Mineral-Resource Assessment of the Iron River 1° x 2° Quadrangle, Michigan and Wisconsin

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ABSTRACT

The Iron River 1° x 2° quadrangle contains identified resources of copper and iron. Copper-rich shale beds in the north part of the quadrangle contain 12.2 billion pounds (5.5 billion kg) of copper in well-studied deposits including 9.2 billion pounds (4.2 billion kg) that are economically mineable by 1980 standards. At least several billion pounds of copper probably exist in other parts of the same shale beds but not enough data are available to measure the amount.

A small amount, about 250 million pounds (113 million kg), of native copper is known to remain in one abandoned mine, and additional but unknown amounts remain in other abandoned mines.

About 13.25 billion tons (12.02 billion t) of banded iron-formation averaging roughly 30 percent iron are known within 500 feet (152.4 m) of the surface in the Gogebic, Marquette, and Iron River-Crystal Falls districts. Some, probably small, percentage of that might someday be mineable as taconite, but none is now believed to be economic. Some higher grade iron concentrations exist in the same iron-formations. Such material was the basis of former mining of iron in the region, but a poor market for such ore and depletion of many deposits has lead to the decline of iron mining in the quadrangle. No iron mines of the quadrangle were being worked in 1981.

Many parts of the quadrangle contain belts of favorable host rocks for mineral deposits. Although no deposits are known in these belts, undiscovered deposits of copper, zinc, lead, silver, uranium, phosphate, nickel, chromium, platinum, gold, and diamonds could exist.

INTRODUCTION

The Iron River 1° x 2° quadrangle is bounded by lat 46° and 47° N. and long 88° and 90° W., and includes several major mining districts, which have produced large amounts of copper and iron. At present, only the White Pine mine remains active, where copper is recovered from an extensive unit of copper-rich shale. In the past, a large number of mines, which are now abandoned, produced native copper. Parts of three major iron-mining districts, the Marquette Range, Gogebic Range, and Iron River-Crystal Falls district, are in the quadrangle. All have produced large amounts of iron ore but are now inactive 1/. Large quantities of mineralized rock remain in the ground, mostly in subeconomic form, but changes in price, mining and processing technology, or demand could revitalize mining.

In addition, many parts of the quadrangle are judged to be favorable ground for undiscovered mineral deposits. Much exploration by the mining industry was carried out during the 1970's and a high level of exploration activity is likely to continue into the 1980's. Such exploration could expectably lead to the discovery of additional deposits or districts.

Although present mineral production is relatively small, about 150 million pounds (68 million kg) or less of copper per year, the potential for future mineral production is great. The mineral potential of the quadrangle should enter into economic and land-use planning for the region and into considerations of future mineral supplies for the United States.

1. Mining is still being done in the Marquette Range, east of the Iron River quadrangle.

This report summarizes a mineral-resource appraisal of the quadrangle carried out by a team of geoscientists from the U.S. Geological Survey (USGS) between 1977 and 1980 as part of the Conterminous United States Mineral Assessment Program (CUSMAP). During that period much new information was gathered and older data were compiled and evaluated. All data were then considered in order to estimate the known mineral resources of the quadrangle and the potential for the existence of undiscovered resources.

The report discusses the philosophy and techniques of resource assessment and summarizes findings and conclusions about the mineral resources of the quadrangle. More detailed technical information will be presented in the Iron River CUSMAP folio, a set of 14 maps which will be available in 1983.

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MINERAL-RESOURCE TERMINOLOGY

Mineral resources are naturally occurring concentrations of materials that are useful to man, and which can be economically extracted now or potentially in the future. Resources, in their broadest sense, include all such existing concentrations, whether or not they have yet been discovered. Mineral resources can be broadly classified, therefore, into identified resources, those which have been discovered, and undiscovered resources, those which reasonably may exist, but which have not yet been found. Identified resources are further subdivided into reserves, material which is presently profitable to mine, and subeconomic resources, material which requires some increase in price, or improved mining or processing technology to become economically mineable.

Undiscovered resources are subdivided into hypothetical resources, material yet to be found in known mining or mineralized districts, and speculative resources, deposits in yet unrecognized districts or yet unrecognized types of deposits. The classification of mineral resources is discussed in detail in USGS Circular 831 (U.S. Bureau of Mines and U.S. Geological Survey, 1980). A simplified version of that classification system is used here (see fig. 1), and the definition of categories as they apply to the Iron River quadrangle is given below.

Identified resources--Concentrations of elements known to exist in specific locations. Information on their existence and nature is derived from direct observations of mineralized rock at the earth's surface, in drill holes, or in mine workings. In general, enough information exists to make at least semi-quantitative estimates of the tonnage and grade of mineralized rock.

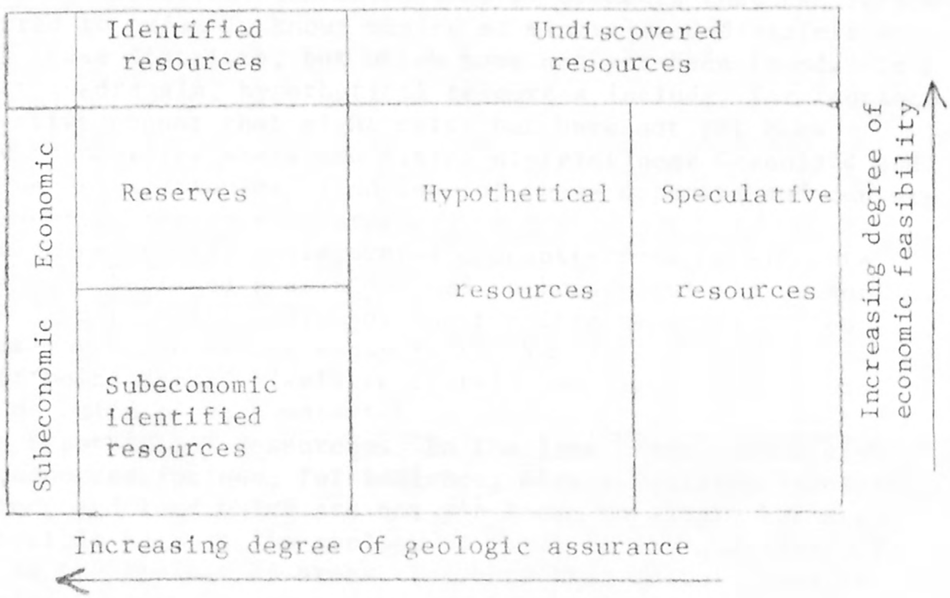

Figure 1.--Classification of resource categories as used in this report. Modified from U.S. Bureau of Mines and U.S. Geological Survey (1980).

Reserves--An identified resource which has been thoroughly measured and tested and which is known with reasonable certainty to be economically exploitable with current technology and economic conditions. The copper-rich shale at the White Pine orebody is the only material in the Iron River quadrangle classed as a reserve in this report.

Subeconomic resources--That portion of identified resources which is not economically exploitable at present. Future increases in price or cost savings from improved mining or processing technology may convert subeconomic material to the reserve category.

Hypothetical resources--Concentrations of elements that can reasonably be inferred to exist in known mining or mineralized districts or extensions of those districts, but which have not yet been found. In the Iron River quadrangle, hypothetical resources include, for instance, deposits of native copper that might exist but have not yet been discovered in or near the abandoned mining district near Greenland and Winona. Future exploration may find some of these deposits and convert them to the identified-resource category.

