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MANGANESE RESOURCES OF THE CUYUNA RANGE, EAST-CENTRAL MINNESOTA

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PREFACE

This report is an outgrowth of an earlier study completed for the U.S. Bureau of Mines (USBM) under grant #G0264002 entitled "Manganese-bearing ores of the Cuyuna iron range, east-central Minnesota, Phase 1" (Minnesota Geological Survey, 1977). Portions of that report have been published previously, namely, "Selected bibliography of Cuyuna range geology, mining and metallurgy" and "Directory of information on Cuyuna range geology and mining" (Beltrame, 1977a, and 1977b respectively).

Several years after completing the USBM report, the need arose to reevaluate the computational procedures which were used in arriving at our previous resource estimates. Major revisions in both the computational procedures and resource estimates form the basis of this report. All computations were performed on a Control Data CYBER 172 computer at the University of Minnesota Computer Center. The computer data base used in this study will be described in a future publication.

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MANGANESE RESOURCES OF THE CUYUNA RANGE, EAST-CENTRAL MINNESOTA

by

R.J. Beltrame, Richard C. Holtzman, and Timothy E. Wahl

ABSTRACT

The Cuyuna range, located in east-central Minnesota, consists of a sequence of argillite, siltstone, iron-formation, graywacke, slate, and quartzite of early Proterozoic age. Manganese-bearing materials occur within the iron-rich strata of the Trommald Formation and the Rabbit Lake Formation. Computer-assisted resource estimates, based on exploration drill hole information, indicate that the Cuyuna range contains a minimum of 176 million metric tons (MMT) of marginally economic manganiferous rock with an average grade of 10.46 weight percent manganese. The calculated 18.5 MMT of manganese on the Cuyuna range could supply this country's needs for this important and strategic metal for nearly 14 years. An additional resource of 6.9 MMT of manganese metal is available in the lower grade deposits. The vast majority of these calculated resources are extractable by current surface mining techniques.

INTRODUCTION

Manganese is indispensable in the production of steel, more than half of which is used by the transportation, construction, and machinery industries (DeHuff, 1980a, p. 96). This, coupled with the fact that our net import reliance is 98 percent of our apparent consumption (U.S. Bureau of Mines, 1979b, p. 36), emphasizes the urgent need of this country to assess its available sources of this important strategic metal. It has been estimated (Dorr and others, 1973, p. 394) that the Cuyuna range contains more than one-third of the total manganese resources of the United States.

In 1976, the Minnesota Geological Survey acquired from the U.S. Bureau of Mines (USBM) 12,833 exploration drill hole logs with accompanying plan maps. Under contract with the USBM, 5,045 drilling logs were entered into a computerized data base management system. This information was used in the present study to estimate the indicated and inferred manganese resources of the Cuyuna range. Attention was concentrated on the relatively high-grade resources (>5 percent Mn) that would be most in demand in the event that manganese imports were significantly reduced.

GEOLOGY AND MANGANESE DISTRIBUTION

The Cuyuna iron range is located about 150 km southwest of Duluth in parts of Aitkin, Cass, Crow Wing, and Morrison Counties in east-central Minnesota (fig. 1). The range is traditionally divided into three distinct areas, the Emily district, the North range, and the South range. The North range was the principal site of mining activity, which had largely ceased by 1970. Only a few underground mines were operated on the South range. Though exploration drilling has been extensive in the Emily district, mining never commenced.

The geology of the Cuyuna range is described in detailed studies by Harder and Johnston (1918), Grout and Wolff (1955), and Schmidt (1963). Regional geologic relationships are reviewed by Marsden (1972) and Morey (1978). An extensive bibliography of Cuyuna range geology was prepared by Beltrame (1977a).

The entire Cuyuna range is mantled by Pleistocene drift ranging in thickness from 6 to 140 m. Typical drift thickness for the areas studied is 20 to 45 m. The topography is generally flat with a maximum local relief of about 50 m for natural features. The entire area is poorly drained and the water table lies close to the surface so that abandoned mines soon fill with water, forming manmade lakes. Because of the persistent drift and near-surface water table, there are no bedrock outcrops, and bedrock geological studies must depend on exploration drilling logs and geophysics.

Bedrock in the Cuyuna range is composed chiefly of early Proterozoic metasedimentary rocks of the Animikie Group (Morey, 1978). The dominant rock type is argillite or slate, with lesser amounts of siltstone, iron-formation, graywacke, and quartzite. The Animikie Group is composed of three conformable units.

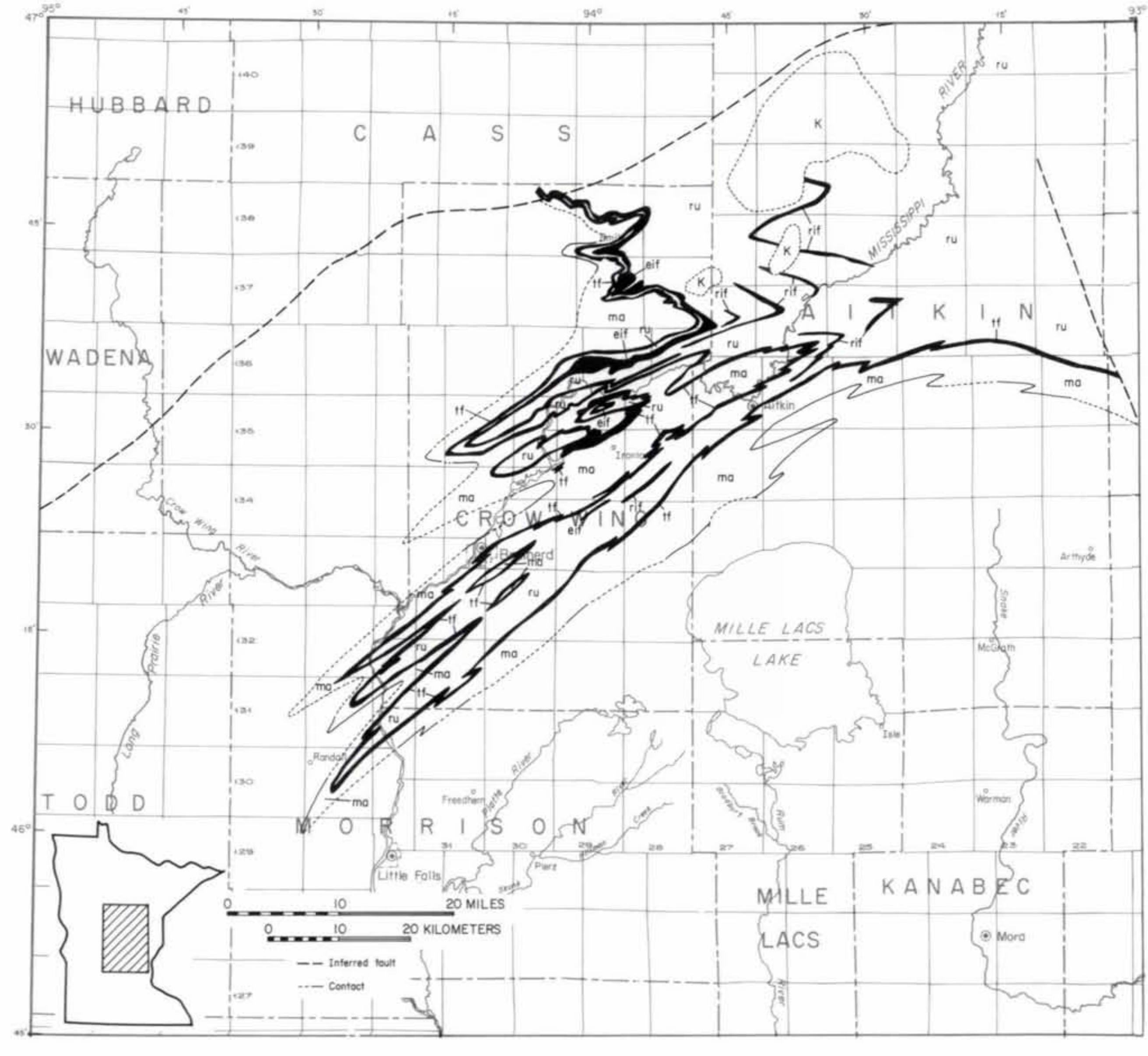

Figure 1 -- Generalized bedrock geologic map of east-central Minnesota. Units include, in ascending order: ma, Mahnomen Formation; tf, Trommald Formation; ru, Rabbit Lake Formation, which includes Emily Iron-formation Member (eif) and other unnamed but mappable bodies of iron-formation (rif); and K, Cretaceous sedimentary rocks, undivided. Modified from Morey (1978).

The principal manganese deposits occur in the Trommald Formation, which is underlain by the Mahnomen Formation and overlain by the Rabbit Lake Formation. Postdepositional tectonism has metamorphosed these rocks and deformed them into a complex series of tight, northeast-trending folds. An examination by Beltrame of the distribution of rock types and aeromagnetic lineaments suggests that extensive northwest-trending faults exist throughout the area, most notably in the South range. This faulting appears to be an extension of faulting in the Thomson Formation and middle Proterozoic (Keweenawan) sedimentary rocks of east-central Minnesota.

