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GEOLOGY AND MANGANESE RESOURCES OF THE CUYUNA IRON RANGE, EAST-CENTRAL MINNESOTA

UNIVERSITY OF MINNESOTA

Minnesota Geological Survey
Priscilla C. Grew, Director

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GEOLOGY AND MANGANESE RESOURCES OF THE CUYUNA IRON RANGE, EAST-CENTRAL MINNESOTA

By

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INTRODUCTION

Ever since their discovery in 1904, it has been recognized that the iron-formations and associated ore deposits of the Cuyuna iron range in east-central Minnesota (Fig. 1) contained appreciable quantities of manganese which was extracted as ferromanganese ores from several mines on the North range from 1911 to 1984. The presence of this manganese resource sets the Cuyuna range apart from other iron-mining districts of the Lake Superior region.

During the past 40 years several attempts have been made to estimate the size of the manganese resource. For example, Lewis (1951) estimated that 455 million metric tons of manganiferous iron-formation containing from 2 to 10 percent manganese were available to open-pit mining to a depth of 45 meters. Dorr and others (1973, p. 394, Table 77) used that estimate to establish that the Cuyuna range contains approximately 46 percent of known manganese resources in the United States. More recently, Beltrame and others (1981) utilitized a somewhat unorthodox method to estimate that the range contains a minimum of 170 million metric tons of manganiferous rock with an average grade of 10.46 weight percent manganese. Both estimates should be considered with a certain amount of skepticism for at least two reasons. First, the manganese data used to make these estimates were, for the most part, by-products of data that were acquired originally by various mining companies as they explored for iron. Second, the various estimates were prepared for different reasons at different times, using different data bases and different methodologies. Therefore the results of these estimates are neither comparable, nor do they necessarily reflect the actual resource.

Despite their problematic nature, the estimates of Lewis (1951) and Beltrame and others (1981) do show that the Cuyuna range contains a large, but low-grade resource. This large size, combined with the fact that the manganese deposits are located in an established mining district, makes the Cuyuna range an ideal place to study geological and technological factors needed to evaluate this and other sedimentary manganese deposits in the United States. Especially important are studies of the geologic habit of the manganese and the controls on its distribution and subsequent concentration into deposits of minable size.

The emphasis of this report is on the geologic factors that seem to control how the manganese is distributed on the Cuyuna range. However because the range was exploited principally for its iron ores, much of the available information is fragmentary. Although the manganese is closely associated with the iron ores, it was carefully evaluated by only a few of the companies operating on the range. Other companies examined the manganese-bearing material in only a cursory manner, and therefore in spite of what appears to be an extensive data base, our knowledge of the geology of the manganese resources is fragmentary and in part confusing. It is not yet possible to construct a coherent, detailed picture of the primary origin of the manganese-bearing strata, the structure and stratigraphic positions of these strata, and the precise tenor, extent, and localization of the several different kinds of manganese-bearing material that have been recognized. The ultimate utilization of the Cuyuna manganese deposits will require new metallurgical and beneficiation techniques that must be designed specifically for the different kinds of ores, and this report, if nothing else, should call attention to the deficiencies of the present geological data base.

GENERAL FRAMEWORK

The Cuyuna iron range is about 160 km southwest of Duluth in Aitkin, Cass, Crow Wing, and Morrison Counties (Fig. 1). It is part of an Early Proterozoic geologic terrane which occupies much of east-central Minnesota. The Cuyuna iron range is traditionally divided into three districts—the Emily district, the North range, and the South range. The Emily district extends from the Mississippi River northward through Crow Wing County and into southern Cass County, and comprises an area of about 1165 square kilometers. Although exploration drilling has been extensive in the Emily district, mining never commenced. The North range, a much smaller area about 19 km long and 8 km wide, is near the cities of Crosby and Ironton in Crow Wing County. Although relatively small, the North range was the principal site of mining activity, which had largely ceased by 1970. The South range, where only a few underground mines were operated, in the 1910s and 20s, comprises an area of northeast-trending, generally parallel belts of iron-formation extending from near Randall in Morrison County northeast for about 100 km. In addition to the three named districts, numerous linear magnetic anomalies occur east of the range proper, and may indicate other, but as yet poorly defined, beds of iron-formation.

All of east-central Minnesota, including the Cuyuna range, is a generally flat area dominated by constructional glacial deposits whose origin is related to several continental ice sheets which covered the area during Pleistocene time. Today the area is drained by the intricately meandering Mississippi River, which passes through the Cuyuna range from northeast to southwest, as well as by several rivers tributary to the Mississippi River. Extremes in altitude are from 320 to 410 meters above sea level, but many of the larger hills have less than 50 meters of relief. In contrast to the natural topography, some of the water-filled open-pit mines on the North range are more than 100 meters deep, and some stripping and lean ore dumps are more than 45 meters high, creating a man-made relief of approximately 150 meters.

Because most of the glacial deposits are quite young, an integrated drainage system has not had time to develop in east-central Minnesota. Consequently the entire region is poorly drained and the water table is very near the mean level of the Mississippi River, and mines fill with water to within several meters of the land surface soon after pumping ceases.

The glacial deposits, which in places are as much as 150 meters thick, obscure much of the bedrock. Bedrock outcrops are confined to the various iron-ore mines. Consequently structural and stratigraphic relationships in the bedrock must be pieced together from subsurface exploration records obtained from projects that focused on the identification and characterization of magnetic anomalies. In fact the Cuyuna range was one of the first, if not the first, mining districts in the United States to be discovered by geophysical methods and supplementary exploratory drilling. Nonetheless, understanding the geology of the Cuyuna iron range is essentially an exercise in subsurface stratigraphic and structural analyses.

Bedrock Geology

There are several useful historic descriptions of the bedrock geology of east-central Minnesota in general and the Cuyuna range in particular, including those of Harder and Johnston (1918); Zapffe (1933); Woyski (1949); Grout and Wolff (1955); Schmidt (1963); Marsden (1972); and Keighin and others (1972). These works were used by Morey (1978) to produce a regional geological synthesis that was founded on the stratigraphic premise that a single major iron-rich interval tied together the Emily district, the North range, and the South range. The tectonic framework of east-central Minnesota, as mapped by Morey and others (1981), was based on that premise and on the assumption that vertical tectonic processes were responsible for a series of large synclines and anticlines in a pattern of superimposed interference folds. That mapping was guided by the gravity (Krenz and Ervin, 1977; McGinnis and others, 1977, 1978) and magnetic (Bath and others, 1964, 1965) data available in the mid-1970s.

In the 7 years since the work of Morey and others (1981), the body of geophysical data and drill-hole information pertaining to the area has grown substantially. A new high-resolution aeromagnetic survey of the region has been flown (Chandler, 1983a, 1983b, 1983c, 1985) and computer-prepared derivative maps and theoretical models based on the aeromagnetic data (Carlson, 1985) have extended the utility of the potential field data beyond qualitative

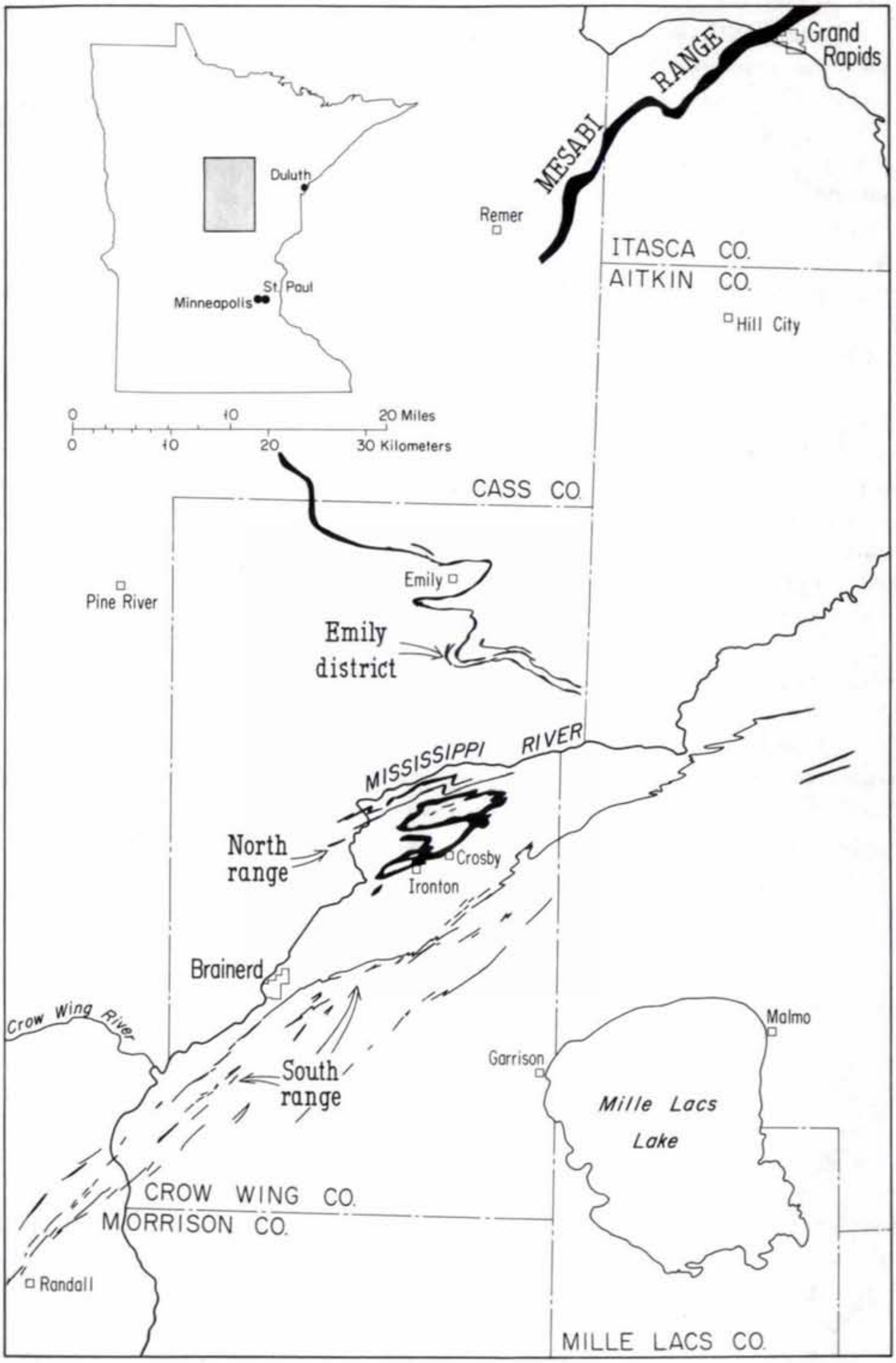

Figure 1. Generalized map of the Cuyuna range in east-central Minnesota showing the locations of the Emily district and the North and South ranges (modified from Schmidt, 1963). Major units of iron-formation are shown in black. Note the location of the Mesabi range to the north and east of the Emily district.

interpretation. Converting the aeromagnetic data into a geologic map was furthered by corroborative scientific test drilling undertaken by the Minnesota Geological Survey, which made it possible to test directly the sources of particular aeromagnetic anomalies and anomaly patterns. During that same period, several of the iron-mining companies formerly active in the area released several thousand exploration records and drill cores. These old data, some dating back to the period 1900-1910, have been especially valuable in deciphering the complex structure of the Emily district (Morey and others, 1990) and the South range (Morey and Morey, 1986) where public information on the geology had been scarce.

Three major insights regarding the geology of the Cuyuna range have emerged from the geologic mapping (Fig. 2) and associated studies of Southwick and others (1988) which utilized the recently acquired geophysical and drilling data. First, there is clear evidence that iron sedimentation occurred at several different times and under varying geological conditions. This observation invalidates the stratigraphic premises of Morey (1978). Major iron-formations are associated stratigraphically with volcanic rocks in the South range, with black shale and argillite in the North range, and with shallow-water deposits of sandstone and siltstone in the Emily district.