Speculative resources--Undiscovered concentrations of elements whose existence is believed possible based on broad geologic reasoning but for which no direct indication of their existence has been found. No deposits of the elements are known in the immediate vicinity. Exploration of belts deemed likely to contain speculative resources may discover deposits of such materials and thereby convert them to identified or hypothetical resources. In the Iron River quadrangle, speculative resources include, for instance, massive-sulfide deposits of copper, zinc, and lead which are not yet known to exist, but are considered possible because the geology of parts of the quadrangle is very similar to the geology of areas elsewhere that contain massive-sulfide deposits.

MINERAL-RESOURCE ASSESSMENT TECHNIQUES

Mineral-resource assessment is the quantification and estimation of the amount and nature of potentially useful minerals and the identification of areas where resources exist or may exist. Assessment is based on data from many sources including geologic mapping, geochemical and geophysical surveys, studies of ore-forming processes, and the distribution patterns of ore deposits and their size and grade in well-explored mining districts.

The objective of the Iron River CUSMAP project has been to assemble the best possible and most up-to-date data base on which to make a resource assessment. It must be understood, however, that such data are never complete and commonly are not totally diagnostic of the presence or lack of mineralization. Any resource appraisal is a state-of-the-art estimate and subject to revision and reevaluation as more data are obtained and better understanding of ore-forming geologic processes is achieved. The assessment presented here is based on our knowledge in 1981.

Judgement is an important factor, especially in estimating undiscovered resources, and it should be expected that somewhat different assessments would be made by different individuals using the same data.

In short, a mineral-resource assessment must be viewed as an estimate. The accuracy of the estimate reflects the quality and amount of data available and the degree of understanding of the geologic occurrence of ore deposits and the processes that formed them. It should be expected that future exploration and research will provide new data and insights that will allow improved estimates to be made.

Assessment of Identified Resources

The assessment of identified resources is relatively straightforward. It is based on data directly indicating the tonnage, grade, and location of mineralized rock. Calculations and estimates of tonnage and grade can be made from available data, and the degree of certainty of the assessment commonly can be expressed in quantitative or qualitative terms.

In the Iron River quadrangle, identified resources include the copper-bearing shale in and around the White Pine orebody, native copper in and near the Greenland and Winona mining districts, and iron in banded iron-formation in the Gogebic, Marquette, and Iron River-Crystal Falls districts. All areas of identified resources have had either past mining or have been rather thoroughly tested by mining company drilling programs. Those companies have generally made much information available to use in evaluation of the resources.

Assessment of Undiscovered Resources

The assessment of undiscovered resources is an estimation generally based on an analogy between the geologic setting of well-known deposits or districts throughout the world and the geologic setting of the area being assessed. As suggested and portrayed on the resource map (fig. 2), undiscovered resources are probably restricted to certain belts or zones. Furthermore, only those zones at or near enough to the earth's surface in areas that contain deposits, which are likely to be discovered, are shown. Hence, the zones having a potential for undiscovered resources might be viewed as those areas where mineral exploration is most likely to occur and where discoveries might be made. As such, the assessment is a prediction of future events--mineral exploration and possible discovery of deposits that might occur. As a prediction, it is subject to uncertainty and error but should be considered in planning.

Mineral deposits can be grouped into genetic types, placing together all deposits that have formed as a result of similar processes, regardless of their location. For each type of deposit, a genetic model can be developed to describe the process or set of processes that operated in the geologic past to form the type of deposit. A set of features recognizeable in rocks and deposits caused by those processes can be defined. Such processes commonly operated over a larger area than just within the ore deposit and therefore have recognizable features that provide a larger target for mineral exploration than does the deposit itself. Recognition of the features indicative of ore-forming processes may lead to the supposition that an orebody could exist nearby, even though it may not be observable at the surface.

Furthermore, ore-forming processes commonly take place in a broader geologic framework. For instance, processes that may form one genetic type of ore deposit may occur only in volcanic regions, whereas processes that form a second type may occur only along marine shorelines. The presence and recognition of rocks formed in such widespread environments provides a regional framework for resource assessment.

As an example of how such reasoning leads to a resource assessment, let us examine a specific case.

Massive-sulfide deposits are ores of copper, zinc, lead, and various byproducts. Such ores are common in many parts of the world, and thorough study of them on a worldwide basis reveals striking similarities in the way that they formed and in the types of rocks that commonly surround them.

It is generally agreed that many massive-sulfide deposits form on the sea floor by crystallization of material from fluids emitted by submarine hot springs in areas of volcanic activity. Such deposits commonly are interlayered with submarine volcanic and sedimentary rocks, near ancient volcanic vents. The vent areas are recognized by characteristic textures preserved in the rocks.

No massive-sulfide deposits are known in the Iron River quadrangle, but some have recently been discovered as little as 20 miles (32 km) south of the quadrangle. To determine if undiscovered massive-sulfide deposits might exist in the Iron River quadrangle, one first looks for areas that contain submarine volcanic rocks because massive sulfides might have formed in the general environment where such rocks formed. Submarine volcanic rocks are found in several belts in the south half of the quadrangle, and these belts are judged to have at least broad favorability for the occurrence of massive sulfides.

Each volcanic belt is then examined in more detail to determine if areas within it can be identified as having been near volcanic vents. If such vent areas can be identified, they are considered to have even higher potential than the volcanic belts in general because rocks within them have formed not only in a generally favorable setting, but in the specific part of that setting where massive sulfides typically have formed elsewhere in the world. Within identified vent areas, further examination might reveal features directly indicative of ore-forming processes, or geochemical or geophysical measurements may suggest that ore is buried beneath the surface. In some cases, mineralized rock might be directly observed, but such is not likely to be the case in the Iron River quadrangle because most bedrock is covered by a veneer of glacially-transported sand and gravel.

Using evidence and reasoning such as this, various parts of the quadrangle are classified as being broadly favorable for mineral occurrence (class C areas of this report). Parts of some class C areas are given additional importance because rocks within them are known to have formed in specific environments where ore might have formed (class B areas). Parts of some class B areas are further identified as having experienced potentially ore-forming processes (class A areas).

The ability to classify areas in this manner is limited by the amount of geologic information on the area and by the detail known and assurance about the mode of origin of a genetic type of deposit.

In many parts of the Iron River quadrangle, knowledge of the bedrock is not detailed because of the cover of sand and gravel. Hence, the information required to define class A and B areas commonly is lacking, and most areas of undiscovered resources can only be identified as class C. Likewise, incomplete understanding of the mode of origin of some genetic types of deposits does not allow the definition of criteria specific enough to differentiate class A or B areas from the general belts of class C favorability. As a result, many favorable belts in the Iron River quadrangle are classified only as class C. It is likely that within these belts the lack of class A or B zones in the present assessment may reflect the lack of information more than the absence of mineralization.

CLASSIFICATION OF RESOURCES IN THE IRON RIVER QUADRANGLE

The Iron River quadrangle has been zoned into seven categories of resource potential as shown in figure 2.

Identified Resources

Identified resources are known deposits whose location can be shown on a map and for which some information on size and grade exists. Three categories of identified resources are used in this report:

1) Reserves--Known concentrations of materials economically exploitable in 1980.
2) Outcrop belts of mineralized strata--Areas in which continuously or discontinuously mineralized rock is exposed or exists in the shallow subsurface.
3) Subsurface mineralized rock--Areas in which mineralized rock is known to exist underground but is overlain by unmineralized rock. These are, in general, the subsurface extensions of outcrop belts of mineralized rocks.

Undiscovered Resources

Undiscovered resources are deposits likely to exist but not yet discovered. They, of course, cannot be shown on a map. Rather, areas can be shown for which varying degrees of favorability for the discovery of such deposits can be inferred. It is important to note that the zones shown in figure 2 are belts in which potentially mineralized rock is at or very near the surface and that contained deposits could be found by standard exploration techniques. Such potentially mineralized rocks generally extend into the subsurface away from their outcrop belts, but these subsurface extensions are not shown in figure 2. Although the rocks in the subsurface may be as likely to be mineralized as those at the surface, deposits that might exist at deep levels are not likely to be discovered in the near future.