The Mahnomen Formation consists of argillite (or slate, phyllite, or schist depending on metamorphic grade) interbedded with siltstone, and minor amounts of quartzite, sandstone, graywacke, and limestone (Schmidt, 1963). Schmidt estimated that the Mahnomen Formation is more than 610 m thick, inasmuch as drilling to this depth had not penetrated the basal contact. The upper contact of the Mahnomen Formation with the overlying Trommald Formation is generally sharp, but in places it is a gradation from quartzite upward to sandy iron-formation.

The main iron-formation of the Cuyuna range is the Trommald Formation, named by Schmidt (1963, p. 18). This unit is stratigraphically most distinct in the North range. It consists primarily of quartz and iron minerals in the form of oxides, carbonates, and silicates. These constituents were precipitated from aqueous solution or colloidal suspension; thus, clastic components are minor to absent. Much of the iron-formation was probably deposited in the ferrous (Fe^{+2}) or unoxidized state and later oxidized to the ferric (Fe^{+3}) state by percolating solutions. These solutions oxidized and locally leached the Trommald Formation removing silica, calcium, magnesium, and carbon dioxide and concentrating iron and manganese oxides. Schmidt (1963) suggested that these processes operated in two stages. The first stage involved hydrothermal solutions which rose along fractures, stimulating additional groundwater circulation and increasing its oxidizing and leaching capacity. The resulting reddish-brown ores are hematitic and are confined to large tabular bodies which extend downward to unknown depths. The second stage of ore formation also involved oxidation and leaching, but involved ordinary near-surface weathering processes. The resulting ores are brown in color and are confined to a shallow, irregular, but widely distributed blanket on both unoxidized iron-formation and previously oxidized reddish-brown ores. Both of these types of leached and oxidized iron-formation form the so-called "natural ores" upon which the mining activity was based.

Schmidt (1963) recognized two mappable facies in the Trommald Formation, one thick bedded and one thin bedded. The thick-bedded facies consists of massive beds ranging from 2.5 cm to 2 m in thickness. The thin-bedded facies is characterized by bedding laminae from 1 cm thick to microscopic, most being about 3 mm thick. Marsden (1972, p. 231) has estimated that the Trommald Formation ranges in thickness from 3 m to 185 m.

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 610 m thick.

Manganiferous iron-formation occurs primarily in the Trommald Formation but also as lenses in the Emily Iron-formation Member of the Rabbit Lake Formation. Though much of the manganese occurs in the secondarily enriched "natural ore" bodies, abundant manganese-rich material also occurs in the "lean ore," or primary iron-formation. Manganese content ranges from near zero to almost 40 percent, and the associated iron ranges from approximately 15 to 60 percent.

The bulk of the manganese in the Trommald Formation of the North range occurs at or near the transition zone between the thin-bedded and thick-bedded facies (Schmidt, 1963, plate 9). Manganese content tends to be low where the thick-bedded facies rocks constitute the entire iron-formation. Although manganese may be present where the iron-formation consists entirely of thin-bedded facies rock, it is erratic both in distribution and grade. These observations are consistent with primary manganese deposition occurring in a limited sedimentary environment within the Animikie depositional basin. However, the extent to which manganese may have been later mobilized remains uncertain.

Unfortunately, our present knowledge of Cuyuna range geology does not permit a thorough understanding of the manganese distribution. In particular, it is not possible to extrapolate the boundaries of manganese-rich bodies over any great distance because neither the degree of spatial continuity between drill holes, nor the complex structural relationships are known in detail. Further research into the environments of deposition, the nature and origin of mineral assemblages, the metamorphic history, and detailed structural geology is essential for good predictive models of manganese occurrence in the Cuyuna range.

RESOURCE CLASSIFICATION

The terms describing manganese resources in this report are used with specific meanings in accordance with the current resource/reserve classification system of the U.S. Bureau of Mines and the U.S. Geological Survey (1980). The definitions of relevant terms as they apply to the Cuyuna range are paraphrased below:

Resource--A concentration of naturally occurring material in a form and amount such that economic extraction is at least potentially feasible.

Measured resource--A resource whose quantity is computed from observations and sampling adequate to accurately establish geometry and compositional variation in the deposit.

Indicated resource--Similar to measured resource; sample spacing is less dense, but adequate to assume continuity between points.

Inferred resource--A resource whose quantity is based on assumed continuity beyond measured or indicated resources. Need not be supported by samples or measurements.

Demonstrated resources--Measured plus indicated.

Identified resources--Demonstrated plus inferred.

Marginal reserves--Resources that border on being economically producible and would become so, given postulated changes in economic or technologic factors.

Subeconomic resources--Resources that do not meet the economic criteria of marginal reserves.

Relationships between these classes are shown in Figure 2. We distinguish ore as mineral-bearing materials that exceed minimum economic criteria. For this reason some traditional terms, such as "lean ore," have been placed in quotation marks.

PREVIOUS ESTIMATES

Two previous studies have resulted in reported estimates of the manganese resources of the Cuyuna range. These studies were conducted by the U.S. Bureau of Mines (Lewis, 1951) and by the Minnesota Geological Survey (1977; Beltrame and others, 1977; Morey, 1977). Neither study provides satisfactory estimates of the short-term manganese potential of the range.

Lewis (1951) reported 454 million metric tons (MMT; 500,000,000 short tons) with an "average" manganese grade of 2 to 10 percent. Of this, 136 MMT (150,000,000 short tons) is reported as a single deposit containing 3 percent manganese. These quantities are equivalent to the combined measured, indicated, and inferred resources. The estimates are based on drill hole logs collected by the U.S. Bureau of Mines in 1949 and 1950, and use a stated 2-percent minimum cutoff grade. No other details of the methods are reported, although Schmidt (1963) states that a 46-m

	IDENTIFIED RESOURCES			UNDISCOVERED RESOURCES	
	Demonstrated		Inferred	Probability Range (or)	
	Measured	Indicated		Hypothetical	Speculative
ECONOMIC	Reserves		Inferred Reserves		
MARGINALLY ECONOMIC	Marginal Reserves		Inferred Marginal Reserves		
SUB-ECONOMIC	Subeconomic Resources		Inferred Subeconomic Resources		

Figure 2 -- Major elements of mineral resource classification. See text for explanation. Modified from U.S. Bureau of Mines and U.S. Geological Survey (1980, p. 5, fig. 1).

maximum depth was used. Two factors render this estimate unsatisfactory. First, the method of computation and the areas included cannot be determined (no further details were available from the U.S. Bureau of Mines, for whom the study was made). Second, a large but otherwise indeterminate portion of the resource consists of grades too low to be of interest in the near future.

In 1977 the Minnesota Geological Survey provided to the U.S. Bureau of Mines manganese resource estimates for 69 legal land sections in the Cuyuna range. The computer-generated estimates were based on 5,045 exploration drill hole logs selected from a total of 12,833 collected by the U.S. Bureau of Mines from 1949 to the early 1960's. These estimates employed a 1-percent cutoff grade and 150-m depth. After reviewing the assumptions and methods used, we now think the resources were overestimated in that study. A critical assumption employed was that drill hole intervals occurring in iron-formation but lacking manganese assays could be treated simply as missing data; that is, they were assigned a manganese content identical to the remainder of the hole. Subsequent discussions with George Weaton and a closer examination of drill hole records revealed that the preponderance of the assays were from areas and depth intervals having high manganese content. A further source of overestimation was the algorithm that determined areas of influence. Although the algorithm worked well for the deposits spot-checked in 1977, we have now found many closely spaced holes that were assigned areas 5 to 10 times greater than would be reasonable. For these reasons we now reject the 1977 estimates (Minnesota Geological Survey, 1977; Beltrame and others, 1977; Morey, 1977).

MANGANESE RESOURCES

The principal objective of the present study was to estimate the manganese resources of the Cuyuna range for grades and depths that could be used most readily, should the need arise. Limits of >5-percent manganese and <120-m depth were set for this purpose. Measured resource quantities derived from the Minnesota Department of Revenue, Office of Ore Estimation, provided reliable, but also very conservative estimates of manganese largely associated with mines. Indicated resources were computed from exploration drill hole records. The indicated resource estimates provided the basis for logical extension to inferred resources.

Measured Resources

Information of sufficient quality for estimates of measured manganese resources is available from the Minnesota Office of Ore Estimation. This agency calculates iron ore reserves for tax purposes, basing the estimates on drill hole assays and geologic cross sections provided by property owners. In order to obtain reliable manganese estimates, modifications of the original iron ore estimates were necessary; they are explained in detail in Appendix A.

Measured marginal reserves of manganese of the Cuyuna range are summarized in Table 1. Quantities in metric tons and average grade are listed by township for three different grade classes using a minimum grade cutoff of 5 percent. The total of 6.2 MMT at an average grade of 11.69 percent corresponds to 0.72 MMT metallic manganese. The depths represented in these estimates are not known in detail, although typical drilling depths on the Cuyuna range are on the order of 100 m. Quantities and average grades for individual properties are listed in Appendix A.

