Gabbro.

The structure of the district proper is simple in broad outline but extraordinarily complex in detail. The gross structure is that of a triangular-shaped basin, the south flank of which is incompletely known. The basin is bounded by discontinuous masses

of Badwater Greenstone. The strata of the Paint River Group within the basin are tightly and complexly folded. Dips everywhere are steep, and overturning is characteristic. In the west apex and to some degree in the northeast apex, folds of the dominant trend are interrupted by and merge into crossfolds of equal intensity. The crossfolds are believed to be virtually of the same age as those of the dominant trend and to have formed during the major post-Animikie orogeny. A dozen or more faults of large displacement have been mapped, and many more doubtless exist. Those in the western part of the district are high-angle reverse faults which have displacements of as much as half a mile, whereas those in the northeastern part of the district are high-angle faults on which the main movement appears to have been lateral. The Cayia fault, the principal fault in the northeast apex, has been traced for about 9 miles and has a lateral shift of 3,000 feet or more. The trend of the faults is generally easterly, about parallel to the trends of the dominant folds, but locally the folds are truncated. Several of the faults are occupied by metadiabase dikes; so, the faulting and the folding predate the metamorphism of the Animikie Series.

The extreme northeastern part of the map area is underlain by steeply dipping strata of the Hemlock and Amasa Formations. These form north- to northwest-trending belts that are on the southwest flank of the Amasa oval, a major domelike uplift that centers several miles to the north.

Iron ore has been mined in the district continuously since 1882. The total yield (through 1961) has been about 175 million tons, with an approximate value of a billion dollars. The ore is classed as "Direct-shipping, Old Range, high-phosphorus, non-Bessemer ore," according to Lake Superior schedules. The iron content of the ore, after being dried at 100°C, is about 56 percent.

Most of the larger ore deposits occur in synclines, some are on flanks of folds, and a few are on anticlines. The ores were formed in their present structural position—that is, they postdate the deformation of the Animikie Series. They probably were formed during the 500-million-year interval between the Keweenawan and the Cambrian. The ore bodies occur within broader tracts of oxidized iron-formation. Most ore bodies extend to the present bedrock surface, but many are of maximum dimension at depths of 500–1,500 feet. In several parts of the district, ore and oxidized iron-formation extend to a depth of at least half a mile.

The direct-shipping ores are dominantly fine-grained porous mixtures of hematite and goethite, the proportions of which vary widely from place to place. The gangue minerals, dispersed in the iron oxides and equally fine grained, are quartz (relict chert), clay mica (illite), kaolinite, gypsum, and apatite(?). The deficiency in calcium in some ores suggests that the phosphorus may in part be present as vivianite or dufrenite. The ores were formed by oxidation of original sideritic carbonate and by both replacement and leaching of the chert. Because of the great increase in porosity, the bulk specific gravity remained almost unchanged during the conversion of chert-siderite rock to ore.

The ores are believed to have been formed in a three-stage process. The first stage was irregular oxidation of the iron-formation to great depths in the zone of aeration and vadose water, during a postulated late Precambrian epoch of aridity and extraordinarily deep water table. The second stage was the entrapment of water in upward-facing structures, virtually perched aquifers, and the gradual dissolution of chert and consequent supersaturation of silica in the stagnant water. The third stage was periodic expulsion of the silica-charged waters in artesian systems of perhaps brief duration. Theories involving hydrothermal waters of deep-seated origin are rejected because of the absence of characteristic hydrothermal minerals and because of complete lack of evidence indicating passage of solutions through the footwall of ore bodies.

A wide variety of minerals is found in postore veins and open-space fillings. Three main groups are recognized: the specularite-sulfide association, dominated by specularite, pyrite, chalcopyrite, and quartz; the manganese association, dominated by hausmannite; and the uraninite-sulfide association. The three groups are sufficiently dissimilar to suggest independent origins. Of the three groups, the minerals of manganese association and the uraninite-sulfide association possibly were formed by postore circulation of waters involved in the main ore-forming process. The minerals of the specularite-sulfide association, though of hydrothermal aspect, apparently formed at low temperatures; the source of the solutions is unknown.

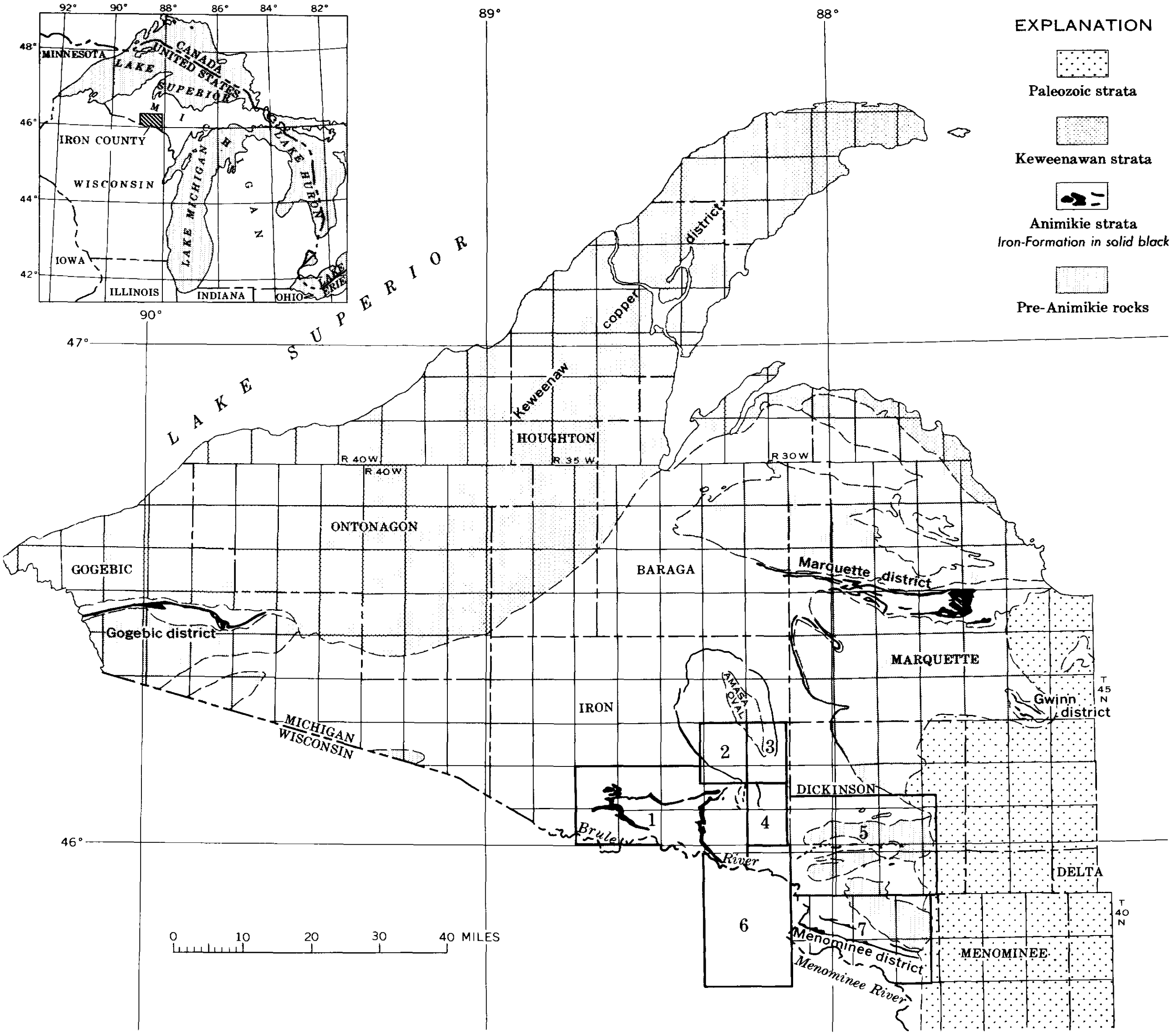
The ultimate reserve of direct-shipping ore in the Riverton Iron-Formation, including the 1961 tax estimate of about 52 million tons (chiefly measured ore), is estimated to be 140 million tons. Oxidized iron-formation containing about 35 percent Fe has a total surface area of about 4 square miles; those parts possibly suited for open-pit mining contain about 350 million tons per 100 feet of depth. The amount of unoxidized iron-formation (25 percent Fe), discounting smaller patches and strips, is about 700 million tons per 100 feet of depth; the most favorable area contains 1 billion tons to a depth of 500 feet. Information is not adequate to make comparable estimates for ore and iron-rich rock in the Amasa Formation, but the reserves of direct-shipping ore are probably small.

INTRODUCTION

LOCATION

The Iron River-Crystal Falls district, also known as the Western Menominee range, is in southern Iron County, in the northern peninsula of Michigan. It occupies an area of approximately 300 square miles, most of which lies between meridians 88°15′ and 88°45′ W. and parallels 46°00′ and 46°07′30″N. The position of the district with respect to other iron-producing districts in the Lake Superior region is shown in figure 1. The report area includes all of the Iron River, Gaastra, Fortune Lakes, and Crystal Falls quadrangles, parts of the Gibbs City, Sunset Lake, and Amasa quadrangles, and the Michigan parts of the Naults and Stager quadrangles.

The town of Crystal Falls, at the northeast end of the district, is the county seat; it had a population in 1960 of 2,203. The largest community, however, is Iron River, at the west end of the district. Iron River had a population of 3,754 in 1960, and the administratively distinct but areally continuous towns of Stambaugh, Caspian, and Gaastra and the village of Mineral Hills raised the population of this "west side" community, including Iron River, to 8,016 (1960 census). The town of Alpha, which had a 1960 population of 317, is in the southeastern part of the district.



1. Iron River-Crystal Falls district
2. Kelso Junction quadrangle (Wier, 1967)
3. Kiernan quadrangle (Gair and Wier, 1956)
4. Lake Mary quadrangle (Bayley, 1959)
5. Central Dickinson County (James, Clark, and others, 1961)
6. Florence area (Dutton, unpub. data)
7. Menominee district (Bayley and others, 1966)

FIGURE 1.—Generalized geologic map of part of northern Michigan, showing the Iron River-Crystal Falls district relative to other mining districts and to other areas of recent U.S. Geological Survey studies. Modified from the centennial geologic map of the northern peninsula of Michigan (Martin, 1936).

Iron mining has been the principal industry of the Iron River-Crystal Falls district, but its importance is waning. Fourteen mines, operated by six different companies, were active in 1953, whereas only four were still in operation in 1963. Lumbering is also of importance, though much less so than it was during the period 1850–1900, when the great hardwood and pine forests were being cut and every stream was choked with logs at the time of spring drives.

The district is well served by transportation lines. U.S. Highway 2 crosses the area from northwest to southeast, passing through the towns of Iron River and Crystal Falls. U.S. Highway 141 extends northward from Crystal Falls. Numerous other graded roads are present, and scarcely any part of the area is more than 2 miles from a route passable by automobiles. Two railroads have lines into the district: The Chicago and North Western Railway Co. and the Chicago, Milwaukee, St. Paul, and Pacific Railroad.

TOPOGRAPHY AND DRAINAGE

The Iron River-Crystal Falls district lies within the Lake Superior highland, between Lake Superior and Lake Michigan. The relief is slight; the highest point in the area, Sheridan Hill, southwest of Iron River, has an elevation between 1,860 and 1,880 feet, whereas the lowest point, the Paint River in the southeast corner of the area, is at an elevation of about 1,200 feet. In few places does the local relief exceed 150 feet. Gentle to moderate slopes are the rule, although the terrain adjacent to the Paint River near Crystal Falls and at Horserace Rapids and the greenstone terrains in the northern part of T. 43 N., R. 33 W., and in the northeast corner of the map area are noteworthy exceptions; here steep rock bluffs are common. Exposed bedrock forms only a fraction of 1 percent of the surface area of the district—in most places bedrock is buried under 50–300 feet of glacial deposits—and with the principal exceptions of the tracts noted above, those outcrops that are present are low and inconspicuous.

Numerous lakes, some of considerable size, dot the area, especially in morainal tracts such as that which extends southwestward through the central part of the district. Swamps are abundant. The area is drained by two principal streams and their tributaries: the Paint River on the north and east and the Brule River on the south. Both drain in a general southeasterly direction and are tributary to the Menominee River, which flows into Lake Michigan. Short stretches of rapids are common on the streams, as are swampy reaches, but falls are not present on any of the major streams within the district.

CLIMATE AND VEGETATION

The climate in general is typical of the northern midwest region; winters are long and summers short. The Department of Agriculture (1941, p. 914) published the following data for Iron County. Data are based on a 37-year period of observations at Stambaugh; average annual precipitation is 33.60 inches distributed through the year as follows:

	Inches		*Inches*
January	1.28	July	4.03
February	1.42	August	3.67
March	1.87	September	4.00
April	2.75	October	2.69
May	3.37	November	3.03
June	4.03	December	1.46

Average July temperature is 65.8°, and average January temperature 11.2°. The highest recorded temperature is 103°, and the lowest recorded temperature −47°. Frost-free period (average) is from June 7 to September 9. In a normal year, the ponds and lakes freeze over in the latter part of November and do not thaw until about mid- or late April. Most of the precipitation falls in late spring, summer, and early fall. Because of the low relief, little difference exists in the precipitation pattern from one part of the area to another.

About 80–90 percent of the district is classed as forest land. Most, if not all, of the present forest cover within the map area is second or third growth. The characteristics of the original forest are described by the following quotation from the soil-survey report on Iron County by Foster, Veatch, and Schoenman (1937, p. 2):

> A dense forest originally covered the entire area, and a few large tracts of hardwood forest remain. Several types of forest and tree associations were represented in the original forest, four of which were characteristic and dominant: (1) The hardwood forests in which hard maple and yellow birch predominated, with smaller proportions of basswood, ash, elm, and hemlock, and a few balsam and spruce, and scattered large white pine; (2) The mixed hardwood and coniferous forest, in which the common hardwoods were intimately mixed with white pine and contained a higher percentage of hemlock, balsam fir, and white spruce; (3) The pine forests, in which white pine, Norway pine and jack pine predominated; and (4) The swamp forests, in some of which cedar, ash, elm, and white birch dominated, and those in which black spruce and tamarack dominated.

The white pine was the principal target for the early logging operations, but little trace now remains of the once extensive forest dominated by this tree. The present forest cover is largely of types 1, 2, and 4 (described in the quotation above) in various stages of development but also contains much elm and poplar. Present-day logging operations are widespread but are on a small scale compared with those of 1850–1900. Maple, yellow birch, and elm are shipped as logs for lumber, and other species, principally poplar, balsam, and spruce, are shipped for pulpwood. During the winter months, the woods are "open," visibility is good, and the forested area may be traversed easily on snowshoes, but during the summer months, visibility is poor because of the thick growth of ferns and the leafing out of the hardwoods, and the thick underbrush makes traversing difficult.

Most of the farms are small and are concentrated in the vicinities of Iron River, Crystal Falls, and Alpha. Most are devoted to dairying, and hay is the chief crop. The short growing season of about 3 months restricts the use of the land, although some of the more extensive sandy tracts in the southern part of the district are successfully planted to potatoes. Abandoned farms are numerous, and although data are not readily available, apparently the percentage of utilized land is decreasing.

FIELDWORK AND ACKNOWLEDGMENTS

The fieldwork on which the present report is based was begun in 1943 by C. F. Park, C. E. Dutton, and J. R. Balsley in the Iron River area and by F. J. Pettijohn in the Crystal Falls area and was continued intermittently for 10 years. H. L. James began work in the area in 1946 and K. L. Wier in 1947. The results of most of this work have been presented as preliminary reports (Dutton and others, 1945; Pettijohn and Clark, 1946; James, Clark, and Smith, 1947; James and Wier, 1948; Pettijohn, 1948; Good and Pettijohn, 1949; Dutton, 1949; James and Dutton, 1951; Pettijohn, 1952).

The fieldwork has been diverse in character. The eastern parts of the Crystal Falls and Stager quadrangles were mapped on enlargements of the topographic base at a scale of 1,000 feet to the inch. The Crystal Falls iron-formation belt was traversed along lines spaced 200 feet apart; magnetic determinations (vertical magnetometer, Hotchkiss Superdip, or dip needle) were made at 100-foot intervals along these lines, and all outcrops were mapped in relation to the magnetic stations. The extensive outcrop area along the Paint River north of Crystal Falls was mapped by planetable. In the Iron River area and in much of the area between Iron River and Crystal Falls, outcrops are exceedingly scarce except locally in the greenstones that border the basin on the north. The outcrop areas were mapped on enlargements of the topographic maps at a scale of 1,000 feet to the inch. Much of the remaining area was mapped magnetically, using the vertical magnetometer or Hotchkiss Superdip. Traverses were made along lines 200–500 feet apart, and determinations were made at 100-foot intervals.

In the Iron River area, in part because of the scarcity of outcrops, all the accessible mine workings were mapped in detail (as of about 1950). Some were remapped, as stratigraphic and structural concepts developed. In the Crystal Falls area, less attention was given to the mine workings, inasmuch as the major aspects of stratigraphy and structure could be determined from outcrop maps and magnetic data.

Extensive search was made for drill core during the course of the study. Much of the core from the explorations prior to about 1925 has been lost or discarded, but that from more recent drilling is properly stored by the mining companies. Core representing several hundred thousand feet of drilling was examined, and the information so obtained has been of critical importance to the solution of stratigraphy and to the construction of map patterns.

The list of geologists who contributed to the field study of the district includes the following: W. D. Allen, J. R. Balsley, R. W. Bayley, John Bokman, L. D. Clark, J. E. Gair, S. E. Good, R. B. Hall, John Hill, Bruce Kennedy, M. W. Leighton, D. M. Lemmon, C. F. Park, W. C. Prinz, Arthur Richards, L. E. Smith, and W. S. White.

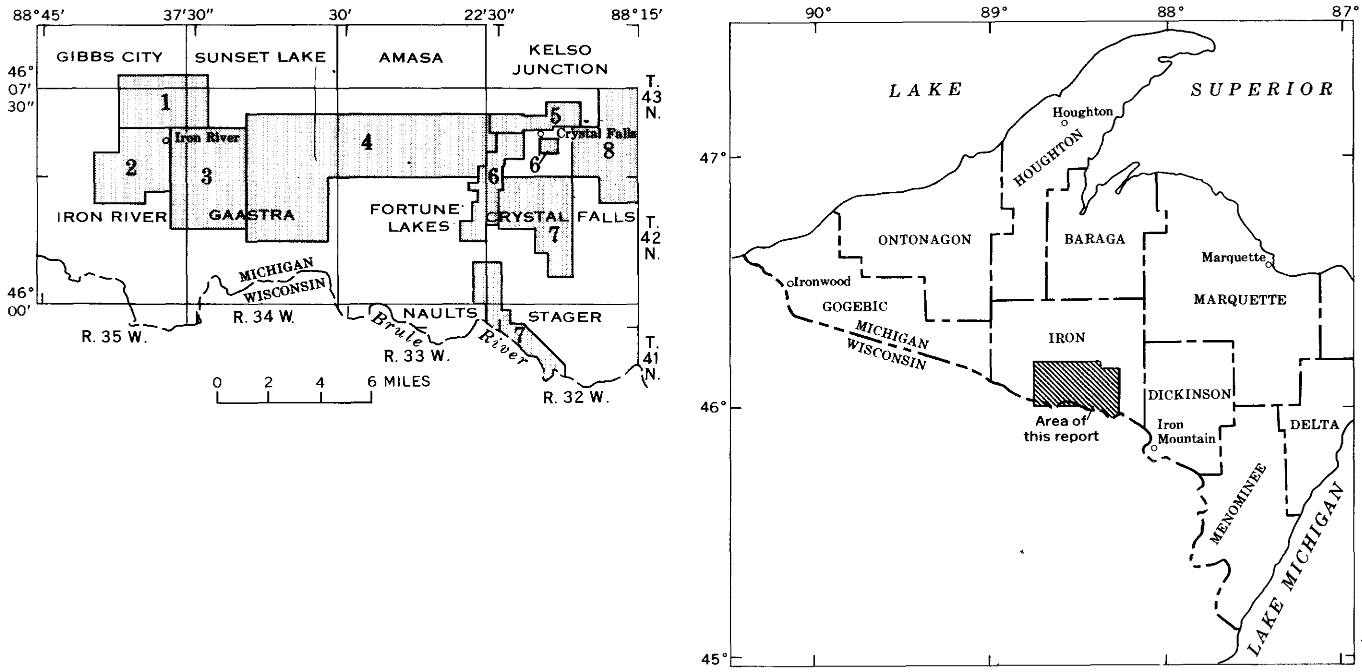
The mining companies active in the district aided very materially, both in providing maps and records and in permitting access to mine workings and to drill-core collections. The authors gratefully acknowledge the friendly cooperation given by officials and employees of the Cleveland-Cliffs Iron Co., the M. A. Hanna Co., the Pickands Mather Co., the Republic Steel Corp., the Mineral Mining Co., the Inland Steel Co., the North Range Mining Co., the Jones and Laughlin Steel Corp., and the Pittsburgh Coke and Iron Co.

The study of the Iron River-Crystal Falls district was made in cooperation with the Geological Survey Division of the Michigan Department of Conservation. The advice, encouragement, and stimulating interest of various members of this organization, particularly F. G. Pardee, (former) State Mine Appraiser and later State Geologist during the period of fieldwork, and G. E. Eddy, who both preceded and succeeded Pardee as State Geologist, were of inestimable value.

SUPPLEMENTARY REPORTS

A series of eight reports presenting geologic and magnetic data on the Iron River-Crystal Falls district is being published by the State of Michigan. The reports contain detailed descriptions of geology, explorations, mines, and magnetic surveys. The areas covered by these publications are outlined in figure 2.

Much of the information on the history of individual mines is from the two volumes "Lake Superior Iron Ores" (Lake Superior Iron Ore Assoc., 1938, 1952), which contain summary statements of location, history, and production of each mine. Further information on earlier mining history is from the annual reports issued by the Commissioner of Mineral Statistics from 1879 to 1909 (Michigan Dept. Mineral Statistics, 1879–1909), and from the 12 volumes of "Mineral Resources of Michigan" (Allen, 1912, 1914, 1915, 1916, 1917, 1918, 1920; Smith, 1922, 1924, 1925, 1929; Smith and Martin, 1923), issued at intervals from 1912 to 1929. The volume for 1910 (Allen, 1912) contains particularly useful data.



1. Northern Iron River area (James, Dutton, and Wier, 1968)
2. Central Iron River area (Dutton, 1968)
3. Southeastern Iron River area (James and Wier, 1968)
4. Area between Iron River and Crystal Falls (James, Pettijohn, and Clark, 1968)
5. Northern Crystal Falls area (Pettijohn, 1968)
6. Southern Crystal Falls area (Pettijohn, 1968)
7. Alpha-Brule River and Panola Plains areas (Pettijohn and others, 1968)
8. Northeastern Crystal Falls area (Wier, 1968)

FIGURE 2.—Iron River–Crystal Falls district, Michigan, showing areas covered by detailed data reports. Topographic quadrangles designated by name.

PREVIOUS WORK AND SUMMARY OF THE LITERATURE

Relatively little has been written on the Iron River-Crystal Falls district, particularly in comparison with other Lake Superior districts. No published report describes the district in its entirety, although brief summary descriptions have been presented by Stephen Royce in Proceedings of the Lake Superior Mining Institute, in the volume "Lake Superior iron ores," and in the volume "Ore deposits as related to structural features." (See following references.) In these reports the district is referred to as the "Western Menominee."

The two major published reports that deal with the district are (1) U.S. Geological Survey Monograph 36, "The Crystal Falls iron-bearing district," by J. M. Clements and H. L. Smyth, published in 1899, and (2) Michigan Geological Survey Publication 3, "The Iron River iron-bearing district of Michigan," by R. C. Allen, published in 1910. These reports contain summaries of previous work, most of which was of reconnaissance nature and of little significance. The Iron River and Crystal Falls areas are described in U.S. Geological Survey Monograph 52, "The geology of the Lake Superior region," by Van Hise and Leith (1911), but the descriptions are simply recapitulations of the two earlier reports.

Monograph 36, although entitled "The Crystal Falls iron-bearing district," actually describes mainly the rocks of the "Amasa Oval," most of which lies northeast of what is here referred to as the Crystal Falls area. The maps of the Crystal Falls area in Monograph 36 give little indication of geology as it is now known. Allen's report on the Iron River district is much more complete, and although most of Allen's concepts of structure and stratigraphy have not stood the test of time, his geologic map of the area, on which all outcrops known at that time are plotted, has been a major contribution.

For 30 years after publication of Monograph 52, geologic work in the district was largely confined to that done by mining companies on local areas. Most of this material is unpublished. No systematic study of the district was done until the work on which the present report is based was begun in 1943.

The reports dealing with the area, in chronological order, are listed below. Those prior to 1899 are not given; for those the reader is referred to summaries in Monograph 52 (Van Hise and Leith, 1911, p. 74–77).

1899

Clements, J. M., and Smyth, H. L., 1899, The Crystal Falls iron-bearing district of Michigan: U.S. Geol. Survey Mon. 36, 512 p. (Discussed above.)

1907

Russell, I. C., 1907, The surface geology of portions of Menominee, Dickinson, and Iron Counties, Michigan: Michigan Geol. and Biol. Survey Ann. Rept., 1906, p. 47–52.

1910

Allen, R. C., 1910, The Iron River iron-bearing district of Michigan: Michigan Geol. and Biol. Survey Pub. 3, Geol. Ser. 2, 151 p. (Discussed above.)

1911

Leverett, Frank, 1911, Surface geology of the Northern Peninsula of Michigan * * *: Michigan Geol. and Biol. Survey Pub. 7, Geol. Ser. 5, 91 p.

Van Hise, C. R., and Leith, C. K., 1911, The geology of the Lake Superior Region: U.S. Geol. Survey Mon. 52, p. 291–300, 308–319.

This report is a complete account of the geologic knowledge of the region as of 1911. The chapters dealing with the Iron River district and with the Crystal Falls district are largely summaries of Monograph 36 (1899) and Allen's report (1910). Separate maps of these areas are included; the Iron River map (prepared by Allen) is considerably modified from that appearing in the earlier report.

1915

Allen, R. C., and Barrett, L. P., 1915, Contributions to the pre-Cambrian geology of northern Michigan and Wisconsin: Michigan Geol. and Biol. Survey Pub. 18, Geol. Ser. 15, 189 p.

1929

Barrett, L. P., Pardee, F. G., and Osgood, Wayland, 1929, Geological map of Iron County: Michigan Dept. Conserv., Geol. Survey Div.

Publication of this map records a major advance in knowledge of the geology of the district. It reveals, for the first time in a published report, the synclinal form of the district and the basic correlation between the Iron River and Crystal Falls areas.

1930

Kraus, E. H., Seaman, W. A., and Slawson, C. B., 1930, Seamanite, a new manganese phospho-borate from Iron County, Michigan: Am. Mineralogist, v. 15, p. 220–225.

New mineral found on the dump of the old Chicagon mine.

1932

Bergquist, S. G., 1932, Glacial geology of Iron County, Michigan: Michigan Acad. Sci. Papers, v. 16, p. 363–372.

In this report, Bergquist described the glacial geology of the district and presented a small-scale map of the surface features.

1933

Zinn, Justin, 1933, Correlation of the Upper Huronian of the Marquette and Crystal Falls districts: Michigan Acad. Sci. Papers, v. 18, p. 437–456.

Suggests correlation on basis of supposed equivalency of Goodrich conglomerate with breccia beds in the northern Crystal Falls area.

1934

Slawson, C. B., 1934, Sussexite from Iron County, Michigan: Am. Mineralogist, v. 19, no. 12, p. 575–578.

Manganiferous sussexite, associated with seamanite. Found on dump of old Chicagon mine.

1935

Bergquist, S. G., 1935, Valley-train deposits in the Northern Peninsula of Michigan: Michigan Acad. Sci. Papers (1934), v. 20, p. 439–447.

Further data on distribution of glacial deposits.

Leith, C. K., Lund, R. J., and Leith, Andrew, 1935, Pre-Cambrian rocks of the Lake Superior region: U.S. Geol. Survey Prof. Paper 184, 34 p.

Includes new map of Lake Superior region and brief notes concerning changes from Monograph 52. Map pattern in Iron River-Crystal Falls district taken mainly from 1929 map of Iron County.

1936

Martin, H. M., compiler, 1936, The centennial geological map of the Northern Peninsula of Michigan: Michigan Dept. Conserv., Geol. Survey Div. Pub. 39, Geol. Ser. 33.

Royce, Stephen, 1936, Geology of the Lake Superior iron deposits: Lake Superior Mining Inst. Proc., v. 29, p. 68–107; Mining Cong. Jour., v. 22, no. 3, p. 16–30.

General review of geology of the region and brief description of each district.

1937

Foster, Z. C., Veatch, J. O., and Schoenman, L. R., 1937, Soil survey of Iron County, Michigan: U.S. Dept. Agriculture, Bur. Chemistry and Soils, Ser. 1936, no. 46.

Soil map shows "stony land," which proved helpful in locating outcrop areas during present study.

1938

Royce, Stephen, 1938, *in* Lake Superior iron ores: Lake Superior Iron Ore Assoc., Cleveland.

Brief description of geology and ore occurrences in the "Western Menominee" range.

1940

Ayres, V. L., 1940, Mineral notes from the Michigan iron country: Am. Mineralogist, v. 25, no. 6, p. 432–434.

Describes occurrence of stilpnomelane adjacent to quartz-adularia veins in the Paint River area, north of the town of Crystal Falls.

1941

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GLACIAL GEOLOGY

More than 99 percent of the area described in this report is mantled by glacial deposits, which locally attain a thickness of nearly 500 feet. This aspect of the geology has not been studied systematically during the course of the present work but obviously is of great importance, particularly to the exploration and development of the iron ores. The discussion that follows is based largely on published reports, modified by field observations made by the present authors. For further detail, the reader is referred to reports by Russell (1907), Leverett (1911), Bergquist (1932, 1935, 1941), and Stanley (in Stuart and others, 1948).

The glacial features within Iron County, like those of most of the Lake Superior region, are attributed mainly to the ice action of the youngest glaciation (Wisconsin) of the Pleistocene. During the Wisconsin Glaciation, the glacial ice moved across the northern peninsula of Michigan from centers to the north and northwest in Canada. Leverett (1929) distinguished five "substages" of the Wisconsin, each of which is related to a period of wasting away (retreat) and readvance of the ice. During each period of retreat, the centers of ice accumulation shifted so that the directions of ice movement in the readvances differed for each "substage."

The dominant physiographic feature of Iron County glacial geology is a tract of terminal (or recessional) moraine that forms a broad band across the northern and eastern part of the county (fig. 3). This moraine was deposited at the margin of ice that moved into the area from the northwest (Superior lobe) and from the east (Green Bay lobe), as indicated by glacial striations on the exposed rocks. The moraine, which ranges in width from 2 to 15 miles, is a broad hummocky tract of high ground that stands 50–300 feet above the surrounding terrain. It is marked by kettle holes and other undrained depressions and, in general, by irregular topography. In the eastern part of the county, the moraine has to a considerable extent been buried under outwash sands and allied deposits, although the crest, which trends in a southerly direction along the east boundary of the county, is well defined.

The moraine encroaches from the north and east on an area mantled by earlier till. This till, or ground moraine, is shown in conflicting manner on Leverett's maps; on plate 1 of Leverett's report (1929) it is included within "substage 4" deposits, whereas on figure 5 of the same report it is included with deposits of "substage 3." The distinction is not especially critical; in either grouping the till is older than the moraine.

For purposes of description of glacial features, the area covered by this study can be divided rudely into three major parts. The western part, extending approximately from the west margin of R. 35 W. to the Chicagon Lake area in the eastern part of R. 34 W., is an undulating till plain characterized by many drumlins. The central part includes the area adjacent to the Chicagon Lake and Fortune Lakes chains. It is characterized by projections of the recessional moraine that lies to the north (incompletely shown in fig. 3) so that local areas of irregular moraine topography and outwash sand are interspersed with areas of older till. The eastern part of the area, which is between the Fortune Lakes chain and the eastern margin of the map area, is a complex unit. The principal feature is a sandy outwash plain through which emerge patches of older recessional and ground moraine and areas of stripped bedrock. The eastern sector is separated from the central sector by a broad bedrock ridge, thinly mantled with ground moraine, that extends southward from Crystal Falls. The

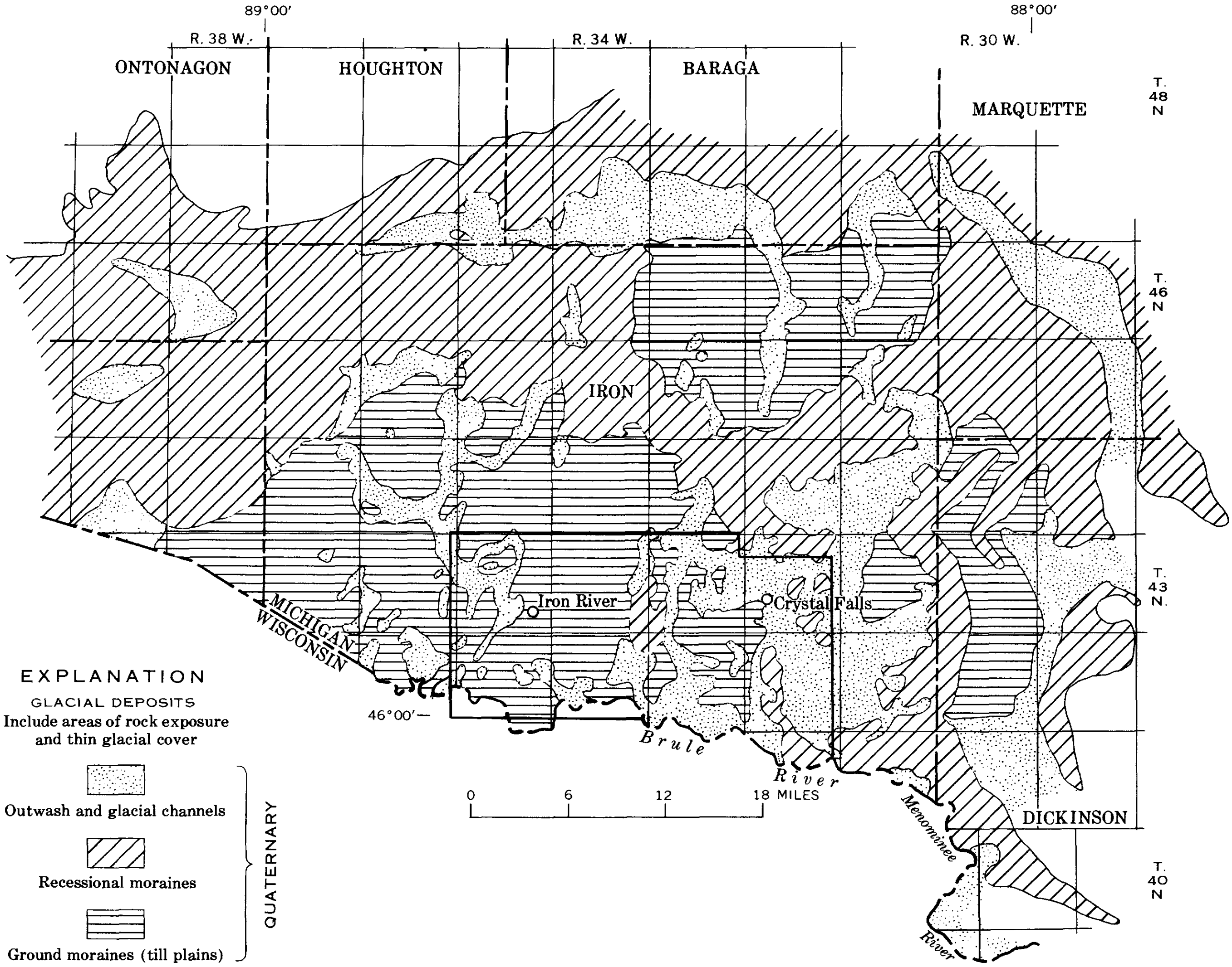

Figure 3.—Glacial deposits of the Iron River-Crystal Falls district (outlined) and its environs. Modified from "Map of the surface formations of the Northern Peninsula of Michigan," compiled by Martin (1957).

distinctive aspect of these three units can readily be observed in crossing the district on U.S. Highway 2.

The bedrock surface on which the glacial deposits rest has a total relief comparable to that of the present surface. This is evident from figure 4, which shows a vertical profile of the present surface and also the bedrock surface along the northern part of the district.

WESTERN SECTOR

The western part of the district is underlain chiefly by ground moraine and associated deposits that predate the recessional moraine to the north. The characteristic feature of the topography is the drumlin. The drumlins are low elongate hills, ranging from several hundred feet to a mile in length and from 20 to 100 feet in height; the longer axes typically trend about S. 25° W. but range from due south to S. 40° W. The drumlin ridges are separated by low sags and shallow valleys, many of which are occupied by lakes and swamps. Most of the drumlins are about 40 feet high, whereas the till sheet itself is much thicker, possibly about 150 feet on the average and locally in excess of 400 feet; so, the drumlins are relatively superficial features that in all probability are due largely to movement of ice over earlier glacial deposits.

Exposures of the glacial deposits on the walls of mine caves show a considerable complexity in the character of materials. Boulder till, consisting of angular to rounded boulders as much as several feet in diameter in a gray to yellow or red sandy clay matrix, is the dominant material. Most of it is without bedding, although in some exposures a rude stratification is visible. Interbedded with the till in some exposures are lenses of stratified sand and gravel. Bergquist (1935), on the basis of ex-

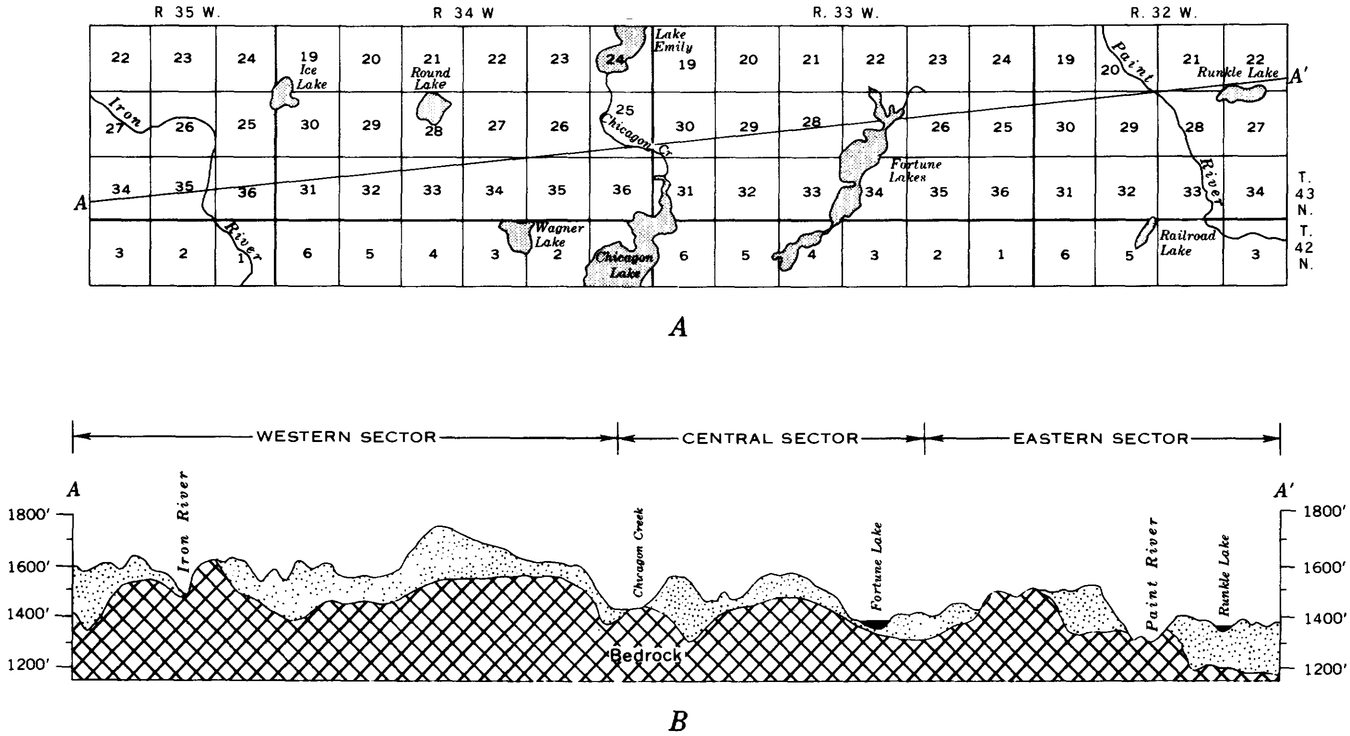

FIGURE 4.—Line of profile (*A*) and vertical profile (*B*) of present surface and bedrock surface across the northern part of the Iron River-Crystal Falls district. Vertical exaggeration about × 20. Glacial deposits indicated by stippling.

amination of several mine cave exposures in the Iron River area, concluded that the till sheet can be divided into three major parts: a discontinuous basal till, 20–40 feet thick or more, which he classed as "Pre-Wisconsin" in age; an intermediate formation consisting of stratified gravel and sand, 15–40 feet thick or more, classed as "Early Wisconsin," and a surface till sheet ranging in thickness from 20 to perhaps a few hundred feet, classed as "Middle Wisconsin." These subdivisions are visible in the caves at the Berkshire and Davidson mines. On the basis of more detailed studies in the area, G. M. Stanley (in Stuart and others, 1948, p. 18) apparently rejected this classification. He stated:

> Local variations in thickness of beds and in slope of contact surfaces * * * caution against attempts to correlate buried beds of till and gravel between places of exposure, or to infer that continuities exist from one place to another.
>
> With a view to the possibility of tracing the buried till and gravel beds, considerable time was spent in studying the logs of wells and borings in the Mineral Hills district. Profiles were drawn in various directions between the more closely spaced and more recent holes. The correlation or continuity of beds between points of record in these profiles proved to be so dubious a matter and involved so many alternatives that no statement of positive findings can be made in this regard.

Observations made by the present authors tend to confirm Stanley's views as to the lack of orderly distribution of members within the glacial deposits, although the fact that boulder till is the surface material in virtually all parts of the area (except for some valley-train deposits of later date) does suggest that the upper till sheet postulated by Bergquist is a discrete unit. The problem is far from being purely academic because the nature of the materials and the areal extent of the units are of profound importance to problems of mine drainage, drilling, and shaft sinking.

Deposits of outwash sand, presumably related to the morainal belt in the northern half of the county, are present in several places in the western sector of the district. The largest areas of such deposits are along the course of the present Iron River, most noticeably near its juncture with the Brule River in sec. 29, T. 42 N., R. 34 W. A smaller area, not related to any present stream, is in the northern part of sec. 29, T. 43 N., R. 34 W. This particular deposit of sand caused great difficulty in the sinking of the Rogers mine shaft, a difficulty that was finally overcome by use of pressure caissons. The continued influx of water into the mine workings from the porous sand was one of the factors that led to the closing of the mine in 1937.

Eskers, which are low sinuous ridges built up by sand and gravel deposition in channels within or beneath the ice sheet, are present in the Stanley Lake-Stanley Creek trough near the west margin of the map area. One of these, in sec. 33, T. 43 N., R. 35 W., is a source of commercial sand and gravel.

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CENTRAL SECTOR

The central part of the district, which is a narrow tract occupied in part by Chicagon Lake and Fortune Lake, is strikingly different in topography from the western sector. Rolling till plain, long ridges with relatively steep slopes, morainal tracts with characteristic knob-and-kettle topography, and sandy outwash plains form a topography that in general is more varied and more irregular than the uniform drumlin topography of the western sector.

The diversity of the central sector is due principally to the projection from the north of the moraine margin and related features into the Chicagon Lake and Fortune Lake channels. Probably these channels were occupied by stagnant ice separated from the main ice front to the north during the later part of "substage 4."

Eskers are a prominent feature of the landscape. One line of eskers extends as discontinuous sharp ridges for 6 miles, from the northern part of sec. 9, T. 43 N., R. 33 W., southward into sec. 8, T. 42 N., R. 33 W. This esker belt is crossed by U.S. Highway 2 in sec. 29, T. 43 N., R. 33 W., where it is a high double-crested ridge. Cuts in the esker show it to be composed of a chaotic assortment of rounded boulders, pebbles, and sand. It is flanked by bedded sand, the crossbedding of which dips away from the esker line. A second esker belt of similar character lies in secs. 14 and 23, T. 43 N., R. 33 W.

A belt of striking morainal topography borders Chicagon Lake on the east and extends northward along the east side of Lake Emily. The well-drained sandy and gravelly soil supports abundant white birch and pine, which here dominate over the yellow birch and elm that characterize the till-plain forest. Somewhat similar topography and vegetation border much of the Fortune Lakes chain, and in fact, the two morainal tracts merge in sec. 5, T. 42 N., R. 33 W.

The intervening till plain that in most places separates the Chicagon Lake and Fortune Lakes chains is a boulder-strewn surface of low relief, similar to that of the Iron River area except for the less notable development of drumlins.

Outwash sand deposits fill many of the lower swales between the ridges and higher ground, particularly adjacent to the eskers and morainal tracts.

The thickness of the glacial deposits in the central sector is highly variable within short distances, partly on account of differences in height of constructional features of the topography (such as eskers) and partly because of irregularities of the bedrock surface. The drift is only about 15 feet deep in the west-central part of sec. 27, T. 43 N., R. 33 W., whereas in the SE¼ sec. 21 of the same township, less than a mile to the northwest and at about the same elevation, it is more than 300 feet thick.

EASTERN SECTOR

The eastern sector of the district is separated from the central sector by a broad discontinuous bedrock ridge lightly mantled with ground moraine. This ridge extends from Crystal Falls southward through Alpha to Mastodon. Swamps or sandy outwash fill the low ground between swells on this high ground. The ridge is flanked on the east in part by segments of moraine and in part by deposits of outwash sands that project into all the lower parts of the ridge in irregular fashion. These outwash sands merge to the east in the central part of the area into a broad sandy plain (the "Panola plains"); 3–4 miles south-southeast of Crystal Falls the margin of this plain is crossed by U.S. Highway 2. The plain is pitted by small undrained depressions that presumably were the sites of isolated bodies of ice that were covered by the outwash and which later melted and caused subsidence of the overlying sand.

In the northern part of the eastern sector a belt of sandy outwash extends through secs. 19 and 20, T. 43 N., R. 32 W., and secs. 23 and 24, T. 43 N., R. 33 W., to connect the margin of the moraine northeast of Crystal Falls with the Fortune Lakes belt of moraine and outwash. The Fortune Lakes mine, an open-pit operation in the northernmost parts of secs. 25 and 26, T. 43 N., R. 33 W., is at the south margin of this belt. The excavation discloses that the surface sands are underlain in that area by a thick deposit of varved glacial clay, which probably was deposited in a lake dammed behind a stagnant ice mass in the Fortune Lakes trough.

A miniature "scabland" is present along the Paint River in the northern part of the town of Crystal Falls. The area is characterized by rocky bluffs and abandoned stream channels. Almost surely the topography was carved in large part by a glacial river rather than by the present stream.

The southernmost part of the eastern sector, especially the area along the Brule River from Pentoga eastward for 6 miles, is a sandy plain. It is separated from the Panola plains to the northeast by an irregular broad southeast-trending belt of recessional moraine that is crossed by U.S. Highway 2 in sec. 33, T. 42 N., R. 32 W., and sec. 4, T. 41 N., R. 32 W. The plain along the Brule River, like similar areas farther west along and adjacent to the river, probably was formed as a flood plain on a river that occupied the same course as the present stream. This stream was probably much larger than the present one; according to Stanley (in Stuart and others, 1948, p. 14), the glacial waters that originated in the present Paint River drainage area to the north were diverted into the Iron River channel, which joins the Brule in sec. 29, T. 42 N., R. 34 W. The terraces related to this glacial stream slope in the direction parallel to the present drainage: in sec. 19, T. 42 N., R. 34 W., the elevation is 1,449 feet; in sec. 20, T. 42 N., R. 34 W., 1,439 feet; in sec. 20, T. 41 N., R. 16 E. (Wisconsin), 1,412 feet; in sec. 30, T. 42 N., R. 33 W., 1,378 feet; and in sec. 35, T. 42 N., R. 33 W., 1,352 feet. The average slope is about 9.2 feet to the mile and is less than the present slope of the Brule River, which is about 13 feet to the mile.

BEDROCK GEOLOGY

The fact that bedrock is almost completely mantled by Pleistocene deposits deserves special emphasis. It is evident that the map of bedrock geology, plate 1, has not been constructed by standard geologic mapping techniques. Rather, in large part it is based on magnetic surveys, drill hole and test pit information, and mapping of underground workings. All geologic contacts are covered, and the degree of reliability of the positions of the units shown on the map varies widely. In the folded belt extending southward from Crystal Falls, the positions of the principal stratigraphic units are subject to only minor error because the folds have a generally consistent trend and plunge, outcrops are fairly common, and exploration data are abundant. However, in the area adjoining Crystal Falls on the north and in the entire western part of the district, the major folds are interrupted, locally within distances of 100 feet or less, by equally intense crossfolds. The resultant map pattern is highly complicated and difficult to predict for a given level of truncation even where the structure is reasonably well known. Maps of successive levels in some of the mines show remarkable differences in horizontal planes as little as 20 feet apart. For a good part of the area, therefore, the map pattern of bedrock geology is virtually diagrammatic, even where the subsurface has been thoroughly explored by mine workings and drill holes. Each new drill hole can be expected to yield data that will call for some modification in the map.

NOMENCLATURE OF PRECAMBRIAN UNITS

The stratigraphic units used in this report have been defined in a previous report (James, 1958). The nomenclature bears little resemblance to that used in older reports. Table 1 presents a summary of the nomenclature of the composite stratigraphy of Iron and Dickinson Counties in comparison with that used by Leith, Lund, and Leith (1935, p. 10). The Crystal Falls district as used by Leith, Lund, and Leith embraces an area much larger than that considered in the present report; in terms of stratigraphy it is comparable to that of the Iron River–Crystal Falls district plus that of the Kiernan quadrangle of eastern Iron County (Gair and Wier, 1956). On the basis of a study of regional metamorphism in northern Michigan (James, 1955), the post-Animikie intrusion is assigned to the late middle Precambrian in preference to the post-Keweenawan age given by Leith, Lund, and Leith. Other differences in nomenclature and stratigraphic relations evident from table 1 are discussed in the descriptions of individual stratigraphic units given later in this report.

GENERAL OUTLINE OF STRATIGRAPHY

The Iron River–Crystal Falls district is in general configuration a triangular-shaped basin of tightly folded strata of the Animikie Series (pl. 1). The sequence of rocks within the basin proper, the Paint River Group, constitutes the uppermost part of the Animikie Series (James, 1958) and includes the Riverton Iron-Formation, which contains the principal ore bodies of the district. The Paint River Group is underlain by the Badwater Greenstone, the Michigamme Slate, the Amasa Formation, and the Hemlock Formation, which together make up the Baraga Group in this area. The Saunders Formation, present only in the southwestern part of the district, is equivalent to the Kona and Randville Dolomites of other parts of northern Michigan. It is bordered on the south by a belt of greenstone of unknown age. The structural and stratigraphic relations between the dolomite and the greenstone on the south and between the dolomite and younger Animikie rocks are not known.

The Paint River Group is divided into two parts by minor unconformity or disconformity. The lower part comprises the Dunn Creek Slate and the Riverton Iron-Formation. The upper part comprises the Hiawatha Graywacke, the Stambaugh Formation, and the Fortune Lakes Slate.

The oldest formation of the Paint River Group, the Dunn Creek Slate, consists chiefly of siltstone and gray slate in the Iron River area and gray slate, siltstone, cherty black slate, and sideritic slate in the Crystal Falls-Alpha area. The uppermost part of the Dunn Creek Slate throughout the district, so far as known, is a graphitic pyritic slate, called the Wauseca Pyritic Member.

The Riverton Iron-Formation conformably overlies the Wauseca Pyritic Member; commonly the two show interbedding at the contact. This zone of interbedding is commonly less than 5 feet, but locally, as in the Chicagon Creek area midway between Iron River and Crystal Falls, it is as much as 50 feet thick, and in some places, particularly in the Bengal mine area in the western part of the district, a thick assemblage of

TABLE 1.—*Comparison of stratigraphic units with those*

System		Series		Crystal Falls	Iron River	Felch Mountain
				Leith, Lund, and Leith (1935)		
Post-Keweenawan rocks				Upper Cambrian sandstone	Ordovician limestone, sandstone, and conglomerate	Upper Cambrian sandstone
				UNCONFORMITY		~~~
Precambrian rocks	Algonkian type	Killarney granite*		Acidic intrusives		Basic and acidic intrusives
		Keweenawan				
					UNCONFORMITY	
		Huronian	Upper	Michigamme slate: Upper slates; Iron River iron-formation member; Lower slates	Michigamme slate: Upper slates; Iron River iron-formation member; Lower slates	
				Paint River belt of greenstone*	Paint River* and Pentoga belts of greenstone*	
				UNCONFORMITY		~~~
			Middle	Negaunee iron-formation		Vulcan iron-formation
				Ajibik quartzite		Felch schist
				Hemlock greenstones		
				UNCONFORMITY	~~~	~~~
			Lower	Randville dolomite	Saunders formation (dolomites and quartzites)	Randville dolomite
				Sturgeon quartzite		Sturgeon quartzite
		Algoman granite				
		Knife Lake (may be Lower Huronian)				
				UNCONFORMITY		~~~
	Archean type	Laurentian granite		Granites and gneisses		Granites and gneisses
		Keewatin				

NOTE.—The asterisk (*) after a geological name indicates doubt as to its stratigraphic position.

used in U.S. Geological Survey Professional Paper 184

Composite sequence based on recent Geological Survey mapping. Units in Iron River-Crystal Falls district (in italics), Kiernan quadrangle, and central Dickinson County.

Ordovician		*Sandstone and dolomite*		
		UNCONFORMITY		
Upper Precambrian	Keweenawan Series	*Diabase*		
Middle Precambrian		*Granitic intrusive rocks*		
Middle Precambrian		*Mafic intrusive rocks*		
Middle Precambrian	Animikie Series	*Paint River Group*	*Fortune Lakes Slate* *Stambaugh Formation* *Hiawatha Graywacke* *Riverton Iron-Formation* *Dunn Creek Slate*	
Middle Precambrian	Animikie Series	*Baraga Group*	*Badwater Greenstone* *Michigamme Slate* *Amasa Formation* *Hemlock Formation* Goodrich Quartzite	
Middle Precambrian	Animikie Series	Menominee Group	Vulcan Iron-Formation Felch Formation	
Middle Precambrian	Animikie Series	Chocolay Group	Randville Dolomite } *Saunders Formation* Sturgeon Quartzite } Fern Creek Formation	
		UNCONFORMITY		
Lower Precambrian		Granite and gneiss		*Greenstone in the Brule River area* (age unknown)
Lower Precambrian		Dickinson Group	Six-Mile Lake Amphibolite Solberg Schist East Branch Arkose	
		UNCONFORMITY		
Lower Precambrian		Granite gneiss with inclusions of quartzite and schist		

chaotic breccia and other rocks separates the two formations. The Riverton in its unoxidized state consists largely of thin-bedded chert and iron-rich carbonate, locally interbedded with layers of sideritic slate and graphitic slate. Some parts of the formation, largely restricted to the Crystal Falls area, contain layers that consist principally of stilpnomelane and others that contain much magnetite. The Riverton Iron-Formation is the host rock for the ore deposits.

The Hiawatha Graywacke is an assemblage of clastic rocks that overlie the Riverton Iron-Formation, at least locally with unconformity. Most of the formation, especially in the Iron River district, consists of massive graywacke and gray slate, but a distinctive breccia consisting of chert fragments in a graywacke matrix forms the basal part of the formation in many places. Locally, sideritic fragments are also present in the breccia, and it seems clear that the breccia facies has been derived by erosion, possibly submarine, of the underlying iron-formation as a consequence of the structural disturbance that halted iron-formation deposition.

Overlying the Hiawatha Graywacke, with gradational contact, is the Stambaugh Formation, which is in part clastic, in part an iron-rich chemical precipitate. Some layers of the Stambaugh Formation contain abundant magnetite; so, it has been possible to trace out the distribution of the formation by means of the magnetic surveys that have formed a considerable part of the fieldwork on which the maps accompanying this report are based. The Stambaugh Formation is overlain by poorly exposed strata referred to the Fortune Lakes Slate. These strata contain graywacke, gray slate, striped silty slates, sideritic slate, and some iron-formation in the vicinity of Crystal Falls, and unexposed rocks of unknown character in the central part of the Iron River-Crystal Falls basin.

Igneous rocks, though not scarce, do not form a large percentage of the bedrock. They consist of four types, which listed in probable order of age (oldest to youngest) are as follows: (1) metagabbro and metadiabase, (2) trachyte, (3) granite (or granodiorite), and (4) diabase. The metagabbro and metadiabase are found as dikes and sheets as much as several hundred feet thick. The original igneous rock has been largely altered to amphibole, albite, chlorite, epidote, carbonate, and "leucoxene." The trachyte forms two or three very thin dikes and sills in the Iron River area. The granitic rock, found only in the eastern part of the district, forms several dikelike or lenslike bodies, the largest of which is about 2 miles long and about 1,000 feet wide. The diabase is known to occur only as a single dike. The rock is magnetic and inversely polarized; thus, it yields a negative magnetic anomaly.

Flat-lying remnants of lower Paleozoic strata—mostly sandstone and dolomite—are present locally in the southwestern part of the district. They are separated by profound unconformity from the Precambrian rocks. The succession is summarized in table 2.

The structure of the Precambrian rocks of the district is simple in general outline but is extraordinarily complex in detail. The broad pattern is that of a shallow basin, within which, however, the rocks are tightly folded. The Riverton Iron-Formation and adjacent strata are particularly strongly deformed into folds and crossfolds of every order of magnitude. Many large faults have been mapped or inferred; most of those known are steeply dipping and have either reverse or lateral displacement.

STRATIGRAPHY

Definition of the stratigraphic succession in the district has not been an easy task, and many uncertainties remain. Even within the basin proper, where information on the iron-formation and adjacent strata is abundant, wide divergence of opinion is possible. The remarkable degree of folding exhibited by the strata generally precludes direct measurement of thickness. In all places, overturned folds and crossfolds (locally overturned also) coupled with faulting and changes in thickness as a result of faulting, shearing, or squeezing, make determination of the succession extremely difficult. Determination of tops of beds is always a problem; no fossils, of course, are available; crossbedding and gradational bedding, except in the Michigamme Slate, are exceedingly sparse; ripple marks are absent. Pillow

TABLE 2.—*Rock units in the Iron River–Crystal Falls district*

			Rock unit	Estimated thickness (feet)	Remarks
Pleistocene			Till, gravel, sand	0–425	Mantle more than 99 percent of area.
				Unconformity	
Ordovician			Sandstone, dolomite	0–100	Flat-lying remnants of sandstone and dolomite in the southwestern part of the area.
				Unconformity	
Upper Precambrian			Silica rock	0–200	Massive cherty rock that probably represents silicified erosion surface on dolomite.
				Unconformity	
Upper Precambrian	Keweenawan Series		Diabase		Rare dikes. Unaltered; magnetic and inversely polarized.
Middle Precambrian			Granite and trachyte		Granite, medium-grained, massive; in eastern part of district only. Trachyte as sparse thin dikes.
Middle Precambrian			Metadiabase and metagabbro		Chloritized, massive. Abundant dikes and sills, a few stocks.
Middle Precambrian	Animikie Series	Paint River Group	Fortune Lakes Slate	4,000+	Character known only for lower part of section, exposed in eastern part of district, where strata consist of gray slate, striped slate, sideritic slate, graywacke, and possible iron-formation. Most of unit not exposed or drilled within district.
Middle Precambrian	Animikie Series	Paint River Group	Stambaugh Formation	100	Cherty laminated rock and massive chlorite slate, some graywacke. Many parts strongly magnetic.
Middle Precambrian	Animikie Series	Paint River Group	Hiawatha Graywacke	0–500	Massive graywacke, commonly sideritic, and gray slate. Lowermost part commonly contains abundant chert fragments.
				Minor unconformity	
Middle Precambrian	Animikie Series	Paint River Group	Riverton Iron-Formation	10–800	Thin-bedded rock, mainly chert and iron-rich carbonate where unoxidized. Includes some graphitic slate, also stilpnomelane beds and magnetite-rich beds in eastern part of district. Host rock for ore bodies.
Middle Precambrian	Animikie Series	Paint River Group	Dunn Creek Slate	400–1,500	In eastern part of district, unit consists of siltstone underlain by black cherty slate, sideritic slate, and chert-carbonate rock. In western part of district, unit is chiefly siltstone and slate. Uppermost part throughout district is graphitic pyritic slate (Wauseca Pyritic Member).
Middle Precambrian	Animikie Series	Baraga Group	Badwater Greenstone	0–15,000	Massive chloritized mafic volcanic rock, in part flows with ellipsoidal structure, in part tuffs and agglomerates. Some parts strongly magnetic.
Middle Precambrian	Animikie Series	Baraga Group	Michigamme Slate	6,000	Mostly interbedded slate and graywacke; in southeastern part of area more highly metamorphosed equivalents. Probably contains some ferruginous beds in uppermost part.
Middle Precambrian	Animikie Series	Baraga Group	Amasa Formation	1,800	Principally martite slate, with layers of cherty iron-formation. Locally strongly magnetic.
Middle Precambrian	Animikie Series	Baraga Group	Hemlock Formation	6,000+	Mostly massive metabasalt, locally with ellipsoidal structures. Contains Bird Iron-Bearing Member (200 ft thick) 1,200–1,400 feet below the top of the formation. Both the greenstone and the Bird Member are locally strongly magnetic.
Middle Precambrian	Animikie Series	Chocolay Group	Saunders Formation	1,000(?)	Mainly massive dolomite. Exposed in only a few places in southern part of district.
?	?		Greenstone in the Brule River area	Not known	Massive metabasalt, in part with agglomeratic and ellipsoidal structures. Some layers are magnetic.

(ellipsoidal) structures in the greenstones, and dragfolds in the sedimentary rocks are the most useful criteria for the spot determination of tops. The dragfold evidence must be used with caution; use of inadequately exposed folds may yield apparently anomalous results, and in some places the axes of the folds plunge at angles greater than 90° so that an anticline may have the appearance of a steeply plunging syncline. Determination of the stratigraphic succession has thus required much detailed mapping and continual reexamination of concepts.

No "type section" exists in which the succession and thickness can be verified. The stratigraphic column shown in table 2 has been established by piecing together segments of information from separated areas in which the structure can be unraveled with a reasonable degree of assurance. This determination of a sound stratigraphy has been one of the most exacting aspects of the geologic study and, if correct, the most important contribution. A measure of the importance of the stratigraphic analysis may be obtained by comparison of the succession here presented with that in older reports, published and unpublished. Thus, in the only major published report dealing with the Iron River area, Allen (1910, p. 45–46) wrote as follows:

> The relations between the various facies of the Michigamme formation [at that time, the entire stratigraphic section within the Iron River-Crystal Falls basin was considered part of the Michigamme formation] are those of gradation and interbedding. Any single type of the rock may grade by mineralogical and textural variations into any other type. The variations take place in the direction of bedding and across it with the result that, in general, the entire formation is made up of dovetailed lenses of various dimensions and compositions with indefinite gradational borders between them.
>
> In attempting to work out the structure in detail of the group one is met with the insuperable difficulty of identifying horizons in the slates. Rocks of identical character are repeated at different stratigraphic horizons and the same stratigraphic horizon may exhibit, even in a small area, facies which are of very different composition and texture.

In general, the present study has indicated that stratigraphic units are traceable over most of the district and that a considerable part of the stratigraphic complexity noted by previous workers is a consequence of structural complexity far greater than was comprehended. The Paint River outcrop area in the SE¼ sec. 20, T. 43 N., R. 32 W., is an example: the outcrops and magnetic data define a complex series of folds that involve several distinct and persistent units that aggregate not over 300 feet total thickness, yet the outcrop area is several times as wide and a series of traverses might suggest a multiplication of stratigraphic units rather than fold repetition of a simple sequence. (See pl. 2.) This interpretation, in fact, has been presented in some earlier unpublished studies made by mining company geologists. Correct determination of the stratigraphic sequence in this area, as in other parts of the district, has required simultaneous solution of both structure and stratigraphy.

GREENSTONE IN THE BRULE RIVER AREA

The belt of greenstone in the southwestern part of the district is of undetermined age. It is exposed in scattered outcrops in secs. 20, 21, and 22, T. 42 N., R. 35 W., and can be traced an additional 3 miles to the east by magnetic data.

The most extensive outcrops are in the S½ sec. 21, T. 42 N., R. 35 W. The greenstone exposed here shows agglomeratic structure and is moderately to strongly sheared. Poorly defined ellipsoidal forms are present in the outcrops near the west edge of sec. 21. The aeromagnetic survey records a strong, persistent magnetic anomaly that in sec. 21 centers approximately along the outcrop belt. In hand specimen the rock from some of the outcrops is moderately to strongly magnetic.

The greenstone is massive, fine grained, and dark gray to grayish green. It consists chiefly of pale-green hornblende, chlorite, albite, and epidote. Magnetite and fine-grained sphene are commonly present. The epidote is typically in small anhedral grains, but in some specimens it occurs as large euhedral or subhedral crystals. The rock contains abundant fine-grained green biotite in the groundmass, and therefore seems to be of slightly higher grade in this southern greenstone belt than does most other greenstone in the district.

The greenstone of the Brule River belt is not exposed within 1,000 feet of any adjacent formation. The closest control is on the southeast side of Sheridan Hill. Here, a test pit about 1,000 feet northwest of a greenstone outcrop enters a yellow slate, presumably part of the Saunders Formation. The pit is about 400 feet north of the projected position of the greenstone along the regional strike. The south margin of the greenstone mass, not shown on the map, is limited by outcrops of dolomitic slate—possibly Saunders Formation—in the southeastern part of sec. 30, T. 41 N., R. 15 E. (Wisconsin), or possibly by the now obliterated test pits that are reported to have cut dolomite in the SE¼SW¼ sec. 26, T. 42 N., R. 35 W. (Allen, 1910).

The structural trend revealed by the magnetic anomaly is concordant with the inferred structural trend of the Saunders Formation that bounds the greenstone on the north. This trend, about N. 80° W., is also shown by agglomerate layers in some of the outcrops.

The age of the greenstone is not known.

SAUNDERS FORMATION

The Saunders Formation, as defined by Allen (1910, p. 36) consists of "cherty dolomite * * * massive white and pink dolomite, quartzose dolomite, impure carbonate slates, quartzites, and talcose slates." Leith, Lund, and Leith (1935) correlated the Saunders with the lower Huronian Kona, Randville, and Bad River Dolomites of other districts in the Lake Superior region. This correlation is accepted by the present authors.

Dolomite is exposed in only two outcrop areas, both of which are in Wisconsin, south of the Brule River; however, outcrops of silica rock that is believed to be silicified dolomite are more numerous. On the assumption that the silica rock does represent a surface silicification of dolomite, a belt of Saunders Formation has been delineated in the southern and southwestern part of the map area. This belt trends west-northwest for a distance of about 12 miles, from sec. 28, T. 41 N., R. 16 E. (Wisconsin), to secs. 13 and 24, T. 42 N., R. 36 W. (Michigan). The outcrops in sec. 28, at the east end of this belt, are composed of massive silica rock that forms a rugged bluff about a quarter of a mile in length. Similar silica rock forms extensive outcrops in the Sheridan Hill area near the west end of the belt. The two outcrop areas of dolomite lie between the two outcrop areas of silica rock, in secs. 19 and 30, T. 41 N., R. 16 E., and sec. 25, T. 41 N., R. 15 E. The width of the belt that includes the outcrop areas is about half a mile.

Allen (1910) reported test pits in dolomite in the SW¼ sec. 26, T. 42 N., R. 35 W. The land is now a pasture and no trace of the pits remains. The analysis given of the dolomitic rock suggests either dolomitic slate or possibly carbonatized greenstone. Allen classed this rock as Saunders Formation. Similarly, a green slate interbedded with thin dolomitic layers is found in outcrop on the west side of the Brule River, about a mile west of the test pit area; this slate was also included in the Saunders. The slate outcrop is not within the present map area, and inasmuch as the test pits are no longer in existence, this area of possible Saunders Formation is not shown.

DESCRIPTION

As stated, dolomite is found in only two outcrops within this area. The principal outcrop area of dolomite is in secs. 19 and 30, T. 41 N., R. 16 E., on the Wisconsin side of the Brule River, where dolomite forms a prominent bluff more than a quarter of a mile in length. The rock is massive, pink to gray, and finely crystalline. Bedding, if present, is very obscure. Parts of the rock are irregularly silicified to a white or pink cherty rock very similar in appearance to the unsilicified dolomite. In one or two places, curving planes of silicification suggest original algal structures.

Dolomite is exposed for a distance of about 300 feet in a shallow railroad cut near the W¼ cor. sec. 25, T. 41 N., R. 15 E. The rock is well bedded, and dips are nearly vertical. The strike is at a high angle to the cut so that at least 200 feet of strata is exposed. The rock consists in part of massive fine-grained dolomite, with bedding well shown on the weathered surfaces. The massive dolomite is interbedded with fissile slate and dolomitic slate. The rock, both massive and slaty, is brown or tan on weathered surfaces but is light colored (gray, pink, or green) on fresh break.

Elsewhere within the belt that is shown as Saunders Formation on the map, the actual outcrops consist of a silica rock, which is described in detail later in this report. The silica rock is massive, white to brown or red; commonly it shows an obscure breccia or conglomerate structure that is more clearly defined on weathered surfaces. The rock is considered to be a product of surface silicification that probably is related to weathering in late Precambrian time although not all the silicification of the dolomite is necessarily of this origin. Some of the silica may be of diagenetic origin, and some may have originated by silicification along fault zones.

Gray to yellow sericitic slate was found in test pits in the Sheridan Hill area (sec. 20, T. 42 N., R. 35 W.) a short distance south of outcrops of the silica rock. This slate is included within the Saunders Formation on the map.

Petrographic examination of rock from the large outcrops in secs. 19 and 30, T. 41 N., R. 16 E. (Wisconsin), shows dolomite in varying stages of silicification. Most of the rock consists of rather fine-grained crystalline dolomite, with abundant quartz as fine-grained interstitial material and as patches and veinlets (fig. 5*A*). Much of the rock apparently has been brecciated (fig. 5*B*), then recemented by secondary carbonate and quartz.

Some of this rock exposed in the railroad cut in sec. 25, T. 41 N., R. 15 E. (Wisconsin), is fairly pure dolomite, but most of it contains abundant chloritic material and is not unlike some carbonatized greenstone schists.

THICKNESS AND RELATIONS TO ADJACENT FORMATIONS

The belt of Saunders Formation is bounded on the north by Badwater Greenstone and on the south by greenstone of unknown age. At no place are contacts exposed—in fact, at no place are outcrops of the units within hundreds of feet of each other. As a result, the relationships are indeterminate, and no adequate estimate can be made for the thickness of the formation. The minimum thickness, as determined in the outcrops described previously, is 200 feet. On the basis of the inferred map pattern, the maximum thickness is about 2,500 feet, but in the complete absence of information regarding the relationship between the dolomite and the adjacent greenstones, this figure has little significance.