Areas are broadly classified as favorable and unfavorable.

Unfavorable areas--Areas for which no strong indications of economic minerals occur either directly or by an analogy with known deposits elsewhere. Unfavorable areas contain types of rocks in which few, if any, important ore deposits occur anywhere in the world. It should be pointed out, however, that no area can be considered totally unfavorable. Additional knowledge, discovery of new classes of deposits, or future needs for minerals not currently in demand could cause areas now considered unfavorable eventually to be reclassified as favorable.

Favorable areas--Areas where some indication, either direct or indirect, of undiscovered mineral deposits is known. Favorable areas are here subdivided into three categories.

Class C areas are those areas for which geologic evidence indicates a general environmental setting where mineral deposits could occur, but no direct evidence of mineralization is known.

Class B areas are those areas where the contained rocks represent the specific parts of the generally favorable environment where mineral deposits could have formed and, hence, have a higher favorability than class C areas.

Class A areas, the most favorable areas, are areas where actual mineralizing processes are known to have occurred. Whether those processes formed ore anywhere is not necessarily known.

MINERAL RESOURCES OF THE IRON RIVER QUADRANGLE

Figure 2 shows areas of the Iron River quadrangle where resources are known to exist or thought likely to exist, and table 1 summarizes the resources of the quadrangle. The resources are discussed separately in identified, hypothetical, and speculative categories.

Identified Resources

Copper--Zones Cu_1 through Cu_5 contain identified copper resources. Zone Cu_1 is the area underlain by the reserves of the White Pine mine. The reserves, for the most part, are in the deep subsurface. The material classed as reserves has an average grade of 1.2 percent copper, a cut-off grade of 1.0 percent copper, and minimum mining height of the mineralized layer of 7.5 feet (2.3 m). The deposit is a gently dipping layer of copper-rich shale extending from the surface to considerable depth, the deepest parts being toward the east. The deposit contains 360 million tons (327 million t) of ore and about 9.2 billion pounds (4.2 billion kg) of copper. Copper is contained in both sulfide minerals and native copper. Small quantities of silver are also in the ore. Part of the silver is recovered as a separate product during refining.

Zone Cu_2 is the belt along which the copper-bearing shale is at or near the surface. Although it is generally mineralized, it is not economic because it has lower grade, is in thinner beds, or is more difficult to mine than the material that constitutes the White Pine reserve.

Table 1.--Mineral resources of the Iron River quadrangle

1. Reserves
   a. Copper
      White Pine orebody--9.2 billion pounds (4.2 billion kg) sulfide and native copper.

2. Subeconomic identified resources
   a. Copper
      Presque Isle deposit--2.7 billion pounds (1.2 billion kg) native and sulfide copper.
      Caledonia mine--250 million pounds (113 million kg) native copper.
      Extensions of mineralized bed at White Pine--Probably at least several billion pounds sulfide and native copper.

   b. Iron
      Banded iron-formation within 500 feet (152.4 m) of the surface containing an unknown percentage of potential taconite bodies.
      Marquette range--1.5 billion tons (1.4 billion t) iron-formation.
      Gogebic range--10 billion tons (9 billion t) iron-formation.
      Iron River-Crystal Falls--1.75 billion tons (1.59 billion t) iron formation.

3. Hypothetical resources (not quantified)
   a. Copper
      Native copper in extensions of Greenland and Winona districts.
   b. Iron
      High-grade iron ore in Marquette, Gogebic, and Iron River-Crystal Falls districts.

4. Speculative resources
   Copper, zinc, lead, silver, gold, platinum, chromium, nickel, cobalt, uranium, phosphate, and diamonds could possibly exist in many belts of favorable host rocks in the quadrangle.

Zone Cu_3 consists of areas where the copper-rich shale is known from drilling to exist in the subsurface. None is now economic because of low grade, thin beds, or mining problems including great depth. An area peripheral to the White Pine reserve is probably close to being economic. The material in the Presque Isle deposit, including belts Cu_2 and Cu_3, is also close to being economic. The Presque Isle deposit is estimated to contain 95 million tons (86 million t) of ore with an average grade of 1.27 percent copper, totaling about 2.7 billion pounds (1.2 billion kg) of copper (Wilband, 1978). The remaining areas of Cu_3 are conservatively estimated to contain at least several billion pounds of copper.

Zone Cu_4 contains volcanic rocks (basalt) that are mineralized with native copper. Many inactive mines are in the area. An unknown amount of mineralized rock of subeconomic grades is still in the ground at some mines and additional mineralized rock may yet be found in the belt. At the Caledonia mine, about 11.5 million tons (10.4 million t) of rock having an average grade of 1.1 percent copper is known to remain in the ground (Wilband, 1978). The discontinuously mineralized rock of Cu_4 forms a thick slab inclined northward so that it continues in the subsurface north of the outcrop belt.

Zone Cu_5 is the extension of known mineralized rock at depth from Cu_4. Its northern limit is defined approximately by the limit of data from mine workings and drilling, but mineralization may extend downward and northward beyond the deepest data points.

Iron--Very large quantities of iron-rich rocks exist in the quadrangle. All those of potential resource importance are banded iron-formations. Production of ore between 1872 and 1978 totalled about 210 million tons (191 million t), mostly from the Iron River-Crystal Falls district. All of that production was of relatively high-grade ore (generally 50-60 percent iron), which occurred as irregular bodies within lower grade iron-formation having about 30 percent iron. Since the 1950's, the production of iron in the United States has shifted away from the use of natural high-grade ores to pelletized iron concentrates produced from iron-formation containing about 30 percent iron, commonly called taconite. As a consequence, the market for high-grade ores has greatly diminished and exploration for new deposits has virtually ceased in the area.

Although most of the iron-formation in the Iron River quadrangle does contain 30 percent or more iron, none now is commercially workable as taconite. Various problems, including thinness of iron-formation layers, steep dips, and large amounts of waste rock above and interlayered with the taconite, make it difficult to mine profitably large tonnages of ore from open pits as taconite must now be mined. In addition, the mineralogic complexity of much of the iron-formation makes most of it untreatable with current metallurgical concentrating processes.

Zones Fe_1 - Fe_7 contain identified resources of iron. The iron resource potential of these zones is shown in figure 2 and described briefly below.

Areas in which iron-formation exists in the subsurface are of little short-term resource importance. Although they could contain undiscovered deposits of high-grade ore, the present poor market for such ores make it unlikely that subsurface iron deposits will be explored for and found in the foreseeable future. Some of the material could be used as taconite but would not be commercially mineable unless mining technology were improved so that underground mining became economically competitive with open-pit mining.

Such areas could have some resource importance sometime in the 21st century if near-surface iron deposits now being exploited elsewhere become depleted and if improved mining and metallurgical technology permit their mining and processing.

The two areas having the best potential for taconite are probably zones Fe_1 and Fe_2 in the western part of the Marquette Range. Both areas contain substantial amounts of iron-formation very similar to that now being mined at the Republic mine only about one mile (1.6 km) east of the quadrangle.

Zone Fe_1 is the outcrop belt of iron-formation in the western Marquette Range. There has been some past production of high-grade ore. Parts of the formation may be amenable to treatment as taconite. About 0.75 billion tons (0.68 billion t) of iron-formation are within 500 feet (152.4 m) of the surface. About 250,000 tons (227,000 t) of that contain a mineralogic makeup that may be treatable with existing concentration processes. The deposits of the western Marquette Range are probably not economic now because of the thinness of iron-formation layers and relatively large amounts of waste rock that would have to be moved to recover the iron-formation.