Table 1 -- Measured marginal reserves of manganese

Location		5-10% Grade Class		10-15% Grade Class		>15% Grade Class		Combined Grade Class	
T	R	Metric Tons	Average Grade	Metric Tons	Average Grade	Metric Tons	Average Grade	Metric Tons	Average Grade
46	29	1,200,000	6.80	760,000	11.60	29,000	16.06	2,000,000	8.79
46	30	0	----	47,000	12.68	0	-----	47,000	12.68
47	28	65,000	8.86	0	-----	0	-----	65,000	8.86
47	29	340,000	9.29	2,000,000	12.83	890,000	17.69	3,200,000	13.79
137	26	370,000	9.32	470,000	11.52	0	-----	840,000	10.56
TOTAL*		2,000,000	7.78	3,300,000	12.36	920,000	17.64	6,200,000	11.69

* Metric ton values are rounded to two significant figures; thus the cumulative totals may not equal the sum of the components.

The Office of Ore Estimation estimates of measured resources are highly reliable, but they are restricted to existing iron-ore reserves and therefore fail to provide a reasonable assessment of the manganese resources for the range. Nevertheless, they provide the only estimate of material occurring in close association with mines. An independent estimate of this material would be extremely time-consuming, requiring plans and sections of workings in addition to drill hole records.

Measured subeconomic resources (manganese content between 1 and 5 percent) also were calculated; they amount to 4.1 MMT at 2.83 percent, equivalent to 0.11 MMT manganese metal.

Indicated Resources

The principal contribution of this study is the computer-assisted calculation of indicated manganese resources of the Cuyuna range. Exploration drill hole logs were used to estimate resources containing more than 5 percent manganese and occurring above 120 m in depth. All rock meeting these criteria was included except for rock already estimated as measured resources. The methods employed were conservative, resulting in a relatively reliable appraisal of the minimum short-term manganese potential of the Cuyuna range.

The estimates of indicated resources employed a computer data base containing 5,045 exploration drilling logs. This data base was constructed from a U.S. Bureau of Mines compilation of 12,833 Cuyuna range drilling logs. Selection criteria for machine processing of logs included (1) as even an areal distribution as possible and (2) presence of manganese assays, so that the resulting data base would be useful for both geologic studies and commodity studies. The data base is described in detail in Appendix B.

The estimating method was based on the surface area of a deposit multiplied by the average depth of the deposit to yield a volume of rock equivalent to the size of the deposit. Separate estimates were made for each of three manganese grade classes: 5 to 10 percent, 10 to 15 percent, and greater than 15 percent. For each class the depth assigned to a hole is the aggregate thickness of drilling intervals whose manganese assay values qualify for the class. Areas were drawn on separate maps for each grade class and were then subdivided into smaller areas, each having a fairly constant drill hole spacing. Thus, the volume of rock estimated for one such area does not generally represent a single large block, but rather a collection of smaller blocks that may be physically separated from one another. Drilling intervals that lack manganese assays were assigned an assay value of zero and were consequently excluded from the estimates. Similarly, there was no vertical extrapolation for holes that did not extend to the 120-m depth cutoff; that is, depths that were not drilled were also excluded from the estimates. A density of 3.3 g/cm^3 was assumed. Details of the estimating procedure are given in Appendix C.

The resulting estimates are classified as indicated marginal reserves, and are shown in Table 2. The total of 80 MMT at an average grade of 10.46 percent is equivalent to 8.4 MMT of manganese metal. This material is distributed through 43 legal sections in the ten listed townships.

Because most of the drill holes do not extend to a depth of 120 m, much of the indicated resource is located well above the 120-m depth cutoff. In order to examine this aspect of the data distribution, identical estimates were made employing a 60-m maximum depth. These are compared with the 120-m estimates in Table 3. Of the 80 MMT occurring above 120 m,

Table 2 -- Indicated marginal reserves of manganese

Location		5-10% Grade Class		10-15% Grade Class		>15% Grade Class		Combined Grade Class	
T	R	Metric Tons	Average Grade	Metric Tons	Average Grade	Metric Tons	Average Grade	Metric Tons	Average Grade
44	31	90,000	7.07	140,000	12.63	62,000	16.03	290,000	11.64
45	28	220,000	6.89	0	---	34,000	34.20	250,000	10.56
45	29	25,000	6.45	0	---	0	---	25,000	6.45
45	30	110,000	6.57	0	---	0	---	110,000	6.57
46	28	0	---	0	---	14,000	15.80	14,000	15.80
46	29	16,000,000	7.12	6,800,000	11.93	3,600,000	20.92	26,000,000	10.26
46	30	100,000	7.38	70,000	11.79	0	---	170,000	9.17
47	28	2,700,000	6.94	1,000,000	11.93	140,000	17.50	3,900,000	8.64
47	29	18,000,000	7.05	8,800,000	12.22	7,200,000	20.55	34,000,000	11.25
48	27	9,900,000	7.01	3,600,000	12.16	1,600,000	19.17	15,000,000	9.50
TOTAL*		47,000,000	7.06	20,000,000	12.10	13,000,000	20.46	80,000,000	10.46

* Metric ton values are rounded to two significant figures; thus the cumulative totals may not equal the sum of the components.

Table 3 -- Indicated marginal reserves to depths of 60 m and 120 m

Depth	5-10% Grade Class		10-15% Grade Class		>15% Grade Class		Combined Grade Class	
	Metric Tons	Average Grade	Metric Tons	Average Grade	Metric Tons	Average Grade	Metric Tons	Average Grade
<60 m	31,000,000	7.04	14,000,000	12.12	8,400,000	20.48	53,000,000	10.50
<120 m	47,000,000	7.06	20,000,000	12.10	13,000,000	20.46	80,000,000	10.46

nearly two-thirds, or 53 MMT actually occur within 60 m of the surface. Thus, most of these resources are more readily accessible than the 120-m depth limit alone would imply.

Inferred Resources

The measured and indicated resources described above are reliable estimates of the readily usable manganese resources of the Cuyuna range. They do not, however, address the broader subject of probable resources that may ultimately be recoverable from the range. Precise estimates of this long-term potential will require additional drilling information as well as more intensive study of the controls on manganese distribution. However, it is possible to draw some additional inferences regarding undrilled resources at greater depths and also to make a rough estimate of the low-grade resources.

Two observations permit an assessment of the approximate amount of manganese below the drill hole bottoms but above the 120-m depth. First, any enrichment of manganese must have involved more than a simple uniform surface-weathering phenomenon. Second, the iron-formation is steeply dipping in nearly all the areas estimated. It is, therefore, reasonable to extrapolate near-surface deposits downward at least for a short distance (on the order of the distance already drilled). Support for the validity of this approach includes the observed occurrence of manganese-rich deposits well below 120 m and the fact that manganese content is poorly correlated with depth below the bedrock surface (correlation coefficient of 0.08).

Extrapolation of the indicated resources to a uniform depth of 120 m can be accomplished using the mean drift thickness (Q) and the mean drilling depth (D). The ratio (R) of unexplored depth to explored depth in any one area is

$$R = (120 - D) / (D - Q)$$

and the inferred resources (T_{inf}) exclusive of the indicated resources (T_{ind}) are given by

$$T_{inf} = RT_{ind}$$

Because drift thickness and drilling depth are variable throughout the Cuyuna range, R and T_{inf} were calculated separately for each township.

The resulting estimates are classified as inferred marginal reserves and are presented in Table 4. In contrast to the 80 MMT of indicated resources, 90 MMT of similar material could probably be recovered by mining each deposit downdip to a depth of 120 m. At an assumed average grade of 10.46 percent, these resources amount to 9.4 MMT manganese.

Additional low-grade resources consisting of 1- to 5-percent manganese can be very roughly estimated using some of the results from the 1977 Minnesota Geological Survey study. Although the quantity estimates from that study are now known to be biased, there is no reason to expect the relative proportions of the various grade classes to be in error. The proportions of the higher grade classes in the 1977 report agree well with the proportions in this report: 63 percent, 22 percent, and 15 percent compared to 59, 25, and 16 percent for the 5-10, 10-15, and >15 percent grade classes respectively. In the 1977 estimate to 120-m depth, the 1-5 percent material was 1.6 times as abundant as the combined higher grades. This ratio, applied to the 80 MMT indicated plus 90 MMT inferred high-grade resources, suggests the presence of 270 MMT of 1-5 percent resources to a depth of 120 m. The average grade of this material is estimated to be 2.52 percent based on the 1977 report, implying the potential of 6.8 MMT of manganese metal. These estimates are classified as inferred subeconomic resources. These estimates of the low-grade resources clearly are not very precise. They serve primarily to demonstrate the existence of a large but poorly known low-grade manganese resource in the Cuyuna range.

Table 4 -- Inferred marginal reserves of manganese
[metric tons]

Location T	Location R	5-10% Grade Class	10-15% Grade Class	>15% Grade Class	Combined Grade Class
44	31	100,000	150,000	68,000	320,000
45	28	370,000	0	58,000	430,000
45	29	25,000	0	0	25,000
45	30	100,000	0	0	100,000
46	28	0	0	1,000	1,000
46	29	22,000,000	9,200,000	5,000,000	36,000,000
46	30	240,000	170,000	0	410,000
47	28	3,800,000	1,400,000	200,000	5,400,000
47	29	23,000,000	11,000,000	9,400,000	43,000,000
48	27	3,000,000	1,100,000	480,000	4,600,000
TOTAL*		53,000,000	23,000,000	15,000,000	90,000,000

* Values are rounded to two significant figures; thus the cumulative totals may not equal the sum of the components.