Second, the iron-rich strata of the Emily district are correlative (Fig. 3) with the Biwabik Iron Formation of the Mesabi range, as inferred by Marsden (1972) and Morey (1978). However, they and the other sedimentary rocks of the well-known Animikie Group occur above a major deformed unconformity that cuts across previously deformed, somewhat older sedimentary and volcanic rocks of the North range. There, a prominent iron-rich unit named the Trommald Formation, as well as several other units beneath the unconformity, forms part of a locally twice-deformed sequence. Therefore the rocks of the North range and the Emily district cannot be correlative, but are separate stratigraphic entities. Because the stratigraphic succession of folded sedimentary rocks on the North range comprises a distinct stratigraphic entity, Southwick and others (1988) referred to it informally as the North Range group with the understanding that a formal name may be justified at a later time. As defined by Schmidt (1963), the stratigraphic sequence in the North range consists of a quartz-rich lower unit named the Mahnomen Formation, a middle iron- and locally manganese-rich sequence assigned to the Trommald Formation, and an upper graywacke-shale interval called the Rabbit Lake Formation.

The North Range group overlies with slight unconformity older rocks provisionally assigned to the Mille Lacs Group of Morey (1978). Iron-formations within the sequence include those along the South range of the Cuyuna area and those in the Glen Township area. Where the intervening strata of the North Range group are missing, the unconformity between the Animikie Group and the Mille Lacs Group is a major tectonostratigraphic break.

Third, Southwick and others (1988) recognized several geophysically defined structural discontinuities in the southern part of the Cuyuna iron range, within and southeast of the South range. These discontinuities are marked by demonstrable contrasts in metamorphic grade, by differing structural styles, and by different lithic components. One of the most pronounced of these, the Serpent Lake structural discontinuity, passes along the south edge of the North range. This discontinuity as mapped on Figure 2 is interpreted as a tectonic boundary, probably involving major thrust faults between slices of folded rocks. Thus it seems fairly certain that the iron-rich strata of the South range are not correlative with either the Trommald Formation of the North range or the iron-rich strata of the Emily district.

The fact that iron-formation occurs within three different stratigraphic and structural contexts in the Cuyuna iron range is of considerable importance to the ultimate development of the manganese resource. Because we now recognize that the Emily district, the North range, and the South range are separate entities, we can no longer develop regional syntheses that extrapolate mineralogical and structural attributes from one entity to another.

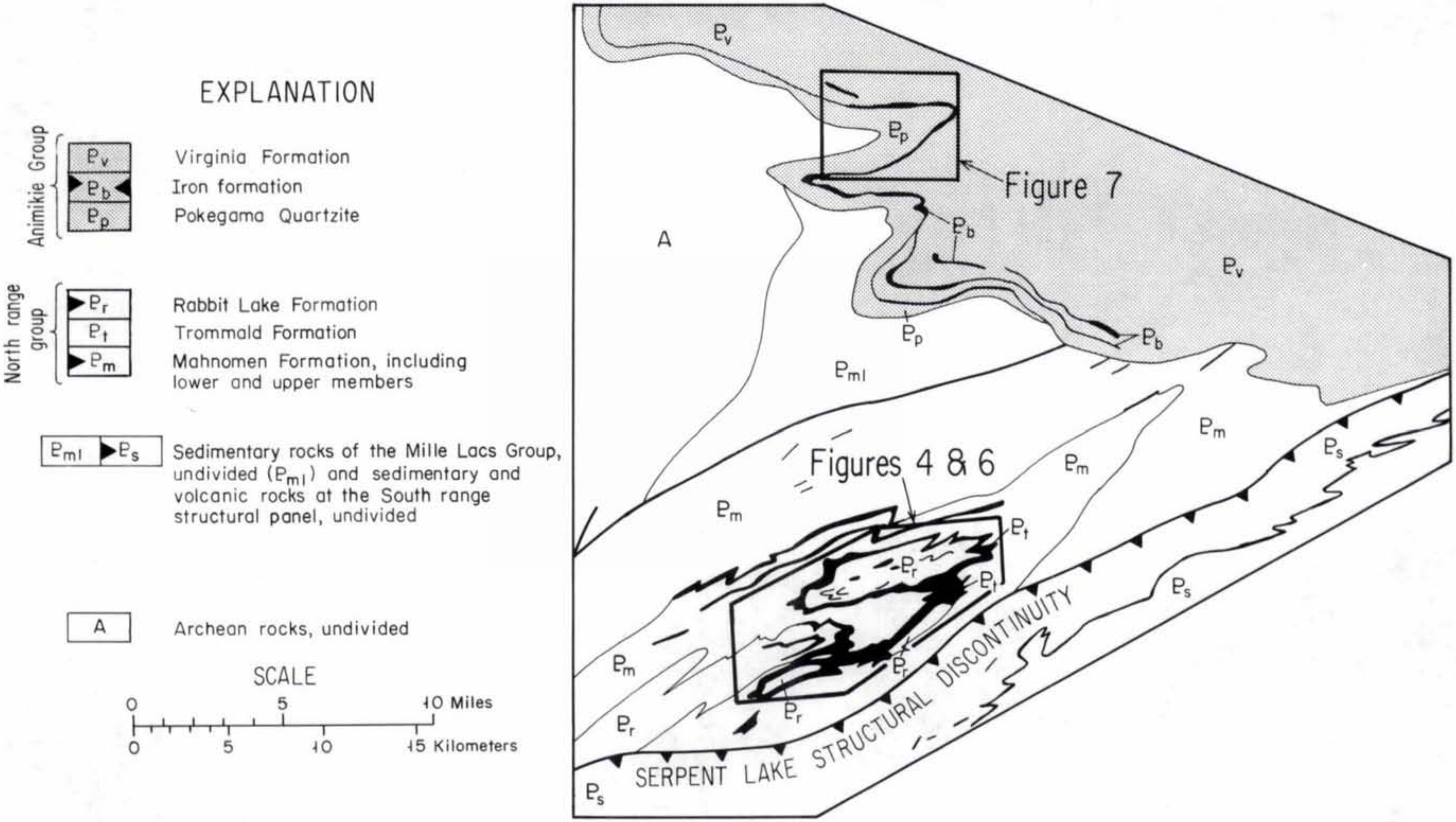

Figure 2. Generalized geologic map of the Cuyuna range (modified from Southwick and others, 1988). Note that the rocks of the Animikie Group unconformably overlie those of the North Range group and that they in turn are separated from those of the South range by the Serpent Lake structural discontinuity.

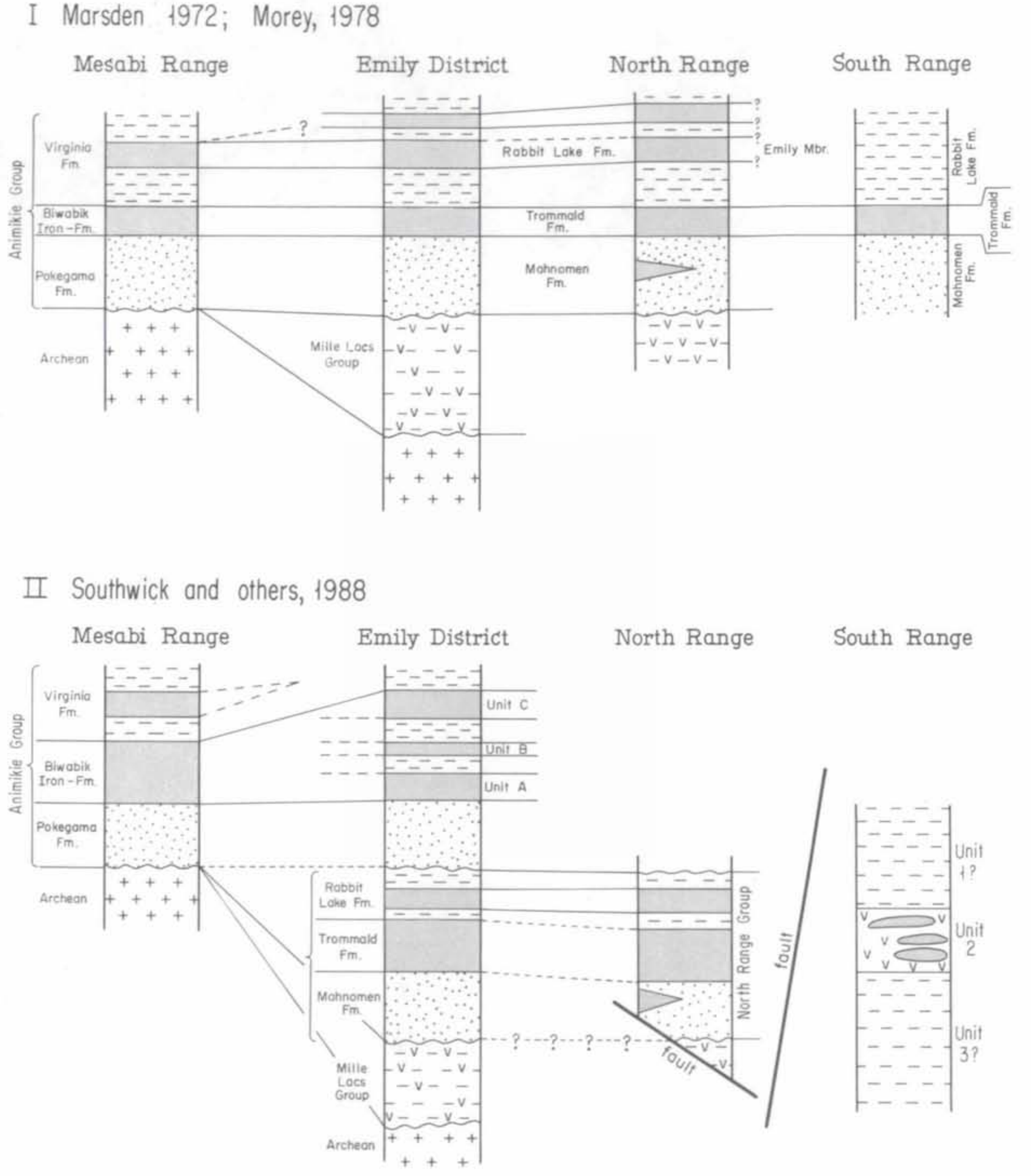

Figure 3. Comparison of stratigraphic correlation schemes of iron-rich strata in east-central Minnesota, as used by Marsden (1972) and Morey (1978), with that used by Southwick and others (1988).

THE SOUTH RANGE

The rocks of the South range, south of the Serpent Lake discontinuity, have been divided by Southwick and others (1988) into three mappable units—(1) a more or less uniform sequence of metabasalt; (2) a sequence composed of complexly interlayered mafic volcanic and hypabyssal rocks, graphitic slate or schist, and iron-formation; and (3) a sequence of nongraphitic slate, argillite, and metasiltstone.

Lacking younging-upward criteria, the stratigraphic positions of the mappable units are uncertain. However, much of the iron-formation occurs in unit 2, closely associated with mafic to intermediate volcanic rocks and hypabyssal intrusions. The distribution of unit 2 is reasonably well known, particularly in the area south of the Mississippi River (Morey and Morey, 1986), where there had been much exploration for iron ore in the early part of the 20th century. The objective of that exploration was to find bodies of high-grade "direct-shipping" ore. Consequently the most common exploration strategy was to seek nonmagnetic breaks or gaps in elongate positive magnetic anomalies that had been defined by dip-needle surveys. Because it was assumed that the iron-formations were more or less continuous layers, the nonmagnetic gaps would be places where a normally magnetic iron-formation had been oxidized and leached, and in the process converted from a magnetite-iron silicate rock into one enriched in hematite and depleted in silica. The drilling record shows that these inferences were incorrect in many situations. Lateral facies changes in ordinary iron-formation (i.e., changes from oxide to carbonate or sulfide facies) are responsible for many of the nonmagnetic gaps, and the lateral thinning and stratigraphic pinching out of iron-formation lenses are responsible for even more. The rather large number of places where lenses of iron-formation terminate within a stratigraphic sequence of green metavolcanic rocks and black carbonaceous slate (Morey and Morey, 1986) implies that the deposition of iron-formation was closely allied with volcanic activity and was controlled by geochemical and sedimentological factors that were specific to small basins of accumulation. Thus in many respects the stratigraphic setting of the South range resembles that of the so-called Algoma-type iron-formation rather than that of the classic Lake Superior type (Gross, 1973).

It is clear from the distribution of lenses and layers of iron-formation that the structure of the South range is dominated by elongate, east-northeast-trending folds that do not seem to have been refolded on a major scale. However, there is some evidence for local refolding, for in places crescentic patterns in folded iron-formation are suggestive of type 2 or transitional type 2-3 interference patterns (Ramsay, 1967), and more than one generation of cleavage is present in schistose or slaty rocks in some drill cores.