Zone Fe_2 is a second outcrop belt of iron-formation having some taconite potential in the western Marquette Range. The tonnages of available rock are about the same as for zone Fe_1 and development of the area faces the same problems.

Zone Fe_3 is the outcrop belt of iron-formation in the Gogebic Range. The area has had some past production of high-grade ore. Some high grade ore may remain to be found. The areas contains about 10 billion tons (9 billion t) of iron-formation within 500 feet (152.4 m) of the surface. Some of that material might be useful as taconite in the future if metallurgical improvements allow treatment of the mineralogically complex iron-formation.

Zone Fe_4 is the outcrop belt of iron-formation in the Iron River-Crystal Falls district. The area has had a large production, about 210 million tons (191 million t), of high-grade ore. James and others (1968) estimated that about 50 million tons (45 million t) of identified ore remain in the ground and that about 90 million tons (82 million t) of undiscovered ore exist. About 1.75 billion tons (1.59 billion t) of iron-formation are within 500 feet (152.4 m) of the surface (James and others, 1968), but this material has very little taconite potential because of mining problems and unsuitable mineralogy.

Zone Fe_5 is the subsurface extension of iron-formation of the Gogebic Range projected to about one-mile (1.6 km) depth. The iron-formation has some potential for high-grade ores and very limited short-term potential as taconite.

Zone Fe_6 is the subsurface extension of the iron-formation of the Marquette Range to a depth of about one mile (1.6 km). The iron-formation contains some potential resources of high-grade ore and, largely because of depth, has very small potential as a resource of taconite.

Zone Fe_7 is the subsurface extension of the iron-formation of the Iron River-Crystal Falls district to a depth of about one mile (1.6 km). The material probably contains undiscovered deposits of high-grade ore but has very limited taconite potential because of depth and unsuitable mineralogic form.

Hypothetical Resources

Hypothetical resources, undiscovered deposits in known mineral districts, as shown in figure 2 are restricted to parts of the native-copper district and the iron-mining districts.

Copper--Zone Cu_6 in figure 2 is the extension along the geologic trend of the same rocks that are mineralized in belts Cu_4 and Cu_5, but only minor (subeconomic) mineralization is known. A high potential for undiscovered native copper and perhaps sulfide copper is indicated by strong similarities in nearly all details between these rocks and the mineralized rocks in zones Cu_4 and Cu_5. Areas of subeconomic mineralization are widespread. A high copper content of soils overlying these rocks, especially in the western part of the quadrangle, is another favorable sign.

Zone Cu_7 contains volcanic rocks that are in many ways similar to those in zones Cu_4 and Cu_5, but that differ in some important details, relating principally to composition of the rocks. No substantial copper mineralization is known. Undiscovered native copper deposits could exist but seem less likely than in zone Cu_6.

Iron--Undiscovered deposits of iron ore could exist in any of zones Fe_1 through Fe_7, all within or extensions of past mining districts. Such ores are of limited importance in the short-term and are not likely to be explored for in the foreseeable future.

Speculative Resources

Speculative resources are those that possibly exist, but which, if found, would be a new type of deposit for the region. Several genetic types of speculative resources are discussed here. They are the ones judged most likely to occur. Other types, not discussed, could also occur, but, at present, either are judged to have insufficient potential to enter into near-term resource considerations, or to have not yet been recognized as possible resources.

Volcanogenic massive-sulfide deposits--Volcanogenic massive-sulfide deposits occur in submarine volcanic rocks and generally near centers of volcanic activity. Massive sulfides are generally polymetallic ores, which may be mined for copper, lead, zinc, silver, and gold. Areas designated Ms_1 in figure 2 are zones where ancient submarine volcanic rocks are at the bedrock surface and are considered favorable for massive sulfides. In most areas, however, the bedrock is so poorly exposed that few details of the volcanic rocks are known; the belts are defined as class C areas and cannot be further subdivided.

Zone Ms_2 is a thick unit of submarine volcanic rocks that is considered to be a class B area because it appears to have formed near a volcanic center and, in addition, causes several distinctive geophysical anomalies (electromagnetic conductors) that could result from massive-sulfide deposits in the subsurface.

Zone Ms_3 is a belt of submarine volcanic rocks about which few details are known, but which is ranked class B because geophysical anomalies there could be caused by massive-sulfide deposits in the subsurface.

Zone Ms_4 is a small belt west of Lake Gogebic that is ranked class A because it shows geophysical anomalies and contains favorable rock types and also subeconomic copper and zinc mineralization.

Sediment-hosted sulfide deposits--Several types of sediment-hosted sulfide deposits are possible in the quadrangle and could contain ores of copper, zinc, lead, silver, or gold.

Carbonate-shale hosted deposits--About 30 miles (48 km) east of the quadrangle, near Marquette, Mich., a large subeconomic copper-sulfide deposit, estimated to contain one billion tons (0.9 billion t) of mineralized rock (Wilband, 1978), occurs in shale beds in a generally dolomitic rock unit. Extensions of the dolomite unit are known in several parts of the quadrangle. Areas containing the dolomite are ranked class C and shown as zones Ss_1 on the map. Zone Ss_2 is ranked class B because geophysical anomalies indicate that subsurface rocks contain either extensive shale beds within the dolomite or possibly sulfide-rich beds. Zone Ss_3 is a small area ranked class A because it contains an outcrop of mineralized bedrock. Copper-sulfide minerals occur in quartzite beds that are interlayered with dolomite. Grades are locally as high as 1 percent copper (Cannon, 1980).

Shale and iron-formation hosted deposits--Several areas contain shale and interbeds of iron-formation, zones Ss_4 in figure 2. Many of these areas are very poorly known because of the scarcity of bedrock exposures but are judged to be potential hosts for sulfide deposits of copper, zinc, and lead. Some low-grade mineralization (generally less than 0.1 percent copper plus zinc) is known locally, and undocumented verbal reports from mining companies indicate discoveries of subeconomic sulfide deposits. Some carbonate-hosted deposits such as those of zones Ss_1 are also possible within the Ss_4 zones.

Volcanic-sediment association--Massive and disseminated sulfide deposits sometimes occur at the fringes of submarine volcanic zones where the volcanic rocks are interlayered with submarine sedimentary rocks. Zone Ss_5 is assigned class C favorability because it contains interlayered volcanic rocks, shale, graywacke, and iron-formation. No direct signs of mineralization are known. Zone Ss_6 is given class A favorability. It contains rocks similar to zone Ss_5, but, in addition, is known to contain sulfide-rich rock units that have subeconomic concentrations of copper and zinc.

Deposits associated with mafic intrusive rocks--Igneous rocks that have undergone strong chemical fractionation as they crystallized from a molten to solid state may contain concentrations of copper, nickel, cobalt, chromium, or platinum. Such strongly fractionated mafic rocks exist in a few places in the quadrangle, but no mineralization is known in them. Zones Mi_1 are areas where such rocks are known. Zones Mi_2 contain rocks formed in that part of the mafic fractionation sequence in which mineral deposits are most likely to occur. They are assigned class B favorability.

Unconformity uranium deposits--During the 1970's some very rich uranium deposits, some also containing nickel and gold, were discovered along ancient erosion surfaces (unconformities) in Australia and Canada. The unconformity extending across the quadrangle from near the northeast corner to Wakefield has many features in common with those uranium-bearing unconformities. In the late 1970's, many mining companies explored for uranium along the unconformity in the Iron River quadrangle. A broad belt parallel to and including the unconformity (Uu_1) is given class C favorability because of similarities of the geology there to that of mineralized unconformities. A zone east of Lake Gogebic (Uu_2) is given class B favorability because it contains some of the specific features directly associated with mineralization elsewhere (as noted in the explanation, fig. 2).