DISCUSSION

The total calculated resources for the five classes previously discussed are summarized in Figure 3. As noted in the introduction to this paper, the importance of the Cuyuna range manganese resources stems from the nearly total dependence of the United States steel industry on foreign imports of manganese. It is, therefore, worthwhile to consider briefly the adequacy of the Cuyuna range resources in supplying U.S. demand if imports were stopped or greatly reduced. The accessibility, quality, and quantity of the resources all bear on this issue.

The indicated manganese resources estimated in this report are readily accessible in that (1) they occur at manageable depths for open-pit mining and (2) the manganiferous rock makes up a large fraction of the bedrock in the areas studied. As noted above, most of the 80 MMT indicated resources lie within 60 m of the surface. A further analysis of the areas outlined for 5-10 percent resource bodies (which include nearly all of the higher grade resources as well) shows that open-pit mining of the 80 MMT of indicated resources would require the removal of about 160 MMT of bedrock. The associated drift cover is 92 MMT (at 2.0 g/cm^3) and the average mine depth would be 62 m. Accessibility is further enhanced by the presence of facilities used in recent iron mining activity.

Little detail is known concerning the quality of the Cuyuna manganese resources. This is due to the inadequate chemical and metallurgical data available. Nearly all of the existing information was acquired for the sole purpose of iron mining. Manganese was merely an accessory commodity for which an additional premium was paid. Nevertheless, the information at hand is adequate to show that at least a third of the indicated resources meet the criteria of current ore marketing practice.

	IDENTIFIED RESOURCES		
	Demonstrated		Inferred
	Measured	Indicated	
ECONOMIC	Reserves		Inferred Reserves
MARGINALLY ECONOMIC >5% Mn	Marginal Reserves 6 (0.7)	80 (8.4)	Inferred Marginal Reserves 90 (9.4)
SUB-ECONOMIC 1-5% Mn	Subeconomic Resources 4 (0.1)		Inferred Subeconomic Resources 270 (6.8)

Figure 3 -- Identified manganese resources of the Cuyuna range. Numbers represent resources in MMT for each category. Numbers in parentheses represent MMT of manganese metal.

The American Iron Ore Association (1980) lists four manganiferous ore grades shipped from Cuyuna range stockpiles in 1979. These are of two types, one with about 27 percent Fe and 13 percent Mn and the other with about 45 percent Fe and 5 percent Mn. A classification of Cuyuna manganese resources approximately isolating these grades is shown in Figure 4. Classes I, II, and III meet or exceed the iron and manganese content of currently marketed Cuyuna ores. Classes IV, V, and VI fall below present marketing requirements. Table 5 shows the tonnage and average analyses for the six classes. The potentially marketable resources in classes I through III amount to 26 MMT with an average grade of 15 percent Mn, corresponding to 4.0 MMT of metallic manganese. This material could presumably be shipped directly for use in existing steel-making facilities.

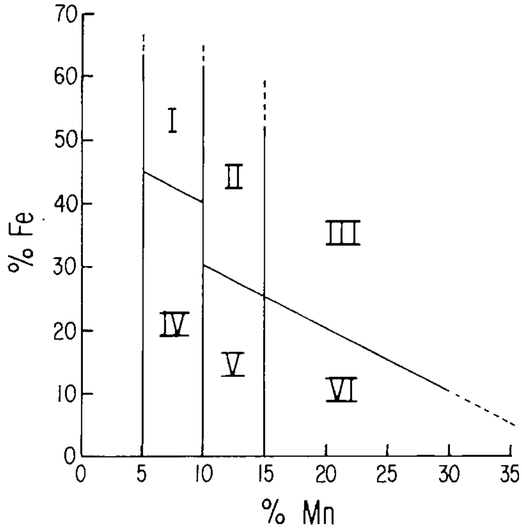

Figure 4 -- Potential marketing classes of indicated manganese resources of the Cuyuna range.

Because the Cuyuna manganese resources are not currently economic, their adequacy in quantity can only be assessed in relation to a hypothetical need. In the foreseeable future the greatest need would arise from cessation of imports. The entire U.S. demand would then rely upon industry and government stockpiles and U.S. production. Immediate demand would be supplied (if possible) from stockpiles while production was starting up. Simultaneous exploration and research programs would be needed to permit the production of successively lower grade and less accessible resources.

The U.S. supply-demand relationships for manganese are summarized for 1977 in Figure 5. The U.S. production of 24.5 thousand metric tons (TMT) of manganese accounted for less than 2 percent of the U.S. demand of 1,382 TMT, the remaining 98 percent of which was supplied by foreign sources, industry stocks, and shipments from government stockpiles. However, the stockpiles have been diminishing for the past 18 years and the rate of depletion has accelerated over the past 3 years. Past and projected stockpiles are shown in Figure 6.

The U.S. Bureau of Mines estimates that demand will continue to increase at an annual rate of 1.6 percent through 1985 (DeHuff, 1980a, p. 97). However, even at the current rate of demand (fig. 6), the industry stocks would be depleted by mid-1981 and the government stockpile would be exhausted by mid-1987. It is more probable that the government stockpile would be used to stabilize our import level after industry stocks are depleted (mid-1981), resulting in total import dependency by mid-1984 (projected from data provided by DeHuff, 1980b).

Table 5 -- Average analyses of indicated manganese resources by potential marketing class

Class	Metric* Tons	Percent Iron	Percent Phosphorus	Percent Silica	Percent Manganese
I	4,100,000	46.72	.203	11.80	7.40
II	12,000,000	35.04	.128	20.57	12.24
III	11,000,000	29.27	.116	16.46	21.04
IV	43,000,000	29.07	.133	32.53	7.02
V	8,700,000	22.50	.117	34.08	11.91
VI	1,900,000	18.82	.109	32.45	17.26
I+IV	47,000,000	30.62	.139	30.70	7.06
II+V	20,000,000	29.69	.123	26.33	12.10
III+VI	13,000,000	27.67	.115	18.91	20.46
All Classes	80,000,000	29.92	.131	27.73	10.46

* Values are rounded to two significant figures; thus the cumulative totals may not equal the sum of the components.

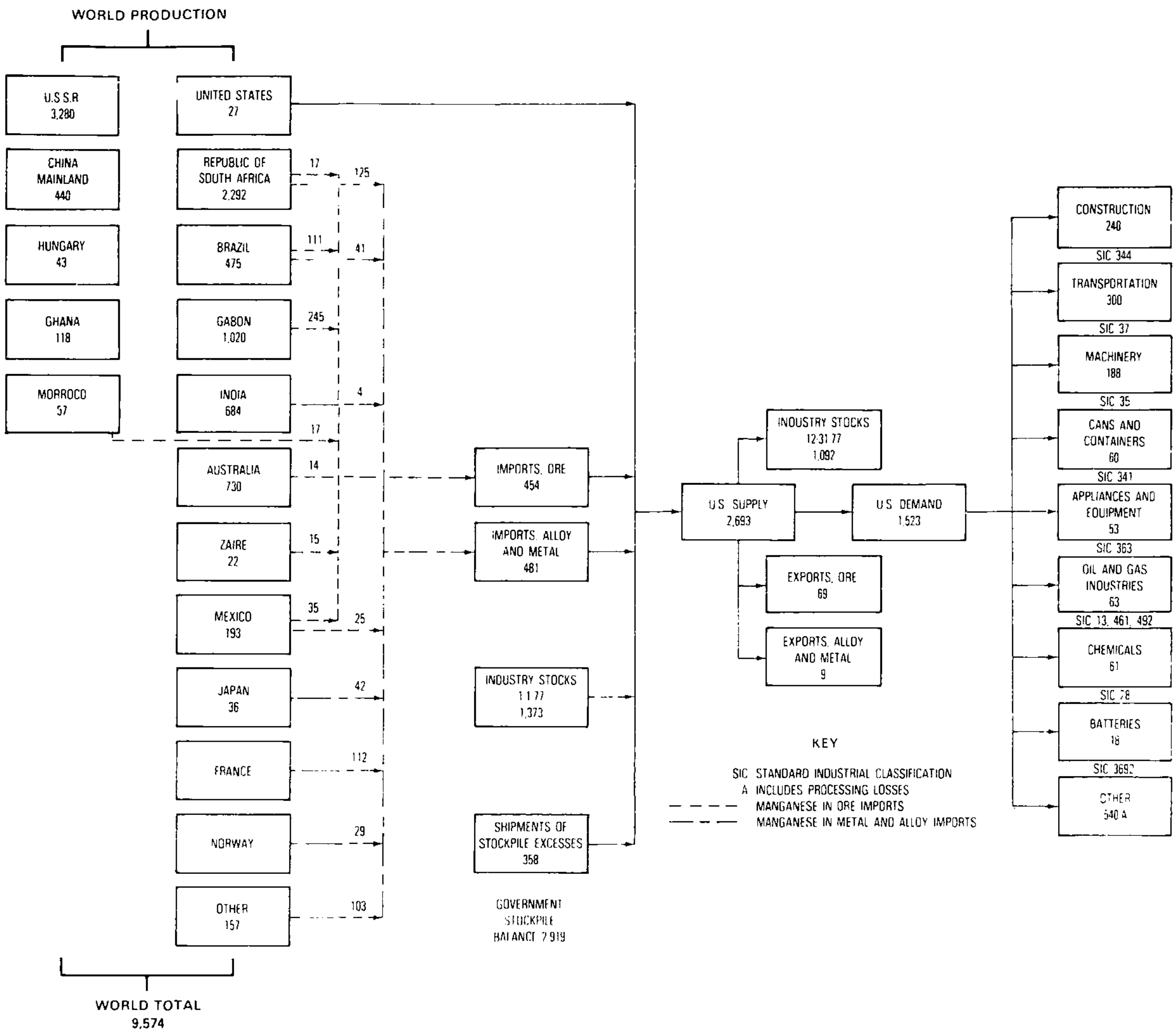

Figure 5 -- U.S. supply-demand relationships for manganese in 1977 in thousands of short tons [1 short ton = 0.9072 metric ton] (U.S. Bureau of Mines, 1979a, p. 47).