Though the Saunders is shown on the map as a belt of fairly uniform width, there is no assurance that it actually is. If the dolomite is an upthrown fault block, then a belt of uniform width might result. If, however, the dolomite was a topographic high on a pregreenstone surface, then the pattern might be highly irregular. And if the dolomite is exposed on a general anticlinal structure flanked by unconformably overlying greenstone—a distinct possibility—then the map pattern is likely to be a series of irregular elongate ovals.

BARAGA GROUP

The Baraga Group (James, 1958) comprises four formations in this area, which are from oldest to youngest: the Hemlock Formation, the Amasa Formation, the Michigamme Slate, and the Badwater Greenstone. The Hemlock and Badwater are composed principally of greenstone (metabasalt) that locally attains thicknesses measurable in miles. The Michigamme is composed largely of graywacke and slate, or their more highly metamorphosed equivalents.

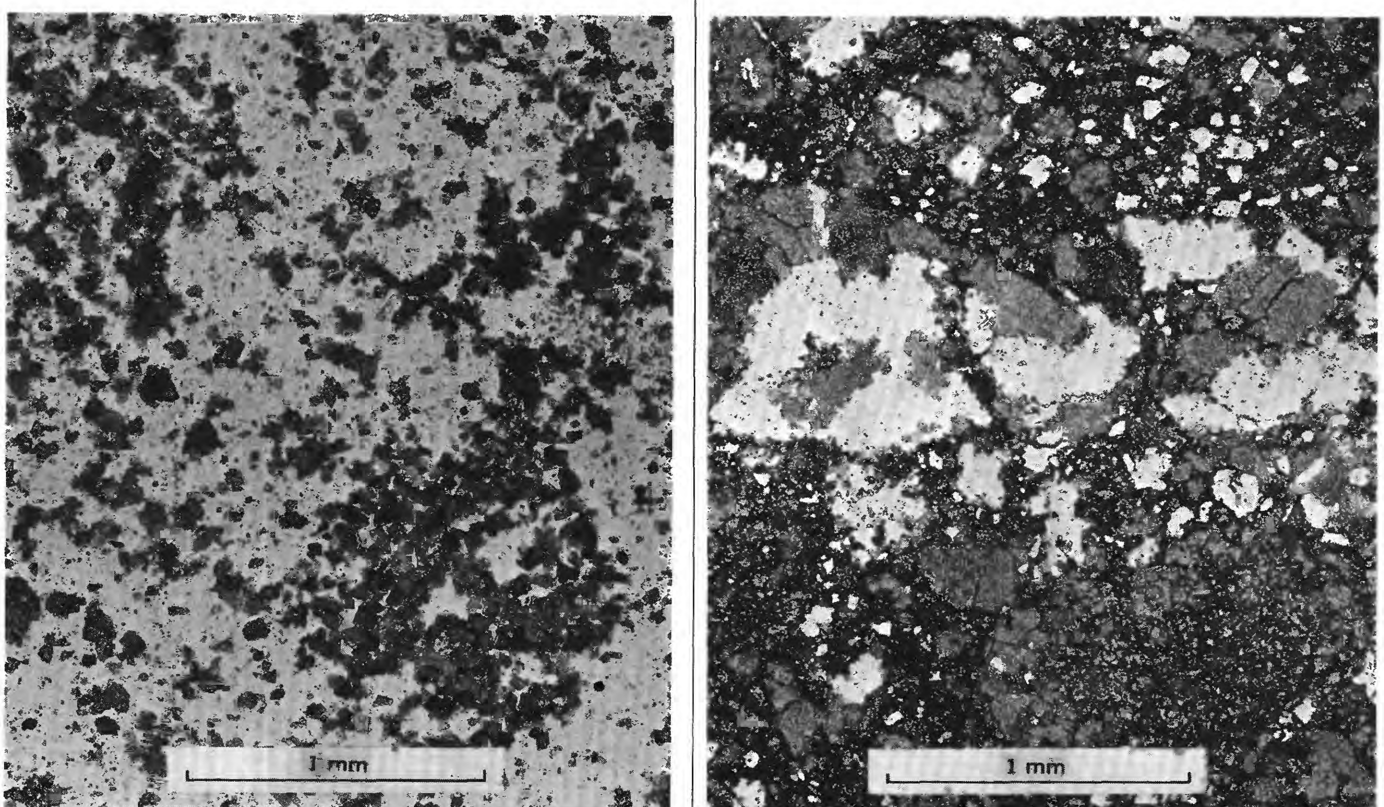
HEMLOCK FORMATION

The Hemlock Formation is present only in the northeastern part of the district, where it consists chiefly of greenstone and some interbedded ferruginous strata (Bird Iron-Bearing Member). The rocks within the district represent only the upper part of the formation; the base lies several miles to the east. The greenstone was well described by Clements (Clements and Smyth, 1899, p. 73–145), and that from adjoining areas to the northeast and east was described in more recent reports by Gair and Wier (1956) and by Bayley (1959).

GREENSTONE IN THE HEMLOCK FORMATION

Most of the Hemlock Formation consists of greenstone, which is well exposed in parts of secs. 13, 24, and 25, T. 43 N., R. 32 W. The rock is a massive dense gray to greenish-gray metabasalt, much of which was originally slightly porphyritic. Much of the exposed rock is structureless, but ellipsoidal structures are present locally, as in the SE¼SW¼ sec. 13, and agglomerate is fairly common. Some of the greenstone is vesicular, in places highly so, but this feature ordinarily is not sufficiently evident or well-enough exposed to permit separation of individual flows. In general, the greenstone of the Hemlock Formation is little if any different lithologically from the rock that makes up the younger Badwater Greenstone.

The greenstone is composed of four essential minerals: albite, chlorite, epidote, and pale-green hornblende. Of lesser importance, but abundant in some rocks, are quartz, greenish-brown biotite, carbonate, and stilpnomelane. Magnetite and leucoxene are accessories. A typical thin section consists of ragged plates of twinned albite (about An_5), as much as 2 millimeters in length, in a fine-grained matrix of chlorite, albite, and acicular pale-green hornblende, through which are scattered anhedral to subhedral epidote and small euhedral magnetite crystals. The proportions of these minerals vary greatly from one slide to another; some thin sections are composed mostly of chlorite and epidote.



A *B*

FIGURE 5.—Silicified dolomite from the Saunders Formation. SE¼SW¼ sec. 19, T. 41 N., R. 16 E. (Wisconsin). Ordinary light. *A*. Rhombs of dolomite in matrix of fine-grained cherty quartz. Specimen HJ–61–48. *B*. Brecciated dolomite, partly recemented by cherty quartz (clear). Specimen HJ–62–48.

Carbonate occurs as coarse-grained irregular patches in many of the rocks, and quartz as small blebs and veinlets is common. The vesicle fillings differ from the body of the containing rock chiefly in proportion and texture of the minerals. Some vesicles are filled with pale-green chlorite (showing anomalous interference colors) and are rimmed with euhedral to subhedral epidote; others contain quartz and carbonate as well.

Specimens from the exposures in sec. 36, T. 43 N., R. 32 W., north of State Highway M69, show features of mineralogy and texture not seen in rocks from other parts of the formation. The original texture ranges from medium-grained diabasic to fine-grained basaltic. The rocks contain a considerable amount, perhaps 5 percent, of a greenish-brown biotite that occurs as tiny flakes in the chlorite. Epidote and hornblende are absent, but coarse-grained patchy carbonate is abundant. In one specimen, golden-brown stilpnomelane is a major constituent; it occurs as small needles and plates which are dispersed throughout the groundmass and cut the plagioclase phenocrysts.

Most of the exposed greenstone is nonmagnetic; locally, however, it is strongly magnetic and gives rise to strong but discontinuous magnetic anomalies.

BIRD IRON-BEARING MEMBER

A steeply dipping or vertical bed of ferruginous sedimentary rock occurs about 1,200–1,400 feet below the top of the Hemlock Formation. This bed, which attains a maximum thickness of about 200 feet, has been trenched and drilled at several places, most extensively at the Bird exploration in the SW¼SE¼ sec. 13, T. 43 N., R. 32 W. Discontinuous segments of this iron-bearing member can be traced by magnetic methods southward from the Bird exploration to SW¼ sec. 25, T. 43 N., R. 32 W., where the unit apparently pinches out within greenstone.

The rock on the dumps of the old test pits at the Bird exploration and elsewhere consists in part of chert interbedded with magnetite and hard blue hematite and in part of ferruginous slate and quartzite. The iron-formation is characteristically oolitic, with rounded granules of finely specular hematite in a recrystallized chert matrix (fig. 6*A*). In some of this rock the boundaries of the granules are indistinct; chert of the matrix merges with that interstitial to disseminated specularite, and magnetite occurs sporadically as euhedral crystals, many of which lie athwart original granule boundaries. At least locally the bed contains intraformational breccia that consists of fragments of oolitic rock in a dense blue hematite matrix.

The oolitic rock grades into ferruginous slate and quartzite by increase in number of clastic grains, many of which form cores to hematite granules. The clastic rocks commonly are rich in magnetite, which occurs as scattered crystals of postdepositional origin (fig. 6*B*, *C*). The relative proportions of chemically precipitated iron-formation and clastic material are not known; probably they are highly variable.

THICKNESS AND RELATIONS TO ADJACENT FORMATIONS

The base of the Hemlock Formation is not within the Iron River-Crystal Falls district. The upper contact is not exposed and cannot be located closer than within a few hundred feet in most places, but it is intersected by accessible workings at the Warner mine, about 8 miles northwest of the map area. The contact between greenstone and the overlying ferruginous strata there is conformable, with some probable interbedding.

In the Kiernan quadrangle, which adjoins the Iron River-Crystal Falls district on the northeast, the Hemlock Formation is underlain, probably conformably, by the Goodrich Quartzite (Gair and Wier, 1956). The aggregate thickness of the Hemlock, including those parts east of the district and excluding intrusive sills, is about 12,000 feet in a cross section extending through the northeast corner of the map area. The maximum thickness within the area is about 6,000 feet (south of State Highway M69).

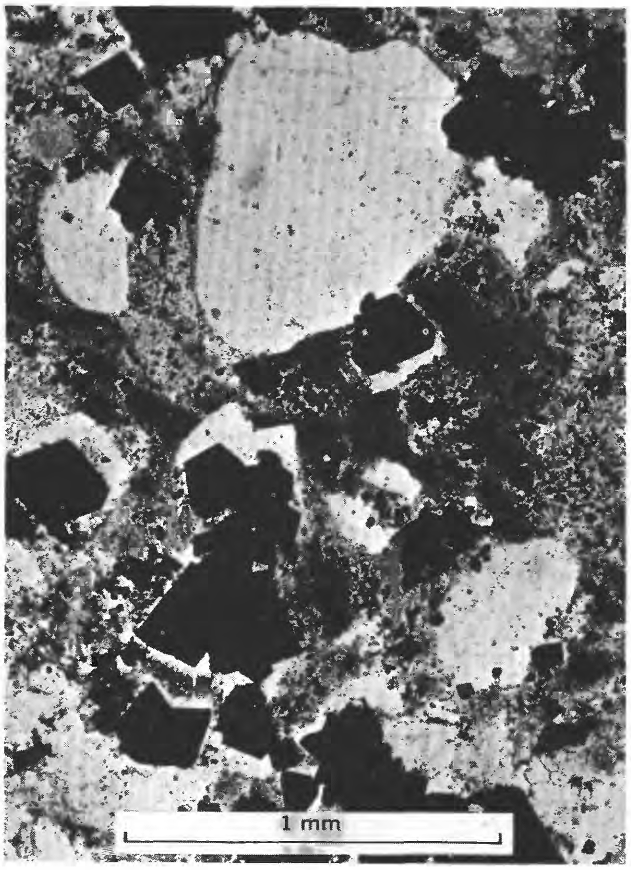
AMASA FORMATION

The Hemlock Formation is overlain, probably conformably, by about 1,800 feet of ferruginous strata of sedimentary origin that constitute the Amasa Formation. The Amasa, which consists of bedded cherty rocks and ferruginous slate, forms a southward-trending belt several miles long in the extreme northeastern part of the district. Iron ore has been mined from the formation at the Hollister, McDonald, Armenia, Lee Peck, Cayia, and Hope mines. Most of this mining, as well as other exploration, however, was done 50–75 years ago, and reliable data are scarce. The Cayia mine operated briefly in recent years (1952–53), and the mine workings were mapped during this period of activity, but the workings entered only a small part of the ferruginous section.

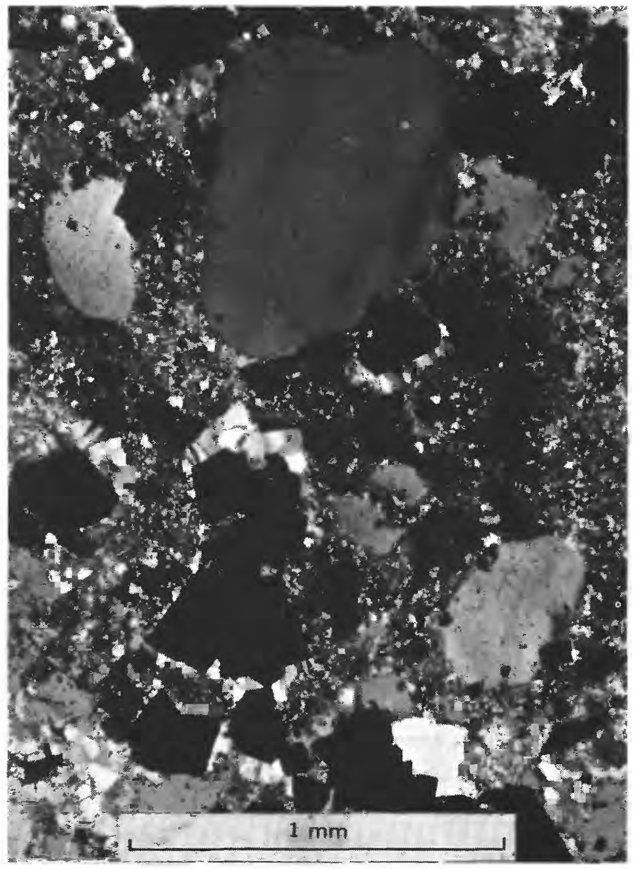
The Fence River Formation (Gair and Wier, 1956) occupies a stratigraphic position between the Hemlock and Michigamme Formations similar to that of the strata described here. Future work probably will show that the two units are equivalent.

DESCRIPTION

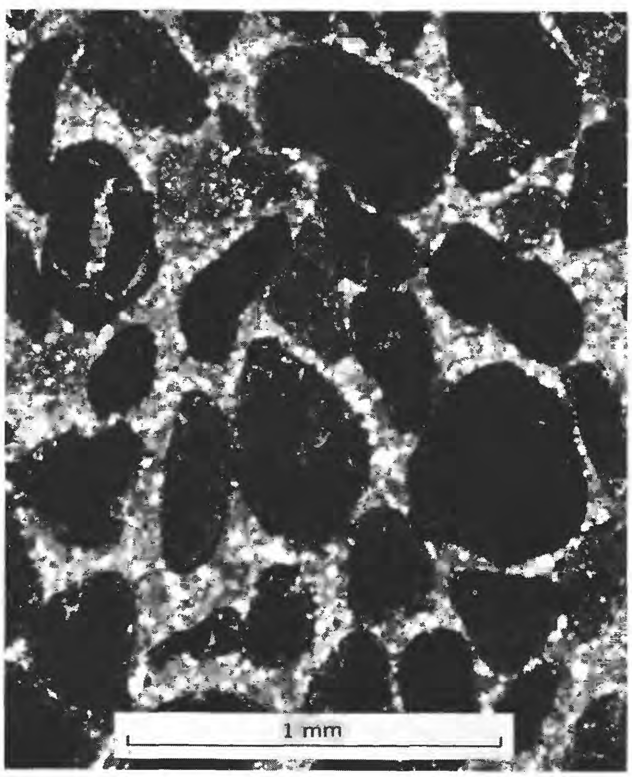
Very little is known about the lithologic characteristics of the Amasa Formation in this area. The rock is exposed in a small outcrop near the center of the SE¼ sec. 14, at the edges of the Armenia mine cave in



B



C



A

FIGURE 6.—Bird Iron-Bearing Member of the Hemlock Formation. *A*. Finely specular hematite oolites in recrystallized chert matrix. Specimen HJ–43–49. Nicols partly crossed. *B* and *C*. Euhedral magnetite crystals in quartzite; some cut boundaries of clastic grains and probably are of diagenetic origin. Matrix is recrystallized chert, sprinkled with hematite and magnetite, locally a few shreds of sericite. Note quartz in pressure shadows of magnetite crystals. Specimen KW–110–54. *B*. Ordinary light. *C*. Crossed nicols. Both specimens from test pit in SW¼ sec. 13, T. 43 N., R. 32 W.

the SE¼ sec. 23, and in a few small outcrops in the SW¼NE¼ and SE¼NW¼ sec. 26, all in T. 43 N., R. 32 W., and it has been observed underground at the Cayia mine. Dozens of old test pits are present in the area; however, the pit walls are slumped, and the dump material is a rather unreliable source of information. Records are available for many drill holes, but little or no core could be located for examination, and the lithologic descriptions in the records are inadequate.

In general, the unit consists of ferruginous slate with interbedded cherty iron-formation at (probably) several horizons. The iron-formation can be seen in the sec. 14 outcrop, at the Armenia pit, and in the most westerly exposure in the SW¼NE¼ sec. 26. The ferruginous slate is exposed in the more easterly outcrops in the SW¼NE¼ sec. 26 and is the material on the dumps of many old test pits.

The exposed iron-formation is a thin-bedded rock composed of alternating layers of gray chert and reddish to bluish hematite or yellow-brown goethite. The layers range from a fraction of an inch to an inch or more in thickness, and most layers show fine lamination on polished surfaces. The exposed rock is nonmagnetic. The brown or yellow oxide probably is the product of deep surface alteration of some preexisting material, possibly siderite; the blue hematite is either a primary constituent or secondary after magnetite. In thin section, the chert is seen to be composed of very fine grained clear crystalline quartz with vermicular to polygonal outlines. The diameter of typical grains is about 0.02 mm. The hematitic iron-formation contains hematite as tiny blood-red plates; in the cherty layers these plates are disseminated and either occur at grain boundaries of the quartz or cut the quartz grains. In "limonitic" iron-formation, brownish-yellow goethite occurs as dense layers and as irregular clumps in the chert. Some thin sections contain a few percent of green sericite as disseminated shreds, and one slide studied contains several percent of colorless apatite.

The ferruginous slate, where least altered, consists of angular silt-sized clastic quartz (0.1 mm or less in diameter) and euhedral magnetite crystals of 0.1–1 mm diameter liberally scattered throughout a fine-grained matrix of pale-green chlorite, sericite, and quartz. Most of the material seen at the surface is the oxidized equivalent of this rock; it is now a red or brownish-red slate containing scattered crystals of martite.

THICKNESS AND RELATIONS TO ADJACENT FORMATIONS

The contact between the Hemlock Formation and the Amasa Formation is not exposed. It is assumed to be conformable on the basis of observation at the Warner mine, several miles northwest of this area.

The upper contact of the Amasa Formation has been observed in workings of the recently abandoned Cayia mine. The contact between iron-formation and the overlying gray slate and graywacke is conformable without interbedding. Northwest along the strike of this contact, however, Leith, Lund, and Leith (1935, p. 13) reported that the contact is unconformable: "The clearest evidence of unconformity has been found in the Hemlock and Michigan mines * * *, where a truncated fold * * * is blanketed by a coarse conglomerate at the base of the upper group. The presence of this conglomerate has now been demonstrated by intermittent exploration along a belt nearly 10 miles in extent." Conglomerate, presumably from this stratigraphic position, can be found on the dumps of these now-abandoned mines, and although drill core from holes that cross the contact at the Warner mine (within the 10-mile belt) does not show conglomerate, the existence of a stratigraphic break at this horizon seems incontrovertible. The inferred pinchout of the ferruginous strata in secs. 1 and 2, T. 42 N., R. 32 W., presumably is due to pre-Michigamme erosion; in any case, these strata do not appear to be present along the strike extension to the southeast (Bayley, 1959).

The maximum thickness of the Amasa Formation in this district is about 1,800 feet.

MICHIGAMME SLATE

The Michigamme Slate is present only in the eastern and northernmost parts of the district, where it is exposed along the course of the Paint River. These areas of occurrence are the margins of much larger tracts that are areally continuous with the Michigamme Lake area from which the formation derives its name. The entire thickness of the formation presumably is present in the northeastern part of the district, east of Crystal Falls, but this is an area without bedrock exposure. The descriptions of the unit are based principally upon observations along the lower Paint River in the vicinity of Little Bull Rapids and Horserace Rapids, upon observations in the mapped quadrangles immediately east of the district, and upon drill-hole data.

GENERAL ASPECTS

Graywacke and slate, probably in about equal proportions, make up all except the uppermost part of the formation. In the east-central part of the district, at the western end of the Peavy metamorphic node (James, 1955), these rocks are represented by more highly metamorphosed equivalents, chiefly granulite and schist that in part is garnetiferous and staurolitic. The approximate positions of the isograds related to this metamorphic high are shown in figure 7.

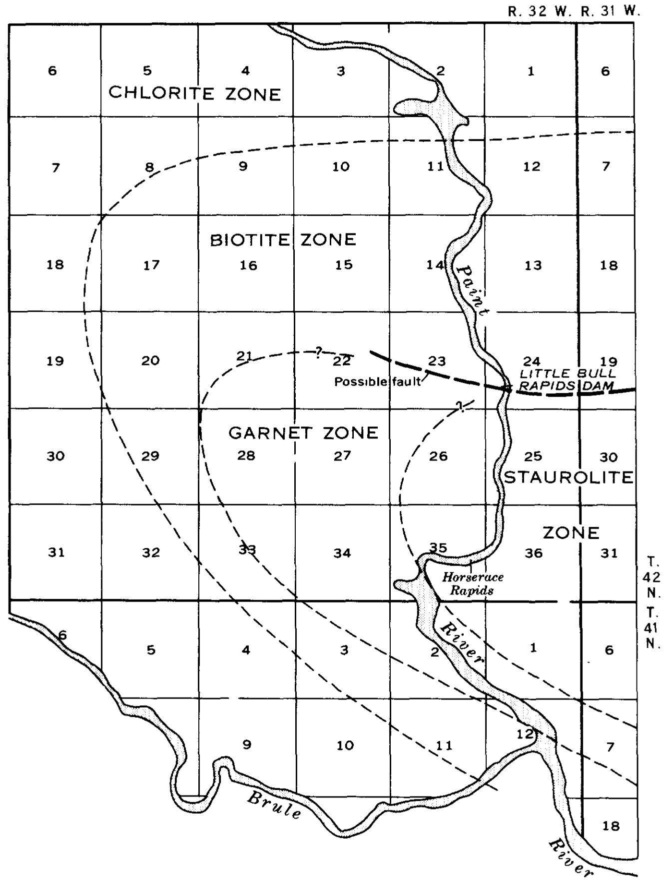


FIGURE 7.—Approximate positions of metamorphic zones in the southeastern part of the Iron River–Crystal Falls district.

The mineralogic composition and the appearance of stratigraphically equivalent rocks vary, depending upon the degree of metamorphism, but a few characteristics hold throughout. The rocks are gray and, in general, evenly bedded. The layers of graywacke intercalated with the slate or schist range in thickness from a fraction of an inch to 20 feet, with a characteristic range of 6 inches to 3 feet. Graded bedding is a common feature; in some places, as at Little Bull Rapids, in sec. 24, T. 42 N., R. 32 W., the rocks range from fine-grained graywacke to slate within layers less than 3 inches thick; in other places, as in secs. 34 and 35, T. 42 N., R. 32 W., the range is from coarse to fine graywacke in layers as much as 18 inches thick. The lower contacts of many coarser grained graded beds have a scalloped form in cross section. Calcareous concretions are characteristic of some beds. Most concretions are 6 inches or less in diameter. Their form is dependent upon the structure of the enclosing rock: (1) in massive layers without cleavage the concretions are stout ellipsoids, with the short axis normal to the bedding direction, (2) in cleaved rock they are discs that lie in the plane of cleavage, with the short axis normal to the cleavage direction, (3) in rocks showing strong linear structure they are drawn out into pencils or elongate ellipsoids in which the long axis, oriented parallel to the linear structure, may be 10–20 times the length of the long axes of the other two forms. The concretions occur within massive unlaminated layers that range in character from coarse graywacke to slate (or schist). The clastic texture of the rock extends without change through a concretion, which actually is defined only by difference in matrix material. In the lower zones of metamorphism (chlorite and biotite), this matrix is a calcitic or dolomitic carbonate; in the intermediate and higher zones, it is feldspathic.

Most of the Michigamme Slate is noncherty and noncarbonaceous. It contains no conglomerate. Some rock of possible tuffaceous origin is present in exposures near the center of sec. 14, T. 42 N., R. 32 W.; however, in general, volcanic material is absent except in the uppermost part of the formation.

UPPERMOST PART OF THE FORMATION

Very little is known of the uppermost part of the Michigamme within the district. Along the north margin, flanking the Paint River belt of Badwater Greenstone, the rock appears to be similar to that typical of the formation as a whole (slate and graywacke), but the rock is exposed only in secs. 5 and 11, T. 43 N., R. 33 W. The uppermost part of the formation is exposed along the east side of Paint River Pond a short distance beyond the southeastern limit of the map area; in that area it consists chiefly of dark thin-bedded phyllite or slate, locally graphitic and cherty, that is separated from the typical Michigamme graywacke and slate by about 50 feet of greenstone. Though not present in the Paint River Pond section, a thin layer of strongly magnetic iron-formation occurs near the top of the Michigamme Slate a few miles farther east, at the Wausau exploration in sec. 17, T. 41 N., R. 31 W. The iron-rich bed is less than 50 feet in maximum thickness; it consists principally of thin-bedded magnetite and chert and is associated with garnetiferous phyllite. This iron-rich horizon is not known for certain to occur in the Iron River–Crystal Falls district, but the presence of a discontinuous magnetic anomaly at the proper stratigraphic position in secs. 3 and 11, T. 41 N., R. 32 W., suggests that similar magnetic iron-formation is locally the bedrock in that area.

Discontinuous beds of iron-formation are characteristic of the uppermost part of the Michigamme in other parts of the region—in southern Dickinson County and in the Gibbs City area north of Iron River, for example. In the SE¼ sec. 21, T. 44 N., R. 35 W., a little more than 2 miles north of the north margin of the area of this report, old test pits have been sunk in graphitic slate and iron-formation at what is called the Morrison Creek exploration. As shown by an outcrop map in Monograph 52 (Van Hise and Leith, 1911, pl. 24), the bedrock at this locality is within a southwestward projection of the "Paint slates" (Michigamme Slate of this report) and would be in the uppermost part of the formation. Fragments of coaly material on the dump of one of these test pits led to bulldozer excavation in 1954 that exposed small lenses of anthracitic coal within black graphitic shale and argillite (Tyler and others, 1957). Analyses of the shale (Tyler and others, 1957, p. 1298; analyst, Wm. Pasich) are as follows:

	Sample A	*Sample B*
SiO_2	59.06	55.58
Al_2O_3	9.78	9.64
FeO	1.58	4.32
CaO	Trace	---------
MgO	1.04	---------
TiO_2	.56	.68
P_2O_5	.007	---------
SO_3	2.25	.12
C	22.87	19.28
N	1.00	---------

Proximate analysis of the coal (p. 1298; analysis by Charles Potter) is as follows:

Volatile matter	3.80
Fixed carbon	79.90
Ash	16.30
Ash fusion temperature	2,850°F
Sp gr	2.03
Ignition temperature	755°F
Btu	11,480

The largest lens of coal exposed was 5 feet long and 3 feet thick, and it was concordant with, and at one contact transitional into, the enclosing slate.

LOWER AND MIDDLE PARTS OF THE FORMATION

The lower and middle parts of the formation, and, at least in some areas, the upper part as well, consist of interbedded graywacke and slate or their more highly metamorphosed equivalents. The characteristics of these rocks are described in the following paragraphs under the headings of the metamorphic zones: chlorite zone, biotite zone, garnet zone, and staurolite zone.

Chlorite zone

Michigamme Slate within the zone of lowest metamorphic grade is exposed in scarce outcrops along the north margin of the district and in the now-abandoned Cayia mine. The rock exposed in sec. 5, T. 43 N., R. 33 W., is fine- to medium-grained graywacke in which clastic grains (quartz much dominant over feldspar) are in a fine-grained matrix of chlorite and sericite. The original outlines of clastic grains have been in part destroyed by marginal reactions with matrix chlorite and sericite (fig. 8). Drill holes at the site of the Cayia mine shaft cut similar rock interbedded with and gradational into slate; dozens of layers from a fraction of an inch to 2 inches in thickness show grain-size gradation. The upper, more argillaceous parts of these graded beds are cut by slip-cleavage planes that steepen and die out toward the lower parts (fig. 9). This cleavage is not due primarily to mineral orientation but rather to slipping and rotation of thin discrete screens of rock (light strips in photomicrograph) in which a preexisting bedding-plane cleavage, marked by scattered oriented flakes of mica, has been progressively rotated into its present position, which is at right angles to the slip cleavage or nearly so. The microfolding and microfaulting of the bedding-plane cleavage has, however, resulted in drag along the slip-cleavage direction so that this plane is also marked by some preferred orientation of micaceous minerals (dark strips in photomicrograph). White (1949) showed that secondary cleavage of this type grades into true schistosity in New England; probably a similar relationship is present in northern Michigan.

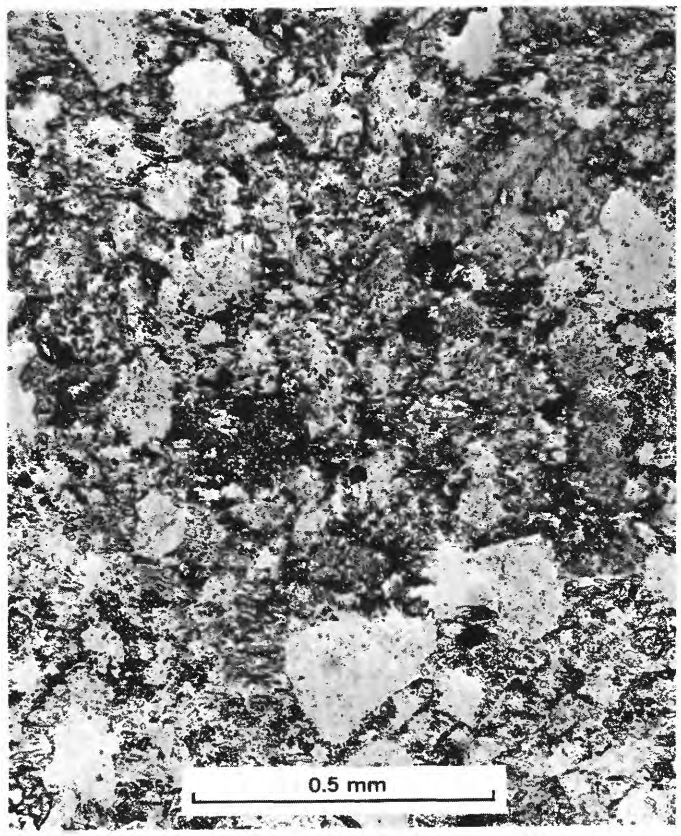


FIGURE 8.—Graywacke from the Michigamme Slate, chlorite zone. Clastic grains show marginal replacement by chlorite and sericite, which are the dominant minerals of the matrix. Ordinary light. Specimen HJ–107–48. From exposure on Net River, in NW¼ sec. 15, T. 45 N., R. 34 W., north of report area.

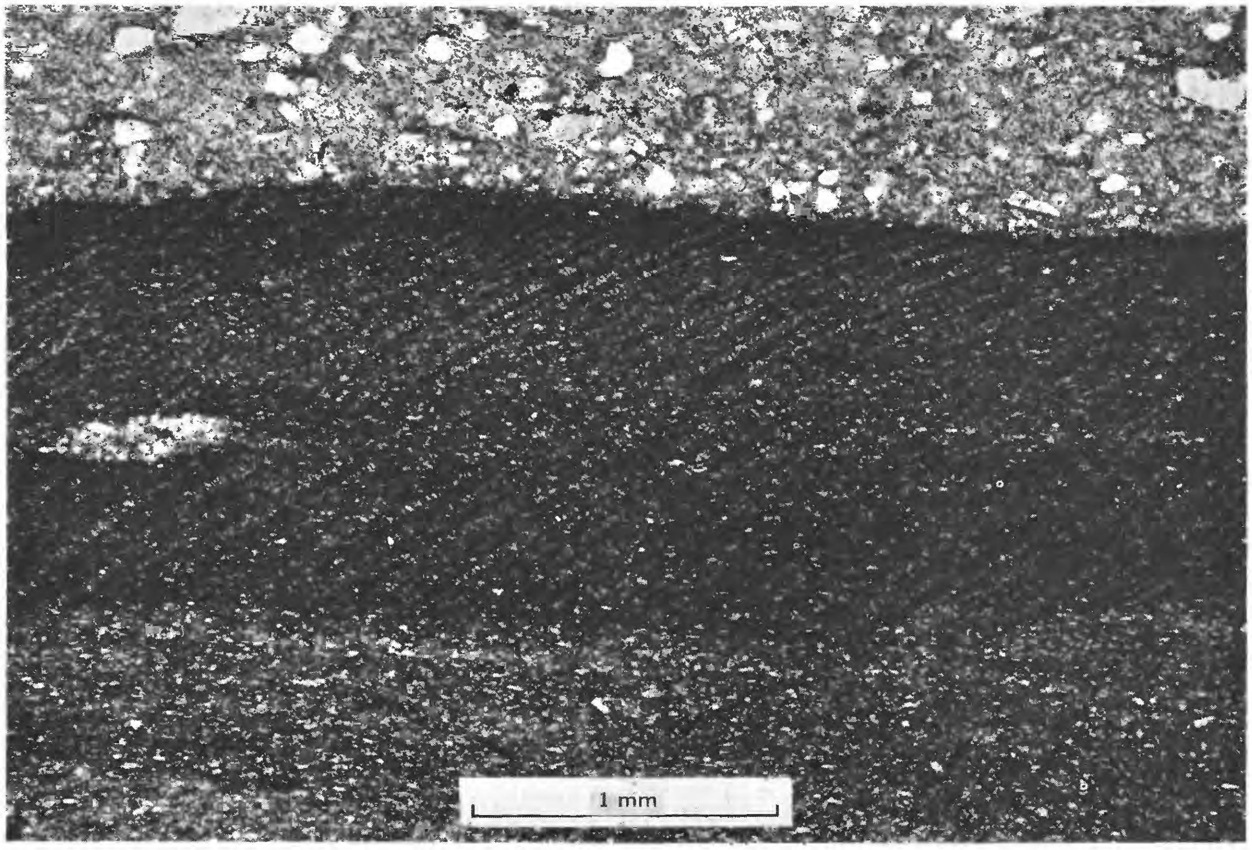


FIGURE 9.—Michigamme Slate, showing slip cleavage in the upper part of an imperfectly graded layer (lower three-fourths of photograph); upper part of photograph shows base of overlying layer of graywacke. Cleavage planes (dark stripes) flatten toward contact with graywacke because of greater slippage and rotation in the more argillaceous top of the graded bed. Ordinary light. Specimen HJ–20–51, from drill hole 1–C, near Cayia shaft in sec. 26, T. 43 N., R. 32 W.

Some of the slate found in drill holes and in the workings of the Cayia mine contains scattered rhombs of calcite as much as a millimeter in diameter. The mineral probably is of diagenetic origin; it is definitely earlier than the deformation, as the crystals have broken margins and appear to have been rotated so that the rhombohedral cleavage of the mineral is at an angle of about 45° to the cleavage in the rock.

Biotite zone

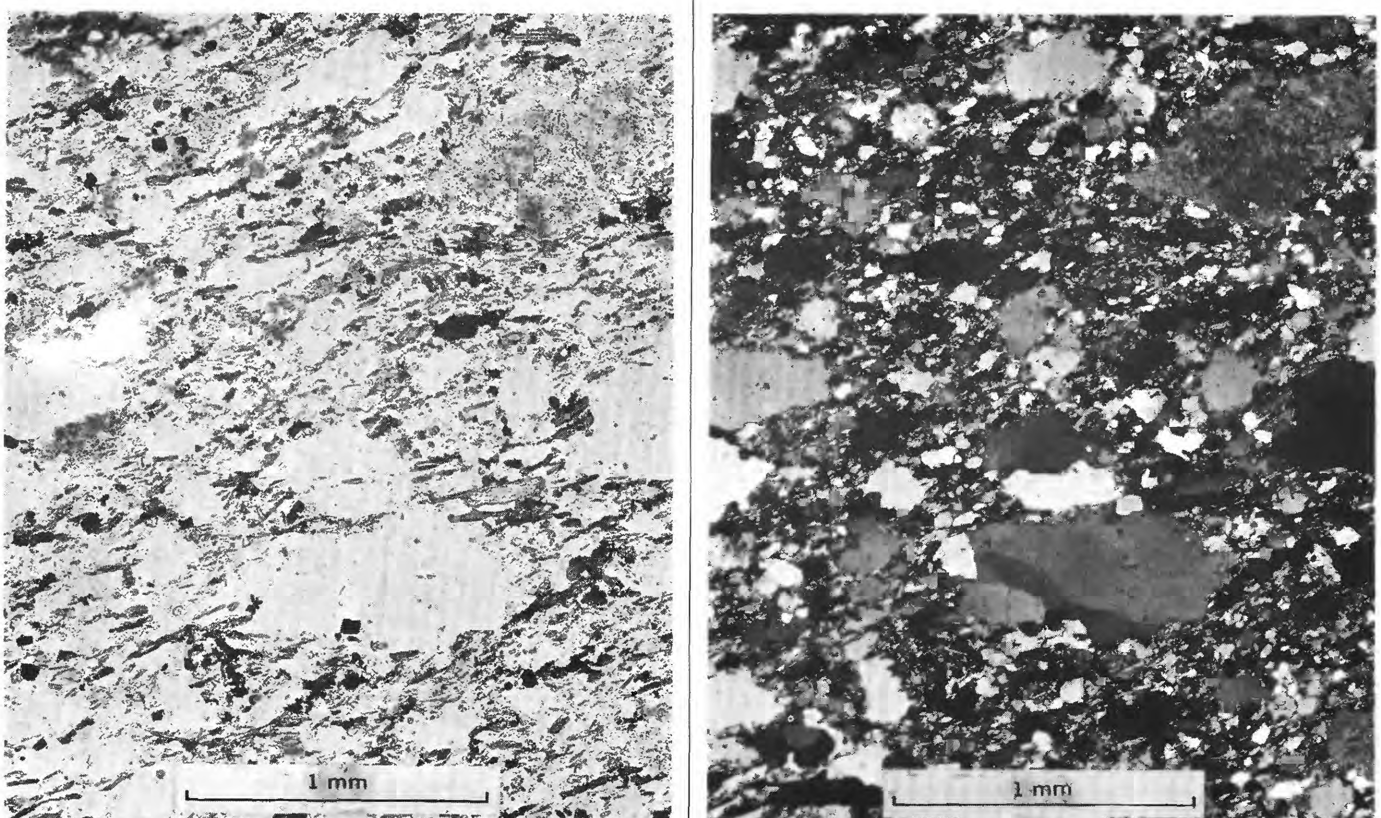
The best exposures of Michigamme Slate within the biotite zone are those near Little Bull Rapids, in sec. 24, T. 42 N., R. 32 W., but rock of similar metamorphic rank is also present in the extreme southeast corner of the area. In the Little Bull Rapids area, the rock ranges from coarse graywacke to slate and differs little in general aspect from that in the chlorite zone. The beds range in thickness from a fraction of an inch to 2 feet. Some of the thicker layers are coarse-grained graywacke, quartzitic in appearance. These layers locally are interrupted by pods of coarsely crystalline milky quartz a foot or more across. The long axis of the pods appears to be nearly vertical or to dip steeply south; it is not parallel to the regional linear structure, which in this area plunges westward at low angles. Graded bedding is visible in some layers in the riverbed exposure immediately below the dam; the gradation is from fine-grained graywacke to slate. Cleavage is fairly distinct in the more argillaceous parts of the rock; in graded beds it steepens toward the base as shown in fiure 9. It is not a slip cleavage, however; it is a true cleavage or weakly developed schistosity that is due to preferred orientations of muscovite and biotite.

Massive beds of reddish feldspathic graywacke are exposed on the west side of the river immediately below the dam. Some of the graywacke layers are well graded from a coarse-grained (almost pebbly) base to a medium-grained top. Petrographic examination shows that both potassium feldspar and sodic plagioclase are abundant as original clastic grains and as matrix material. The original grains are exceedingly irregular in outline, and the feldspars are sericitized and reddened.

In thin section the rocks of the biotite zone differ from their counterparts in the chlorite zone chiefly by their coarser grain and by the presence of biotite. The clastic grains consist of quartz and minor feldspar (both perthite and plagioclase); the matrix is biotite, sericite, and chlorite. At least some of the chlorite is secondary after biotite; in fact, in some rocks the biotite has been completely replaced by this retrograde mineral. The boundaries of the clastic grains are irregular (fig. 10), and in some localities the grains are decidedly elongate because of deformation.

A coarse ill-defined breccia of feldspathic graywacke and slate is exposed in an islandlike area on the east bank of the river 400 feet below the Little Bull Rapids dam and also in the SW¼SE¼ sec. 27, T. 42 N., R. 32 W. The breccia at both localities consists of tightly packed angular blocks and fragments, few of which are more than several inches in diameter. Cleavage orientation varies from fragment to fragment, and the deformation clearly is later than the metamorphism (fig. 11*A*). The breccia zone near the Little Bull Rapids dam marks a break, or exceedingly abrupt transition, in the degree of metamorphism (see fig. 7); the garnet zone in this area is either narrow or faulted out.

Michigamme Slate in the biotite zone is also exposed on the south side of the Peavy metamorphic node, in sec. 12, T. 41 N., R. 32 W., and in areas adjacent to the southeast. The rock in this area, particularly that in the NE¼ sec. 12, is more "metamorphic" in appearance than that in the Little Bull Rapids area; it probably lies in the upper part of the biotite zone. It is coarsely crystalline, and the argillaceous members are medium- to coarse-grained mica schist. These rocks characteristically are crinkled, the crinkles being due to deformation of the principal schistosity. In thin section the schist is seen to be composed of large flakes of biotite and muscovite (0.5 mm) in a quartz-oligoclase matrix. The micas are now bent and twisted along microfolds that trend nearly normal to the primary schistosity (fig. 11*B*). The interbedded graywacke is a granulite made up of a quartz-plagioclase mosaic in which grain size varies from one part of the rock to another, probably reflecting original sedimentary differences. Through this mosaic are scattered plates of biotite and muscovite, a sprinkling of epidote and magnetite, and some apatite and sphene.



A *B*

FIGURE 10.—Graywacke from the Michigamme Slate, biotite zone. Slightly stretched clastic grains, mostly quartz, with some feldspar (cloudy grains). Matrix is biotite, sericite, and chlorite, with scattered grains of epidote and magnetite. *A*. Ordinary light. *B*. Crossed nicols. Specimen KW–91–54. From 50 feet south of Little Bull Rapids dam, sec. 24, T. 42 N., R. 32 W.

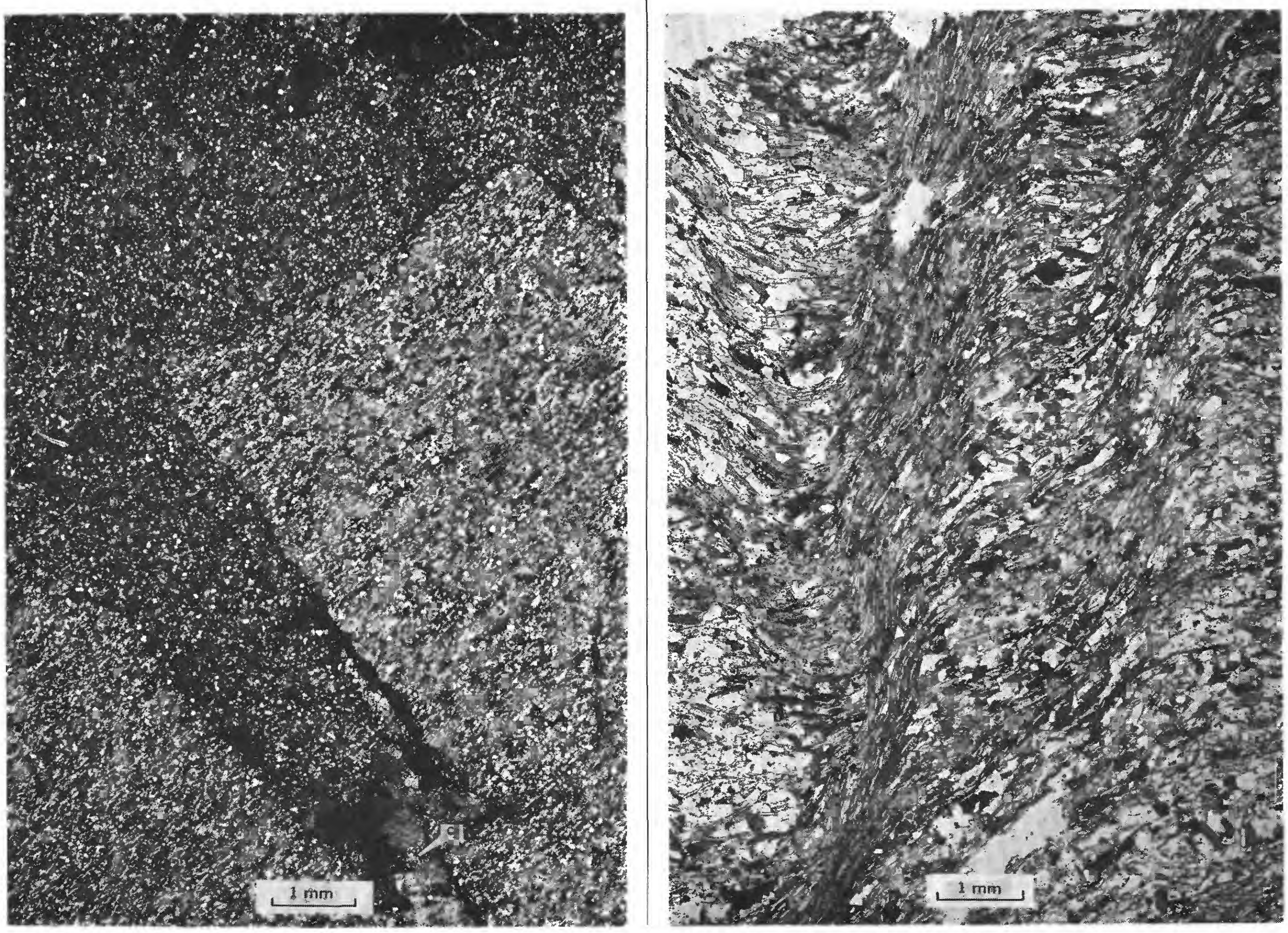
Garnet zone

Michigamme Slate in the garnet zone of metamorphism is widely exposed in secs. 27, 34, and the western part of sec. 35, T. 42 N., R. 32 W. Two features distinguish these rocks from equivalent rock in the biotite zone: the local presence of garnet, and feldspar rather than carbonate in the calcareous concretions.

Most of the rock is uniformly bedded graywacke and medium- to fine-grained mica schist. Graded bedding, best shown in the coarser graywacke layers, is visible in many exposures, and calcareous concretions are common.

In thin section the typical graywacke in this area is an interlocking mosaic of quartz with about 10 percent plagioclase, sprinkled with well-oriented flakes of mica (dominantly biotite but variable amounts of muscovite) and scattered grains of magnetite, sphene, and apatite. The outlines of original clastic grains are completely lost, but the grain size of the mosaic clearly is controlled in part by the original sedimentary texture; this control is evident in graded beds, in which the quartz-feldspar mosaic becomes progressively finer grained toward the top of the bed. A common range in mosaic grain size, in terms of mean diameter, is from about 0.3 mm at the base to 0.1 or less at the top. The plagioclase in unaltered graywacke is untwinned or rarely twinned oligoclase that is not readily distinguished from quartz, but in most specimens examined the oligoclase has been altered to albite and sericite and is stained reddish by finely disseminated hematite. In such rock the biotite is largely replaced by chlorite.

The schist associated with the graywacke is fine to



A B

FIGURE 11.—Michigamme Slate. *A*. Postmetamorphic breccia. Tightly packed fragments locally separated by a thin film of carbonate, c. Crossed nicols. Specimen HJ–134–55. SW¼SE¼ sec. 27, T. 42 N., R. 32 W. *B*. Secondary microfolds and microfaults almost at right angles to principal schistosity in crinkled schist. Ordinary light. Specimen HJ–138–55. NE¼ sec. 12, T. 41 N., R. 32 W.

(See next page for 11*C* and 11*B*.)

medium grained. Biotite is the dominant mineral, but some muscovite is usually present. Quartz and untwinned plagioclase form the interstitial material. The micas show strong preferred orientation (fig. 11*C*).

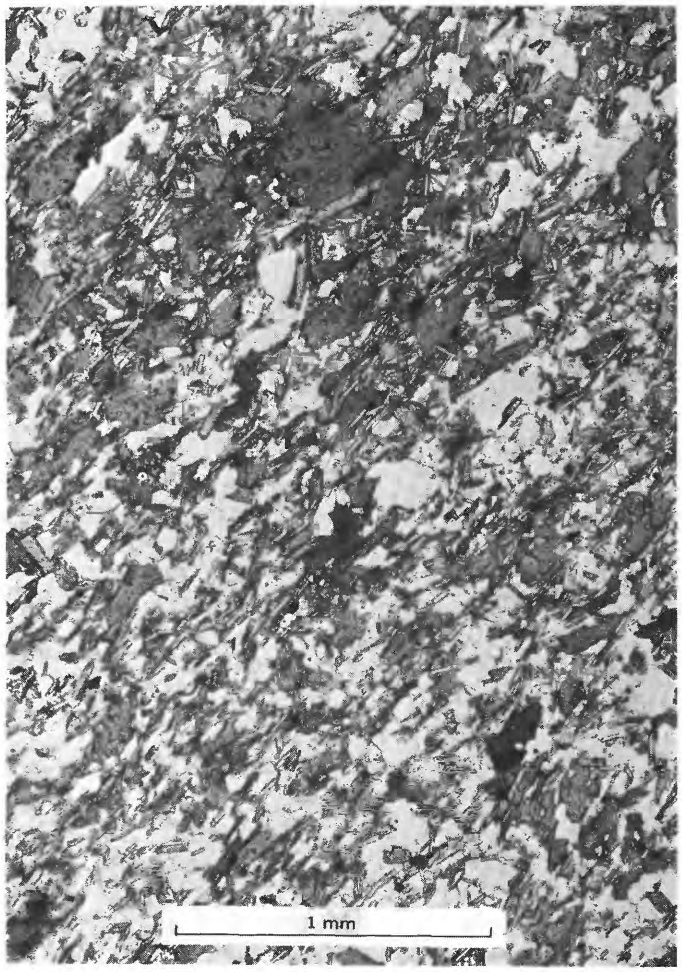
Garnet is a relatively rare mineral in both graywacke and schist. It seems to form in rocks of somewhat aberrant composition; in one specimen, for example, it is in a light-colored graywacke that contains considerable green hornblende, a mineral not present in the normal graywacke in the area.

Breccia similar to that near Little Bull Rapids occurs in the southern part of sec. 27, T. 42 N., R. 32 W. The breccia occurs as poorly defined zones in massive graywacke. It consists of tightly packed aggregate of randomly oriented small blocks and fragments. (See fig. 11*A*.)

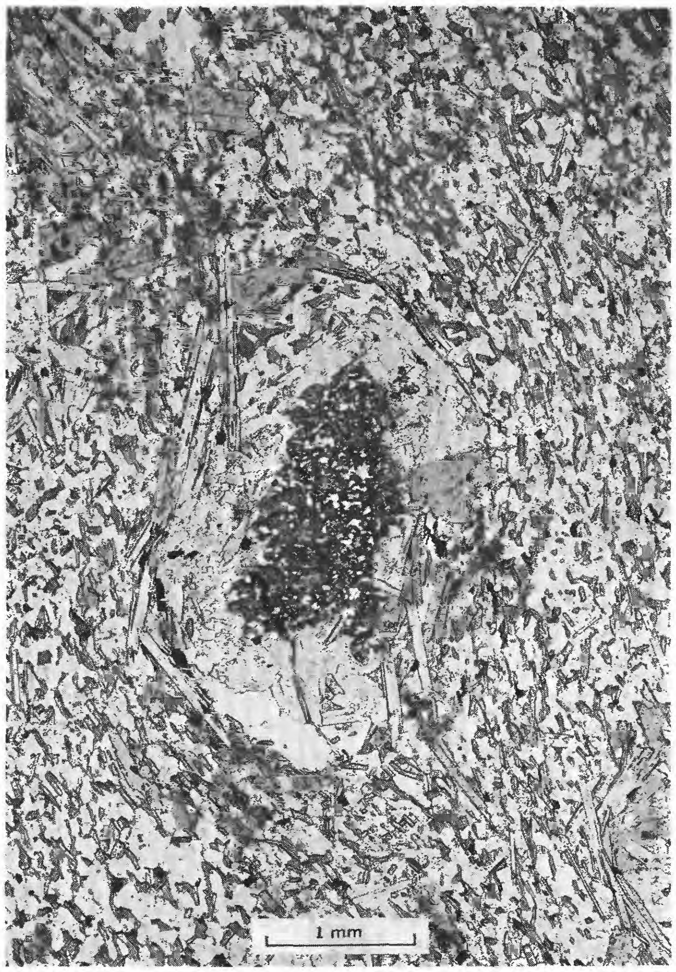
Staurolite zone

The most strongly metamorphosed rocks in the district are exposed along and in the area of Horserace Rapids on the Paint River. Along the course of the river these rocks are in tight folds and crenulations, most of which are difficult to define. The general trend of strata is northeasterly, but most observed bedding strikes northwest.

The graywacke granulite and much of the interbedded schist are similar to those of garnet rank except that the grain size of metamorphic minerals is somewhat larger and garnet is more abundant. The distinguishing feature of the zone is large crystals of staurolite in some of the schist layers. The staurolite is strongly altered to aggregates of muscovite with some quartz (fig. 11*D*). In many rocks the original presence of staurolite



C



D

FIGURE 11—Continued. *C*. Biotite-muscovite-quartz schist of the garnet zone. Well-oriented blades and plates of brown biotite and muscovite, some in parallel intergrowth in an interlocking matrix of quartz and untwinned plagioclase. Ordinary light. Specimen HJ–129–55. NE¼NE¼ sec. 34, T. 42 N., R. 32 W. *D*. Staurolite schist showing relict staurolite preserved in core of crystal altered to muscovite, quartz, and some biotite. Groundmass is biotite-muscovite-quartz-oligoclase schist. Ordinary light. Specimen HJ–127–55. SW¼NW¼ sec. 36, T. 42 N., R. 32 W.

can only be inferred from the presence of such aggregates, and in all, the original outlines of the staurolite have been lost. Both partly altered staurolite and the secondary aggregates are more resistant to weathering than the enclosing rock and are etched out as formless to rudely euhedral lumps, most of which are 1–2 cm across. The plagioclase in the rocks of the staurolite zone is oligoclase (rarely andesine), in which albite twinning and normal gradational zoning are common features.

THICKNESS AND RELATIONS TO ADJACENT FORMATIONS

Neither the base nor the top of the Michigamme Slate is exposed in the district although the basal contact has been cut by workings of the Cayia mine (sec. 26, T. 43 N., R. 32 W.). In the Commonwealth quadrangle (Michigan), immediately adjacent to the southeast, unpublished U.S. Geological Survey mapping in sec. 6, T. 41 N., R. 31 W., showed that basal graywacke and schist rest directly on amphibolite, which is believed to be part of the Hemlock Formation, or are separated from the amphibolite by a thin layer of magnetic iron-formation (Amasa(?) Formation). The upper contact, though not actually exposed in the Commonwealth quadrangle, is approached within a few feet at several localities along the Menominee River, and the contact between the normal graywacke and schist with the greenstone and phyllite of the uppermost part of the formation is exposed in the eastern part of sec. 12, T. 41 N., R. 32 W. Between the exposed base and the closely approached upper contact, outcrops in which top direction can be determined are sufficiently numerous to permit a fair estimate of thickness.

The cross-strike distance between the basal and upper contacts in the Commonwealth quadrangle is about 7,800 feet. The average dip of bedding is about 70°, and some duplication by folding doubtless is present. Appraisal of these factors reduces the 7,800 feet to about 6,000 feet of stratigraphic thickness, a figure that probably is within 10 percent of the correct value for the Michigamme Slate in the southeastern part of the district. Of this thickness, about 5,000 feet is a unit of normal graywacke and schist that constitutes the lower and middle parts of the formation; about 1,000 feet is a unit of phyllite, locally containing some iron-formation, that makes up the uppermost part of the formation.

The entire thickness of the formation presumably is present in the northeastern part of the district, but only the base of the formation has been located. If one considers the probable thickness of the Dunn Creek Slate northeast of Crystal Falls, however, the maximum thickness of Michigamme Slate in that area cannot exceed 6,000 feet and may be somewhat less.

BADWATER GREENSTONE

The sedimentary rocks of the Iron River-Crystal Falls basin are believed to be bounded almost completely by Badwater Greenstone. Closure on the west end is largely inferred, however, and the areas of actual outcrop are widely separated. For these reasons, the greenstone bordering the district proper to the north is described as the North belt, that on the south side as the South belt, and the main body to the east as the East belt. The greenstone of the East belt is continuous to the southeast with that of the Badwater Lake area of Dickinson County from which the unit derives its name. The inlying area of greenstone in sec. 19, T. 42 N., R. 32 W., and the anticlinal area of greenstone known from drilling in secs. 33 and 34, T. 43 N., R. 35 W., are described in the section, "Other occurrences of greenstone."

GENERAL ASPECTS OF THE GREENSTONE MASSES

The rocks making up the greenstone masses are somewhat varied in detail, but in general they are massive fine-grained dark-greenish-gray rocks that consist chiefly of chlorite, actinolitic hornblende, albite, clinozoisite-epidote, and carbonate. Ellipsoidal (fig. 12) and agglomeratic structures are common. In a few specimens the original minerals—mainly labradorite and augite—are partly preserved, and in most, the original texture can be seen under the microscope despite the extensive alteration. The rocks almost certainly originated as submarine flows and fragmental volcanics and are dominantly, if not entirely, of primary basaltic composition.

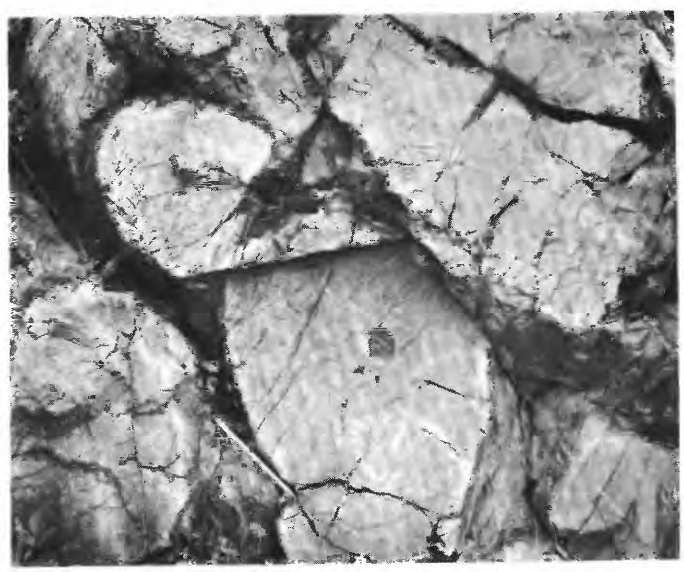


FIGURE 12.—Ellipsoidal (pillow) structure in greenstone adjacent to quarry in NE¼ sec. 20, T. 43 N., R. 32 W. Pencil in lower center gives scale.

Observations of attitude of ellipsoidal structures and bedding in the tuffs show the greenstones to be steeply dipping or vertical in most places. Except locally, the rocks are not extensively sheared, and primary structures such as vesicles are not greatly distorted. Some layers of the greenstones contain abundant magnetite and yield strong magnetic anomalies. No consistent association between specific greenstone types and magnetism is apparent: in the North belt, near Crystal Falls, a tuffaceous zone yields a large anomaly, whereas in the South belt strong anomalies can be attributed to ellipsoidal greenstone in one place and agglomeratic greenstone in another. A characteristic feature of the individual magnetic anomalies caused by greenstone is that they rarely extend for more than a few miles along the strike.

NORTH BELT

The North belt of greenstone forms a broad arc from Crystal Falls to the west edge of the map area, a distance of approximately 20 miles. The average width is about 4 miles. The belt apparently pinches out completely at the east end and probably merges with the South belt of greenstone near the west margin of the map area. The principal area of outcrop is in the vicinity of Chicagon Creek, in the northern part of T. 43 N., R. 33 W. Ellipsoidal greenstone is the most abundant exposed rock, but agglomerate is common. Massive porphyritic greenstone is exposed in scattered outcrops at the south margin of the eastern part of the North belt from the elbow that juts southward about midway between Iron River and Crystal Falls eastward to Crystal Falls.

In several drill holes north of Iron River (in secs. 1, 11, 15, and 16, T. 43 N, R. 35 W.) slate was found within the greenstone. Some of this "slate" may well be sheared greenstone or tuff, but some is referred to as graphitic, and there seems little doubt that at least a small amount of sedimentary material is interbedded within the greenstone.

Most of the North belt of greenstone is nonmagnetic, but a strong anomaly is recorded in sec. 17, T. 43 N., R. 32 W. The anomaly is caused by a sheared tuff that is interbedded with the massive or ellipsoidal greenstones in that locality. Two or three relatively weak anomalies are recorded by the aeromagnetic survey in the area northwest and north of Iron River (crests are shown on the geologic map, pl. 1). None of these could be definitely related to specific rock units, but the anomalies serve to delineate structural trends.

Petrography of the greenstone

The porphyritic greenstone, mentioned above, is a massive dark-greenish-gray rock. Specimens from the outcrops in sec. 25, T. 43 N., R. 34 W., contain plagioclase phenocrysts as much as several millimeters in length (fig. 13*A*). The phenocrysts average An_{55} in composition and are not zoned. They are extensively altered to sericite and chlorite. The phenocrysts are set in a matrix consisting of pyroxene and plagioclase and are grains typically 0.5 mm or less in maximum dimension. The groundmass plagioclase is An_{50-55}. The pyroxene is augite, with $2V_z=46°$ (44°, 46°, 47°, 48°). The matrix minerals are partly but not extensively altered to chlorite. Rock from the outcrops in sec. 20, T. 43 N., R. 33 W., is much more altered, although the plagioclase phenocrysts are about the same composition—An_{52}—and the rock is similar in texture. No augite is present; epidote is abundant as small grains and, except for a small amount of chlorite, is the only mafic mineral. The plagioclase of the groundmass is in small laths, some of which are slightly zoned.

The greenstone exposed at and in the vicinity of the quarry in sec. 20, T. 43 N., R. 32 W., near the east end of the North belt, is very fine grained. In thin section, specimens from the ellipsoidal rock show, in plane light, an intersertal texture dominated by abundant narrow laths as much as about 0.5 mm in length. The texture is not distinguishable under crossed nicols. The laths, presumably originally a calcic plagioclase, now consist of very fine grained pale-green chlorite and untwinned albite. The original matrix material has been altered largely to chlorite that contains scattered grains of carbonate and patchy, opaque leucoxene. Other specimens from the quarry area are composed chiefly of very fine grained carbonate and chlorite. Some contain undeformed vesicles that now are filled with carbonate and pale-green virtually isotropic chlorite. These materials commonly have a characteristic arrangement within the vesicle—a discontinuous outer ring of carbonate, an intermediate ring of chlorite, and a core of carbonate.

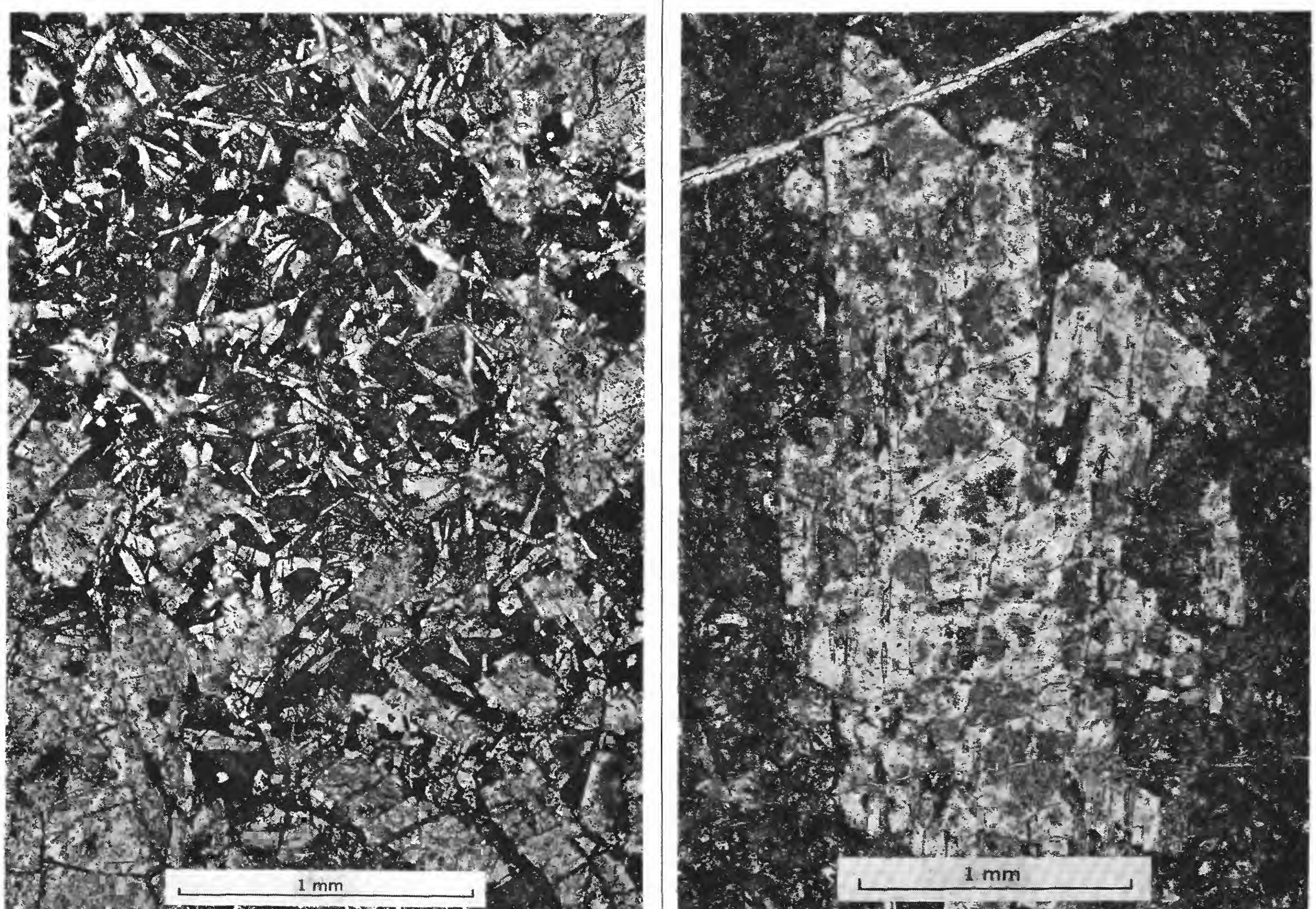
The Chicagon Creek outcrop area, about 6 miles west-northwest of Crystal Falls, contains greenstones of several structural types—ellipsoidal, agglomeratic, and massive. Most of these rocks consist principally of pale-green actinolitic hornblende ($C \wedge Z=16°–17°$; very weakly pleochroic), in small plates rarely more than 0.05 mm in length set in a matrix of untwinned albite. Clinozoisite is abundant as small grains. Very little trace of the original texture remains.

The outcrops in sec. 17, T. 43 N., R. 35 W., and adjacent areas along the Iron River valley are of massive fine- to medium-grained greenstone. In the coarser grained varieties, the original intergranular texture is clearly shown by plagioclase laths about 0.5 mm in length and by scattered plates, as much as 3 mm in diameter, of what originally was augite. The original plagioclase laths now consist of chlorite and generally untwinned albite that has a maximum refractive index about equal to or slightly less than 1.540. The original augite formed stubby phenocrysts that now consist of fibrous pale-green hornblende ($C \wedge Z = 18°$; weakly pleochroic) and pale-green nearly isotropic chlorite. In some slides the original plagioclase is entirely altered to clinozoisite, in others to chlorite. Carbonate is abundant as scattered patches and in one slide forms lathlike plates, probably as a replacement of plagioclase. Some specimens contain large grains of opaque material, originally magnetite-ilmenite but now largely altered to leucoxene. Some of the grains retain the original stripes, with leucoxene alternating with relict magnetite. The rock in the sec. 17 outcrops is cut by thin veinlets composed of quartz, tremolite, clinozoisite, and pink adularia.

Thickness

The general structural pattern of the North belt of greenstone, confirmed by the trends of aeromagnetic anomalies, is that of a broad arc concave to the south; in the eastern part, trends are slightly north of west, in the western part definitely southwest. Major divergence from the arcuate pattern is indicated only in the southward-projecting elbow that lies about halfway between Crystal Falls and Iron River.

The direction of "tops" in the greenstone, as determined from the form of ellipsoids, is consistently to the south. Dips appear to be vertical or nearly so. Observations on top directions are confined to the eastern part of the belt; elsewhere exposures are not adequate or the exposed rock does not show the required ellipsoidal structure. Assuming that top directions are to the south throughout and that there is no major structural com-



A *B*

Figure 13.—Porphyritic Badwater Greenstone. *A*. Original plagioclase (light gray), with extensive alteration to chlorite and sericite, in matrix of fine-grained partly altered augite and labradorite. Ordinary light. Specimen HJ–165–50. *B*. Pyroxene phenocryst altered to nearly isotropic chlorite. Phenocryst is virtually indistinguishable from the matrix under crossed nicols. Ordinary light. Specimen HJ–25–51. Drill hole H26, sec. 34, T. 43 N., R. 35 W.

plexity within the belt, the greenstone reaches a maximum thickness of about 15,000 feet in the area north of Iron River and gradually lessens to the east. The belt probably terminates just northeast of Crystal Falls.

SOUTH BELT

The South belt of greenstone extends for a distance of about 15 miles in an east-southeast direction along the south margin of the Iron River-Crystal Falls basin. The maximum width, 2½ miles, is at the west end. The width lessens progressively to the east, and near Pentoga, where the belt begins to leave the map area, it is less than a mile.

Outcrops of the greenstone along the South belt are not numerous but are widespread. The most extensive are in sec. 23, T. 42 N., R. 34 W., where rock is exposed in a series of outcrops three-fourths of a mile in length adjacent to the Brule River. Ellipsoidal greenstone, some of which is strongly sheared and brecciated, is the dominant rock type. Other areas of possible or actual outcrop are briefly noted (from west to east) as follows:

1. Sec. 13, T. 42 N., R. 36 W. Several small outcrops of (mostly) ellipsoidal greenstone. Rock is unsheared and contains well-formed ellipsoids that are not adequately exposed to establish top directions with certainty. The best estimate indicates that the stratigraphic top faces north.

2. Sec. 16, T. 42 N., R. 35 W. Outcrop shown on several older maps could not be located.

3. Sec. 4, T. 42 N., R. 35 W. Possible outcrop of greenstone in roadcut on north flank of hill. Exposure not adequate for determination of structural features.