Uranium-iron association--In the Iron River-Crystal Falls district, concentrations of uranium were discovered in several places at the fringes of iron-ore bodies in the Sherwood and James mines (James and others, 1968). These deposits are of small size and subeconomic grade. Consequently, the belts in which the iron ores of the district occur (zones Fe_4 and Fe_7) are considered to have class C favorability for uranium.

Uraniferous phosphate deposits--In 1976, small deposits of phosphate-rich rock, some with small concentrations of uranium, were discovered at several localities in the northeast part of the quadrangle (Cannon and Klasner, 1976b). Since then, additional low-grade occurrences have been found in the Gogebic Range. All known deposits are very near (within a few hundred feet) the unconformity separating very ancient crystalline rocks from somewhat younger metasedimentary rocks. That unconformity is shown, wherever it is known to exist, in figure 2, and a class C favorability belt is considered to exist along it, although that belt is too narrow to show at this scale.

Silver-bearing shale--A belt of black shale and slate in the northeast part of the quadrangle (zone Ag) contains unusually high concentrations of silver, which, in places, are accompanied by molybdenum. Soil overlying these rocks commonly is also silver-rich. Although these rocks are far from being economically exploitable for silver, or molybdenum, they are considered to have class C favorability for silver or molybdenum deposits, because within the shale belt, some process locally might have further concentrated the widespread high silver and molybdenum values to potentially economic levels.

Diamond--About 15 miles (24 km) northeast of Crystal Falls, a small body of kimberlite was recently discovered (Cannon and Mudrey, 1981). Kimberlite is a rare type of rock and is the only natural source of diamonds. About one kimberlite body in 10 contains diamonds. Only one kimberlite occurrence is known in the quadrangle, but it is likely that others exist nearby, so possibly diamond-bearing rocks exist in the quadrangle.

CONCLUSION

The Iron River quadrangle is part of a mineral-rich region that contains large identified deposits, which are currently or potentially economic to mine. In addition, large areas of promising ground for exploration exist, and future discoveries of presently unknown deposits are possible. Despite the relatively low level of mining in the quadrangle in 1981, the Iron River quadrangle has the potential to produce large amounts of minerals in the future.

Within the quadrangle, about 12.2 billion pounds (5.5 billion kg) of copper are known to exist in well-studied deposits. Material that is presently economic includes 9.2 billion pounds (4.2 billion kg) of copper in the White Pine orebody. It is likely that at least several billion additional pounds are in known mineralized rocks in areas where data do not allow quantification.

About 13.25 billion tons (12.02 billion t) of banded iron-formation are estimated to exist within 500 feet (152.4 m) of the surface in three principal mining districts, the Marquette, Gogebic, and Iron River-Crystal Falls districts. Some, probably small, percentage of that material might someday be mineable as taconite if improved mining or metallurgical technology or increased iron prices permits profitable extraction of iron.

Possibly, parts of the quadrangle contain undiscovered deposits of copper, zinc, lead, silver, uranium, phosphate, nickel, chromium, cobalt, platinum, gold, and diamonds. Future exploration seems likely to find some of these and add to the known mineral wealth of the region.

ANNOTATED SELECTED REFERENCES

The following references were selected from among a great many publications on the Iron River region because they are considered principal references on the geology of certain areas or certain problems or bear directly on ore deposits and mineral resources of the quadrangle. Each reference includes a brief annotation which indicates the nature of material presented in the publication.

Allen, R. C., 1910, The Iron River iron-bearing district of Michigan: Michigan Geological and Biological Survey Publication 3, Geological Series 2, 151 p.
Discussion of the iron resources in the Iron River district of Michigan, including maps of individual mines. Also discussion of geology of this district, including a geologic map at scale 1:2640 (2 inches = 1 mile).

__________ 1912, Mineral resources of Michigan with statistical tables of production and value of mineral products for 1910 and prior years: Michigan Geological and Biological Survey Publication 8, Geological Series 6, 456 p.
Discussion of mineral resources of Michigan, statistics of mining industry, and production, including copper and iron. Includes maps of mine locations and yearly production of individual mines.

__________ 1920, Mineral Resources of Michigan with statistical tables of production and value of mineral products for 1918 and prior years: Michigan Geological and Biological Survey Publication 29, Geological Series 24, 200 p.
Discussion of metallic mineral resources, copper and iron, and a statistical review of iron ore shipments by districts from 1905 to 1918. Discussion of non-metallic minerals, including production tables.

Allen, R. C., and Barrett, L. P., 1915, Contributions to the Precambrian geology of northern Michigan and Wisconsin: Michigan Geological and Biological Survey Publication 18, Geological Series 15, p. 13-164.
Geologic discriptions and magnetic data of the eastern part of the Gogebic Iron Range and several other iron-bearing areas in the western part of the Iron River quadrangle.

Anderson, G. J., 1968, The Marquette district, Michigan, in Ore deposits of the United States, 1933-1967 (Graton-Sales volume): New York, American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., v. 1, p. 507-517.
Discussion of the mining history of the area, the physiographic and geologic history, the econmic geology and the genessis of the ores. Generalized maps and sections, stratigraphic table.

Bailey, S. W., and Tyler, S. A., 1960, Clay minerals associated with the Lake Superior iron ores: Economic Geology, v. 55, no. 1, p. 150-175.
Discussion of the accessory clay-size minerals found in the Marquette, Gogebic, and Iron River districts in Michigan. Differences in assemblages between these and the Mesabi, Cuyuna, and Vermillion district of Minnesota indicate different environments of formation. No maps.

Balsley, J. R., Jr., Davis, F. J., Nelson, R. A., Reinhardt, and P. W., Stead, F. W., 1950, Airborn radioactivity survey of parts of Marquette, Dickinson, and Baraga Counties, Michigan: U.S. Geological Survey Geophysical Investigations Series Map.
A map showing the approximate locations of radioactive anomalies over an area of about 1,600 mi^2, indicating areas in which uranium and thorium may occur. Brief text.

Barghoorn, E. S., Meinschein, W. G., and Schopf, J.W., 1965, Paleobiology of a Precambrian shale: Science, v. 148, no. 3669, p. 461-472.
Studies on the geology, organic geochemistry and paleontology of the White Pine area of Michigan to investigate the problem of detection of ancient life. Deals mostly with the Nonesuch Shale.

Barrett, L. P., 1953, A sampling and radiation analysis of the pre-Cambrian rocks of Michigan, Minnesota, and Wisconsin: U.S. Atomic Energy Commission RME-3032, 15 p.
A brief description of the general geology of the area and a summary of the results of a scintillometer survey and radiologic sampling of the Precambrian formations. Some indications of uranium and thorium were found. A generalized map.

Bayley, R. W., 1959, Geology of the Lake Mary quadrangle, Iron County, Michigan: U.S. Geological Survey Bulletin 1077, 112 p., 7 pls., scale 1:24,000.
Detailed geology of a 7 1/2 - min quadrangle, including descriptions of stratigraphy, structure, magnetic surveys, and economic geology. Geologic and magnetic maps, photos.

Bayley, R. W., Dutton, C. E., and Lamey, C. A., 1966, Geology of the Menominee iron-bearing district, Dickinson County, Michigan, and Florence and Marinette Counties, Wisconsin: U.S. Geological Survey Professional Paper 513, 96 p.
Major references on the geology, structure, and economic geology of an area slightly larger than three 7 1/2 - min quadrangles. Geologic maps and sections, photographs.