No modern description of iron-formation in the South range has been prepared, but Harder and Johnston (1918) describe unoxidized parts of it as a medium- to fine-grained, greenish-gray to black, commonly laminated "magnetitic slate" and "amphibole magnetite rock." Typical magnetite slate consists of interlaminated light-green, finely crystalline amphibole and black, siliceous or argillaceous, fine-grained magnetite. The typical amphibole-magnetite rock is finely banded and consists of alternating layers of magnetite, amphibole, and minor amounts of quartz. Oxidation and leaching of the iron-formation to depths of 35 to 60 meters has resulted in bedded, limonitic or hematitic, ferruginous chert, ferruginous slate, paint rock, and yellow-brown, red, or black ore (Marsden, 1972).

Distribution of Manganese-Bearing Materials

In general the iron-formations of the South range appear to consist dominantly of "non-granular," "thin-bedded" or "slaty" rocks. Both Grout and Wolff (1955) and Schmidt (1963) refer to generally small manganese values in these rocks, and Lepp (1968) reports that 29 composite samples have a mean manganese tenor of 0.34 percent and a range of 0.03 to 1.16 percent. In general these values are similar to manganese values in the Biwabik Iron Formation and in other iron-formations of the Lake Superior region (Morey and Morey, 1990).

Despite generally low background values, several properties on the South range (Clearwater Lake Reserve, Willcuts Reserve, and the Omaha Mine) were estimated by the Office of Ore Estimation of the University of Minnesota (Beltrame and others, 1981) to collectively contain 2.3 million metric tons of material averaging 3.07 weight percent Mn. Although data are sparse, it seems likely that the South range will never be an economically important source of manganese.

THE NORTH RANGE

The North range (Fig. 4), centered on the former iron-mining towns of Crosby and Ironton, extends along a northeast-trending fold whose dominant structural element is a synclinorium that is inclined toward the northwest (axial surfaces dip southeast) and is doubly plunging on a regional scale (Schmidt, 1963; Morey and Morey, 1986). The rocks of the North range were once correlated with the Animikie Group of the Mesabi range, but now are believed to be part of an older sequence, the North Range group of Southwick and others (1988).

The North Range group consists of three formations, from oldest to youngest, the Mahnomen Formation, the Trommald Formation, and the Rabbit Lake Formation (Schmidt, 1963). The Mahnomen Formation has been described as containing chiefly argillite and siltstone in the lower part, and those rocks, together with quartzite and limestone, in the upper part. Its lower contact has not been penetrated anywhere by drilling, and therefore the thickness of the formation, the exact meaning of "upper" and "lower" parts, and the nature of the subjacent rocks are all matters of interpretation. Its upper contact with the Trommald Formation of Schmidt (1963) is relatively abrupt in most places; it has been well described in the main mining district near Crosby and Ironton (Schmidt, 1963; Marsden, 1972).

On the basis of aeromagnetic data and very sparse drilling in the northwestern part of the North range, the Mahnomen can be divided into an upper more magnetite-rich member and a lower member less rich in magnetite (Southwick and others, 1988). The upper member contains beds of ferruginous argillite and lean iron-formation, some of which have been leached and oxidized as at the Snowshoe mine, interlayered with nonferruginous argillite, siltstone, and quartzose sandstone. The lower member—on the north side of the North range—lacks the ferruginous components except near its inferred base. It overlies, with an apparent low-angle unconformity, an older sequence of metasedimentary and metavolcanic rocks probably correlative with the Mille Lacs Group of Morey (1978).

The Mahnomen Formation is conformably overlain by the iron-rich Trommald Formation (Schmidt, 1963), the unit of greatest economic importance in the North range. The Trommald is overlain in turn by the Rabbit Lake Formation, or more specifically, by the lower member of the Rabbit Lake Formation as defined by Marsden (1972). The lower member of the Rabbit Lake consists chiefly of carbonaceous argillite and slate, together with minor interbeds of volcanic rocks and a few lenses of ferruginous chert (Schmidt, 1963). These rocks pass upward into a second major iron-formation layer that is overlain in turn by slate, argillite, graphitic slate, graywacke, and local cherty iron-formation of the upper member of the Rabbit Lake Formation (Fig. 3). The rocks of the upper member are limited to the cores of closed synclines in the keel region of the North range synclinorium. Beds of iron-formation within the Rabbit Lake sequence are an important marker in the North range. They formerly were designated as the Emily Member of the Rabbit Lake and were correlated with the intermediate iron-formation layer in the Emily district (Morey, 1978).

As noted above, the southern boundary of the North range is inferred to be tectonic, because linear magnetic trends associated with units of iron-formation in the South range cut across and

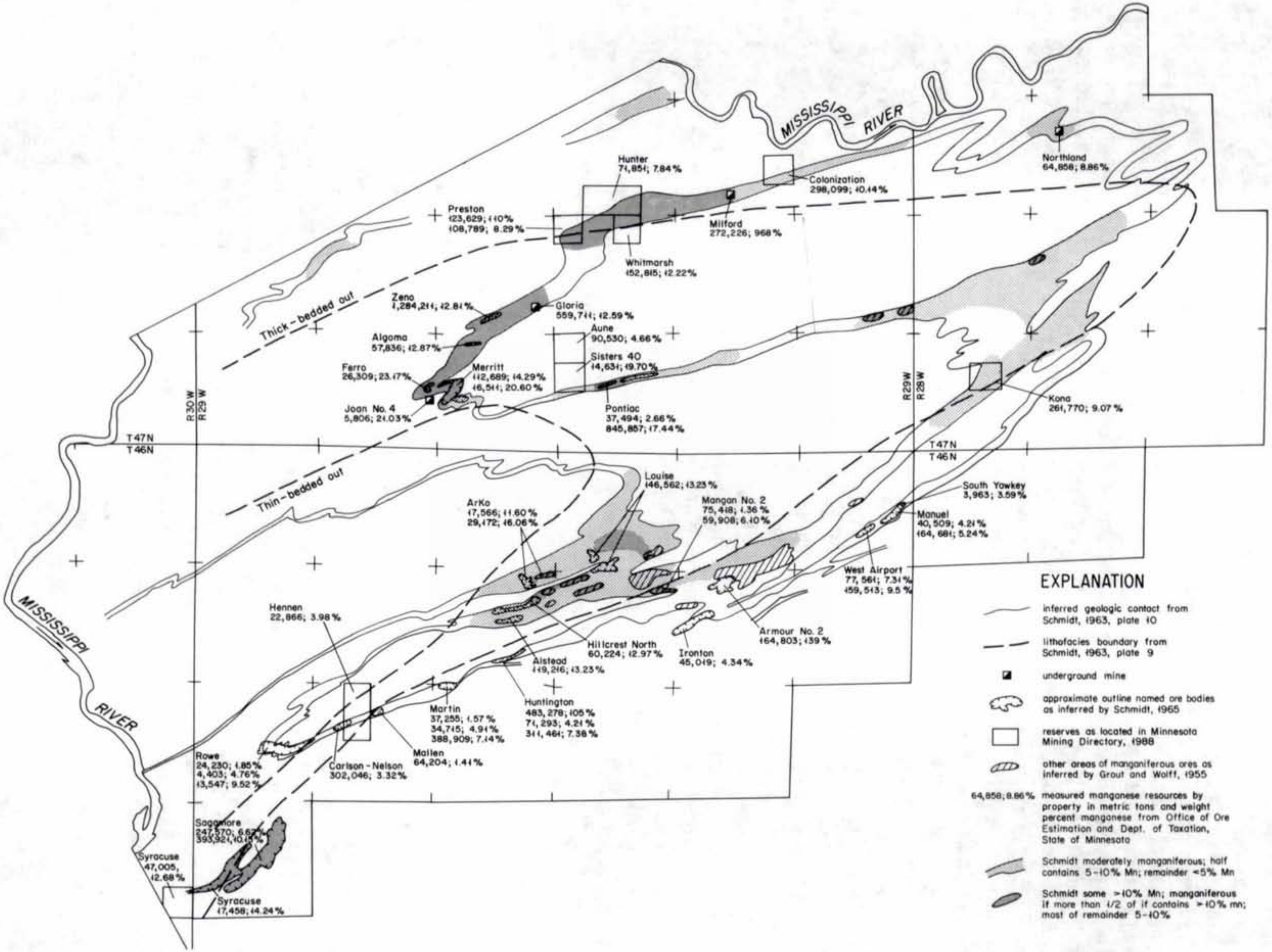

Figure 4. Geologic map of the North range (modified from Schmidt, 1963) showing the locations of mines and reserve properties and their estimated manganese resources as determined by the Office of Ore Estimation and the Minnesota Department of Revenue (Beltrame and others, 1981).

truncate linear magnetic trends associated with units of iron-formation in the North range. The tectonic boundary—the Serpent Lake structural discontinuity—also separates vastly different lithologic associations. Volcanic rock—mainly metabasalt and compositionally related metadiabase—form a major component of the lithostratigraphic succession on the South range, but only a minor component on the North range (Grout and Wolff, 1955; Schmidt, 1963; Marsden, 1972). Also the rocks of the North range are less strongly foliated than those of the South range, and they are less recrystallized metamorphically.

The Trommald Formation ranges in thickness from 15 to more than 150 meters and consists of two mappable iron-formation facies, one thick bedded (or granular or cherty) and the other thin bedded (or nongranular or slaty). The thick-bedded facies is typified by wavy-bedded, granule-chert layers ranging in thickness from several centimeters to 2 meters, which are intercalated with thinner beds of hematite or magnetite. The cherty layers consist of ovoid granules of cherty quartz, carbonates, silicates, and hematite and magnetite. Matrix material may or may not be mineralogically similar to the granules, but regardless of mineralogy, it is generally rich in quartz. The thin-bedded facies is characterized by bedding laminae generally less than several millimeters thick. Individual layers in this facies are composed of various proportions of quartz, siderite, magnetite, stilpnomelane, minnesotaite, and chlorite; individual laminae may be monomineralogic, but more typically consist of carbonates and chert, or carbonates and silicates. Each of these assemblages may or may not contain magnetite. The thin-bedded facies generally corresponds to the carbonate or silicate-carbonate facies, and the thick-bedded facies resembles the oxide facies as described by James (1955). In parts of the North range the entire Trommald Formation is represented by the thin-bedded facies, whereas in other places only the thick-bedded facies is represented. In about a third of the North range, the thin-bedded facies underlies the thick-bedded facies and grades upward into it.

The Rabbit Lake Formation, the uppermost of the three conformable sedimentary units, is composed predominantly of gray to black carbonaceous argillite and slate with intercalated lenses of siliceous, argillaceous iron-formation. Also present are small lenses and thin beds of chert, ferruginous chert, ferruginous argillite, and slate or schist (Schmidt, 1963). Schmidt estimated that the Rabbit Lake Formation is at least 610 meters thick.

Both the Trommald Formation and the iron-rich strata in the Rabbit Lake Formation were probably deposited in the ferrous or unoxidized state and later oxidized to the ferric state by percolating solutions. These solutions locally leached the iron-rich strata, removing silica, calcium, magnesium, and carbon dioxide, and concentrated iron and manganese oxides to form a variety of so-called "natural ore" bodies upon which mining in the range was based. Schmidt (1963) suggests that the natural ore deposits of the North range formed during two separate and distinct stages. There is some evidence (Peterman, 1966) that the first period of ore formation occurred around 1.5 to 1.6 b.y. ago when warm or hot waters, presumably of meteoric origin, leached and oxidized the iron-formation in places. The resulting orebodies are largely hematitic, tabular or lenticular in shape, and generally elongate parallel to bedding. It seems likely that the second period of ore formation occurred during the latter part of the Mesozoic Era in Late Jurassic or Early Cretaceous time, when all of the bedrock in Minnesota was subjected to a period of intense chemical weathering. Thick saprolites including iron ores were developed. The resulting iron ores are largely goethitic or limonitic in composition and have a blanket-like shape. They occur mostly over thin-bedded-facies iron-formation, but several bodies were developed over the tabular bodies of older hematitic ore. However, how the several periods of iron-ore formation affected the mineralogy, grade, and tenor of the associated manganiferous ores is unknown.