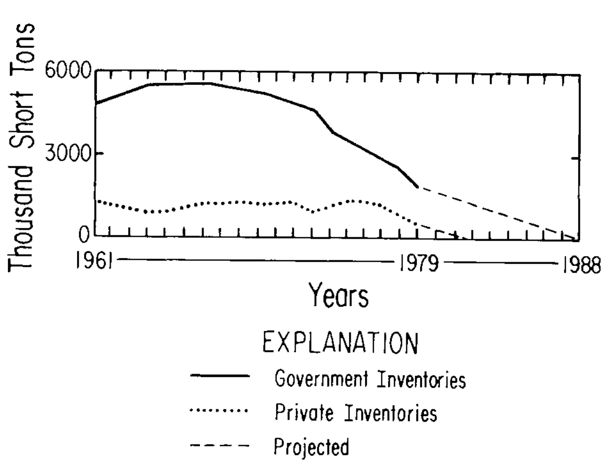

Figure 6 -- Manganese inventory status and projections assuming demand remains constant [1 short ton = 0.9072 metric ton]. Modified from DeHuff (1980b, p. 40).

The combined industry and government inventories for 1979 of 2,541 TMT would supply the current U.S. demand of 1,340 TMT (DeHuff, 1980b) for 23 months. This is the time available to start domestic production if imports were curtailed. Current trends suggest that this potential start-up period will soon drop to zero.

The marginally economic manganese resources (18.5 MMT metal) of the Cuyuna range are capable of meeting current U.S. demand for nearly 14 years. In addition, the subeconomic resources could supply another 5 years of current U.S. demand. Recovery of this subeconomic material, however, would require additional research in geology and beneficiation because of its low grade. Figure 7 is a classification of Cuyuna manganese resources showing quantities and duration at current U.S. demand.

CONCLUSIONS

We estimate that the Cuyuna range of east-central Minnesota contains a demonstrated 9.1 million metric tons (MMT) and inferred 9.4 MMT of manganese metal, which is marginally economic and extractable by current surface mining techniques. Some of this manganese could be easily recovered, but major geologic and metallurgical problems need to be resolved before all of this manganese can be recovered. Our dependency on foreign imports, the rapid depletion of industry and government stockpiles, the lack of any other potential sources in the near future, and the strategic importance of this metal necessitates a thorough geologic and metallurgical study of Cuyuna range manganese deposits.

ACKNOWLEDGMENTS

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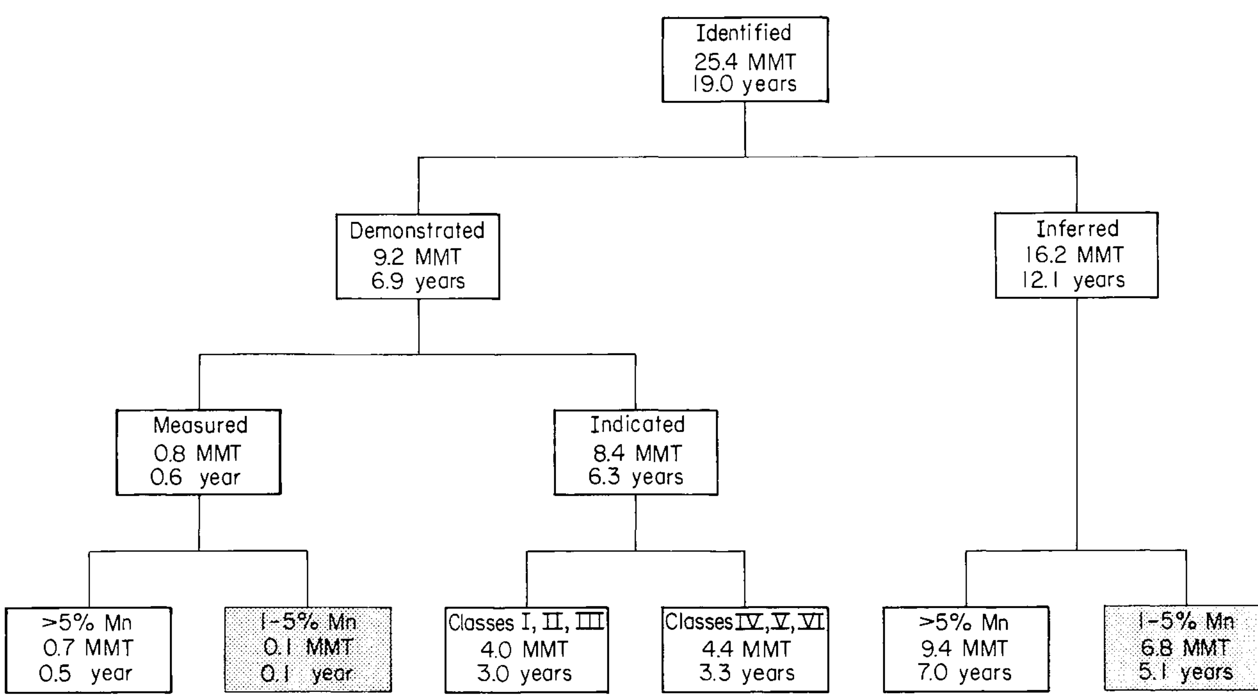


Figure 7 -- Cuyuna manganese resource quantities and duration at current rate of demand.

REFERENCES CITED

American Iron Ore Association, 1980, Iron Ore 1979: 115 p.

Beltrame, R.J., 1977a, Selected bibliography of Cuyuna range geology, mining and metallurgy: Minnesota Geological Survey Information Circular 12, 22 p.

_____ 1977b, Directory of information on Cuyuna range geology and mining: Minnesota Geological Survey Information Circular 13, 52 p.

Beltrame, R.J., Holtzman, R.C., and Morey, G.B., 1977, Preliminary manganese resource estimates for the Cuyuna district: a statistical approach [abs.]: Institute on Lake Superior Geology, 23rd, Thunder Bay, Ontario, 1977, Abstracts with Programs, p. 5.

DeHuff, G.L., 1980a, Manganese, in Mineral Commodity Summaries 1980: U.S. Bureau of Mines, p. 96-97.

_____ 1980b, Manganese: in Minerals and Materials/a monthly survey, September 1980: U.S. Bureau of Mines, p. 40-41.

Dorr, J.V.N., II, Crittenden, M.D., Jr., and Worl, R.G., 1973, Manganese: in Brobst, D.A., and Pratt, W.P., eds., United States Mineral Resources: U.S. Geological Survey Professional Paper 820, p. 385-399.

Grout, F.F., and Wolff, J.F., Sr., 1955, The geology of the Cuyuna district, Minnesota: a progress report: Minnesota Geological Survey Bulletin 36, 144 p., 6 plates.

Harder, E.C., and Johnston, A.W., 1918, Preliminary report on the geology of east-central Minnesota including the Cuyuna iron-ore district: Minnesota Geological Survey Bulletin 15, 178 p., 22 plates.

Lewis, W.E., 1951, Relationship of the Cuyuna manganiferous resources to others in the United States: in Mining Symposium--Geology of the Cuyuna range: University of Minnesota, Center for Continuation Study, Minneapolis, p. 30-43.

Marsden, R.W., 1972, Cuyuna district, in Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: a centennial volume: Minnesota Geological Survey, p. 226-239.

Minnesota Geological Survey, 1977, Manganese-bearing ores of the Cuyuna iron range, east-central Minnesota, phase I: Report submitted to the U.S. Bureau of Mines, 177 p.

Morey, G.B., 1977, Geology and mineral resources of east-central Minnesota--some new perspectives: Mining Symposium, 38th, University of Minnesota, 1977, Proceedings, p. 23-1 to 23-24.

_____ 1978, Lower and Middle Precambrian stratigraphic nomenclature for east-central Minnesota: Minnnesota Geological Survey Report of Investigations 21, 52 p., 1 plate.

Schmidt, R.G., 1963, Geology and ore deposits of the Cuyuna north range, Minnesota: U.S. Geological Survey Professional Paper 407, 96 p., 11 plates.

Trethewey, W.D., ed., 1979, Minnesota Mining Directory, 1979: University of Minnesota, Mineral Resources Research Center, 264 p.

U.S. Bureau of Mines, 1979a, Minerals in the U.S. Economy: ten-year supply-demand profiles for nonfuel mineral commodities (1968-77), p. 46-47.