4. Sec. 14, T. 42 N., R. 35 W. Small outcrop of massive agglomeratic greenstone, somewhat magnetic.

5. Sec. 24, T. 42 N., R. 35 W. Several scattered outcrops. Largest forms rib several hundred yards long; composed of fine-grained greenstone, some of which is banded; probably tuff originally. Nonmagnetic.

6. Sec. 18, T. 42 N., R. 34 W. Small outcrops, several test pits in weathered greenstone. May be intrusive; underground workings and drill holes (Wild Cat exploration) show clearly that at least one large dike is present in this area.

7. Sec. 22, T. 41 N., R. 15 E. (Wisconsin). Outcrops of massive greenstone facing Brule River.

8. Sec. 29, T. 42 N., R. 34 W. Long low ridge, mostly massive greenstone, emerging from sandy terrace. Locally, some poorly formed ellipsoidal structures, as at southeast end of outcrops. Nonmagnetic.

9. Sec. 21, T. 42 N., R. 34 W. Small knob of greenstone agglomerate. Fragments are porphyritic, vesicular, and unsheared. Rock is strongly magnetic and doubtless responsible for magnetic anomaly that has been traced for some distance both west and east of outcrop.

10. Sec. 23, T. 42 N., R. 34 W. Outcrops are largely ellipsoidal greenstone, some of which is magnetic in specimen. Magnetic anomaly traced by ground surveys west from outcrop area virtually connects with that traced east from sec. 21 agglomerate. Aeromagnetic surveys show that anomaly continues eastward to establish approximate connection with outcrops described below. Some of the rock vesicular; vesicles filled with zeolite.

11. Sec. 29, T. 42 N., R. 33 W. Greenstone forms prominent bluff facing Brule River. South part of outcrop shows ellipsoidal structure; north margin is agglomeratic. Original layering trends west-northwest, dips steeply. Form of pillows in greenstone yields only dubious top directions. Rock not notably magnetic.

12. Sec. 31, T. 42 N., R. 33 W. Outcrop in eastern part of section, on west side of Brule River.

In general, the South belt is characterized by moderate to strong but discontinuous magnetic anomalies, the most persistent of which lies above the sec. 21 and sec. 23 outcrops in T. 42 N., R. 34 W. This anomaly, which has a maximum recorded ground intensity of about 2,000 gammas, can be traced for about 7 miles. The magnetic pattern exhibited by the South belt as a whole is rather typical of those produced by greenstone terranes in other parts of the region; characteristically, the anomalies lack the persistence of those caused by sedimentary rocks. Presumably, the greenstone anomalies are due to volcanic flows, breccias, or tuffs of particular composition or cooling history, which by their nature would not be expected to have had an original surface extent of more than a few miles in any direction.

Thin beds of slate and iron-formation probably are interbedded or intimately associated with the greenstone at several localities. These occurrences are described in the following paragraphs.

Occurrence and character of associated sediments

Sedimentary rock, consisting chiefly of gray to black slate and containing a small amount of cherty magnetite-bearing material (iron-formation(?)), has been drilled and explored by several test pits and some underground workings at the "Wild Cat exploration" in sec. 18, T. 42 N., R. 34 W. The slates are carbonate rich, and some are pyritic. The "iron-formation," which can be seen only as scattered pieces on the dumps of the old workings, is a cherty magnetite-rich rock; bedding, if present in the rock, is not conspicuous, and it is by no means certain that the rock is actually a sedimentary iron-formation. It may be a metamorphosed and mineralized volcanic tuff, the chert owing its origin to silicification such as is commonly associated with volcanism.

Sedimentary strata are known to be present at or near the base of the greenstone in the vicinity of Pentoga. The rocks are exposed in low, narrow outcrops along the Wisconsin side of the Brule River, just above river level. The most northerly outcrops are of green fine-grained slate, possibly tuffaceous, and massive dark-green rock, probably originally a volcanic flow. The most southerly outcrop, a hundred yards or so in length, consists in part of chert-carbonate iron-formation and in part of slate. Most of the iron-formation observed is a breccia of chert fragments in a sideritic matrix. Presumably this iron-formation is the same bed that was test pitted at the Jumbo exploration in secs. 20 and 21, T. 41 N., R. 16 E. (Wisconsin), immediately east of the outcrop area. Little is known of this exploration, but locations of several test pits and a shaft are shown on older maps. The pits were sunk prior to 1909 and were noted by Allen (1910, p. 65) as follows: "The pits are now filled with debris but the dumps disclose slate and iron formation of the characters shown in the outcrop on the river." The area is now heavily grown to brush, and no trace of the original pits or their dumps could be found in 1952.

The apparent interbedding of slate and greenstone at the north side of the Jumbo exploration belt and the interbedding of slate and iron-formation in the more southerly outcrops indicate that the slate and iron-formation are conformable layers intimately associated with the greenstone.

Petrography of the greenstone

The thin sections studied of rocks from the South belt indicate somewhat greater petrographic uniformity than those from the North belt. A typical specimen consists of chlorite, albite, actinolitic hornblende, clinozoisite or epidote, and leucoxene. Primary texture is visible in most, and specimens from secs. 21 and 29, T. 42 N., R. 34 W., and sec. 29, T. 42 N., R. 33 W., show original augite, partly altered to green chlorite and pale-green amphibole, as abundant small grains and euhedra as much as 0.5 mm in diameter.

All the rocks are now fine grained and contain scattered needles and laths of green low-birefringent chlorite and very pale green amphibole (weakly pleochroic, $C \wedge Z = 16°–19°$) set in a matrix of clear untwinned albite. Magnetite is present in some, generally associated with sphene; in others, original magnetite-ilmenite grains have been altered to opaque leucoxene. Most specimens contain some epidote or clinozoisite as small scattered grains. Some porphyritic varieties contain large plates of actinolitic hornblende, 2 mm or more long, pseudomorphic after original pyroxene.

The vesicular greenstones display the greatest range in mineral composition. Fragments of vesicular rock in the agglomerate in sec. 21, T. 42 N., R. 34 W., contain vesicle fillings of coarse carbonate, green chlorite, sphene, and stilpnomelane (Z=golden yellow brown, X=pale yellow). The vesicles in the rock from sec. 23, T. 42 N., R. 34 W., contain an abundant pink zeolite. In thin section the mineral is colorless to faint brown and has irregular polysynthetic twinning and distinct rhombohedral cleavage; it is optically positive, with a $2V$ of about 85°, and the indices are below the index of Canada balsam. The mineral probably is mesolite. Some of the vesicles are filled with radial growths of green chlorite showing ultrablue interference colors.

Thickness

Structural concordance of the South belt of greenstone with adjacent formations is indicated by comparison of the magnetic trends with known structural trends of the adjacent formations. The greenstone probably forms a north-facing steep-dipping homoclinal belt that is stratigraphically above the Saunders Formation and stratigraphically below the strata of the Paint River Group. If this assumption is correct, then the South belt of greenstone, with its associated sediments, has a thickness that ranges from about 10,000 feet at the west margin of the map area to 5,000 feet (or less) at the margin of the map area in the vicinity of Pentoga.

EAST BELT

The East belt is a mass of greenstone that is exposed mainly in the west-central part of T. 42 N., R. 32 W., and is believed to extend southward into the "Spread Eagle belt" of Florence County, Wis. (Leith and others, 1935). The Spread Eagle belt extends eastward to the Badwater Lake area of central Dickinson County, Mich., from which the formation derives its name.

The greenstone of the East belt is not widely exposed. The most abundant outcrops are in the S½ sec. 17 and the NE¼ sec. 20, T. 42 N., R. 32 W., and along and adjacent to the Brule River east of U.S. Highway 2. Some of the rock exposed in sec. 9, T. 41 N., R. 32 W., is agglomeratic, but most of the exposed rock is massive or schistose and has no visible primary structure.

In thin section the rock is equally lacking in distinctive characteristics. Most of it appears to have been a fine-grained nonporphyritic basalt containing microlites and thin laths of feldspar less than 0.5 mm in length. These crystals, now entirely albite, are in a felted groundmass of chlorite and either pale-green hornblende or epidote. Leucoxene or fine-grained sphene and scarce magnetite are accessories. Specimens from sec. 17 and sec. 20, T. 42 N., R. 32 W., contain small amounts of green biotite as tiny shreds in the groundmass.

The greenstone of the East belt attains a probable maximum thickness of about 5,000 feet. It probably pinches out entirely in the area southeast of Crystal Falls so that the Dunn Creek Slate is in direct contact with the Michigamme Slate.

OTHER OCCURRENCES OF GREENSTONE

Greenstone occurs in an area surrounded by younger rocks in sec. 19, T. 42 N., R. 32 W., and the adjacent part of sec. 24, T. 42 N., R. 33 W., and it forms the core of an eastward-projecting anticline in secs. 33 and 34, T. 43 N., R. 35 W.

The greenstone in secs. 33 and 34, immediately southwest of the town of Iron River, is known only from one outcrop and from a few churn drill holes that entered bedrock only a foot or so. The exposure is in the SE¼NW¼ sec. 33, just west of U.S. Highway 73. The rock is generally massive and unsheared. It is porphyritic, both in the outcrop and in the material recovered from the drill holes. In thin section the greenstone is seen to consist of altered phenocrysts, as much as several millimeters in length, set in a groundmass made up of nearly isotropic chlorite, interstitial albite, and small amounts of quartz, sericite, leucoxene, and magnetite. The original phenocrysts were of both plagioclase and pyroxene. The plagioclase is altered to albite and chlorite, and the pyroxene is completely altered to chlorite and other fine-grained secondary minerals (fig. 13*B*). The greenstone is flanked on the north, south, and east by Dunn Creek Slate and is assumed to widen to the west (pl. 1). This interpretation is based on scanty evidence, and possibly the known area of greenstone is wholly isolated.

The greenstone in secs. 19 and 24, a short distance southeast of the town of Alpha, also is exposed at the core of an anticlinal structure. It is similar to that of the nearby East belt; massive fine-grained metabasalt is the dominant type. Thin sections of specimens from the SW¼ sec. 19 show the rock to consist of abundant small laths (0.1–0.2 mm length) of plagioclase and small blebs of carbonate in a matrix of nearly isotropic pale-green chlorite. The margins of the laths are irregularly embayed with chlorite, and the plagioclase now has the composition of albite (about An_5). Leucoxene, pyrite, and magnetite are accessory minerals. Some coarser grained metadiabase, probably intrusive, occurs with the fine-grained greenstone in the SW¼SW¼ sec. 19. Like the greenstone of the East belt, that of secs. 19 and 24 does not contain sufficient magnetite to cause appreciable magnetic anomalies.

THE GREENSTONES AS POSSIBLE SPILITES

Because of the abundance of albite in most of the greenstones, the possibility was considered that the rocks may have been of an originally soda-rich suite, that is, spilites. Although this seemed unlikely in view of the fact that minerals typical of ordinary basalt are present as relicts in a few of the specimens studied, the possibility was tested further by determination of calcium and sodium content in several samples of both extrusive and intrusive types. The results are given in table 3, which also shows the molecular ratios of $CaO:Na_2O$. Of the specimens determined, only sample 10 contains a primary plagioclase (labradorite); the rest contain albite as the modal plagioclase. The results show clearly that the rocks actually are of basaltic character rather than spilitic. The rather considerable range in values is of interest; it indicates that although the bulk composition of the rocks has remained almost unchanged (except for addition of H_2O and CO_2), the calcium and sodium have been sufficiently mobile during metamorphism to permit considerable local migration. Samples 8 and 9 are from adjacent outcrops of rock that appears to be of a single flow, but the two samples show a difference of 29 percent in anorthite content of the normative plagioclase.

TABLE 3.—*Calcium and sodium determinations, in weight percent, of greenstone and metadiabase from the Iron River–Crystal Falls district*

[Rapid method analyses by Joseph Dowd. Average basalt (Tyrrell, 1926, p. 131) given for comparison]

Sample	Sample locality			Field description	CaO	Na_2O	Normative plagioclase (molecular percent)
	Sec.	T. (N.)	R. (W.)				
1	20	43	32	Badwater Greenstone.	10.8	2.2	An_{73}
2	19	43	35	Metadiabase	11.3	1.9	An_{77}
3	11	43	33	Badwater Greenstone, massive.	8.7	3.0	An_{62}
4	23	42	34	Badwater Greenstone, amygdaloidal.	7.3	3.2	An_{56}
5	24	43	33	Metadiabase	7.8	2.6	An_{62}
6	17	42	35	Badwater Greenstone.	5.4	3.8	An_{44}
7	29	42	33	Badwater Greenstone, ellipsoidal.	9.5	2.3	An_{70}
8	17	43	35	Badwater Greenstone.	3.1	2.8	An_{38}
9	17	43	35	do	9.4	2.6	An_{67}
10	25	43	34	Badwater Greenstone, porphyritic.	8.9	2.6	An_{65}
11	20	43	33	do	10.4	2.4	An_{70}
12	20	42	35	Greenstone, Brule River area.	5.1	3.4	An_{45}
13	21	42	35	Greenstone agglomerate, Brule River area.	8.8	2.7	An_{64}
14	8	43	33	Badwater Greenstone, ellipsoidal.	7.4	.9	An_{81}
Average					8.1	2.6	An_{63}
Average basalt					8.9	3.2	An_{60}

STRATIGRAPHIC RELATIONS

The stratigraphic position of the greenstone masses is a highly critical feature of the appraisal of the Animikie Series in the district. On the map accompanying Professional Paper 184 (Leith and others, 1935), the greenstones were shown as "Pre-Cambrian basic extrusives, unclassified" although in the text (p. 4) these writers stated "that the evidence is probably in favor of placing the series in the lower part of the Upper Huronian, below the Michigamme slate * * *." On the 1936 Centennial Map of the Northern Peninsula of Michigan (Martin, 1936), the greenstone bodies were shown as "unclassified Precambrian."

The position of the greenstone in the stratigraphic column has been established by U.S. Geological Survey mapping in the area adjoining the Iron River-Crystal Falls district on the southeast. In the Commonwealth quadrangle of southeastern Iron County, according to C. E. Dutton (unpub. data), top determination by means of graded bedding in graywacke of the Michigamme Slate at one locality close to the contact with greenstone that is continuous with the East belt of this report shows without doubt that the greenstone is the younger rock. Top determinations made by means of ellipsoidal structure within the greenstone, from its contact with the Michigamme to the contact with the sedimentary strata of the Florence district, are consistently toward the southwest. The adjacent strata of the Florence district, which are physically continuous with those of the Iron River-Crystal Falls district, are, therefore, younger than the greenstone, and the East belt of greenstone is established as a stratigraphic unit between the Michigamme Slate and the Dunn Creek Slate of the Paint River Group. Moreover, mapping has demonstrated the physical continuity of this greenstone mass with the Badwater Greenstone in its type locality in central Dickinson County.

Data bearing on the stratigraphic position of the North belt of greenstone are more incomplete than those for the East belt, but they are in no way contradictory. North of Iron River, about 6 miles north of the map area, the greenstone is interbedded with the upper part of the Michigamme Slate (Van Hise and Leith, 1911, p. 318), and all observed top determinations within the greenstone of this belt are to the south. The gap in the vicinity of Crystal Falls between the east termination of the North belt and the north termination of the East belt is believed to represent nondeposition of the volcanic rock; the two belts are thought to be cross sections of submarine volcanic piles that failed to merge in this locality.

The stratigraphic position of the South belt is established almost entirely from its relationship to the Dunn Creek Slate and its general similarity of position to the North belt. Evidence is very scarce regarding its lower contact, but apparently it either rests unconformably on the Saunders Formation or is in fault contact with that unit. The Michigamme Slate, which underlies the greenstone elsewhere, is not present.

CONDITIONS OF ORIGIN OF THE PAINT RIVER GROUP

A composite section of the Baraga Group of the eastern part of the Iron River-Crystal Falls district, together with those of the adjacent Lake Mary quadrangle (Bayley, 1959) and Kiernan quadrangle (Gair and Wier, 1956), would consist of the following formations (oldest to youngest): Goodrich Quartzite, Hemlock Formation (containing two interbedded iron-rich members), Amasa Formation, Michigamme Slate, and Badwater Greenstone.

The contact between the basal Goodrich Quartzite and older rocks is one of unconformity or disconformity. In some parts of the region all pre-Goodrich Animikie strata were stripped off in consequence of a widespread structural disturbance, a disturbance that halted deposition of the iron-formation that makes up much of the Menominee Group ("Middle Huronian" of older reports). This disturbance resulted in a profound change in the character of Animikie sedimentation: the stable-shelf clastic and chemical deposits of the Chocolay Group and the chemically precipitated iron-formation of the Menominee Group give way to sediments and volcanic rocks that were deposited in an orogenically much more active environment than that which existed previously.

After deposition of thin but variable thicknesses of the sands that now form the Goodrich Quartzite, volcanism became dominant and the Hemlock Formation accumulated, largely as submarine flows and breccias in rapidly subsiding basins. The thickness of this unit varies greatly; on the west side of the present Amasa oval, north of the Iron River-Crystal Falls district, it may be as much as 6 miles, whereas on the east side of the oval it is about half a mile, and in parts of central Dickinson County (James, Clark, and others, 1961) the formation is absent. The Mansfield Iron-Bearing Slate Member and Bird Iron-Bearing Member of the Hemlock Formation were deposited as partly chemical, partly clastic sediments during lulls in the volcanic activity. The iron-formation of the Mansfield was formed as chert and siderite under reducing conditions. but that of the Bird is hematitic and oolitic and therefore accumulated under oxidizing nearshore or shallow-water conditions. Since both of these iron-formation units probably were deposited in local basins formed by irregular distribution of the submarine lavas, neither can be expected to have much lateral continuity.

The volcanism now represented by the greenstones of the Hemlock apparently terminated rather abruptly and the Amasa Formation was then deposited on the surface of the lavas, in part as ferruginous clastic material and in part as chemically precipitated chert and (probably) iron oxide, again under oxidizing, shallow-water conditions. Deposition of this material was halted by minor structural disturbance that is represented by local truncation of the ferruginous rocks in the Amasa area, north of the Iron River-Crystal Falls district. The inferred pinchout of the ferruginous strata within the district may be due either to erosion or to nondeposition.

The Amasa Formation is succeeded by a thick sequence of graywacke and slate—the Michigamme Slate. Most of the Michigamme Slate is remarkably similar over a broad area of northern Michigan; it contains neither conglomerate nor chemical precipitates such as limestone, dolomite, or chert. Graded bedding is a highly characteristic feature of the graywacke layers, but crossbedding and ripple marks are absent, as are intraformational breccias and other evidences of contemporaneous deformation. The rocks are not ferruginous, except locally in the uppermost part of the formation. The sediments must have accumulated below wave base on a broad marine plain in which the chief transporting agent was turbidity currents that are now reflected by the graded bedding of many layers. The local presence of dark ferruginous rocks, together with a little chert, graphitic slate, and iron-formation in the uppermost part of the formation, suggests small restricted basins that were barred from the submarine plain. The formation of these smaller basins coincided with the beginning of volcanic activity, as in at least two areas immediately adjacent to the district (the Gibbs City area north of Iron River and the Commonwealth quadrangle) some volcanic rock is interbedded with the sediments.

The Badwater Greenstone overlies the Michigamme Slate. These rocks accumulated as submarine volcanic piles that failed to merge in some parts of the region, as in the area east and southeast of Crystal Falls. Because the rocks are now steeply dipping or vertical, the map pattern of a given mass, such as the North belt, is virtually a cross section of one of these piles. In this belt, the formation probably is about 3 miles thick in the northwest and north-central part of the district and seems to pinch out entirely in the northeastern part within a horizontal distance of about 10 miles. The spatial relations indicate greenstones formed broad submarine mounds, 20 miles or more in diameter. Even assuming that the base did not subside, an unlikely assumption, the surface slope of a pile such as that represented by the North belt would have been only a little more than 15°.

PAINT RIVER GROUP

The Paint River Group comprises five formations, oldest to youngest: (1) Dunn Creek Slate, (2) Riverton Iron-Formation, (3) Hiawatha Graywacke, (4) Stambaugh Formation, (5) Fortune Lakes Slate. These strata, which form the bedrock of the Iron River-Crystal Falls district proper, were considered part of the Michigamme Slate in older reports on the district and were assigned to the upper Huronian. (See, for example, Leith and others, 1935.)

The group, which aggregates about 6,500 feet in thickness, is divided into lower and upper parts by an unconformity or disconformity between the Riverton Iron-Formation and the overlying Hiawatha Graywacke. The local and district lithologic variations in formations of the group are summarized in figure 14.

DUNN CREEK SLATE

The Dunn Creek Slate is named for Dunn Creek, which cuts through an area of numerous outcrops of the unit in sec. 31, T. 43 N., R. 32 W. As defined, the formation comprises all strata between the Badwater Greenstone and the Riverton Iron-Formation. The gross aspect of the unit is strikingly different in the eastern part of the district as compared with that in the central and western parts. (See fig. 14.) Throughout the district, however, the uppermost part of Dunn Creek is a distinctive graphitic pyritic slate that is underlain by a considerable thickness of gray sericitic slate and siltstone.

Outcrops of the Dunn Creek are virtually confined to the eastern part of the district, and even there they are small and scattered. Nowhere—in mine workings, outcrops, or drill core—is there a continuous cross section of the unit accessible for study. The upper part of the section is reasonably well known from underground explorations and can be adequately described, but the subdivisions and descriptions of the lower part are much more uncertain.

The graphitic slate and sericitic slate-siltstone sequence are present throughout the entire area and the descriptions that follow deal with characteristics of these units for the whole district. The lower part of the Dunn Creek Slate in the Crystal Falls area is described as a separate unit, inasmuch as these strata apparently have no counterpart in other parts of the district.

LOWER PART OF THE DUNN CREEK SLATE IN THE CRYSTAL FALLS AREA

The lower part, in fact, the lower four-fifths, of the Dunn Creek Slate in the Crystal Falls area is unlike that of the western and central parts. The part of the formation here described comprises four gradational members; oldest to youngest, these are (1) cherty black slate, 700–800 feet thick, (2) slaty iron-formation, 100–200 feet, (3) laminated to "striped" slates, 200–300 feet, and (4) slaty iron-formation, 400–500 feet. None of

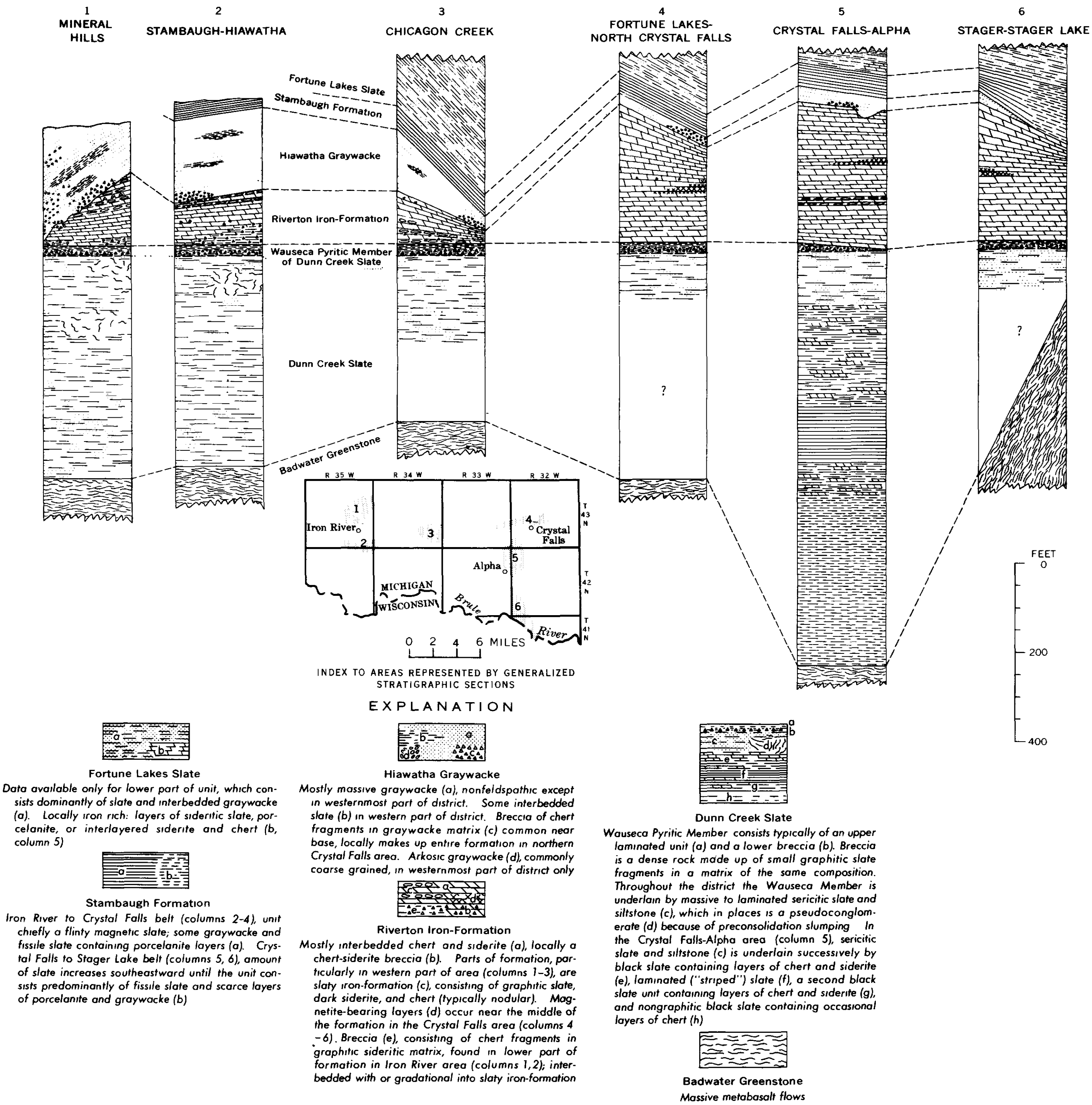


FIGURE 14.—Local and district lithologic variations within the middle Precambrian Paint River Group.

these members are sufficiently well defined or sufficiently well exposed to permit expression as separate units on the map. The occurrence and characteristics of these units are briefly summarized.

The basal member, the cherty black slate, consists mainly of gray to black laminated nongraphitic fissile slate and scattered layers of light-colored chert that rarely exceed 3 inches in thickness. Slaty cleavage commonly is well developed. In the NW¼NE¼ sec. 19, T. 42 N., R. 32 W., a chert breccia, which consists of angular slabs of chert in a siliceous matrix, is interbedded with black slate.

Overlying the cherty black slate member and gradational into it is a slaty iron-formation that consists of graphitic black slate with interbedded chert and siderite. The rock is well exposed in a quarry and in outcrop near the road Y in the NW¼SE¼ sec. 7, T. 42 N., R. 32 W., and is exposed in many poor outcrops in sec. 6 of the same township. The chert-siderite layers are very similar to much of the unoxidized Riverton Iron-Formation, and the rocks are indistinguishable in hand specimen. Analysis of one of the carbonate layers showed 27.0 percent Fe, 8.72 percent Mn. The rock is strongly contorted in the exposures near the road Y, and the chert-carbonate layers are cut by thin quartz veinlets. In some of the outcrops the carbonate layers show a thin veneer of oxidation, but so far as known, this rock has not been oxidized to ore anywhere in the district.

A distinctive striped slate overlies the slaty iron-formation just described. This rock is well exposed in large outcrops in the northern part of sec. 18, T. 42 N., R. 32 W.; in the western part of sec. 7 of the same township; and in the SE¼ sec. 13, T. 42 N., R. 33 W. A closeup view of an outcrop is shown in figure 15. The rock is thin banded and commonly shows a slaty cleavage at an angle to bedding. On fresh breaks the rock is dark colored and the bedding is indistinct, but on exposed surfaces the layers are differentially oxidized to shades of brown and green so that bedding is emphasized.

Above the striped slate lie strata somewhat similar to those underlying the unit. Black slate, interbedded with chert and iron-rich carbonate, is the dominant lithologic type. The chert and carbonate are sufficiently abundant in some parts of the section to form lean iron-formation of considerable thickness; outcrops along an old railroad grade in the SW¼SW¼ sec. 6, T. 42 N., R. 32 W., expose 400–500 feet of interbedded chert, siderite, and black slate.

FIGURE 15.—Striped Dunn Creek Slate in NE¼SW¼ sec. 7, T. 42 N., R. 32 W.

GRAY SERICITIC SLATE AND SILTSTONE

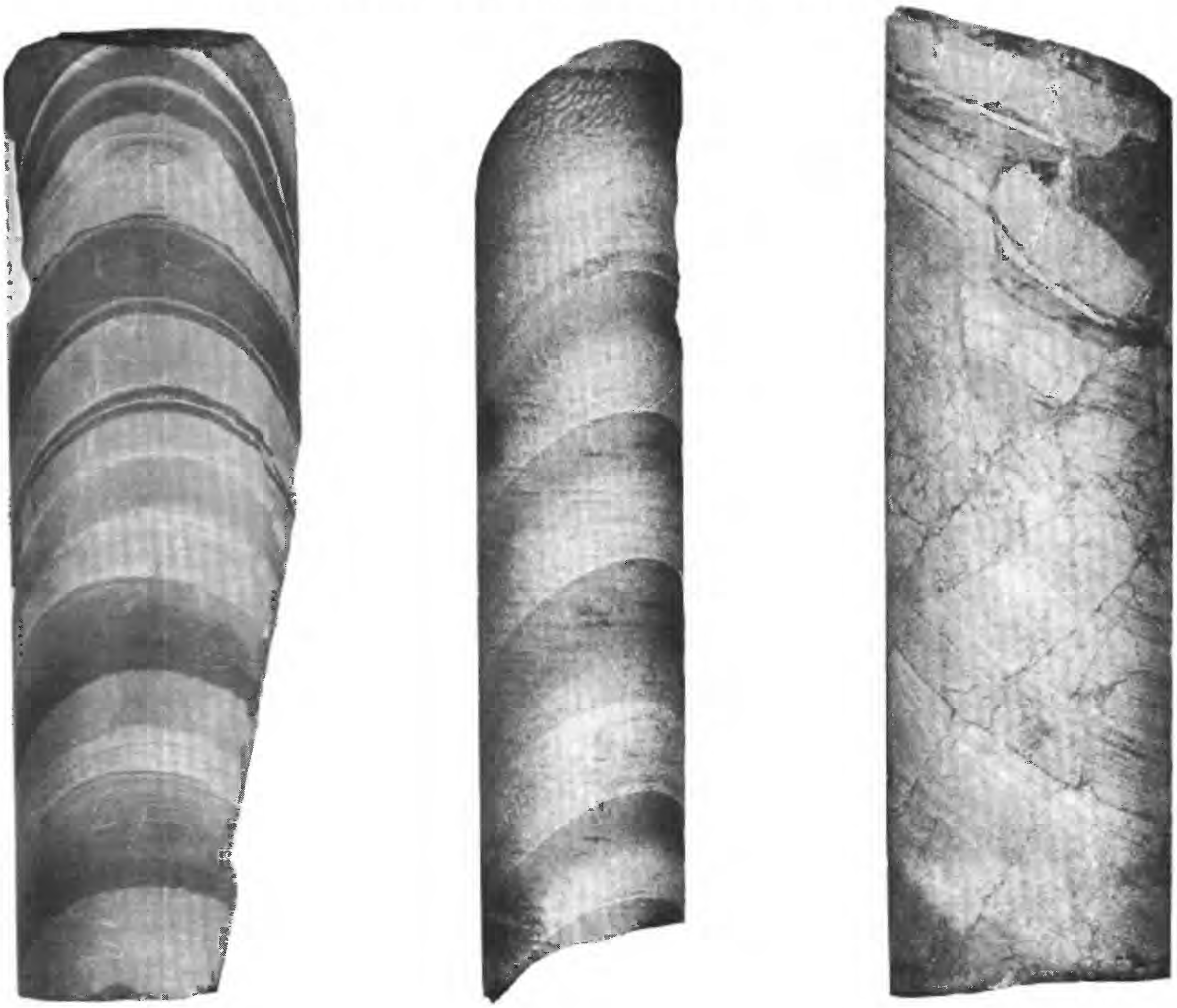
A stratigraphic unit consisting chiefly of a distinctive gray sericitic slate and interbedded siltstone underlies the graphitic slate of the Wauseca Pyritic Member throughout the district and forms the major part of the Dunn Creek Slate in the western and northern parts of the district. Even though the rock is exposed in only a few places, its characteristics are well known from mine workings which penetrate it extensively and from drill holes. The shaft of the Berkshire mine, at the lower levels, is in this material. In the Crystal Falls area, because of the greater thickness and complexity of the stratigraphy of the Riverton Iron-Formation and immediately underlying strata, the unit is not found in as many explorations, but the rock seems to be entirely similar to that in the Iron River area. The rock is exposed in the shaft area at the lower levels of the Bristol mine, has been cut in scattered drill holes elsewhere, and is exposed locally on the north wall of the open pit at the Fortune Lakes mine. One or more beds of coarse-grained massive graywacke occur within the sericitic slate and siltstone in the vicinities of the Kimball mine and of the Tobin mine in the Crystal Falls area; these beds seem to be of local extent and are not discussed further.

Lithology

The rock is light to dark gray and massive. It stands well and makes excellent sites for pump stations and other underground installations. It is generally nongraphitic although locally it is as dark as the overlying graphitic slates. The unit consists of about equal parts sericitic slate and siltstone or fine graywacke, commonly interlayered (fig. 16*A*); medium- or coarse-grained graywacke is not uncommon, but it does not form a major part of the unit as known at present. The slate and some of the siltstone are thinly banded, whereas the coarser siltstone and graywacke are massive, without much bedding. Some layers show graded bedding, though it is not easily seen except in drill core (fig. 16*B*). Pyrite in the form of large cubes is observed in many places in the slaty beds in the upper part of the unit.

In general, finer grained rock seems to predominate in the upper part of the unit and coarser grained material in the lower.

In much of the banded siltstone and slate, the bedding is broken by small displacements of approximately a few tenths of an inch. This minor faulting grades into a breccia or pseudoconglomerate structure that is due to displacement of some layers accompanied by rotation and rounding of the fragments (fig. 16*C*). Generally,



A B C

FIGURE 16.—Dunn Creek Slate in drill core. *A*. Typical interbedded dark sericitic slate and lighter colored siltstone. Specimen HJ–122–47, from drill hole 1–A–47, Hiawatha mine. *B*. Graded bedding in siltstone, top up. Specimen HJ–41–48, from drill hole 3, Buckholtz exploration. *C*. Pseudoconglomerate. Specimen HJ–180–48, from drill hole 214, Bates mine. Natural scale.

this pseudoconglomerate is massive, without indication of shearing; it is due to preconsolidation slumping within the beds. Some drill holes have passed through hundreds of feet of pseudoconglomerate, but the material does not seem to have well-defined stratigraphic significance.

Petrography and chemical composition

Under the microscope the siltstone and sericitic slate show little that is unusual. The siltstones consist of angular fine clastic grains, most of quartz but some of feldspar, in a fine-grained matrix of sericite, chlorite, and scattered patches of carbonate. The slates are similar to the siltstones except for fewer and smaller clastic grains and a greater abundance of sericite. The sericite, particularly in the slates, shows strong preferred orientation parallel to bedding, and this orientation yields a bedding-plane parting or fissility. Near the axes of folds this bedding-plane cleavage is cut by slip cleavage.

Analyses of samples of typical slate and siltstone are given in table 4. The analyzed materials are high in ferrous iron, compared with analyses of similar rocks from other areas. In the siltstone, the iron is largely in the form of chlorite; in the slate, much of the iron is present as carbonate and sulfide. The general range in iron content, as determined by routine analyses of drill sludge, is 6–12 percent.

TABLE 4.—*Chemical analyses of two samples from the sericitic slate-siltstone unit of the Dunn Creek Slate*

[Analyst: Charlotte Warshaw]

	Siltstone (1)	*Slate* (2)
SiO_2	59. 19	49. 85
Al_2O_3	14. 61	13. 88
Fe_2O_3	1. 51	3. 75
FeO	11. 28	14. 10
MgO	2. 94	3. 32
CaO	. 09	. 20
Na_2O	. 12	. 10
K_2O	2. 38	2. 74
TiO_2	1. 45	1. 45
MnO	. 10	. 24
H_2O+	4. 69	4. 90
H_2O-	. 07	. 14
P_2O_5	. 01	. 09
CO_2	1. 25	4. 09
C	. 25	. 69
S	. 08	1. 51
Subtotal	100. 02	101. 05
Less O for S	. 04	. 76
Total	99. 98	100. 29

1. Massive. From drill hole 8002 (620–625 ft), Homer mine, Iron River.
2. Sericitic. From same hole as 1 (980–985 ft).

WAUSECA PYRITIC MEMBER

Throughout the Iron River-Crystal Falls district, the "footwall" of the Riverton Iron-Formation is a graphitic pyritic slate which has a gradational interbedded contact with the underlying sericitic slate-siltstone unit. Outcrops are exceedingly scarce, in part because the rock is not resistant to weathering and in part because it is extensively sheared. The pyritic slate seems to be structurally the weakest rock in the stratigraphic section, and many of the major faults are in this unit. Because of its proximity to the iron-formation, the pyritic slate is penetrated in many places by mine workings and drill holes. The name is derived from the Wauseca mine in Iron River, where the unit is crossed by several levels of mine workings.

Lithology

In places where information is adequate and the rock is not strongly sheared, the Wauseca Pyritic Member can be divided into two units: a basal slate breccia (the "speckled gray" of field terminology) and a laminated slate. In most places the laminated slate grades with fairly abrupt transition into the chert-carbonate rock of the overlying iron-formation, but locally in the Iron River area, a chert breccia separates the laminated graphitic slate from the layered chert-carbonate of the Riverton Iron-Formation.

The slate breccia ("speckled gray") is a marker bed throughout the district, though in some localities it is not recognizable because of shearing. Where unsheared, the rock is black or dark bronze and consists of small angular fragments of graphitic slate in a dense graphitic matrix (fig. 17). The fragments rarely exceed an inch in diameter. The rock is massive, in contrast

FIGURE 17.—Graphitic slate breccia ("speckled gray") from Wauseca Pyritic Member of the Dunn Creek Slate, showing irregular slate fragments in dense matrix. Light-colored areas are pyrite. Polished specimen, from the Wauseca mine, Iron River. Natural scale.

to the laminated structure of the overlying slate. The true stratigraphic thickness of the breccia typically is about 10 feet, with a range of from 1 to 30 feet, but like other units in the area, it locally may be either absent or several times the maximum stratigraphic thickness because of folding or squeezing. The slate breccia is recognizable in most mines in the Iron River district, but in many places the Wauseca as a whole is so strongly sheared that the separate units cannot be distinguished. The breccia has been recognized in drill holes as the basal unit of the graphitic slate in the Chicagon Creek area, halfway between Crystal Falls and Iron River. In the Crystal Falls area the rock is present at the 12th level of the Bristol mine although structural complexities are such that details of its stratigraphic position are not clear. It is recognized in a test pit in the

NW¼SE¼ sec. 13, T. 42 N., R. 33 W., and in drill holes near the Delphic mine in sec. 24, T. 42 N., R. 33 W.

The slate breccia is overlain by the laminated graphitic slate, a dark-bronze to black rock in which layers that are rich in pyrite alternate with those that contain less pyrite. The layers typically are one-eighth to half an inch thick. On polished surface the pyrite-rich layers are strongly light reflecting, and in photographs the rock appears to be striped with light-colored bands of pyrite (fig. 18). In ordinary specimens the rock is dull, and the pyrite is not visible to the unaided eye. In test pits and the sparse outcrops, the rock is fissile, but this structure is not especially apparent in underground exposures except where the rock is sheared. Where sheared, the rock breaks on many closely spaced slightly curved planes along which the carbonaceous material has been smeared to form lustrous black surfaces. The true stratigraphic thickness of the laminated graphitic slate ranges from 5 to 20 feet, but as with the underlying slate breccia, the unit may be sheared out entirely or squeezed and folded to several times normal thickness.

Petrography and chemical composition

In thin section the pyritic slate breccia and the laminated pyritic slate are almost completely opaque except for scattered flakes of sericite and a few silt-sized clastic quartz grains. Polished sections of rocks of both types reveal abundant pyrite in the form of very small grains, most of which show partial cubic or pyritohedral outlines (fig. 19). X-ray examination by F. A. Hildebrand of the U.S. Geological Survey indicates that greenalite is present, but this mineral has not been recognized in thin section. A complete chemical analysis of the laminated rock is given in table 5, and partial chemical analyses of 19 samples are given in table 6.

TABLE 5.—*Chemical analysis, in percent, of pyritic slate from Buck mine, 10th level, Iron River district*

[Analyst: Charlotte M. Warshaw]

	Percent		Percent
SiO_2	36. 67	V_2O_5	0. 15
Al_2O_3	6. 90	P_2O_5	. 20
Fe_2O_3[1]	------	H_2O^-	. 55
FeO[1]	2. 35	H_2O^+	1. 25
FeS_2[2]	38. 70	SO_3[3]	2. 60
MnO	. 002	Organic matter + C[4]	7. 6
CaO	. 13		
MgO	. 65	Total	100. 21
Na_2O	. 26	Total C[4]	7. 28
K_2O	1. 81	Total S	21. 2
TiO_2	. 39		

[1] Direct determination of FeO was not possible because of organic matter. Iron in excess of the amount in pyrite reported as FeO.
[2] Pyrite determined by separation with dilute HCl-HF treatment, residue oxidized with aqua regia plus bromine, and resulting solution analyzed for Fe and S.
[3] The sulfur not present as pyrite is reported as SO_3. Most of it is soluble sulfate.
[4] Total carbon determined by combustion. Organic matter determined roughly by weighing residue from HCl-HF treatment and subtracting the weight of the pyrite determined. The percentages of total carbon are not as high as the values obtained by the acid method, which shows that there is a fair amount of organic matter in addition to graphite, as was suspected when the FeO determinations were attempted.

FIGURE 18.—Polished surface of laminated pyritic slate from Wauseca Pyritic Member, Dunn Creek Slate. Pyrite-rich layers (light colored) are strongly reflecting and are more conspicuous in the photograph than in the actual specimen. From the James mine, Iron River. Length of specimen, about 5 inches.

TABLE 6.—*Partial chemical analyses of pyritic slate*
[n.d., not determined]

Sample	Sample locality	Fe	S	C	Analyst
	Pyritic slate breccia [Hand samples [1]]				
HJ-10-50	James mine, 7th level	19.5	17.0	n.d.	Pickands, Mather & Co.
858-A	Sherwood mine, 1,200-ft level	16.6	18.8	18.2	Union Assay Office, Salt Lake City.
858-E	Wauseca mine, 9th level	21.2	24.5	13.9	Do.
858-G	Hiawatha No. 1 mine, 9th level	22.8	26.2	13.9	Do.
858-H	Test pit, NW¼SE¼ sec. 13, T. 42 N., R. 33 W	21.4	23.9	15.3	Do.
HJ-139-51	do	23.7	29.0	n.d.	Inland Steel Co.
871	Bristol mine, 12th level	17.7	16.6	n.d.	Union Assay Office, Salt Lake City.
HJ-138a-51	do	15.2	18.1	n.d.	Inland Steel Co.
HJ-138b-51	do	15.4	17.1	n.d.	Do.
Average		19.3	21.2	15.3	
	Laminated pyritic slate [Hand samples]				
858-B	Sherwood mine, 1,200-ft level	15.6	17.5	6.3	Union Assay Office, Salt Lake City.
858-D	Wauseca mine, 9th level	14.0	15.5	10.4	Do.
858-F	Hiawatha No. 1 mine, 9th level	25.2	28.9	8.0	Do.
HJ-11-50	James mine, 7th level	19.4	19.2	n.d.	Pickands, Mather & Co.
Average		18.5	20.3	8.2	
	Pyritic slate [Bulk samples]				
857-B	Hiawatha No. 1 mine, 9th level	20.1	22.1	10.2	Union Assay Office, Salt Lake City.
813	do	19.9	20.5	12.6	Humphreys Investment Co.
857-C	Wauseca mine, 9th level	13.4	15.0	9.7	Union Assay Office, Salt Lake City.
814	do	14.1	14.9	11.4	Humphreys Investment Co.
857-A	Sherwood mine, 1,200-ft level	[2] 11.3	11.2	13.1	Union Assay Office, Salt Lake City.
812	do	[2] 11.5	10.6	17.2	Humphreys Investment Co.
Average		15.1	15.7	12.4	

[1] Except for 871, which is a bulk sample of several hundred pounds.

[2] Sample includes some chert breccia from the base of the overlying Riverton Iron-Formation, which is distinctly lower in pyrite than the rest of the Wauseca Pyritic Member.

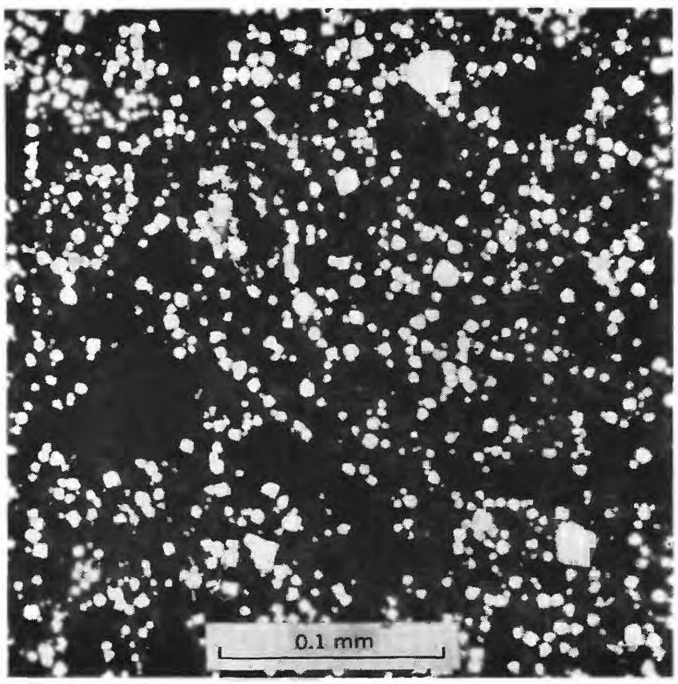


FIGURE 19.—Polished section of typical pyritic slate, Wauseca Pyritic Member, Dunn Creek Slate. Pyrite (white) mostly in the form of cubes and pyritohedrons. Specimen HJ-410-47, from drill hole B23, SW¼SW¼ sec. 6, T. 42 N., R. 34 W.

The average calculated pyrite content of the slate breccia is 39.7 percent, and that for the laminated slate 38.0 percent. The bulk sample average is lower in pyrite content than the averages for the two lower units, mainly because of the inclusion in two of the samples of basal chert breccia from the overlying Riverton Iron-Formation.

All the units, but especially the slate breccia, are strikingly rich in carbon, and the rock is referred to as graphitic, which it certainly appears to be in hand specimen. R. H. Nanz (written commun., 1952), however, noted that X-ray photographs of samples failed to show the typical lines of graphite. Further examination by F. A. Hildebrand showed that the material gives negative results when subjected to Brodie's reaction (treatment with HNO_3+KClO_3 by which true graphite yields micaceous brown flakes). Hildebrand concluded that most of the carbon occurs as "poorly crystalline carbon, possibly disordered graphite." Not all the carbon is present in this form, however; an appreciable amount—about 0.3 percent in the analysis—is "organic carbon"; this percentage indicates that the rock contains roughly half a percent organic material. At several places in the Iron River area, lenticles and veinlike patches of a black lustrous coallike material have been observed. A sample of such material from a drill hole at the Wauseca mine was analyzed in the Analytical Division of the Illinois Geological Survey, and results were reported by Tyler, Barghoorn, and Barrett (1957, p. 1302). The data are given in table 7.

TABLE 7.—*Analyses of coaly material from the Wauseca Pyritic Member, Dunn Creek Slate*

[Analysis by Anal. Div., Illinois Geol. Survey, as reported by Tyler, Barghoorn, and Barrett (1957, p. 1302)]

	As received	Moist free	Moist and ash free
Moisture	0. 9	--------	--------
Volatile matter	2. 6	2. 6	4. 2
Fixed carbon	59. 5	60. 1	95. 8
Ash	37. 0	37. 3	--------
Total	100. 0	100. 0	100. 0
Hydrogen	0. 73	0. 64	1. 02
Carbon	58. 36	58. 91	94. 05
Nitrogen	. 76	. 77	1. 22
Oxygen	2. 16	1. 33	2. 15
Sulfur	. 97	. 98	1. 56
Ash	37. 02	37. 37	--------
Total	100. 00	100. 00	100. 00
Calorific value:			
Cal/g	4882	4926	7862
Btu/lb	8788	8868	14151

The pyritic slate fires readily in the presence of air, because of the abundant finely divided pyrite. Nearly all mines in the district have areas that are on fire and which are sealed off from the active workings. Any loose pile of the slate more than a few feet deep will burn spontaneously if the air supply is adequate; even on the mine dumps the burning is evident. Drill core begins to deteriorate soon after it is stored and in a few years is reduced to a loose mass of black and white powder (fig. 20).

THICKNESS AND RELATIONS TO ADJACENT FORMATIONS

The Dunn Creek Slate probably is about 500 feet thick in the western and northern parts of the district (fig. 14). In the east-central part of the district (Crystal Falls-Alpha belt), the thickness probably is nearly 1,500 feet, and in the extreme southeastern part of the district it may be less than 200 feet. The increase in thickness in the Crystal Falls-Alpha belt coincides with a greater diversity in rock types and also with a pinchout in the Badwater Greenstone, which underlies the slate in most of the area. It seems likely that the greater thickness and the more complex lithology are related to the existence of a depositional basin between the uncoalesced submarine volcanic piles now represented by the North and East belts of Badwater Greenstone.

The contact of the Dunn Creek Slate with underlying rocks is not intersected by mine workings or drill holes and is exposed in only one place—sec. 19, T. 42 N., R. 32 W. In contrast, the upper contact with the Riverton Iron-Formation is exposed at thousands of places in underground workings and is cut by countless drill holes. In most places this contact is conformable, with interbedding occurring through a narrow zone that rarely is more than a few feet thick.

FIGURE 20.—Drill cores of pyritic slate after a few years' storage, showing deterioration caused by burning (oxidation) of the fine-grained pyrite. Natural scale.

RIVERTON IRON-FORMATION

The principal iron-bearing unit of the Paint River Group, and the only one of economic importance at present, is the Riverton Iron-Formation. This formation is named for the old Riverton mine at Iron River, which was the site of the first successful attempt at exploitation of the iron ores of the district. The Riverton is exposed at this locality adjacent to and on the walls of the old pits, on the west side of the hill on which the town of Stambaugh is built. The original discovery of iron-rich rock in the district, made within a few hundred feet of the old Riverton pits, is credited to Harvey Mellen, a Government land surveyor. On August 8, 1851, Mellen recorded an "outcrop of iron ore 5 feet high" on the west face of Stambaugh Hill, 52 chains north of the SW. cor. sec. 36, T. 43 N., R. 35 W., which is one of the very few places in the western part of the district where the iron-formation is exposed. Exposures are much more abundant in the Crystal Falls-Alpha belt, though most are low and unimpressive. One of the best exposures in the district is that at the apron of the power dam on the Paint River, in sec. 20, T. 43 N., R. 32 W. At this easily accessible place, the iron-formation is unoxidized; the rock consists of bedded chert and siderite with interbedded layers of stilpnomelane, the whole of which is compressed into tight folds typical of the structure of the district.

In older reports the strata here designated the Riverton Iron-Formation have been assigned to various positions in the Huronian (Animikie) and given various designations. The first major publication dealing with a part of the district, Monograph 36 (Clements and Smyth, 1899), placed the iron-bearing strata of the Crystal Falls area within an undivided Upper Huronian. Allen (1910) correlated the iron-rich strata of the Iron River district with the Vulcan Iron-Formation of the Menominee district of southern Dickinson County; he stated (p. 50): "The term Vulcan has been applied to the iron bearing members of the Michigamme slate following the use of this name by the United States Geological Survey to designate equivalent formations in the Menominee and Crystal Falls districts." Presumably the usage referred to that in Monograph 36, though in that publication Clements did not apply the term "Vulcan" to the iron-bearing strata of the main part of the Iron River-Crystal Falls district; he placed these rocks in an undivided Upper Huronian.

In 1915 the stratigraphic correlations of northern Michigan were reviewed by Allen and Barrett (1915), who proposed that their Vulcan of southern Iron County, together with the Vulcan of the type area in Dickinson County, be correlated with the major iron-formations of other districts, and that all should be assigned to the middle Huronian. On the geologic map of Iron County published by the State of Michigan in 1929 (Barrett and others, 1929), the Vulcan, together with the Michigamme, was shown on the map explanation as Upper Huronian. In Professional Paper 184 (Leith and others, 1935) the iron-rich strata of the Iron River-Crystal Falls district were referred to as the Iron River Iron-Formation Member of the upper Huronian Michigamme Slate. The nature and stratigraphic limits of this iron-formation member were not specifically stated, but presumably they are the same as the Vulcan of Allen's earlier reports. If so, the Iron River Iron-Formation Member, a term now abandoned, included several distinct stratigraphic units of the present report.

The authors have not found it possible to make subdivisions of the Riverton that will apply to the district as a whole although local subdivisions can be made that are useful. The formation is distinctly different, in thickness and in some aspects of lithology, from one part of the district to another. (See fig. 14.)

GENERAL ASPECTS

Most of the iron-formation found in outcrops, in underground workings, and in drill core is oxidized so thoroughly that many of the original characteristics have been destroyed, but unoxidized iron-formation is found locally in parts of most mines and other explorations, and in a few outcrops. The best surface exposure of unoxidized material forms the apron of the dam on the Paint River in Crystal Falls (fig. 21). Excellent exposures of oxidized iron-formation can be seen at the margins of many of the caves and open pits over old mine workings throughout the district.

The iron-formation is thin bedded and, where unoxidized, consists mostly of interbedded chert and siderite (figs. 22, 23). Thin partings and seams of argillaceous or carbonaceous material are common. Prelithification slump structures and stylolites are common features though not readily observable except in drill core or on polished surfaces. The stylolites rarely have amplitudes of more than a quarter of an inch; they occur within the carbonate layers or between the siderite and chert layers (fig. 24). The columns normally are at right angles to the bedding, and by inference from Stockdale's studies (1922, 1943), this orientation shows that they were formed while the beds were horizontal. (Bedding-plane stylolites formed in tilted beds have columns that are vertical at time of formation regardless of the angle of bedding.) The surfaces of the stylolite seams are covered with a thin film of carbonaceous material. In at least two places in the Iron River area—on the south flank of the Hiawatha syncline and in the vicinity of the James and Davidson mines—normal cherty iron-

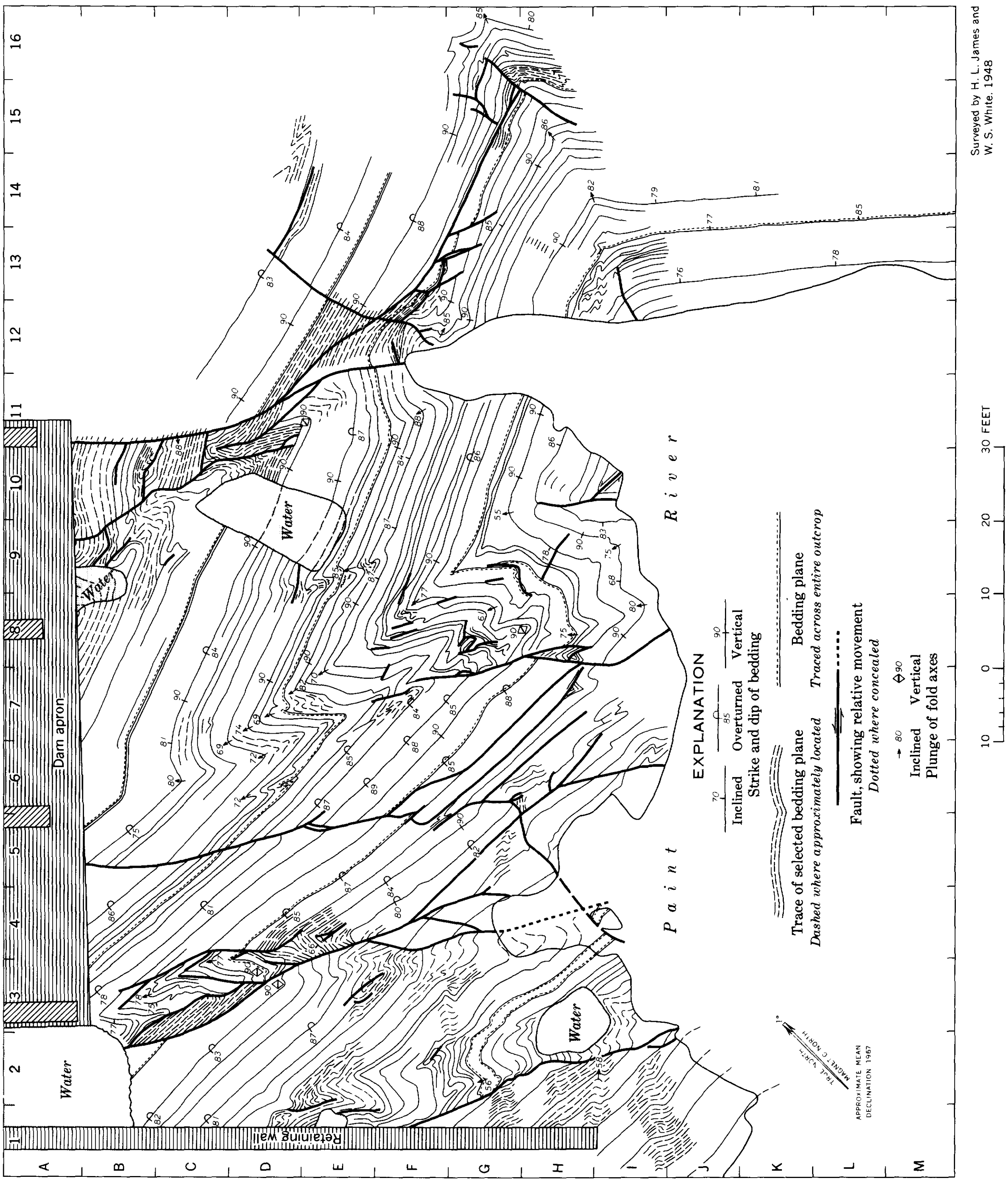


FIGURE 21.—Structural map of iron-formation outcrop at Paint River dam, Iron County, Mich.

formation grades laterally within about 1,000 feet into rock that is almost entirely siderite.

As the number and thickness of carbonaceous seams increase, the chert-siderite rock grades into "slaty iron-formation"; this change is accompanied by an increase in the amount of pyrite and a concomitant decrease in the amount of siderite. In some of this slaty iron-formation, the chert forms abundant thin layers, but more commonly it decreases in amount and occurs as lenses and nodules as shown in figure 25. Figure 25 also shows interbedding of impure dark-gray siderite with pyritic carbonaceous material (black in the photograph). The slaty iron-formation may, in turn, grade into a pyritic carbonaceous slate indistinguishable from the Wauseca Pyritic Member of the Dunn Creek Slate that underlies the Riverton. Most of the pyrite in the slaty iron-formation is exceedingly fine grained, but some occurs as coarsely crystalline bleblike patches as much as a quarter of an inch across, most commonly along some structural discontinuity such as a bedding plane. Slaty iron-formation occurs as a distinctive unit about 30 feet thick in the lower part of the Riverton in the Crystal Falls area; the rock commonly contains much nodular chert with pyrite localized around the chert nodules (fig. 26).

The Riverton Iron-Formation in the Crystal Falls area contains two lithologic types very scarce or not present in the western part of the district. In some parts of that area, but best seen at the apron of the Paint River dam in Crystal Falls, the chert-siderite iron-formation contains layers that consist dominantly of stilpnomelane. These layers, which are from a fraction of an inch to several inches in thickness, are readily distinguished in outcrop from the chert and siderite by their inferior hardness and by their peculiar closely spaced cross fracture that resembles that of some coal. The second variant type is one in which much of the iron is in the form of magnetite. Such megnetite-bearing rock is exposed in test pits and outcrops in the NW¼SE¼ sec. 30, T. 43 N., R. 32 W., and in a roadside exposure in the SE¼SW¼ sec. 36, T. 43 N., R. 33 W. Magnetic surveys in the Crystal Falls area show that the magnetite-bearing part lies about in the middle of the formation and is a discontinuous unit. The best section of this rock was seen in Jones and Laughlin drill hole 2111, in the SW¼NW¼ sec. 21, T. 43 N., R. 32 W. Much of the rock penetrated in the upper part of the hole consists of white to reddish-brown chert interlayered with magnetite and locally with stilpnomelane; it is very similar in general appearance to some of the magnetite-bearing facies of iron-formation of the Marquette district. Magnetite-bearing rock has been observed at only one locality in the western part of the district; namely, in core from holes drilled in the SE¼ NW¼ sec. 30, T. 43 N., R. 34 W., adjacent to Ice Lake. The magnetic facies here seems to be of only minor extent, as the related magnetic anomaly can be traced for no more than half a mile.

In parts of the Iron River area, a graphitic chert breccia is the basal unit of the Riverton Iron-Formation. The breccia is present in most mines of the Mineral Hills area, where it rarely is more than 5 feet thick. It has been recognized locally in the southeastern part of the Iron River district (in the Zimmerman mine), but its greatest thickness, 200 feet or more, is in the area immedately south and southeast of Stambaugh.

Where unoxidized, the breccia is black, massive, and unbedded and has chert fragments and plates that typically are less than 2 inches long but which may be as much as 12 inches long. The fragments are angular and unoriented, and most are rimmed by coarse pyrite. Despite its dark color, the iron in the breccia is principally in the form of carbonate; a typical sample from the 7th level of the James mine contains 35.3 percent siderite and 12.5 percent pyrite, as calculated from partial analysis.

In the area of the Bengal, Cannon, and Caspian mines, in the Iron River area, the stratigraphic position of the chert breccia is occupied by a complex assemblage of chert breccia, graphitic slate, and slaty iron-formation, with local interbeds of graywacke. The sequence is similar in almost all respects to that which overlies the Riverton Iron-Formation in many places; it differs only in that it grades downward into typical laminated pyritic slate and slate breccia of the Wauseca Pyritic Member of the Dunn Creek Slate. The contact with the Riverton Iron-Formation is one of gradation and interbedding. The thickness of this assemblage probably reaches a maximum in the S½ sec. 36, T. 43 N., R. 35 W., where, even after allowance for probable folding, it must be nearly 200 feet. Graywacke with chert fragments also occurs at approximately this stratigraphic position in at least two localities in the Crystal Falls area: at the Bristol mine and in outcrop near the SE. cor. sec. 29, T. 43 N., R. 32 W. The local presence of material so similar to the basal strata of the overlying Hiawatha Graywacke, particularly in thicknesses as at the Bengal mine area, is an exceedingly unfortunate circumstance so far as exploration in the district is concerned; stratigraphic classification of rock such as the chert breccia ("chert conglomerate") found by drilling in the SE¼ sec. 23, T. 43 N., R. 34 W., is impossible without further information.

Breccias of chert and siderite are fairly common at or near the top of the formation, where they may grade into the basal breccia of the overlying graywacke, but

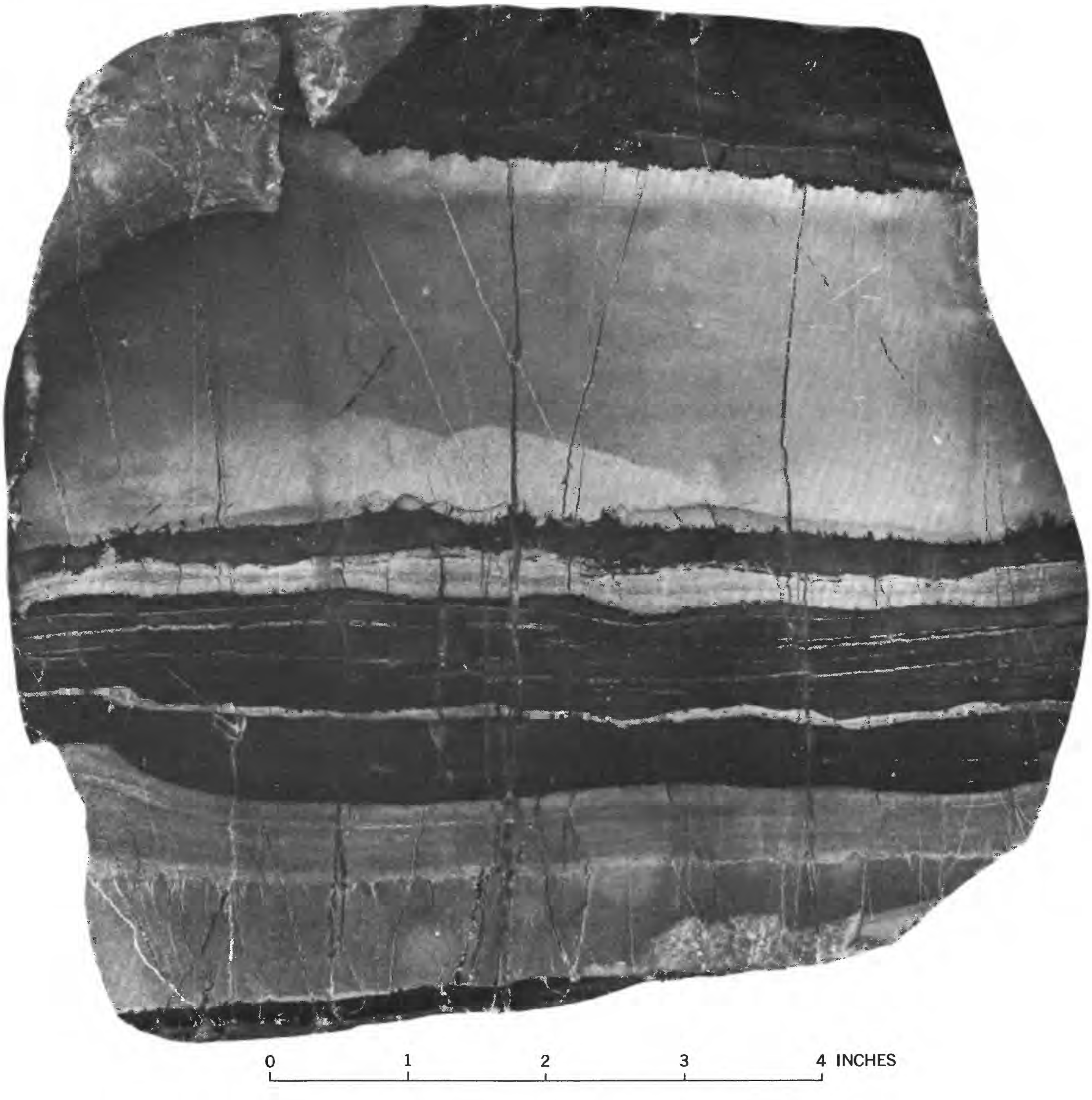


FIGURE 22.—Chert-siderite rock of the Riverton Iron-Formation. Polished surface, etched with HCl. Chert dark, siderite light. Veinlets mainly quartz. The thickest siderite layer, which is unusual both in thickness and in lack of lamination, shows well-formed stylolites at both contacts. Specimen from 6th level of Spies mine.

some are interbedded and are to be classed as intraformational. These breccias are tight, dense rocks and ordinarily show no evidence of having been sheared or broken (fig. 27). Stylolites are not as common as in the banded iron-formation but locally are present. They do not show distortion. The breccia shown in figure 27*A* has an entirely chaotic arrangement but that shown in 27*B* grades into broken bedding and is confined to a single layer. The breccias probably are to be ascribed to slumping during sedimentation.

Much of the iron-formation seen in outcrop, drill core, and underground workings is oxidized. The oxidized iron-formation retains the banded structure of the original rock, and in fact, the layering may be accentuated; otherwise, the rock is quite different in appearance. The carbonate (or silicate) is altered to red

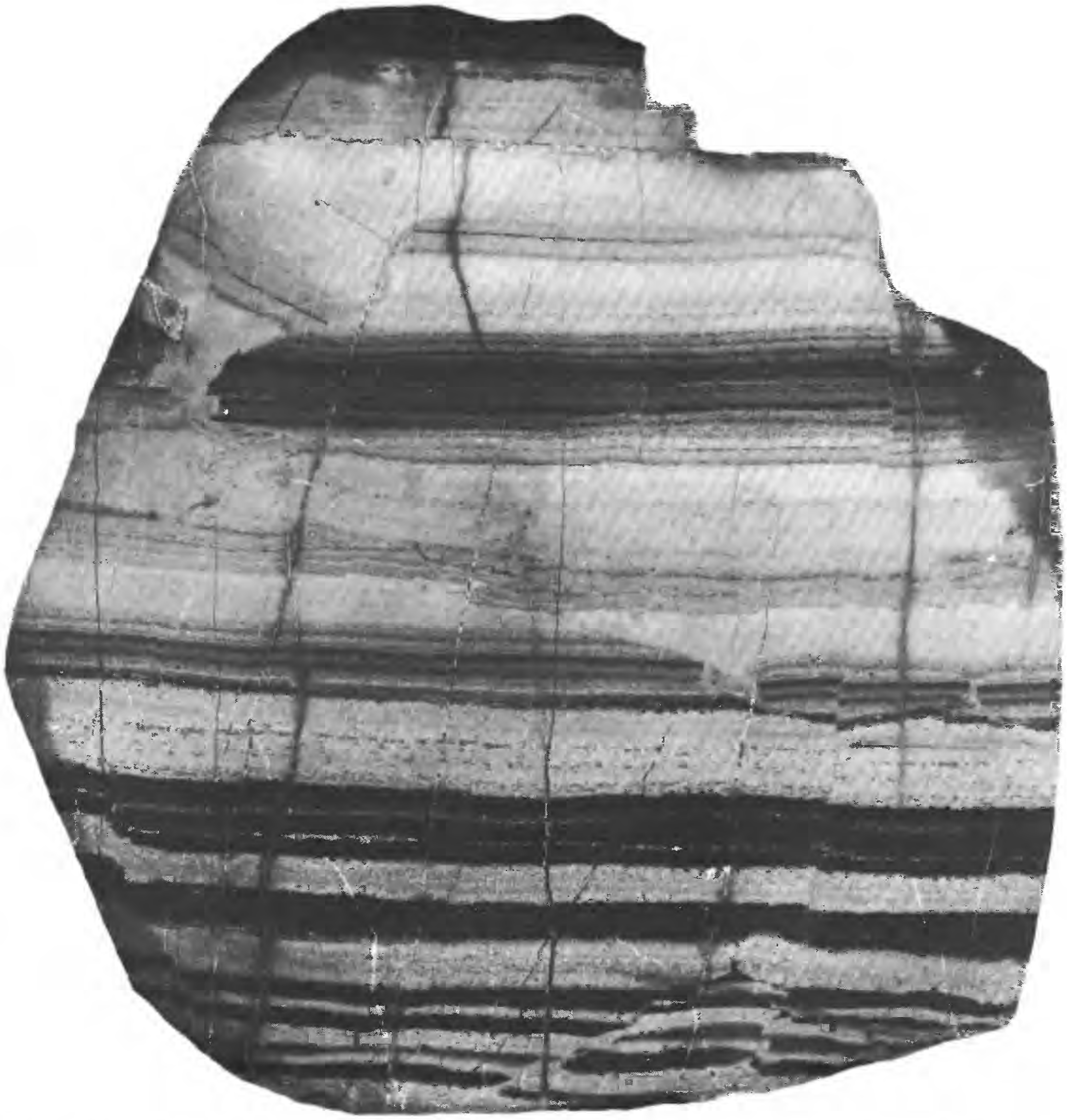


FIGURE 23.—Chert-siderite rock from the Riverton Iron-Formation. Polished surface, etched with HCl. Chert dark, siderite light. Note prelithification slump structures, such as the one at upper left that does not displace stylolite seam above. Specimen from 6th level of Spies mine. About natural size.