Distribution of Manganese-Bearing Materials

Manganiferous material is abundant on the North range, where it is largely restricted to the subcrop limits of the Trommald Formation. However, some manganiferous ore has been mined from iron-formation in the lower part of the Rabbit Lake Formation. The manganiferous materials may be classified into three broad categories. These are (1) manganiferous iron-formation containing 20 to 35 percent iron and 0.5 to 16 percent manganese; (2) manganiferous iron ores containing 35 to 40 percent iron and from 5 to 8 percent manganese; and (3) ferromanganese ore containing 31 to 36 percent iron and 11 to 15 percent manganese. The first category represents the original iron-formation protolith, whereas the other categories represent ore concentrated by oxidation and leaching.

The bulk of manganese in the Trommald protolith occurs at or near the transition zone between the thick-bedded and the thin-bedded facies (Fig. 5). Sites near this transition zone include nearly all of the manganiferous iron ore and ferromanganese orebodies that were mined in the past (Fig. 4). Manganese values tend to be generally low where the thick-bedded facies constitutes the entire formation. Although manganese may be present where the Trommald Formation consists entirely of the thin-bedded facies, it is erratic both in grade and distribution. The two facies were deposited under considerably different sedimentological conditions—the thin-bedded facies in "deeper" water below wave base under somewhat reducing conditions, and the thick-bedded facies near or above wave base under somewhat oxidizing or at least less reducing conditions (Morey, 1973). Thus it seems reasonable to assume that the manganese was preferentially deposited in a relatively specific sedimentological regime, the geometry of which was constrained by the paleogeographic configuration of the depositional basin.

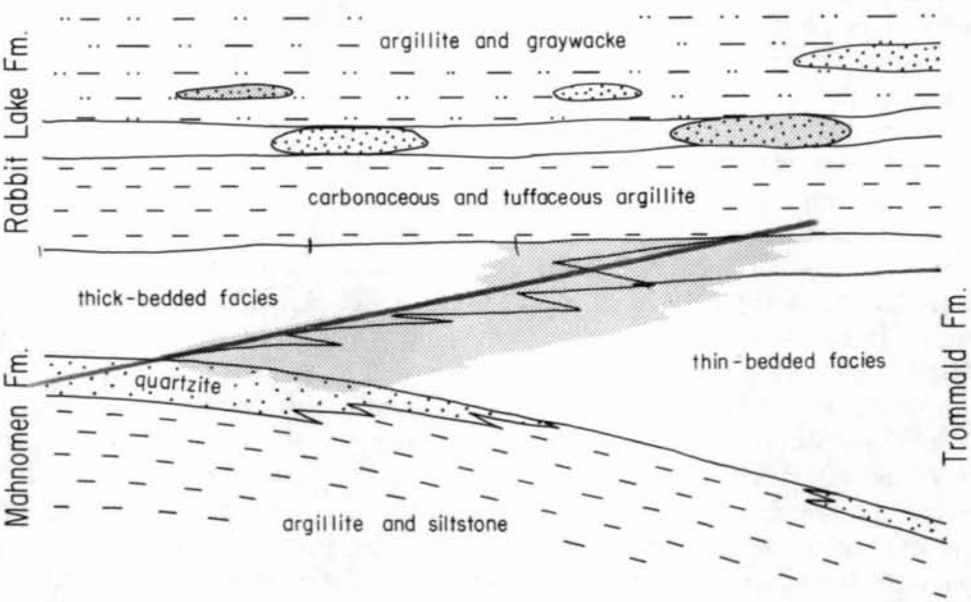

Figure 5. Pretectonic cross section of the Trommald Formation showing stratigraphic relationships between the thin- and thick-bedded facies of Schmidt (1963) and their relationship to the inferred distribution of syngenetic manganese (stippled). No horizontal or vertical scale intended.

It has been generally assumed that much of the manganese in the manganiferous parts of the Trommald Formation is associated with what has been called "green carbonate slate," that is, iron-formation in which most of the iron and manganese are present as carbonates (Harder and Johnston, 1918; Thiel, 1924a; and Grout and Wolff, 1955). Assay data suggest that these "green carbonate slates" can carry as much as 16 percent manganese, and very limited petrographic data imply that they consist of quartz, manganiferous calcite or siderite, fibrous silicates, and some magnetite. Although data are sparse, it may be significant that no specific manganese minerals have yet been identified. Stratigraphic studies show that the "green carbonate slates" are very irregularly distributed, both in thickness and in lateral extent, and the available data are insufficient to establish geologic criteria that can be used to predict how the "green-carbonate slates" are distributed. Another problem is that manganese has also been assayed in rocks of the Trommald Formation that appear to lack appreciable quantities of "green carbonate slate," and thus some manganese may be present in the silicates, especially in stilpnomelane (Schmidt, 1963).

Manganese also occurs in several of the iron-formations in the Rabbit Lake Formation. For example, Grout and Wolff (1955) report that manganiferous iron ore was removed from the Virginia mine, which according to Schmidt (1963) was developed in the Rabbit Lake Formation. Similarly Schmidt (1963) reports that several lenses of iron-formation in the upper part of the Rabbit Lake Formation also are maganiferous, but in all situations, specific geologic details are lacking.

Despite the lack of substantive data, it seems reasonable to conclude that the manganiferous parts of the various iron-formations of the North range are not the result of post-depositional phenomena that remobilized manganese, but rather are a primary depositional feature. Therefore the acquisition of mineralogical data within a carefully constrained stratigraphic framework is essential if the manganiferous parts of iron-formations of the North range are to be understood and developed.

All of the mines producing manganiferous iron ore and ferromanganese ore, with the exception of the Snowshoe and Virginia mines, have been opened in the Trommald Formation. Some ores are dense or massive, but others are friable or earthy. Regardless of texture, the manganese content of the orebodies varies considerably from place to place, depending on the original tenor of the iron-formation. Generally, an increase in the manganese tenor is accompanied by a decrease in the iron tenor, and the combined percentage of iron plus manganese in commercially usable ore was fairly constant at around 45 to 50 percent. As the combined percentage decreases toward the edge of an ore body, the percentage of silica and alumina increases and the material passes transitionally into unaltered protolith.

In the manganiferous ores, only a very small part of the manganese occurs as discrete masses of macrocrystalline materials; most of it is finely disseminated and forms a integral part of the iron ore. Small quantities of disseminated manganese minerals are difficult to identify by ordinary optical methods, and unfortunately most of the earthy manganiferous ore contains manganese distributed in this way. Of 24 earthy samples studied by X-ray methods (Schmidt, 1963), manganite was detected in only three samples. Schmidt also examined specimens where the manganese minerals were obviously crystalline. Four manganese minerals were identified. One specimen contained groutite, a mineral compositionally similar to manganite; two specimens contained groutite, manganite, and a trace of goethite; four contained manganite; two contained pyrolusite; and one contained pyrolusite and cryptomelane, a potassium-bearing manganese oxide. Even though the frequency of occurrence of the minerals identified by X-ray diffraction techniques cannot be considered to be even roughly representative of the relative abundance of the minerals in the ores, the data do indicate the presence of diverse mineral assemblages.

No modern data are available regarding the paragenetic history of the various manganese minerals that have been recognized. Thiel (1924b) suggested that particular manganese minerals and particular iron-ore types are associated, and both are related to the kind of iron-formation from which they formed. Thiel recognized two ore types, hematitic and limonitic, but subsequently Schmidt (1963) recognized seven distinctly different types of iron ore on the basis of texture and mineralogy of the iron oxides. Most orebodies comprise a mixture of types, and so no simple classification can be applied to any one orebody. In general, however, limonitic ores are associated with both thick- and thin-bedded iron-formation throughout the North range, whereas hematitic ores are restricted to thin-bedded iron-formation and to orebodies rich in manganese. Manganese does not occur in all the orebodies, but Thiel (1924b) has suggested that where it does occur, pyrolusite is most abundant in the soft limonitic ores, whereas manganite is more abundant in the hard hematitic ores; cryptomelane occurs in both ore types.

In both ore types, the iron oxides appear to have formed first and to have been replaced by the manganese minerals. The paragenetic sequence in ore formed from thick-bedded iron-formation appears to be rather simple. Much of the original magnetite is pseudomorphically replaced by martite. Some of the martite grains are replaced in turn by fine intergrowths of limonite, manganite, and pyrolusite. Additionally, intergranular void spaces between martite grains are filled with manganite, which in places is partly replaced by pyrolusite. However, the paragenetic sequence in hematitic ores formed from thin-bedded iron-formation appears to be complex. Early-formed hematite is pseudomorphically replaced by limonite, and both iron oxides are partly to entirely replaced by manganite. Manganite also replaces a manganese-rich carbonate and quartz. The manganite is replaced locally by pyrolusite. Manganite and limonite also occur as discrete, more or less homogeneous layers which seem to reflect original sedimentary layering. Many of the limonite layers also contain psilomelane, a barium-bearing manganese oxide, either as nodules or as pseudomorphs after hematite.

Well-crystallized manganese minerals of uncertain classification also are present in void fillings in the natural orebodies and in fracture-filling veins in the top of the Mahnomen Formation. These kinds of deposits reflect the greater chemical mobility of manganese relative to that of iron, but the total amount of manganese in such occurrences appears to be relatively insignificant.

The manganese-bearing ores of the North range occur as residual concentrates of admixed iron and manganese oxides and quartz that formed after some silica, mangesium, calcium, and carbon dioxide were removed from the original iron-formation by oxidizing and leaching solutions. Oxidation and leaching were more or less pervasive throughout the North range. Ore extends, at least locally, to depths of more than 305 meters (Zapffe, 1933), although the deepest mined ore was from the 800-foot (244 meters) level of the Armour No. 1 mine (Marsden, 1972).

In summary, there are two factors which controlled the development of the manganiferous ores. The first and more important control was stratigraphic. The highest grade ferromanganese ores, which were selectively mined by underground methods, occur within or near the manganese-bearing transition zone between thin- and thick-bedded iron-formation. Thus the manganiferous ores occur only where manganese was a relatively abundant constituent of the unoxidized iron-formation. The second control was structural. Many small orebodies are located on steep, virtually monoclinal limbs of large folds. Larger bodies, however, are developed in areas of intense folding where fracturing provided channelways for migrating solutions, and more importantly, where the tight folding increased the subcrop width of iron-formation exposed to oxidation and leaching and consequently the width of any minable orebody. Thus, large orebodies are found in the axial areas of tight folds, particularly where the fold axes have gentle plunges.