Bayley, W. S., 1904, The Menominee iron-bearing district of Michigan: U.S. Geological Survey Monograph 46, 513 p.
Major reference on an area of 112 mi^2 which was one of the major iron ore producers in Michigan. Detailed geology and description of iron ore. Many geologic maps, cross sections and diagrams.

Bodwell, W. A., 1972, Geologic compilation and nonferrous metal potential, Precambrian section, northern Michigan: Michigan Technological University, Houghton, Mich., M.S. thesis, 106 p.
General geology of area with locations of nonferrous-metal occurrences discussed in detail, especially copper, pyrite, uranium and gold. Geologic map and numerous tables.

Books, K. G., 1968, Magnetization of the lowermost Keweenawan lava flows in the Lake Superior area: U.S. Geological Survey Professional Paper 600-D, p. 248-254.
Discusses correlation of magnetization in the lowermost Keweenawan lava flows on opposite sides of Lake Superior. Uses paleomagnetic data and 145 drill core samples. Includes a general geologic map, summary of paleomagnetic data, diagrams of directions of magnetization.

__________ 1972, Paleomagnetism of some Lake Superior Keweenawan rocks: U.S. Geological Survey Professional Paper 760, 42 p.
Discusses natural remanent magnetization of rocks. Paleomagnetic studies were conducted at the Keweenaw Peninsula, Ironwood-Mellen area and north shore of Lake Superior. Includes many equal-area diagrams showing direction of remanent magnetizations.

Brecke, E. A., 1968, Copper mineralization in the upper part of the Copper Harbor Conglomerate at White Pine, Michigan: Economic Geology, v. 63, no. 3, p. 294.
Discussion of color change in shale and limestone and alteration of ferric iron. Attributes change to hydrothermal activity.

Broderick, T. M., 1929a, Zoning in Michigan copper deposits and its significance, part I: Economic Geology, v. 24, no. 2, p. 149-162.
Arsenic occurs in small quantities in all known Michigan copper deposits. The ratio of arsenic to copper increases with depth. One very generalized map, two graphs of arsenic ratios.

__________ 1929b, Zoning in Michigan copper deposits and its significance, part II: Economic Geology, v. 24, no. 3, p. 311-326.
A study of the changes of the ratio of arsenic to copper with depth makes it possible to group formations and predict mineralogical changes likely to occur in mining. It is also possible to extend zones beyond known lode deposits. No map.

__________ 1931, Fissure vein and lode relations in Michigan copper deposits: Economic Geology, v. 26, no. 8, p. 840-856.
A discussion of the relationship of fissure veins to lode formation and application of this relationship to the exploration for new lode deposits of copper.

__________ 1952, The origin of Michigan copper deposits: Economic Geology, v. 47, no.2, p. 215-219.
Brief discussion of the differences of opinion on origin of copper held by author and H. R. Cornwall. See other references by the two authors for more details.

_______ 1956, Copper deposits of the Lake Superior region: Economic Geology, v. 51, no.3, p. 285-287.
A letter in the "Discussion" section, comments on his view that a theory, to be acceptable, must explain all deposits of a district studied. Refers to work done by a USGS team in the Lake Superior region and their proposal of varied modes of origin.

Broderick, T. M., and Hohl, C. D., 1935, Differentiation in traps and ore deposition: Economic Geology, v. 30, no. 3, p. 301-312.
A study of differentiation in Keweenawan lava flows of the Michigan copper district furnishes new data concerning the amounts of copper and its distribution in the traps. No map; a table of sulphur and copper percentages in various rock types.

Broderick, T. M., Hohl, C. D., and Eidemiller, H. N., 1946, Recent contributions to the geology of the Michigan copper district: Economic Geology, v. 41, no. 7, p. 675-725.
A discussion of the general geology of the area, the internal features of the ore bodies, the geologic relations as guides to exploration, and the origin of the deposits. A very generalized map and cross-section and a stratigraphic column.

Brown, A. C., 1968, Zoning in the White Pine copper deposit, Ontonagon County, Michigan: Ann Arbor, Mich., University of Michigan, Ph. D. thesis, 194 p.
Entertainment of the proposal that mineralization of the basal Nonesuch Formation was accomplished by the introduction of copper from Copper Harbor Formation after burial of Nonesuch sediments. Uses infiltration and diffusion models.

_______ 1974, An epigenetic origin for stratiform Cd-Pb-Zn, sulfides in the lower Nonesuch Shale, White Pine, Michigan: Economic Geology, v. 69, no. 2, p. 271-274.
Proposes an epigenetic origin for layers of Cd-Pb-Zn, which requires the metals to be pulsed to a higher level by an influx of cupriferous solution from the underlying strata.

Burnie, S. W., Schwarcz, H. P., Crocket, J. H., 1972, A sulfur isotopic study of the White Pine mine, Michigan: Economic Geology, v. 67, no. 7, p. 895-914.
Discussion on the Nonesuch Shale, including analysis by sulfur extraction, isotopic analysis, carbon analysis and boron analysis.

Butler, B. S., and Burbank, W. S., 1929, The copper deposits of Michigan: U.S. Geological Survey Professional Paper 144, 238 p.
Detailed study of copper deposits in northern Michigan. Includes 27 geologic maps and 16 longitudinal sections. Sections include general features, ore deposits, and detailed descriptions of lodes and fissures.

Cannon, W. F., 1973, The Penokean orogeny in northern Michigan, in Young, G. M., ed., Huronian stratigraphy and sedimentation: Geological Association of Canada Special Paper 12, p. 251-271.
Discussion of the structural style and orogenic sequence of the event known as the Penokean orogeny. Geologic sketch map and numerous cross-sections.

____________ 1976, Hard iron ore of the Marquette Range, Michigan: Economic Geology, v. 71, no. 6, p. 1012-1028.
Discussion of petrology and origin of specularite, clastic, and magnetite ores found in the Marquette Range, Michigan. General geologic map, isometric maps, stratigraphic sections and photos included.

____________ 1977, Map showing Precambrian geology in parts of the Baraga, Dead River and Clark Creek basins, Marquette and Baraga Counties, Michigan: U.S. Geological Survey Open-File Report 77-467, 1 pl, scale 1:62,500.
Detailed geologic map of the area. No text.

____________ 1980, Copper-bearing quartzite near Watersmeet, Michigan: U.S. Geological Survey Open-File Report 80-390, 7 p.
Brief description of a copper occurrence in Precambrian quartzite. Includes assays and two maps.

Cannon, W. F., and Gair, J. E., 1970, A revision of stratigraphic nomenclature for middle Precambrian rocks in northern Michigan: Geological Society of America Bulletin, v. 81, no. 9, p. 2843-2846.
Proposal to introduce the name Marquette Range Supergroup to supplant the term Animikie Series for the middle Precambrian sequence of the Northern Peninsula and areas in Wisconsin. Includes sketch map and stratigraphic correlation chart.

Cannon, W. F., King, E. R., Hill, J. J., and Mory, P. C., 1980, Mineral resources of the Sturgeon River Wilderness Study Area, Houghton and Baraga Counties, Michigan: U.S. Geological Survey Bulletin 1465, 49 p.
Discussion of geology and geophysical interpretations and investigation of known and potential mineral deposits. General geologic maps, aeromagnetic maps, and partial chemical analysis of samples.

Cannon, W. F., and Klasner, J. S., 1975, Stratigraphic relationships within the Baraga Group of Precambrian age, central upper peninsula, Michigan: U.S. Geological Survey Journal of Research, v. 3, no. 1, p. 47-51.
Correlation of units between geographically separated area has been greatly aided by mapping in the Witch Lake 15-min quadrangle. Various iron-formation units can now be correlated. A generalized geologic map and section.