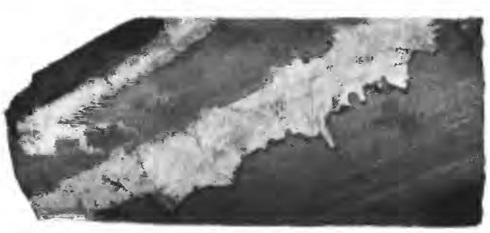


FIGURE 24.—Stylolite seam between chert and siderite in drill core of Riverton Iron-Formation. Chert white, siderite dark gray. Natural scale.

or yellow oxides, and the originally dark chert layers are changed to white or gray. The latter change is not a true color change, as the dark appearance of the chert in the unoxidized iron-formation is due to internal reflection rather than to pigmentation; this is brought out by the fact that in drill core such chert is white because of surface abrasion by the drill bit. The change to light color in consequence of oxidation probably is due to slight alteration of the quartz at grain boundaries, which permits light to be reflected.

The iron oxides range from bluish red to light yellow and consist of both hematite and goethite in varying proportions. This material may be very hard and massive or earthy, and commonly it is very porous. Iron oxides also can be seen to have effected partial or complete replacement of chert layers, with the end product of this replacement being a hematitic or goethitic iron ore. In general, the slaty iron-formation yields a more varied assemblage of oxidized materials than does the nonslaty iron-formation. Very commonly, the oxidized slaty iron-formation is varicolored, with green, buff, and gray predominating; locally it may be altered to dark-colored hematitic slate. The aspects of the ore deposits and processes involved are discussed in greater detail later in this report, in the section "Ore deposits."

SUBDIVISIONS

The Riverton Iron-Formation cannot be subdivided into members that extend throughout the district (see fig. 14), but useful subdivisions can be made that hold for local areas. Some of the more significant are summarized below:

1. A graphitic chert breccia commonly occurs at the base of the formation in the western part of the district. In most places, as in Mineral Hills, it is a thin unit, rarely more than 5 feet thick; however, in the area of the Caspian, Bengal, and Cannon mines, it is a complex unit as much as 200 feet thick, in which chert breccia is interbedded with and gradational into dark slaty iron-formation, pyritic slate, and dark graywacke.

2. Also in the western part of the district, and especially in the eastern part of the Mineral Hills area, the iron-formation can be divided into two principal units exclusive of the thin basal breccia. The lower member, about 100 feet thick, consists of interbedded chert and siderite; the upper member, which consists of interbedded siderite, nodular chert, and pyritic slate in varying proportions, is about 200 feet thick. Locally the upper member is absent because of pre-Hiawatha erosion.

3. In the Chicagon mine area, core available from holes drilled in sec. 26, T. 43 N., R. 34 W., shows that the formation consists of a lower slaty unit 50–100 feet thick and an upper cherty unit, about 125 feet thick, that also is slaty in part. The lower unit is characterized by chert nodules and, where unoxidized, is black and pyritic.

4. In the Crystal Falls area, two locally distinctive units are present within the iron-formation. The first is a slaty iron-formation member (see fig. 26), well exposed in the Tobin and Book mines. The bed, which is perhaps 30 feet thick, is within the lower third of the formation and forms the footwall of many ore bodies. A second distinctive unit consists of magnetite-rich strata that lie approximately in the middle of the formation. The thickness of this unit is not known but is probably about 50 feet. The rock is exposed in the SW¼NE¼ and the NW¼SE¼ sec. 30, T. 43 N., R. 32 W. The magnetic surveys indicate that the magnetic unit is discontinuous, probably in part because of gradation in primary sedimentary facies to nonmagnetic rock and in part because of later oxidation.

FIGURE 25.—Drill core of slaty Riverton Iron-Formation. Carbonate, gray; chert (nodules), white; slate layers, black. Length of specimen about 2 inches.

PETROGRAPHY AND CHEMICAL COMPOSITION OF UNOXIDIZED ROCK

The two dominant constituents of the normal unoxidized iron-formation are chert and siderite. The

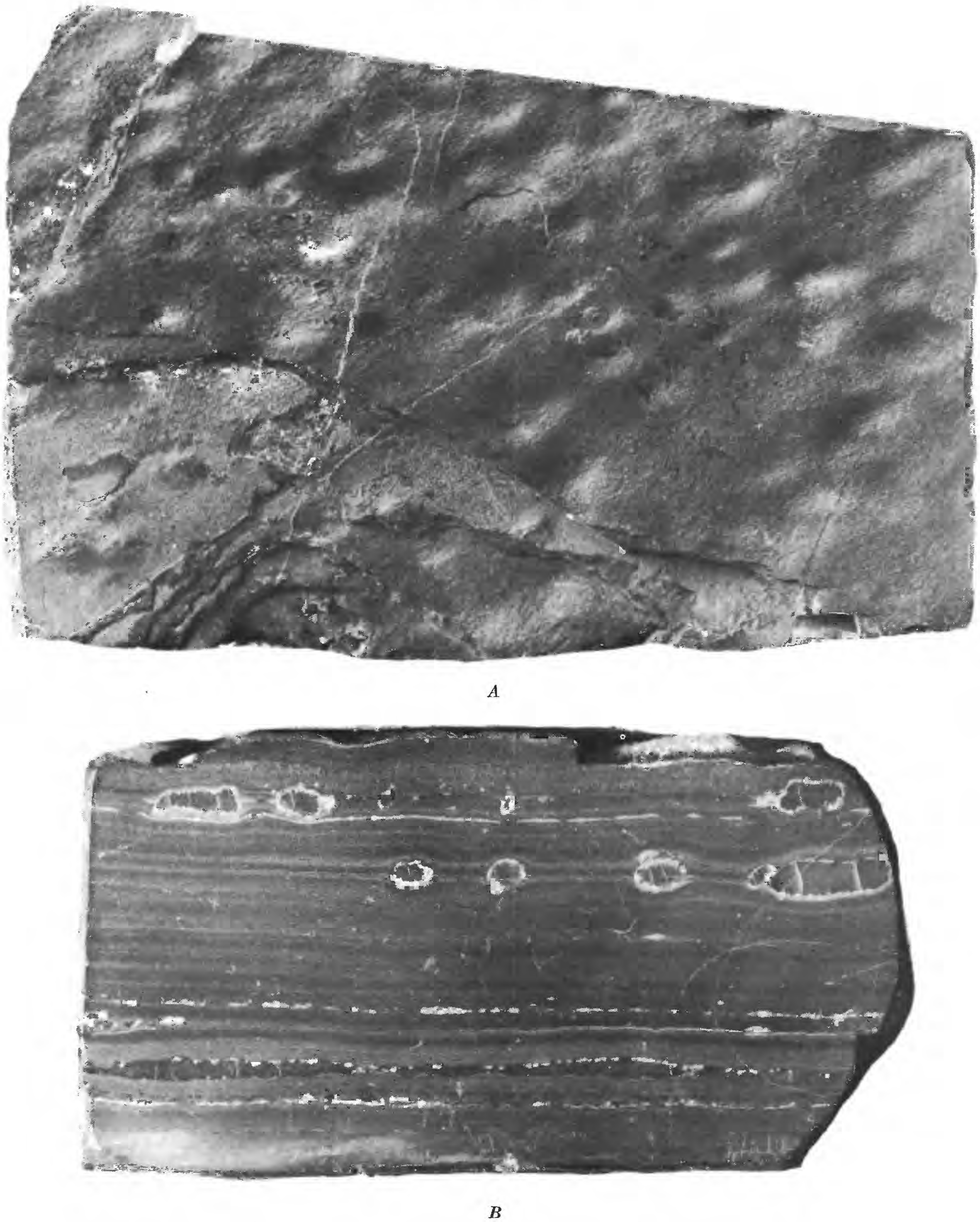
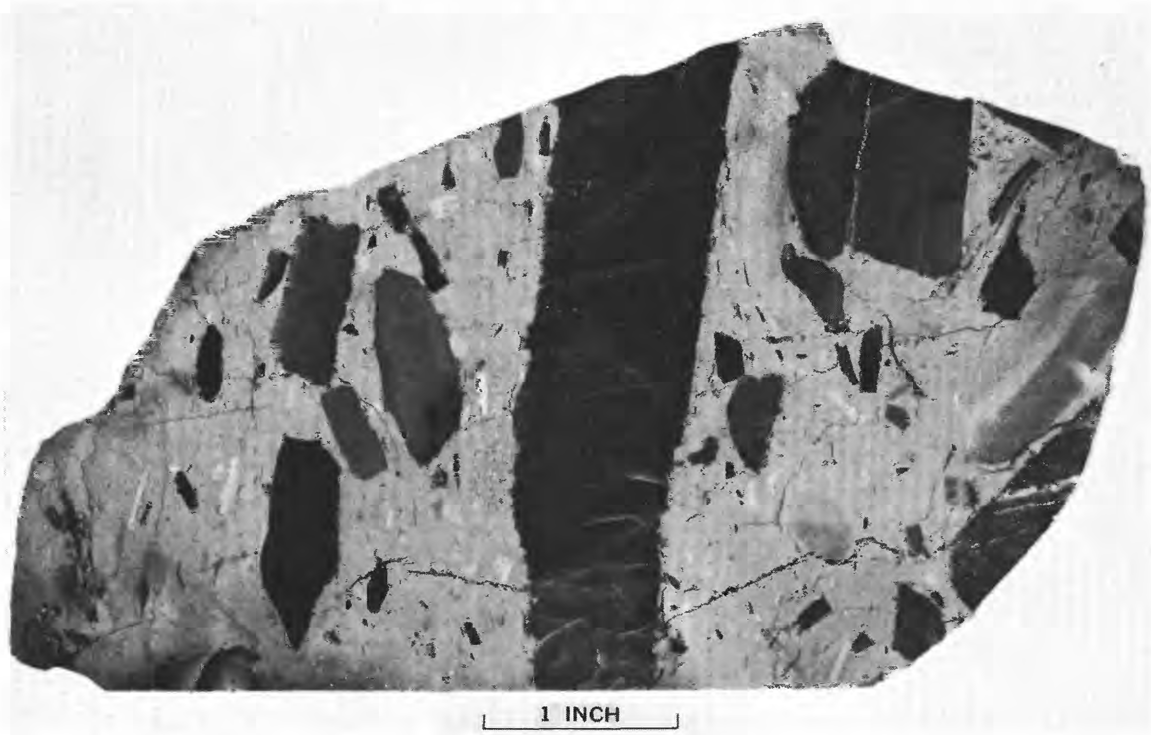


FIGURE 26.—Nodular chert in the lower part of the Riverton Iron-Formation in the Crystal Falls area. *A*. Appearance of bedding surfaces. *B*. Appearance in polished cross section; light-colored pyrite around chert nodules and along bedding planes. Specimens from the Tobin mine. Length of specimens, about 6 inches.



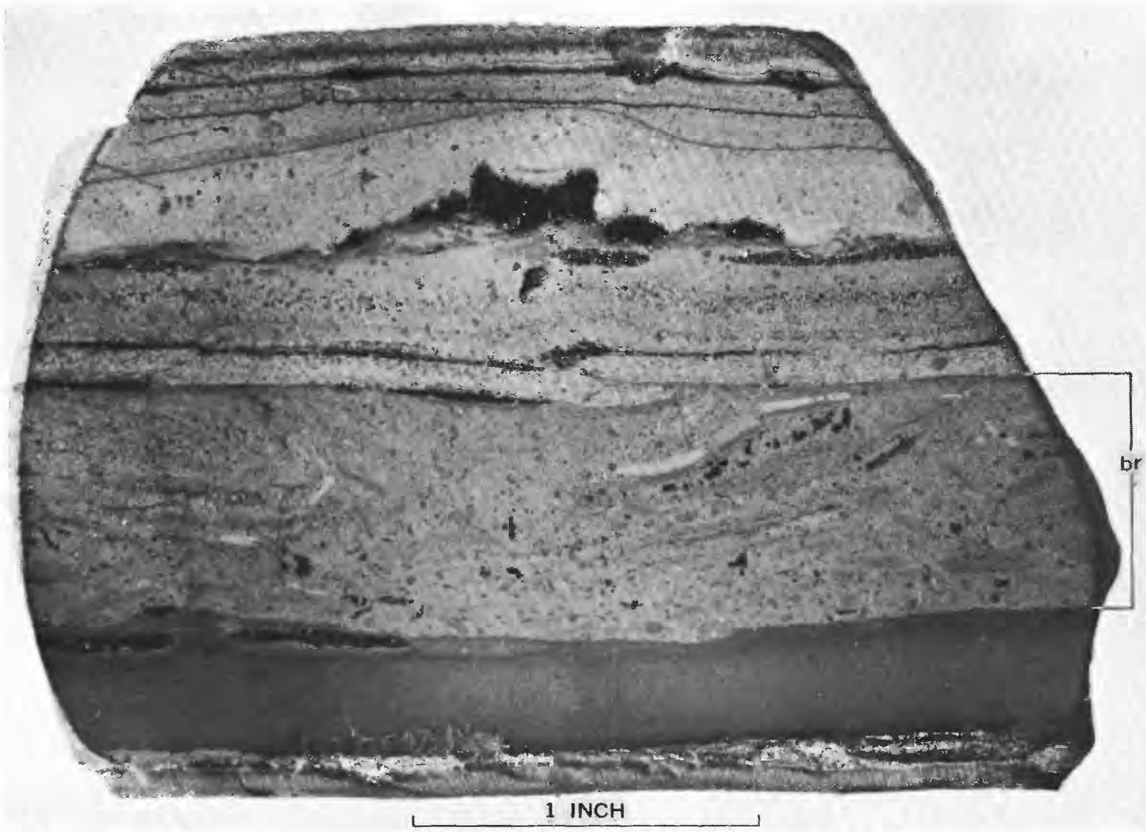
A

FIGURE 27.—Breccias from the Riverton Iron-Formation. Polished surfaces, etched with HCl. Chert, dark; siderite, gray. *A*. Chaotic breccia from thick layer of massive unbedded rock, from Buck mine. *B*. Small-scale breccia confined to a single layer (br), from Hiawatha mine.

chert layers consist of fine-grained crystalline quartz that is clear in ordinary light under the microscope. Under crossed nicols, the quartz is seen to be in the form of small grains of exceedingly intricate outline. The average diameter of the quartz grains in chert from the Iron River area is about 0.01 mm, whereas that from the eastern part of the district is about 0.03 mm. This grain size of the quartz in the chert layers is a valid index of degree of metamorphism (James, 1955), and although both the Iron River and Crystal Falls areas fall within the chlorite zone of regional metamorphism, the increase in the quartz grain size is clear evidence that the eastern part of the area is of slightly higher metamorphic rank than the western part.

The siderite in the unoxidized iron-formation is somewhat more variable in grain size than the chert, but most of it is almost equally as fine grained. In general, it is dark gray with a mottled, "dirty" appearance except where it has crystallized in the form of rhombs; in its crystallized form, it is clearer and lighter in color. The carbonate layers rarely are entirely pure; commonly they contain some interstitial chert and silicate (chlorite in the western part of the district, chlorite and stilpnomelane in the eastern part).

The stilpnomelane that is in the iron-formation in the eastern part of the district occurs both as massive layers and as scattered grains in the chert and siderite (fig. 28). The layers that consist dominantly of stilpnomelane are brown in thin section, and discrete grains cannot be seen. Under crossed nicols the material is dark. Where the stilpnomelane is disseminated in the siderite or chert, however, the form and characteristic pleochroism is evident under high magnification, as it is in powders of the more massive layers (fig. 28). The stilpnomelane is somewhat similar to biotite in appearance. It is very strongly pleochroic, sensibly uniaxial, with $Z=Y=$dark olive green or very dark brown; $X=$ pale yellow or nearly colorless. Hutton (1956) showed that the stilpnomelane group has properties that vary chiefly with the relative amounts of ferrous and ferric iron. Optically, these variations are recorded in a difference in pleochroism (dark brown or black for the ferric types, greenish for the ferrous types) and in the indices of refraction. The gamma index is especially useful, as it can be determined on the cleavage flakes. Measurements on iron-formation rocks of the Crystal Falls area show that this index typically ranges from 1.625 to 1.685 (higher values, as much as 1.732, are observed on stilpnomelane in the Stambaugh Formation). According to the chart given by Hutton (1956), the 1.625 value



B

indicates a composition, in terms of the (Fe, Mg, Mn)O : (Fe, Al)$_2$O$_3$ ratio, of about 24:76; the 1.685 value, a composition of 47:53. It is interesting to note that considerable differences in the ferrous-ferric ratio are found within adjacent laminae (fig. 28), a feature that must reflect original differences in the oxidation potential existing in the sediment at the time of deposition.

Several less common features are noted in the petrography of the unoxidized iron-formation. Locally, especially where impure, the siderite is granular or spherulitic (fig. 29). The granules are about 0.025 mm in diameter, and most have a tiny core of dark material that probably is chlorite. The spherules are larger and commonly less clearly defined. Both structures probably are due to concretionary growth of the carbonate after deposition. Another minor feature of note in the unoxidized iron-formation is the relationship between crosscutting veinlets and stylolite seams. Some of the veinlets cut the stylolites, but others are truncated at the contact (fig. 30).

Thousands of partial analyses of the iron-formation are available from the drill records of the mining companies. These analyses show the average iron content of the unoxidized iron-formation to be about 25 percent and the range to be from less than 10 percent in those parts that are exceedingly cherty to as much as 40 percent in parts that consist predominantly of carbonate. The iron content of the slaty iron-formation is little different from that of the purer chert-siderite rock—if anything, it may be a little higher—but the iron is in the form of sulfide and silicate as well as carbonate.

Two complete analyses of unoxidized iron-formation are given in table 8. Sample 1 was split from 3 feet of drill core that seemed typical of a drilled 310-foot section of iron-formation from the Iron River area. The total iron of the sample, however, is about 28 percent, whereas the average iron content of the 310 feet, from analyses made by the mining company of sludge for 5-foot intervals, is 24.7 percent. The analysis has been recalculated so as to give an iron content of 25 percent, each value, except that of SiO_2, being reduced proportionately. SiO_2 is added to bring the total to 100 percent. The results of this calculation, given as analysis 2 in the table, represent approximately the average composition of the normal iron-formation. The second complete analysis, given as analysis 3 in the table, is of a sample taken from the Paint River dam outcrop and believed to be approximately representative of the exposure. The presence of stilpnomelane is shown by the relatively low content of CO_2 and slightly high Fe, as compared with

VOLUME PERCENT			
CHERT	SIDERITE	STILPNOMELANE	PYRITE
50	25	25	-
3	90	2	5
70	20	10	-
90	5	5	-
70	30	-	-
-	85	-	15
95	3	2	-
85	5	10	-
30	70	-	-
-	100	-	-
-	50	-	50
20	60	20	-
-	75	25	-
-	-	95	5
-	50	50	-
-	-	95	5
-	40	60	-
-	-	95	5
5	3	92	-
5	50	45	-

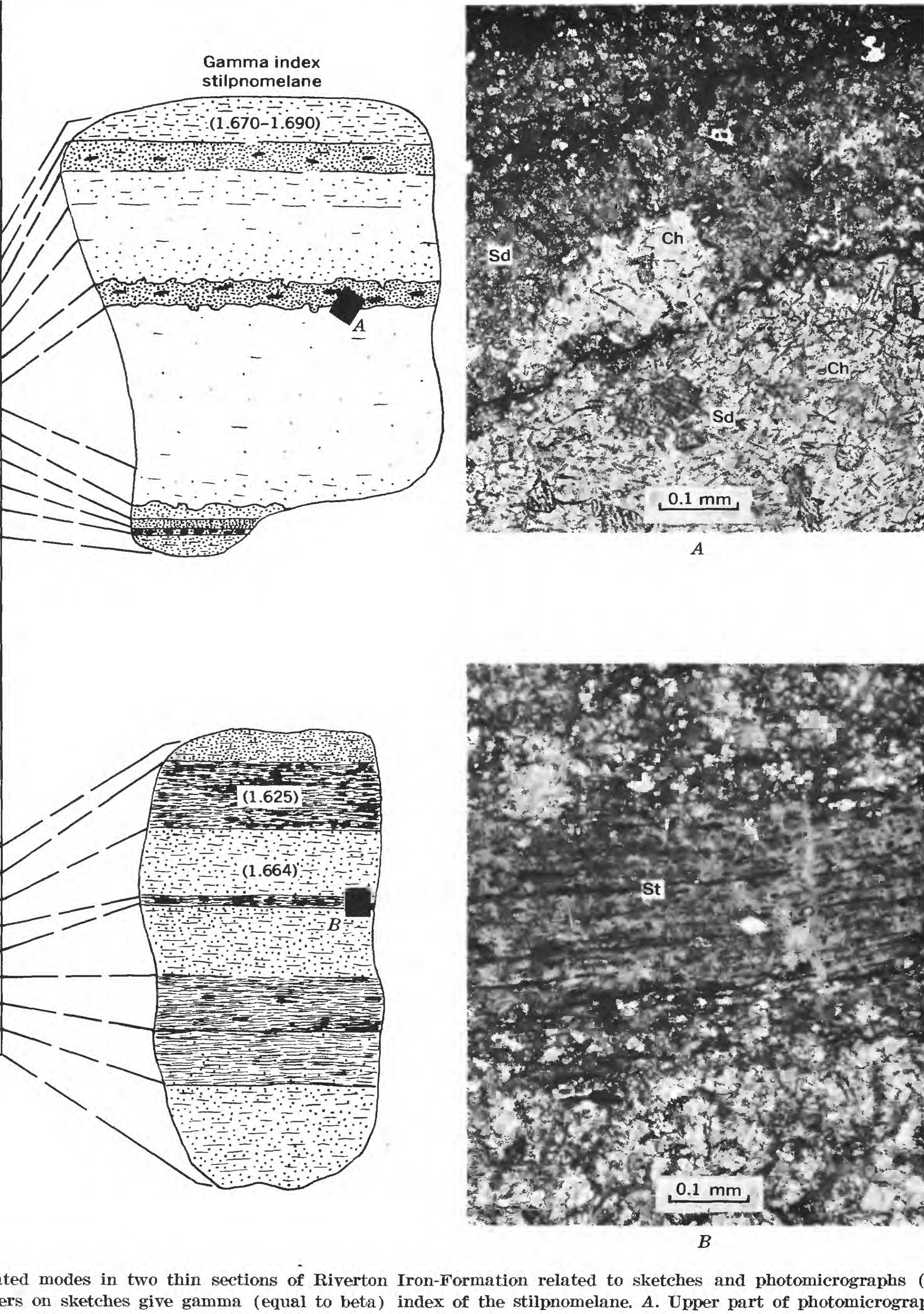
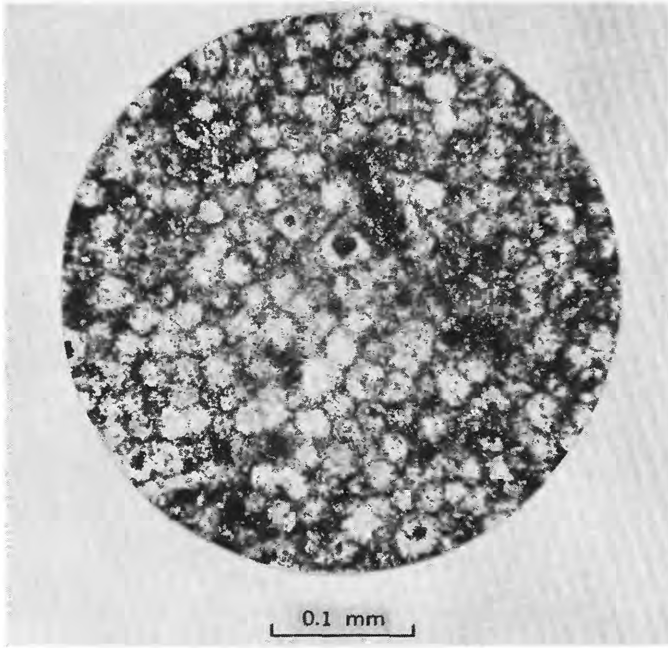
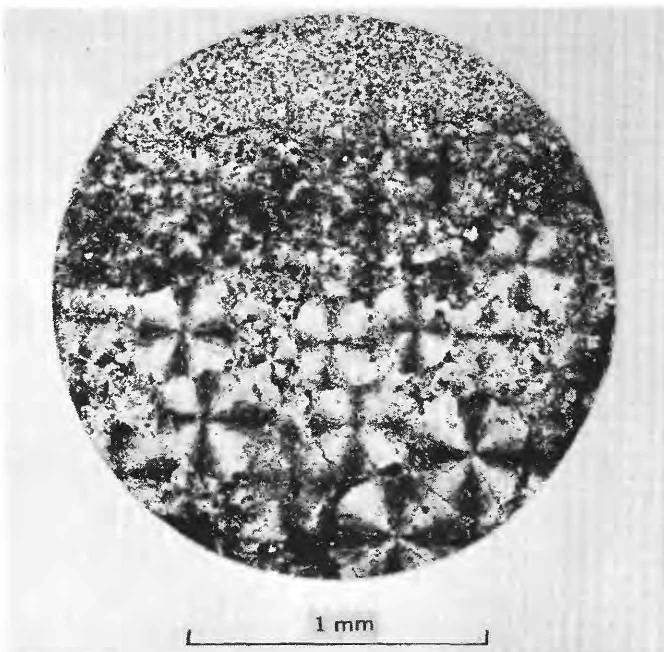


FIGURE 28.—Estimated modes in two thin sections of Riverton Iron-Formation related to sketches and photomicrographs (*A* and *B*). Numbers on sketches give gamma (equal to beta) index of the stilpnomelane. *A*. Upper part of photomicrograph shows principally siderite (Sd) with some pyrite (black); lower part is chert (Ch), with stilpnomelane needles and patches of siderite. Note stylolite seam. *B*. Photomicrograph shows massive stilpnomelane layer (St), interbedded with siderite containing scattered stilpnomelane needles. Ordinary light. Specimen HJ–308–47.



A



B

FIGURE 29.—Siderite from the Riverton Iron-Formation. *A*. Siderite granules, some with cores of greenish material, probably chlorite. Ordinary light. Specimen HJ-14-47, from 9th level of Hiawatha mine. *B*. Siderite spherulites, showing uniaxial cross that is due to radial arrangement of crystal fibers. Crossed nicols. Specimen 43-MC-526, from 8th level of Spies mine.

the recalculated analysis for chert-carbonate rock given under analysis 2.

TABLE 8.—*Chemical analyses of iron-formation and chert*

[Analysts: Charlotte Warshaw and Leonard Shapiro. n.d., not determined]

	1	2	3	4
SiO_2	24. 25	32. 2	31. 84	88. 94
Al_2O_3	1. 71	1. 5	2. 09	. 15
Fe_2O_3	. 71	. 6	[1] 26. 3	. 61
FeO	35. 22	31. 6		5. 77
MgO	3. 16	2. 8	3. 80	. 04
CaO	1. 78	1. 6	1. 49	. 32
Na_2O	. 04	------	n.d.	. 04
K_2O	. 20	. 2	n.d.	. 04
TiO_2	. 00	. 0	. 12	. 00
MnO	2. 11	1. 9	2. 35	. 67
H_2O^+	. 04	------	[2] 1. 80	. 10
H_2O^-	. 16	. 1		. 02
P_2O_5	. 91	. 8	. 83	. 22
CO_2	27. 60	24. 8	19. 40	2. 80
C	1. 96	1. 8	n.d.	. 26
S	. 21	. 2	. 33	. 04
Total	100. 06	100. 1	------	100. 02
Less O for S	. 10	. 1	------	. 02
Total	99. 96	100. 0	------	100. 00

[1] Total iron. Direct determination of FeO not made because of presence of organic matter.
[2] Includes organic material.

1. Chert-siderite rock, from Beta 2 hole, footage 550-620; sec. 26, T. 43 N., R. 35 W.
2. Analysis 1 recalculated so as to give 25 percent total Fe.
3. Iron-formation; principally chert-siderite but with some stilpnomelane. Paint River dam, sec. 20, T. 43 N., R. 32 W.
4. Impure chert, interbedded with siderite 2 of table 10.

The recalculated analysis 2 can be used to determine the mineralogical composition of the chert-siderite rock (table 9). In the calculation, CO_2 was assigned to the MnO, MgO, and CaO to satisfy the requirements as carbonates; the remaining CO_2 was assigned to FeO. The amount of CO_2 present almost exactly fulfills the requirements of the four oxides (0.2 percent excess FeO) so that the error possible in the value obtained for the composition of the carbonate is small. The rock contains a small amount of iron-rich chlorite, 1 percent or less, so, 0.2 percent SiO_2 is arbitarily allotted to this mineral. The remaining silica is quartz.

TABLE 9.—*Mineralogical composition of iron-formation*

	Weight percent
Carbonate (81.0 $FeCO_3$, 4.9 $MnCO_3$, 9.5 $MgCO_3$, 4.6 $CaCO_3$)	62. 4
Chert	32. 0
Carbon	1. 8
Miscellany (phosphate, sulfide, chlorite, iron oxide)	3. 8
Total	100. 0

Analysis 4, in table 8, is of a chert sample chipped from banded chert-carbonate rock at the same locality as the siderite of sample 2 in table 10. The analysis indi-

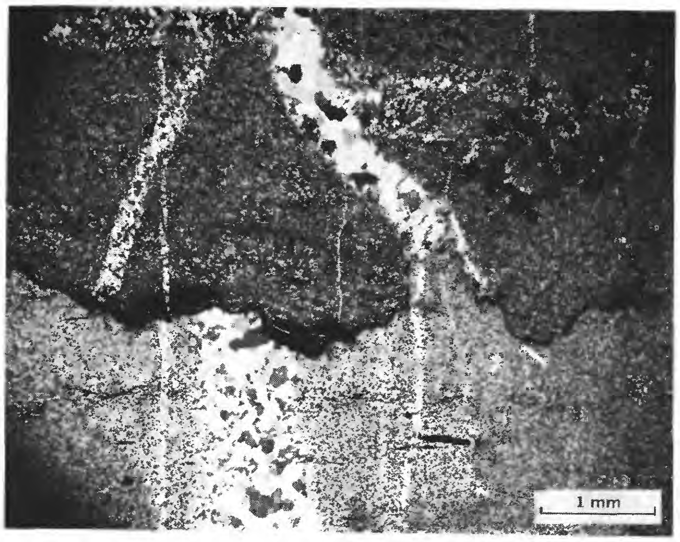


FIGURE 30.—Quartz veinlets truncated by stylolite seam along contact between siderite layer (dark gray) and chert. Partly crossed nicols. Specimen HJ–186–47, from underground drill hole in SE¼ sec. 24, T. 43 N., R. 35 W.

cates about 7 percent carbonate and an appreciable amount of iron oxide, presumably magnetite.

No samples of the slaty iron-formation were taken for complete analysis, but the mineralogical evidence indicates that all gradations could be found between compositions such as those given and compositions such as that represented by the analysis of pyritic slate (table 5) in which virtually all the iron is in the form of sulfide.

Eight analyses of carbonate layers in the iron-formation are given in table 10. Analyses 1 and 2 are of composite samples obtained by splitting carbonate layers from cherty iron-formation; analyses 3–8 are of individual thin layers. The greatest variation in composition is in manganese, which varies inversely with iron; the calcium and magnesium components are relatively constant. The analyses are also given in mineralogic terms in table 11, which gives the calculated composition of the carbonate. X-ray examination of the carbonate shows it to be a single phase, with lattice spacing close to that of siderite (fig. 31). The P_2O_5 is assumed to be present as apatite, but this has not been confirmed by X-ray data, possibly in part because some of the principal reflections of apatite are near those of the siderite.

The isotopic composition of the carbon has been investigated by Oana and Deevey (1960). The sample measured was chert-siderite with graphitic partings, from drill hole 207, sec. 30, T. 43 N., R. 34 W. The

TABLE 10.—*Chemical analyses of siderite layers in iron-formation*

[Analysts: 1, Charlotte Warshaw. 2, Leonard Shapiro. 3–8, H. F. Phillips, P. L. D. Elmore, and P. W. Scott; rapid-method analyses, except for vanadium; vanadium determined by spectrographic analysis, Janet D. Fletcher. n.d., not determined]

	1	2	3	4	5	6	7	8
SiO_2	18.11	22.97	0.65	0.45	0.35	0.09	0.22	0.53
Al_2O_3	.18	1.08	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Fe_2O_3 [1]	.34	3.59	------	------	------	------	------	------
FeO [1]	40.68	33.17	46.7	47.3	48.0	46.0	48.3	49.0
MgO	3.59	2.02	4.2	4.9	4.8	5.2	5.3	4.8
CaO	1.31	1.48	1.1	2.1	1.7	3.5	.80	2.2
Na_2O	.06	.06	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
K_2O	.04	.10	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
TiO_2	Trace	.10	0.00	0.00	0.00	0.00	0.00	0.00
MnO	2.56	6.77	8.2	4.8	5.0	5.0	4.7	4.2
H_2O+	.05	.14	.09	.08	.07	.12	.14	.10
H_2O-	.09	.16						
P_2O_5	.47	.62	.64	1.1	.97	2.4	.33	1.4
CO_2	30.52	26.50	38.0	37.0	37.5	36.4	38.4	37.4
C	1.41	2.02	.20	2.5	1.7	1.5	1.7	.38
V	n.d.	n.d.	.003	.001	.001	.002	.002	.0008
S	.06	n.d.	.06	.02	.02	.02	.02	.03
Total	99.47	100.78	99.9	100.2	100.1	100.2	99.9	100.0
Fe+Mn	33.6	30.6	42.2	40.2	40.9	39.4	41.0	41.1

[1] Total iron for samples 3–8 recorded as FeO; probably little or no Fe_2O_3 is present.

1. Siliceous siderite layers, from cherty iron-formation. Drill hole Beta 6, 392–395 feet, sec. 27, T. 43 N., R. 35 W.
2. Siliceous siderite, from upper part of iron-formation. Spies mine, sec. 24, T. 43 N., R. 35 W.

3–8. Thin layers of siderite, from iron-formation at James mine, 6th level, near shaft. Samples were selected from material that had been mined for a large-scale metallurgical test and then left exposed to the weather for about a year. The rock, strongly coherent when mined, split along bedding planes as a result of frost action. The five samples represent five separate layers a quarter to half an inch thick, three of which (3, 4, 5) were adjacent and in that order.

TABLE 11.—*Calculated mineral compositions and carbonate compositions, in weight percent, of analyzed carbonate layers*

	1	2	3	4	5	6	7	8
Mineral compositions (calculated from analyses)								
Quartz	18.1	23.0	0.6	0.4	0.3	0.1	0.2	0.5
Carbonate	76.9	68.0	96.2	93.9	94.7	91.3	96.6	94.6
Apatite	1.3	1.3	1.3	2.7	2.3	5.7	.7	3.4
Pyrite	.2	([1])	.2	.1	.1	.1	.1	.1
Carbon	1.4	2.0	.2	2.5	1.7	1.5	1.7	.4
Other constituents	[2] 2.1	[2] 5.7	1.5	.4	.9	1.3	.7	1.0
Carbonate compositions								
$FeCO_3$	83.9	76.3	76.3	78.8	80.0	77.9	79.8	81.2
$MnCO_3$	5.3	16.0	13.8	8.3	8.4	8.9	7.9	7.2
$MgCO_3$	9.9	6.2	9.1	11.4	10.6	11.9	11.5	10.7
$CaCO_3$	.9	1.5	.8	1.5	1.0	1.3	.8	.9

[1] Sulfur not determined in analysis.
[2] Probably hematite for the most part.

C^{13}/C^{12} ratios, expressed as parts per thousand (‰) above or below the PDB standard (a marine carbonate), are as follows:

Material	‰ C^{13}
1. Chert layer	−10.7
2. Siderite layer	−13.7
3. Free carbon, from (2)	−30.5

All are markedly depleted in C^{13} as compared with both marine carbonates and mean crustal carbon, which were reported by Oana and Deevey (p. 266) to contain −5.7. The significance of the results is not readily apparent, but Oana and Deevey suggested that they may support Hough's interpretation (1958) that the rocks accumulated in a fresh-water lake.

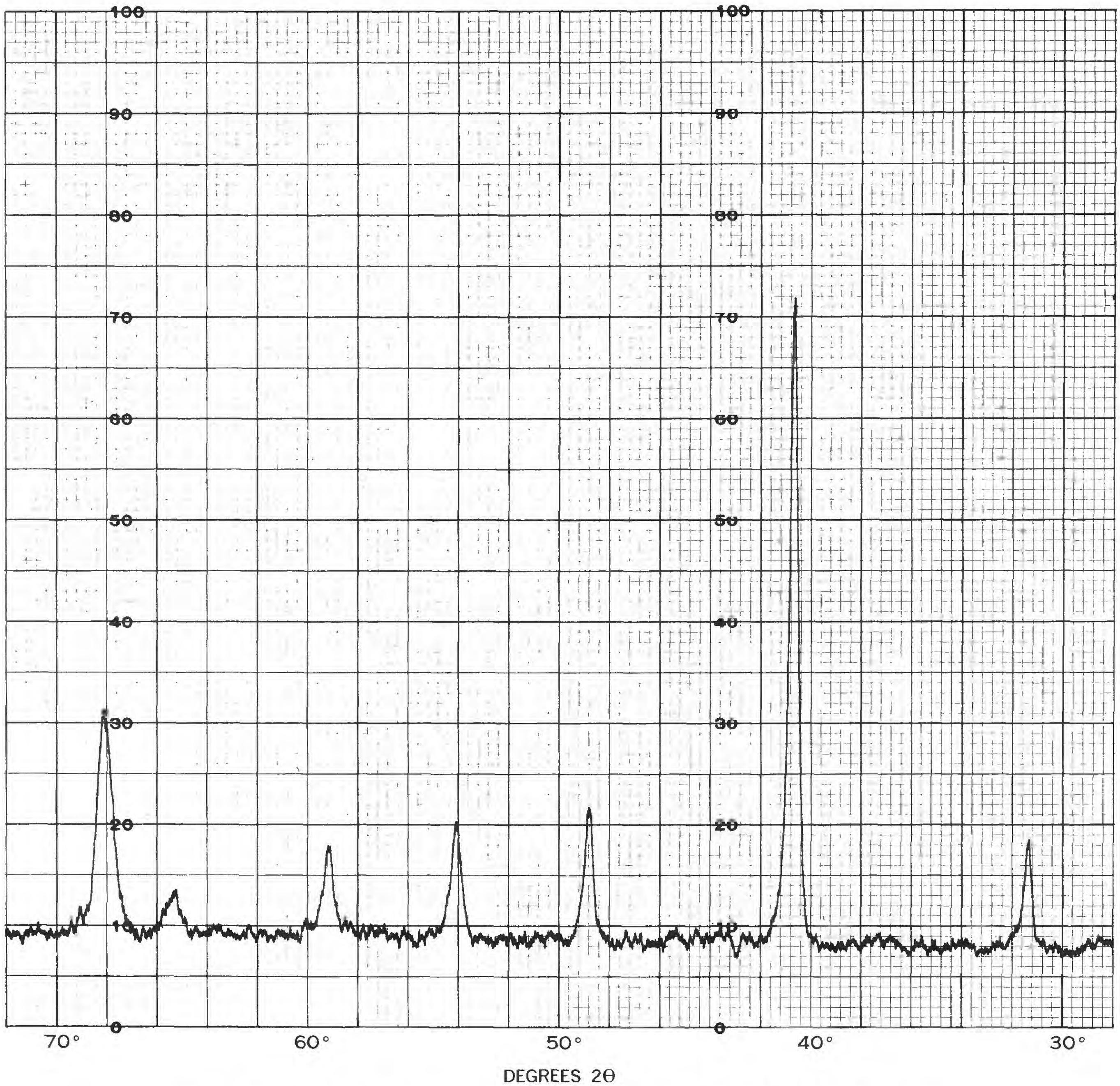


Figure 31.—X-ray diffraction record of siderite "4" in tables 10 and 11. FeKα radiations.

THICKNESS AND RELATIONS TO ADJACENT FORMATIONS

The thickness of the Riverton is difficult to determine, in part because of original differences but in larger part because of the complex crumpling that is characteristic of the unit. The thickness is most readily measured on the limbs of major structures, particularly where such structures are crossed by mine workings, but even here uncertainties persist. At such localities the question arises as to whether the dragfolds should be "unraveled" so as to reduce the stratigraphic measurement. This seemingly correct procedure, however, may yield values that are too low; the apparent thickening by internal folding may no more than compensate for the thinning caused by squeezing on the limbs of the major structure so that the thickness measured without discounting repetition on the minor folds may be a fair approximation of the original stratigraphic thickness.

The most reliable determinations indicate typical thicknesses of 500–800 feet in the eastern part of the district and 150–300 feet in the western part. In the latter area, as much as half the iron-formation may consist of slaty iron-formation and pyritic slate that are not ordinarily included with the iron-formation in mine mapping. In all parts of the district, the formation may locally be much thinner than normal because of erosion prior to deposition of the overlying Hiawatha Graywacke. This erosional truncation is most prominent in the western part of the Mineral Hills area, north of Iron River; at the Cardiff mine (NE¼NE¼ sec. 22, T. 43 N., R. 35 W.), the iron-formation in the western part of the workings is less than 50 feet thick, and drill holes to the west and south have shown that in some places the iron-formation is less than 10 feet thick. Erosional thinning of the iron-formation also is indicated from drilling in sec. 25, T. 34 N., R. 35 W., and in workings of the Odgers mine in Crystal Falls; these and other examples are discussed further in the description of the Hiawatha Graywacke.

The relationship between the Riverton Iron-Formation and the underlying pyritic slate most commonly is one of abrupt gradation, with interlayering of pyritic slate and chert-siderite rock through a few feet of thickness. In some places, however, the interbedded zone is tens of feet thick, as in the Chicagon Creek area; in the area of the Caspian, Bengal, and Cannon mines, the normal iron-formation is separated from the Wauseca Pyritic Member by as much as 200 feet of graphitic chert breccia, slaty iron-formation, pyritic slate, and dark graywacke.

The relationship between the Riverton Iron-Formation and the overlying Hiawatha Graywacke is discussed in detail under the section dealing with the Hiawatha; briefly, the contact is a disconformity or an unconformity without perceptible angular truncation.

HIAWATHA GRAYWACKE

The Hiawatha Graywacke is a clastic unit that, as the name implies, consists dominantly of graywacke. Slate and siltstone are abundant in some areas and may make up as much as 25 percent of the unit. The lowermost part of the Hiawatha Graywacke commonly, though not invariably, is a breccia that consists of angular fragments of chert in a graywacke matrix. This distinctive breccia marks the unconformity or disconformity that separates the upper part of the Paint River Group from the lower part. In part of the Crystal Falls area, nearly the whole formation may be breccia; in the Iron River area, the breccia is quantitatively as abundant but is much subordinate to graywacke as a component because of a greater total thickness of the formation.

Most of the rock is a dark-gray massive medium-grained graywacke in which clastic grains are readily distinguishable. Small fragments of slate and of chert are not uncommon. Interbedded with the graywacke are layers of massive light- to dark-gray slate and (very rarely) thin layers of chert. The slate is not normally as sericitic as the Dunn Creek Slate, and the graywacke typically is considerably coarser in grain than the siltstones of that unit. In the western part of the Iron River area, particularly in secs. 22, 26, and 27, T. 43 N., R. 35 W., the graywacke is particularly coarse grained and contains a large amount of clastic feldspar.

BRECCIA FACIES

The breccia facies of the Hiawatha Graywacke is well exposed in the outcrop area along the Paint River in Crystal Falls (see detailed outcrop map, pl. 2), where it can be seen to grade into normal graywacke along the strike. The rock consists of angular fragments of chert set in a matrix of dark-gray graywacke; these fragments are commonly an inch or more in diameter but locally are slabs as much as 2 feet in length. The chert is clearly derived from the underlying iron-formation, and although siderite is not common as fragments it is abundant in the matrix. All gradations can be found, from rock consisting dominantly of chert debris (fig. 32) to normal graywacke containing scattered chert fragments, or to graywacke containing none. Locally the breccia resembles a true conglomerate (fig. 33). In the northern part of the Iron River district, the breccia commonly is black and graphitic rather than sandy. Such material is particularly abundant in the Davidson mine at Iron River and is not uncommon in other mines and explorations in the area. The material is difficult, if not impossible, to distinguish from chert

FIGURE 32.—Breccia facies of the Hiawatha Graywacke as exposed in NW¼SE¼ sec. 20, T. 43 N., R. 32 W. Rock mainly a disordered aggregate of chert fragments.

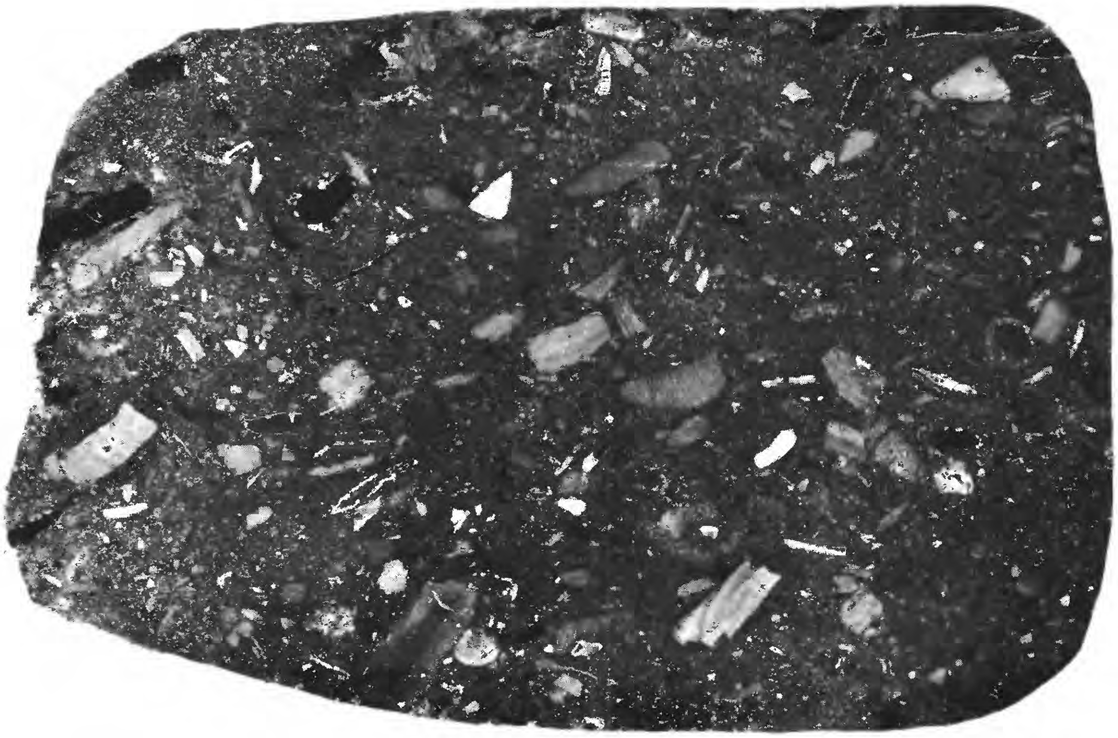


FIGURE 33.—Breccia-conglomerate facies of the Hiawatha Graywacke. Polished specimen from the Hiawatha mine, Iron River. Most fragments are chert (both light and dark), but some are rounded gray pebbles of siderite. Natural scale.

breccia that locally occurs at the base of the Riverton Iron-Formation.

The upper part of the Riverton Iron-Formation commonly is a breccia also, and in places the iron-formation breccia grades into the breccia facies of the Hiawatha Graywacke. At the Hiawatha mine, for example, drill hole 501 passed successively through massive graywacke, a graywacke with chert fragments, an iron-formation breccia, and banded chert-siderite typical of the Riverton Iron-Formation (fig. 34). The difference between the breccia facies of the graywacke and that of the iron-formation lies in the nature of the matrix: in the iron-formation it is wholly siderite, without clastic material, whereas in the graywacke it consists of clastic grains in a paste of siderite and chloritic material.

PETROGRAPHY AND CHEMICAL COMPOSITION

The graywacke consists of scattered subangular clastic grains in a fine-grained matrix that ordinarily constitutes 25–40 percent of the rock. Most of the clastic grains are quartz, but chert grains and fragments are common. Feldspar is scarce in the normal graywacke, and "heavy" minerals are exceedingly sparse. The matrix consists of very fine grained pale-green chlorite, randomly oriented, and scattered patchy siderite. Locally the siderite is the major matrix material, and in a few thin sections from the Crystal Falls area, golden-brown stilpnomelane is abundant.

The clastic chert and quartz typically show replacement by chlorite. In most thin sections examined, the chert is at least 50 percent replaced, and the quartz slightly embayed, but in others the chert is inferred only from phantom outlines and the quartz grains are all marginally replaced (fig. 35). This replacement does not bear any spatial relation to ore bodies or to structural features. Similar marginal replacement has been described for many iron-rich sediments; it probably is due to diagenetic reactions that affected the rock shortly after deposition, rather than to later metamorphism. There is no apparent chemical or crystallographic difference between the quartz of the chert grains and that of the quartz grains at the present time, but the alteration probably took place at a time when the chert was chalcedonic or opaline.

The feldspathic graywacke of the western part of the Iron River area is coarser and more poorly sorted than the normal graywacke. Much of it might well be classed as an arkose because feldspar (both plagioclase and orthoclase) constitutes about 25–35 percent of the clastic grains. The matrix also is different from that of the normal graywacke in that it contains fairly abundant sericite, in addition to chlorite, and little or no car-

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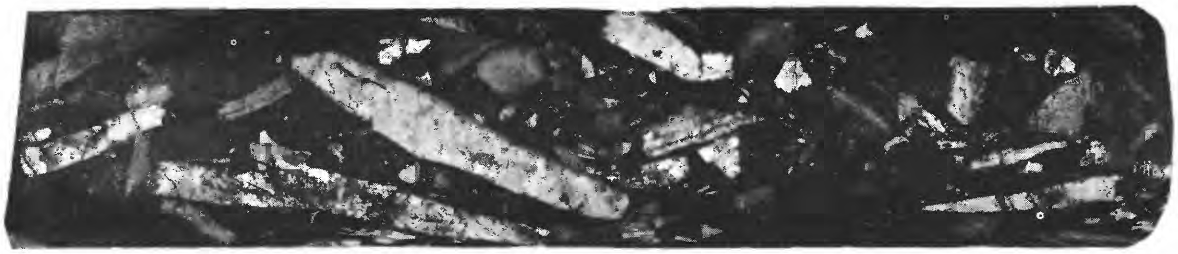
A



B

C

FIGURE 34.—Transition from breccia facies of the Hiawatha Graywacke to iron-formation breccia. Hiawatha mine drill hole 501. The drill hole passed successively through massive graywacke, graywacke with abundant chert fragments (*A*), iron-formation breccia (*B*), iron-formation with segmented chert layers (*C*), and then into normal bedded chert-siderite rock of the Riverton Iron-Formation. Natural scale.

bonate. The clastic grains in the sericite-chlorite matrix show virtually no marginal alteration, in contrast to the strong alteration of the rocks with chlorite-siderite matrix. The slates associated with the graywackes are fine-grained aggregates of chlorite, sericite, carbonate, and fine clastic quartz. Sericite is less abundant than in similar rocks of the Dunn Creek Slate, and cleavage is not conspicuous.

Most of the graywacke and slate of the Hiawatha Graywacke is relatively rich in iron. Routine iron analyses of drill-hole sludge by the mining companies show the normal slates and graywackes to contain 12–22 percent Fe, an amount considerably more than that of the lithologically similar sericitic slate and siltstone of the Dunn Creek Slate. A complete analysis of a graywacke sample is given in table 12. The analyzed material, which is typical of the normal graywacke of the area, consists of about equal parts of quartz grains and matrix material; the matrix consists of about 80 percent chlorite (aphrosiderite) and 20 percent siderite. The rock contains much less alumina and alkalis than the average graywacke, a feature that is reflected mineralogically in the almost complete absence of clastic feldspar.

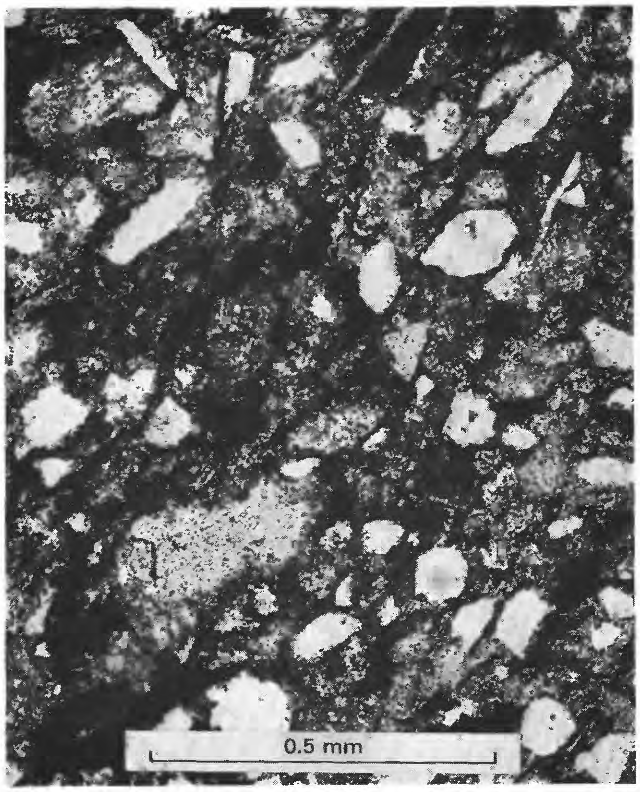
TABLE 12.—*Chemical analysis, in percent, of Hiawatha Graywacke, from Hiawatha mine, drill hole 501*

[Analyst: A. L. White]

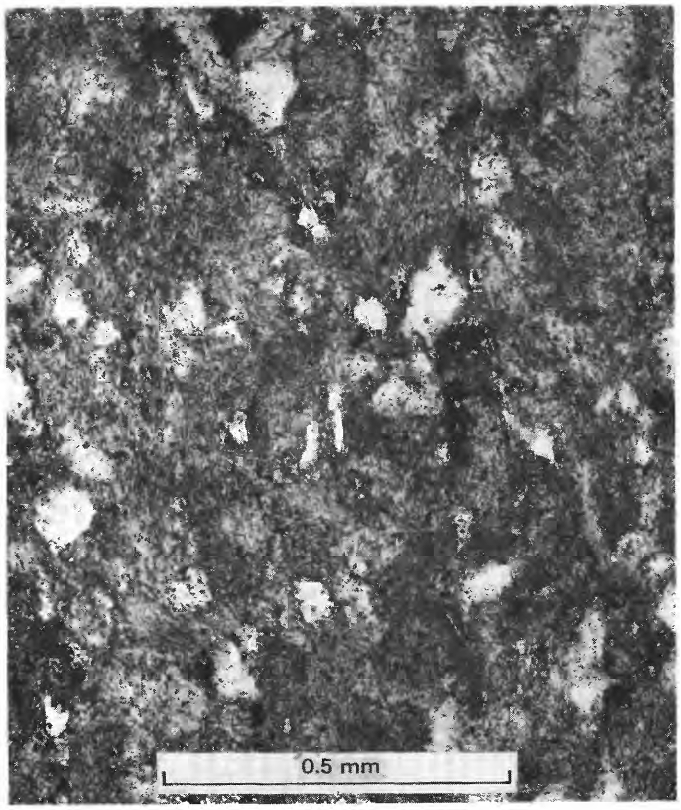
SiO_2	62.75	H_2O^-	0.23
Al_2O_3	7.05	H_2O^+	3.14
Fe_2O_3	1.84	TiO_2	.40
FeO	16.36	CO_2	3.83
MgO	2.95	P_2O_5	.10
CaO	.38	MnO	1.17
Na_2O	.05		
K_2O	0	Total	100.25

The feldspar-rich graywacke and the associated slates are much lower in iron than the normal type. Sludge analyses show that these rocks contain less than 10 percent Fe and that values of less than 5 percent are not uncommon.

In many places the rocks of the Hiawatha Graywacke have been oxidized and kaolinized as a result of the deep oxidation that produced the ore in the Riverton Iron-Formation. Locally, as for example in the Bengal mine area, some of the graywacke has an iron content of as much as 40 percent, and some of the slate is almost an iron ore. In other places the rocks may be altered almost entirely to clay minerals.



A



B

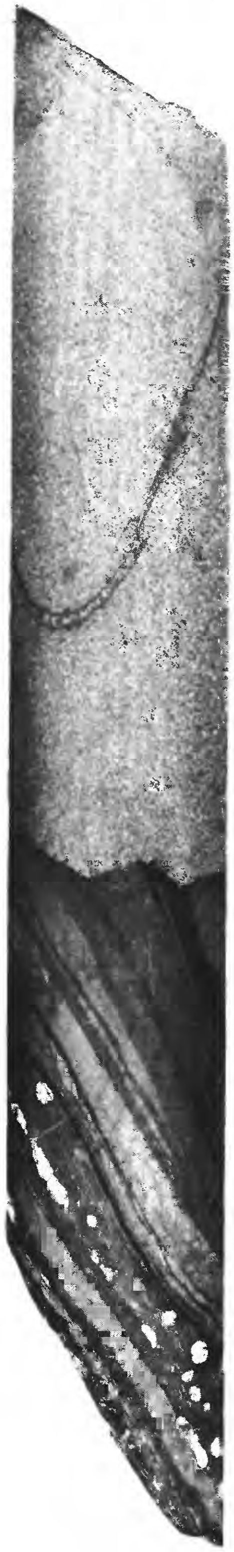
FIGURE 35.—Hiawatha Graywacke. *A*, Quartz grains show slight marginal replacement by chlorite, and chert grains (such as that in lower left quadrant) are cloudy because of alteration to chlorite. *B*, No chert grains preserved, and quartz grains are extensively replaced. Ordinary light. Specimens HJ–16–47 and HJ–17–47, from 9th level of Hiawatha mine.

THICKNESS AND RELATIONS TO ADJACENT FORMATIONS

The Hiawatha Graywacke has a great range in thickness (fig. 14). In the western part of the district, the thickness probably is as much as 500 feet in places, in the eastern part it is rarely more than 50 feet, and in the extreme southeastern part, the formation pinches out entirely. This pattern, it may be noted, is the reverse of that for the underlying Riverton Iron-Formation. The entire formation in the Crystal Falls area may be of the breccia facies, and this facies is locally of even greater thickness in the Iron River area, though much subordinate to graywacke in the formation as a whole.

The westward thickening of the formation is not entirely gradual; the major increase takes place within a short distance in the Chicagon Creek area (fig. 14), which is the vicinity of a southward-projecting "elbow" in the greenstone boundary (pl. 1). Very possibly this major irregularity in the greenstone outline reflects some structural feature that came into existence during the disturbance that halted iron-formation deposition or that existed earlier; such a structural feature might have caused significant local differences in the bottom topography that are now reflected by abrupt lateral changes in the thickness of the graywacke.

The abrupt passage of an epoch of chemical sedimentation into one of clastic deposition and the presence of basal breccia are evidence of a structural disturbance that halted iron-formation deposition. In single exposures the breccia might well be interpreted as a deformational feature, and in fact such an explanation was advanced by Clements (in Clements and Smyth, 1899, p. 166), who described some of the rock as a reibungsbreccia. This interpretation, however, is effectively disproved by the occurrence of the rock in a



characteristic stratigraphic position throughout the district; it is, in fact, a key horizon.

A sharply defined contact between breccia and the underlying iron-formation is well exposed in a bluff east of the Paint River, near the north line of lot 5 in the SE¼ sec. 20, T. 43 N., R. 32 W.

The Riverton-Hiawatha contact is not everywhere marked by a breccia; in places the iron-formation is overlain by normal graywacke or slate. Direct evidence of the unconformity has been seen in core from drill holes that have crossed the contact (fig. 36); angular discordance, marked by a basal conglomerate, reportedly has been observed in the now-abandoned and inaccessible workings of the Odgers mine.

The extent and intensity of the post-Riverton disturbance are difficult to evaluate, but locally the iron-formation has been substantially reduced from normal thickness. In the Mineral Hills area, for example, holes drilled in a westerly direction from the 9th level of the Homer mine penetrated only a few feet of iron-formation breccia between slates of the Wauseca Pyritic Member and graywacke of the Hiawatha, and other data suggest that the Riverton Iron-Formation may be missing entirely in some areas west of the Homer property. The thinning of iron-formation in some parts of this area and possible absence in others coincides with a change in character of the Hiawatha Graywacke from the sideritic nonfeldspathic type to a coarser grained feldspar-rich graywacke or arkose.

The evidence for a pre-Hiawatha interval of some structural disturbance and at least local erosion seems clear. But one feature needs further consideration. It is an observed fact that the graywacke or breccia immediately overlying the iron-formation does not contain oxidized material such as would be expected if the iron-formation had been exposed to subaerial erosion. The absence of iron oxides in the basal Hiawatha suggests that the erosion of the iron-formation was accomplished by submarine slumping and sliding of partly consolidated iron-formation, in consequence of structural disturbance that changed the contours of the basin of

FIGURE 36.—Unconformable contact between Riverton Iron-Formation and Hiawatha Graywacke in drill core. Bedding in graywacke (not visible in photograph) is nearly parallel to bedding in iron-formation, and graywacke is probably a channel filling. Iron-formation is slaty with chert nodules. Specimen HJ–152–50, from drill hole Hilltop No. 1, sec. 26, T. 43 N., R. 35 W., at 1,000 feet. Natural scale.

deposition. In such a situation, the iron-formation would have slumped down the newly formed slopes; the chert, which evidently was lithified prior to the siderite (as shown by the breccias within the iron-formation itself), would have accumulated locally as rubble; and most of the siderite would have been dispersed by currents to be mixed with the clastic material derived from active erosion of some more distant source area.

The transition between the Hiawatha Graywacke and the overlying Stambaugh Formation is relatively gradual; it is discussed in greater detail in the section dealing with that formation.

STAMBAUGH FORMATION

The Stambaugh Formation is referred to locally as the magnetic slate, on account of the strong magnetic anomaly that it causes. The magnetic aspect of the unit has been of inestimable value to the regional study, as it has permitted the tracing of the formation in areas lacking in exposure and consequent construction of rational map patterns for adjacent stratigraphic units. Largely by magnetic methods, the formation has been traced from near the Brule River in the southeastern part of the district, through the Alpha-Crystal Falls belt, thence westward to the Iron River area. The formation is not, however, uniformly magnetic; in fact, in a few areas it is entirely nonmagnetic. In places, the lack of magnetism may be due to oxidation, but in others it seems to be due simply to the original absence of magnetite in the rock.

The formation is named for the town of Stambaugh, which is built on a hill in sec. 36, T. 43 N., R. 35 W., on which some of the characteristic facies of the formation are exposed in several small outcrops. These are the only exposures of the formation in the western part of the district. The formation is exposed in several places in secs. 25 and 36, T. 43 N., R. 34 W., and in many places in the eastern part of the district. The most detailed information on thickness, physical character, and relations to adjacent formations has been gained from study of the outcrop area along the Paint River in the SE¼ sec. 20, T. 43 N., R. 32 W.

GENERAL ASPECTS

The Stambaugh Formation is in part a clastic deposit, in part a chemical precipitate. In terms of the sedimentary history of the Paint River Group, it represents a partial return to conditions of chemical sedimentation after an interlude during which the basin of deposition was flooded with the clastic material that now forms the Hiawatha Graywacke. Some of the most characteristic and distinctive parts of the unit are sufficiently iron-rich to be classed properly as iron-formation, but the rock lacks the interbedded chert.

The strata that constitute the Stambaugh Formation in the Paint River outcrop area (pl. 2) are grouped as follows: (1) a basal nonmagnetic slate, waxy green in color and delicately laminated, about 20 feet thick, (2) a strongly magnetic, gray, flinty, thinly laminated slate, about 40 feet thick, containing porcelanic layers of mixed chert and carbonate in the upper part, and (3) olive-drab mudstone interbedded with 2- to 4-inch layers of laminated white to dark-gray porcelanite, about 35 feet thick. Not uncommonly the porcelanite layers are separated from the mudstone by a layer of pyrite one-eighth to one-half an inch thick. A polished surface of one of these porcelanite layers is shown in figure 37. The border of dark material on the specimen, which is characteristic, consists chiefly of dark iron oxides; the rock is extremely susceptible to oxidation, so much so that fresh breaks on the rock will be entirely oxidized within a year.

In much of the district, the basal member and the most characteristic rock type of the Stambaugh Formation is a dense, tough, laminated rock of cherty aspect,

FIGURE 37.—Polished specimen showing laminated porcelanite in rock composed chiefly of intermixed chert and siderite, with scattered magnetite. Dark border partly surrounding porcelanite area is caused by alteration to secondary iron oxides, accompanied by bleaching at margin. Specimen HJ-23-49, from outcrop of Stambaugh Formation in SE¼ sec. 20, T. 43 N., R. 32 W. Natural scale.

gray and white in drill core but dark in color with a distinct purplish tint in outcrop (fig. 38). This rock is well exposed along the north side of the road at the old Monongahela location (SE¼ sec. 25, T. 43 N., R. 33 W.); in the SE¼ sec. 25, and the NE¼ sec. 36, T. 43 N., R. 34 W.; and on Stambaugh Hill in sec. 36, T. 43 N., R. 35 W. (immediately south of the high school buildings). It has been drilled in several places and rather commonly is described in drill logs as unoxidized iron-formation, which it resembles somewhat, or as cherty sideritic slate. Small-scale deformation is a common feature of the rock, one that can readily be seen in the Monongahela location outcrop and in most drill core. Typically the deformation consists of nonsystematic crumpling (fig. 39*A*), more rarely of small-scale faulting (fig. 39*B*). The deformation seems to be of preconsolidation origin. Layers of graywacke, some of which is magnetic, are found interbedded with the laminated rock in the Stambaugh Hill outcrops, in the outcrops in the SE¼ sec. 25, T. 43 N., R. 34 W., and in some of the drill cores. The sec. 25 outcrops also show pyrite layers such as were mentioned earlier in the description of the Paint River outcrop area. The pyrite occurs at the base of porcelanite layers (fig. 40); the relative position of pyrite and porcelanite is a reliable indication of original top directions in the bed (pyrite on the bottom).

Apparently overlying the laminated cherty facies of the Stambaugh Formation in the Iron River area is a massive dark slate that is strongly magnetic. This material was found in a drill hole in the NE¼NW¼ sec. 6, T. 42 N., R. 34 W. (Borland exploration), but little is known of its distribution.

Chloritic mudstones somewhat similar to those described for the Paint River outcrop area are well exposed in the northern part of sec. 1, T. 42 N., R. 33 W. (Dunn area), where they form the upper part of the formation. The rock is massive, thick bedded, and olive drab in color. It contains some layers of porcelanite.

In the extreme southeastern part of the district, between Alpha and the Brule River, the formation consists chiefly of a fissile dark-gray to olive-drab slate, part of which is magnetic. In this area, the formation apparently contains very little rock that can be classed as a chemical sediment; the distinctive lithologic attributes that permit the formation to be readily separated elsewhere are lacking, and the unit is distinguished from the overlying graywacke and slate chiefly by its magnetic properties.

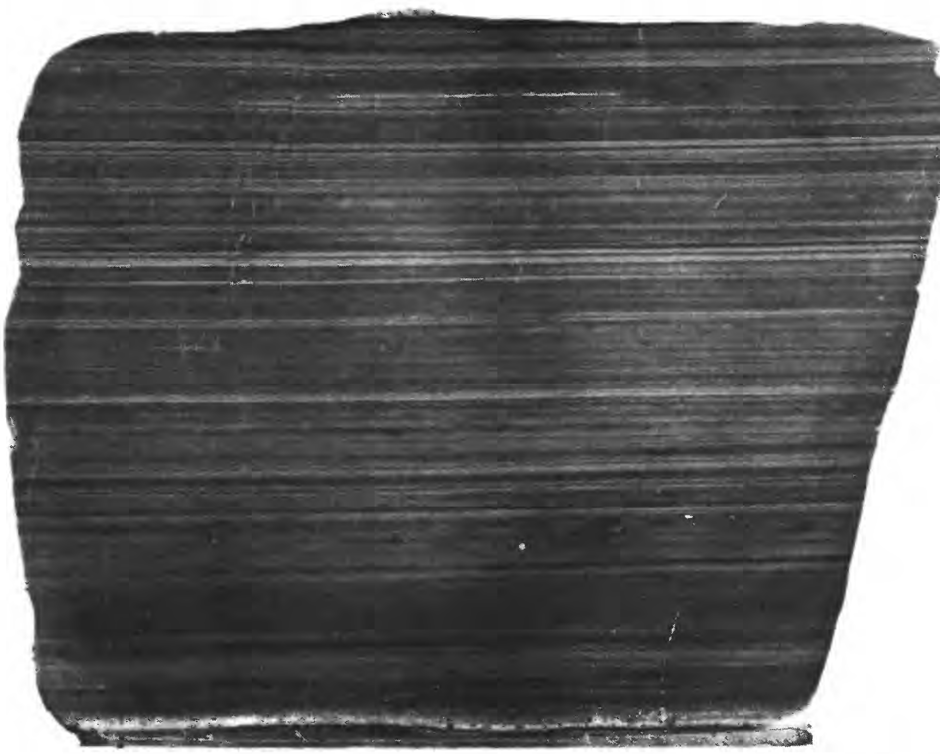


FIGURE 38.—Polished specimen of flinty magnetic slate, Stambaugh Formation. Rock is dark colored with purplish tint. From test pit in NW¼ sec. 25, T. 43 N., R. 34 W. Natural scale.

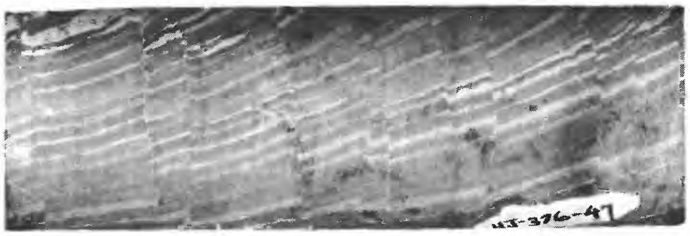


FIGURE 39.—Preconsolidation structures in drill cores of laminated flinty magnetic slate from the Stambaugh Formation. Slate contains chert, siderite, chlorite, and magnetite. From underground drill hole C–A–47, Hiawatha mine. *A*. Specimen HJ–381–47. *B*. Specimen HJ–376–47. Natural scale.

PETROGRAPHY AND CHEMICAL COMPOSITION

The rocks making up the Stambaugh Formation are, for the most part, exceedingly fine grained. Chlorite, siderite, chert, and magnetite are the principal constituents of the laminated rock that is the most characteristic facies of the formation, and chlorite is the principal constituent of the mudstones. At least 90 percent of the rocks is mixtures of these four minerals, in almost all proportions and combinations. Light-colored layers generally consist dominantly of siderite and chert, dark-colored layers of chlorite and magnetite. Stilpnomelane, sericite, and detrital quartz and feldspar are abundant in those beds of clastic or partly clastic origin. Pyrite is a common mineral in the rhythmically banded porcelanite; biotite and tourmaline are rare constituents.