_____ 1979b, Status of the Mineral Industries, October 1979: p. 36.

U.S. Bureau of Mines and U.S. Geological Survey, 1980, Principles of a resource/reserve classification for minerals: U.S. Geological Survey Circular 831, 5 p.

APPENDIX A

MEASURED RESOURCES BY PROPERTY

The following list shows measured resources derived from Office of Ore Estimation abstracts. These abstracts are bound into annual reports and kept on file at the Office of Ore Estimation, Eveleth, and the Department of Revenue, St. Paul, Minnesota. Beltrame (1977b) lists the available abstracts for the Cuyuna range by property name and year of estimation.

These abstracts report estimates of iron resources. Some also include the associated manganese content or grade. The grades are reported in one or two ways depending on how the water content was treated. Materials listed as natural iron or natural manganese include water in the composition and the percentage of water is usually reported. For materials listed simply as iron or manganese, the reported grades represent the percentage of metal content exclusive of water. Often the material is reported as a concentrate product resulting either from washing or heavy media separation.

Because both concentrate and "ore" tonnages are reported, these estimates cannot be directly summed to obtain manganese resource estimates. For this reason we analyzed each report, adjusting the reported values to reflect unshipped tonnage prior to concentration. The manganese grade was adjusted when necessary to exclude water. For concentrates, recovery factors were used to convert tonnage and grade back to crude "ore." Where recovery factors were not given, we assumed 45 percent bulk recovery for heavy media concentrates and 55 percent for "wash-ore" concentrates. We further assumed for concentrates that 7 percent of the original manganese was lost in heavy media separation and 5 percent lost in a "wash-ore" separation. (These values were based on oral communication with George Weaton in 1976.)

Quantities are given on Table A-1 for individual properties or fractions thereof, for which abstract estimates were available. Because these estimates are made for individual properties at intervals of several years, the listed quantities may include material that has already been shipped. Such shipments, as reported in Trethewey (1979), were deducted and do not appear on Table A-1. Values on the table that correspond to areas for which indicated resources were estimated were excluded from the tabulations of measured resources. Note that the estimates on the table include more than one tonnage and grade for some properties.

Table A-1 -- Measured manganese resources by property
[*, tonnage from an area covered by estimate of indicated resources, and therefore excluded from measured resource totals]

Location T	Location R	Property	Metric Tons	Weight Percent Manganese
43	32	Willcuts Reserve (H-47)	232,767	1.45
45	28	Clearwater Lake Reserve (X-43)	140,030	1.24
			441,519	4.29
45	30	Omaha Mine	1,507,189	3.14
46	29	Alstead Mine	119,216	13.23
		Arko Mine	17,566	11.60
			29,172	16.06
		Armour No. 2 Mine	164,803	1.39
		Carlson-Nelson Mine	302,046	3.32
		Hennen Reserve (H-49)	22,866	3.99
		Hillcrest Mine-North	60,224	12.97

Table A-1 -- continued

Location T	Location R	Property	Metric Tons	Weight Percent Manganese
46	29	Huntington Mine	483,278	1.05
			71,293	4.21
			311,461	7.38
		Ironton Mine	45,019	4.34
		Louise Mine	146,562	13.23
		Mallen Mine	64,204	1.41
		Manuel Mine	40,509	4.21
			164,681	5.24
		Martin Mine	37,255	1.57
			34,715	4.91
			388,909	7.14
		Mattson Rectangle Mine Mangan No. 2	75,418	1.36
			59,908	6.10
		Rowe Mine	24,230	1.85
			4,403	4.76
			13,547	9.52
			8,941	12.87
		Sagamore Mine	247,570	6.62
			393,921	10.15
		South Yawkey Mine	3,963	3.59
		Syracuse Mine	17,458	14.24
		Wearne Mine	1,348	1.67
		West Airport Mine	77,564	1.31
			159,513	4.57
46	30	Syracuse Reserve (St-4)	47,005	12.68
47	28	Kona Reserve (X-21)	261,770*	9.07
		Northland Mine (N1/2 NW1/4 sec. 20)	64,858	8.86
47	29	Algoma Mine	57,836	12.87
		Aune Reserve (H-40)	90,530	4.66
		Colonization Reserve (H-41)	298,099*	10.14
		Ferro Mine	26,309	23.17
		Gloria Mine	559,711	12.59
		Hunter Reserve (X-35)	71,851	7.84
		Joan No. 4 Mine	5,806	21.03

Table A-1 -- continued

Location T	Location R	Property	Metric Tons	Weight Percent Manganese
47	29	Merritt No. 1 Mine	112,689	14.29
		Merritt No. 2 Mine	16,511	20.60
		Milford Mine	272,226	9.68
		Pontiac Mine	37,494	2.66
			845,857	17.44
		Preston Reserve (I-1)	123,629*	1.10
			108,789*	8.29
		Sisters 40 Reserve (H-67)	14,631*	19.70
		Whitmarsh Reserve (H-66)	152,815*	12.22
		Zeno Mine	1,284,211	12.81
137	26	Emily-Shawmut Reserve (P-27)	365,598	9.32
			468,111	11.52

APPENDIX B

INDICATED RESOURCES DATA BASE

The most complete and consistent data set available for study consists of drill hole information compiled by the U.S. Bureau of Mines (USBM) between the late 1940's and early 1960's for their Minnesota Mineral Development Atlas (MMDA). The source of information was the drill hole data from the Minnesota Office of Ore Estimation that had been obtained from mining companies for iron-ore taxation purposes. The USBM obtained permission from these mining companies for confidential use of the data. The USBM compiled these drill hole data in a standard format as shown in Table B-1 and plotted drill hole locations on 1:2,400-scale maps of legal sections. Sections with a high density of drill holes were plotted on 1:600-scale government lot, or quarter-quarter section, maps. The USBM compilation consisted of 12,833 drill hole records, 125 full section drill plan maps at a scale of 1:2,400, and 55 quarter-quarter section drill plan maps at a scale of 1:600. These maps and records were catalogued by Beltrame (1977b, p. 35-42).

Of the 12,833 available drill hole records, 5,045 were selected for entry into a computer data base on the basis of areal distribution, availability of manganese assay data, depth of hole, and whether or not the rock was still in place. Financial constraints precluded the entry of all the available drill hole records.

The areal distribution of drill holes was the first criterion used in the selection process. For those sections with 80 or fewer drill holes, all were selected. For those sections having more than 80 drill holes, 5 drill holes from each quarter-quarter section were selected. For quarter-quarter sections that contained fewer than 5 drill holes, the additional holes were selected from neighboring quarter-quarter sections so that the resulting total of drill holes for that section numbered 80. In some sections the density of drill holes was so great that additional maps of quarter-quarter sections at a scale of 1:600 were compiled by the USBM.

Table B-1 -- Sample of a Minnesota Mineral Development Atlas data sheet.

Serial No. 236
Hole No. S-506
Collar Elevation: 565
Depth of Hole: 370 Inclined 70° N
Location: Maroco - NW-NW

Date Completed:
Drilled by:
Logged by:
Type of Drilling:

Depth From	Depth To	Material	Crude Iron	Crude Mang.	Crude Sil.	Conc. Iron	Conc. Mang.	Conc. Sil.	Conc. Rec.
0	225	Surface							
225	230		2.27	.19	63.97	29.60		51.50	42.00
230	235		27.35	.19	54.49	41.51		32.39	49.40
235	240		17.54	.11	67.90	34.43		43.84	28.40
240	245		24.94	.15	57.49	44.09		29.20	44.00
245	250		12.87	.15	71.94	37.17		38.41	9.80
250	255		25.90	.19	54.50	42.07		32.03	36.50
255	260		27.51	.39	53.56	47.30		25.24	37.60
260	265		31.71	.11	44.60	50.83		19.70	23.40
265	270		22.22	.15	61.23	46.28		24.12	8.40
270	275		35.24	.23	40.58	46.41		23.52	44.10
275	280		29.56	.19	50.20	50.85		16.67	66.80
280	285		22.72	.19	61.07	46.98		23.09	35.18
285	290		29.02	.19	51.00	49.57		18.57	28.70
290	295		34.59	.15	44.06	52.88		14.54	61.40
295	300		39.49	.11	34.70	53.36		11.63	56.00
300	305		30.65	.15	49.26	51.98		14.20	42.00
305	310		37.06	.27	41.44				
310	315		34.71	.19	42.65	52.34		13.69	46.26
315	320		33.57	.19	45.63				
320	325		38.32	.27	38.40	48.23		23.82	64.58
325	330	d.d. sludge analysis	35.24	.70	35.36				
330	335		31.61	3.19	40.13	45.71	4.33	17.60	63.38
335	354	d.d. no sludge							
354	360		23.52	3.47	47.75				
360	365	sludge analysis	36.98	3.59	29.73				
365	370		30.21	1.53	43.93				

For each of these quarter-quarter sections an additional 5 drill holes were selected. Thus for 55 quarter-quarter sections, 10 drill holes were selected for study. The maximum number of drill holes from any one section was 115 for a section with seven detailed quarter-quarter section maps.