Resource Estimates

According to estimates by the Minnesota Department of Revenue, taxable reserves of ore on the North range decreased markedly from nearly 41.4 million metric tons in 1953 to approximately 21.8 million metric tons in 1973 and approximately 15.5 million metric tons in 1989. Over the same time

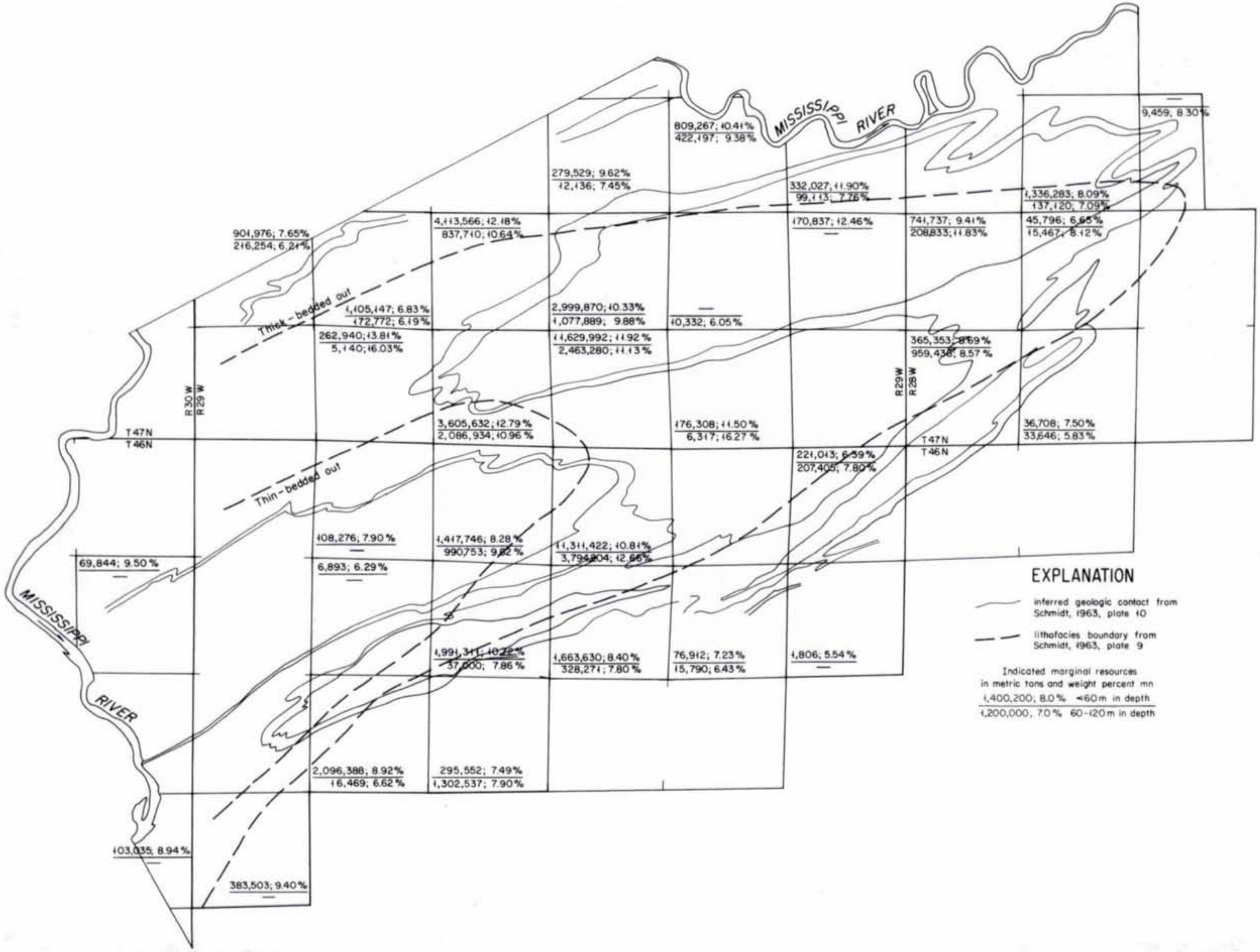

Figure 6. Geologic map of the North range (modified from Schmidt, 1963) showing manganese resource estimates, exclusive of mines and reserve properties, as calculated by Beltrame and others (1981).

interval, shipments declined from about 3.3 million metric tons in 1953 to 281,000 metric tons in 1973 and 55,500 metric tons in 1984. No ore was shipped during the period 1985-1987 (Lipp, 1988). Only approximately 25 percent of the ore shipped in 1953 was manganiferous, whereas 55 percent of the ore shipped in 1973 contained on the average 13 percent manganese. All of the ore shipped in the 1980s was manganiferous, averaging approximately 13-14 percent manganese (Aase, 1982). Clearly the only economic value of the material that could be mined on the Cuyuna North range today is a function of the manganese content.

Under current economic conditions, the commercial potential for naturally formed manganese-bearing ores from the Cuyuna range is rather small. Nonetheless, a fairly large quantity of this material is still available on the North range. Using data from the Office of Ore Estimation and the Minnesota Department of Revenue, Beltrame and others (1981) estimated that approximately 5.5 million metric tons of measured ore averaging 11.69 percent manganese is available on 39 separate properties (Fig. 4). This estimate excludes materials containing less than 5 percent manganese and materials from depths of more than 100 meters. Of the 39 properties, the Zeno mine is estimated to contain 1.28 million metric tons of ore averaging 12.81 percent manganese. The estimated average tenor of these ores is very similar to the general tenor of ferromanganese ore shipped from the North range from 1976 through 1980, which ranged from 12.80 to 14.04 percent and averaged 13.40 percent manganese (Aase, 1982).

Data from the Office of Ore Estimation are very reliable, and are important in that they provide a measure of how much ferromanganese ore is readily available for large-scale mining and processing in the event of a national emergency. Nonetheless, because the data are geographically restricted to existing iron ore mines and iron ore reserves, they fail to provide a reasonable estimate of the manganese resources of the entire North range.

More important for the future production of readily attainable manganese ore is the technology for concentrating low-grade manganese-bearing iron-formation. So far attempts to concentrate this material into a marketable commodity have not been successful. Nonetheless from a geologic point of view, large quantities of low-grade materials are present at many places on the North range (Fig. 6). For example, approximately 80 million metric tons of iron-formation averaging 10.46 percent Mn with a cutoff grade of 5 percent, have been indicated to occur above a depth of 120 meters in 43 legal sections in 10 separate townships (Beltrame and others, 1981). Of the 80 million metric tons occurring above 120 meters, about 53 million metric tons averaging 10.50 percent manganese occur within 60 meters of the surface. Of that total, 8.4 million metric tons average 20.48 percent manganese, 14 million metric tons average 12.12 percent manganese, and 31 million metric tons average 7.04 percent manganese. Like the measured manganese resources associated with existing iron-ore properties, the indicated manganese resources within 60 m of the surface, as calculated by Beltrame and others (1981), are readily accessible using conventional mining techniques.

The present geologic data base is insufficient to make a comprehensive estimate of the entire manganese resource of the range at this time. In particular, it is not possible to extrapolate the boundaries of manganese-rich units over any great distance, because neither the degree of spatial continuity between drill holes, nor the complex stratigraphic and structural relationships are known in detail. Nonetheless Beltrame and others (1981) have suggested that in addition to the 80 million metric tons of indicated ore present to a depth of 120 meters, an additional 90 million metric tons of inferred resource also may be present to that depth. Of that total, they estimate that 15 million metric tons contains more than 15 percent manganese, 23 million metric tons contains 6-15 percent manganese, and an additional 53 million metric tons contains 5-10 percent manganese. If these inferred resources have an assumed average grade of 10.5 percent manganese as in the indicated ores, Beltrame and others (1981) have defined a total resource of at least 170 million metric tons of manganese ore averaging 10.46 percent or more manganese, equivalent to about 18 million metric tons of contained manganese metal.

Beltrame and others (1981) have suggested that at least 270 million metric tons of inferred resources containing between 1 and 5 percent manganese and averaging 2.52 percent manganese also occurs to a total depth of 120 meters. Although these data are greatly speculative and serve primarily to demonstrate the existence of a large but poorly known low-grade resource, they are consistent with subeconomic resources amounting to 4.1 million metric tons averaging 2.83 percent manganese as measured by the Office of Ore Estimation for established mining properties.

THE EMILY DISTRICT

The Emily district at the far northern end of the Cuyuna range defines the southwestern closure of the Animikie basin as Southwick and others (1988) described it. The rocks of the basin are particularly well developed on the Mesabi range where the sedimentary fill consists of the Pokegama Quartzite, the Biwabik Iron Formation, and the Virginia Formation, all assigned to the Animikie Group (Morey, 1983).

Stratigraphic and structural relationships are imperfectly known between the westernmost end of the Mesabi range and the Emily district (Fig. 1), owing to a very thick mantle of glacial materials. Nonetheless aeromagnetic patterns and scattered drill-hole information lead to several conclusions. The Biwabik Iron Formation thins to the west along the Mesabi range, and apparently continues to thin as it curves around the western end of the Animikie basin. In the Emily district proper, the stratigraphic position of the Biwabik is occupied by three broadly lenticular units of iron-formation that are separated from one another by intervening sequences of black argillite. The lowermost of these was mapped as the Biwabik by Marsden (1972), who referred to the two higher iron-formation units as the Emily iron-formation (Fig. 3). Morey (1978) proposed that Marsden's Biwabik of the Emily district correlated with the Trommald Formation in the North range. Morey also correlated the Emily Member of the Rabbit Lake Formation as defined by Marsden (1972) with an unnamed unit of iron-formation in the lower part of the Virginia Formation that was first recognized by White (1954) on the westernmost end of the Mesabi range. In this scheme, the third iron-formation of the Emily district was yet another and unnamed unit in the Virginia Formation. In contrast to this scheme, Southwick and others (1988) have suggested that all three iron-rich lenses in the Emily district are informal units that together occupy the approximate stratigraphic position of the Biwabik Iron Formation on the Mesabi range.

The map geometry of the Emily district shown in Figure 2 was first inferred by Marsden (1972) from geophysical and drilling data then held as proprietary information by United States Steel who did a considerable amount of exploration in the district in the late 1940s and early 1950s. Subsequently U.S. Steel donated much of that information to the State of Minnesota, where it is now available at the offices of the Department of Natural Resources, Division of Minerals, in Hibbing, Minnesota.

Marsden (1972) showed that regionally, the rocks of the Animikie Group in the Emily district comprise parts of a broad eastward-plunging synclinorium. However, the extent to which the stratified rocks within the synclinorium were deformed varies considerably from north to south. In the northern part of the synclinorium, in the area just south of the Mesabi range, the beds dip gently southward and the surface between the basement and overlying rocks appears to be relatively undisturbed. Incipient slaty cleavage first appears about 15 km south of the Mesabi range where the rocks are thrown into a series of broad, open, eastward-plunging folds with near-vertical axial planes. This type of structure persists in the Emily district where geometric relationships imply that the basal contact of the Animikie Group overlies an unconformity cut onto older folded rocks of the North range. This conclusion is supported geophysically by an analysis of gravity and magnetic data (Carlson, 1985) that detected anomaly patterns characteristic of the folded rocks of the North range far northeast of their surface termination.

The iron-formations and associated rocks of the Emily district have been pervasively oxidized and leached, particularly along the crests of folds and their associated fractures. However, the development of oxidized and leached iron-formation is quite variable from place to place. In some drill holes fresh rock was encountered at depths of only a few meters below the bedrock surface, whereas thoroughly oxidized and partially leached iron-formation has been encountered at other places at depths of more than 240 meters (Marsden, 1972).

Although manganese has been reported at various places in the Emily district (e.g., Marsden, 1972; Beltrame and others, 1981), its distribution has not been studied in detail, partly because of the pervasive alteration, partly because of a relatively thick glacial cover, and also partly because the resource was considered to be an extension of that in the better known North range (Schmidt, 1963). An analysis of exploration records and nearly 1000 meters of core and churn-drill cuttings from 20 holes (Fig. 7) shows that a substantial resource occurs in sections 20 and 21, T. 138 N., R. 26 W. These deposits have been studied in a preliminary way by Morey and others (1990) and because these results are new, they are discussed here in some detail.