__________________ 1976a, Geologic map and geophysical interpretation of the Witch Lake quadrangle, Marquette, Iron, and Baraga Counties, Michigan: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-987, 1:62,500.
Detailed geologic map of the area, also showing available geophysical information. Brief text on map.

__________________ 1976b, Phosphorite and other apatite-bearing sedimentary rocks in the Precambrian of northern Michigan: U.S. Geological Survey Circular, 746, 6 p.
Brief discussion of occurrences of phosphate with sedimentary rocks in the Precambrian of northern Michigan. Includes a geologic sketch map.

Cannon, W. F., and Mudrey, M. G., Jr., 1981, The potential for diamond-bearing kimberlite in northern Michigan and Wisconsin: U.S. Geological Survey Circular 842, 15 p.

Cannon, W. F., Powers, S. L., and Wright, N. A., 1978, Computer-aided estimates of concentrating-grade iron resources in the Negaunee iron-formation, Marquette District, Michigan: U.S. Geological Survey Professional Paper 1045, 21 p.
Analysis of resource potential and estimation of the maximum amount of recoverable iron via a statistical simulation model. Includes generalized geologic map, numerous histograms, graphs, and charts.

Carpenter, R. H., 1963, Some vein-wall rock relationships in the White Pine mine, Ontonagon County, Michigan: Economic Geology, v. 58, no. 5, p. 643-666.
The dominant facies of copper mineralization at White Pine is characterized by the relationship of copper to sedimentary features and by its restriction to the base of the Nonesuch Shale. A second minor facies is fracture-controlled and of two types: (1) fracture-filled veins, and (2) halos.

Chaudhuri, Sambhudas, and Faure, Gunter, 1967, Geochronology of the Keweenawan rocks, White Pine, Michigan: Economic Geology, v. 62, no. 8, p. 1011-1033.
Report deals with age determinations made by the Rb-Sr method applied to suites of total-rock specimens and isotope analyses of lead from the White Pine copper mine.

Clements, J. M., and Smyth, H. L., 1899, The Crystal Falls iron-bearing district of Michigan: U.S. Geological Survey Monograph 36, 512 p., scale 1:125,000.
A comprehensive report on an area of 1300 mi^2 in northern Michigan describing the geography, geology and mining history. Many detailed geologic maps, cross sections, diagrams and photos.

Cornwall, H. R., 1951, Ilmenite, magnetite, hematite, and copper in lavas of the Keweenawan series: Economic Geology, v. 46, no. 1, p. 51-67.
The opaque minerals in 10 lava flows were studied microscopically and two groups of minerals and their alteration production were distinguished which provide an index to the degree of differentiation of basaltic lavas of the area. No map.

Dutton, C. E., 1949, Geology of the central part of the Iron River district, Iron County, Michigan: U.S. Geological Survey Circular 43, 9 p.
General geology of an area of 5 mi^2. Description of iron-formation, past and present mining and future possibilities. Geologic maps and sections, mine level maps, magnetic data.

____________ 1969, Geology and magnetic data for central Iron River area, Michigan: Michigan Geological Survey Division Report of Investigation 5, 17 p., maps, scale 1:6,000.
Supplements USGS Professional Paper 570 with detailed geology, mines, exploration, and magnetic surveys of the area.

Dutton, C. E., and Bradley, R. E., 1970, Lithologic, geophysical, and mineral commodity maps of Precambrian rocks in Wisconsin: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-631, 6 shts., scale 1:500,000, 15-p. text.
Six maps plus text. Text discusses lithology, aeromagnetic and gravity data, and geology of specific areas as it relates to mineral deposits. Tables show geochronological data and mineral occurrences. Maps show geology, lithology, geophysical data. One map shows mineral localities and metamorphic zones extending into northern Michigan.

Dutton, C. E., and Linebaugh, R. E., 1967, Map showing Precambrian geology of the Menominee iron-bearing district and vicinity, Michigan and Wisconsin: U.S. geological Survey Miscellaneous Geologic Investigations Map I-466, scale 1:125,000.
Map of an area of about 1000 mi^2 showing geology and iron-bearing formations. No text.

Ensign, C. O., Jr., and others, 1968, Copper deposits in the Nonesuch Shale, White Pine, Michigan, <u>in</u> Ore deposits of the United States, 1933-1967 (Graton-Sales volume): New York, American Institute of Mining, Meatallurgical, and Petroleum Engineers, Inc., v. 1, p. 460-488.
Discussion of mining and exploration, physiographic history, general geology, structure of area. Extensive descriptions of stratigraphy, mineralogy, and form of ore bodies as well as their origin and time of mineralization. Sketch maps of geology, structure, and thickness of beds.

Fritts, C. E., 1969, Bedrock geologic map of the Marenisco-Watersmeet area, Gogebic and Ontonagon counties, Michigan: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-576, scale 1:48,000. 5-p. text.
Detailed geologic map of three 15-min quadrangles with four cross sections, some aeromagnetic data, and locations of mineralized areas.

Gair, J. E., and Wier, K. L, 1956, Geology of the Kiernan quadrangle, Iron County, Michigan: U.S. Geological Survey Bulletin 1044, 88 p., 5 pls. scale 1:24,000.
Detailed geology of a 7 1/2-min quadrangle, including stratigraphy, structure, magnetic surveys, and economic geology. Geologic maps and sections, magnetic maps, diagrams, tables, photos.

Good, S. E., and Pettijohn, F. J., 1949, Magnetic survey and geology of the Stager area, Iron County, Michigan: U.S. Geological Survey Circular 55, 4 p.
Very generalized geology of an area of 4 mi^2, and more detailed magnetic data. Brief description of mining possibilities. Geologic map and magnetic data map.

Hamblin, W. K., 1958, The Cambrian sandstones of northern Michigan: Michigan Geological Survey Division Publication 51, 149 p.
A comprehensive study of the Cambrian sediments, by means of areal mapping, and a detailed study of the stratigraphy, sedimentation, and paleontology. Geologic maps, sections, tables, stratigraphic charts, and many photos.

Hamilton, S. K., 1967, Copper mineralization in the upper part of the Copper Harbor Conglomerate at White Pine, Michigan: Economic Geology, v. 62, no. 7, p. 885-904.
Points out the nature and distribution of copper mineralization in the upper parts of the Copper Harbor Conglomerate. Controls of copper distribution and mode of origin are discussed.

Heran, W. D., and Smith, B. D., 1980, Description and preliminary map, airborne electromagnetic survey of parts of Iron, Baraga, and Dickson Counties, Michigan: U.S. Geological Survey Open-File Report 80-297, 13 p., 1 sht., scale 1:62,500.
Map showing location and magnitude of electromagnetic anomalies. Brief text describing method of survey.

Hobbs, W. H., 1899, The diamond field of the Great Lakes: Journal of Geology, v. 7, p. 375-388.
Text covers physical characteristics of the lake diamonds, their distribution and the question of their origin.

Hubbard, H. A., 1974, Bedrock geology of the Porcupine Mountains, Michigan: U.S. Geological Survey Open-File map, scale 1:62,500.
Detailed geologic map of the area. No text.

_____________ 1975a, Geology of Porcupine Mountains in Carp River and White Pine quadrangles, Michigan: U.S. Geological Survey Journal of Research, v. 3, no. 5, p. 519-528.
Detailed geology of an area of about 75 mi^2 with description of stratigraphy and structure. Geologic map and cross sections, stratigraphic correlation table.