For 22 quarter-quarter sections containing an excessive number of drill holes the selection process was based on the availability of manganese assay data, the depth of the hole, and the present availability of the material encountered. The decision as to whether or not a hole represented exhausted material (mined out) was based on the outlines of open-pit areas from the MMDA, the Abstracts of Mineral Reports, topographic maps, and blue-line air photos. Some holes located within the outlines of open-pit areas were selected when it could be shown that deep material in the hole was still available. Deep holes with an abundance of manganese assay data in areas that had not been exhausted were given the highest priority. Because of the distribution and density of drill holes, it was necessary in some cases to select drill holes that represented exhausted material.

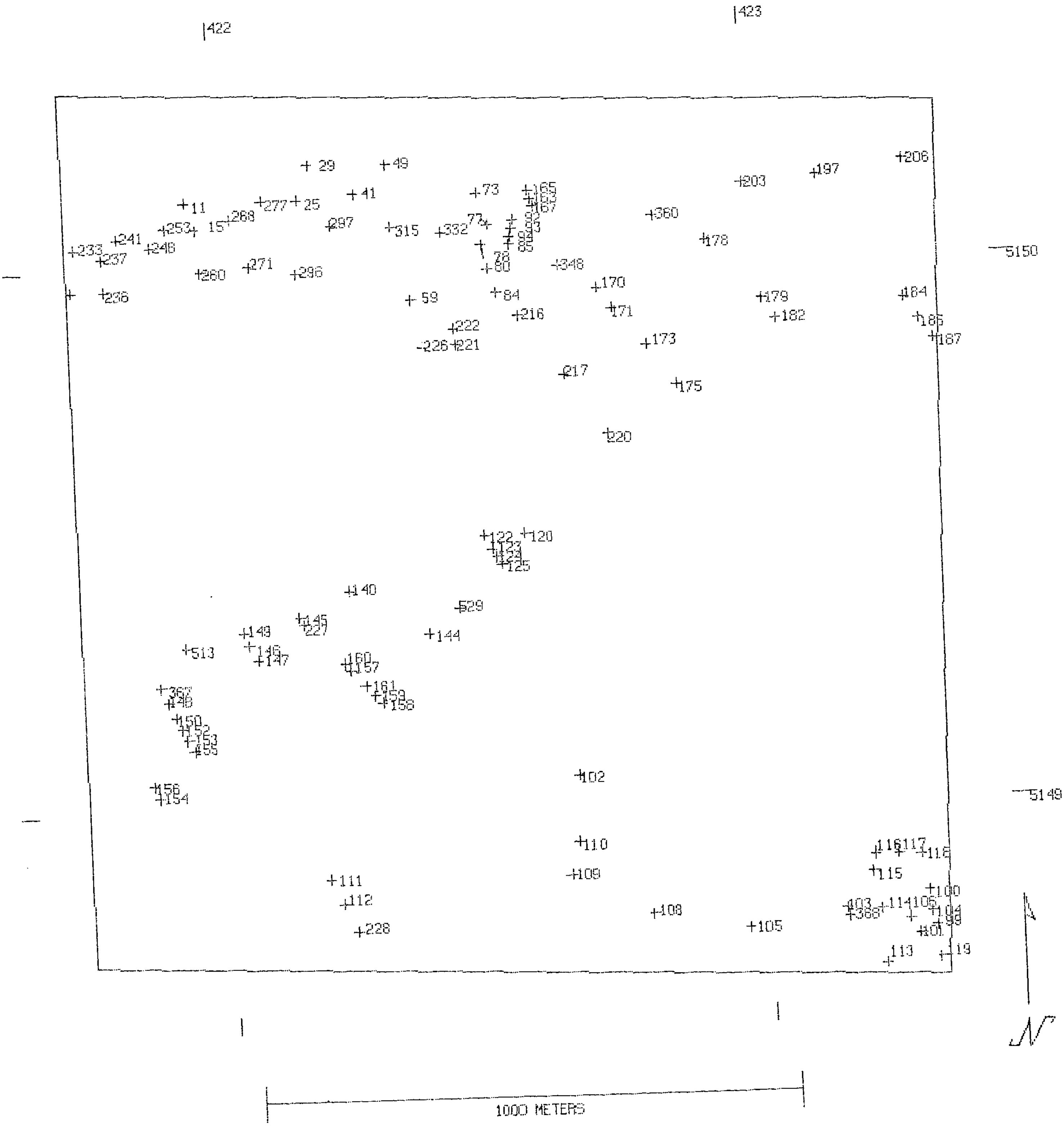
The depth to bedrock, depth to iron-formation, depth to the base of the iron-formation, and the present availability of the material for each drill hole was determined and included on the data sheets.

Because of gradational changes in iron content, the exact depth to iron-formation was often ambiguous. An attempt was made to determine the depth to the main iron-formation, ignoring the numerous small lenticular bodies of iron-rich material present in the overlying Rabbit Lake Formation. The criteria used for distinguishing the top of the main iron-formation were that the iron-rich material should exceed 15 weight percent iron for a minimum thickness of 7 m (20 ft on the original data sheets).

Some data sheets contained chemical assays for more than one type of material. The types of materials for which information was available consisted of core material (obtained from diamond drilling), sludge material (obtained from churn drilling), and concentrated material (beneficiated ore). Assays from core material were used where available. Assays from sludge material were used only where data from core material were not available. Assay data for concentrated materials were always ignored.

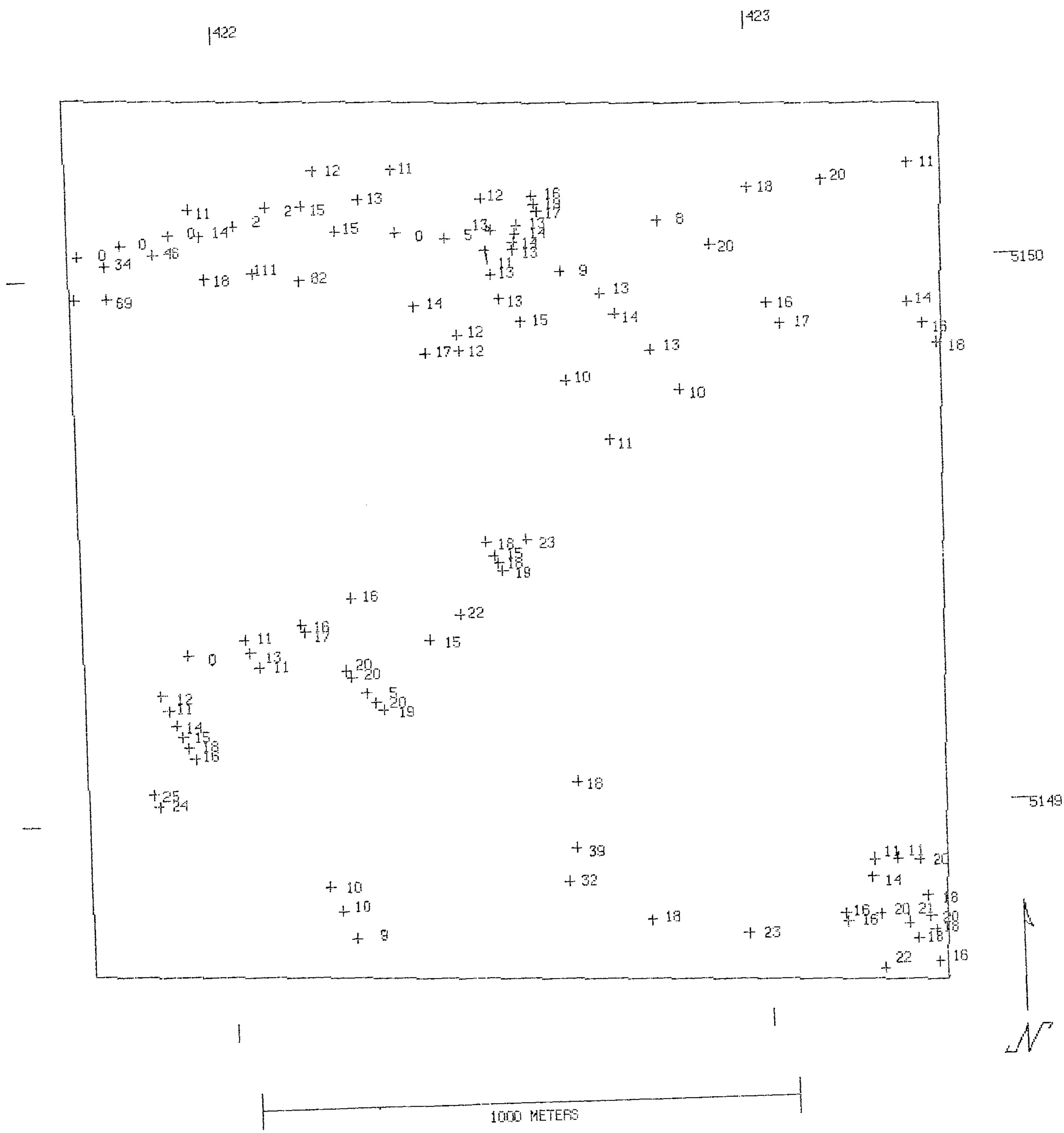
Following this preparation, the selected drill hole logs were keypunched, verified and edited to create a fixed format computer file. Universal Transverse Mercator (UTM) coordinates of the drill hole locations were obtained by electronic digitizer from MMDA maps, and the collar elevations were determined from the U.S. Geological Survey (USGS) topographic maps. Both were subsequently merged into the computer file.