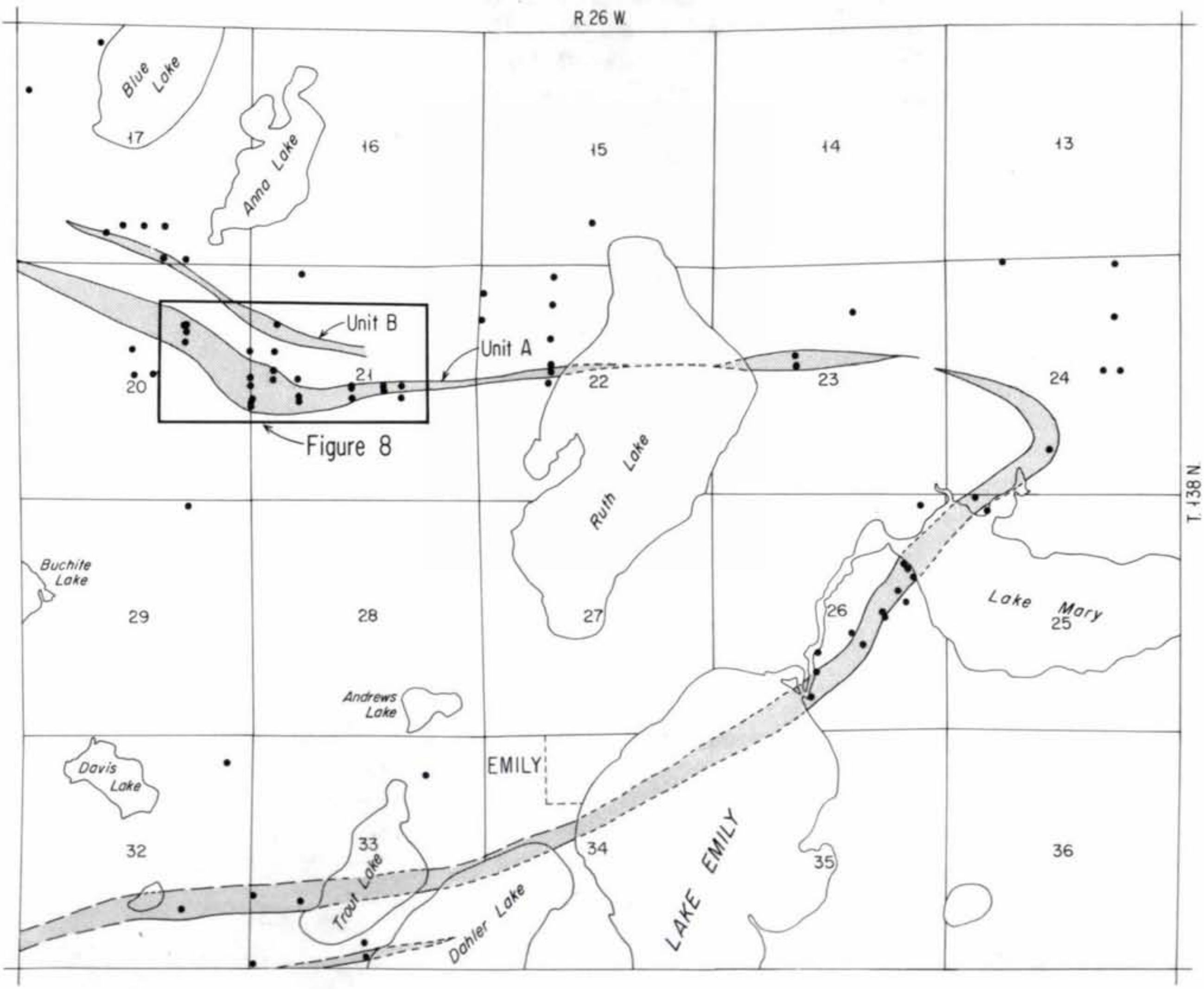

Figure 7. Generalized geologic map of the south half of T. 138 N., R. 26 W. in the Emily district showing the inferred distribution of iron-rich strata (stippled) as established by Marsden (1972) and refined by Morey and others (1990) using drill-hole data available at the Department of Natural Resources, Division of Minerals, Hibbing, Minnesota.

In the Ruth Lake area, the iron-formation lies along the north limb of an east-northeast-plunging anticline. Because of this position on the fold, beds of iron-formation strike to the east and dip 15°-40° to the north (Fig. 8). The strata seem to flatten toward the north and away from the anticlinal axis; if so, the fold either has a riser-and-tread type of configuration, or the regional structure flattens to the north. The iron-formation and associated strata also are broken by a conjugate set of north-northeast- and west-northwest-trending faults that have apparent displacements on the order of several tens of meters.

The iron-rich strata of the Ruth Lake area have many of the features typical of Precambrian iron-formations as defined by James (1955, p. 239). They are chemical sedimentary rocks that contain at least 15 percent iron and they commonly contain layers of chert. Moreover, Morey and others (1990) showed that the chemical constituents exhibit distribution patterns characteristic of Precambrian iron-formations in general (Lepp, 1968) and the Biwabik Iron Formation in particular (Morey and Morey, 1990). However, the basal sequence in the Ruth Lake area, informally called Unit A by Morey and others (1990), is atypical in that it is neither thin bedded nor finely laminated—features also considered to be indicative of Precambrian iron-formations (James, 1955).

The lowermost iron-rich unit at Ruth Lake has been divided by Morey and others (1990) into six distinct lithotopes (Fig. 9). These are: (1) Clastic lithotope; (2) Mixed clastic and algal or jaspery chert; (3) Oolitic or pisolitic; (4) Thick-bedded granular; (5) Mixed thick-bedded and thin-bedded; and (6) Ferruginous chert. Lithotopes 1 and 2 are complexly intercalated and compose a basal unit that marks a change from clastic sedimentation in Pokegama time to chemical precipitation in Unit A time. Similarly lithotope 6 occurs predominantly in the upper part of Unit A where the top of it is intercalated with a black argillaceous unit like those in the overlying Virginia Formation. Thus the upper contact of the ferruginous chert lithotope marks a brief hiatus in chemical sedimentation in the Ruth Lake area.

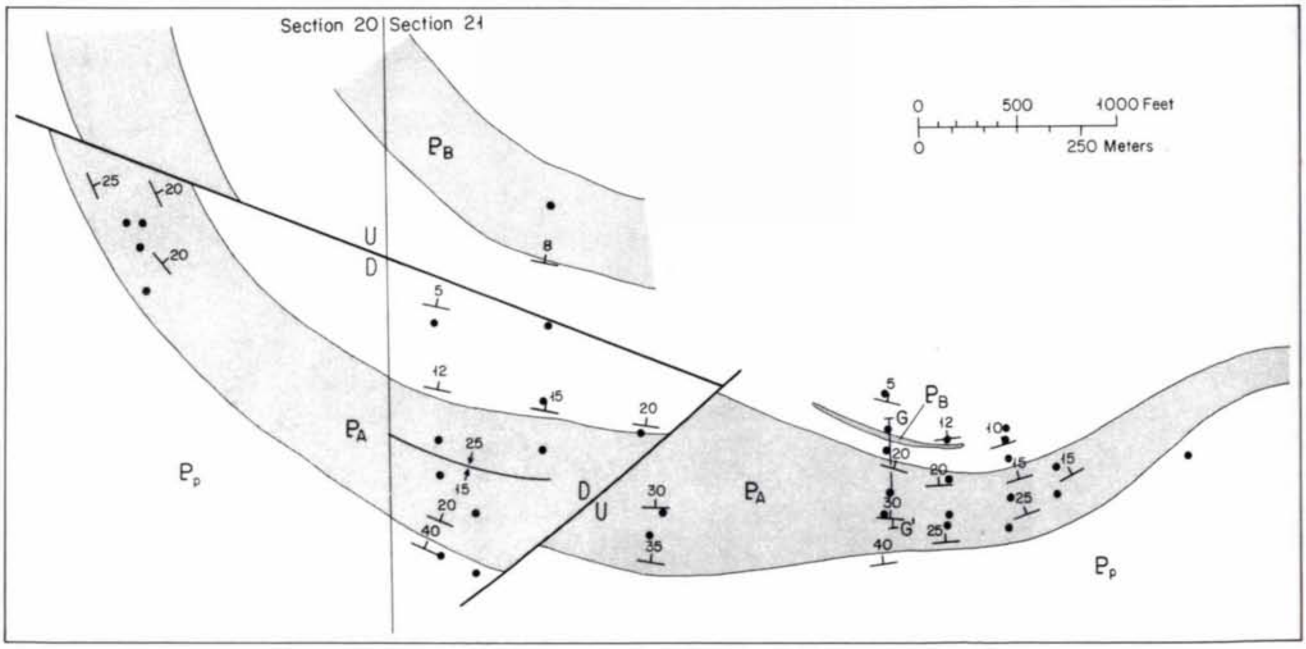

Figure 8. Geologic map of the Ruth Lake area in parts of sections 20 and 21, T. 138 N., R. 26 W. Units PA and PB are iron-rich strata; Pp is the Pokegama Quartzite. The map and location of cross section G-G' are modified from Morey and others (1990).

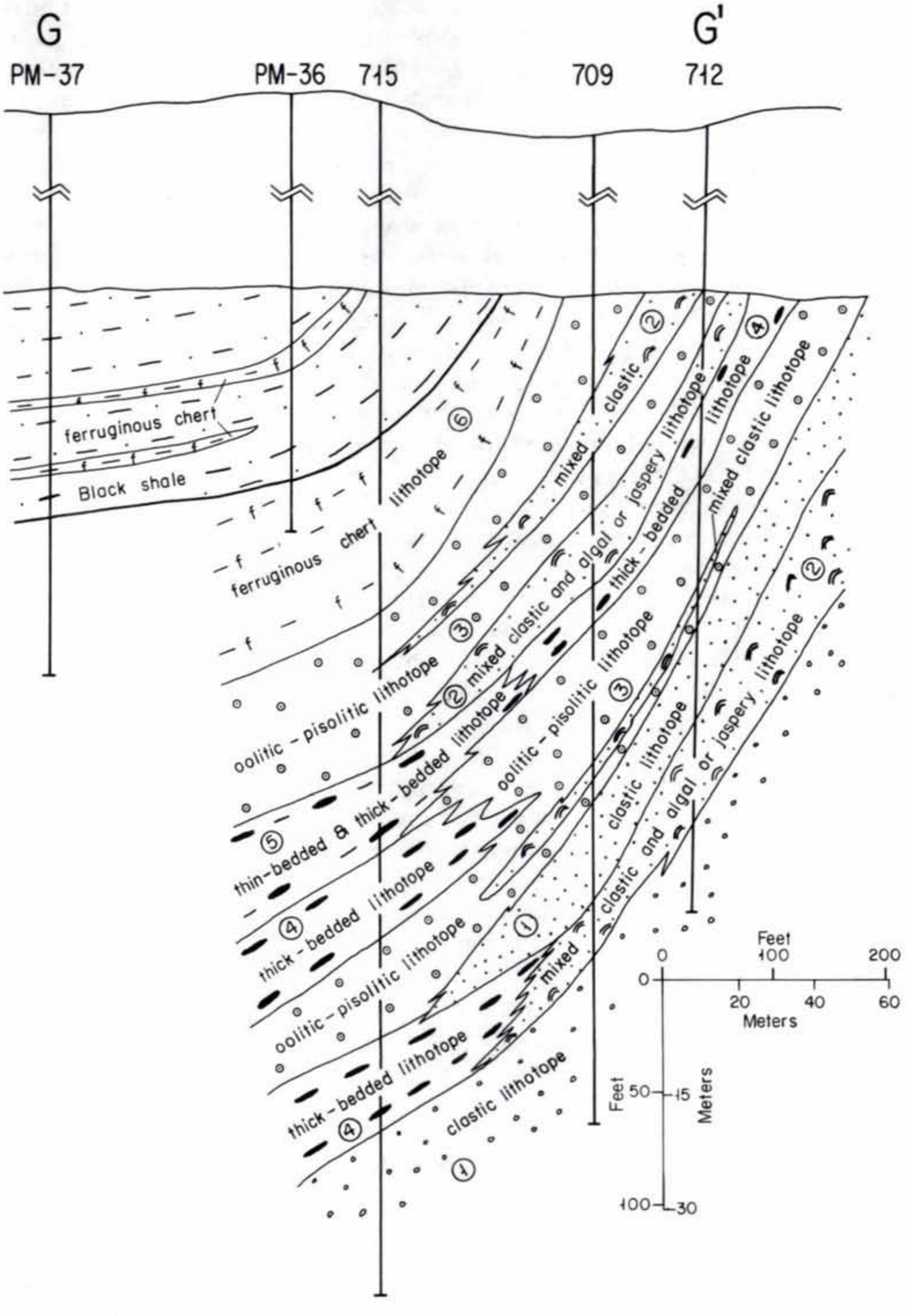

Figure 9. Representative cross section through Unit A of the Ruth Lake area showing inferred vertical relationships between lithotopes recognized by Morey and others (1990). See Figure 8 for location of cross section.

Except for the oolitic or pisolitic rocks, the six lithotopes are broadly similar to the "facies" as recognized by Marsden (1972) who lumped together the algal and oolitic rocks into a single unit. A brief description of each lithotope follows. The clastic lithotope consists predominantly of very thin to thin-bedded, quartz-rich siltstone and shale intercalated with intervals 1 to 3 meters thick of medium- to thick-bedded quartz arenite. Thus this lithotope is a continuation of the dominantly epiclastic sequence of rocks assigned to the Pokegama Quartzite. Intervals of quartz-rich siltstone and shale are typically aluminous clastic rock, characterized by various proportions of quartz and sericite as well as lesser amounts of minnesotaite, kaolinite, or a septechlorite. Beds of medium- to coarse-grained quartz arenite that occur at several stratigraphic levels in the lithotope typically consist of round or subrounded to rarely angular, sand-size grains of terrigenous quartz and in a few places, chert and jasper. Most are relatively well sorted and lack matrix material. Nonetheless a few arenitic beds are poorly sorted and lithified by a matrix of silt-size quartz, sericite, and a septechlorite. Beds of quartz arenite that lack appreciable matrix material contain some interstitial calcite or siderite, but they are for the most part indurated by a silica cement. In contrast, similar beds toward the top of the lithotope are cemented by manganese oxides.