The chlorite most commonly occurs as a mat of fine plates and fibers interstitial to other minerals. In the Iron River area it is so fine grained as to be virtually unresolvable as discrete grains even under the highest magnification of the microscope, but in the Crystal Falls area it is somewhat coarser though still very fine grained, typically forming plates 0.02–0.04 mm long. Some optical properties of this coarser chlorite are as follows: Pleochroism: $Z{=}Y{=}$green, $X{=}$pale green to colorless; absorption: $Z{=}Y{>}X$; optically negative, $X\perp 001$, positive elongation; $N_z{=}1.640$–1.653 (in specimens from separate areas); birefringence (estimated) $=0.003$–0.015.

These properties, according to the table given by Winchell and Winchell (1951, p. 383), place the chlorite in the aphrosiderite-thuringite-daphnite field of composition. Chlorites of this compositional range are typical of weakly metamorphosed iron-rich rocks in many parts of the world. The chlorite shows strong preferred orientation in sections where the grain is sufficiently coarse to permit determination. Siderite occurs as fine-grained granular aggregates intermixed with chert or chlorite or both, and in some layers it forms rhombs (fig. 41*A*). Chert is most abundant in the porcelanite

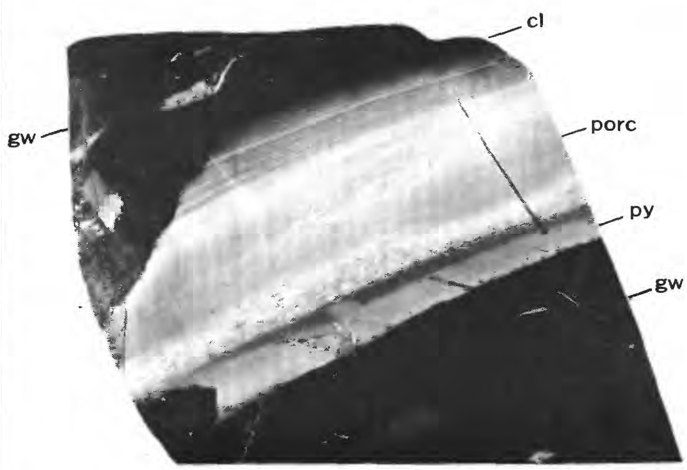
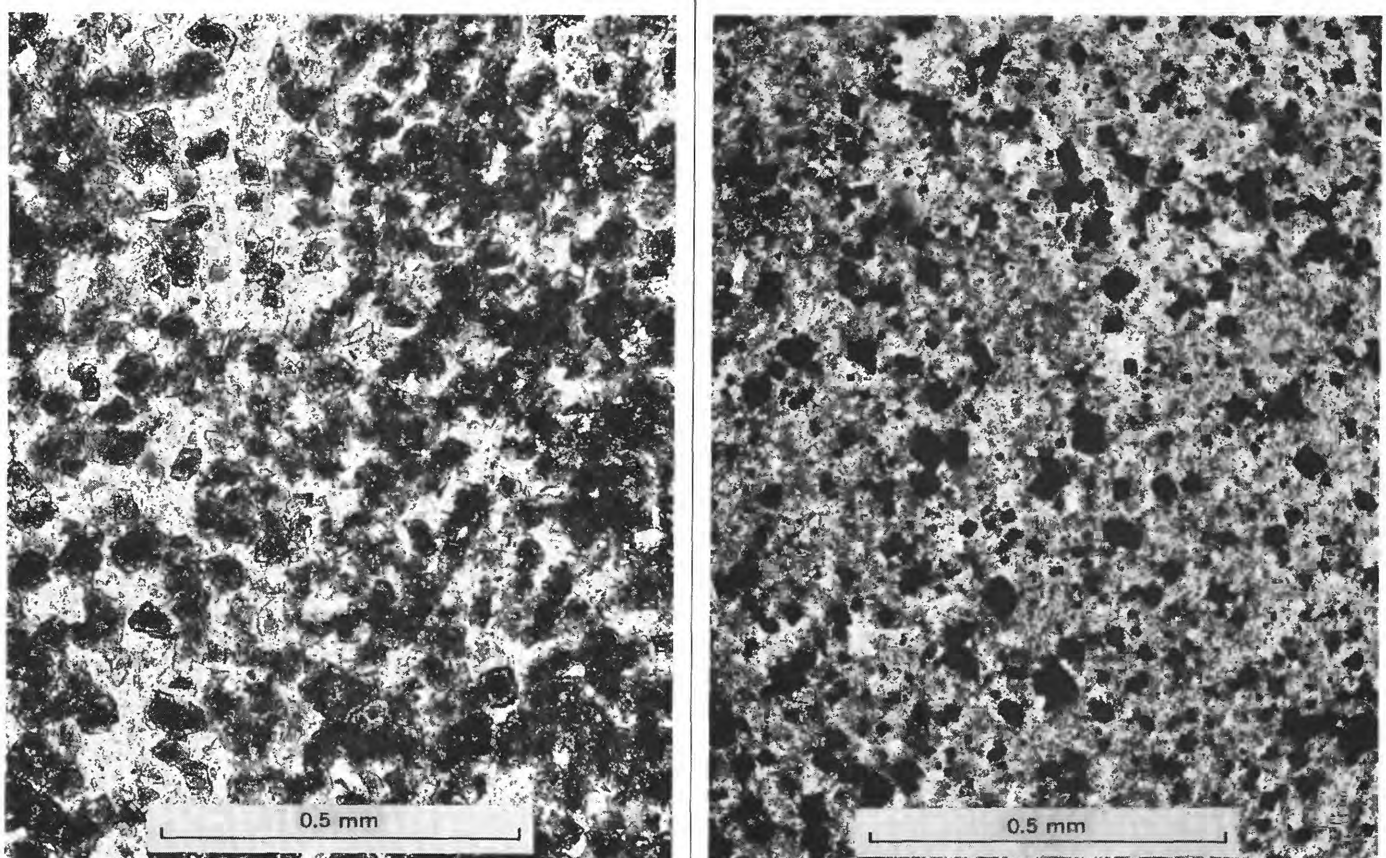


FIGURE 40.—Polished specimen of Stambaugh Formation, showing in original stratigraphic order, graywacke (gw), pyrite (py), and porcelanite (porc) grading upward into chloritic rock (cl). Graywacke at upper left is part of a clastic dike that cuts the slate; it contains fragments of both porcelanite and pyrite. From outcrop in SE¼ sec. 25, T. 43 N., R. 34 W. Natural scale.

layers where it forms, with siderite, a fine-grained mosaic, but it is a finely disseminated constituent in almost all types of the rock. The grains are irregular, vermicular in outline. The chert rarely or never occurs as pure layers as it does in the Riverton Iron-Formation. Magnetite occurs as euhedral or subhedral grains, most of which are 0.01–0.05 mm diameter (fig. 41*B*). Like the other constituents of the rock, the amount of magnetite varies greatly from layer to layer. Some layers contain as much as 40 percent, adjacent layers none. The magnetite is most commonly associated with chlorite, somewhat less commonly with siderite, and rarely with chert.

Detrital quartz and feldspar (mainly plagioclase) form important fractions of some layers of the flinty slate, and in fact some beds approach graywacke in makeup. In chlorite-carbonate-chert-magnetite beds, silt-sized clastic grains form thin laminae hardly more than one grain in thickness. Stilpnomelane has been observed only in rocks from the eastern part of the district; its presence there probably reflects the slightly higher metamorphic grade of rocks of that area as compared with those of the western part of the district. The mineral was found in greatest abundance in a siltstone exposed on the northeast side of the Paint River, in the SE¼ sec. 20, T. 43 N., R. 32 W.; this rock is olive green on fresh break and has an iridescent tarnish on exposed surfaces. The stilpnomelane (with some green biotite) forms the matrix material to clastic quartz grains, which are marginally replaced. The stilpnomelane is strongly pleochroic: $Z=Y=$dark olive yellow, $X=$golden yellow. The N_z index is 1.707, which classes it as a ferric variety. Stilpnomelane is also found as a minor constituent in most of the massive mudstones, which are composed mainly of chlorite; mudstone from Monongahela drill hole 222 contains perhaps 1–2 percent of a very dark stilpnomelane, strongly pleochroic ($Z=Y=$nearly black, $X=$pale yellow); its N_z index is 1.732. Sericite, as fine shreds, is a minor constituent throughout the formation, but the amount rarely exceeds 5 percent.



A B

FIGURE 41.—Laminated flinty slate of Stambaugh Formation. *A*. Light-colored lamina, consisting of siderite rhombs in dense chlorite matrix. Ordinary light. Specimen HJ–243–47, from underground drill hole 302, Hiawatha mine. *B*. Dark-colored lamina, consisting of subhedral to euhedral magnetite in chlorite matrix. Ordinary light. Specimen HJ–208–47, from drill hole B11, NE¼NW¼ sec. 6, T. 42 N., R. 34 W.

Pyrite is present most characteristically as layers such as shown in figure 40, though not uncommonly it occurs as scattered crystals in the chloritic mudstones. The base of the pyrite layer in figure 40 is sharply defined in thin section, with solid pyrite on one side of the contact and quartz grains in a chlorite-carbonate matrix on the other. Upward, the pyrite becomes interspersed with chert and chlorite; small aggregates of carbonate increase in number toward the top of the pyrite layer so that the upper contact with the overlying layer of fine-grained mixed siderite and chert is gradational. The pyrite appears bleblike or massive in form, but under high magnification, some grains show crystallographic boundaries. The overlying porcelanite becomes increasingly rich in chlorite and in disseminated magnetite toward the top of the layer, above which it may be in abrupt contact with another pyrite layer (the basal graywacke in the illustrated specimen is not wholly typical and may, in fact, be part of the clastic dike that cuts the upper part of the specimen). The pyrite-porcelanite sequence is repeated many times within a few feet in some of the outcrops studied.

Dark-green biotite is a very minor constituent in several of the specimens examined. The only measured index, N_z=1.665, suggests a high-iron type. Tourmaline occurs in many samples as scattered small prisms with irregular terminations. The grains are 0.05–0.10 mm in length, dirty green in color, strongly pleochroic (Z=Y=dirty green to nearly black; X=nearly colorless), and have an N_z index of 1.68–1.69.

Analyses of typical facies of the Stambaugh Formation (table 13) show clearly the iron-rich character of the unit. The rocks differ from common varieties of iron-formation in that they contain a relatively high content of alumina and the alkalis, which are reflected mineralogically in the abundance of chlorite, sericite, and stilpnomelane.

THICKNESS AND RELATIONS TO ADJACENT FORMATIONS

Only in the eastern half of the district are the data adequate for thickness determinations of the Stambaugh Formation. In the Paint River outcrop area (SE¼ sec. 20., T. 43 N., R. 32 W.) (pl. 2), the aggregate thickness is 95 feet, and this value, plus or minus 50 feet, seems fairly representative of the belt that extends from the Chicagon Creek area eastward through Crystal Falls and southward through Alpha. No direct information on thickness is available for the western part of the district, but the width of the magnetic anomalies, after accounting for the damping effect of the cover of glacial debris and allowing for local repetition by folding, is consistent with that to be expected from a unit 100–200 feet thick. Broad magnetic anomalies, such as those in the Stambaugh Hill area, are due to closely folded beds within complex synclines that contain no younger strata.

The Stambaugh Formation is conformable with and to some extent gradational into the Hiawatha Graywacke below and the Fortune Lakes Slate above.

TABLE 13.—*Chemical analyses, in percent, of rocks from the Stambaugh Formation*

[Analysts: 1 and 2, Leonard Shapiro. 3, J. G. Fairchild. 4, B. Brunn. n.d., not determined]

	1	2	3	4
SiO_2	48.11	51.18	52.85	43.43
Al_2O_3	3.27	11.95	8.71	[1] 11.25
Fe_2O_3	13.62	8.09	[2] 24.03	.18
FeO	16.69	12.15	(2)	21.00
MgO	2.91	2.42	2.87	1.39
CaO	.80	1.12	.10	.70
Na_2O	.24	2.12	1.48	1.21
K_2O	2.32	1.86	1.89	3.99
H_2O^-	.18	.03	n.d.	n.d.
H_2O^+	1.84	1.42	[3] 5.56	.50
TiO_2	.52	.51	.60	n.d.
P_2O_5	.44	.54	.78	n.d.
CO_2	5.62	3.70	.20	15.76
MnO	3.27	2.71	1.10	n.d.
C	n.d.	n.d.	n.d.	.08
S	n.d.	n.d.	[4] .03	n.d.
Total	99.83	99.80	100.20	99.49

[1] Includes MnO, TiO_2, and P_2O_5.
[2] Total iron as Fe_2O_3.
[3] Includes organic material.
[4] Total sulfur.

1. Laminated facies, from the Hiawatha mine, Iron River; split core from drill hole C–A–47, 280–295 feet.
2. Laminated facies, from outcrops on Stambaugh Hill, sec. 36, T. 43 N., R. 35 W.
3. Chlorite mudstone, from outcrop in sec. 1, T. 42 N., R. 33 W.
4. Porcelanite, from roadside outcrop in SE¼ NW¼ sec. 1, T. 42 N., R. 33 W.

FORTUNE LAKES SLATE

The Fortune Lakes Slate is the uppermost formation of the Paint River Group, and the youngest Precambrian stratigraphic unit in the district. It also underlies the largest area and is the least known. The unit is named for the Fortune Lakes chain, most of which lies within the area assumed to be underlain by the formation. Most of the exposures, however, are in and adjacent to Crystal Falls. The strata assigned to the formation include those that underlie the central part of the Iron River-Crystal Falls basin, strata whose character is almost entirely unknown. It is possible that the succession includes iron-formation of economic interest, as iron-rich rocks are known at several widely separated localities.

GENERAL ASPECTS

The lower several hundred feet of the Fortune Lakes Slate is reasonably well known from exposures in the easternmost part of the district. Slate and graywacke are the principal rock types. Graywacke probably does not make up more than a quarter of the sequence, but because of its greater resistance to weathering it forms about half of the outcrops.

The strata immediately above the Stambaugh Formation are best exposed along and adjacent to the Chicago & North Western Railway grade in the SE¼ sec. 20, T. 43 N., R. 32 W. The rock is a dark-gray laminated slate and siltstone characterized by well-formed axial-plane cleavage. The slate in this area is about 250 feet thick and is overlain by interbedded slate and graywacke.

Farther south along the Crystal Falls-Alpha belt, the lower part of the Fortune Lakes Slate contains rocks of different character. In the NW¼ sec. 12, T. 42 N., R. 33 W., and at several places elsewhere in the area north of Alpha, the succession includes carbonate slate with pyrite-porcelanite beds similar or identical to those in the underlying Stambaugh Formation. South of Alpha, particularly in sec. 36, T. 42 N., R. 33 W., the succession consists principally of interbedded graywacke and slate.

About 500 feet stratigraphically above the base of the formation in the Crystal Falls-Alpha belt is a zone about 200 feet thick that contains layers of coarse massive graywacke. The strata of this zone are exposed in numerous outcrops west of the Tobin location in the N½SW¼ sec. 30, T. 43 N., R. 32 W. They also are exposed in the SE¼ sec. 25, T. 43 N., R. 33 W., and in the NE¼NW¼ and the NE¼SW¼ sec. 1, T. 42 N., R. 33 W. Most individual graywacke beds are devoid of internal structure, although crossbedding is visible in one outcrop in the SE¼ sec. 25, T. 43 N., R. 33 W., and some slight gradation of grain size can be seen locally. Many beds show a large-scale conchoidal fracture that crosses both bedding planes and individual grains. Jointing is conspicuous, and in many places the joints are filled with quartz veins that contain a small amount of pink feldspar. These veins, 1–4 inches wide, terminate abruptly against the slate beds on either side. They resemble the rungs of a ladder, the sides of which are the slates. So massive are most beds that strike and dip cannot be determined unless the contact with an adjacent slate is exposed.

The graywackes weather but slightly, and most exposed rock is light to dark gray. The fresh surface is glistening gray black. Large rounded glassy quartz grains are conspicuous, and angular fragments of chert and flakes of dark-gray slate are common. The matrix, as seen under the microscope, most commonly consists of chert and chlorite, or chert, chlorite, and siderite; in one specimen, the matrix is brown stilpnomelane.

Few of the individual graywacke beds are less than 1 foot thick, and none was observed to exceed 30 feet. A 77-foot section of interbedded graywacke and slate, exposed at the intersection of Superior and High Streets in Crystal Falls, contains six graywacke beds that are 1–12 feet thick.

Above the unit of massive graywacke is a series of beds that consist of fine-grained graywacke and slate, exposed in several outcrops in the western part of sec. 30, T. 43 N., R. 32 W., and adjacent parts of sec. 25, T. 43 N., R. 33 W. The sequence includes a distinctive striped slate similar to that found in the lower part of the Dunn Creek Slate in the Crystal Falls area.

Information concerning strata higher in the succession than those described is exceedingly fragmentary. A drill hole in the SW¼SW¼ sec. 26, T. 43 N., R. 33 W., cut massive gray slate in a position believed to be about 2,000 feet above the base of the formation. Two outcrops in the SE¼ sec. 34, T. 43 N., R. 33 W., are of chert-carbonate-slate similar to slaty phases of the Riverton Iron-Formation. This rock probably is at least 2,000 feet higher in the section than the slate.

THICKNESS AND RELATIONS TO ADJACENT FORMATIONS

The Fortune Lakes Slate as now defined probably is more than 4,000 feet thick. Structural complexities not indicated by present data might reduce the estimates for those parts of the formation that are exposed, but considering the total area underlain by the unit, the true thickness is likely to be more than 4,000 feet rather than less.

The Fortune Lakes Slate is conformable with the Stambaugh Formation, and in some areas the separation between the two formations is somewhat arbitrary. Roadside outcrops in sec. 12, T. 42 N., R. 33 W., for example, show carbonate slate with pyrite-porcelanite layers in both formations. In most places the separation is based chiefly on the absence of magnetite-bearing rock in the Fortune Lakes Slate. In the extreme southeastern part of the district, near the Brule River, the Stambaugh Formation is dominantly clastic in origin and the two formations cannot be clearly separated.

The upper limit of the Fortune Lakes Slate is established only by the limits to which the strata have survived Precambrian and more recent erosion.

REVIEW OF THE IRON-FORMATION PROBLEM

Before appraising the conditions of deposition of the Paint River Group, a general review of the iron-formation problem is in order, inasmuch as iron-formation is one of the major rock types involved. This problem has been discussed at some length in previous publications (James, 1951; 1954; 1966; Pettijohn, 1957, p. 449–464), and the following conclusions have been drawn:

1. Four distinct sedimentary facies of iron-formation can be defined on the basis of the dominant iron mineral: sulfide, carbonate, silicate, and oxide. The silicate facies

can be further divided on the basis of the specific mineral—greenalite, minnesotaite, stilpnomelane, or chlorite; similarly the oxide facies is divided into hematite and magnetite subfacies.

2. Each facies has certain distinctive physical and chemical characters in addition to the diagnostic iron mineral. For example, the sulfide facies is marked by a high content of free carbon; the carbonate facies by stylolites and an iron content of about 25 percent; the chlorite subfacies by presence of recognizable clastic material; the hematite subfacies by oolitic and fragmental textures and an iron content of about 35 percent.

3. Minnesotaite, stilpnomelane, and chlorite probably are products of low-grade metamorphism of some preexisting primary silicates, such as greenalite, glauconite, and chamosite.

4. On the basis of observed interlayering with siderite, iron silicates, and hematite, and lack of correlation with degree of metamorphism, magnetite is considered to be a "primary" mineral. In detail, however, the relationships to other minerals, particularly to oolitic hematite, show that at least some of the magnetite is of diagenetic rather than of direct sedimentary origin, and it is possible that all of the magnetite is to be so classed.

5. Chert, a characteristic component of most types of iron-formation, apparently originated as a quickly hardened sea-bottom precipitate, rather than as a diagenetic or postdiagenetic replacement. This origin is indicated by the nearly constant amount of chert in a given iron-formation facies and by its occurrence and relationships to other rock components in penecontemporaneous slump structures.

6. The iron-rich beds, in general, originated as chemical precipitates in marginal basins of restricted circulation and of moderate sizes, probably rarely more than a few hundred miles in greatest dimension.

7. With allowance for some modification by diagenesis, the present facies of iron-formation reflects original depositional environments that ranged from well-oxygenated shallows, now represented by the hematitic facies, to poorly ventilated bottoms represented by the sulfide facies. In terms of decreasing oxidation potential of bottom environments, the depositional sequence is oxide, silicate, carbonate, and sulfide.

The ultimate source for the iron and silica remains an unsettled question. Normal weathering under present-day conditions yields large amounts of both elements to stream waters, but it provides no mechanism for the extraordinarily high degree of separation from clastic material and from other elements, particularly aluminum and calcium.

Borchert (1960) and Strakhov (1959), both noting the inefficiency of normal weathering processes in separating iron from clastic sediments, suggested that the separation occurs in the oceanic environment; Strakhov emphasized the role of diagenesis, and Borchert the role of vertical and lateral variations in the anionic chemistry of sea water. Neither hypothesis would seem quantitatively adequate to satisfy the material environments for thick units of iron-formation.

A volcanic or igneous source for iron and silica has been advocated by many; such a source would place the deposits in the "exhalative-sedimentary" class of Oftedahl (1958) and other European writers. This possibility has been discounted by the present authors because direct evidence of contemporaneous volcanic or igneous activity generally is lacking and because the content of other metals in the iron-formation is extremely low. Nevertheless, it must be granted that the chemical effects of such activity might be far separated from the obvious physical evidence. Furthermore, time-stratigraphic relations in the Precambrian are much less precisely established than they are for younger fossiliferous strata; true time equivalences between volcanic and nonvolcanic rocks might easily go unrecognized.

A reasonable alternative to the exhalative-sedimentary theory can be constructed on the proposition that the Precambrian atmosphere was significantly different from that at present. It is rather generally accepted that the atmosphere has evolved through time, even though there is little agreement as to the quantitative chemistry of the process and even less as to its timing. (See, for example, Holland, 1962; Rubey, 1955; Urey, 1959.) Speculation governed by the nature of depositional products seems permissible, particularly in view of the conflicting conclusions drawn from theoretical analysis. Oxygen might well have been much less abundant, but that the atmosphere was even then dominantly oxidizing is indicated by the occurrence of oxidic sediments in appropriate environments. To satisfy the need for greater efficiency in transport and separation of iron, it seems not unreasonable to postulate a substantially greater amount of atmospheric CO_2 than at present. If the partial pressure of CO_2 were 0.03 atmospheres, instead of the present 0.0003 atmospheres, the equilibrium pH of surface waters would be lowered from 8.17 to about 6.1 (Rubey, 1951, p. 1129), assuming oceanic volume and salinity comparable to that of today (reduction in either factor would further lower the pH value). Obviously this decrease in pH would result in much more intense leaching of iron from land surfaces, and it would strongly inhibit precipitation of calcium carbonate.

This mechanism would account for iron transport and concentration. It also would provide for a source of silica, which would be derived from breakdown of silicate minerals. The exhalative-sedimentary process would also provide a source. The fact that in the Iron River-Crystal Falls district and it environs iron-formation was formed during periods of structural quiescence tends to discredit the exhalative-sedimentary theory, inasmuch as volcanic or igneous activity, even in fairly distant areas, would likely be accompanied by widespread structural disturbance that would be reflected by influx of clastic materials to the basins of deposition. No definitive choice, therefore, seems possible between the two leading possibilities—nor, for that matter, are the two mutually exclusive.

CONDITIONS OF ORIGIN OF THE PAINT RIVER GROUP

The pre-Paint River environment, as recorded by strata of the underlying Baraga Group, was one of long-continued unstable orogenic conditions. The repetition of iron-formation at many horizons in the Baraga, however, reveals the existence of some overriding environmental condition, which, when combined with appropriate bottom conditions and temporary cessation in clastic sedimentation and volcanism, permitted accumulation of the iron-silica chemical precipitates. Both the orogenic aspect and the potential for iron-formation deposition continued during accumulation of the Paint River Group.

The stages in the depositional history of the Paint River Group may be outlined as follows:

1. Deposition of clastic materials, now represented by the slate and siltstones of the Dunn Creek Slate, accompanied by brief and probable local periods of iron-formation deposition in the eastern part of the district. Offshore accumulation, probably in relatively deep water, is indicated by absence of crossbedding, ripple marks, and mud cracks, and by presence of graded beds that indicate turbidity currents as the means of transportation. The primarily ferrous nature of the rock (see analyses in table 4) suggests deposition in basins with restricted circulation. The analyses also express another feature of the rock, namely the very low content of clastic feldspar as indicated by the fractional percentages of CaO and Na_2O (the K_2O is in the form of sericite, probably derived from illite). The scarcity of clastic feldspar in the sediments indicates thorough chemical weathering of the adjacent land surface.
2. Deposition of the Wauseca Pyritic Member. Though a considerable fraction of this rock probably is clastic in origin, the slate, containing 35–40 percent pyrite, is actually a sulfide facies of iron-formation; the rock is transitional in character between the wholly clastic underlying slate and wholly chemical overlying iron-formation. The abundant pyrite and free carbon (see analyses in tables 5 and 6) show that the rock accumulated under bottom conditions of very low oxidation potential. This fact may but does not necessarily imply deep water. White (1954) interpreted somewhat similar material on the western Mesabi range of Minnesota as a shoreward facies of chert-carbonate and chert-silicate iron-formation. A strongly reducing near-shore bottom environment doubtless can exist in areas protected from strong wave action and where land-derived organic material is being supplied in abundance, and, in fact, such conditions are present today in parts of the Baltic Sea (Twenhofel, 1950). The rather remarkable uniformity in physical character and composition of the pyritic members throughout the district, however, is more readily interpreted to indicate a depositional environment removed from disturbing factors that would necessarily be present adjacent to the shoreline. Furthermore, the slate breccia unit, the significance of which is discussed again in later paragraphs, could scarcely be the product of a nearshore environment. It is concluded, therefore, that the Wauseca Pyritic Member was deposited offshore, probably under a considerable depth of water.
3. Deposition of the Riverton Iron-Formation. The physical and chemical differences between the iron-formation and the underlying pyritic slate are very great, yet many of these differences could be accounted for by little more than a moderate change in the circulation within the basin. If slightly more oxygen were available (but reducing conditions were still maintained), most of the organic material would be destroyed, bacterial reduction of sulfate would not take place, and siderite instead of pyrite would be stable. The pyritic slate, however, is in part clastic and doubtless contained a moderate percentage of clay (the single analysis shows 6.90 percent Al_2O_3) so that the chert-carbonate rock represents more than simple change in bottom environment, important though this is; the iron-formation accumulated at a time when clastic contribution to the basin was very slight. Lateral gradations of chert-carbonate rock into carbonate slate and pyritic slate nevertheless show that locally some clastic material was available and

that variations in oxidation potential did exist. Variations in oxidation potential also are indicated by magnetite-bearing layers in the iron-formation in the Crystal Falls area. For the formation of magnetite the shift in environmental conditions was toward a higher oxidation potential, in contrast to the shift for the pyritic beds, which seems to have been toward a lower oxidation potential.

4. Slight structural disturbance in the region, which halted deposition of the Riverton Iron-Formation. Locally some actual truncation of the iron-formation occurred, mainly by submarine slumping and erosion, but the principal effect was the flooding of the basin with clastic material now represented by the Hiawatha Graywacke. The 10-fold thickening of the graywacke toward the west, together with a transition to arkosic graywacke in the extreme western part of the district, suggests a westerly source for the sand. That the sea water still was rich in iron is indicated by the generally high content of iron in the graywacke, typically about 12–15 percent, which is two to three times the amount in an ordinary graywacke. Like the siltstones in the Dunn Creek Slate, the graywackes of the Hiawatha are generally low in clastic feldspar, and this fact suggests continuation of deep chemical weathering on the land surface.
5. Gradual decrease in clastic sedimentation and partial renewal of iron-formation conditions. Although some of the most characteristic rock types of the Stambaugh Formation are chemical precipitates, the formation as a whole is an example of material accumulated under hybrid conditions of chemical and clastic sedimentation. The abundance of carbonate, chlorite, and locally sulfide indicates that the bottom environment was reducing.
6. Resumption of dominantly clastic sedimentation. The Fortune Lakes Slate, the youngest formation of the Paint River Group, is similar in many respects to the lower part of the Dunn Creek Slate in the eastern part of the district. Local intercalations of iron-rich strata show that the sea water remained high in iron and silica; so, the transcending influence of chemical weathering of the land area was still evident. Significant thicknesses of iron-formation conceivably may be present in the unexplored parts of the formation in the central part of the district.

Significantly, each of the major iron-formations in the Iron County–Dickinson County area—Vulcan, Amasa, Riverton—is in gradational contact with underlying beds but is separated by an unconformity (or disconformity) from the overlying beds. This repeated relationship suggests a rudely cyclic pattern: each structural paroxysm followed a period of structural quiescence so that, when the flood of clastic materials (with or without volcanic rocks) tapered off, deposition of iron-formation was renewed, only to be halted again by further structural disturbance.

Several physical characteristics of the strata can be attributed to the structurally unstable nature of the environment. These features are listed and discussed:

1. Graded bedding in the graywackes and siltstones of the Dunn Creek Slate (fig. 16*B*).

   It is now generally recognized that graded bedding in this type of rock is commonly produced by turbidity currents generated in unconsolidated sand and clay on slopes that are steeper than the angle of repose of such water-soaked material and that the currents often are triggered by earth tremors.
2. Pseudoconglomerate and breccia in the siltstones of the Dunn Creek Slate (fig. 16*C*).

   Every gradation can be found from minor displacements of the bedding to a chaotic arrangement of partly rounded and "smeared" fragments. Some drill holes in the Iron River area have cut hundreds of feet of pseudoconglomerate. The rock is compact and shows no indication of shearing; the structure is interpreted to be due to slumping of partly consolidated material, a slumping very possibly caused by slight structural disturbances.
3. Breccias in the Wauseca Pyritic Member.

   The slate breccia (fig. 17) of the Wauseca Pyritic Member is one of the most remarkable rocks in the sequence. The bed, which has a thickness generally less than 10 feet, is known to extend throughout the district. It is a nonbedded jumble of graphitic and pyritic material virtually identical in bulk composition to the overlying laminated facies. It contains no foreign material, though in a few places it has been observed to grade downward into pseudoconglomerate of the underlying siltstone slate. The breccia almost surely originated simultaneously throughout the district as a great sheet of slumping and sliding material that had been deposited as laminated sediment. The slump probably was set in motion by an earthquake in the same manner that modern earthquakes have triggered flowage of unconsolidated or partly consolidated material on the Atlantic floor. If so, the breccia represents a perfect time line in the stratigraphic column; the rock in the eastern part of the district probably is not more than an hour or so different in age from that in the western part of the district.

4. Breccias and slumped bedding in the Riverton Iron-Formation.

   The chert breccia that forms the basal part of the Riverton in parts of the Iron River area, though of much lesser areal extent, probably also originated by submarine slump. The angular chert fragments and the abundance of carbonate in the matrix indicate that this disturbance took place shortly after the beginning of iron-formation deposition so that the pyritic slate and iron-formation were thoroughly mixed to form the present heterogeneous assemblage. Layers of breccia are fairly common throughout the iron-formation. Most are only a few inches thick and are to be classed as intraformational. In several places, however, the basal breccia of the overlying Hiawatha Graywacke grades downward into iron-formation breccia (fig. 34). The iron-formation breccia at this horizon probably was produced by submarine slumping consequent upon the structural disturbance that was to usher in the epoch of clastic deposition. It is distinguished from the overlying breccia of the Hiawatha Graywacke chiefly by the complete absence of extraneous material.
5. Breccia at the base of the Hiawatha Graywacke (figs. 32, 33, 34).

   The lack of oxidation of siderite fragments in the breccia suggests submarine origin for much if not all of this material.
6. Minor faulting and crumpling in the Stambaugh Formation.

   Most outcrops and drill core of the laminated flinty facies of the Stambaugh Formation show minor crumpling, and a few show numerous tiny faults (fig. 39). Such structures are well shown in the outcrops in the SE¼SE¼ sec. 25, T. 43 N., R. 33 W. The crumpling is obviously due to contemporaneous slumping of partly consolidated material, and the faulting is probably of the same origin.
7. Clastic dikes in the Stambaugh Formation.

   Clastic dikes of graywacke can be seen to cut the Stambaugh Formation in several places. Figure 40 shows a part of such a dike in the SE¼ sec. 25, T. 43 N., R. 34 W. Clastic dikes are common in rocks deposited in orogenic environments.

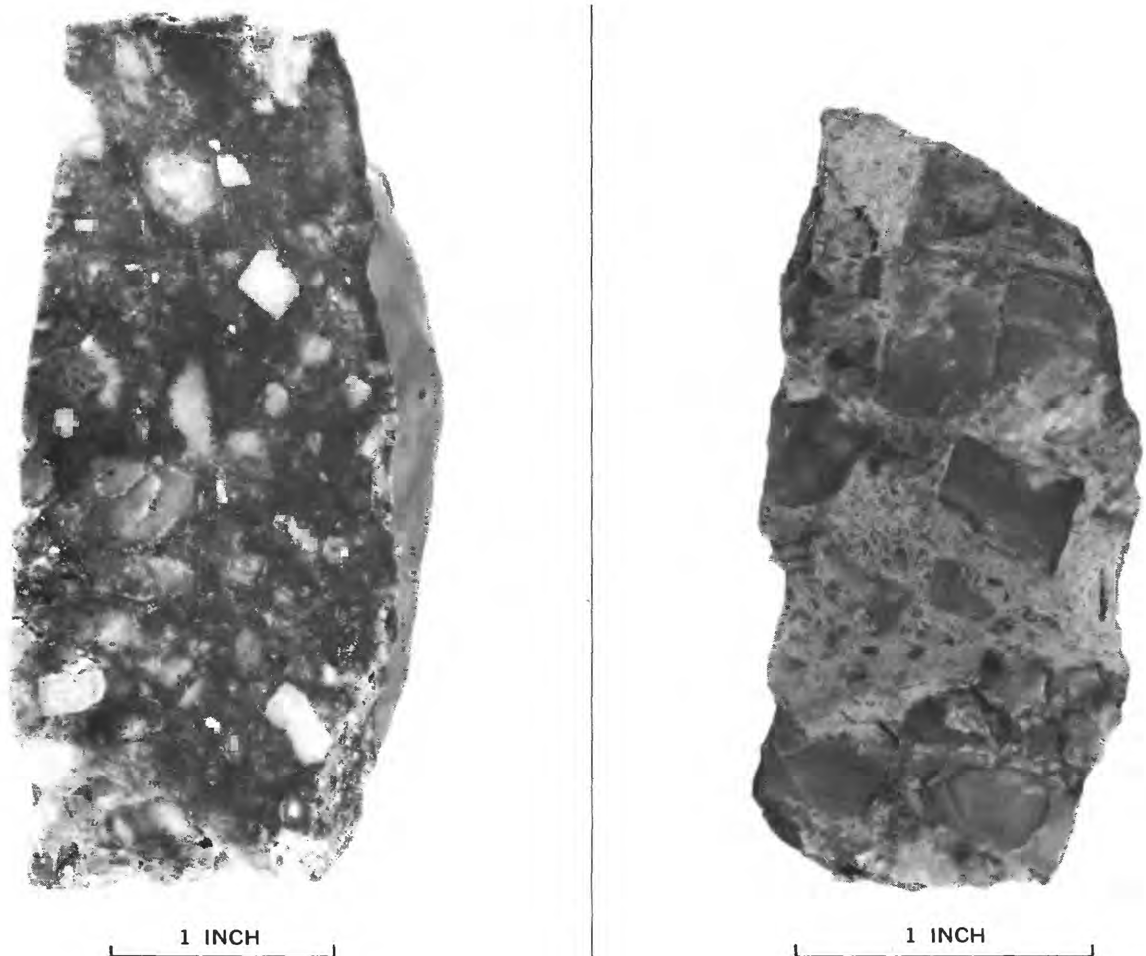
None of these features taken singly would be of special significance, yet in aggregate they preserve a record of unstable tectonic conditions that persisted throughout deposition of the Paint River Group, even though the only structural event of sufficient magnitude to produce a significant change in the depositional environment is that recorded as a disconformity between the Riverton Iron-Formation and the Hiawatha Graywacke.

SILICA ROCK (SILCRETE)

A siliceous rock of somewhat problematical origin and significance forms scattered outcrops along a belt 11 miles long in the southwestern part of the district. These outcrops are in secs. 16, 17, 18, and 23, T. 42 N., R. 35 W., and in sec. 28, T. 41 N., R. 16 E. (Wisconsin). The largest exposures are in the vicinity of Sheridan Hill, in secs. 16 and 17, T. 42 N., R. 35 W. These exposures are shown separately on the district map (pl. 1), within the belt of Saunders Formation, and the siliceous rock is believed to represent a surface alteration of the dolomite. According to Allen (1910, p. 40), some of the siliceous rock observed by him from the Sheridan Hill locality contained relict carbonate; here and elsewhere Allen considered the siliceous rock to be part of the Saunders Formation.

The siliceous rock is uniformly massive and has no trace of bedding, although a few exposures show a rude sheeting that is nearly horizontal. The rock, however, varies greatly in appearance from one outcrop to another. The most westerly exposures, in sec. 18, T. 42 N., R. 35 W., are of massive dense white to gray rock that resembles fine-grained quartzite. In the Sheridan Hill area and in sec. 23, T. 42 N., R. 35 W., most of the rock is a massive breccia with fragments of white to gray silica as much as an inch across in a matrix of yellow and red silica (fig. 42 *A*, *B*); small cavities, some lined with tiny quartz crystals, are common. In the most easterly outcrops, in sec 28, T. 41 N., R. 16 E. (Wisconsin), massive dense yellow to brown jasperoid, locally a breccia, forms a rugged ledge almost a quarter of a mile long.

The rock is composed almost entirely of silica in irregular-locking grains, most of which are 0.01–0.05 mm in diameter. Veinlets, irregular seams, and patches of coarser grain are common. Most, perhaps all, of the silica is crystalline quartz, but some of the larger grains have the flamboyant extinction characteristic of chalcedony. In the breccia facies, fragments are generally indistinct in thin section (fig. 43*A*), though some are sharply defined by large grain-size difference between matrix and fragment. Some of the apparent fragments are either filled vugs or replaced fragments, for they consist of coarse quartz oriented normal to the margins (fig. 43*C*). The chief accessory minerals are yellow to red iron oxides, which occur as dusty patches and staining along grain boundaries. In one sample, however, the oxides occur as rings within individual quartz grains (fig. 43*B*). The only other accessory observed is a colorless micaceous mineral resembling sericite, which occurs



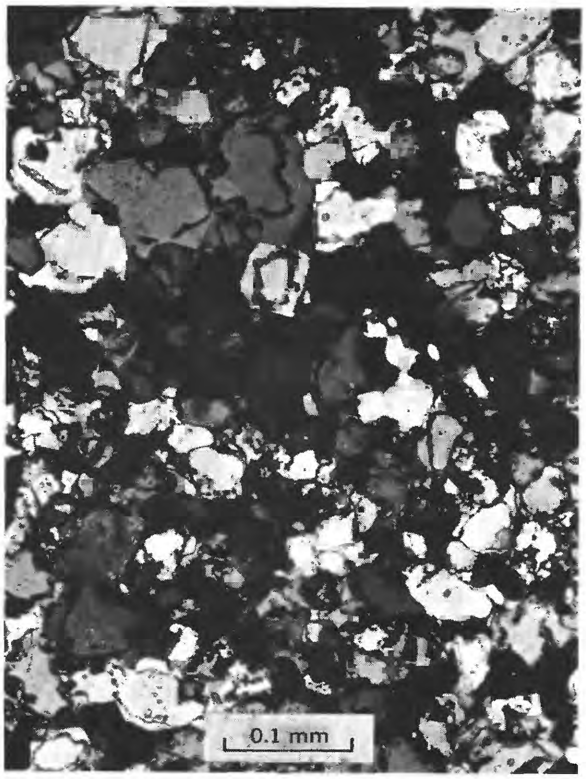
A *B*

Figure 42.—Polished surfaces of silcrete photographed under water to increase contrast. *A*. Light-colored fragments having sharp to indefinite boundaries in matrix of red silica. Specimen HJ–278–48, from outcrop in SW¼SW¼ sec. 16, T. 42 N., R. 35 W. *B*. Gray fragments in matrix of yellowish-tan silica. Specimen HJ–115b–52.

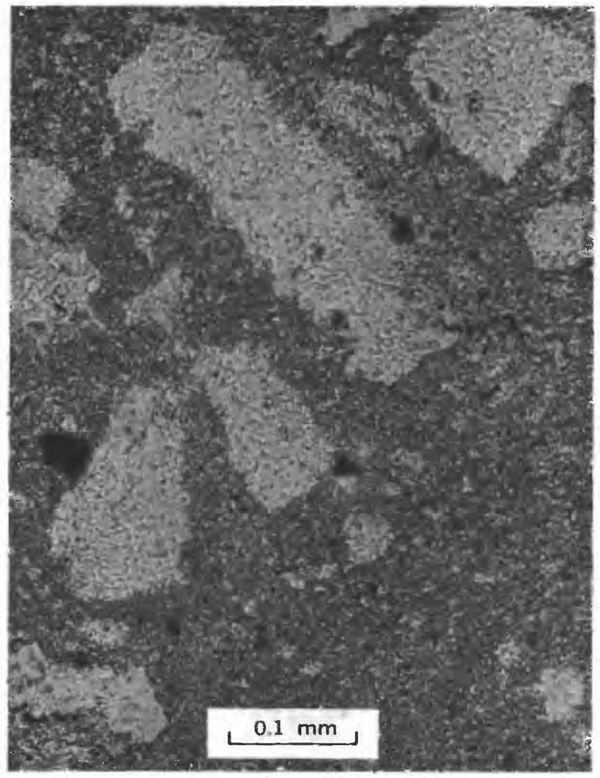
as very fine flakes that rarely make up as much as 1 percent of the rock.

These siliceous rocks are similar in almost all respects to the silcrete of Australia and South Africa (Frankel and Kent, 1938; Mountain, 1952; Frankel, 1952; Williamson, 1957). The silcrete of these areas has been shown to be the product of chemical weathering in relatively arid regions of low relief. A conglomeratic or breccia structure is a characteristic feature of silcrete; it is ascribed to resilicification of earlier formed silcrete that has been brecciated during denudation. As with the rocks described in this report, the silica is in part chalcedonic, in part crystalline quartz. The Australian and South African silcretes apparently formed on many different rock types, and accessory mineral content has been shown to be closely related to parent material (Frankel and Kent, 1938), as for example, in the Grahamstown (South Africa) occurrences. Williamson (1957, p. 36) noted that many silcretes have a relatively high content of TiO_2. For that reason, chemical analysis for TiO_2 (and SiO_2) was made of seven Michigan samples. The results are given in table 14. The TiO_2 content is uniformly low, as might be expected if the rock is in fact an alteration of dolomite.

The silcrete is pre-Ordovician in age, for fragments are found in the basal conglomerate of the overlying Paleozoic strata. The area of greatest exposure, in the vicinity of Sheridan Hill, is in the immediate vicinity of the only known occurrence of Paleozoic rocks in the district; the scarce outcrops of silcrete elsewhere probably represent the last remnants of material that may have had widespread distribution. The possibility that the silcrete represents an interval of weathering of post-Saunders, pre-Badwater age seems to be ruled out by the distribution pattern: the present contacts between these units are steeply dipping, and the silcrete occupies



B



A

C

FIGURE 43.—Microtextures of silcrete. *A*. Breccia facies. Fragments of fine-grained quartz identical to matrix except for lack of disseminated iron oxide. Ordinary light. Specimen HJ–115b–52. *B*. Silcrete consisting of quartz grains with growth rings marked by dark iron oxide. Crossed nicols. Specimen HJ–115c–52. *C*. Quartz-filled vug in fine-grained quartz matrix. Crossed nicols. Specimen HJ–115a–52. These varieties of silcrete are from the same outcrop in sec. 28, T. 41 N., R. 16 E. (Wisconsin).

TABLE 14.—*Partial chemical analyses, in percent, of silcrete*

[Rapid-rock analyses by M. D. Mack and S. D. Botts (method as in Shapiro and Brannock, 1956)]

Sample	Sample locality			SiO_2	TiO_2	Description
	Sec.	T.(N.)	R.(W.)			
Michigan						
1 [1]	16	42	35	96.9	0.02	Conglomerate, white fragments in red matrix.
2	18	42	35	94.6	.05	Gray, with vague fragmental structure.
3	18	42	35	93.8	.06	Similar to sample 2.
4	17	42	35	94.0	.01	Conglomerate, rubbly appearance on weathered surface, with angular white to gray fragments in brownish-yellow matrix.
5	17	42	35	95.3	.01	Dense, tan yellow.
Wisconsin						
6	28	41	16	95.8	0.02	Yellow to red, with fragments(?) and streaks of chalcedonic quartz.
7	28	41	16	95.9	.02	Breccia, angular, white to gray fragments in yellow matrix.

[1] Sheridan Hill area.

a cross-strike distance of at least a quarter of a mile in places. If the silcrete were pre-Badwater, this width would represent approximate thickness, which seems very unlikely; there is some evidence locally for a rude but nearly horizontal layering. Furthermore, Leith (1925) noted the occurrence of silicified erosion surfaces elsewhere in the Lake Superior region.

PALEOZOIC ROCKS

The only known Paleozoic rocks in the Iron River-Crystal Falls district are small patches of limestone and sandstone in the southwestern part of the map area. These strata were named the Sheridan Formation by Allen (1910, p. 113), but there seems little reason to perpetuate the name, particularly since it includes lithologically distinct units that occur in separated areas.

The sandstone is known only from material thrown out of old test pits on the north and east sides of Sheridan Hill, in secs. 17 and 20, T. 42 N., R. 35 W.; there it rests unconformably on silcrete breccia. (See preceding section.) The sandstone is buff to reddish brown, medium grained, and friable; it consists dominantly of quartz grains loosely cemented with iron oxide. No fossils have been observed. Under the microscope, scattered grains and chips of cherty and chalcedonic silica similar to that in the underlying silcrete can be seen to make up a few percent of the rock, but the outstanding feature is that every quartz grain shows secondary enlargement. Many grains now have one or more well-developed crystal boundaries, and in consequence the rock has a characteristic sparkle that is due to reflection from the multitude of crystal faces.

The thickness of the sandstone is not known. Allen (1910, p. 113) suggested perhaps 35 or 40 feet, but this figure has little significance, as the depositional surface obviously is highly irregular and the upper contact erosional. The silcrete surface ranges in elevation from less than 1,600 feet to 1,760 feet, and the sandstone has been penetrated in pits between the elevations of 1,640 feet and 1,700 feet.

The limestone occurs as a single exposure in the bed and banks of the Brule River in the SW¼ sec. 27, T. 42 N., R. 35 W. The rock is light gray to tan, flaggy, and irregularly bedded. The general attitude of bedding probably is horizontal, although in the streambank, possibly because of slumping, some strata dip as much as 15° E. Fossils are abundant; Ulrich (in Allen, 1910, p. 114–116) identified 20 species and correlated the beds with the Lowville Limestone of New York and the Platteville Limestone of Wisconsin. The age is Middle Ordovician (Black River), equivalent in part to the Au Train Formation farther east.

The relationships between the limestone and the sandstone can only be inferred, as the two rocks occur in separate small areas 2 miles apart. The limestone is at an elevation of about 1,500 feet, or 150–200 feet lower than the sandstone. For this reason, Allen (1910, p. 114) concluded that the sandstone was the younger unit, despite the fact it is the basal bed of the Paleozoic at the locality of occurrence; he assumed that the beds had not been disturbed structurally except for broad uplift. Elsewhere in Michigan, however, strata equivalent in age to the limestone are underlain by the Munising Sandstone of Late Cambrian age (Hamblin, 1958), which is similar in appearance to the sandstone of Sheridan Hill, and in some places these strata have been faulted. The possibility exists, therefore, that the sandstone is the older unit and that it is separated from the limestone by an unrecognized fault.

IGNEOUS ROCKS AND FELDSPAR-BEARING QUARTZ VEINS

Rocks of intrusive igneous origin, though found throughout the Iron River-Crystal Falls district, constitute only a small fraction of the bedrock.

The oldest igneous rocks, and the most abundant and widespread, are metadiabase and metagabbro, which occur mainly as dikes and sills. Granitic rock forms several sill-like and stocklike masses in the eastern part of the district, and trachyte forms a few very thin dikes in the Iron River area. The youngest and only unmetamorphosed Precambrian rock in the district is diabase, of Keweenawan age, which occurs as a single dike in the Iron River area.

Irregular thin feldspar-bearing quartz veins occur at several places in the district. They are commonly referred to as "pegmatite" and are therefore discussed here even though they are not igneous.

METADIABASE AND METAGABBRO

Metadiabase occurs throughout the district as dikes and sills as much as 300 feet thick. Dikes are particularly common along the principal fault zones, and many are lenticular or podlike. One stocklike mass of metagabbro is present in secs. 23, 24, 25, and 26, T. 43 N., R. 33 W., just north of the Fortune Lakes open-pit mine, and a complex body, possibly 1,000 feet or more wide and a mile in length, is known from drill holes in secs. 21 and 28, T. 43 N., R. 34 W. Two well-defined dikes of metadiabase, known chiefly from drilling, cross structural trends in the Dunn Creek Slate immediately south of Alpha, and one dike estimated to be about 200 feet thick can be traced by drill-hole information and magnetic surveys for a mile or more in secs. 11, 14, and 15, T. 43 N., R. 35 W. As many as three dikes are present in the North Mineral Hills fault zone where that zone is crossed by mine workings. The fault that bounds the iron-formation on the north at the Fortune Lakes mine also is marked by a thin irregular dike. The Fogarty shaft of the Buck group of mines in the Iron River area, at the 9th, 10th, and 11th levels, is in a large metadiabase body of unknown form.

The dikes postdate the principal structural deformation of the area, and they are partly to completely metamorphosed; so, they can be classed as post-Animikie, pre-Keweenawan in age.

The rocks are compact, massive, generally unsheared, and greenish yellow to dark greenish gray. Most are relatively soft; the original pyrogenic minerals are altered to chlorite, albite, epidote-clinozoisite, actinolitic hornblende, and leucoxene—minerals typical of the greenschist facies of metamorphism (fig. 44). Many of the dikes found in underground workings have been further altered to clay minerals and iron oxides by the solutions that formed ore in the iron-formation.

In at least two of the larger bodies, the metadiabase dike in secs. 11, 14, and 15, T. 43 N., R. 35 W., and the metagabbro body north of the Fortune Lakes open pit, original minerals are preserved. A drill hole in sec. 14 cut the south contact of the metadiabase dike and continued into the dike for about 100 feet. The rock at the contact and for several feet toward the interior is fine grained and dull grayish green. In thin sections from this chill zone, a fine-grained diabasic texture is readily visible in ordinary light, but under crossed nicols the thin section is almost opaque; the original minerals are entirely altered to a fine-grained aggregate, chiefly chlorite. Toward the center of the dike the altered rock grades into only moderately altered diabase within approximately 30 feet. The rock in the interior of the dike is porphyritic medium-grained diabase that consists chiefly of partly altered labradorite (An_{57}) and augite, with $2V_z \cong 48°$ (49°, 48°, 48° 52°, 48°). The labradorite is rimmed with needles and blades of sericite and chlorite and is gradationally zoned to a more albitic rim that merges with the plagioclase of the groundmass. Chlorite is the chief alteration product of the pyroxene. Magnetite-ilmenite is present as scattered euhedral or skeletal crystals; the rock is perceptibly magnetic, in contrast to the nonmagnetic chloritized chill zone, and gives rise to a small or moderate magnetic anomaly. Specimens from the interior of the metagabbro body north of the Fortune Lakes open pit are similar to those from the interior of the metadiabase dike, but the alteration of the primary minerals is more extensive. Pale-green hornblende, epidote-clinozoisite, and sphene are present as secondary minerals, in addition to chlorite and sericite, and little if any of the original magnetite-ilmenite remains.

FIGURE 44.—Metadiabase, now consists entirely of secondary minerals but original texture is preserved. Albite (Ab), chlorite (Chl), hornblende (Hb), clinozoisite (Cz), and magnetite-leucoxene (Mt). White areas (H) are holes in the section. Ordinary light. Specimen HJ–281–48 from outcrop near W¼ cor. sec. 19, T. 43 N., R. 35 W.

TRACHYTE

A dense pale-yellow or pinkish-yellow rock was found in several drill holes of the Buckholtz exploration, in sec. 27, T. 43 N., R. 35 W. It appears to form a thin sill. Somewhat similar material forms two, perhaps three, very thin dikes in and adjacent to the South Mineral Hills fault zone, as seen on the 1000 level of the Sherwood mine and the 6th level of the adjacent Wauseca-Minckler mine. The dikes are only a few inches wide.

The rock in sec. 27 is a very fine grained aggregate of sericite, quartz, and feldspar, with scattered grains of carbonate. The original rock seems to have been composed chiefly of subhedral to euhedral feldspar crystals, stubby to lathlike in form and typically 0.1–0.2 mm in maximum dimension. The crystals are now in large part altered to fine-grained sericite and quartz. All the feldspar has indices near or below the index of balsam; some is definitely albite (optically positive; some grains show faint albite twinning with maximum extinction about 19°), and some is a potassium feldspar (optically negative). The rock contains no mafic constituent. The quartz occurs with sericite, as noted, or as clear irregular grains interstitial to the original feldspars.

The dikes of South Mineral Hills fault zone are of rock similar to that described above except that they contain small quantities of very pale fine-grained chlorite and abundant scattered plates of leucoxene.

METAGRANITIC ROCKS

Granitic rocks are present only in the eastern part of the district. The largest mass, 2 miles long and a quarter of a mile in maximum thickness, is in secs. 16, 21, and 28, T. 42 N., R. 32 W.; it will be referred to as the Little Tobin Lake dike. A second and smaller dike in sec. 4, T. 42 N., R. 32 W., will be referred to as the Railroad Lake body. An elongate stock occurs just east of Crystal Falls, in sec. 28, T. 43 N., R. 32 W. A narrow dike, approximately parallel to the western border of the stock, lies a few hundred yards to the west, and small dikes occur in secs. 30 and 33 of the same township.

The granitic bodies all have been sheared to some extent, and all have been metamorphosed. Their present structure and mineralogic composition, therefore, reflect not only original differences but postintrusion events as well. In general, the rocks are gray to reddish gray and fine to medium grained and are composed dominantly of microcline microperthite, albite, and mica.

Little Tobin Lake dike

The Little Tobin Lake dike, the largest of the intrusive masses, shows the greatest range in composition. The main part of the body is fine- to medium-grained massive gray to reddish-gray granite. The essential primary minerals are plagioclase, potassium feldspar, quartz, and biotite, and the texture is hypidiomorphic. A typical mode is as follows:

	Percent
Albite	17
Microperthite	32
Quartz	22
Biotite	19
Sericite, carbonate, chlorite	10

The plagioclase is in stout laths, 1 mm or less in length, that show broad twinning lamellae and some gradational zoning. The present composition is albite (An_{10}–An_0), but the previous existence of a more calcic composition is indicated by abundant clinozoisite, particularly in the central parts of the grains. The plagioclase is also speckled with sericite and minor chlorite. The potassium feldspar is microcline showing faint to conspicuous twinning. The microcline is visibly perthitic in some sections; in others it is mottled, probably with submicroscopic exsolved albite. Both the microcline and the albite are charged with a dust of very fine hematite.

A specimen from the northern part of the mass (locality 1,100 ft west, 100 ft south of the NE. cor. sec. 21) has a distinct granophyric texture, with geometric patterns of quartz in microcline microperthite.

The most northerly and most southerly exposures of the dike are of a fine- to medium-grained dark-gray rock, somewhat diabasic in appearance. The feldspars are similar in composition and habit to those of the granite facies previously described. The essential primary minerals are hornblende and biotite (in variable proportions but aggregating about 20 percent), quartz (about 20 percent), plagioclase (about 60 percent); potassium feldspar is minor. The hornblende is in subhedral to euhedral crystals 1 or 2 mm long and is pleochroic (pale brown to pale green); it is generally altered in part to biotite, less commonly to chlorite, clinozoisite, and sphene. The biotite has two habits, as separate crystals comparable in size to the hornblende and as patchy replacements of hornblende and other minerals. The separate crystals commonly are extensively altered to chlorite, sericite, and clinozoisite. An analysis of a dark facies of the Little Tobin Lake body, given by Clements and Smyth (1899, p. 231), is as follows:

[Analyst: H. N. Stokes]

	Percent		Percent
SiO_2	58.51	K_2O	4.08
TiO_2	.72	Na_2O	3.11
Al_2O_3	16.32	H_2O-	.23
Fe_2O_3	2.11	H_2O+	2.00
FeO	4.43	P_2O_5	.30
MnO	Trace	CO_2	None
CaO	3.92		
MgO	3.73	Total	[1] 99.17

[1] As reported. Column actually totals 99.46.

The original rock in the Little Tobin Lake body ranged in composition from quartz diorite to granite; most of it probably was quartz monzonite. The abrupt change to more mafic quartz diorite at both ends of the belt of granitic rock suggests that the body may not extend far beyond the exposures. The primary minerals are plagioclase (probably oligoclase-andesine originally), potassium feldspar, quartz, biotite, and hornblende. Minerals of metamorphic origin are epidote, clinozoisite, sericite, biotite (in part), sphene, calcite, and chlorite.

Railroad Lake body

The body of metagranitic rock near Railroad Lake is about a mile long and not more than 300 feet wide. The rock is sheared, in places very strongly, but it retains an original porphyritic texture. The rock now consists of albite (about 75 percent), in stubby phenocrysts about 1 mm in length showing complex twinning and slight gradational zoning; quartz (10–15 percent); and sericite, carbonate, epidote, and iron oxides (15–20 percent). The rock probably was originally a quartz diorite which had a very low content of mafic minerals.

Stock near Crystal Falls and other occurrences

The body of granitic rock on the east side of the Paint River near Crystal Falls is about a mile long and a maximum of a quarter of a mile wide. The rock is massive, pinkish gray, and fine to medium grained. The few thin sections studied showed it to be composed mainly of irregularly perthitic potassium feldspar, twinned albite, and quartz. The average original grain size was about 1 mm, and the original rock was probably a granite. Sericite and carbonate are very abundant throughout, and what probably were original biotite flakes are now patches of chlorite (green, with ultrablue interference color) and dusty magnetite. More detailed descriptions are given by Clements (in Clements and Smyth, 1899, p. 227–228), who stated: "the rocks are found to consist of automorphic biotite and plagioclase, with xenomorphic orthoclase and quartz, these last forming the cement. Some of the slides show beautiful micropegmatitic intergrowths of quartz and feldspar."

The scattered small dikes elsewhere near Crystal Falls are composed of a sheared, fine-grained granular, and generally iron-stained rock. Potassium feldspar, twinned albite, and quartz are the principal minerals, but alteration products, principally sericite and chlorite, are abundant.

Origin

The granitic rocks described predate the deformation and metamorphism of the Animikie Series and therefore are not to be considered comagmatic with the syntectonic and posttectonic igneous rocks of the Peavy Pond complex a few miles to the east described by Bayley (1959). Rather, they seem to be related to the premetamorphic sheets of differentiated metagabbro in the adjoining Kelso Junction, Kiernan, and Lake Mary quadrangles (Wier, 1967; Gair and Wier, 1956; Bayley, 1959). The metagabbro in these adjoining areas forms sheets a mile or more thick that contain irregular masses of granophyre in the upper parts. The dark facies of the Little Tobin Lake dike, with subophitic texture and local granophyre, is similar to differentiated parts of the metagabbro, and probably the granitic bodies of this district represent separate intrusions of granophyric magma from these metagabbro sheets or from buried masses of metagabbro.

The granitic rocks commonly show some evidence of deformation, and the secondary minerals are characteristic of those of the lower zones of metamorphism—sericite, chlorite, albite, clinozoisite-epidote. Significantly, a secondary biotite is present in the Little Tobin Lake dike but not elsewhere. This association is in keeping with the position of the biotite isograd as determined from other evidence (see fig. 7); the Little Tobin Lake dike is within the garnet and biotite zones, whereas the other bodies of similar rock are in the chlorite zone.

An age determination, by the potassium-argon method, of biotite from the Little Tobin Lake dike gives an apparent age of 1320 million years (Aldrich and others, 1965). This value, however, almost certainly represents an event (or events) later than that of the initial crystallization of the rock; the petrography, described previously, shows both a primary biotite and a regenerated biotite.

DIABASE

An essentially unaltered diabase dike follows the North Mineral Hills fault zone for a mile or more. It is about 40 feet thick and dips steeply to the south. The dike, together with several older metamorphosed dikes, is intersected by workings of the Forbes mine and is cut by drill holes in sec. 13, T. 43 N., R. 35 W. It seems to diverge from the fault in the SW¼SW¼ sec. 13 and continues in an easterly direction at least as far as the Bates mine. The dike is magnetic and is polarized in direction opposite to the present magnetic field of the earth; as a result, the trace of the dike is marked by a pronounced negative anomaly that is entirely similar to those anomalies produced by Keweenawan diabase dikes elsewhere in northern Michigan (Balsley and others, 1949).

The diabase is dark gray, medium to fine grained. Glistening laths of feldspar are visible to the unaided eye. Under the microscope, the rock is seen to consist of slightly sericitized and chloritized laths of plagioclase in a matrix made up chiefly of chlorite. Magnetite-ilmenite crystals are scattered throughout. In contrast to the older metadiabase, which forms parallel dikes in the fault zone, the plagioclase is labradorite (An_{55}) rather than albite. The original matrix mineral, presumably augite, is entirely altered to a dark-green chlorite.

FELDSPAR-BEARING QUARTZ VEINS

Quartz veins containing small amounts of pink feldspar occur at several places in the district. The best examples are in the SE¼ sec. 20, T. 43 N., R. 32 W., where veins cut the Stambaugh Formation exposed on the east bank of the Paint River below the bridge. The veins are flat lying or nearly so. Most are less than 4 inches thick, but one or two are as much as 18 inches thick. None can be traced more than a few yards. The rock consists of coarse white quartz and 10–20 percent salmon-pink adularia. Where the veins cut stilpnomelane-bearing beds of the Stambaugh Formation, they are bordered by coarse-grained black stilpnomelane. The stilpnomelane has been described and anlyzed by Ayres (1940). The analysis shows it to be a highly ferric variety (33.24 percent Fe). The indices given by Ayres are $N_y = N_z = 1.730 \pm 0.001$; $N_x = 1.634 \pm 0.002$. The higher index has been verified, but the lower index seems to be slightly high; new measurements indicate 1.632 as the probable value.

Adularia-bearing quartz veins also are common as ladder veins cutting the massive graywackes of the Fortune Lakes Slate described previously.

The veins probably originated during the regional metamorphism, with the materials being in large part or entirely derived from the enclosing rock. They are analogous to adularia-tremolite-epidote veinlets found locally in the greenstones of the district.

STRUCTURE

The structure of the Iron River-Crystals Falls district, though tremendously complex in detail, is relatively simple in broad outline. The district proper is a deep basin, rudely triangular in shape, with apices (with respect to the Riverton Iron-Formation) at Iron River and Crystal Falls, and an attenuated apex at the southeast end of the district. The sedimentary strata are intensely folded, more so perhaps than those of any other area in the Lake Superior region. Dips of less than 60° are scarce, and overturning is common. Many faults with throws measurable in thousands of feet have been recognized, and many more doubtless exist; most are high-angle reverse faults although some in the northeastern part of the district show large lateral displacement. The principal structures that have been mapped are shown in figure 45. Many of the folds shown in figure 45 extend greater distances than indicated, but extrapolation of fold axes for much beyond the actual traced parts is of doubtful value because of curvature of fold axes and intersection with crossfolds. Underground mapping, particularly in the Iron River area, has shown that faults can be extended with much greater degree of certainty than folds.

IRON RIVER-CRYSTAL FALLS BASIN

The Iron River-Crystal Falls basin is bounded but not entirely closed off by the Badwater Greenstone, in part because of structural complications and in part because the greenstone masses pinch out laterally, as in the northeastern part of the district. Closure on the west end of the district, though not proved, is suggested by the marked convergence of the North and South belts of greenstone and by magnetic anomalies in the covered area between. It is very possible that the area of post-Badwater sediments is merely "necked down," and that it may widen again on a regional reversal of plunge. The Conover district of Wisconsin, known only from magnetic data and a few drill holes (Allen and Barrett, 1915), lies approximately on the strike of the Iron Rixer apex and could represent an extension of the Iron River-Crystal Falls district on just such a reversal. Allen and Barrett (1915, p. 124) stated: "The Conover slates are exactly similar to those associated with the Vulcan iron formation [Riverton of this report] in the Crystal Falls and Iron River districts."

The southeast end of the Iron River-Crystal Falls basin is not closed off. The East belt of Badwater Greenstone, which bounds the eastern part of the district, continues southeastward into Florence County (Wisconsin) as the "Spread Eagle belt," where it is flanked on the southwest by post-Badwater sedimentary strata. The South belt, which bounds the district on the south, seems to thin toward the southeast, but it can be traced as far as sec. 29, T. 42 N., R. 33 W., and has been recognized in adjacent areas of Wisconsin.

The major structural axis of the district is not easily defined, but most likely it should be considered as a curved line, markedly convex to the north, extending eastward and southeastward from the Iron River apex through the gap between the East and South belts of greenstone, into the adjacent Florence district of Wisconsin. The trend of this axis swings from due east in the Iron River area to about S. 40° E. in the southeast apex. It is readily apparent from figure 45 that the district is asymmetrical with respect to such a line. Irregularity in form and thickness of the flanking Badwater Greenstone seems the most likely reason for the lack of symmetry. The great extension of the district northeastward into the Crystal Falls apex probably is due to the absence of underlying greenstone in that

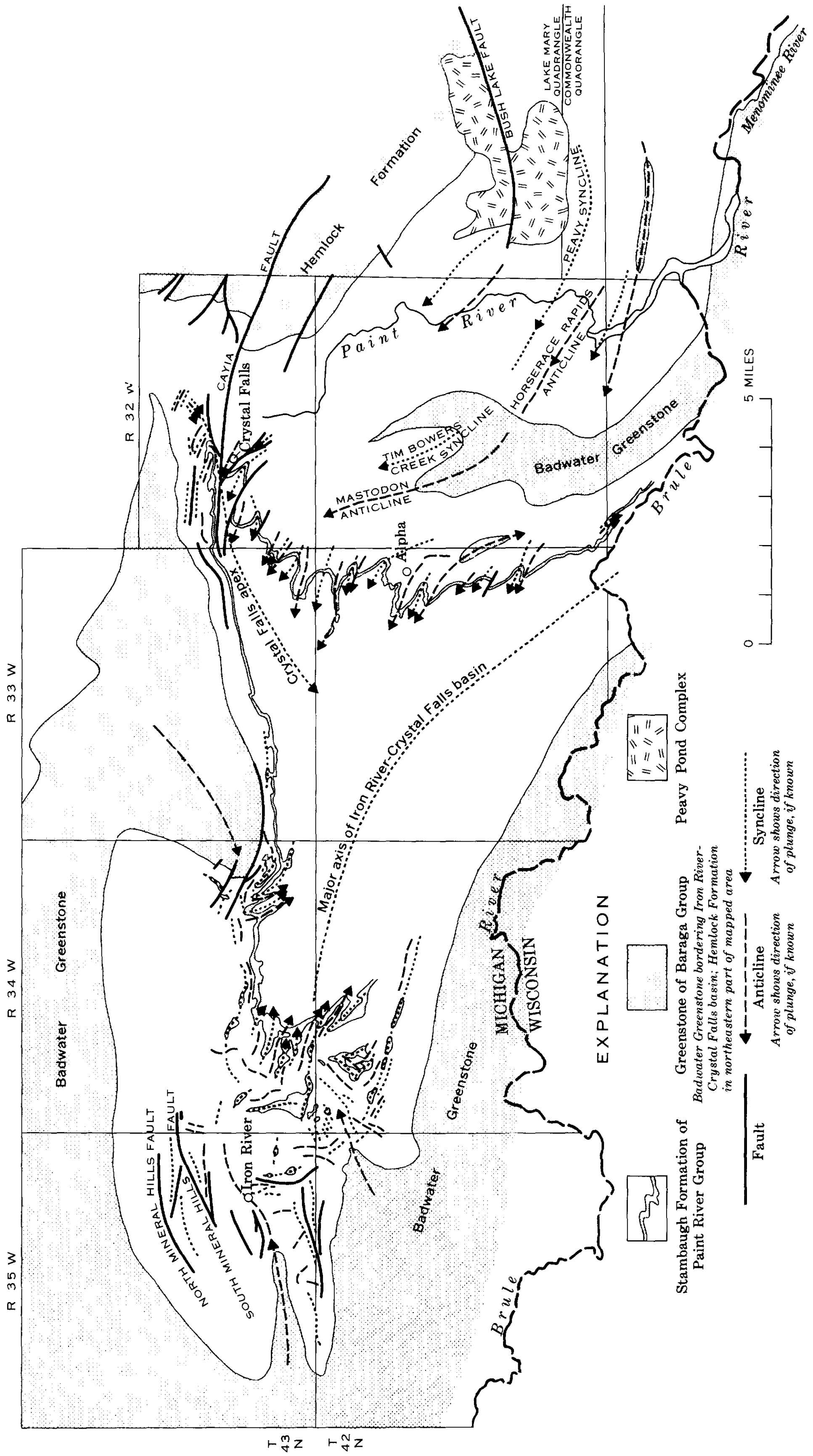


FIGURE 45.—Geologic structure of the Iron River-Crystal Falls district and adjacent areas of the Lake Mary and Commonwealth quadrangles.

area; in a sense, the strata in this northeast syncline might be considered as squeezed through the gap between the ends of the North and East belts of Badwater Greenstone. The southward-projecting elbow of greenstone between Iron River and Crystal Falls, which at least in part is related to original differences in thickness and lithology of the greenstone mass, is clearly responsible for the divergent trends and extreme deformation of the postgreenstone sediments in that area. A major anticlinal zone divides the west end of the district into two parts, approximately along the westward projection of the greenstone elbow; probably if erosion had beveled the district to greater depths, a northern synclinorium would have been isolated from the district proper.

The structure of the Iron River-Crystal Falls basin is reflected remarkably well by the regional Bouguer gravity map published by Bacon and Wyble (1952). (See fig. 46.) The anomaly yielded by the iron-rich relatively heavy rocks of the basin has a total relief of 47 milligals in a distance of about 10 miles. The explanation for the northwesterly trending reentrant in the western part of T. 42 N., R. 33 W., is not known, but certainly its presence suggests that the south limb of the basin does not continue in a straightforward manner. The area is barren of outcrop, and there has been no exploratory drilling.

FOLDS

The sedimentary strata within the basin are intensely distorted. All the strata are involved, but the thinly bedded units, especially the Riverton Iron-Formation, are more noticeably deformed than the more massive units such as the Hiawatha Graywacke. The folds have steeply dipping axial planes, and most are overturned. Plunges are moderate to steep and commonly not in accord with the overall pattern of the district; except for a few areas, such as the Crystal Falls-Alpha belt, reversal of plunge within short distances is typical.