_____________ 1975b, Lower Keweenawan volcanic rocks of Michigan and Wisconsin: U.S. Geological Survey Journal of Research, v. 3, no. 5, p. 529-541.
Detailed geology of an area about 70 mi^2 showing new correlations and stratigraphic nomenclature between rocks of unconformable sequences of Keweenawan volcanic. Geologic map, chemical analyses, stratigraphic table.

Irving, R. D., and Van Hise, C. R., 1890, The Penokee iron-bearing series of Michigan and Wisconsin: U.S. Geological Survey Monograph 19, 534 p.
A summary of previous work on the area, and a detailed description of the current geology, with emphasis on the iron-bearing formations. Geologic maps, diagrams, and sections.

James, H. L., 1951, Iron formation and associated rocks in the Iron River district, Michigan: Geological Society of America Bulletin, v. 62, no. 3, p. 251-266.
Discusses origin of iron-formation linking climate with other factors. Includes tables showing stratigraphic succession in the Iron River district and chemical analysis of graphite slate, iron-formation, graywacke, magnetic ironstone.

_____________ 1953, Origin of the soft iron ores of Michigan: Economic Geology, v. 48, no. 8, p. 726-728.
A letter in the "Discussion" section on the theory of soft iron ore formation in Michigan as proposed by V. I. Mann versus other ideas as proposed by USGS.

_____________ 1955, Zones of regional metamorphism in the Precambrian of northern Michigan: Geological Society of America Bulletin v. 66, 12, pt. 1, p. 1455-1487.
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A detailed discussion of the metamorphism of the rocks and its relationship to intrusive igneous rocks and structure. Tables and diagrams.

____________ 1958, Stratigraphy of pre-Keweenawan rocks in parts of northern Michigan: U.S. Geological Survey Professional Paper 314-C, p. 27-44.
Discussion of stratigraphic nomenclature used for lower and middle Precambrian rocks in Iron and Dickinson Counties, and detailed description of the various lithologies. Proposes correlation of layered rock sequence containing the iron formations with Animikie series.
A generalized geologic map and stratigraphic tables.

James, H. L., Clark, L. D., Lamey, C. A., and Pettijohn, F. J., 1961, Geology of central Dickinson County, Michigan: U.S. Geological Survey Professional Paper 310, 176 p., 1 pl., scale 1:24,000.
Extensive summary of the geology of an area of 250 mi^2 with detailed discussions of stratigraphy, structure, and economic geology. Iron ore is principal mineral resource. Other minerals are dolomite and uranium. Geological and geophysical maps, stratigraphic and chemical analysis tables.

James, H. L., and Dutton, C. E., 1951, Geology of the northern part of the Iron River district, Iron County, Michigan: U.S. Geological Survey Circular 120, 12 p.
General geology of an area of 12 mi^2 area. Description of stratigraphy and brief discussion of iron-formation and future mining possibilities. Geologic maps and cross sections, stratigraphic chart, and magnetic data.

James, H. L., Dutton, C. E., and Wier, K. L., 1967, Geologic and magnetic data for northern Iron River area, Michigan: Michigan Geological Survey Division Report of Investigation 4, 46 p., maps, scale 1:6,000.
Supplements USGS Professional Paper 570 with detailed geology, descriptions of mines and explorations, and magnetic surveys of the area.

James, H. L., Dutton, C. E., Pettijohn, F. J., and Wier, K. L., 1968, Geology and ore deposits of the Iron River-Crystal Falls district, Iron County, Michigan: U.S. Geological Survey Professional Paper 570, 134 p., 4 pls., scale 1:24,000.
Detailed discussion of geology of an area 300 mi^2. Stratigraphy, structure, and ore deposits described, as well as ore mineralogy. Iron is chief ore. Uranium present. Geologic maps, stratigraphic charts, chemical analyses, and production data.

James, H. L., Pettijohn, F. J., and Clark, L. D., 1970, Geology and magnetic data between Iron River and Crystal Falls, Michigan: Michigan Geological Survey Division Report of Investion 7, 17 p., maps, scale 1:6000.
Supplements USGS Professional Paper 570 with detailed geology, descriptions of mines and description of explorations, and magnetic surveys of the area.

James, H. L., and Wier, K. L., 1948, Magnetic survey and geology of the eastern and southeastern parts of the Iron River district, Iron County, Michigan: U.S. Geological Survey Circular 26, 18 p., 4 pls. Discussion of geology in the eastern and southeastern parts of the Iron River district with detailed section-by-section descriptions. Includes a stratigraphic chart of characteristics of the iron-formation. Maps include:

(1) Geologic cross-section in eastern and southeastern parts of the Iron River District, scale 1:2,400.

(2) Inferred geology in southeastern part of Iron River district, 1:6000.

(3) Magnetic data in southeastern part of Iron River District, 1:6000.

(4) Magnetic data and inferred geology in eastern part of the Iron River district, 1:6,000.

__________________ 1969, Geology and magnetic data for the south eastern Iron River area, Michigan: Michigan Geological Survey Division Report of Investigation 6, 30 p., maps, scale 1:6,000. Supplements USGS Professional Paper 570 with detailed geology descriptions of mines and explorations, and magnetic surveys of the area.

Johnson, R. F., and White, W. S., 1969, Preliminary report on the bedrock geology and copper deposits of the Matchwood quadrangle, Ontonagon County, Michigan: U.S. Geological Survey Open-File Report, 29 p., 1 pl., scale 1:62,500. Discussion of general geology, stratigraphy, structure, and economic geology of a 15-min quadrangle. Black and white geologic map.

Jolly, W. T., 1974, Behavior of Cu, Zn, and Ni during prehnite-pumpellyite rank metamorphism of Keweenawan basalts, northern Michigan: Economic Geology, v. 69, no. 7, p. 1118-1125. A study of metamorphic zonation and its affect on metal distribution Native copper deposits appear to be formed by leaching of copper in higher temperature zones and reprecipitation in lower temperature zones.

Kalliokoski, J. O. K., 1976, Uranium and thorium occurrences in Precambrian rocks, Upper Peninsula of Michigan and northern Wisconsin: Houghton, Mich., Michigan Technological University, 274 p. Regional geologic setting and detailed geologic descriptions of known occurrences of uranium and thorium. Contains detailed maps of most occurrences and assay data for most.

Klasner, J. S., and Cannon, W. F., 1974, Geologic interpretation of gravity profiles in the western Marquette district, northern Michigan. Geological Society of America Bulletin, v. 85, no. 2, p. 213-218. Interpretation of gravity profiles, specifically of the Marquette Trough near Humboldt, Mich., Marquette Trough near Michigamme, Mich., Republic Trough and the Michigan River Trough. Includes gravity profiles, geologic sections, stratigraphic column, and gravity models.

________________ 1978, Bedrock geologic map of the southern part of the Michigamme and Three Lakes quadrangles, Marquette and Baraga Counties, Michigan: U.S. Geological Survey Miscellaneous Investigations Series, Map I-1078, scale 1:24,000.
Detailed geologic map with text covering stratigraphy, structure, metamorphism, and iron resources. Includes table of mine production from the Negaunee Iron-formation and the Bijiki Iron-formation Member of the Michigamme Formation.

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Studies of the distribution, nature, and paragenesis of an unusual variety of microcline found in copper rich areas of Michigan.

Lane, A. C., 1911, The Keweenaw Series of Michigan: Michigan Geological and Biological Survey Publication 6, Geological Series 4, v. 1 and 2, 984 p.
Major references on geology and copper deposits of area, with detailed descriptions of stratigraphy of each deposit. Geologic maps and sections, diagrams, and tables.

Lane, A. C., 1924, Native Silver in an iron mine [abs.]: Geological Society of America Bulletin, v. 35, no. 1, p. 127-128.
Brief abstract discussing origin and inclusion of silver in Michigan iron-formations.

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