The mixed clastic and algal or jaspery chert lithotope consists of beds of manganese-oxide-cemented quartz arenite intercalated with beds of jasper that are as much as 1 meter thick. The jasper beds are characterized by *in situ* stromatolitic structures intercalated with thin beds of jasper-cemented conglomerate. Pebble-size clasts in the conglomerate beds have an angular shape and consist either of broken stromatolitic material or of jasper identical in composition to that of the enclosing cement. The clasts obviously are locally derived and are of intraformational origin. Sand-size grains of terrigenous quartz are ubiquitous, as are manganese oxides, mainly cryptomelane, which occur as interstitial grains in the arenitic and conglomeratic units. In places manganese oxides are so abundant that they form distinct lens-shaped masses where the original textural attributes are all but obscured.

The oolitic and pisolitic lithotope forms stratigraphic units as much as 18 meters thick consisting predominantly of oolitic and pisolitic structures. Some of the pisolites are as much as 8 centimeters in diameter and may be of oncolitic origin. The pisolites, as well as the much smaller oolites, have rims of manganese oxides that surround shells of alternating quartz and either hematite or geothite. The iron oxides in turn rim core grains of terrigenous quartz. Similar quartz grains that lack rim material also occur randomly scattered throughout the lithotope. These framework grains and structures are cemented in places by goethite but more commonly by manganese oxides, chiefly manganite, cryptomelane, and psilomelane. The lithotope also contains thin to thick beds composed predominantly of manganese oxides mosaically intergrown with various amounts of goethite and in places, quartz. Nodules or lenses of chert and jasper also occur at several places in the lithotope. Because of diverse textural and mineralogical attributes, chemical characteristics vary widely, even over stratigraphic intervals of only about 10 cm.

The thick-bedded lithotope occurs within stratigraphic intervals as much as 12 meters thick. It consists for the most part of beds of so-called "granular" or "cherty" iron-formation characterized by ovoid granules, 1 to 2 mm in diameter and by scattered patchy concentrations or mottles of goethite or hematite. As with other lithotopes, sand-size grains of terrigenous quartz are scattered throughout. The lithotope also contains various manganese minerals, including manganite as disseminated grains in the granular layers. Manganite also occurs as thin, sharply bounded monomineralic layers within granular intervals, and together with psilomelane and cryptomelane, it forms thin to thick, regularly and irregularly bedded layers or lenses, both with and without iron oxides.

The mixed thick- and thin-bedded lithotope can be as much as 12 meters thick. It is texturally and mineralogically identical to the thick-bedded lithotope and is distinguished from it only by the presence of thick layers of so-called "nongranular" or "slaty" iron-formation. These slaty intervals are typically very thin bedded to laminated and are seemingly fine grained because they lack granules and coarse interstitial chert. The slaty or nongranular rocks contain only a few scattered grains of terrigenous quartz, and are unique in that they contain minnesotaite, a 10Å mica, most likely sericite, and kaolinite or a septechlorite—silicate minerals not obviously associated with granular strata in the Ruth Lake area. As in the thick-bedded lithotope, various manganese oxides, including manganite, psilomelane, and cryptomelane, occur in the granular intervals as disseminated grains and as thin to thick beds where they are mosaically intergrown with iron oxides. However, manganese oxides occur very sparingly in the nongranular or slaty intervals in this lithotope.

The ferruginous chert lithotope is a special kind of "nongranular" or "slaty" iron-formation. This lithotope, which in places is as much as 40 meters thick, is composed entirely of thin-bedded to laminated jasper and chert. Individual laminae are defined by various proportions of chert and hematite and in some places, by lesser amounts of siderite and minnesotaite. In general, the lithotope lacks appreciable quantities of manganese although discrete layers or lenses of cryptomelane, generally less than 5 cm thick, occur within the lithotope near boundaries with the mixed thick- and thin-bedded lithotope.

The ferruginous chert lithotope passes transitionally upward into a thin-bedded sequence of black shale and siltstone which contains scattered lenses and layers of ferruginous chert very much like that in the lithotope proper. Regular and sharply defined contacts between layers of shale or siltstone and ferruginous chert imply that detrital and chemical sedimentation were separate and discrete processes.

The general arrangement of lithotopes in the Ruth Lake area implies a gradual change over time from predominantly clastic shallow-water sedimentation, through a period of predominantly chemical precipitation of silica and iron, to a second period of clastic sedimentation under "deeper" water conditions (Fig. 10). This broad trend from shallower to deeper water deposition can be in turn subdivided into two smaller shallow-water to deeper water cycles like those observed in the Biwabik Iron Formation. The ubiquitous presence of appreciable quantities of terrigenous quartz implies that sedimentation probably occurred relatively close to a strandline in shallow water, a probability also indicated by sedimentological attributes associated with the clastic, mixed clastic and algal or jaspery chert, and oolitic-pisolitic lithotopes. Abrupt changes in lithotopes in a downdip direction also imply rapidly changing sedimentological conditions in a basin that deepened to the north.

The obviously shallow-water lithotopes are interlayered with and overlain by the thick-bedded lithotope. In general, the thick-bedded rocks, with and without beds of algal and jaspery chert, are more abundant in the updip parts of the section, whereas thin-bedded material is better developed to the north in a downdip direction. This arrangement implies that the thick-bedded and the mixed thick- and thin-bedded lithotopes were deposited under generally similar sedimentological conditions, but that the thinner bedded components of the iron-formation were deposited in slightly deeper water. The position of the ferruginous chert lithotope in this reconstruction is even more uncertain. However, because it is everywhere overlain by, and in places is interbedded with black shale having "deeper water" affinities, the ferruginous cherts most likely accumulated under very quiet conditions in water presumably deeper than that responsible for the other lithotopes.

Stratigraphic reconstructions by Morey and others (1990) suggest that the Ruth Lake sequence forms part of a shelf to basin sequence that deepened to the north. In this model storm wave base, or where waves first infringe upon the bottom, is marked by the appearance of grainy beds (lithotope 4). The grainy units pass offshore into muddier beds (lithotopes 5 and 6) and onshore into oolitic and pisolitic shoals (lithotope 3) that also contain lenses and layers of conglomeratic material.

The shoal rocks in turn grade laterally into a back-ramp platform sequence characterized by cyclic shallow to supratidal deposits (lithotopes 1 and 2).

Distribution of Manganese-Bearing Materials

It is apparent from the previous descriptions that manganese oxides are an important component of the iron-formation in the Ruth Lake area. A cutoff grade of 1 weight percent manganese averaged over sample intervals of 1.3 meters was used in Figure 10, which shows that manganese first appears as a significant constituent in the quartz arenitic parts of the clastic lithotope and all but disappears with the appearance of the ferruginous chert lithotope. Thus in a stratigraphic sense, manganese appears in the stratigraphic column before iron appears, and disappears from that column before the iron disappears. Thus iron and manganese have dissimilar stratigraphic distributions, even though their chemical features predict that they should behave similarly in dilute aqueous solutions.

Manganese oxides typically occur as disseminated grains, mottles, lenses, and pods in iron-rich strata and as a pore-filling cement in quartz arenite. They are, however, concentrated in appreciable quantities at two levels in the iron-formation that more or less conform to the stratigraphic occurrences of the oolitic-pisolitic lithotope. Given an arbitrary cutoff grade of 10 percent manganese, the upper enriched zone forms a stratabound lens some 750 meters in strike length and as much as 15 meters in thickness that occurs in the central part of the Ruth Lake study area (Fig. 11). The lower enriched zone is much larger. It forms a stratabound lens that can be as much as 30 meters thick although most of it ranges in thickness from 15 to 20 meters. The lower enriched zone clearly pinches out to the east, but it can be traced with certainty to the west along strike for at least 1000 meters; it can reasonably be inferred to continue to at least the west edge of the Figure 11 area for a total strike length of more than 1600 meters. The original exploration records and associated assays imply that both ore zones are constructed of a series of lens-shaped masses that have average manganese values of 10-20 weight percent. These lenses in turn contain somewhat smaller lenses having 20-30 weight percent manganese. They in turn consist of lens-shaped masses 1.5 to 3 meters thick and generally less than 30 meters long where values of greater than 50 weight percent manganese can be found. None of the higher grade intervals seem to be stratigraphically constrained within the ore zones. This situation creates a problem in that measured manganese values for any given set of samples are as much a function of the size of the stratigraphic interval over which the sample is taken, as they are a function of the actual manganese content.

Manganese minerals in both the upper and lower enriched zones are chiefly manganite, psilomelane, and cryptomelane. Pyrolusite also was identified from the lower enriched zone, as was braunite, a manganese mineral believed to be of high-temperature origin. The significance of this mineral in the Ruth Lake area has not been established. Although dominated by manganese oxides, both zones also contain appreciable quantities of goethite, hematite, chert, and terrigenous quartz. Representative ratios of manganese to iron in the upper zone range from 0.43 to 1.55, whereas in the lower zone these ratios range from 0.52 to 4.51.

Manganite appears to be the most abundant of the manganese minerals and is clearly of secondary origin in both zones. Psilomelane and cryptomelane are most likely primary phases, but it is difficult to determine the relative abundances from X-ray diffraction data. The upper zone contains appreciable potassium (0.4-0.9 percent) and barium (0.69-0.86 percent), consistent with the presence of both cryptomelane and psilomelane.

As in the upper enriched zone, it is difficult to determine by X-ray techniques the relative abundances of cryptomelane and psilomelane in the lower zone. Potassium values ranging from 0.18 to 2.58 percent suggest that cryptomelane may be a fairly abundant phase. Similarly, samples from

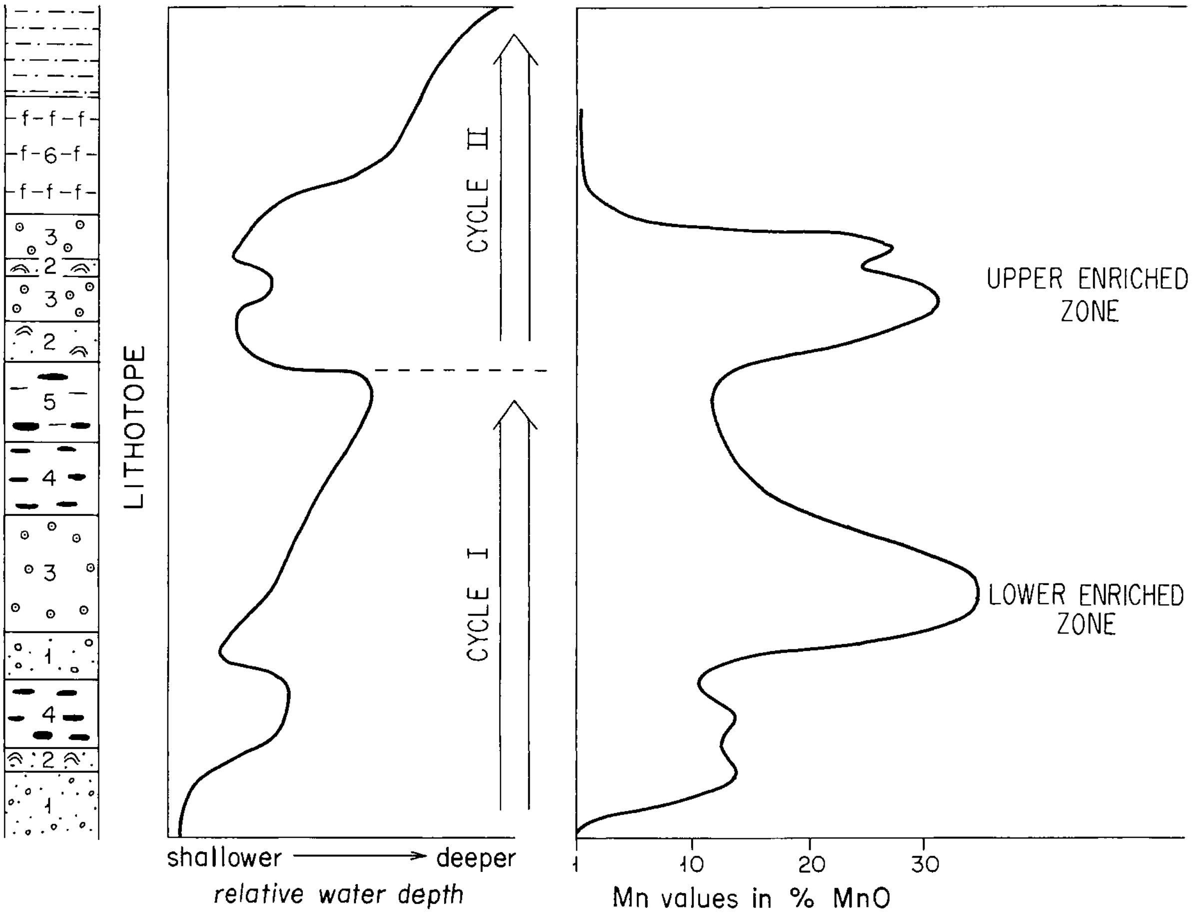

Figure 10. Diagram showing sedimentological explanation for the distribution of lithotopes in Unit A. The diagram also shows distribution of manganese based on manganese (MnO) assay data acquired mostly over 1.5-meter intervals as recorded in logs available at the Department of Natural Resources, Division of Minerals, Hibbing, Minnesota. Note the correlation of high manganese values with the position of the oolitic-pisolitic lithotope . Modified from Morey and others (1990); no vertical scale intended.

the lower zone containing from 0.5 percent to as much as 3.2 percent barium imply that psilomelane also may be an important phase in the lower zone.