The principal folds are recognized by the pattern, in map and section, of recognizable stratigraphic units, particularly the Stambaugh Formation, which can be traced magnetically. Few structures can be defined by dip-and-strike data. Some structures, especially those involving the stratigraphic units found in the mines, are recognized chiefly by dragfolds, almost all of which are consistent with the structures of the next order of magnitude. This general consistency rules out the theory, often advanced by geologists who have not mapped such rocks in detail, that the highly contorted structures typically exhibited by iron-formation were formed prior to consolidation of the rocks. Cleavage is not a dominant feature of most of the rocks in the district but, where present, can be used to help locate the traces of fold axes (fig. 47). Because folds generally are tight and bedding on both limbs is parallel or nearly so to the axial planes, in most places the cleavage and bedding are not readily distinguishable; only in the axial regions is there a pronounced angle between the two.

In most parts of the district, the trends of the fold axes are parallel or subparallel to the principal axis of the district—that is, west to northwest. In some areas, however, and most noticeably in the tightly compressed west apex, highly divergent trends are present. In this apex, in the vicinity of the city of Iron River, the dominant trend of folds ranges systematically from westerly in the southeastern part of the area, to northerly in the central part, to easterly in the northern part. (See fig. 45.) These "peripheral" trends are interrupted by radially arranged crossfolds that lie approximately at right angles to the peripheral folds. The crossfolds are not superimposed upon the peripheral folds; that is, the structure is not one of folded folds, but rather there is a gradual transition, the plunge of the peripheral fold becoming the dip of one limb of the crossfold (fig. 48). Minor dragfolds are systematic with respect to the nearest major structure, a feature well shown in the Buck mine and illustrated by a map of part of the 10th level (fig. 49). The peripheral folds shown on figure 49 trend northwestward and are overturned to the southwest. The radial folds trend northeastward; axial planes are vertical or nearly so. The transition from one fold trend to another occurs in the vertical as well as in the horizontal sense in some places. Maps of the old Berkshire mine (NW¼SW¼ sec. 6, T. 42 N., R. 34 W.) show that from the bedrock surface downward for about 500 feet the folds and the ore bodies have a trend and plunge that are almost due east. Below this level the eastward-trending folds pass imperceptibly into folds that trend and plunge nearly south so that the ore bodies merge with those of the adjacent Buck property.

The structure at the northeast apex of the district, immediately north of Crystal Falls, also is strongly modified by cross trends, although here they are represented more by plunge reversals on generally east-trending folds than by discrete cross structures. Nevertheless, inspection of the map (pl. 1) shows that at the east end of the belt, the major synclinal axis, as indicated by distribution of Hiawatha Graywacke, plunges southeast, whereas that indicated by the Riverton Iron-Formation plunges southwest.

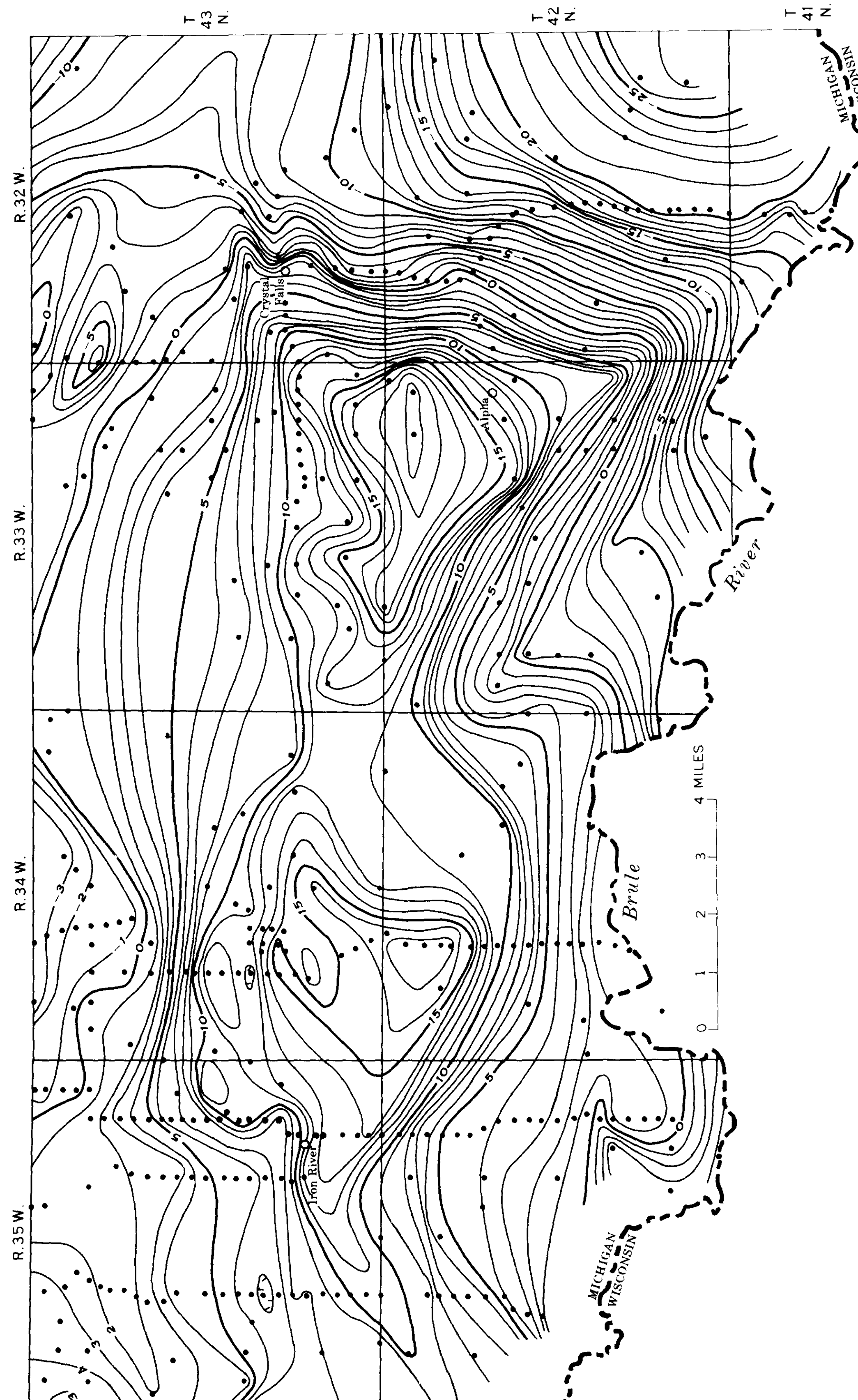


FIGURE 46.—Regional Bouguer gravity map of the Iron River–Crystal Falls district. Contour interval, 1 milligal; gravity stations shown by dots. (Modified from Bacon and Wyble, 1952.)

FIGURE 47.—Tight symmetrical anticline in Fortune Lakes Slate; anticline is cut by nearly vertical axial-plane cleavage. Outcrop is SW¼SE¼ sec. 20, T. 43 N., R. 32 W.

The nature of the folding is illustrated clearly by the detailed map of the Paint River dam outcrop area (fig. 21). This outcrop was mapped with great care; the maximum error in position of individual bedding planes shown in solid line is not more than 6 inches. The rock consists mainly of interbedded chert and carbonate and has some layers that are dominantly stilpnomelane.

The outcrop reveals many features, such as relationship between folds of divergent trends, relationship of faults to folds, persistence of folds across bedding, and structural differences between different layers, that are believed typical of the district as a whole. The rocks have deformed by flexure rather than by shear—that is, by movements along external bedding planes rather than by movements along internal shear surfaces. Massive layers show no thickening at crests of folds; the gaps beneath structural arches (see, for example, area D7–E7 in fig. 21) are filled with the contorted and squeezed material of intervening incompetent layers. Direct evidence for bedding-plane movements is shown at area E9, where continued slippage during folding has resulted in offset of earlier formed gash veins.

The major fold present in the outcrop—a westerly plunging syncline-anticline couple—is virtually without expression at the lip of the dam apron. It is instructive to view the map as a section by orienting it so that one "looks down" the plunge of the fold and then to consider the structure at different levels in this "cross section." The strata at the upper edge dip to the right at steep to moderate angles. But at a "depth" of 60 feet in the section, the strata are involved in a complex group of folds, and the structure bears little resemblance to that of the upper level. Similar changes in structural aspect commonly are seen in underground workings, but without complete information such as is available in this outcrop, the relationships between different levels are difficult to understand.

The north-plunging anticline in areas H15 and G16 (fig. 21) is little more than a moderate change in strike in the nearly vertical beds. The trend of this fold, in the terminology used in earlier discussions, is radial, whereas the west-plunging structures are peripheral. The westerly plunge of the peripheral fold is reversed to the east within a short distance beyond the outcrop.

Reversals of plunge give rise to some of the most characteristic map patterns in the district (fig. 50). Many examples of the canoe-shaped trough, in varying degrees of complexity, are present in the district, particularly near the west and northeast apices. Several are recognized in the Chicagon Creek area, midway between Iron River and Crystal Falls. The concept of the isolated trough is of considerable importance in the interpretation of magnetic data: if the magnetic bed is represented by the solid black line in figure 50, the isolated folds at level c contain no younger beds, and the trough, which structurally consists of two limbs, yields but one linear anomaly. Many such anomalies, now known or believed to be caused by tight synclines of the Stambaugh Formation, formerly were believed due to faulted segments of a single limb.

FAULTS

A dozen or more faults having displacement measured in thousands of feet have been delineated or inferred during the course of this study, and doubtless many more actually exist. The positions of the known and inferred faults are shown in figure 45.

The best known fault system lies at or near the north margin of the district. It comprises a group of faults in the northern part of the Iron River area, several faults in the Chicagon Creek area, and several in the Crystal Falls area. These three groups of faults, all of which have an easterly trend, are separated by gaps of from 2 to 3 miles in which geologic information is scanty. In all likelihood, the fault system is a continuous one, though individual faults doubtless die out along bedding or merge with other faults. The most completely mapped faults of this system are those in the northern part of the Iron River area, where two principal faults bound a synclinal trough that has been extensively drilled and entered by mine workings. These faults are high-angle reverse faults of opposing dip: the North Mineral Hills fault dips southward at about 60° and the South Mineral Hills fault dips northward at a somewhat steeper angle. In consequence, the rocks between the two faults have been thrust upward and outward so that actually the syncline is a downwarp in the crest of an uplifted block. Somewhat similar faults bound the Hiawatha mine syncline; as in Mineral Hills, this syncline is within a block thrust outward over its immediate environs along high-angle fault planes.

As seen in underground openings, the faults are zones of intense shearing commonly marked by squeezed and slickensided black slate and irregular seams of vein quartz. Commonly the zone is several feet wide and in places the movement has been distributed over a width of several hundred feet. But in at least one place—the 5th level of the Hiawatha No. 1 mine—a fault with displacement of on the order of half a mile is marked only by a quartz vein a few inches wide. As many as three metadiabase dikes are along the North Mineral Hills fault zone at the Davidson mine, where the zone of sheared rock is several hundred feet wide. In areas such as the 1200 level of the Sherwood mine, where iron-formation is on both sides of the South Mineral Hills fault, deep oxidation has destroyed most of the evidence of the fault which is readily mapped in adjacent areas.

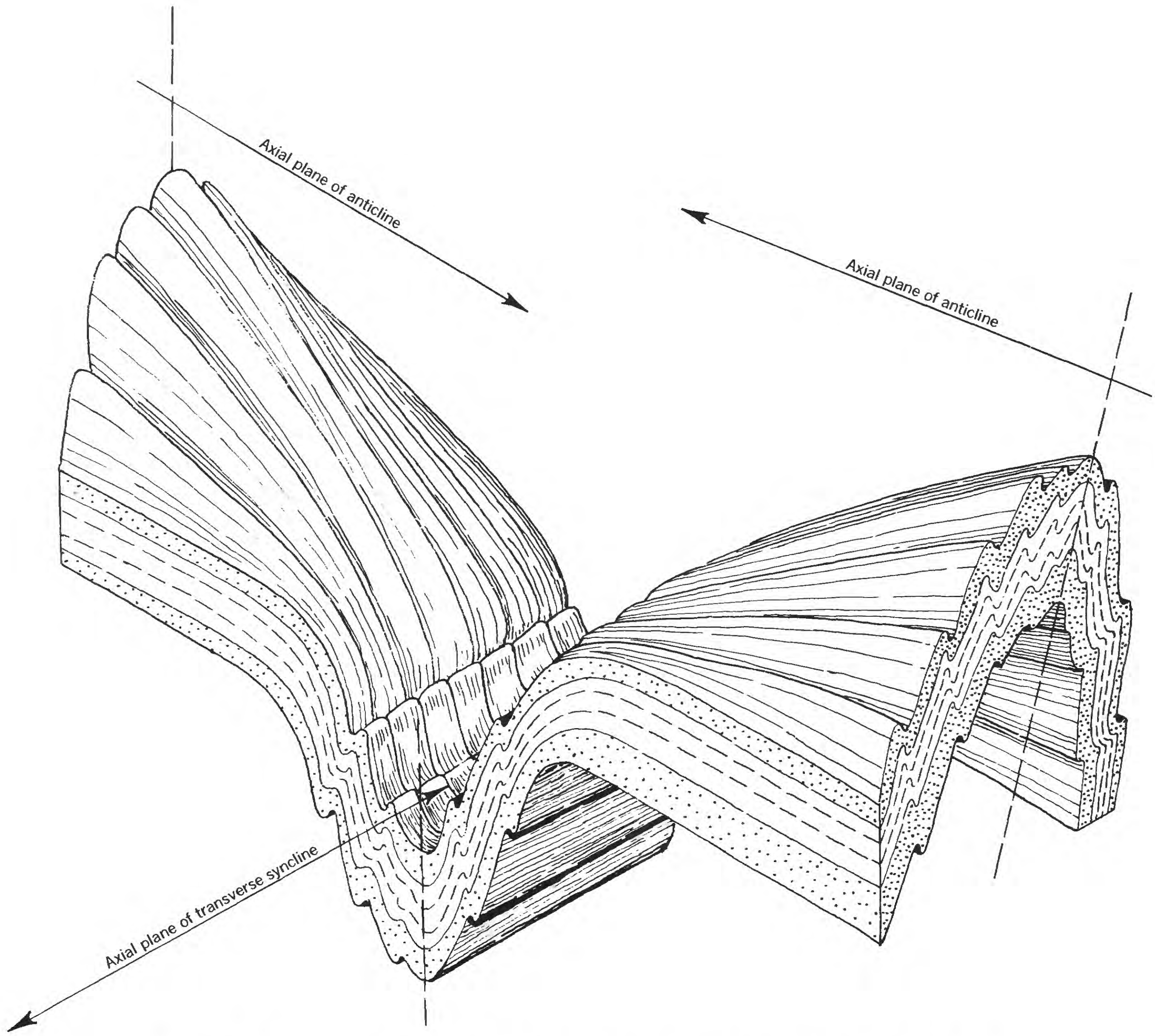


FIGURE 48.—Transition of two plunging anticlines into a transverse syncline of the same age.

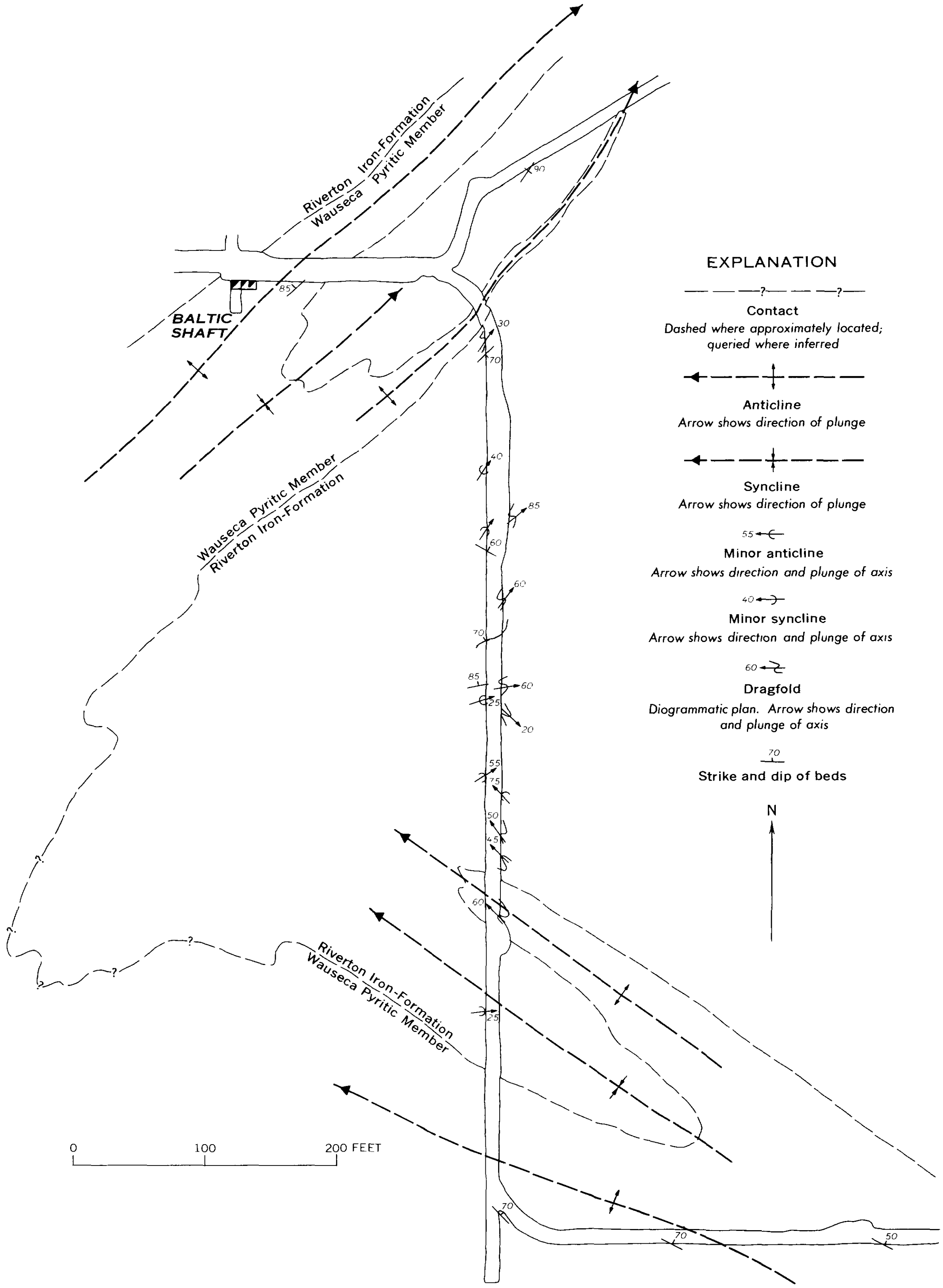


FIGURE 49.—Attitudes of folds in transitional zone between northwest-trending peripheral folds and northeast-trending crossfolds, 10th level in part of the Buck mine.

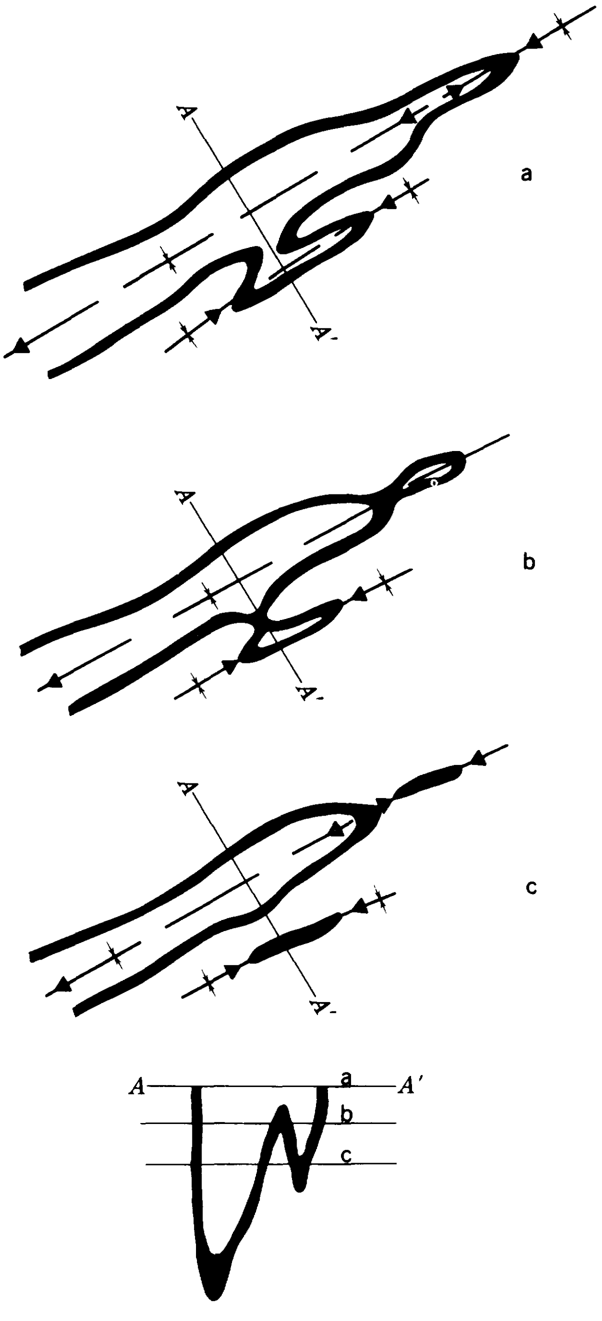


FIGURE 50.—Development of partly or completely detached canoe-shaped troughs by erosion of doubly plunging synclines. Map patterns at levels a, b, and c shown in cross section. Synclinal axes and plunge directions shown by conventional symbols.

EASTERN PART OF THE DISTRICT

The eastern part of the district—east of the belt of Riverton Iron-Formation that extends southward from Crystal Falls—is underlain mainly by rocks of the Baraga Group. Structurally it can be divided into two parts: the area of the Hemlock and Amasa Formations in the SE¼ T. 43 N., R. 32 W., and the area of the Badwater Greenstone, Michigamme Slate, and associated rocks, mainly in T. 42 N., R. 32 W.

The Hemlock and Amasa Formations form a steeply dipping northward-trending belt that is cut by several major faults. Folding is subordinate to faulting, though some minor crumpling can be observed in the walls of the open pit at the Armenia mine. The faults strike in a general westerly direction, almost at right angles to the general trend of the beds. The apparent offset on most is right lateral (north side moved east), as determined by abrupt terminations and offsets of magnetic anomalies, by exploration data in the ferruginous rocks, and by offsets in the well-exposed greenstone. The greatest lateral displacement, about 3,000 feet, is on the Cayia fault. The probable extensions of the Cayia fault are recognized in the Lake Mary quadrangle to the east (Bayley, 1959) and in the Crystal Falls area to the west; the total known length is about 8 miles. The Cayia fault and others in the area are subparallel to a well-developed foliation in the greenstone, a foliation that strikes nearly west and is nearly vertical.

The Michigamme Formation that is exposed along the valley of the Paint River south of the area just described is tightly compressed into northwesterly trending folds. This area will be described in some detail here.

On the basis of evidence within the district and in the adjacent Lake Mary quadrangle (Bayley, 1959) and Commonwealth quadrangle (unpub. data by H. L. James and K. L. Wier), three northwest-plunging synclines and complementary anticlines are recognized (fig. 45). Other major folds may exist, particularly in the southwestern part of the belt underlain by the formation, and many minor folds doubtless are present.

The Michigamme strata dip steeply and are overturned in many places. No key beds have been recognized. Some fold axes are recognized by transverse strikes or by convergence of strike, although even in axial areas most segments of bedding are parallel to the fold axes because of minor crumpling and boudinage. For others, the critical evidence is opposing directions of tops of beds, as determined by grain-size gradation. Cleavage seems to be of no aid in defining the structures in this area, and at least in some places the attitude is anomalous; for example, throughout sec. 34 and the western part of sec. 35, T. 42 N., R. 32 W., the cleavage strikes northwestward and dips southwest at considerably lower angles than bedding, yet grain-size gradations prove that the strata are not overturned.

The most northerly syncline extends through the center of sec. 13, T. 42 N., R. 32 W. It is inferred from evidence of northeast-facing top directions in the SW¼ sec. 13 and southwest-facing top direction in the adjoining Lake Mary quadrangle (Bayley, 1959). The complementary anticline is about three-fourths of a mile southwest; it crosses sec. 24, T. 42 N., R. 32 W., just north of Little Bull Rapids. This fold also is projected on the basis of evidence in the Lake Mary quadrangle, but the structure is confirmed by closure of strike near the center of sec. 14, T. 42 N., R. 32 W., and by observed reversal in top directions. The axial plane of this structure is overturned to the southwest; the bedding at Little Bull Rapids dips 75°–80° NE., but grain-size gradation shows tops to the southwest. Both the anticline and the syncline are similarly overturned to the east in the Lake Mary quadrangle (Bayley, 1959).

The next structure to the south is the Peavy syncline, which crosses secs. 25 and 26, T. 42 N., R. 32 W. In the adjoining Commonwealth quadrangle, the position of the Peavy syncline is well established by top determinations in the graywackes, but in this area it is recognized only by convergence of strike in sec. 25. The axial plane of the syncline appears to dip steeply north. The axial region of the anticlinal fold to the south—the Horserace Rapids anticline—is well exposed for nearly half a mile along the Paint River at Horserace Rapids, in secs. 35 and 36, T. 42 N., R. 32 W. Outcrops in this area are granulite and schist, and in most places structure is difficult to see. The rocks are crenulated along sheared westerly plunging minor folds, but the general trend of the beds is northeasterly despite the predominance of northwest strikes. In sec. 27, however, along the northwest projection of the axis, the rocks are uniformly steeply dipping, and the axial plane of the anticline must be nearly vertical.

The Horserace Rapids anticline is one of the principal folds in the eastern part of the map area, but it probably does not persist to the east into the Commonwealth quadrangle. Instead, the next anticline to the south (most southeasterly in fig. 45) becomes the main structure. Within the map area this anticline is very poorly defined, but to the east, in the Commonwealth quadrangle, it brings to the surface amphibolite that represents the underlying Hemlock Formation. The evidence for the complementary syncline is a single determination of northward-facing top of beds in the SW¼SW¼ sec. 35, T. 42 N., R. 32 W., and the presence of crumpling and opposing tops of beds in the southeastern part of the outcrop in sec. 1, T. 41 N., R. 32 W. The axial planes of these inferred structures are overturned to the north, in contrast to southward overturn of the folds north of the Horserace Rapids anticline. This opposing direction of overturn also is present in the quadrangles to the east; the reversal takes place along the Peavy node of metamorphism, the axis of which is coincident with the anticlinal arch at Horserace Rapids and with the Peavy Pond Complex in the Lake Mary quadrangle (Bayley, 1959).

Interpretation of the folds in the Michigamme Slate of this area is complicated by the probable existence of faults that cannot be well enough defined to show on the map. The postmetamorphic breccia zone immediately south of Little Bull Rapids coincides with an abrupt increase in metamorphic grade to the south, and it may well mark the westward extension of the Bush Lake fault (fig. 45). A zone of breccia similar to that near Little Bull Rapids crosses the SE¼ sec. 27, T. 42 N., R. 32 W. The zone trends N. 74° E. and has a maximum observed width of 200 feet and a minimum length of about 2,500 feet. The absence of brecciation or faulting in outcrops a few hundred feet beyond the southwest termination of the breccia indicates that no large fault displacement is involved. A second possible important fault is along the north side of the amphibolite of the Hemlock Formation mentioned previously as occurring in the Commonwealth quadrangle. The projected position of this fault is along the north side of the most southerly anticline shown in the structure map (fig. 45).

The Horserace Rapids anticline possibly is continuous to the northwest with the Mastodon anticline, which is marked by the northward projection of the Badwater Greenstone in sec. 17, T. 42 N., R. 32 W. The Mastodon anticline can be extended farther in a northerly direction into the Dunn Creek Slate for a distance of about 2 miles. The northward-plunging nose of this fold is shown by the distribution of a distinctive laminated slate within the Dunn Creek Slate in secs. 6, 7, and 8, T. 42 N., R. 32 W. This major anticlinal arch in the Dunn Creek Slate coincides with a broad magnetic anomaly which probably is due to magnetic units that occur at depth in the underlying Badwater Greenstone.

The Horserace Rapids anticline is paralleled on the northeast by the Peavy syncline, which may be continuous with the Tim Bowers Creek syncline in the Badwater Greenstone and younger rocks. The Dunn Creek Slate exposed along the grade of the Chicago and North Western Railway Co., near the east margin of sec. 17, T. 42 N., R. 32 W., is near the inferred axis of the Tim Bowers Creek syncline; the structure, as shown by a thin layer of chert in the slate, is a series of very tight folds such as typically occur near the axes of major structures.

It is the opinion of one of the authors (FJP) that the folds in the Michigamme Slate are unrelated to those in the Badwater Greenstone and Dunn Creek Slate and that in fact they are separated by a northerly trending fault marked by the Little Tobin Lake granite dike and similar dikelike bodies to the north. This inferred fault would terminate to the north or be displaced along the Cayia fault and, for much of its length, would separate Michigamme Slate to the east from Dunn Creek Slate to the west. In this view, the Badwater Greenstone would not necessarily be a continuous mass; rather it might reach bedrock surface on a series of anticlines comparable to that in sec. 19, T. 42 N., R. 32 W., and the adjacent part of sec. 24, T. 42 N., R. 33 W.

ORE DEPOSITS

MINING AND PRODUCTION

The first discovery of iron ore in the district was made by Harvey Mellen, a United States land surveyor. On August 8, 1851, according to Allen (1910, p. 3), Mellen recorded the occurrence of an "outcrop of iron ore five feet high" on the west slope of Stambaugh Hill, 52 chains north of the SW cor. sec. 36, T. 43 N., R. 35 W. Mining began in 1881, and the first shipments were made in 1882, when the Chicago & North Western Railway constructed spur lines into the Crystal Falls and Iron River areas. That year, 1882, shipments were made from eight mines in the district: Mastodon, Columbia, Crystal Falls, Great Western, Paint River, and Youngstown in the Crystal Falls area, and Nanaimo and Riverton (Iron River) in the Iron River area. The total production for 1882 was 73,706 gross tons, valued (then) at more than $400,000. Except for 1894, following the financial panic of 1893, this production has been exceeded every year since.

The production record for the district is summarized in table 15 and in figure 51, the data for which are drawn largely from the two volumes "Lake Superior Iron Ores" (Lake Superior Iron Ore Assoc., 1938, 1952), supplemented for the years 1951–61 by the annual statistical summaries by the State Mine Appraiser

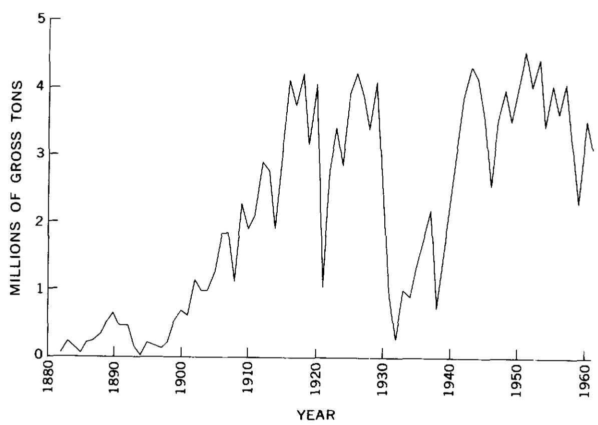


FIGURE 51.—Shipments of iron ore from the Iron River–Crystal Falls district, 1882–1961. (See also table 15.)

(Michigan Dept. Conserv., Geol. Survey Div., 1951–61). Some confusion and inconsistency in the presentation of production records is inevitable because of changes in the names of individual properties and because of merging of two or more adjoining properties into single operations. For merged operations, production may or may not be reported by individual properties, depending upon the nature of the ownerships.

During the 80-year period 1882–1961, the district shipped a total of about 175 million tons of ore. Most of this is classed, according to Lake Superior schedules, as "Direct-shipping, Old Range, high-phosphorus, non-Bessemer ore"—that is, it is ore shipped virtually as mined; it has a minimum iron content of 51.50 percent (before drying) and a phosphorus content in excess of 0.18 percent. The base price at Lake Erie ports for ore of this type has ranged from a low of $1.85 per ton in 1898 to $11.14 in 1958. Adjustments of the price are made on the basis of actual iron, manganese, phosphorus, and sulfur content of individual shipments, and in earlier years contracts were negotiated for each mine. The cost of transportation to the Lake Erie ports is a major item; in 1961 this amounted to $3.22 per ton, or about 30 percent of the Lake Erie base price. The actual value of the ore at the mine in 1961, therefore, was somewhat less than $8.00 per ton. It is of interest to note that ice sawed from the lakes during the winter months is sold locally for about 1 cent a pound, or $22.40 per long ton.

The gross value for ore production through 1961 is about a billion dollars, at the Lake Erie base values.

Except in the early years of the district, when many properties were operated as small open-pit mines in areas of shallow overburden, most of the ore has been extracted by underground mining. A common method of mining is sublevel caving, in which the ore is mined in successive slices from the top down and transferred by chutes to haulage levels below; the material overlying the ore, together with a separating mat of timbers and cribbing, is permitted to cave progressively. Some ore bodies are mined by open stopes, and in a few mines these stopes are backfilled later to prevent caving of the walls. One of the major hazards to mining in the district is caused by the (stratigraphically) underlying pyritic slate; if, as is common, the ore-bearing bed dips at high angles or is overturned, the pyritic slate will cave into the open area and will burn if exposed to air. Virtually all the mines in the district during their operation have had some section bulkheaded off to control an area of mine fire.

The ore bodies, in general, are steeply dipping and highly permeable masses that are in contact with a water-soaked cover of glacial deposits. As a result, the flow of water into underground openings is very large, particularly in the early stages of development, and pumping draws water from a large surrounding area. Pumping of water from the now-abandoned Rogers mine, for example, lowered the level of Sunset Lake, 2½ miles away. The drainage problems, and methods of coping with them, are discussed for the Iron River area by Stuart, Theis, and Stanley (1948).

GENERAL CHARACTER OF THE ORE BODIES

The ore bodies occur exclusively in beds of iron-formation: the Riverton Iron-Formation in the Iron River and Crystal Falls areas and the Amasa Formation in the northeastern part of the map area. The discussion that follows will be in specific reference to deposits in the Riverton Iron-Formation, which account for all but a trifling part of the district production.

The ores vary considerably in physical aspect, but the typical ore is yellow to bluish red, compact, and highly porous. Most of the ore is soft—in some mines it is drilled with an auger—but layers and lumps of hard goethite are common in some deposits. The original layering of the iron-formation from which the ore is derived commonly is well preserved, in places even accentuated by alternation of layers rich in yellowish goethite or reddish hematite. Most of the mined deposits are tabular bodies with thicknesses of 100 feet or more, and they extend laterally and vertically for hundreds or thousands of feet. Except in detail, variations within such ore bodies are relatively slight, and selective mining is not necessary. Single ore bodies, which are not easily defined because of complex folding and because ownerships are divided, may contain more than 20 million tons of minable ore. All deposits for which adequate information is available can be shown to be continuous to the surface (or to a subsurface contact with overburden) although many are of far greater dimension in depth. Most of the ore bodies terminate downward by reason of structure; laterally, they terminate either by structure or by abrupt gradation into oxidized iron-formation in which chert still remains.

Most of the iron ore bodies contain only a minor amount of manganese, but in certain parts of the ore bodies in several mines (particularly the Bengal-Cannon and Bristol) the ore is highly manganiferous. The manganese occurs almost entirely as hausmannite, which veins the iron ores. The manganiferous ore bodies grade laterally and vertically into the normal type of iron ore. The occurrence and mineralogy of these ores are described under "Manganiferous ores," later in this report.

ROCK ALTERATION

IRON-FORMATION

The ore bodies occur within iron-formation that is oxidized over far wider tracts than the area of ore. This oxidation has converted the original ferrous minerals (siderite, principally) to hematite or goethite, and the dark-appearing chert layers have been whitened, have become somewhat more brittle, and have been partly replaced by iron oxides. All gradations can be found from oxidized iron-formation consisting of interlayered white chert and iron oxides to iron ore containing almost no chert. An example of the oxidized iron-formation is shown in figure 52.

"Slaty" iron-formation, which in the unoxidized form contains chlorite or stilpnomelane, in addition to siderite and chert, oxidizes to a mottled red and green rock. A typical specimen (HJ–35–47, from the Baltic mine)

FIGURE 52.—Oxidized iron-formation. White chert interlayered with and in part embayed by red and yellow iron oxides (dark). Layered oxides secondary after siderite. From Spies mine. Natural scale.

TABLE 15.—*Shipments, in gross tons, of iron ore from mines*

1882–1908

Tracing No.	Mine	1882	1883	1884	1885	1886	1887	1888	1889	1890	1891	1892	1893	1894
1	Alpha													
2	Armenia								50, 275	26, 649				
3	Berkshire													
4	Beta					1, 585	1, 226				1, 400			
5	Bristol-Youngstown									6, 844		57, 352	9, 612	
	Buck group:													
6	Baltic													
7	Fogarty													
8	Caspian													
9	Chatham													
10	Columbia	15, 948	4, 334	6, 774		15, 072	3, 679	10, 936	11, 385	60, 133	70, 770	57, 682	22, 426	10, 300
11	Crystal Falls	[2] 1, 341								3, 974				
12	Delphic		3, 410	508	9, 880	17, 648	2, 272							
13	Dunn						24, 677	118, 096	151, 828	156, 963	162, 721	133, 666	58, 590	24, 538
14	Genesee													
15	Great Western	687	22, 825	20, 710		22, 267	23, 239	21, 860	38, 454	72, 546	62, 464	87, 487	661	
	Hiawatha group:													
16	Hiawatha No. 1												1, 683	
17	Hilltop													
18	Hollister									2, 020	1, 057	1, 021		
19	Hope											15, 543	2, 275	
20	James (Osana)													
21	Kimball													
22	Lamont (Monitor)								12, 348	31, 139	26, 226	42, 819	13, 777	2, 600
23	Lee Peck											2, 844		
24	Lincoln										1, 813	26, 019	8, 757	
25	Mastodon [3]	3, 477	18, 577	18, 187	11, 737	41, 640	48, 792	51, 463	63, 511	66, 526	45, 370	9, 150	23, 485	
26	Monongahela													
27	Nanaimo	2, 480	29, 221	37, 620		5, 400	30, 460	5, 744		3, 441	13, 200			
28	Paint River	14, 560	6, 428	11, 652	2, 373	13, 933	10, 240	12, 506	32, 700	62, 654	45, 435	18, 390		
29	Riverton group [4]	29, 115	100, 369	52, 584	55, 693	78, 591	83, 018	110, 000	179, 238	155, 458	59, 345	1, 176		
30	Sheridan								1, 102	595	7, 137	45, 745	2, 234	
31	South Mastodon							2, 722	4, 005	1, 476				
32	Tobin													
33	Youngs													
34	Youngstown	6, 198	15, 292	8, 344		25, 635	34, 418	12, 699		44, 460	3, 705			
35	Zimmerman													
36	Yearly total	73, 706	200, 456	156, 379	79, 683	221, 771	262, 021	346, 026	544, 846	694, 878	500, 643	498, 894	143, 500	37, 438

1909–35

Tracing No.	Mine	1909	1910	1911	1912	1913	1914	1915	1916	1917	1918	1919	1920	1921
1	Armenia		65, 473	51, 863	150, 808	83, 142	50, 501							
2	Baker	45, 003	39, 417	3, 290		24, 286	113, 733	41, 378						
3	Balkan-Judson						6, 619	144, 284	391, 714	321, 249	458, 231	270, 012	220, 613	150, 151
4	Bates							45, 171	73, 188	141, 890	98, 194	91, 522	90, 427	35, 638
5	Bengal					23, 259	5, 539	39, 615	140, 961	260, 377	303, 788	229, 501	265, 035	60, 839
6	Berkshire [5]	34, 295	97, 999	22, 273	33, 419		23, 824	15, 413	38, 467	57, 791	38, 439	49, 076	159, 991	32, 104
7	Bristol-Youngstown	396, 825	270, 742	322, 647	435, 619	379, 168	172, 034	378, 786	462, 559	188, 907	245, 151	58, 183	368, 479	13, 555
	Buck group:													
8	Baltic	174, 426	171, 930	66, 502	100, 736	130, 631	29, 206	10, 078	110, 965	89, 307	141, 903			76, 878
9	Buck													
10	Fogarty	77, 356	51, 071	67, 616	84, 074	124, 568	15, 329	27, 718	89, 506	37, 291	24, 979	15, 405	16, 384	49, 789
11	Cardiff [6]													
12	Carpenter						51, 146	284, 088	240, 114	269, 387	384, 148	396, 224	123, 409	127, 299
13	Caspian	189, 023	171, 334	165, 660	306, 913	295, 841	279, 379	479, 084	448, 631	411, 705	346, 028	315, 327	421, 822	
14	Chatham	68, 730	51, 988	58, 056	134, 079	107, 608	19, 454	132, 779	188, 808	244, 934	246, 648	51, 758	15, 624	
15	Chicago			108, 947	149, 619	137, 002	114, 848	155, 711	100, 640	90, 786	109, 574	82, 655	135, 700	83
16	Cortland				17, 498	19, 332	15, 318							
17	Cottrell							45	75, 089					
18	Crystal Falls	986		710	665	7, 389								
19	Davidson group			45, 434	126, 207	195, 448	122, 567	152, 430	164, 248	223, 990	113, 779	248, 298	220, 993	42, 487
20	Davidson No. 4					1, 750				16, 032	5, 071	13, 750	51, 330	40, 666
21	Delta												8, 366	42, 979
22	Dunn	193, 396	136, 144	232, 093	242, 304	14, 912	52, 883	8, 304						
23	Forbes					69, 435	77, 960	99, 050	121, 010				126, 581	
24	Genesee	65, 585	66, 185	25, 342	4, 248			1, 184						
25	Great Western	112, 747	80, 709	84, 339	3, 342	50, 465		35, 759		7, 692	63, 449	42		
	Hiawatha group:													
26	Hiawatha No. 1	136, 739	128, 884	116, 736	220, 106	160, 510	91, 369	93, 455	187, 070	62, 847	126, 962	86, 138	125, 030	41, 503
27	Hiawatha No. 2													
28	Hilltop						8, 223			36, 239	32, 164	1, 347		
29	Hollister	25, 842	49, 434	5, 021		25, 251	16, 429							
30	Homer							103, 546	161, 286	202, 351	213, 059	202, 463	300, 111	92, 630
31	James (Osana)	90, 851	78, 388	50, 439	75, 702	188, 966	73, 832	121, 655	167, 115	171, 001	201, 090	137, 579	170, 882	10, 064
32	Kimball							19, 533						
33	Lamont (Monitor)		3, 183											
34	Lincoln	1, 657												
35	McDonald	1, 144	6, 022	5, 240	1, 384	16, 499								
36	Monongahela								21, 922		25, 739	66, 013	178, 849	12, 468
37	Odgers								53, 177	169, 668	257, 637	100, 061	222, 336	21, 561
38	Paint River					2, 289								
39	Ravenna-Prickett				18, 301	70, 763	49, 309	116, 724	3, 476	37, 848				
40	Richards					46, 170	7, 069	92, 808	29, 382	43, 890	56, 087	111, 116	87, 465	80
41	Riverton group [4]	171, 200	84, 269	198, 589	177, 496	160, 818	176, 274	262, 382	175, 147		100, 527	72, 875	161, 778	115, 494
42	Rogers						27, 080	53, 158	81, 842	117, 323	84, 196	50, 341	94, 061	
43	Sherwood													
44	Spies									6, 310	48, 782	109, 740	190, 593	28, 467

See footnotes at end of table.

in the Iron River–Crystal Falls district, 1882–1961

1882–1908—Continued

1895	1896	1897	1898	1899	1900	1901	1902	1903	1904	1905	1906	1907	1908	Mine total[1]	Tracing No.
								1,370						1,370	1
2,045						18,750	100,864	31,901	16,577		27,882	36,665			2
													3,440		3
															4
				80,915	51,639	36,593	129,035	246,581	132,420	210,388	298,031	345,676	190,300		5
						17,326	64,664	123,236	151,114	133,246	186,495	189,119	129,037		6
												7,949	32,560		7
								2,088	4,242	10,248	80,875	138,867	102,628		8
												14,883	45,826		9
70,867	87,202	24,623	14,199	126,290	97.531	19,963	186,798			27,883				944,795	10
13,037	44,526	95,210	128,233	147,346	197,770	230,614	195,555	117,096	180,983	152,255	111,871	114,158	296		11
	52													33,770	12
90,885	47,081	31,062	49,381	7,458			2,816	5,365		21,051	91,476	141,992	8,829		13
							14,455	61,694	132,380	77,370	80,971	38,984			14
	14,643		33,851	43,316	98,550	123,261	42,470	100,751	68,318	191,265	311,218	234,492	124,246		15
1,201					11,008	20,355	74,596	53,828	38,288	9,704	20		138,190		16
				3,496	6,410	2,503					7,820				17
												6,371	10,671		18
							3,373	7,339						28,530	19
												2,360	59,760		20
												16,224			21
				67,652	31,323		47,267	43,736	29,393	74,991	89,980	42,090			22
														2,844	23
				43,622	72,959	19,727	7,747	15,606	17,577	19,539	5,890	714			24
23,733	60														25
						2,397		6,913							26
									9,086	91,238	91,792	53,778	305	373,765	27
					1,316		10,383	9,863	11,257	11,973	28,321	75,805			28
			5,009	13,242	120,207	119,860	215,850	97,633	81,543	82,611	161,701	90,358	47,073		29
16,754	3,419	146		31,104	8,063									116,299	30
														8,203	31
						18,957	55,238	45,386	113,669	166,529	235,867	237,781	161,642		32
										10,926	47,583	92,632	70,094		33
13		661												151,425	34
													1,832		35
218.535	196,983	151,702	230,673	564,441	696,776	630,306	1,151,111	970,386	986,847	1,291,217	1,857,793	1,880,898	1,126,729		36

1909–35—Continued

1922	1923	1924	1925	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	Mine total[1]	Tracing No.
														713,395	1
														267,107	2
209,798	197,308	208,659	217,401	213,819	228,981	228,353	216,257	145,157	30,337		52,682	19,177	63,682	3,994,484	3
112,959	49,288	101,420	32,420	179,396	156,225	151,404	125,843	110,658	117,489	90,755	58,473	148,078	193,351		4
163,042	157,311	322,540	243,097	181,295	215,513	231,874	241,790	41,633			22,647	7,668	16,923		5
118,871	209,994	259,892	271,076	338,115	299,107	253,34	215,635	146,477							6
124,146	455,026	110,489	270,650	398,236	402,917	333,092	562,836	174,296	85,688	2,537	50,531	162,594			7
132,809	38,791	28,418	67,683	56,328	15,722	1,425	9,456	11,470	537		1,827				8
5,660	4,685	20,319	103,774	118,979	150,585	45,443	105,485	76,343	17,295		53,948	10,629	21,538		9
131,359	81,745	42,802	21,091	35,191	53,257	43,869	38,734	18,986	5,538	7,538	25,464	7,874	25,232		10
28,982	115,433													144,415	11
206,837	132,617	197,278	138,481	99,419	8,858	76,147								2,735,452	12
158,063	234,199	180,668	314,738	286,293	282,891	247,102	335,885	148,252	33,422		71,231	23,404	20,695		13
														1,381,175	14
48,774														1,234,339	15
														52,148	16
														75,134	17
														1,744,015	18
166,376	202,586	71,335	252,137	250,337	245,425	251,282	311,631	176,678	82,735		139,084	50,588	96,336		19
														128,599	20
	11,508	18,408	14,498											95,759	21
														2,208,511	22
	119,036	74,117	100,535	149,768	152,342	152,181	161,569	91,221				19,796	122,884		23
						699	135,098	167,406		85,814	99,197	114,485	27,286	1,198,383	24
59,800			38,914											2,296,739	25
126,885	146,257	196,427	263,054	191,716	169,755	171,062	208,960	151,589	116,444	41,446	143,542	152,598	284,228		26
													424		27
														98,202	28
														143,117	29
135,975	231,854	139,401	152,258	134,729	182,431	195,747	176,749	136,866			84,776		13,638		30
185,675	63,143	104,953	227,511	303,118	302,891	233,052	302,301	176,847	69,953		30,457	42,061	175,014		31
														35,757	32
														558,524	33
														241,627	34
														30,289	35
114,839	164,107	173,112	187,176	182,446	63,255				18,014		63,289	71,885			36
55,481	295,951	80,022	178,342	272,625	185,106	42,499	30,441	16,719		1,607	531	52,285	65,332	2,101,381	37
														382,078	38
															39
	17,206			32,550	10,625									534,448	40
119,916	211,279	111,340	344,903	200,994	185,215	239,822	240,375	161,076	64,568				60,113		41
193,845	199,028	218,698	215,093	254,175	285,922	179,927	323,883	128,721	169,692	40,449	27,476		20,775		42
									1,027		398				43
35,123		19,667	54,698	8,445	3,264										44

See footnotes at end of table.

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TABLE 15.—*Shipments, in gross tons, of iron ore from mines in*

1909–35

Tracing No.	Mine	1909	1910	1911	1912	1913	1914	1915	1916	1917	1918	1919	1920	1921
45	Tobin	359,668	235,812	308,457	319,318	154,896	65,351	18,624	146,113	188,590	202,775	97,674	153,544	--------
46	Tully	--------	2,726	8,324	--------	16,650	63,411	242,049	236,302	121,426	125,087	134,141	--------	72,342
47	Virgil	--------	--------	--------	2,996	48,945	5,913	--------	36,307	--------	40,321	--------	--------	--------
48	Wauseca	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
49	Wickwire	--------	--------	1,919	40,417	47,697	25,329	--------	13,265	242	--------	--------	--------	--------
50	Wilkinson	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	584	--------
51	Youngs	154,150	98,399	89,451	83,528	44,091	--------	--------	53,691	23,197	2,601	--------	8,376	--------
52	Zimmerman	10,303	25,555	112,029	189,482	150,817	172,720	108,217	145,716	219,873	145,217	197,048	170,585	--------
53	Yearly total	2,309,926	1,915,664	2,150,977	2,918,261	2,798,598	1,932,649	3,283,028	4,157,711	3,762,143	4,241,626	3,188,289	4,088,948	1,067,077

1936–61

Tracing No.	Mine	1936	1937	1938	1939	1940	1941	1942	1943	1944	1945	1946	1947
1	Bates	154,385	153,5'6	85,336	186,472	170,064	158,173	185,888	148,813	221,800	195,484	136,658	54,258
2	Bengal [7]	--------	102,059	43,367	300,691	280,945	397,645	521,961	367,790	281,652	--------	--------	--------
3	Berkshire [5]	87,935	52,784	10,086	51,450	3,178	--------	--------	39,179	--------	--------	--------	--------
4	Beta	--------	--------	--------	--------	--------	[8] 18,998	[8] 3,947					
5	Book	--------	--------	--------	--------	--------	--------	--------	288,447	320,976	129,009	116,798	210,638
6	Bristol-Youngstown	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
7	Buck group [9]	--------	--------	--------	--------	--------	--------	--------	--------	683,089	665,674	455,511	701,394
8	Baltic	--------	8,905	5,509	8,224	2,738	7,924	5,959	34,738	--------	--------	--------	--------
9	Buck	123,134	227,604	52,422	58,935	224,507	323,625	501,499	630,033	--------	--------	--------	--------
10	Fogarty	30,510	93,648	3,109	15,348	43,607	39,851	12,722	--------	--------	--------	--------	--------
11	Cannon	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
12	Caspian	106,401	10,381	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
13	Cayia	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
14	Davidson group	149,572	191,629	19,376	50,784	300,920	318,624	335,933	334,069	210,169	224,924	76,429	191,639
15	Forbes	164,054	289,296	54,940	107,030	--------	--------	--------	3,415	13,666	11,856	2,080	--------
16	Fortune Lakes	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
17	Hiawatha group	--------	--------	--------	--------	--------	--------	--------	--------	543,423	542,161	381,422	507,618
18	Hiawatha No. 1	203,649	282,413	191,897	251,464	279,095	298,696	355,014	316,332	--------	--------	--------	--------
19	Hiawatha No. 2	[10] 167,502	105,896	64,678	187,007	274,232	230,984	283,093	191,390	--------	--------	--------	--------
20	Homer	55,006	181,030	57,212	142,288	218,448	316,316	324,787	231,497	296,083	322,205	230,415	296,006
21	James (Osana)	142,755	218,973	81,709	167,630	210,360	318,008	450,148	505,227	323,565	285,668	273,373	304,933
22	Lawrence	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
23	Mastodon [3]	--------	--------	--------	--------	--------	--------	21,607	--------	--------	--------	--------	--------
24	Monongahela	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
25	Ravenna-Prickett	--------	--------	--------	--------	62,082	91,774	66,528	118,422	--------	--------	--------	--------
26	Riverton group [4]	109,698	35,728	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
27	Rogers	12,885	17,980	--------	--------	3,074	55,950	38,951	--------	--------	12,850	--------	--------
28	Sherwood	1,292	--------	--------	--------	--------	--------	--------	271,345	312,935	303,223	238,003	383,428
29	Spies	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	150,606
30	Tobin [11]	113,293	59,352	34,985	40,113	24,681	232,240	348,067	374,140	425,697	526,664	324,842	358,659
31	Virgil	121,255	172,498	36,021	29,543	172,090	275,562	193,470	115,024	101,818	83,073	52,565	--------
32	Wauseca	--------	--------	--------	--------	41,305	47,002	142,155	262,287	305,394	218,808	248,445	421,940
33	Zimmerman	67,724	2,574	--------	--------	--------	--------	155,459	105,050	122,020	50,789	4,001	8,795
34	Yearly total	1,811,050	2,206,296	740,647	1,596,979	2,311,326	3,131,372	3,947,188	4,337,198	4,162,287	3,572,388	2,540,542	3,589,914
35	Total shipments all mines, 1882–1961.	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------

[1] Figure indicates no subsequent shipments. Leaders indicate additional shipments in subsequent years.
[2] Shipments apparently came from Lot 3 mine.
[3] Mined as part of the Balkan-Judson operation from an eastern extension of the Balkan ore body.
[4] Includes Riverton, Iron River, Dober, Duff, Isabella. Ore from Dober, Duff, and Isabella included with that from Hiawatha No. 2 beginning in 1935.

contains hematite, goethite, and quartz, and an abundant chlorite with a (001) spacing of 14.3 A; it also contains lesser amounts of clay mica with a (001) spacing of 10.0 A, similar if not identical to that of the ores. The relative values of the (001), (002), and (003) peaks in the X-ray diffraction pattern of the chlorite suggest, according to Weaver (1958, p. 266), an iron-rich variety.

The depth of oxidation is half a mile or more in at least two parts of the district. Completely oxidized iron-formation has been drilled at a depth of 2,600 feet in the Chicagon Creek area, and ore was being mined at the Hiawatha mine at the time of this report to a depth of 2,520 feet. At the Hiawatha mine, unoxidized rock is at the surface within half a mile laterally, along the strike of the formation.

The areal extent of oxidation of the iron-formation is difficult to appraise accurately. A rough estimate can be obtained from the fact that of the approximately 400 forty-acre tracts that are in part or wholly underlain by Riverton Iron-Formation, the iron-formation is oxidized at the surface in about half (excluding the purely superficial oxidation related to conditions of the present and recent past). This estimate, based mainly on exploration data, doubtless is weighted in favor of the oxidized iron-formation, inasmuch as a given drill hole in oxidized iron-formation would tend to encourage further exploration that perhaps would increase the known area of iron-formation, whereas this would not be true for a hole in unoxidized formation. The area of known iron-formation in the north part of sec. 13, T. 43 N., R.

the Iron River-Crystal Falls district, 1882–1961—Continued

1909–35—Continued

1922	1923	1924	1925	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	Mine total [1]	Tracing No.
105,344	49,874	102,715	91,642	--------	67,945	66,949	--------	19,598	--------	9,802	38,258	12,903	86,297	--------	45
62,129	--------	--------	--------	67,036	--------	--------	--------	--------	--------	--------	--------	--------	--------	1,151,623	46
--------	--------	--------	9,596	55,195	12,904	22,334	175,078	137,854	79,497	4,551	48,889	--------	64,792	--------	47
--------	--------	--------	--------	50,342	41,306	75,543	50,305	--------	--------	--------	--------	--------	--------	--------	48
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	128,869	49
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	584	50
--------	--------	--------	--------	--------	15,912	8,120	--------	--------	--------	--------	--------	--------	--------	802,751	51
33,504	51,772	96,351	132,467	189,727	180,706	157,223	149,860	62,740	35,300	7,582	--------	6,245	52,073	--------	52
2,836,192	3,439,998	2,879,031	3,943,235	4,250,274	3,919,060	3,408,496	4,118,171	2,300,587	927,536	292,081	1,012,700	902,270	1,410,613	--------	53

1936–61—Continued

1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	Mine total	Tracing No.
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	4,054,666	1
--------	39,378	163,682	198,205	116,122	--------	--------	--------	--------	--------	--------	--------	--------	--------	5,987,744	2
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	2,963,657	3
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	27,156	4
93,193	114,386	75,913	128,112	207,717	135,233	60,980	143,039	115,419	100,409	32,853	--------	--------	--------	2,273,122	5
--------	--------	105,018	192,286	199,763	259,662	268,516	324,984	300,564	353,280	339,941	215,853	287,115	338,458	11,806,519	6
622,160	571,287	435,687	638,482	644,648	507,835	311,037	556,229	422,596	390,084	187,442	223,278	264,418	--------	15,191,625 (7–10)	7
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------		8
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------		9
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------		10
--------	--------	--------	--------	--------	270,816	205,380	238,075	327,487	731,903	610,358	450,232	746,728	567,582	4,148,561	11
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	6,623,320	12
--------	--------	--------	--------	--------	--------	44,492	--------	--------	--------	--------	--------	--------	--------	44,492	13
319,245	273,790	337,518	423,385	322,040	164,557	--------	--------	--------	--------	--------	--------	--------	--------	8,197,014	14
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	2,283,822	15
--------	--------	--------	--------	--------	227,016	226,000	375,509	346,816	139,274	2,290	--------	--------	--------	1,316,905	16
535,231	569,302	590,885	583,706	556,592	630,423	530,229	613,709	542,187	661,551	425,918	355,249	490,792	541,813	17,576,162 (17–19)	17
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------		18
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------		19
350,926	393,029	501,499	588,913	435,652	655,257	433,633	459,603	433,354	521,146	386,864	360,116	569,607	553,857	12,174,619	20
215,048	192,064	178,586	213,832	158,903	191,304	77,596	--------	--------	--------	--------	--------	--------	--------	8,326,342	21
--------	--------	--------	--------	--------	--------	--------	--------	6,379	--------	--------	--------	--------	--------	6,379	22
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	447,315	23
--------	--------	--------	--------	31,361	107,098	103,612	98,277	94,884	--------	--------	--------	--------	--------	1,787,656	24
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	635,227	25
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	5,881,550	26
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	2,907,375	27
491,918	420,718	414,617	499,619	433,603	413,144	430,679	402,947	393,991	452,088	471,358	286,543	369,669	418,240	7,410,785	28
183,574	88,452	257,838	250,123	126,727	177,406	101,368	222,944	32,893	--------	--------	--------	--------	--------	2,097,020	29
440,794	346,287	406,993	293,433	252,596	198,571	186,274	164,313	96,045	144,085	--------	76,664	91,346	--------	9,497,352	30
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	2,098,091	31
747,839	527,666	591,342	578,476	550,119	488,487	481,855	480,820	503,716	596,632	553,465	360,330	696,985	690,014	9,752,578	32
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	3,321,356	33
3,999,928	3,536,359	4,059,578	4,588,572	4,035,843	4,426,809	3,461,651	4,080,449	3,616,331	4,090,452	3,010,489	2,328,265	3,516,660	3,109,964		34
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	174,978,316	35

[5] Includes Cottrell, 1917–30. Operated as part of Buck group beginning in 1944.
[6] Operated as part of Homer after 1924.
[7] Listed as Bengal-Tully beginning 1949; operated as part of Cannon beginning 1953.
[8] Stockpile shipments only.
[9] Beginning 1944, includes Baltic, Buck, Fogarty, Berkshire; beginning 1948 includes Zimmerman; beginning 1950 includes DeGrasse.
[10] 4,200 tons from Brule (Hiawatha No. 3) included with 1936 shipment from Hiawatha No. 2.
[11] Listed as Tobin-Columbia or Columbia in reports after 1940.

35 W., for example, certainly would be extended if the iron-formation discovered by drilling had been oxidized.

The restrictions on the extent of oxidation are of five types:

1. Areal restriction. The majority of the "forties" in which the iron-formation is unoxidized occur in four areas, namely, the westernmost part of the district, west of the Hiawatha mine; the poorly known south flank of the Iron River-Crystal Falls basin, east of Gaastra; the Fortune Lakes "straightaway" (the belt between Chicagon Creek and the Fortune Lakes mine); and the Alpha-Brule River belt, in the southeastern part of the district.

2. Structural restriction. Areas in which the iron-formation is at bedrock surface on anticlinal structures are much more likely to be unoxidized than those in synclinal structures.

3. Stratigraphic restriction. This restriction is much more pronounced in the eastern part of the district than in the western. In the Crystal Falls-Alpha belt of iron-formation, commonly only the stratigraphically middle half of the formation is oxidized at depth; the upper part of the formation, and the lower part (including the interbedded "raindrop slate") are unoxidized in many places, even in the vicinity of ore bodies. See, for example, figure 53.

4. Lithologic restriction. Slaty iron-formation—that characterized by abundant chlorite or stilpnomelane or by seams of graphitic slate—is much less likely to be oxidized than cherty facies.

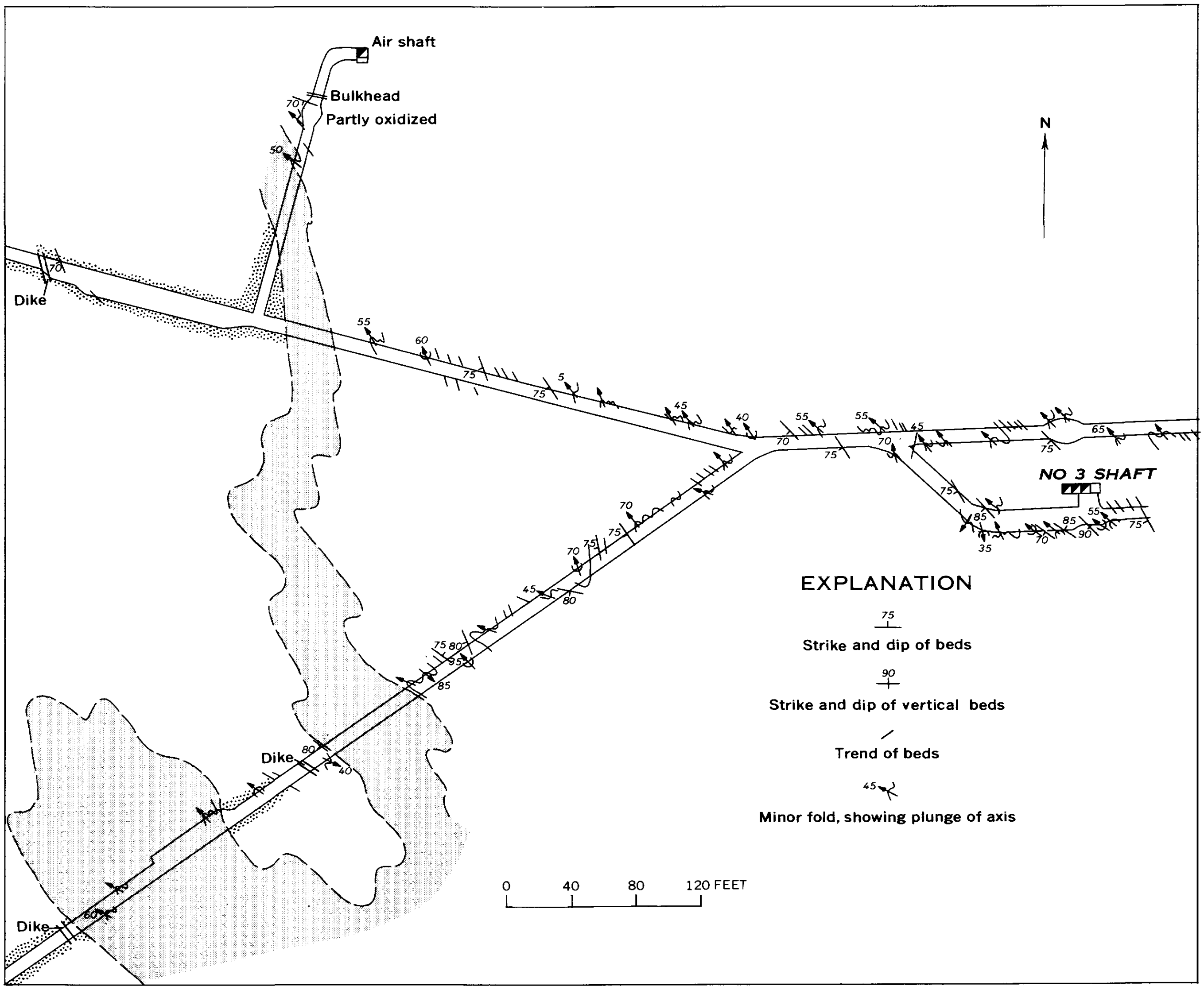


FIGURE 53.—Attitude of bedding and minor folds and plunge of fold axes in iron-formation, 7th level Tobin mine. Slaty iron-formation ("raindrop slate" unit) shaded; oxidized iron-formation, which contains ore bodies, stippled. Geology by H. L. James and M. W. Leighton, 1949.

5. Depth restriction. Though numerical data are difficult to obtain, nevertheless there can be no doubt but that the percentage of oxidized iron-formation decreases rapidly with depth, particularly below 1,000 feet.

ROCKS OTHER THAN IRON-FORMATION

In areas where the Riverton Iron-Formation is oxidized, rocks of the "hanging wall" strata—that is, the Hiawatha Graywacke—commonly are deeply altered. Virtually all the rock contained within the major syncline of the Mineral Hills area, for example, is deeply oxidized to soft reddish-brown to cream-colored material in which the only original constituent recognized is clastic quartz. In the area of the Bengal-Cannon mine, graywackes now have an iron content of as much as 40 percent, several times as much as in the original rock. Drill holes in the Buckholtz area (sec. 27, T. 43 N., R. 35 W.) penetrated many hundreds of feet of soft white to cream-colored "kaolinitic slate and graywacke." X-ray examination of the rock shows it to consist almost entirely of quartz and a clay mica. The mica is identified as dominantly a 2*M* polymorph by comparison with the X-ray patterns given by Yoder and Eugster (1955, p. 245), particularly by the moderately strong peaks with *d*-values from 3.7 A to 4.0 A, and 2.8 A to 2.9 A. Possible mixture with some 1*M* mica is suggested by a peak at 3.66 A. Quartz is the only other mineral present.

X-ray examination of samples from many other parts of the area indicate that in general the altered slates and graywackes now consist of relict quartz, iron oxides (both hematite and goethite), kaolinite, clay mica, and 14A chlorite, in varying proportions.

The "footwall" strata, that is, the Dunn Creek Slate and specifically the Wauseca Pyritic Member, are much less subject to deep oxidation than are the "hanging wall" strata. In the vicinity of ore bodies, the slate immediately underlying the ore is oxidized for distances of a few inches to a maximum of perhaps several feet. An important exception exists, however, where the pyritic graphitic slate is faulted out and the oxidized iron-formation is in direct contact with the nongraphitic slate and siltstone deeper in the Dunn Creek Slate. In this situation, the "footwall" strata may be oxidized for considerable distances. A fine example is in the Johnson workings of the Spies mine, where the ore body is bounded on the east by a fault. The Wauseca Pyritic Member is missing, and the underlying slate and siltstone are oxidized for many hundreds of feet away from the ore body, and to a depth of 1,000 feet below the surface.

Many of the dikes in the district are along principal faults and in a few places are in contact with or close to oxidized iron-formation. Normally these dike rocks consist of minerals of the usual greenschist facies—chlorite and albite, mainly—but adjacent to oxidized rocks they are altered to soft clay or claylike minerals and are commonly mottled with iron oxides.

The deep alteration of rocks to iron oxides and clay minerals is most common where one of the units is the iron-formation, but it is not entirely restricted to the vicinity of iron-formation. The rocks cut in drill holes in sec. 24, T. 42 N., R. 34 W., for example, are mostly slate and metadiabase that probably are at a considerable distance from iron-formation. In one of the holes the slate is thoroughly oxidized at a depth of several hundred feet, and the metadiabase is altered to clay minerals.

FORM AND SIZE

Of the 65 mines in the Iron River-Crystal Falls district reported to have shipped ore, about half have produced more than 1 million tons each, and one, the Hiawatha mine, has produced about 17 million tons. The production figures are to some extent misleading insofar as size of ore bodies is concerned, because many physically continuous ore bodies were extracted by two or more mines. On the other hand, single operations, such as the Buck mine, may produce from several separated ore bodies of small or large size. Data on the tonnage of individual ore bodies are rendered more incomplete by the fact that few ore bodies have been mined out completely.

The largest known ore body in the district, in terms of both ore produced and potential tonnage, is that forming the southern part of Mineral Hills; this ore body, continuous at one level or another, has been mined for a horizontal distance of about 1½ miles and to a depth of as much as 1,700 feet below the surface in the Spies, Virgil, Sherwood, Wauseca, and Homer mines. Doubtless the ore body continues to considerably greater depth. To 1961 it had yielded more than 20 million tons of direct-shipping ore, and two major mines, the Sherwood and the Wauseca, were still in production. Except at fold axes, the ore body is about vertical. The width (thickness) is generally about 100 feet. At maximum development (fig. 54), the form in plan view is simply that of a folded steeply dipping bed.

Some ore bodies are disc shaped, having long directions in the directions of the strike and of the dip of the containing bed; those of the Bristol mine, for example, are nearly vertical bodies roughly equal in strike and dip length (¼–½ mile) and about 100 feet in maximum thickness. (See fig. 55.) Other ore bodies, particularly the smaller ones, are simply podlike masses only slightly longer in strike and dip length than in width. A few ore bodies at the keels of synclines are pod shaped in plan but have a great vertical extension. The ore body of the Dunn-Richards mine (fig. 56) is an excellent illustration of this form; the ore body is a greatly attenuated lens that continues down the 45° plunge of the synclinal axis for a distance of more than half a mile, 10 times or more the average length in plan view. The great Hiawatha ore body (fig. 57) is of this type in the upper part; at greater depth it spreads out along the flanks of the structure.

Some ore bodies are at maximum horizontal dimension at the surface; examples are the Caspian (fig. 58), Rogers (fig. 59), and the Baltic. Many of the largest bodies, however, enlarge downward from a relatively modest surface expression and attain maxium dimensions at depths of 500–1,500 feet. This downward enlargement is particularly evident for the ore bodies of south Mineral Hills, the Buck, and the Hiawatha. In general, though it may be true that the total amount of ore per unit area of iron-formation is greatest at or near the present bedrock surface, there is an optimum depth of about 1,000 feet at which the largest individual ore bodies reach their maximum size.

STRATIGRAPHIC POSITION

Most of the ore bodies in the district have well-defined stratigraphic control within the Riverton Iron-Formation. The favored stratigraphic position in the western part of the district is different, however, from that in the eastern part.