The question of the origin of the manganese oxides has not been resolved completely. Because the Emily district was oxidized pervasively during Late Mesozoic time, it has not been possible to establish with certainty a syngenetic or an epigenetic origin for the oxides. Stratigraphic and textural attributes in the iron-formations of the Emily district are very much like those in unoxidized magnetite-rich parts of the Biwabik Iron Formation on the Mesabi range and the Trommald Formation on the North range, and Marsden (1972) inferred that the rocks of the district, including those at Ruth Lake, were simply the strongly oxidized equivalents of those units.

Thus in Marsden's view, all of the iron and manganese oxides were of epigenetic origin. Although not explicitly stated, this scenario implies that manganese oxides at Ruth Lake were derived from some sort of carbonate and/or silica protolith, presumably like the green carbonate slate of the Trommald Formation on the North range. Unfortunately there is only circumstantial evidence to suggest that the manganese was deposited at Ruth Lake as carbonate or silicates and subsequently remobilized or at least transformed to oxides by a weathering event. If such an event occurred, it totally obliterated all indication of the original mineral phases.

Using a slightly different approach, Morey and others (1990) have suggested that many of the stratigraphic, textural, and mineralogical features of the Ruth Lake sequence are consistent with a simple depositional model involving the precipitation of silica and iron oxides as primary phases in a shallow-water, well-agitated aerobic (oxic) environment. In their view, the Ruth Lake sequence is an ordinary Precambrian iron-formation which contains ordinary quantities of iron and silica, together with lesser constituents such as alumina, phosphorous, and titanium. Thus the Ruth Lake rocks are an example of a Precambrian oxide (hematite) facies iron-formation as defined by James (1955). Because manganese carbonates would not be expected to occur in iron-formation formed in such an environment, it seems more likely that the manganese was precipitated as an oxide phase.

Both iron and manganese have similar solution geochemistries, particularly under oxic conditions, and therefore any syngenetic depositional sequence should be characterized by a direct relationship between the two constituents. The only exception involves the situation where iron is removed from the depositional system before oxic conditions were attained and where manganese oxides would be precipitated (Cannon and Force, 1983). This situation did not occur in the Ruth Lake area where appreciable quantities of both constituents are closely associated. Morey and others (1990) suggest that the iron and manganese oxides do not occupy coincident stratigraphic intervals at Ruth Lake because the latter are concentrated in the coarser grained parts of the iron-formation. Therefore they suggest that the Ruth Lake sequence was the product of two separate but interrelated chemical processes that were somewhat separated in geologic time. The first process involved the syngenetic precipitation of ordinary oxide-facies iron-formation in a shallow-water oxic environment, whereas the second involved the epigenetic formation of manganese oxides at selected stratigraphic levels by reflux processes involving anaerobic ground waters capable of carrying manganese in solution. In this model, Morey and others (1990) assume that folded and fractured manganese-bearing strata of the North Range group were the source of the manganese.

Resource Estimates

No complete estimate has been made of the manganese resource present in the Emily district. However the Ruth Lake area in general, and sections 20 and 21 in particular, seems to contain more than 1 million metric tons, and it could contain as much as 2 million metric tons of potential ore averaging 20 weight percent or more manganese. Thus the Ruth Lake area in itself could be one of the largest manganese resources in the United States. Scattered drill-hole data available in the files of the Minnesota Geological Survey indicate that appreciable quantities of manganese also occur elsewhere in the district. Manganese also occurs as a significant resource approximately 3 km to the southeast of Lake Emily in section 5, T. 137 N., R. 26 W. There the so-called Emily-Shawmut Reserve contains, according to the Office of Ore Estimation, 468,111 metric tons of material averaging 11.52 weight percent manganese. The Office of Ore Estimation also reports that the Reserve contains an estimated 365,598 metric tons of additional material averaging 9.32 weight percent manganese. Lastly, Beltrame and others (1981) inferred that an additional 840,000 metric tons of material averaging 10.56 weight percent manganese occurs scattered over that township. Of that additional tonnage, 470,000 metric tons have an average of 11.52 weight percent manganese and another 370,000 metric tons have an average 9.32 weight percent manganese.

PROPOSED RESEARCH

It is evident from the foregoing review that there is a considerable manganese resource on the Cuyuna iron range. However, it still is not possible to construct a coherent, detailed model of the structure and stratigraphy of the several different kinds of manganese-bearing materials, their tenor and extent, and their paragenetic development. Natural exposures of the manganiferous materials are very sporadic, and subsurface exploration data are fragmentary. The various kinds of manganese-bearing materials themselves are mineralogically highly complex, variable, and fine grained, and the deposits are structurally complex.

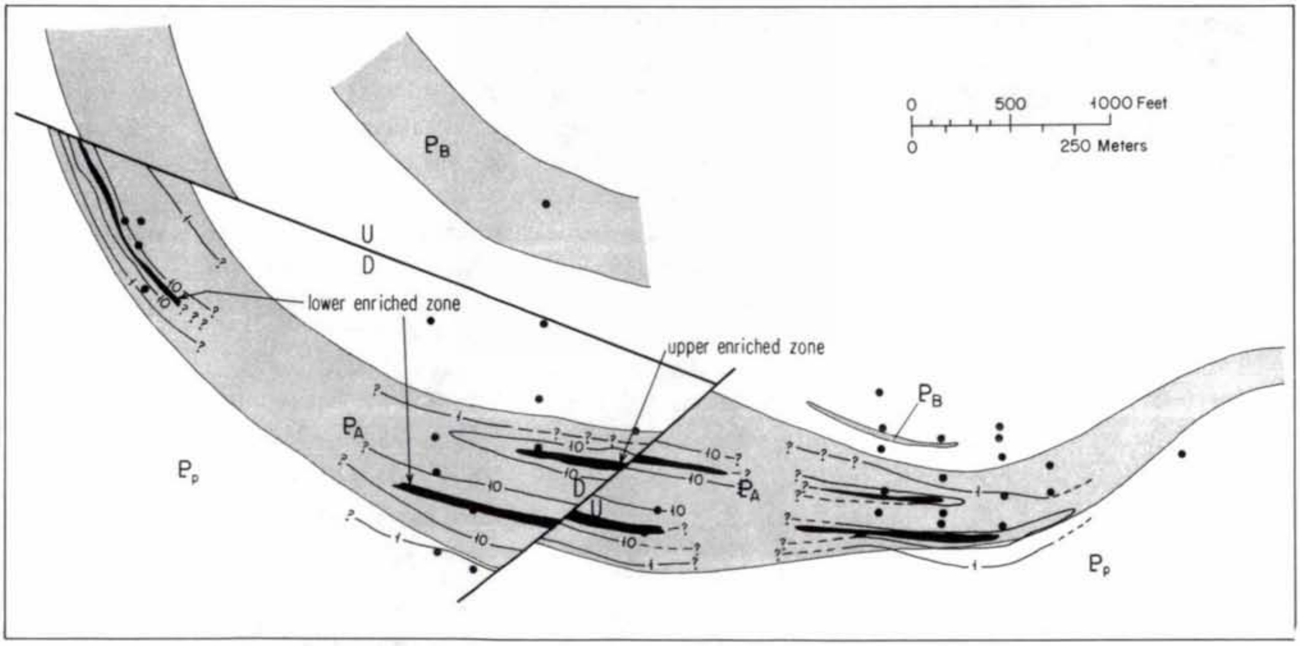

Figure 11. Geologic map of Unit A of the Ruth Lake area showing the inferred subcrop distribution of manganese-enriched zones (modified from Morey and others, 1990). Contours at 1, 10, and >30% (black) manganese values.

On the other hand, a modern coordinated investigation still needs to be made. Much information, not hitherto available, is now accessible because active mining has all but ceased on the Cuyuna range. Proprietary information has been released and now is part of the public record. Furthermore many of the fine-grained, complex materials, intractable to older methods of analysis, can now be investigated by modern analytical techniques. A modern attack has much to offer, both scientifically and practically. A scientific understanding of the nature, origin, and occurrences of the various manganese-bearing materials is basic to describing and evaluating the known resources, providing targets for further exploration and development, and providing a basis for the evaluation of various possible metallurgical and beneficiation techniques.

From an operational standpoint, there are two phases to any proposed research. The first is to collect, organize, and evaluate existing data and materials, and to apply modern theoretical concepts and techniques to them. The second is to acquire new data where information is most critical. These phases of research are not necessarily sequential or interdependent, but it must be recognized that the second phase of acquiring new data is necessary to any intelligent research program. The ultimate utilization of manganese from the Cuyuna range will not be advanced if we continue to confine ourselves to the study of archival materials. This is true partly because it is not always possible to place the archival data into context either stratigraphically or structurally. Therefore we can never be sure if the archival materials we can study are representative of the entire system. This difficulty is complicated by the fact that most archival materials were acquired as part of an iron-mining program, where as often as not, the presence of manganese was thought of as secondary. What is needed to complement the archival approach is a systematic drilling program involving only a few sites, if the sites are carefully selected using the full array of geologic tools to establish the stratigraphic and structural frameworks in which the manganiferous materials occur.

On the North range, probably enough data are compiled in Schmidt (1963) to select several potential drilling sites. However, the selection of a specific site or sites is complicated by the fact that manganiferous layers in the Trommald Formation are presumably lenticular in shape and that individual layers occupy different stratigraphic positions within the transition zone between Schmidt's thin-bedded facies and thick-bedded facies. Furthermore, the rocks are complexly folded and buried by as much as 135 meters of glacial debris. Thus the selection of a specific site is no trivial task. That process should be aided by geophysical techniques including potential field studies, induced polarization (IP) techniques, and electromagnetic (EM) techniques.

In the Emily district, the selection of potential drilling sites should be less complicated because extensive information and materials are now in the public record. The geologic materials in particular are of considerable value and should be more fully utilized than has been done to date by Morey and others (1990). Nonetheless, new drilling to the north of the iron-formation subcrop in the Ruth Lake area will be necessary to test several of the ideas regarding the sedimentological aspects of the manganese model that they have proposed.

It goes without saying that petrographic and petrologic studies of the manganiferous materials from the North range and the Emily district are necessary. It has never been feasible economically to recover manganese from the Cuyuna range. The ore-bearing zones are fairly small and relatively deeply buried, but the main problem is developing metallurgical methods that can effectively separate manganese from the iron without expending large quantities of energy. It is obvious that the more or less standard beneficiation techniques that were tried in the past do not work, largely because the mineral and textural systematics of the ores were not well understood. This time, we need to design metallurgical and beneficiation techniques that are specifically matched to particular mineral systems. To match ore and technique requires a comprehensive understanding of the physical and chemical parameters that characterize the various manganese materials. We have the tools to characterize the potential ores. We need only to drill the holes to obtain the materials to do so.

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