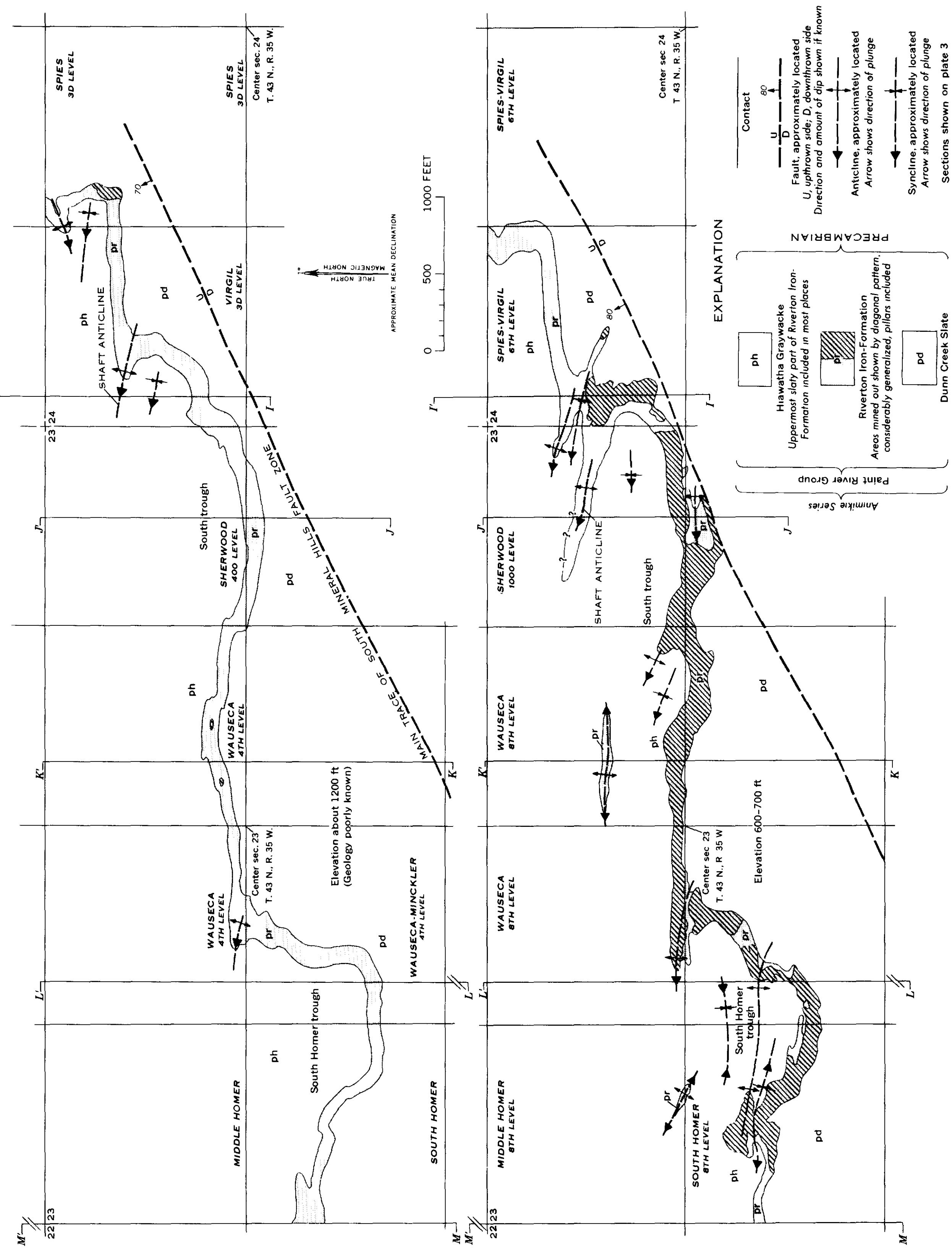


FIGURE 54.—Southern part of the Mineral Hills area showing distribution of ore bodies in relation to structure at two elevations.

In the western part of the district, most of the ore occurs in the basal part of the formation and in direct contact with the underlying pyritic graphitic slate (the Wauseca Pyritic Member of the Dunn Creek Slate). Oxidation may extend stratigraphically higher in the iron-formation into the (typically) slaty upper part, but the ore itself generally is limited to the basal 100 feet or less. The only important exceptions are in places such as the Cannon mine area, where a thick body of chert breccia and slate forms the basal part of the formation, and locally in places where the formation is overturned. In the latter position, the ore body may be in the upper part of the formation, on a structural footwall made up of the Hiawatha Graywacke. (For an example, see pl. 4, section *B–B′*.)

In the eastern part of the district, relations are less definite, but evidently most of the ore bodies are stratigraphically well up in the Riverton Iron-Formation. The footwall to the ore rarely is the pyritic slate of the Wauseca Pyritic Member; more commonly it is a bed of slaty iron-formation (the "raindrop slate" in the Tobin mine), 25–40 feet thick, that is approximately 100 feet above the base of the formation. This rock is equally as rich in iron as the other parts of the formation, but clearly it has formed an effective barrier to downward movement of ore-forming solutions in many places; in the Tobin mine it separates the ore-bearing part of the Riverton from a lower bed of cherty sideritic iron-formation that has remained unoxidized. In places where the ore-forming process has been particularly intense, however, oxidation may extend into, and locally perhaps through, this "perched" footwall. As a result, the footwall contact of ore bodies in the eastern part of the district, particularly in the southern Crystal Falls area, may be irregular and may cross stratigraphic units within the formation. In contrast, the footwall contact in the western part of the district generally precisely locates the Riverton–Dunn Creek stratigraphic contact.

The stratigraphic control is to some extent a lithologic control. The favored parts of the formation are those that consisted originally of well-bedded chert and siderite. (Note, however, that the lithologically favorable lowermost part of the formation in the southern Crystal Falls area has been effectively "protected" from oxidation by the overlying slaty unit.) Iron-formation characterized as "slaty", because of abundant silicates (chlorite or stilpnomelane) or graphitic partings, generally has an original iron content equal to or greater than the bedded chert and siderite but rarely is it the host rock for ore bodies. Chert is either absent or occurs in nodular forms in such rock. In at least two places where the normal cherty iron-formation grades into almost pure siderite rock (in the James-Davidson mine area and in the Hiawatha mine area), oxidation and ore formation have been halted; again, the absence of chert layers may be a controlling factor.

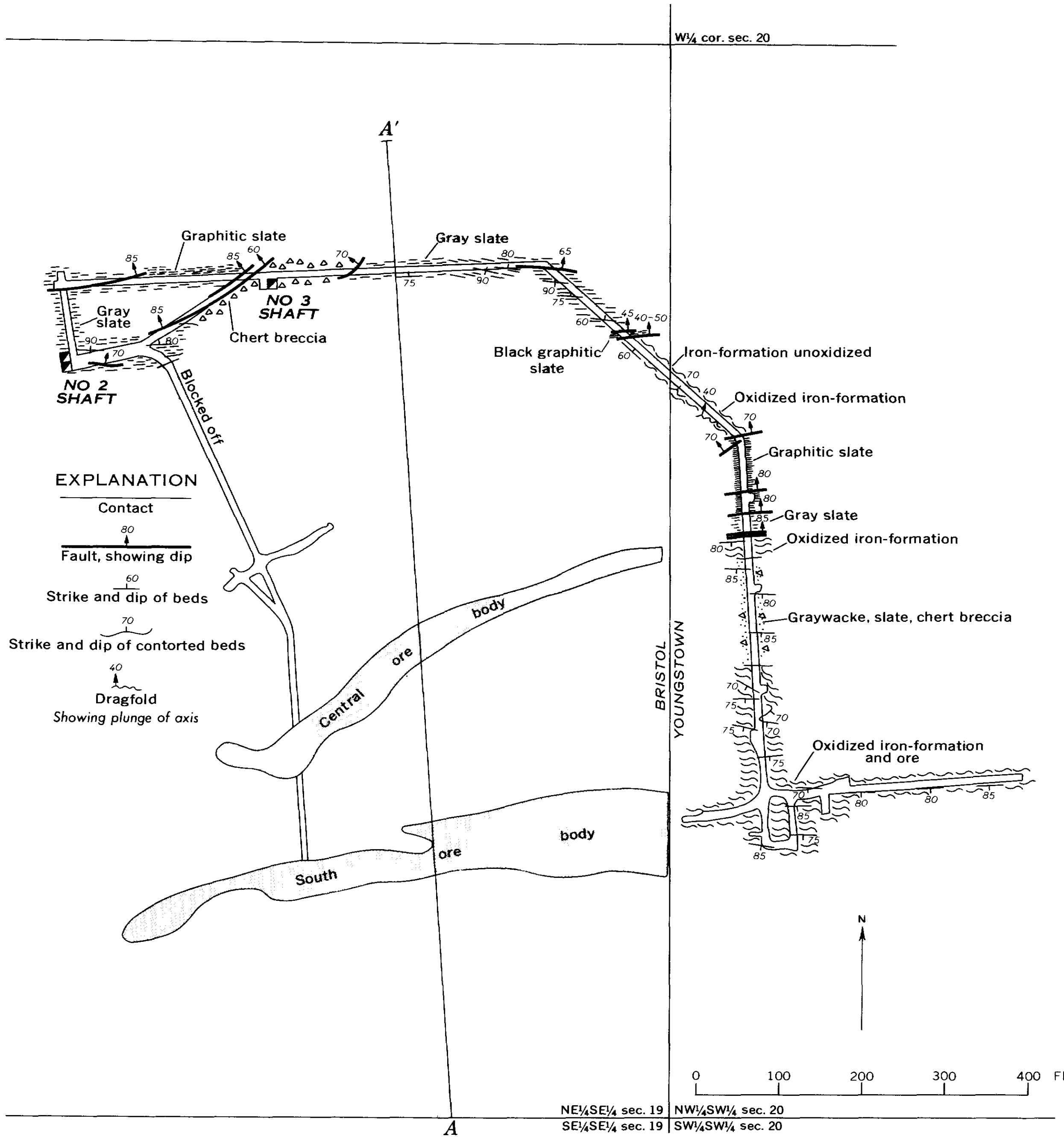
RELATION TO STRUCTURE

A large percentage of the ore bodies in the Iron River-Crystal Falls district clearly are related to synclinal structures. The association is rather easily overemphasized, however, by neglecting to note that in a tightly folded terrane such as this, the flanks of each syncline are also the flanks of adjacent anticlines. To avoid ambiguity in the discussion that follows, each anticline-syncline couple is divided into three parts: the anticline or the anticlinal position, which consists of the axial zone and one-third of the common limb; the syncline or synclinal position, which consists similarly of the axial zone and one-third the common limb; and the flank or limb, which consists of the remaining third of the common limb. This terminology, even though it can be applied only in a qualitative way in actual practice, will provide some basis for objective designation of position.

The ore bodies occupy structures that were formed prior to the ore. With only insignificant exceptions the ore has not been deformed since its formation. This is shown by two features: first, the general lack of evidence for shearing within the ore itself, and second, the delicate relationship that has been observed in several places between overturning of the bed and position of the ore. Ore in an overturned syncline will extend from the axial position up the flatter limb, whereas it terminates much more abruptly on the overturned limb; also on the overturned limb it may migrate to a stratigraphically higher position—that is, toward the structural footwall. Where a major fault projects into an ore body, the fault may be difficult to recognize because of the later alterations related to formation of the ore; the South Mineral Hills fault, for example, crosses part of the Sherwood ore body and can be recognized there only with difficulty.

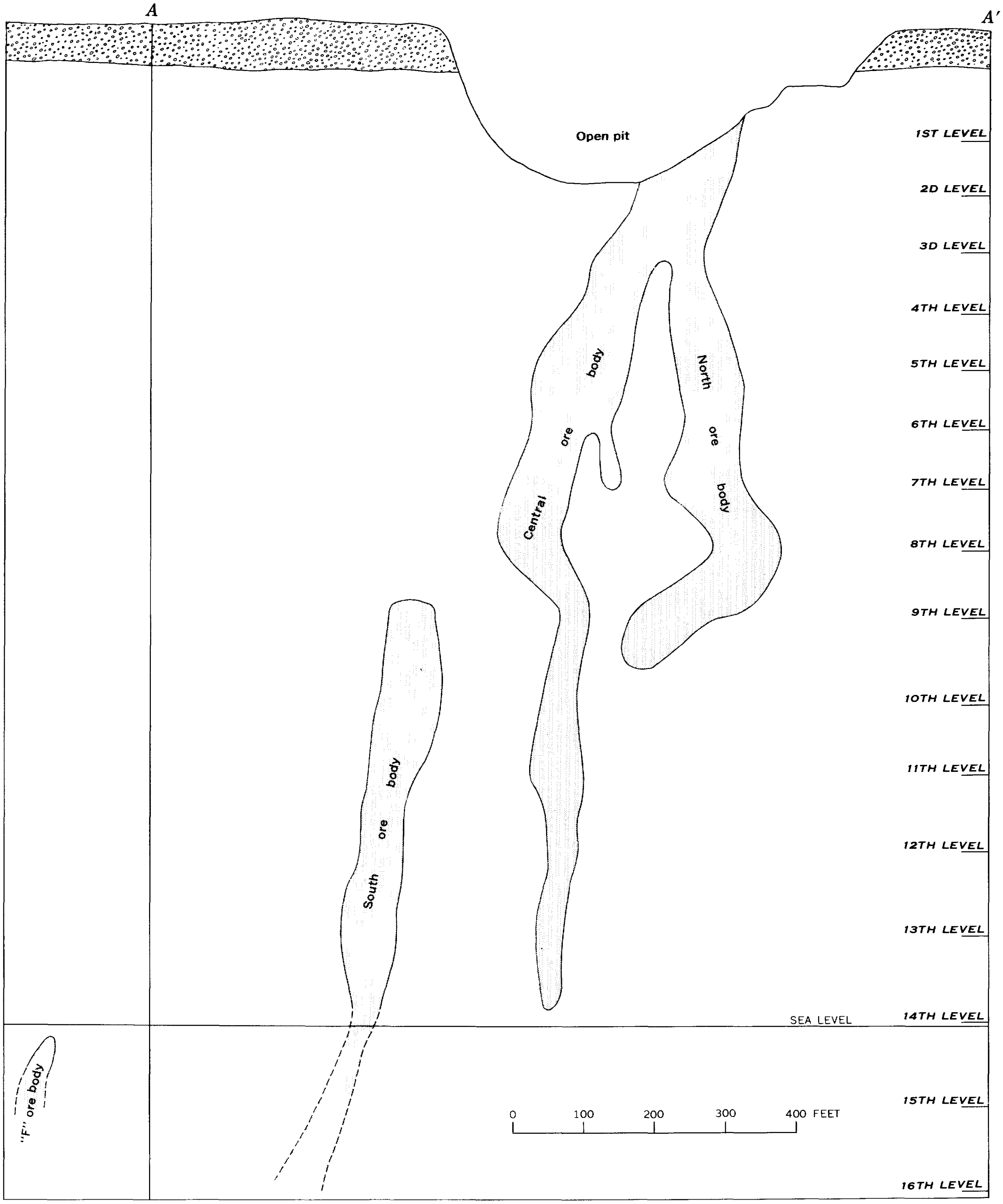
SYNCLINAL ORE BODIES

The main Hiawatha ore body is a magnificent example of ore in the synclinal position in the western part of the district. As can be seen from figure 57, the near-surface expression of this ore body at the Isabella and Dober mines is at the axis of a west-plunging syncline. At about half a mile depth, the highly complex root of the structure is reached. Most of the ore is in the synclinal position, but important extensions continue up the north flank. The south flank is largely unoxidized, but as shown in figure 57, at lower levels the unoxidized rock actually gives way to ore that has developed along



A

FIGURE 55.—Bristol mine. *A*. Plan of 12th level showing mined ore bodies (shaded), and geology of workings accessible in 1951. Geology by H. L. James and F. J. Petijohn. *B*. Cross section along line *A–A'* showing form of mined ore bodies (shaded).


A
A′
Open pit
1ST LEVEL
2D LEVEL
3D LEVEL
4TH LEVEL
5TH LEVEL
6TH LEVEL
7TH LEVEL
8TH LEVEL
9TH LEVEL
10TH LEVEL
11TH LEVEL
12TH LEVEL
13TH LEVEL
14TH LEVEL
15TH LEVEL
16TH LEVEL
SEA LEVEL
Central ore body
North ore body
South ore body
"F" ore body
0
100
200
300
400 FEET

B

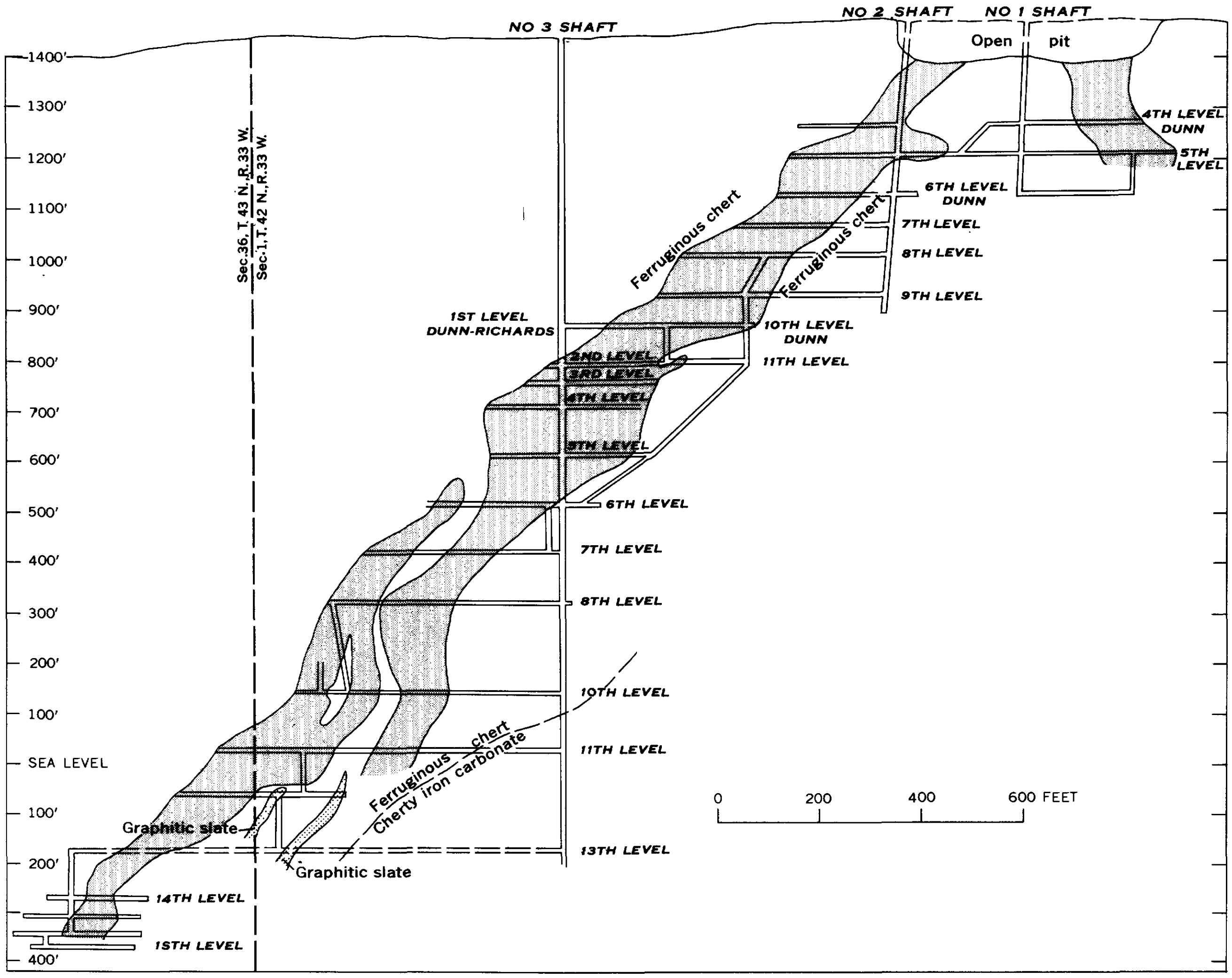


FIGURE 56.—Section through Dunn-Richards mine. Looking northeast. Shows generalized outlines of mined ore (shaded), pillars included. Adapted from mining company records.

the keel of the syncline. Many other examples could be cited of synclinal ores in the western part of the district: most of the ore mined on the north flank of Mineral Hills was principally in the synclinal part of a complex first-order dragfold, with important extensions up the north limb (fig. 60; pl. 3); the Zimmerman ore body (pl. 4, sections *D–D'*, *E–E'*) was of very similar configuration, with extension up the flattened south limb; and the Sherwood ore body lies along a westward-plunging syncline (fig. 61). The main Buck ore body (fig. 62; pl. 4, sections *A–A'*, *B–B'*) is a particularly interesting example of synclinal control, with maximum development of ore in the deepest parts of doubly plunging synclinal folds of more than one orientation. Ore bodies in the Youngs and Baltic mines also are in synclinal structures (pl. 4, section *C–C'*). In the Cannon mine the ore body is mainly in a doubly plunging syncline (fig. 63); the anticlinal area apparently is a minor fold on the east flank of a larger syncline.

In the eastern part of the district, the synclinal control is more obvious in gross pattern than it is in detail, probably in large part because of the much greater thickness of the iron-formation and because most of the ore bodies rest on a "perched" footwall within the iron-formation. Ore bodies clearly related to major synclinal structures are those of the Carpenter-Monongahela, Dunn, and Balkan-Judson mines. Other ore bodies, such as the Great Western, Crystal Falls, Tobin, and Book, may be related to smaller synclines within larger structures. In general, most of the ore bodies throughout the eastern part of the district are in either synclinal or flank positions; none of importance, with the possible exception of the Odgers, is on a major anticline although some extend over minor anticlinal folds.

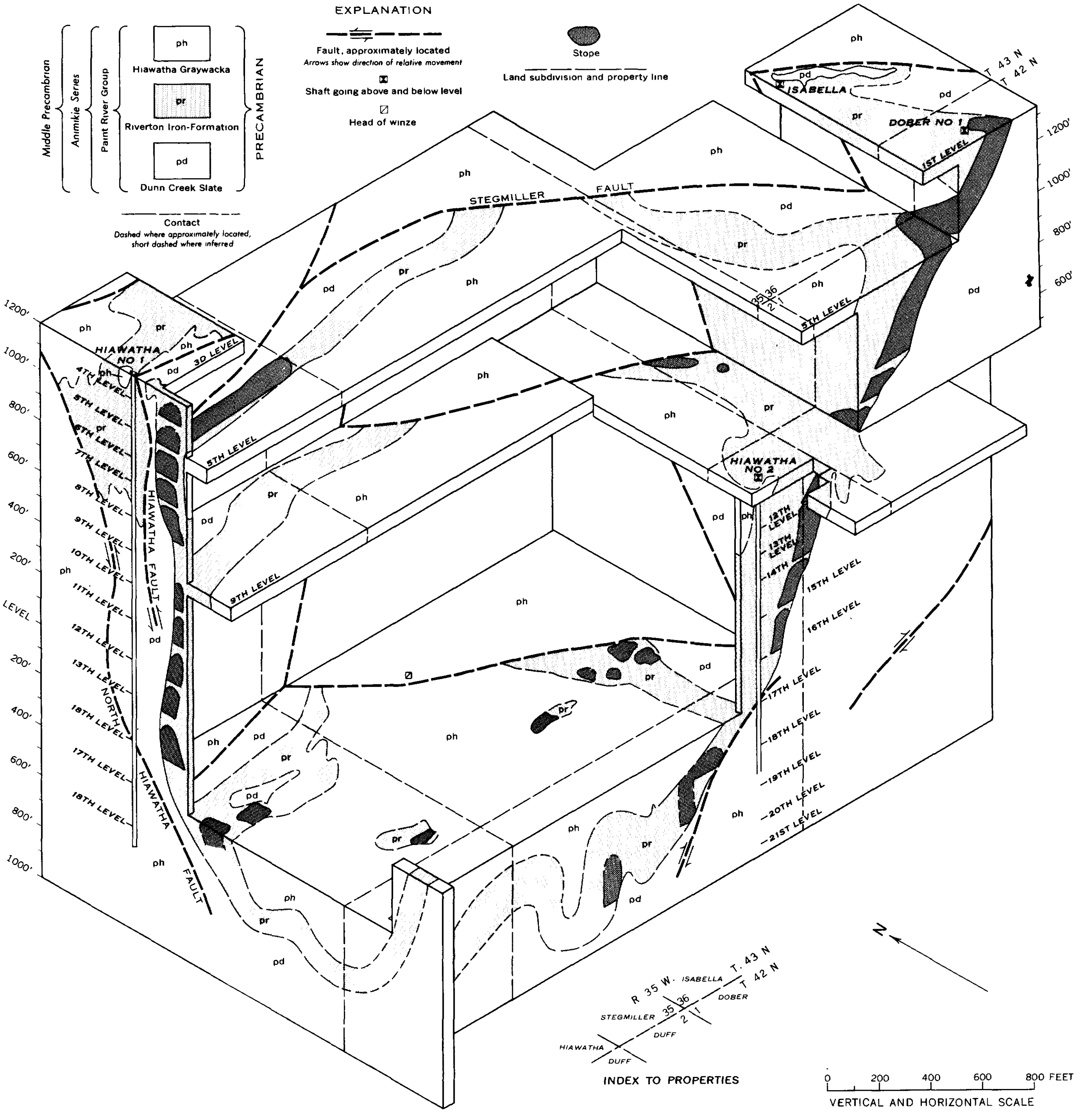


FIGURE 57.—Isometric diagram showing geology of part of the Hiawatha mine.

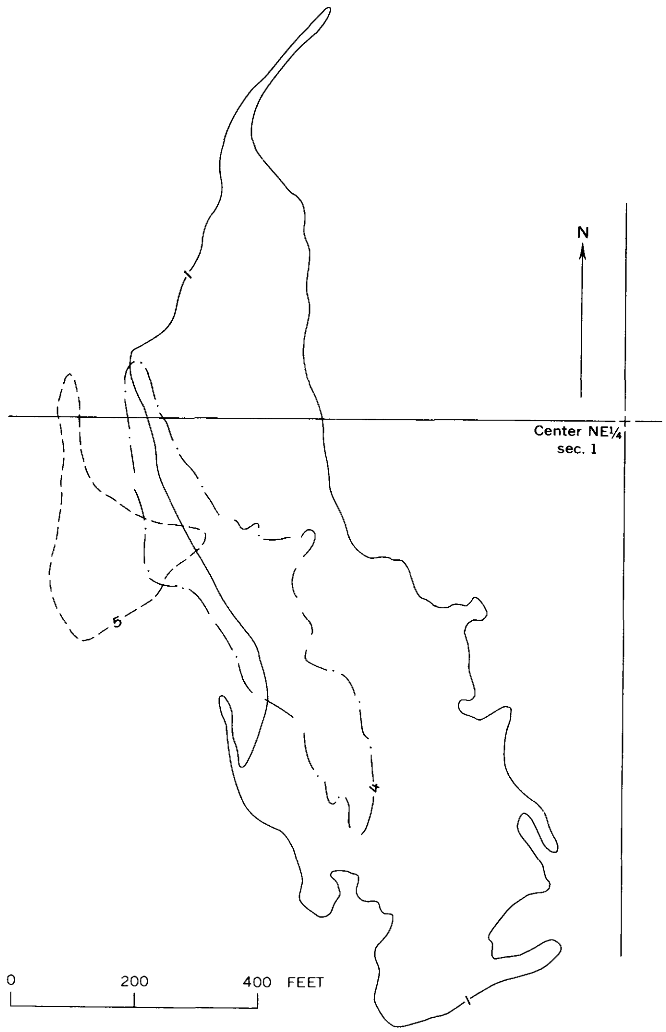


FIGURE 58.—Plan of mined ore body in Caspian mine at levels 1, 4, and 5 (elev 1,345, 1,115, and 965 ft), sec. 1, T. 42 N., R. 35 W.

ANTICLINAL ORE BODIES

Most anticlinal areas of Riverton Iron-Formation are barren of ore, although as previously mentioned, many ore bodies extend over minor anticlinal axes within a larger synclinal structure. No ore bodies are known in the district to occupy only the axial portion of even minor anticlinal structures.

The best example of an anticlinal ore body is that of the Bengal mine (fig. 64). Even here, however, the relationship is less impressive in fact than suggested by the illustration because the plunge of the structure is nearly vertical and the ore continues into companion synclinal flexures. Nevertheless, on the basis of the general geology of the area, the ore body is one of the few in the district that clearly is in a general anticlinal area of Riverton Iron-Formation.

The "north" and "central" ore bodies of the Bristol mine are continuous in some sections over a probable anticlinal axis (fig. 55). The geology of these ore bodies is only poorly known, however, and it is entirely possible that the juxtaposition is due to faulting rather than folding. Another possible anticlinal ore body is that of the Odgers mine, but again the details of structure are obscure; it seems more likely that the body is on the flank rather than in the axial zone of an anticline.

ORE BODIES ON STRUCTURAL FLANKS

A considerable amount of ore has been produced in the district from bodies structurally on the flanks of folds, but most of this ore can be considered upward extensions of synclinal bodies at greater depth. The great ore body of southern Mineral Hills is an example; the ore continues upward from principal loci in large-scale dragfolds such as in the Virgil-Sherwood area (pl. 3) and the south Homer area (fig. 54; pl. 3). Other ore bodies, of which those of the Fogarty and Baltic mines in the western part of the district and the Tobin and Bristol in the eastern part of the district are examples, are tabular bodies along structural flanks, but for each body there is some reason to suspect that they are fault related.

In a typical cross section, ore will be present as thick continuous masses in minor synclines and on structural terraces and as fingers and pods of lesser extent on the steeper flanks.

ORE BODIES RELATED TO FAULTS

As mentioned above, there is a possibility that several major ore bodies are along unrecognized faults. For a few, this relationship is more explicit: the "Johnson" ore body of the Spies mine (fig. 65) and the ore body mined at the Fortune Lakes mine are examples. One of the best examples of a fault-related ore body is that of the Bates mine. In cross section (pl. 3) the main ore body is seen to be parallel to the dip of the fault for nearly 2,000 feet of depth and to continue downward beyond the structural divergence of the iron-formation. In plan (fig. 66), the ore body, which trends parallel to the strike of the fault in upper levels, swings progressively southward from a focal position on the fault, to conform with the axial part of a west-plunging syncline.

For other ore bodies, a spatial relation exists between faults and ore but does not seem of genetic significance. The ore body on the north flank of the Mineral Hills structure, mined in the Davidson No. 3, Davidson No. 2, Forbes, and Purcell (Wapama) mines, is bounded at upper levels by the nearly parallel North Mineral Hills fault. (For sections, see pl. 3.) At depth, however, the formation migrates southward on dragfolds and the ore body continues downward to the axial areas of the synclines (fig. 67). Horses of unoxidized iron-formation

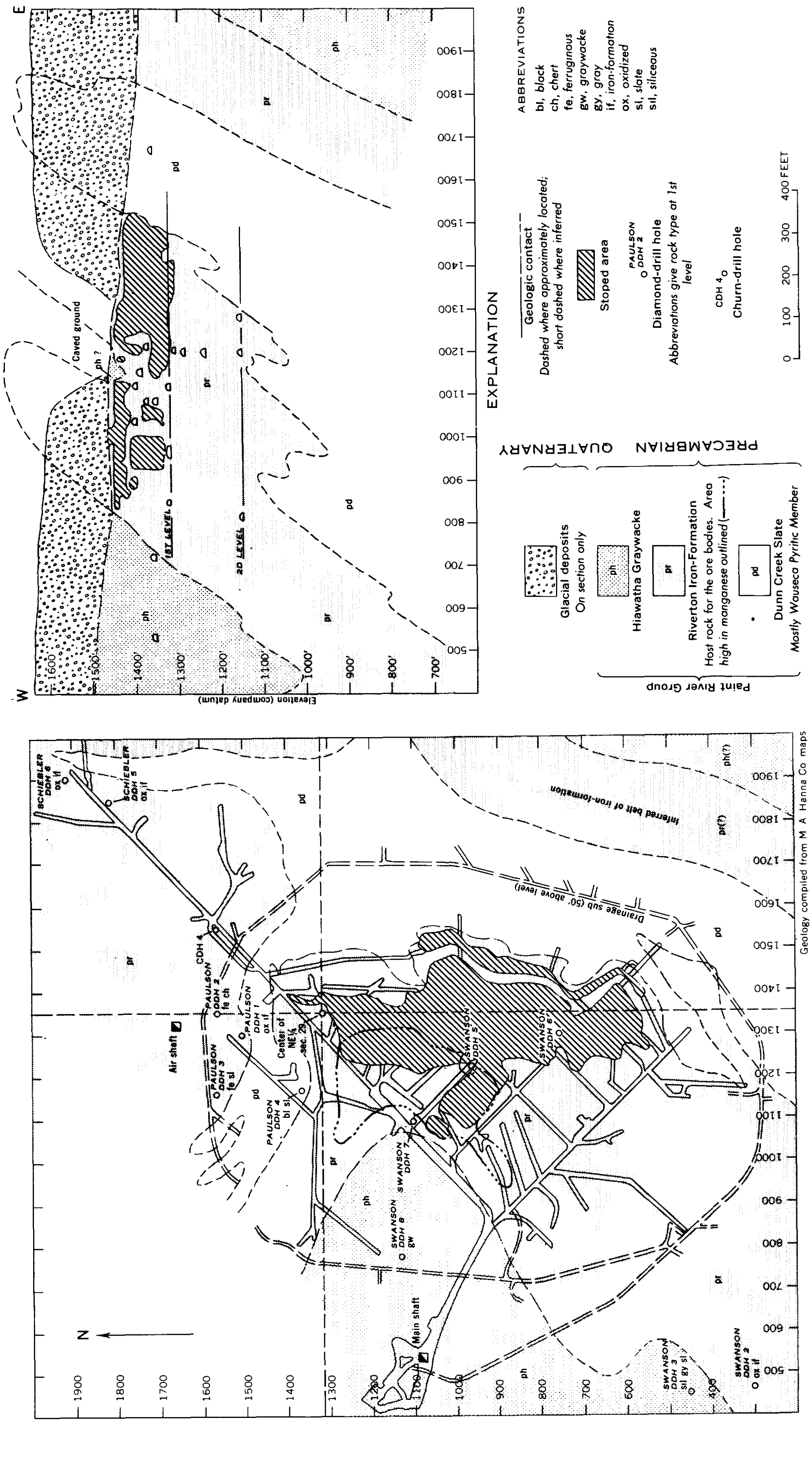


FIGURE 59.—Rogers mine, sec. 29, T. 43 N., R. 34 W. Plan of 1st level, and cross section along coordinate 900 N.

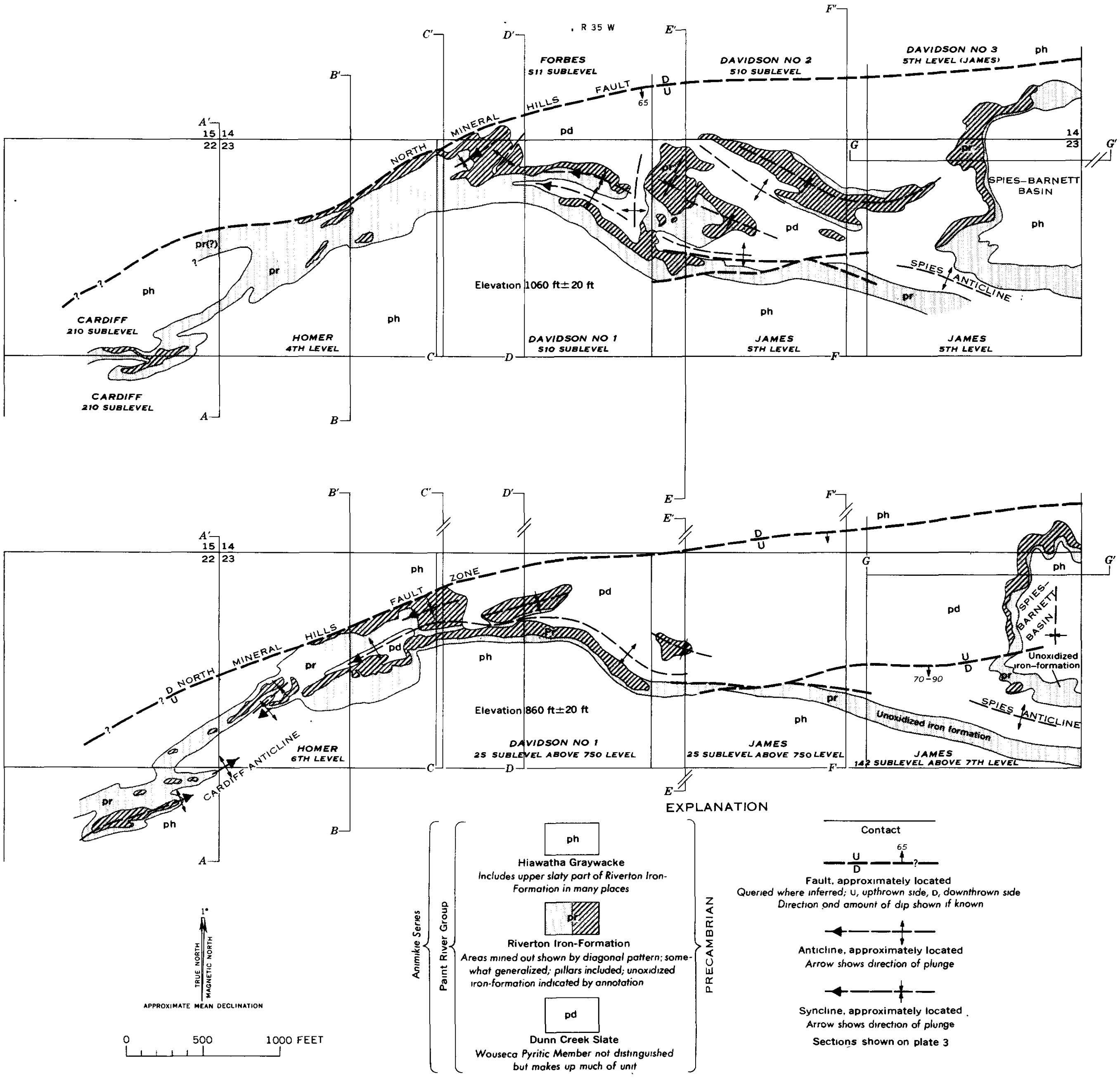


Figure 60.—Northern part of Mineral Hills area showing distribution of ore bodies in relation to structure at two elevations.

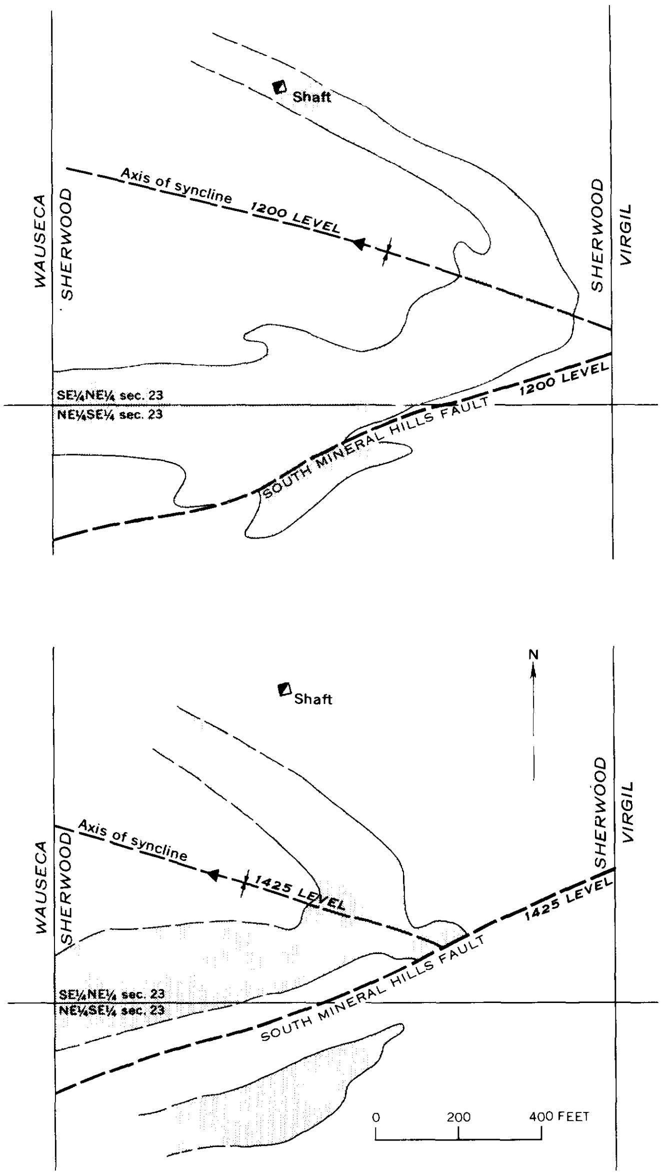


FIGURE 61.—Progressive shift to west of Sherwood ore body with depth, shown on 1200 and 1425 levels. Ore body shaded.

have been observed in the fault zone below the point of divergence. Doubtless the fault was a significant factor in the greater-than-usual upward extension of the ore from its synclinal position, but evidently it was of no significance with respect to the larger bodies of ore deeper in the synclines. Similarly the South Mineral Hills fault locally intersects the main ore area in the Sherwood mine and may likewise have been a factor in the extension of the ore body. But half a mile to the east, in the Spies mine, the iron-formation near the fault is entirely unoxidized.

From facts such as those cited, it is evident that the faults have not acted as important channels for ore-forming fluids. Indeed, except where the faults cut iron-formation, they are more likely to be circulation barriers than water conduits; most are tight and contain much squeezed graphitic slate. If the district is viewed as a whole, the scarcity of ore bodies along or adjacent to the principal faults is striking, except in the Mineral Hills area where it has been shown they are of only incidental importance.

ORE BODIES CONTROLLED BY DIKES

In contrast to the Gogebic and Marquette districts of Michigan, dike-controlled ore bodies are very scarce in the Iron River-Crystal Falls district. A principal reason for this is that the dikes, though common enough, typically are oriented parallel or subparallel to major structures rather than across them. Consequently they do not form structural troughs by intersections of the footwall contact, as they do in so many places in the Gogebic and Marquette districts.

The only dikes structurally of the Gogebic-Marquette type are the pair that transect folded rocks at the Balkan mine, south of Alpha. The principal control of the main ore body is the Balkan syncline, and most of the ore is in the axial zone of that fold. The ore body is bounded on the northwest, however, by the northern dike, which is about 50 feet thick and which dips to the southeast at 45°. The dike evidently formed a barrier to solution movement because no ore is present on the north side. A smaller ore body to the west also ended against the same dike. The southern dike, similar in strike and dip, is about half as thick and evidently was not an adequate barrier to solution movement. Drill holes on both sides show the iron-formation to be of equal iron content, at below ore grade.

MINERALOGY AND CHEMICAL COMPOSITION OF THE IRON ORES

The ore minerals are goethite and hematite. These minerals occur in all proportions—and in many places in alternate layers. An individual deposit characteristically is similar throughout but may differ in hematite-goethite ratio from a nearby deposit; the ore produced from the James mine, for example, was mostly yellowish goethite, whereas that from the Homer mine was dominantly reddish hematite.

The hematite and goethite, like all other constituents of the ores, are exceedingly fine grained although physically the material ranges from hard and lumpy to soft and earthy. The hematite and goethite yield normal X-ray diffraction patterns as compared with standard data for these minerals. According to Correns (1952, p. 29), goethite may contain 10 percent or more AlOOH in solid solution, with significant shift in the lattice

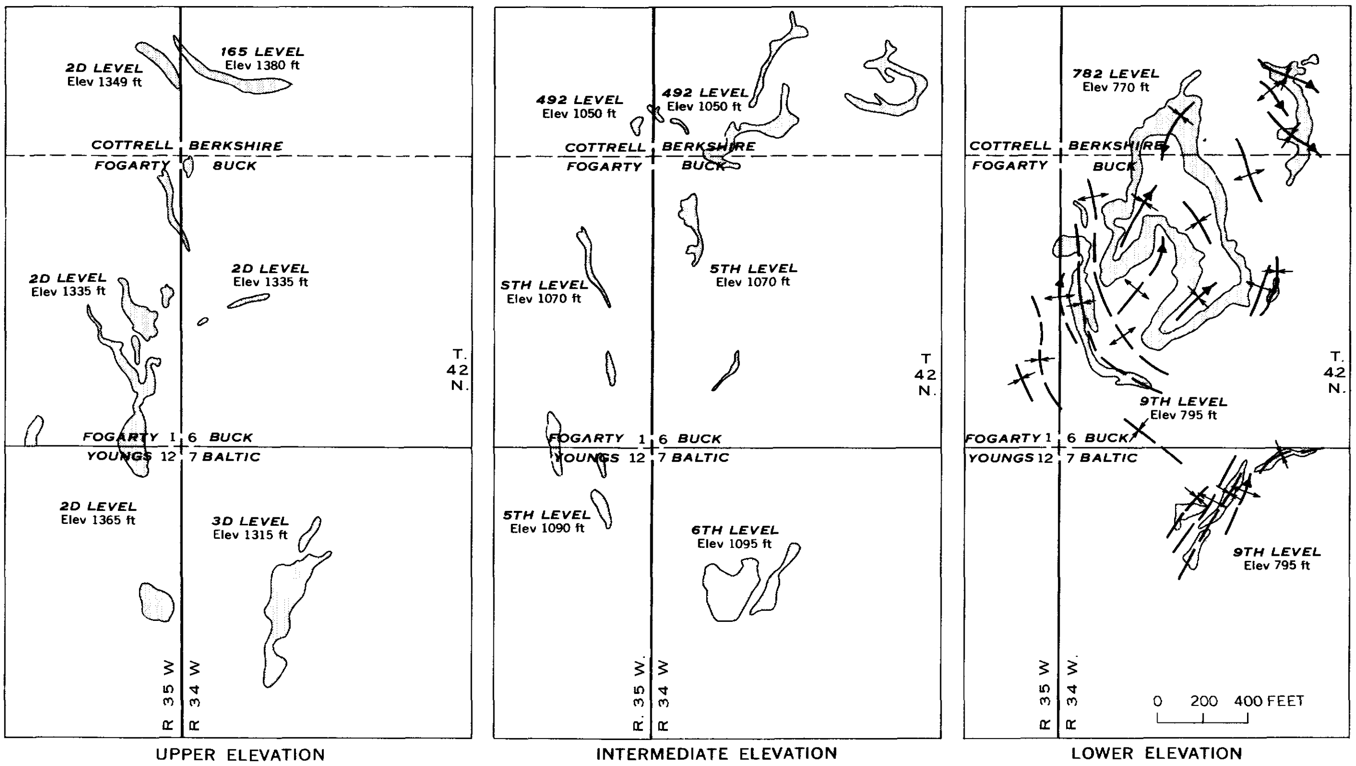


FIGURE 62.—Generalized distribution of mined ore bodies in the Cottrell, Berkshire, Fogarty, Buck, Youngs, and Baltic mines at three elevations. Structural axes shown on lower level.

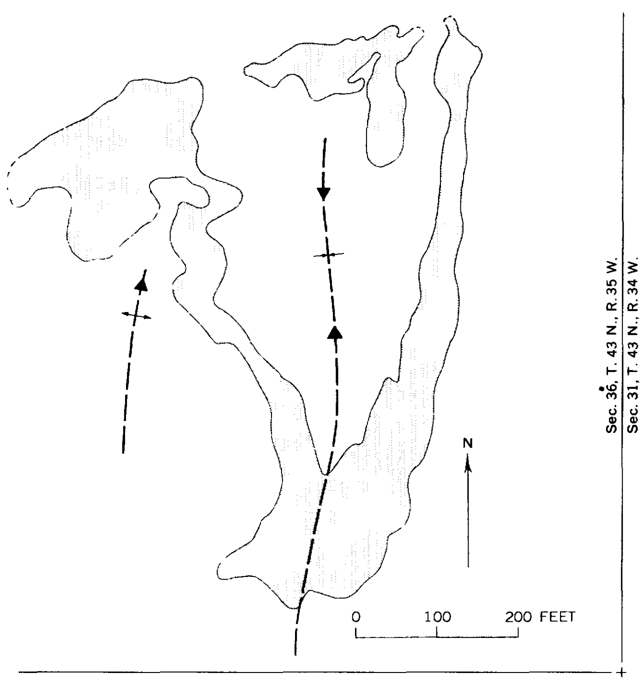


FIGURE 63 (lower left).—Cannon mine at approximately 8th level, showing mined ore bodies (shaded) and probable anticlinal and synclinal axes.

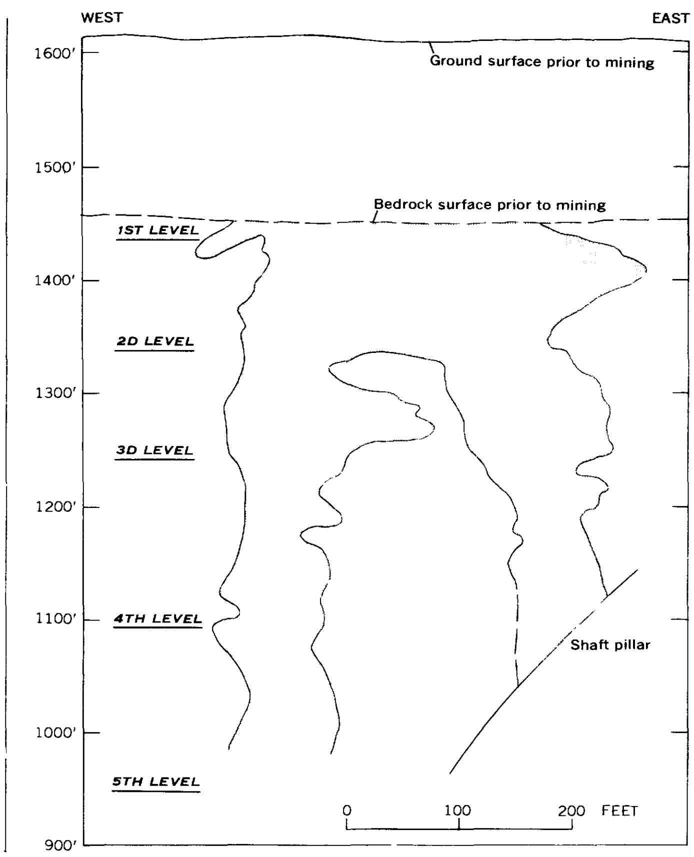


FIGURE 64 (lower right).—Generalized outline of stoped one (shaded) in the Bengal mine. East-west section along line approximately 900 feet south of center line of sec. 36, T. 43 N., R. 35 W.

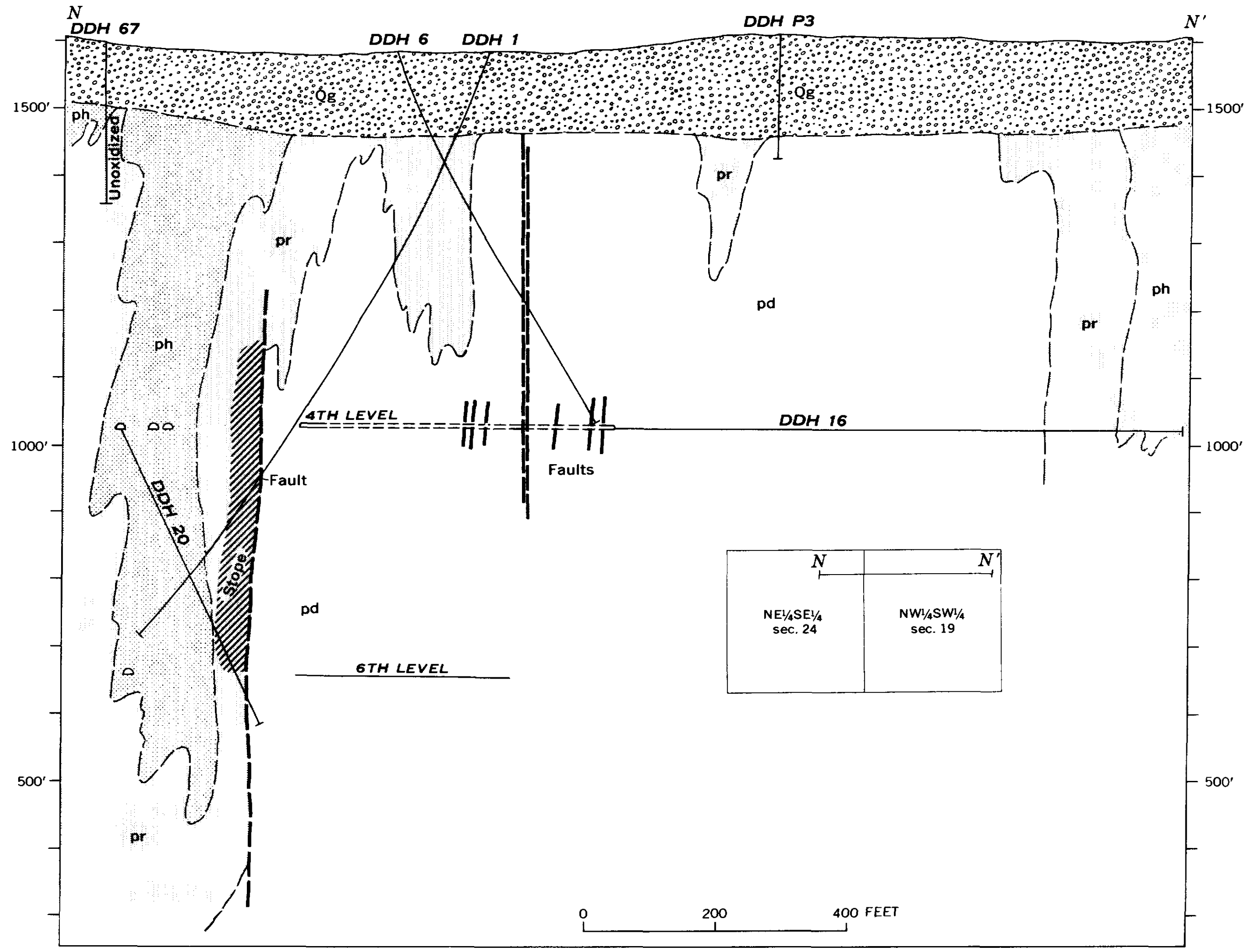


Figure 65.—Cross section showing stope in the Spies-Johnson ore body. Riverton Iron-Formation (pr), overlain by Hiawatha Graywacke (ph), and underlain by Dunn Creek Slate (pd); glacial deposits (Qg). Mined ore body shown by diagonal pattern. The ore was lifted through the Spies shaft, about three-fourths mile to the northwest.

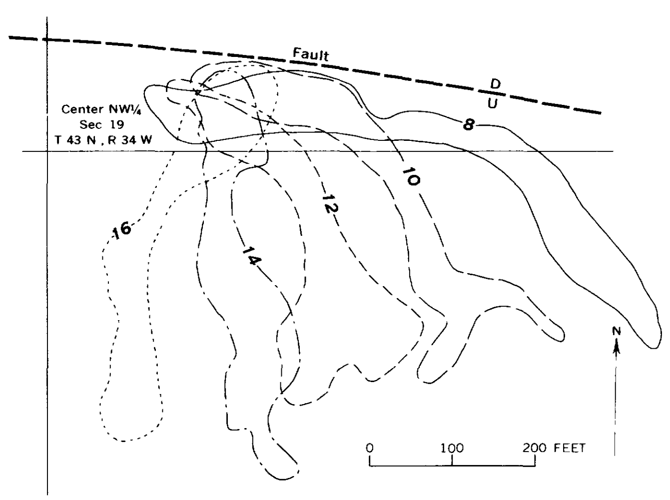


Figure 66.—Outline of the main ore body in the Bates mine, on the 8th, 10th, 12th, 14th, and 16th levels.

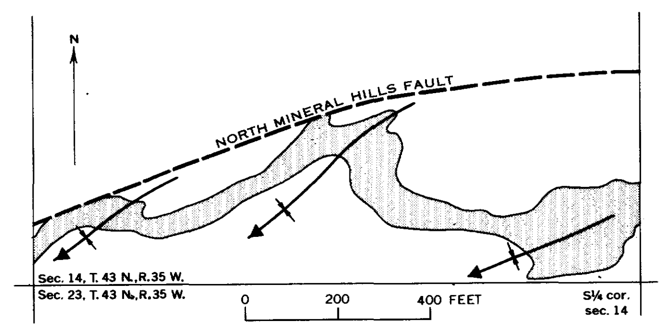


Figure 67.—Forbes mine, 275 level, showing area of mined ore (shaded) and synclinal axes.

spacings. No deviations from standard values for pure goethite were noted for the ores of the Iron River-Crystal Falls district.

Eleven complete analyses of ore from the district are presented in table 16. The materials analyzed are composite pulp samples of yearly shipments from individual mines; as such, most represent hundreds of thousands of tons of ore. These analyses may be compared with five new analyses of ore from the Marquette district, including two from "hard ore" mines, and one from the Mesabi district (Gruner, 1946, p. 90), given in table 16. The samples, including the one from the Mesabi, were dried at 100°C before analysis; prior to drying, the moisture content of ores (other than the low-moisture hard ores of the Marquette district) ranged from 6 to 13 percent. Hematitic ores, such as those from the Buck and Tobin mines (analyses 3 and 10 in table 16), characteristically have higher moisture content than the goethitic ores.

The only megascopically visible gangue minerals in the ore are quartz (relict chert) and sparse calcite and gypsum. Other gangue minerals have been determined by X-ray examination. The iron oxides of the analyzed ores listed in table 16 were taken into solution, either by cold hydrochloric acid-stannous chloride or by sodium dithionate-citrate. Residues in water suspension were evaporated on glass slides and were run for X-ray diffraction patterns. This treatment gives strong preferred orientation to the clay particles and resultant intensification of the basal reflections. A few mounts were made of residues without water suspension so as to obtain unoriented or more weakly oriented patterns.

All the ore samples contain a clay-size mica which yields a symmetrical diffraction peak at approximately 10.0 A, together with the integral series of other (001) peaks. The pattern is substantially unaffected by treatment of the sample with ethylene glycol or by heat treatment at 550°C. The method of study is not adequate to provide definitive classification of the mica, but comparison of the results with those presented by Yoder and Eugster (1955, fig. 9) suggests a *1M* polymorph. The intensity of the (002) reflection is relatively low compared with the (001) and (003) reflections and indicates, according to Weaver (1958, p. 267–268), an iron-rich variety. In general, the mica appears to have similar properties to those of many described illites, and for purposes of calculation its chemical composition is assumed to be similar to that of the relatively iron-rich "Illite B" of Brindley (1951, table 5, 3).

Three of the analyzed ore samples contain kaolinite in addition to mica. The (001) peak of the kaolinite has a value of about 7.0 A, the same as the (002) peak for chlorite, but it collapses after heating to 550°C. The three kaolinite-bearing ores show the highest Al_2O_3 contents of those analyzed.

More precise studies have been made of the clay minerals in the Iron River area by Bailey and Tyler (1960), mostly on materials from fracture fillings in oxidized iron-formation. They reported (p. 172) the occurrences of dickite (4 locs.), talc (1 loc.), kaolinite (1 loc.), kaolinite, gypsum, and alunite (1 loc.), kaolinite and alunite (1 loc.), 2 *M* muscovite and alunite (1 loc.), and alunite (1 loc.).

No phosphate mineral could be specifically identified in the analyzed ores of the district, but apatite as tiny well-formed crystals that coat cracks has been found in ore from the Cannon mine (specimen contributed by Paul Zimmer). Apatite has been found by Bailey and Tyler (1960, p. 153) in similar ores from the Marquette and Mesabi districts, and the authors assume that this mineral is present in the ores of the Iron River-Crystal Falls district to the limit of available calcium.

Many other minerals occur as vug fillings and as veins which cut the ores. This suite is described in later pages of this report, in the section "Postore minerals."

An attempt has been made to calculate the ore compositions in terms of normative minerals, using the following rules:

1. Calcite calculated to limit of CO_2.
2. Gypsum calculated to limit of SO_3 (as S in analysis).
3. P_2O_5 calculated as apatite if sufficient CaO remains after calcite and gypsum calculations.
4. P_2O_5 calculated as vivianite ($3FeO \cdot P_2O_5 \cdot 8H_2O$) if CaO is not adequate for calculation as apatite.
5. Mica calculated to limit of K_2O, using composition of Brindley's illite B referred to previously.
6. Chlorite, assumed composition $1.5FeO \cdot 0.5MgO \cdot Al_2O_3 \cdot SiO_2 \cdot 2H_2O$ (approximate composition of aphrosiderite), calculated to limit of MgO, FeO, or Al_2O_3.
7. Kaolinite calculated to limit of remaining Al_2O_3 after steps 5 and 6.
8. Quartz calculated to limit of remaining SiO_2 after steps 5, 6, and 7.
9. Goethite calculated to limit of H_2O remaining after steps 4, 5, 6, and 7.
10. Hematite calculated to limit of Fe_2O_3 after step 9.

Three examples of calculated norms are given in table 17. The presence of normative chlorite and vivianite, minerals not specifically identified in the ores, points up the mineralogically unexplained presence of MgO and FeO and the deficiency in CaO in the analyses; aside from these aspects, the normative assemblage is probably in fair agreement with the modal assemblage in the ores. The normative assemblages contain

TABLE 16.—*Complete analyses of ore from the Iron River-Crystal Falls and Marquette districts, Michigan, and the Mesabi district, Minnesota*

[Samples prepared by company laboratories and dried at 100°C before analysis. Chemical analyses 1-16 by Lucille M. Kehl and Ruth Stokes; spectrographic analyses by H. J. Rose, Jr. n.d., not determined]

	Iron River-Crystal Falls district, Michigan											Marquette district, Michigan					Mesabi district, Minnesota
Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17 [1]
Mine	David-son group	James	Buck group	Spies	Bengal	Homer	Hiawatha No. 1	Hiawatha No. 2	Wauseca	Tobin	Book	Cliffs-Shaft	Negaunee	Mather A	Mather B	Cham-pion	One of pits at Hibbing
Total tons of shipment from which composite sample taken.	337,518	178,586	435,687	257,838	145,587	[2] 500,000	347,731	243,154	500,404	19,881	75,913	[3] 587,655	998,187	[2] 1,000,000		[3] 125,680	(4)
Date of shipment	1950	1950	1950	1949	1950	1950	1950	1950	1950	1950	1950	1950	1947–48	1950	1951	1949	1935
Chemical analyses (percent)																	
SiO_2	7.15	7.76	9.75	6.84	6.55	7.65	4.92	6.39	6.19	13.65	11.76	9.66	12.34	9.70	4.54	9.55	8.65
Al_2O_3	2.63	1.68	3.31	2.29	3.89	4.71	2.61	3.22	3.78	2.08	2.58	1.70	2.37	3.13	1.78	4.34	1.34
Fe_2O_3	77.75	77.43	76.43	82.08	79.00	75.58	79.81	77.45	78.78	77.55	79.41	81.53	81.33	82.71	87.50	80.61	81.87
FeO	1.99	2.16	2.61	.30	.72	2.86	2.61	3.15	1.98	1.71	1.80	4.21	.30	.11	[5] 0.00	2.57	.15
MgO	.50	.51	1.25	.21	2.04	.71	.70	.90	.39	.71	.80	.63	.15	.70	.20	.34	.22
CaO	.45	.54	1.67	.09	1.04	.93	.97	1.03	.51	1.03	.89	.60	.46	.73	1.64	.38	.25
Na_2O	.02	.01	.00	.00	.02	.05	.00	.03	.11	.05	.01	.10	.04	.01	.02	.44	n.d.
K_2O	.32	.14	.34	.16	.24	.37	.21	.27	.18	.11	.14	.27	.26	.13	.13	.37	n.d.
H_2O-	.17	.18	.22	.29	.21	.19	.12	.08	.14	.23	.16	.07	.24	.37	.34	.02	n.d.
H_2O+	7.46	7.85	2.31	6.47	3.84	4.71	6.44	5.74	6.07	1.42	1.35	.45	2.00	1.42	1.21	.69	5.82
TiO_2	.10	.07	.18	.10	.15	.18	.10	.14	.11	.10	.14	.08	.10	.15	.05	.65	n.d.
CO_2	.35	.16	.02	.42	.52	.08	.22	.22	.06	.23	.21	.65	.24	.13	.08	.11	.48
P_2O_5	.99	.99	1.12	.57	.83	.85	1.09	1.00	1.11	.58	.61	.24	.18	.26	.32	.20	.112
S	.07	.08	.10	.08	.08	.36	.10	.12	.22	.12	.04	.01	.02	.17	.69	.02	.012
MnO	.19	.19	.12	.20	.93	.12	.15	.15	.19	.22	.15	.20	.23	.37	.78	.09	[6] 1.35
C	.13	.10	.16	.18	.13	.43	.15	.19	.36	.06	.07	.04	.25	.05	.03	.04	n.d.
Total	100.27	99.85	99.59	100.28	100.19	99.78	100.20	100.08	100.18	99.85	100.12	100.44	100.51	100.14	99.31	100.42	100.25
Less O for S	.04	.04	.05	.04	.04	.18	.05	.06	.11	.06	.02	.00	.01	.09	.35	.01	.01
Total	100.23	99.81	99.54	100.24	100.15	99.60	100.15	100.02	100.07	99.79	100.10	100.44	100.50	100.05	98.96	100.41	100.24
Specific gravity	4.02	3.98	4.11	4.17	4.34	4.20	4.21	4.20	4.20	4.34	4.40	4.63	4.34	4.47	4.71	4.59	n.d.
Fe	55.93	55.74	55.49	57.64	55.81	55.08	57.85	57.63	56.64	55.57	56.84	60.31	57.11	57.94	61.20	58.38	57.25
Spectrographic analyses (weight percent)																	
V	0.024	0.013	0.058	0.020	0.031	0.054	0.016	0.019	0.028	0.018	0.024	0.0066	0.016	0.013	0.016	0.020	
Cu	.0x	.0x	.0x	.0x	.0x	.0x	.0x	.0x	.0x	.00x	.00x	.00x	.0x	.00x	.00x	.00x	
Mo							.00x	.00x									
Zn	.0x																
Co					.00x												
Ni	.0x	.0x	.0x	.0x	.0x	.00x	.0x	.0x	.00x	.00x	.00x	.00x	.00x	.00x	.00x	.00x	
Cr	.0x	.0x	.0x	.0x	.x	.x	.0x	.0x	.0x	.0x	.0x	.0x	.0x	.0x	.0x	.0x	
Ti	.x	.0x	.x	.x	.x	.x	.0x	.x	.0x	.0x	.x	.0x	.x	.x	.0x	.x	
Be	.00x	.00x	.00x	.00x	.000x	.000x	.00x	.00x	.000x	.000x	.000x		.000x	.000x		.000x	
Sr	.00x	.00x	.0x	.0x	.0x	.0x	.00x	.0x	.0x	.0x	.0x		.00x	.0x	.0x	.00x	
Ba	.0x	.00x	.0x	.0x	.0x	.0x	.00x	.0x	.0x	.0x	.0x	.00x	.0x	.00x	.00x	.0x	
B			.0x		.0x	.00x	.0x	.0x		.0x	.0x		.0x	.0x	.0x		

NOTE.—Looked for but not found: Ag, As, Au, Bi, Ce, Cd, Ga, Ge, La, Nb, Pb, Pt, Sb, Sc, Sn, Ta, Th, Tl, U, Y, Yb, Zr.

[1] Gruner (1946, p. 89–90).
[2] About.
[3] "Hard ore."
[4] "Large tonnage of ore."
[5] This sample contains enough MnO_2 to oxidize any FeO present when the sample is put into solution. The figure, therefore, does not necessarily indicate that FeO is absent.
[6] Reported as MnO_2.

mica in quantities that would appear reasonably consistent with the amounts determined, and the ores that contain kaolinite, as determined by X-ray, also contain kaolinite in the norm. The absence of any identified (FeO, MgO)-bearing mineral is puzzling, and no adequate explanation can be advanced. Possibly these elements are contained in the mica, as discussed by Yoder and Eugster (1955, p. 254–255), to a greater degree than that allotted.

TABLE 17.—*Normative mineral composition, in weight percent, of ore from the Iron River-Crystal Falls district*

Field No. / Mine	HJ-26-51 (Davidson)	HJ-28-51 (Buck)	HJ-31-51 (Homer)
Hematite	28. 9	64. 7	58. 9
Goethite	54. 1	12. 7	18. 0
Mica (illite)	4. 2	5. 5	5. 5
Chlorite	1. 2	5. 9	4. 5
Kaolinite	3. 0	--------	5. 5
Quartz	3. 4	5. 9	1. 6
Apatite	--------	2. 6	--------
Vivianite	3. 5	--------	3. 0
Gypsum	. 5	. 4	1. 9
Calcite	. 7	--------	. 2
Manganese oxide	. 2	. 1	. 1
Graphite	. 1	. 2	. 4
Water	. 2	. 2	. 2
Excess constituents	--------	1. 8	. 2
Total	100. 0	100. 0	100. 0

The minor-element contents of the ores, as well as complete analyses of major constituents are given in table 16. All the minor elements are believed to be camouflaged; that is, they occur as random substitutions for major elements of similar atomic radii and charge. None of the concentrations is significantly higher than is normal in crustal rocks.

The conversion of the original iron-formation to ore involves principally a large loss of SiO_2 and CO_2 and a considerable increase in iron and oxygen. The changes between average unoxidized iron-formation (analysis 2 of table 8) and average ore (average of 8 analyses, 1–8 of table 16) are given numerically in table 18 and graphically in figure 68. The use of the same value for specific gravity for both materials requires explanation, given below.

The unoxidized iron-formation is a compact rock for which values of specific gravity for individual specimens should not be significantly different from bulk specific gravity in undisturbed ground. The measured values for four "typical" samples are 3.37, 3.27, 2.99, 3.22; the average of the four is 3.21, which is also the calculated specific gravity of "average" iron-formation given in table 9. The ore, on the other hand, is a highly

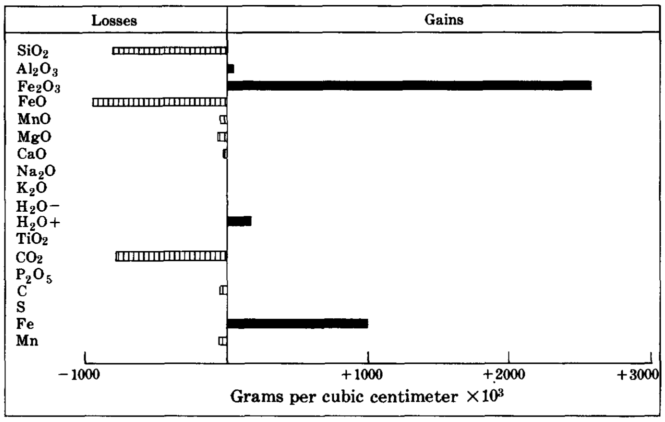


FIGURE 68.—Graphic expression of significant chemical changes in conversion of iron-formation to ore. (Based on data of table 18.)

TABLE 18.—*Chemical changes in conversion of iron-formation to ore*

[Composition of iron-formation is analysis 2 of table 8; composition of ore is average of eight analyses, 1–8 of table 16. Bulk specific gravity for both materials assumed to be 3.2]

	Iron-formation		Ore		Differences in g/cc×10³	
	Weight percent	Grams per cc	Weight percent	Grams per cc	Losses	Gains
SiO_2	32. 2	1. 030	7. 1	0. 228	802	--------
Al_2O_3	1. 5	. 048	3. 0	. 096	--------	48
Fe_2O_3	. 6	. 019	78. 2	2. 502	--------	2, 483
FeO	31. 6	1. 011	2. 1	. 067	944	--------
MgO	2. 8	. 090	. 8	. 026	64	--------
CaO	1. 6	. 051	. 8	. 026	25	--------
Na_2O	0	. 000	0	. 000	--------	--------
K_2O	. 2	. 006	. 3	. 010	--------	4
H_2O-	. 1	. 003	. 2	. 006	--------	3
H_2O+	0	. 000	5. 6	. 179	--------	179
TiO_2	0	. 000	. 1	. 003	--------	3
CO_2	24. 8	. 794	. 3	. 010	784	--------
P_2O_5	. 8	. 026	. 9	. 029	--------	3
S	. 2	. 006	. 1	. 003	3	--------
MnO	1. 9	. 061	. 3	. 010	51	--------
C	1. 8	. 058	. 2	. 006	52	--------
Total	100. 1	--------	100. 0	--------	--------	--------
Fe	25. 0	0. 800	56. 3	1. 802	--------	1, 002
Mn	1. 5	. 048	. 2	. 006	42	--------

porous and vuggy rock, and values for individual specimens are much larger than the value of ore in the ground. In computing tonnages of ore bodies in this district, a long ton of ore is generally considered to have a volume of 12 cubic feet (equivalent to a bulk specific gravity of 3.0), but this value allows a certain margin of safety to cover losses during mining. A figure of 11 cubic feet to the ton is closer to the true value (equivalent to a specific gravity of 3.27). A general value of 3.2, therefore, seems reasonably appropriate, as well as remarkably convenient. The fact that there are no significant differences in specific gravity between unoxidized iron-formation and ore, incidentally, provides the explanation for the lack of success of the gravity method of geophysical exploration.

MANGANIFEROUS ORES

Most of the iron ore mined in the district is distinctly lower in manganese content than is the unoxidized iron-formation. The unoxidized rock contains about 2 percent Mn on the average, whereas the ordinary ore contains less than 0.5 percent. During the ore-forming process, while the iron content of the rock was being doubled, in most places the manganese content was being reduced to a fourth or less of the original amount. Several mines, however, have manganese-rich ore locally within generally manganese-poor bodies of iron ore. Seven mines have shipped a manganiferous-grade ore: Bengal (Cannon), Rogers, Chicagon, Fortune Lakes, Bristol, Balkan-Judson, and Mastodon.

Partial analyses, in percent, of the average ore shipped for two representative years are reported in Lakes, Bristol, Balkan-Judson, and Mastodon.

Year	Mn	Fe	P	SiO_2	H_2O	*Shipments (gross tons)*
1943	11. 30	38. 97	0. 336	5. 91	7. 07	91, 000
1951	4. 11	44. 23	. 480	8. 42	9. 10	287, 000

The minor importance of the manganiferous ores is made evident by comparison of the shipments of these 2 years in terms of iron and manganese contents:

Year	*Iron ore shipments, as gross tons* Fe	*Manganiferous ore shipments, as gross tons* Mn
1943	[1] 2, 440, 000	10, 280
1951	[1] 2, 580, 000	11, 800

[1] Assuming 56.3 percent Fe content of ore (see table 18).

Assuming that the average manganese content of the iron ores is 0.2 percent, then the total amount of manganese represented by the shipments of both iron ore and manganiferous ore in 1951, as an example, is 20,400 tons, or about 0.8 percent that of the iron. In the original iron-formation, the manganese abundance is about 7 percent that of iron. Clearly most of the manganese has been lost from the system during formation of the iron ores.

None of the occurrences of manganiferous ore has been studied in detail, but brief examinations were made of an occurrence in the Bengal mine. Between the 5th and 6th levels, drifts entered areas of goethitic iron ore as much as 100 feet wide heavily veined with medium- to coarse-grained hausmannite. The veins were highly irregular and, in part, cut iron ore that seems to have been brecciated (fig. 69). Locally the hausmannite formed solid crystalline masses a foot or more across, and individual crystals were as much as an inch in diameter.

In and around the manganiferous ore body of the Bengal mine, the ground tended to be vuggy and contained much plastic greenish-gray clay mica and also crystalline goethite (as colloform bodies). Discontinuous thin veins of rhodochrosite, calcite, and sussexite are present. (See section on "Postore minerals".) The limits of the manganese mineralization were indefinite, with assay walls, but the manganiferous zone evidently extended to the uppermost workings of the mine.

FIGURE 69.—Polished section of manganiferous iron ore shows black hausmannite, which cuts brecciated goethitic iron ore. Specimen HJ–8–51. Bengal mine.

Little is known to the authors of the distribution of the manganiferous ore in the Bristol, which is the only mine in the district still producing that grade ore. Hausmannite has been identified, however. The distribution of manganiferous ore in the Rogers mine at the 1st level is shown in figure 59. A considerable body of manganiferous ore recently was drilled at deep levels in one of the mines in the Mineral Hills area. Sludge analyses of 5-foot runs show as much as 16 percent Mn.

Hausmannite is assumed to be the principal ore mineral of all the manganiferous ore bodies. Other manganiferous minerals present in minor quantity are rhodochrosite, sussexite, seamanite (from the Chicagon mine only), and neotocite. Braunite may be present in the Cannon mine, according to Paul Zimmer, geologist for the M. A. Hanna Co.

The absence of a readily identified manganese mineral in the upper workings in manganiferous ore bodies suggests that perhaps hausmannite either is restricted to deeper levels or that it has broken down to higher oxides in near-surface environments.

POSTORE MINERALS

The oxidized iron-formation and ores of the district are highly porous and commonly vuggy. In many places they contain postore minerals as irregular veinlets, as interstitial grains, or as open-cavity fillings. These postore minerals are a diversified group, taken as a whole, but in no place is the entire group represented. Commonly they are well crystallized and project into open spaces. The minerals that have been recognized are listed and then are briefly described in alphabetical order:

Apatite	Magnetite
Barite	Neotocite
Braunite	Pyrite
Calcite	Quartz
Chalcopyrite	Rhodochrosite
Chlorite	Seamanite
Copper, native	Specularite
Galena	Sphalerite
Goethite	Sussexite
Gypsum	Uraninite (pitchblende)
Hausmannite	Mineral X

Apatite.—Probably not scarce but generally too fine grained for determination. Clear well-formed crystals about 1 millimeter in diameter coat hard hematite ore in the Cannon mine.

Barite.—Not common. Found as vug fillings in association with pyrite, chalcopyrite, quartz, and calcite on 16th level Hiawatha No. 2 mine. Zoned, white to flesh colored; crystals as much as 1 inch in diameter.

Braunite.—Scarce. Not observed by present authors. Reported by Paul Zimmer, M. A. Hanna Co., to occur with hausmannite in the Cannon mine.

Calcite.—Fairly common. Best examples are from vug fillings in Hiawatha No. 2 mine; associated with specularite or sulfides. Where crystal outline shown, occurs commonly as acute scalenohedra; more rarely as unit rhomb. Also occurs disseminated in some soft hematitic ores, particularly in places at Buck mine, as poikiloblastic crystals as much as several inches across.

Chalcopyrite.—Common. Well-formed crystals of tetrahedral aspect, as much as 1 millimeter in diameter, associated with quartz, specularite, pyrite. Generally projects into open spaces in ore and in oxidized iron-formation. Found in brecciated unoxidized iron-formation at Hiawatha and Buck mines.

Chlorite.—Not common. Dark-green clusters, associated with sulfides in Hiawatha mine. Not identified as to species.

Copper, native.—Scarce. Reported to have occurred as thin foils in iron ore at Bengal mine.

Galena.—Scarce. Observed in polished sections of uraninite-bearing rock from Sherwood mine by Charles Milton, U.S. Geological Survey.

Goethite.—Common. Other than as a major constituent of ores, occurs as small botryoidal masses lining cavities, in many places encrusted with other minerals. Also common as very fine needles coating other vug minerals.

Gypsum.—Probably widespread as fine-grained constituent of ores. Also found as clear pink or white fillings of small cavities in some ore bodies. Masses several inches across found on dumps of Great Western mine.

Hausmannite (Mn_3O_4).—Locally abundant. Medium to coarse grained, crystalline. (See previous discussion in section on "Manganiferous ore.")

Magnetite.—Scarce. Observed as fine-grained crystalline material associated with specularite, in vugs in the Hiawatha mine.

Neotocite (*hydrated manganese silicate*).—Scarce. Dark brown, resinlike in appearance. Found as open-space fillings in core from drill holes in the Chicagon mine area. A partial analysis, made by H. F. Phillips in the laboratories of the U.S. Geological Survey, using the "rapid method," is as follows (Rept. 1WC–418):

	Percent		Percent
SiO_2	35.0	Available oxygen	1.0
Total Fe as Fe_2O_3	3.0	H_2O	15.0
Na_2O	.1	BaO	None
K_2O	.1		
P_2O_5	.3	Sum	91.0
MnO	37.0		

Neotocite has also been observed in core from drill holes in the area of the Great Western mine and from drill holes in the Monongahela mine.

Pyrite.—Abundant. Occurs as coatings of small crystals in vugs and as irregular veins; occurs locally in the Hiawatha mine as botryoidal masses as much as 4 inches in diameter, with well-formed crystalline (lineage) structure visible on surface; associated with barite.

Quartz.—Abundant. Occurs alone or with other minerals, generally as clear crystals of millimeter dimension.

Rhodochrosite.—Locally common. Occurs in Bengal (Cannon) mine as pink interstitial material in hausmannite and as discrete thin veins which cut iron ore in the vicinity of hausmannite-rich bodies.

Seamanite (Approximately $3MnO\cdot(B_2O_5)\cdot P_2O_5)\cdot 3H_2O$).—Very scarce. Mineral found in dump material of the Chicagon mine (Kraus and others, 1930), fills fractures in oxidized iron-formation, is associated with sussexite. Only known locality.

Specularite.—Common. Found in many places as films or patches in ore. Well crystallized in flat rhombs 2 millimeters in diameter associated with magnetite in Hiawatha mine. With chalcopyrite in unoxidized iron-formation in Buck mine.

Sphalerite.—Scarce. As nearly colorless crystals in unoxidized iron-formation in the Hiawatha mine; in oxidized iron-formation in drill core in the Bengal mine, associated with pyrite.

Sussexite ($2(Mn, Mg)O \cdot B_2O_3 \cdot H_2O$).—Not common. First recognized in district in dump material from Chicagon mine (Slawson, 1934). Since observed as irregular veins as much as 3 inches thick adjacent to manganiferous iron ore in Bengal (Cannon) mine. Pink, fibrous. Two analyses made in the laboratories of the U.S. Geological Survey are given in table 19. The mineral is optically negative, with $2V$ less than 5°. Indices (±0.002) are $\alpha=1.675$, $\beta=1.735$, $\gamma=1.738$. Specific gravity 3.31.

The veins of sussexite commonly have an irregular border of a bright black mineral that is structurally continuous with the sussexite. The black material was tentatively identified as hydrohausmannite by W. F. Schaller (written commun., Aug. 19, 1952).

TABLE 19.—*Chemical analyses, in percent, of sussexite from Bengal (Cannon) mine*

[Laboratory report IWC-291. Analyst: Charlotte M. Warshaw]

	1	*2*
MnO	49.42	49.42
MgO	9.02	9.40
B_2O_3 [1]	32.05	32.38
H_2O-	.00	.00
H_2O+	8.42	8.42
SiO_2	.06	.04
Fe_2O_3 [2]	.05	.05
Al_2O_3	.03	.03
CaO	.00	.00
Insoluble	.09	.15
Total	99.14	99.89

[1] Calculated from MnO and MgO on basis of formula $2(Mn, Mg)O \cdot B_2O_3 \cdot H_2O$.
[2] Determined as total iron.

Uraninite (*pitchblende*).—Scarce. Thin discontinuous seams and disseminated grains in oxidized iron-formation adjacent to graphitic slate in the Sherwood and Buck mines. Associated with pyrite, chalcopyrite, sphalerite, and galena in microscopic grains. Most of uraninite not visible to unaided eye, but one pod measured half an inch across.

Mineral X.—Very scarce. Yellow-brown micalike mineral discovered in 1951 by Alan T. Broderick, then geologist for the M. A. Hanna Co. and now chief geologist, Inland Steel Co.; in the Bengal (Cannon) mine on 118-foot sub above 6th level, at mine coordinate position 1200 S.–1700 E. With sussexite vein in manganiferous ore body. Resembles phlogopite, in books as much as half an inch in diameter. Only a few grams were found. Part was used up in tests; the remainder was lost during a reorganization of the mining company offices where it was being stored. Qualitative spectrographic analysis and X-ray examination in the laboratories of the U.S. Geological Survey indicated it to be a hydrated sulfate of manganese and aluminum (zincaluminite group). Optically negative with very small $2V$, clear canary to golden yellow in thin flakes; $\alpha=1.51$ approx., $\beta\cong\gamma=1.530$.

Possibly also to be classed with the postore minerals are alunite, dickite, and talc; these minerals were found by X-ray examination of fracture fillings in the ore by Bailey and Tyler (1960).

Most of the postore minerals fall into one or more of three groups that can be distinguished on the basis of occurrence: the sulfide-specularite association, the manganese association, and the sulfide-uraninite association.

SULFIDE-SPECULARITE ASSOCIATION

The sulfide-specularite group contains the minerals pyrite, chalcopyrite, sphalerite, specularite, magnetite, goethite, quartz, calcite, barite, and chlorite. These minerals are common both within ore bodies and in unoxidized iron-formation in the Hiawatha mine. The assemblages include specularite; specularite and magnetite; specularite and quartz; specularite and calcite; specularite, chalcopyrite, and quartz; specularite, chalocopyrite, barite, and goethite; pyrite; pyrite and barite; pyrite, chalcopyrite, and sphalerite.

Of particular interest is the occurrence of secondary minerals in oxidized chert breccia in the Buck mine. The rock, originally a chert-siderite breccia, now consists of angular chert fragments in a matrix of yellow and red iron oxides. The interiors of some of the chert fragments have been dissolved and are now lined with small crystals of quartz on which are perched abundant bright crystals of chalcopyrite. All examples seen of chert fragments so dissolved and so lined contained secondary sulfides. It seems reasonable to conclude, therefore, that the dissolving of the chert fragments was accomplished by the same solutions that deposited the quartz and the chalcopyrite. The breccia also provides clear evidence for a postore age of the sulfide; certainly preexisting chalcopyrite could not have survived the intense oxidation that produced the red and yellow iron oxides that form the matrix to the fragments.

MANGANESE ASSOCIATION

The manganese group is dominated by hausmannite, which in a few places is abundant enough to yield a manganiferous iron ore. (See previous section, "Manganiferous ores".) The mineralogic association is hausmannite, rhodochrosite, sussexite, and calcite, all of which have been observed as veins cutting goethitic ore in the Bengal mine. Braunite is reported to occur also with this group, and goethite as botryoidal clusters commonly borders veins of hausmannite. Native copper has been found in the vicinity of the manganese ores, as have neotocite and seamanite, but whether these minerals can be considered part of the suite is uncertain.

No clear relation can be established between the manganese association and the sulfide-specularite association, other than the obvious fact that both are younger than the minerals of the iron ores. The only minerals common to both are goethite and calcite.

SULFIDE-URANINITE ASSOCIATION

The occurrence of uraninite in the district was not known until 1951, when Robert C. Reed, working under the direction of L. P. Barrett, geologic consultant to the Atomic Energy Comm., in company with J. M. Ohlson, Inland Steel Co. geologist, discovered a radioactive anomaly in the Sherwood mine. The area was studied and sampled in 1952, and the discussion that follows is taken largely from a file report by L. P. Barrett and H. L. James to the Atomic Energy Comm.,[1] dated January 1953. The results showed that the deposits are not of economic importance.

The mineralogic association is uraninite, pyrite, chalcopyrite, galena, and sphalerite. Except for pyrite and possibly chalcopyrite, the minerals are not generally visible to the unaided eye, although one half-inch pod of uraninite was found.

The radioactive deposits occur within the Riverton Iron-Formation approximately at the contact of oxidized cherty iron-formation with an overlying graphitic pyritic bed that also is stratigraphically part of the Riverton. The structural relations are shown in figure 70, and the results of sampling are shown in figure 71.

Five principal areas of radioactivity, designated A, B, C, D, and E (fig. 70), all lie within oxidized cherty iron-formation. Four of them—A, C, D, and E—are immediately above the overturned contact with graphitic slate on the north flank of an anticline. The fifth zone, B, appears to be several feet above the contact but, by reason of complex internal folding, may be closer to the contact than is suggested by the position on map and section.

[1] Barrett, L. P., and James, H. L., 1953, The occurrence and sampling of radioactive zones in the Sherwood mine, Iron River district, Michigan: Memorandum report to the Atomic Energy Comm., 9 p., 4 pl.

The host rock for the radioactive material at the sample localities is as follows:

Locality A: Banded red jasper and hematite, with seams of black slate
Locality B: Layer of yellow ocherous limonite, with seams of black slate
Localities C, D, and E: Soft reddish hematite with seams of black slate.

The normal radioactive content of the unoxidized cherty iron-formation is about 0.001 percent U_3O_8 equivalent; that of the graphitic slate is higher, on the order of 0.003–0.004 percent U_3O_8 equivalent. The highest value for U_3O_8 equivalent in the radioactive zones is 0.513 percent, in area A, where a cut was blasted at the site of a previously determined concentration.

The stratigraphic position of most of the radioactive concentrations might suggest that a particular unit is uranium rich, but the sampling shows this unit to possess only normal radioactive content where unoxidized. Two generalizations can be made. First, the radioactive concentrations are confined to oxidized iron-formation. None has been found in either the graphitic slate or in unoxidized iron-formation. Second, except at locality B, the concentrations are found on a structural footwall of graphitic slate. In places where the graphitic slate is in its normal position as structural (and stratigraphic) hanging wall, no concentrations were noted, even where the iron-formation is oxidized.

Subsequent to the work in the Sherwood mine, similar concentrations were reported to have been found in the Buck mine by R. C. Vickers, who concluded that the uranium and other metals were leached from the black shales under near-surface oxidizing conditions and deposited adjacent to oxidized rock under reducing conditions (Vickers, 1956a, 1956b).

Isotopic analysis of the uraninite from the Sherwood mine (Kulp and others, 1953) gave the following results, as reported by Vickers (1956b, p. 51):

Ratio	*Apparent age (millions of years)*
207:206	653
Pb:U	380
206:238	371
207:235	420

AGE OF THE ORES

On the basis of data from within the district, the age of the ores can be given only within very broad limits. The ores obviously postdate the deformation and metamorphism of the Animikie Series, also that of the post-Animikie metadiabase and metagabbro intrusives. The age of this epoch is estimated by Goldich and his co-workers (Goldich and others, 1961, p. 168) to be 1,700 my (million years). Age determinations of Michigan rocks indicate a probable age of from 1,700 to 2,000 my for the post-Animikie metamorphism (Aldrich and others, 1965).

The younger limit of age, in this district, is set only by the age of the uraninite that cuts the iron ores of the Sherwood mine. As previously mentioned, the uraninite yields discordant apparent ages. The $Pb_{207}:Pb_{206}$ age, probably closest to actual age, is 650 my; according to present estimates this would correspond to very late Precambrian. In the Menominee district, 30 miles to the southeast, ores of similar character are overlain unconformably by sandstone of Late Cambrian age, which has a probable geochronologic age of about 500 my.

The only rock in the district, other than the ores, known to have been formed during this vast interval of time (about 1,200 my) is a single diabase dike in the northern part of the Iron River area, and its relation to the ore is equivocal. This diabase, not to be confused with the many metadiabase dikes in the same locality, is one of a swarm of unmetamorphosed, inversely magnetized dikes that center some distance to the north (Balsley and others, 1949). These dikes almost certainly are comagmatic with the Duluth Gabbro, which has an apparent age of 1,100 my (Goldich and others, 1961, p. 161). The dike in the northern Iron River area follows the North Mineral Hills fault for some distance, and locally it is adjacent to the main ore body on the north flank of the Mineral Hills syncline. In upper levels of the Forbes mine it may have been in actual contact with ore, but where observed (on the 650 level) it was well below the ore body, which with depth migrates southward on dragfolds. Specimens from drill holes east of the mines are of entirely unaltered diabase consisting of labradorite, augite, and magnetite-ilmenite. Specimens from the mine workings are similar in general appearance, but the augite is largely or entirely altered to dark-green chlorite. Whether this alteration can be related to the ore-forming process is problematical. The lack of oxidation of magnetite-ilmenite in the dike argues against this relationship; nevertheless the fact remains that the diabase in the vicinity of the ore has undergone an alteration of a type and intensity not seen elsewhere in dikes of this suite.

The time relation between formation of ore and the igneous epoch represented by the Mineral Hills dike and by the Duluth Gabbro may be indirectly inferred. As has been mentioned earlier in this report, the distribution of ores of the Lake Superior type bears an inverse relation to metamorphism. The main metamorphic zoning of the Mesabi district of Minnesota is related to the Duluth Gabbro rather than to the post-Animikie of considerably greater age. If it is assumed that the iron ores of the principal Lake Superior districts formed during the same general period of time, as seems reasonable considering the great similarities from district to district, then the time of ore formation postdates the Duluth Gabbro.

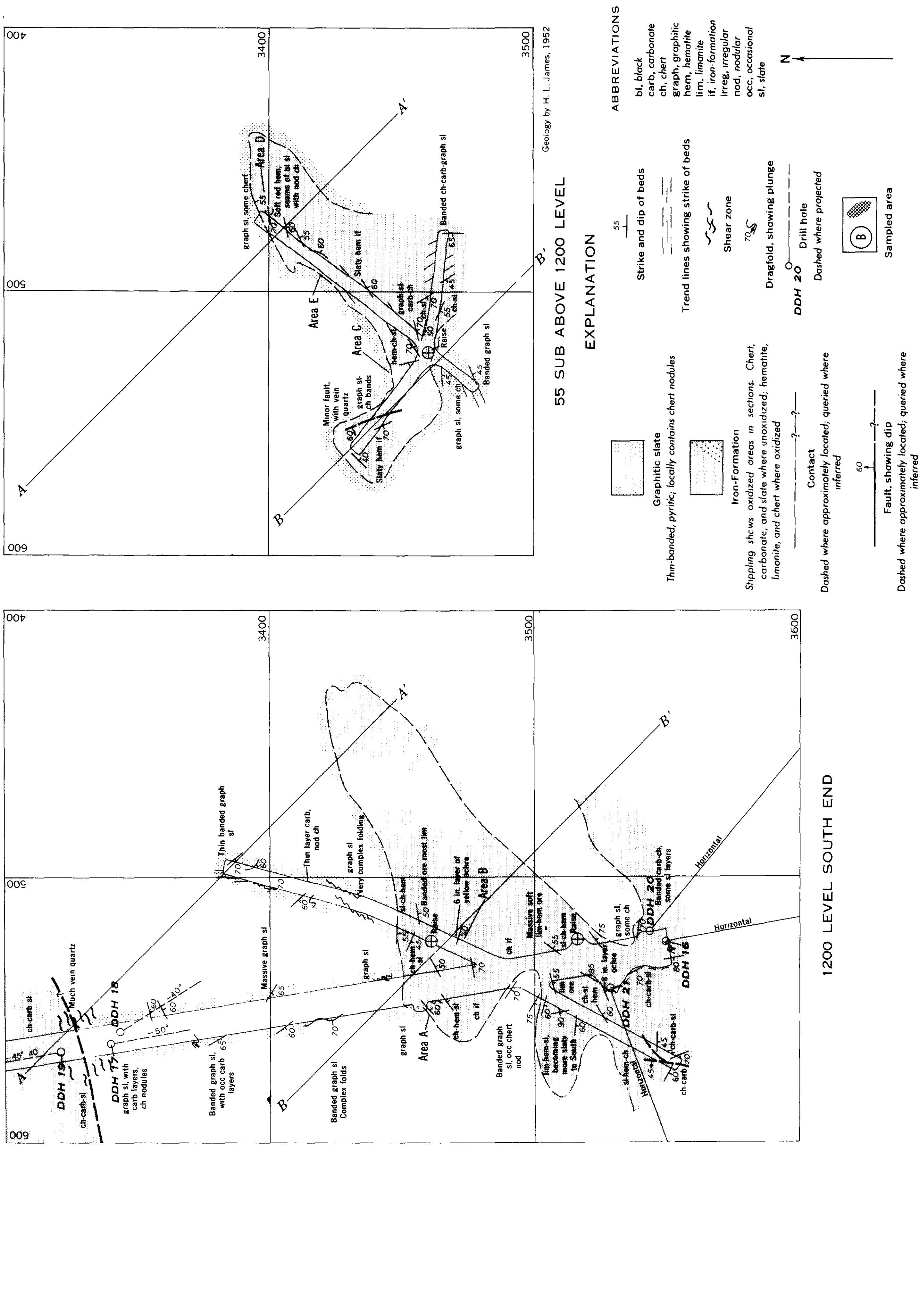
Tentatively, therefore, it is concluded that the ores of the Iron River-Crystal Falls district formed at some time, perhaps continuously, between the time of emplacement of the Duluth Gabbro at 1,100 my and the formation of the uraninite from the Sherwood mine at about 650 my.

ORIGIN OF THE ORES

Although it can be stated at the outset that the question of origin of the ores remains virtually unsolved, the range of concepts that can profitably be considered is tightly restricted by the array of facts and reasonable inferences that can be assembled. These facts and inferences are organized as follows:

General

1. The ores occur only in iron-formation, which in its preore state consisted mainly of interbedded chert and siderite.
   The concept of a preore conversion of chert and siderite to metamorphic silicates as a requisite step in the ore-forming process (Tyler, 1949; Mann, 1953) is wholly without support in the Iron River–Crystal Falls district, as it is in the Mesabi district (White, 1954, p. 82). Indeed, there is a negative correlation between preore abundance of silicates and the occurrence of ore.
2. The ores are of Precambrian age and probably formed during the interval from 650 to 1,100 million years ago.
   Neither limit is certainly established. The lower limit of 1,100 million years is set only by an inferred relation to the Mesabi district.
3. The amount of oxidized iron-formation and ore per unit area of iron-formation for the district as a whole is greatest at the surface and decreases progressively with depth.
   The actual distribution of oxidation is not regular, however. Unoxidized iron-formation is at the present surface in places where immediately adjacent iron-formation is oxidized to depths of a thousand feet or more. Also, in several large areas the iron-formation is wholly unoxidized at the surface; these tracts may represent areas topographically high during the epoch of deep oxidation and from which the oxidized rock has since been eroded.


55 SUB ABOVE 1200 LEVEL
1200 LEVEL SOUTH END
Geology by H. L. James, 1952
EXPLANATION
Graphitic slate
Thin-banded, pyritic; locally contains chert nodules
Iron-Formation
Stippling shows oxidized areas in sections. Chert, carbonate, and slate where unoxidized; hematite, limonite, and chert where oxidized
Contact
Dashed where approximately located; queried where inferred
Fault, showing dip
Dashed where approximately located; queried where inferred
Strike and dip of beds
Trend lines showing strike of beds
Shear zone
Dragfold, showing plunge
Drill hole
Dashed where projected
Sampled area
ABBREVIATIONS
bl, black
carb, carbonate
ch, chert
graph, graphitic
hem, hematite
lim, limonite
if, iron-formation
irreg, irregular
nod, nodular
occ, occasional
sl, slate
N

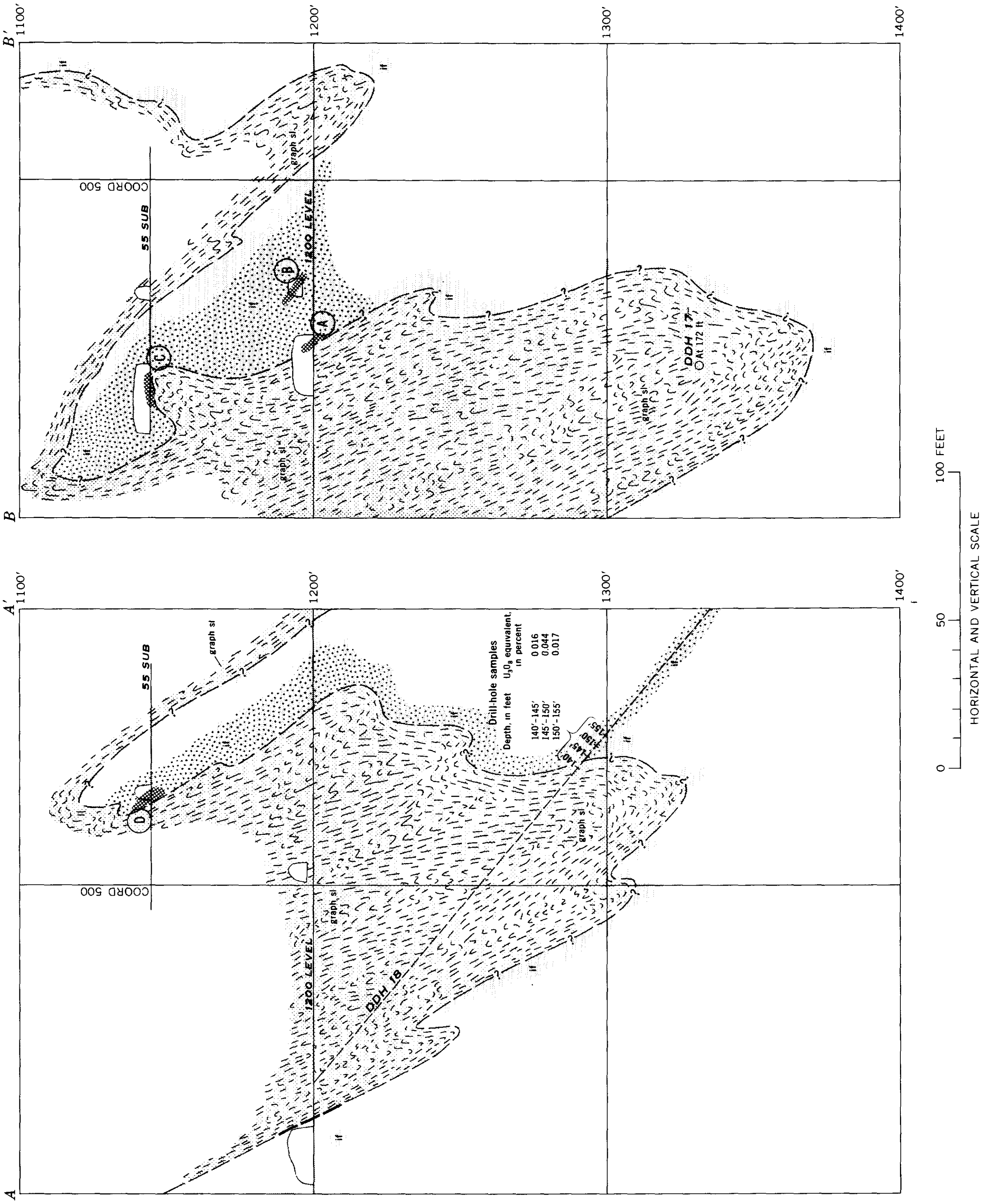


FIGURE 70.—Maps and cross sections showing radioactive areas A–E in Sherwood mine. Sherwood mine coordinates. Elevations below collar of Sherwood shaft.

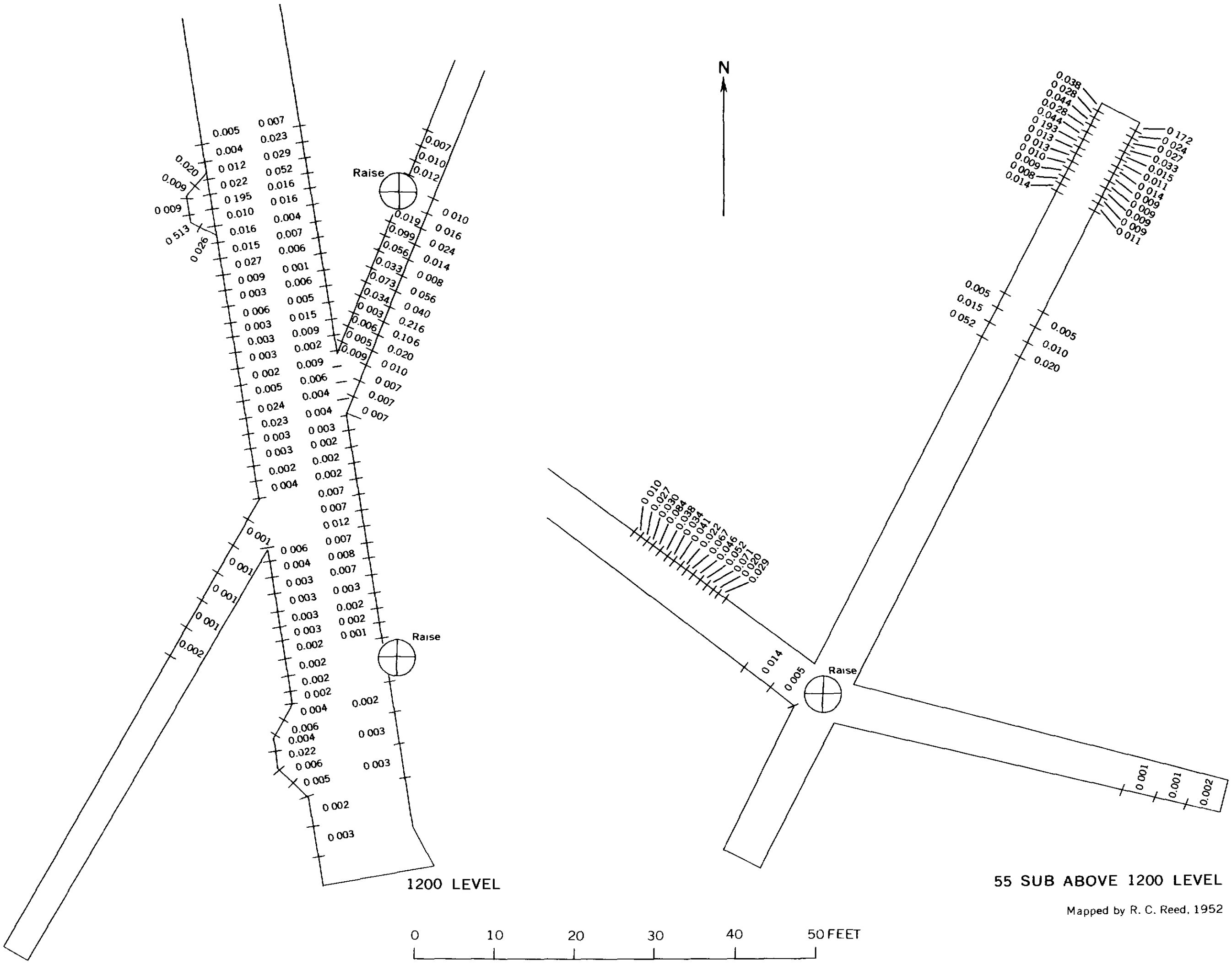


FIGURE 71.—U_3O_8 equivalent values, in percent, in part of Sherwood mine. (See fig. 70 for geology.) Location of workings from company records, sampled by R. C. Reed, 1952.

4. Ore bodies are most numerous and largest in areas where the iron-formation is most extensively oxidized, and all ore bodies grade laterally into oxidized iron-formation.
5. Most ore bodies connect to the surface in some dimension, though often indirectly or in diminished size. For some small ore bodies, exploration has not been adequate to demonstrate an extension to the surface, but certainly all connect to the surface via oxidized iron-formation if not by ore.
6. Many large ore bodies reach their maximum dimensions at depths of 500–1,500 feet.
   The two largest ore bodies known in the district—the Hiawatha No. 2 ore body and the ore body on the south flank of Mineral Hills—have far greater size at depth than they do at the surface.
7. Oxidized iron-formation and ore bodies extend to a known depth of half a mile.
   Extensive and complete oxidation is known to extend to depth of half a mile in at least four places in the district, and a reasonable assumption is that locally at least it may extend to 3,000 feet.

Structural

1. The ore bodies were formed in their present structural position.
   In many places, the form of the ore body bears a delicate relation to overturning of the beds; an ore body in a syncline will extend for some distance up the flattened limb but will terminate abruptly on the overhanging limb. Furthermore, ore in which color banding reflects the original layering

is contorted typically into tight crumples and dragfolds—structures that could not possibly form in material of the present composition. Local zones of rubbly or breccialike aspect can be attributed to slumping during the ore-forming process.

2. Most of the ore bodies that have a definable structural position are in upward-facing structures, generally synclines.
   A few ore bodies are related to faults or to dikes that become one side of a structural trough. In general, the faults have been barriers to circulation rather than channels for it.
3. The ore bodies typically rest on a well-defined footwall of less permeable (or at least less readily altered) rock.
   The footwall for most ore bodies is pyritic graphitic slate; locally, in the eastern part of the district, it is a slaty unit within the iron-formation. The oxidation characteristically fades out abruptly in the footwall unit—within a few feet under major ore bodies in the western part of the district—whereas the oxidation is likely to extend to the surface in the hanging-wall rocks.
4. Ore bodies occur on very few major anticlinal structures.
   The relation between oxidation and structure is less clear. Many major anticlinal areas are deeply oxidized, but there is a suggestion in the map patterns that this is true mainly in areas of steep plunge. In the Crystal Falls–Alpha belt of folded iron-formation, in which the folds plunge to the northwest at 40°–50°, unoxidized iron-formation is more common in the anticlinal areas than in the synclinal parts of the folds.
5. Some very large bodies of ore attain their maximum size at depth in the lowest parts of tight doubly plunging synclines.
   The best example of ore in a doubly plunging synclinal structure is in the Buck mine. (See fig. 62.) In terms of a possible circulation system, structural basins of this sort would tend to be stagnant, yet clearly they have been favorable loci for the formation of ore.

Mineralogical and chemical

1. The ores are porous very fine grained mixtures of (dominantly) hematite and goethite.
   Hematite and goethite vary in proportions within short distances. No relation of proportion to depth has been noted. Interlayering of goethite-rich and hematite-rich layers suggests some control by original layer-to-layer compositional differences in the iron-formation.
2. The ores have formed by oxidation of original siderite and by at least partial replacement of chert layers by iron oxides.
   The replacement of chert layers by iron oxides is obvious in hand specimens and is further indicated by the fact that the stratigraphic thickness of the formation does not change measurably in the passage from unoxidized iron-formation to oxidized iron-formation to ore.
3. Gangue minerals are of microscopic dimensions and consist mainly of relict chert, clay mica (illite), and kaolinite dispersed through the iron oxides.
4. The stable mineral assemblage is goethite, hematite, illite, kaolinite, gypsum, and apatite(?).
   The quartz identified in the ores is assumed to be relict from incomplete replacement of chert. The deficiency of many ores in calcium suggests that the phosphate may be present, at least in part, as vivianite or some other comparable hydrous phosphate, such as dufrenite.
5. The ore-forming process resulted in separation of the iron and manganese.
   The iron ores are noticeably deficient in manganese relative to the original iron-formation. Local concentrations of manganese, chiefly as hausmannite, postdate the iron ores.

Regional

1. Ores of the "Lake Superior" type are virtually restricted to iron-formation of low metamorphic grade.
   This stricture is true not only for the Michigan iron districts (James, 1955) but also for the Mesabi and Cuyuna districts of Minnesota and the Labrador trough of Canada. Presumably the metamorphic increase in grain size of the quartz of the chert layers inhibits leaching and replacement.
2. A period of very deep chemical weathering preceded deposition of Cambrian strata on the Canadian Shield.
   Baker (1939) has found widespread evidence to indicate an important epoch of deep chemical weathering in late Precambrian time. In most places, the weathered rocks were stripped before deposition of basal Paleozoic strata, or have since been eroded. In New York, caverns were formed in marble of the Grenville Series to a depth of a thousand feet prior to deposition of the Potsdam Sandstone (A. E. J. Engel, oral commun.). In Dickinson County, a short distance east of the Iron River–Crystal Falls district, gneisses and

schists bordering the overlapping sandstone of Cambrian age locally are altered to clay minerals to a depth of several hundred feet (James, Clark, and others, 1961, p. 76–77). The patches of silcrete in the southwestern part of the district (see p. 72–75) and elsewhere in the region (Leith, 1925) may be relicts of a duricrust formed during a cycle of aridity and deep weathering.

CRITICAL REVIEW OF CURRENT THEORIES [2]

Three theories of origin of iron ores of the Lake Superior type have current status: (1) action of meteoric waters—essentially deep weathering (as stated by Van Hise and Leith (1911, p. 544), "The agents of alteration are surface waters carrying oxygen and carbon dioxide from the atmosphere"); (2) action of hydrothermal solutions derived from magmatic sources at depth (Gruner, 1930); and (3) action of waters dominantly meteoric in origin but added to and activated by fluids from magmatic sources (Gruner, 1937). These three theories will be referred to respectively as meteoric, hydrothermal, and modified hydrothermal.

METEORIC THEORY

The meteoric theory of Van Hise and Leith is supported by many of the facts presented in the preceding section. The mineral assemblage is one that is stable only under highly oxygenated, primarily atmospheric conditions, and the ore bodies bear an evident relation to the surface. The formation of the ores required the addition of large volumes of oxygen, for which the atmosphere is the only adequate source.

Two major objections can be raised to the meteoric theory: the removal of silica on a large scale and the apparent inadequacy of any reasonable ground-water system to circulate to the great depths required.

The solubility of quartz is not easily established. Some natural waters contain as much as several hundred parts per million SiO_2 (Krauskopf, 1956), but most contain far less. The true solubility of quartz in water is low, 6 ppm at 25°C and 100 ppm at 136°C according to Morey, Fournier, and Rowe (1962), but these same investigators obtained concentrations of nearly 400 ppm at 25°C by tumbling crushed quartz in water for a period of about a year. The great increase in amount of quartz in solution is not attributed to abrasion; rather, it is believed to be a supersaturation due to excess solution from high-energy surfaces formed during the grinding of the quartz. The role of tumbling is to permit more rapid removal of dissolved silica (presumably as $Si(OH)_4$) from surfaces of the grains. Morey, Fournier, and Rowe (1962, p. 1040) noted that the rate and amount of supersaturation is dependent upon several factors, among them time and the grain size of the quartz. The grain size of quartz used in the experiments was about 0.15 mm. In comparison, the quartz of the chert layers is about an order of magnitude less (0.01–0.03 mm), which means the surface area of individual grains is about 100 times greater. It does not seem unreasonable to assume an effective solubility of SiO_2 of 100 ppm for this fine-grained quartz during the ore-forming process, even at normal ground-water temperatures. Whether this degree of solubility is adequate to account for the large-scale removal would depend on the volume of solution passing through the rock being altered.

A rough estimate of the volume of water necessary to form the ore can be obtained from the oxygen requirement. The absorption coefficient for oxygen in water at 20°C is 0.031 cc(g) per cc H_2O at $P_{O_2}=760$ mm (volume of the gas reduced to 0°C, 760 mm). At present atmospheric concentration, water saturated with O_2 would contain 0.0065 cc(g) per cc H_2O, or about 9.3×10^{-6}g. Each cubic centimeter of average ore (table 18) contains about 2.5g Fe_2O_3. The iron, whether in the form of siderite or in solution, originally was in the ferrous state, yielding ferric oxide according to the reaction

$$2FeO+1/2(O_2)=Fe_2O_3$$

Each mole (160 g) Fe_2O_3 requires ½ mole (16 g) of O_2. Formation of the ore, therefore, required addition of 10 percent oxygen by weight for each unit of ferric oxide, or 0.25 g of O_2 per cc of ore. If the dissolved oxygen content of the water was 9.3×10^{-6}g cc, then each cubic centimeter of ore required the passage of 2.7×10^4 cc of water, assuming that all the oxygen was extracted. Now, assuming silica to be dissolved to the extent of 100 ppm (1×10^{-4}g per cc), each gram extracted would require the passage of 10^4 cc of water. From table 18 it is seen that the formation of each cubic centimeter of ore involved a loss of 0.8 g SiO_2. This would require the passage of 8×10^3 cc H_2O per cc of ore at 100 ppm solubility for SiO_2, or a third of that required to transmit the necessary amount of oxygen in solution. This calculation cannot, of course, be taken to indicate anything more than order-of-magnitude, but it does suggest that the two major aspects of ore formation—removal of silica and oxidation of iron—are not seriously in imbalance in a postulated ground-water system.

The second major doubt concerning the meteoric theory is with respect to the adequacy of a normal ground-water system to circulate the required volumes of water. Two extreme situations may be visualized, one in which the flow of water was in an unconfined system,

[2] In preparing this section, use has been made of a U.S. Geological Survey file report by C. V. Theis, entitled "The nature of the hydraulic system involved in the enrichment of iron ore near Iron River, Michigan," dated June 1945.

with an outlet at levels below the ore bodies, and the other in which the flow was confined; in the latter the ore bodies represent zones of greatest permeability in an aquifer—that is, the iron-formation. In the western part of the district, the ore bodies typically are floored by impermeable graphitic slate, and the geometry of many of the structures precludes an outlet below that of the ore bodies; an unconfined system therefore is improbable. An artesian system, on the other hand, is theoretically possible, even though the beds overlying the iron-formation are by no means impermeable and the flow would therefore not be strictly confined, at least with respect to the upper surface of the aquifer.

If the typical system is assumed to be artesian and if the variations in degree of confinement are ignored, the rate of water movement would depend chiefly on the relative difference in elevation of inlet and outlet and the permeability of the aquifer. Mathematical solution of the problem, however, is difficult unless further large and possibly fatal simplifying assumptions are made. The oxidized iron-formation, with its contained ore bodies, is now an aquifer, but it is so because of oxidation of the original rock, which was relatively impermeable. The permeability, therefore, was a constantly changing factor in time and space. The hydraulic gradient is also dependent on relative elevations of inlet and outlet; these were continually changing with time as a result of erosion. Thermal gradients then existing are not known; they would affect not only the movement of the water but also the solubility of oxygen and silica.

Bearing these major uncertainties in mind, we may arrive at an arithmetic solution of a highly simplified system. Consider an ore-bearing bed folded into a U-shape with a cross-sectional length of 2,000 meters, one arm of the U reaching to a higher level topographically. Within this consider a parallelepiped of ore having a cross-sectional area of 1 cm^2. The volume of the parallelepiped would be 2×10^5 cm^3. From the previous estimate of oxygen requirements (2.7×10^4 cc H_2O per cc of ore), the total volume (Q) of water necessary for conversion to ore would be

$$Q=(2.7\times10^4)\ (2\times10^5)=5.4\times10^9 \text{ cc } H_2O.$$

The velocity of flow can be approximated from Darcy's law, expressed here as

$$V=K \sin\theta$$

where

V=velocity of flow

K=coefficient of permeability

θ=slope of pressure surface.

The permeability coefficient (K) cannot be determined satisfactorily on specimens because most of the water moves through fractures and larger spaces. The only in situ value available is that made for the Spies-Johnson ore body, where the value is estimated to be about 2 gallons per day per square foot (Stuart and others, 1948, p. 45), or approximately 110 millidarcys. The permeability of unoxidized iron-formation in place has not been determined. In specimen it is very low (on the order of 1×10^{-3} millidarcys), and although it doubtless is somewhat larger in situ, it still can be considered practically as zero. Let us assume a logarithmic mean value of about 10 millidarcys for the iron-formation during its conversion to ore. Let us further assume that the pressure surface between inlet and outlet maintains a slope of 0.5°. Then,

$$\begin{aligned} V&=K \sin\theta \\ &=10\times0.009 \text{ millidarcys} \\ &=9\times10^{-5} \text{ darcys.} \end{aligned}$$

The time (t) required for passage of the required volume (Q) of unit viscosity at the estimated velocity (V) per unit of cross section (A) is

$$\begin{aligned} t&=\frac{Q}{VA} \\ &=\frac{5.4\times10^9 \text{ cm}^3}{9\times10^{-5} \text{ cm/sec}\times1 \text{ cm}^2} \\ &=6\times10^{13} \text{ sec} \\ &\cong 2\times10^6 \text{ yr} \end{aligned}$$

The conditions postulated are not unreasonable and the amount of time required on this basis is within the realm of possibility. In a very general way, therefore, it can be concluded that the concept of artesian circulation has a gross quantitative adequacy. Nevertheless, some serious objections remain.

The principal objection is based on the actual distribution of ore in a trough of the type just discussed. The ore is not evenly distributed in the iron-formation. The major loci are along the axial zones of minor synclines or structural terraces on the flanks of the trough and, if the trough is not excessively deep, along the keel of the main structure. Water at many of these positions would be relatively stagnant. The steep limbs of the folds, where circulation would have been most vigorous, are not favorable loci for development of ore. Nor in an aquifer would there seem any particular reason for the ore to select, as it does, a position on the footwall. Furthermore, it is common in such a structure for the hanging-wall strata to be thoroughly oxidized and otherwise altered, which indicates that the ground water was not necessarily confined with respect to the upper surface.

HYDROTHERMAL THEORY

The possibility that the ores were formed in a hydrothermal system of the classic type—that is, one in which the fluids are of magmatic derivation—has little to commend it. The stable mineral assemblage is a fine-grained porous mixture of goethite, hematite, clay mica, kaolinite, and gypsum. Although these minerals are known to occur individually in magmatic hydrothermal ores, the assemblage as a whole certainly bears little resemblance to those of true hydrothermal character, and all the minerals in the ore, including the clay mica, are compatible with a low temperature origin (illitic mica has been synthesized by Henin (1956) at temperatures as low as 20°C).

The confinement of ores to original iron-formation, the absence of ore in downward-facing structures, the evident relation to the surface, the absence of sulfides except as minor postore fillings, and the inverse relation to igneous activity and metamorphism all are potent objections to the hydrothermal theory. One of the major aspects—introduction of oxygen on a large scale—would, at even modest hydrothermal temperatures, require passage of enormous volumes of solution; yet, the rock beneath ore bodies is unaltered.

MODIFIED HYDROTHERMAL THEORY

The theory of origin by hot magmatic fluids proposed by Gruner (1930) was vigorously attacked by Leith (1931) and others. Later, Gruner (1937) proposed a modified hydrothermal theory, based on analogy with the hot spring activity of Yellowstone Park. According to this theory, the ores were formed in waters dominantly of meteoric origin but added to and heated by fluids of magmatic derivation. As expressed by Gruner (1937, p. 125–126):

> Hot emanations rising from a deeper source, chiefly as gases, seem to be ideal for these processes. They possess high mobility, great heat capacity, and are of a large enough order of magnitude. Steam would be the chief constituent. It would, of course, condense if brought in contact with sufficient amounts of meteoric water.

The theory is an attractive one. The high oxygen requirement would be satisfied by the meteoric water, the increase in temperature would increase greatly the solubility of silica and provide a driving force for deep circulation and expulsion of fluids, and the activated system would bear the requisite type of relation to upward-facing structures and to the surface. Quantitative evaluation of the system is not worthwhile since most intensity factors of the magmatically derived component could be increased or decreased at will, but there is little doubt that reasonable conditions could be postulated that would be adequate.

Despite the fact that the modified hydrothermal theory would meet many of the principal geologic criteria and probably is quantitatively adequate, several serious objections can be raised. The first objection is the complete lack of evidence indicating passage of magmatically derived fluids into the meteoric system—that is, into the structures now occupied by ore. In many of the mines, workings have been developed in the footwall below large ore bodies, which in some mines, such as the Buck, is beneath the keels of ore-filled synclines. The footwall rock typically is oxidized for a few feet below the ore but otherwise is unaltered. It is almost inconceivable that hot fluids of the volumes required could pass through without a trace. Faults intersected in the mines away from or below ore bodies are not bounded by altered rock, which certainly would be true if these faults had acted as conduits (as they do in most "hydrothermal" districts).

The second objection is geological. In proposing the theory, Gruner used the Yellowstone Park hot-spring activity as the prime example of the process in action. In contrast to the Yellowstone area, which is one of long-continued igneous and volcanic activity abundantly reflected in the rocks, the Iron River-Crystal Falls district shows no evidence of such a volcanic epoch. Except for the one dike of Keweenawan age in the northern part of the Iron River area, the igneous rocks predate the metamorphism and are much older than the ore.

The third objection is mineralogical. Though probably most of the minerals of the ores are not incompatible with moderately elevated temperatures (100°–250°C), the absence of more characteristic hydrothermal minerals is striking. Noticeably absent are albite, adularia, calcite, barite, zeolites, and sulfides. Whereas, in most areas of hydrothermal activity, quartz and chalcedonic silica are abundant as depositional products, they are wholly absent in the ores except as a relict and probably unstable phase. The only minerals of hydrothermal aspect have been shown to be postore in age.

To the present authors, at least, these objections seem insuperable and constitute refutation of the hydrothermal theory, even in its modified form.

PREFERRED THEORY OF ORIGIN

None of the current theories of origin seems adequate to encompass the known facts regarding the iron ores and their environs. All are unsatisfactory in some major respect. The same is true, at least to some degree, of the eclectic theory here presented.

The key postulate of the preferred theory is that of a long period of extraordinarily deep water table during later Precambrian time, an epoch possibly unmatched in later history of the earth. During this epoch of aridity, the iron-formation was irregularly oxidized to great depths in the zone of aeration and suspended (vadose) water, above the permanent water table. The great addition of oxygen and loss of carbon dioxide involved in the change of siderite to iron oxides, therefore, would not require long-continued circulation of oxygen-bearing waters; it would be accomplished principally by exchange with "soil air," perhaps through the medium of ephemeral water.

The pattern of this oxidation would be controlled by local topography, structure, and the vagaries of movement of vadose water, but it would be irregular, particularly at depth. Once oxidation began at a particular site, the rock would become more permeable, further local oxidation would be speeded up, and original chance irregularities would be accentuated. Axial zones of synclines, marked as they are by more crumpled rock and floored by less permeable strata, would be natural loci for deeper oxidation. This process would result in irregular zones of highly permeable rock, which would serve as aquifers during periods of greater inflow. The end product, it is to be noted, is oxidized iron-formation, not ore.

During wetter cycles in this epoch, water would accumulate in upward-facing traps. These traps could be synclines or other structural troughs, or they could be simply oxidized zones in the iron-formation bottomed by unoxidized rock. They could be at any elevation, down to the limits of oxidation. The water accumulating in these stagnant pools would be charged with carbon dioxide from breakdown of siderite and would contain ferrous salts to the limit of solubility. Under stagnant conditions, silica would dissolve to the limits permitted by the presence of quartz as aggregates of very fine grains of irregular shape and great surface area. Some replacement of the chert by secondary siderite probably would occur as a result of gradual loss of carbon dioxide by evaporation.

The next step in development of ore would be periodic expulsion of the silica-saturated waters from these stagnant basins. In places this could be accomplished or aided by the addition of magmatic fluids as proposed in Gruner's modified hydrothermal theory, but more likely the expulsion would be in imperfectly confined artesian systems of brief duration.

A typical situation may be visualized as follows: A trough of oxidized iron-formation is floored by a relatively impermeable unit—graphitic slate, slaty iron-formation, or even unoxidized iron-formation—and overlain by partly to completely oxidized iron-formation, slate, or graywacke, all of varying degrees of permeability. The impermeable unit reaches a higher elevation on one side of the trough than the other but does not necessarily reach the surface. Eventually, the iron-formation in the troughs is saturated with water that enters both from updip positions of the permeable iron-formation and from the irregularly permeable overlying rocks. After complete saturation, water will move laterally down any hydraulic gradient that may exist. The system as a whole might be classed as unconfined, but with respect to deeper parts of the principal aquifer (that is, the oxidized iron-formation), the circulation will be semiartesian, with water moving downward to the lower part of the structure, migrating upward on one flank, and leaving the structure at an elevation relatively higher than that of the keel.

During this semiartesian cycle, any secondary siderite in the troughs would be oxidized. In reference to the previous calculations of volume and time of circulation in an artesian system, it can be pointed out that the permeability would have a much higher value, the oxygen requirement would be practically eliminated, and degree of supersaturation by silica could be much greater. This process of stagnation and periodic expulsion, repeated many times, would result in elimination of silica, and in addition of iron, both by formation and later oxidation of secondary siderite and by infiltration of colloidal iron oxides from higher levels; the ultimate product is iron ore. In a very real sense, the ore bodies would "grow from the bottom up," in contrast to the initial oxidation, which was from the top down.

As previously stated, the key postulate is that of a period of aridity of extraordinary intensity and duration, perhaps hundreds of millions of years, during which the permanent water table was at a minimum depth of 3,000 feet and probably considerably more. The concept of such a period of aridity may appear to do violence to the doctrine of uniformitarianism, which has proved as an invaluable a control on geologic thinking as have the laws of thermodynamics in physics and chemistry. Woolnough (1928; 1937; written commun., Aug. 24, 1951) has pointed out, however, that the ideas of what constitutes uniformitarianism have been formulated mainly from experience with the geology of the Northern Hemisphere and with observations of processes operating in temperate climates. By analogy with Australia, he stressed the possible great importance, during long periods of geologic time, of deep chemical weathering of an intensity not now recognized on the present surface of the earth.

Even under present-day conditions in Australia, artesian water is obtained in arid areas from aquifers at depths of more than 4,000 feet; single wells yield more than a million gallons a day (Meinzer, 1923, p. 45). Widespread remnants of siliceous duricrust (silcrete), mantling bedrock altered to unknown depths, testify to the existence of an earlier epoch of chemical weathering under arid conditions (Williamson, 1957).

The conditions leading to the formation of the iron ores are conceived to be somewhat comparable to those of the desert regions of Australia of the present and relatively recent past, but of greater intensity and longer duration.

Independent evidence bearing on the postulated epoch of aridity in the Lake Superior region is almost completely lacking. The geologic record of the last 500 million years of Precambrian history—that is, of the time between the Keweenawan and the Cambrian—is virtually a blank. The only evidence remaining is that of indications of widespread deep weathering of the Precambrian surface, as previously noted, and of a few patches of possible duricrust. It is tempting to use the deep oxidation itself as evidence, but the argument of course is circular. Because of the almost complete absence of independent factual support, the concept of origin presented must be considered as only plausible speculation until some new critical data are obtained or some other means can be devised to test it. In its favor, however, is the fact that once the main postulate is granted, the predictable results fit all the known facts regarding the ores.

POSTORE MINERALIZATION

Once formed, the oxidized iron-formation and the ores would be natural channels for movement of solutions from any source. As described previously, three main groups of postore minerals are present: the sulfide-specularite association, the manganese association, and the sulfide-uraninite association. Despite a certain degree of overlap in mineralogy, these groups are sufficiently different in makeup and occurrence to suggest the possibility of independent systems. Among these systems would be the possibility of circulating sea water inasmuch as porous and permeable iron-formation and ores extended to bedrock surface at the time of encroachment of Paleozoic seas.

Of the three groups, the uraninite-sulfide association is the most likely to be related to the processes that formed the iron ores. The uraninite and associated sulfides occur in ore or oxidized iron-formation at footwall contacts with pyritic graphitic slate. They probably were formed from oxidized solutions that had leached metals from slates at higher levels; the precipitation occurred when the downward-percolating solutions came to the pyrite slate footwall (Vickers, 1956a, b).

Concentration of the manganese minerals also may be related to the main ore stage, and it is assumed that the manganese is derived from the iron-formation itself. Evidently, during the formation of the iron ores (or during oxidation of the iron-formation), the solutions were of such character as to permit manganese to be carried off in solution while iron was being precipitated as the oxide. The problem of separation of iron and manganese in dilute solutions has been reviewed by Krauskopf (1957, p. 73), who stated:

> Theoretically the prior precipitation of iron could be accomplished as carbonate, silicate, sulphide, or oxide, since the iron compounds of all of these anions are more insoluble than the manganese compounds. The difference in solubility is greatest for the oxides, and separation by this means is easy to demonstrate experimentally.

Precipitation of the manganese can be accomplished by increase in oxidation potential or by increase in silicate or carbonate anion concentration. It also can be accomplished by increase in alkalinity of the solution. Krauskopf (1957, p. 77) wrote:

> One can readily imagine local conditions, however, that might lead to precipitation even from such very dilute solutions. The manganese might become more concentrated by evaporation in an arid region; the solution might become gradually alkaline, so that all iron would be eliminated, and then might ultimately reach an alkalinity at which very small concentrations of manganese would precipitate; the precipitation might be accelerated by bacteria, by catalytic action of MnO_2, or by unusual concentrations of silicate or carbonate. If the original concentration of manganese were even slightly greater than normal, the precipitation would of course be aided.

On the basis of Krauskopf's discussion, it may be concluded that the manganese was concentrated in circulating waters as a result of solution of original manganese-bearing siderite of the iron-formation and subsequent selective precipitation of iron oxides. Locally these manganese-enriched ground waters accumulated in or circulated through environments in which either the Eh or the pH, or both, were sufficiently high to cause precipitation. The local presence of borate minerals (sussexite and seamanite) doubtless is significant but in what respect is not known.

The third group of postore minerals—the sulfide-specularite association—most resembles the "hydrothermal" type in general aspect. The minerals occur as fillings in the ore, but they also are commonly found outside the oxidized iron-formation and ore bodies, particularly in brecciated unoxidized iron-formation. The character of the assemblage and the occurrence suggest an origin from hydrothermal fluids derived from outside the ground-water system. Isotopic analyses of the oxygen of the magnetite, specularite, quartz, and calcite, however, indicate (1) origin in isotopically light waters, comparable to present-day Lake Michigan, and (2) deposition at temperatures of 20°–100°C (James and

Clayton, 1962, p. 230). The minerals of sulfide-specularite association, therefore, appear to have been deposited at low temperatures from solutions similar isotopically to ordinary fresh waters. In contrast to the waters forming the iron ores, however, this water was oxygen poor and carried sulfur and base metals in solution. Its origin and the nature of the circulation are not known.

ECONOMIC ASPECTS OF THE RIVERTON IRON-FORMATION

SHIPPING-GRADE ORE

The "total tonnage" of shipping-grade ore was estimated in 1911 to be 8,054,000 tons for the Crystal Falls district and 42,122,000 for the Iron River district (Allen, 1912, p. 158, 163). The aggregate reserve of "ore in sight" at the same date for the two districts was 11,403,113 tons. In 1961, the tonnage estimated for tax purposes for Iron County (mainly the Iron River-Crystal Falls district) was 52,166,834 tons. The production 1911–61 was about 155 million tons. In tabular form:

	Tons
Total reserve estimate, 1911	50, 176, 000
Total mined, 1911–61	155, 000, 000
Reserves, 1961 tax estimate	52, 166, 834

The 1961 estimate of tax reserves is not strictly comparable with the 1911 estimate of total reserves; in fact, the estimate is more comparable with the much lower "ore in sight" figure. It is obvious, however, that new discoveries more than kept pace with the mining over the 50-year period and that a reserve estimate made for tax purposes reflects intensity of exploration more than actual reserves.

A valid estimate of the total amount of ore remaining in the district is difficult to obtain. An approximation, however, can be made on the basis of the total area of iron-formation at bedrock surface, the percentage of iron-formation that is oxidized, and the amount of ore per unit of oxidized iron-formation.

The total area of Riverton Iron-Formation at bedrock surface is estimated to be 8.7 square miles. The extent of deep oxidation previously has been assessed as about 50 percent of the exposed rock. As a basis for calculation, then, a conservative estimate is made that the total surface area of oxidized iron-formation is 4 square miles.

The ratio of ore to oxidized iron-formation has been obtained as follows. Three areas were selected: the Buck mine area, in and adjacent to sec. 7, T. 42 N., R. 34 W.; the Hiawatha area, in and adjacent to sec. 35, T. 43 N., R. 35 W.; and the Odgers-Tobin area, in and adjacent to sec. 30, T. 43 N., R. 32 W. Each of these areas has been thoroughly explored, and it is believed that most of the ore present has been discovered and extracted; that is, it is assumed that the tonnage of unmined ore in these tracts is relatively small. The surface area of oxidized iron-formation was determined from the detailed maps of the areas and compared with the ore tonnage:

Area	Area of oxidized iron-formation (square miles)	Tonnage mined (million tons)	Approximate tonnage per square mile (million tons)
Buck	0. 15	22	150
Hiawatha	. 30	25	80
Odgers-Tobin	. 20	14	70

Of the three areas, the Hiawatha, which includes the highly productive Hiawatha and Riverton mines, and the less productive Chatham, Sheridan, Wickwire, and Delta mines, is probably the most nearly representative of the district. If so, then the estimate for the district as a whole (4 sq mi of oxidized iron-formation) is 320 million tons, of which about 180 million tons has been mined. The total remaining, therefore, would be about 140 million tons of shipping-grade ore.

Objection may be raised that the tonnage mined does not fairly represent the amount of ore actually present. This contention doubtless is true to some degree; certainly the addition of unmined and undiscovered ore would increase substantially the amount of ore per unit area. Further objection may be that the ratio of ore to oxidized iron-formation of the areas chosen may be somewhat higher than for the district as a whole. The errors due to these uncertainties would tend to cancel each other. Other uncertainties similarly are both positive and negative in character. On the whole, the estimate of 140 million tons of total minable ore remaining seems a fairly reasonable one. If the 1961 estimate of taxable reserves (52,166,834 tons)—mainly "proved" ore—is subtracted, the resulting figure means that about 90 million tons of shipping-grade ore remains to be discovered.

A rough check on the preceding calculation is provided in the following way. The surface area of caved ground in the well-explored belt of iron-formation extending south from Crystal Falls has been estimated to be 3 percent of the total area of iron-formation. This caved ground represents fairly well the surface area of ore deposits prior to mining, and this surface cut probably is reasonably representative of ore distribution in the district. The iron-formation of the belt is about 50 percent oxidized; so, the ore constitutes 6 percent of the surface area of oxidized iron-formation. If we assume the mean depth for oxidation and ore for the district to be 1,000 feet, and the total area of oxidized iron-formation to be 4 square miles, then the volume of oxidized iron-formation is about 1×10^{11} cubic feet, or about 8×10^{9} tons. If ore constitutes 6 percent of this volume, the total amount of ore originally present in the district was 500 million tons. The figure, though somewhat high, certainly is of the right order of magnitude as compared with the estimate of 320 million tons made on the basis of previous calculation.

OXIDIZED IRON-FORMATION

The area underlain by deeply oxidized Riverton Iron-Formation has been estimated at about 4 square miles. The iron content, in general, is about 35 percent, perhaps somewhat more.

The gross tonnage of oxidized iron-formation, based simply on area, is about a billion tons per hundred feet of depth of rock containing 35 percent Fe or more. In terms of consideration of a possible low-grade ore, however, this figure must be greatly qualified.

About half the total area of oxidized iron-formation is in the western part of the district, west of the Chicagon mine. Throughout this area, the iron-formation is relatively thin (200 ft or less), and it is complexly interfolded with older and younger strata to a greater extent than can be indicated on the maps. Except in a few places, open-pit operations would be hampered by the need for selective mining to avoid contamination by these infolded units.

From the Chicagon mine east to the Fortune Lakes mine the iron-formation is mainly unoxidized as it is in the belt southeast of Alpha. The remaining areas are the northern Crystal Falls belt—from the Fortune Lakes mine east to the Hilltop mine—and the southern Crystal Falls area, from Crystal Falls to Alpha. Both contain long tracts of steeply dipping oxidized iron-formation several hundred to several thousand feet wide. The total surface area of iron-formation is about 2½ square miles, but even in these belts there is a substantial percentage of unoxidized iron-formation, perhaps 25 percent in the northern belt and about 50 percent in the southern belt.

If other economic considerations, such as topographic position, depth of overburden, and inflow of water, are discounted, the surface area of oxidized iron-formation acceptable for open-pit operations on moderate scale is about 1.5 square miles, or about 350 million tons for each 100 feet of depth. If the approximate limit of open-pit mining is 500 feet, the available reserve of oxidized iron-formation (35 percent Fe or more) is about 1,750 million tons.

UNOXIDIZED IRON-FORMATION

About half of the 8.7 square miles of iron-formation exposed at bedrock surface is unoxidized and consists mainly of interbedded siderite and chert, with an iron content of about 25 percent. Some of this total surface area occurs in relatively small sporadically distributed strips and patches. As previously described, however, most of it is found in four separated areas: (1) the westernmost part of the district, west of the Hiawatha mine, (2) the southern flank of the Iron River-Crystal Falls basin, east of Gaastra, (3) the Fortune Lakes belt, between the Chicagon and Fortune Lakes mines, and (4) the Alpha-Brule River belt in the most southeasterly part of the district. These four areas probably contain 70 percent of the estimated 4.35 square miles of unoxidized iron-formation, or about 3 square miles. This area would be equivalent to about 700 million tons for each 100 feet of depth. To a depth of 500 feet, the available reserve of material containing 25 percent Fe aggregates 3,500 million tons.

The most extensive belt of unoxidized iron-formation is that south of Alpha. The iron-formation in this belt has an average width of 1,000 feet for a linear distance of 5 miles. Dips are steep and folding is minor. The belt contains about 200 million tons for each 100 feet of depth. To a practical mining limit of 500 feet, it contains about a billion tons of carbonate iron-formation containing 25 percent Fe. Most of the belt is topographically high. The proximity of the Brule River, as a source of water, and of the railroad are factors of economic importance should a commercial means be devised for profitable recovery of iron from iron-formation of this type.

SUMMARY OF RESERVE ESTIMATES

The estimates of tonnages of ore and other categories of iron-rich rock are summarized as follows:

	Gross tons
Direct-shipping ore:	
Tax estimate, 1961 (mainly "proved" ore)	52, 166, 834
Estimated total reserve	140, 000, 000
Oxidized iron-formation (35 percent Fe or more):	
Gross tonnage, per 100 ft of depth	1, 000, 000, 000
Estimated tonnage of rock available for open-pit mining, per 100 ft of depth	350, 000, 000
Unoxidized iron-formation (25 percent Fe):	
Gross tonnage, per 100 ft of depth, in four principal areas	700, 000, 000
Tonnage in most favorable area, to 500 ft of depth	1, 000, 000, 000

ORE IN THE AMASA FORMATION

The iron-rich Amasa Formation, within the map area of the Iron River-Crystal Falls district, is a nearly vertical bed that is at bedrock surface for a linear distance of 5 miles, with an average width of more than a quarter of a mile. Ore has been produced from six mines, mostly prior to 1914. The aggregate production was 962,667 tons, of which 713,395 tons was from the Armenia mine.

Little is known of the detailed stratigraphy and original character of the Amasa Formation, and even less is known of the character and geologic occurrence of ore. Substantial parts of the formation consist of magnetite (or martite) slate, and the ore-bearing unit appears to have been a bed of cherty iron-formation approximately in the middle of the formation.

As seen on the mine dumps and underground in the short-lived (and probably atypical) Cayia mine, the ore is similar in general aspect to the ores of the Riverton Iron-Formation—soft fine-grained red to yellow iron oxides, chiefly. The analysis of the 1913 shipments of the Armenia mine is as follows (Lake Superior Iron Ores, 1938, p. 144):

	Dry	*Natural*
Fe	57.30	51.25
P	.320	.286
SiO_2	8.56	7.66
Mn	.58	.52
Al_2O_3	2.45	2.19
CaO	1.16	1.04
MgO	.74	.66
S	.008	.007
Loss on ignition	3.85	3.44
Moisture	------	10.55

The ore from the Armenia and from other mines in the belt is distinctly lower in phosphorus and sulfur content, and higher in moisture content, as compared with most ores from the Iron River-Crystal Falls district proper. Doubtless these differences reflect differences in the original iron-formations.

No basis is available for an estimate of reserves of direct-shipping ore in the Amasa Formation, but they probably are small. The formation itself, at least the iron-formation part, conceivably is of interest as a source of low-grade ore. Most of this rock, as recorded in drill records and seen on mine dumps, in test pits, and bordering mine caves, is chert interlayered with red and yellow oxides. The iron content of sludge from drill holes as recorded in company files is generally 30 percent Fe or greater. Again, however, too little is known of the stratigraphy of the formation to make an estimate of possible tonnage worthwhile.

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