As part of our 1977 study, three types of computer-generated maps were produced from the Cuyuna range data base. These are (1) a composite map at a scale of 1:24,000 of the entire range used to validate the UTM coordinates of the section corners, (2) individual section maps at a scale of 1:10,000 showing the locations of the drill holes and their serial numbers, and (3) individual section maps at a scale of 1:10,000 showing hole locations and the associated drift thickness. Samples of the last two types appear as Figures B-1 and B-2.



DATA LOCATION MAP OF T46N R29W SEC 4

Figure B-1 -- Computer-generated drill hole location map.



DRIFT THICKNESS MAP OF T46N R29W SEC 4
THICKNESS IN METERS

Figure B-2 -- Computer-generated drift thickness map.

APPENDIX C

PROCEDURES FOR ESTIMATING INDICATED RESOURCES

Indicated resources were estimated in this study as follows: For each of three grade classes, manganese-rich bodies were delineated and the average aggregate thickness calculated. The product of the average aggregate thickness and the area of the body was converted to tonnage using a density of 3.3 g/cm^3. The average grade, weighted by tonnage, was calculated for each body and each class.

I. In the first step, the data base was scanned by Program MNRES2 which calculated for each hole the number of meters and average weight percent of manganese in each of three grade classes, namely 5-10, 10-15, and greater than 15 weight percent manganese metal. The detailed operation of MNRES2 was as follows:

A. Serial number, depth, trend, inclination, depth to iron-formation, depth to base of iron-formation, township, range, section, UTM coordinates, and availability data (whether or not the material has been mined out) were read in for a hole.

B. Coefficients (sine of plunge angle) for rotation and scaling if hole is not vertical were computed. All depths were projected to the vertical.

C. The assay records for the hole were scanned and running totals were kept for the thickness and thickness multiplied by grade (meters-percent) for each grade class. Holes designated as exhausted on the identifier record were considered to have no manganese. Intervals or holes without manganese assays were considered to have no manganese. Only intervals or parts of intervals within the main iron-formation containing greater than 5 percent Mn and above the 120-m depth were included in the computed totals.

D. For each hole and grade class the meters-percent were divided by the associated total meters to give an average grade.

E. The township, range, section, serial number, UTM coordinates, and the total meters and average percent for each grade class were written to the output file.

The average manganese grade and thickness computed by MNRES2 reflect only the manganese material which was assayed. There was no vertical extrapolation. This is consistent with most mining company assaying practices on the Cuyuna range where, in general, holes or intervals not assayed for manganese are assumed to contain little or no manganese.

II. Manganese grade maps were produced as follows: For each section and grade class a computer-generated map at 1:10,000 or 1:5,000 scale was produced for each grade class showing the average weight percent manganese associated with each drill hole (fig. C-1). Only those assay values falling within the range of the grade class were considered for any one map. If, for example, a drill hole had assay values in both the 5-10 percent grade class and in the >15 percent grade class but none in the 10-15 percent class, then a zero would be plotted at the drill hole location on the 10-15 percent manganese grade map. The resulting maps show the areal distribution of manganese-bearing material.

III. Step three, perhaps the most critical phase of the estimating procedure, involved outlining areas of manganese-bearing material on the manganese grade maps. U.S. Bureau of Mines maps, topographic maps, and Office of Ore Estimation maps were used as aids.

It is common practice to weight the areal influence of each drill hole depending on its distance from neighboring drill holes. In this study the manganese-rich areas were subdivided into smaller areas or bodies, in order to obtain a rather uniform distribution of drill holes within each body (see fig. C-2, bodies B, C, and D). Thus, each drill hole within a body had approximately the same area of influence. Manganese resources were calculated separately for each of these bodies. Areas defined by open-pit boundaries were considered exhausted of any manganese-bearing rock and thus were excluded from the manganese-rich bodies.

IV. In step four, the drill hole summaries computed in step one were given reference codes assigning them to the appropriate manganese bodies. The areas of the manganese bodies were measured (by digitizer) directly from the manganese grade maps, assigned the appropriate reference code, and then entered into a computer file to be used in the final step of the estimates.

V. Program MNTOT computed the tonnage and average percent manganese by section for each grade class and for the combined grade classes. The total tonnages and average grades were also computed for the entire range.

In detail, the operation of MNTOT was as follows:

A. Read in manganese body reference codes and areas.

B. Read in drill hole summaries from Step I for one section.

C. For each body and each grade class within the section,
   1) compute average meters per hole of manganese material
   2) compute average manganese grade for the body
   3) multiply average meters times the appropriate area and convert the resulting volume to metric tons using 3.3 g/cm^3 as the density of the material.

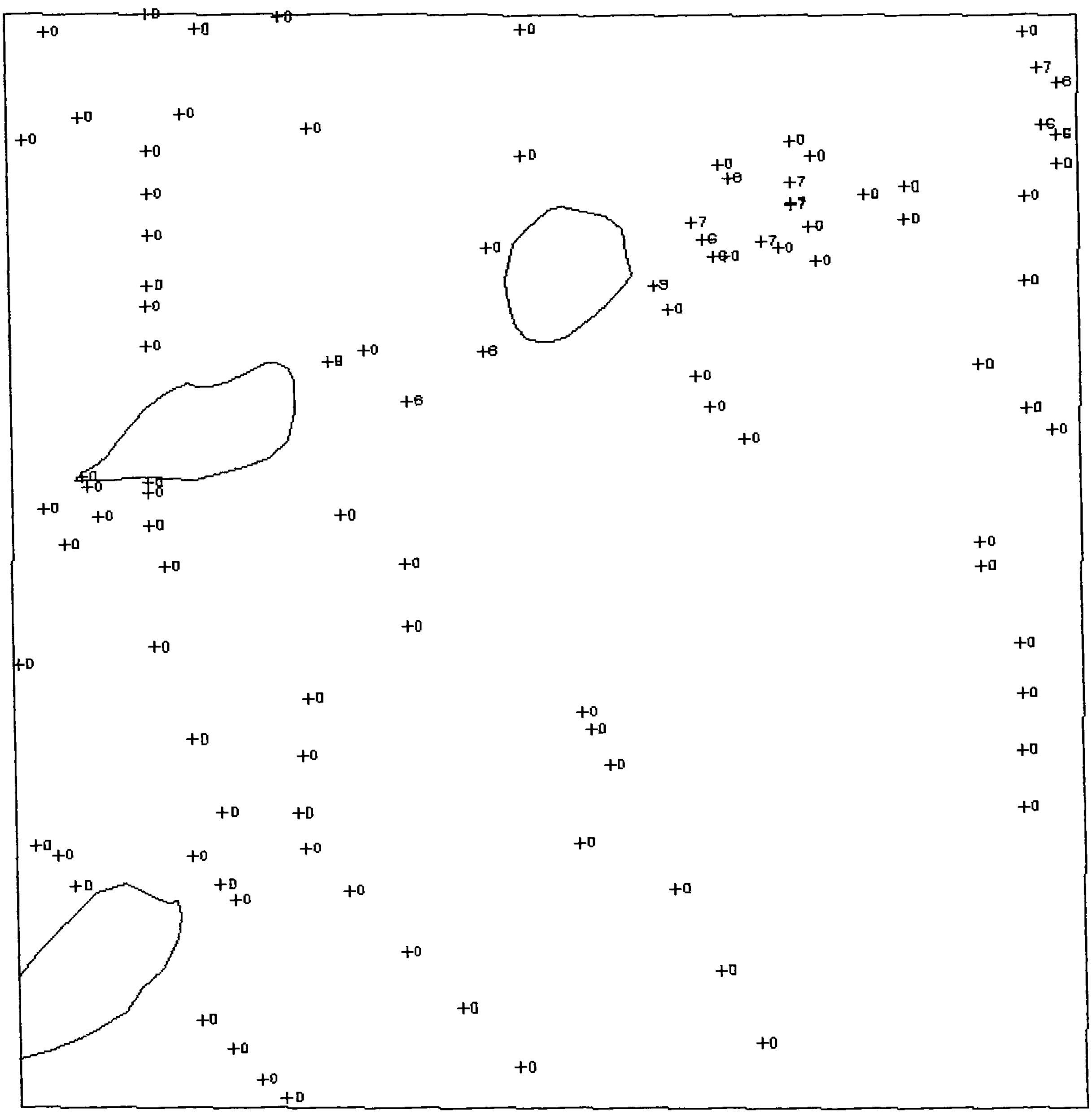


Figure C-1 -- Computer-generated manganese grade map for the 5-10 percent grade class. Outlines are boundaries of exhausted material. Numbers represent the average manganese content for each drill hole.

D. Sum the tons of material for each class for the entire section and compute the average grade in each class.

E. Keep running totals of tonnages and average grades for the entire range.

F. Tabulate resource estimates for each section for the three grade classes by township. On Table 2 the 5-10 percent grade class estimates comprise 42 sectional estimates; the 10-15 percent estimates comprise 29 sectional estimates; and the >15 percent estimates comprise 26 sectional estimates.

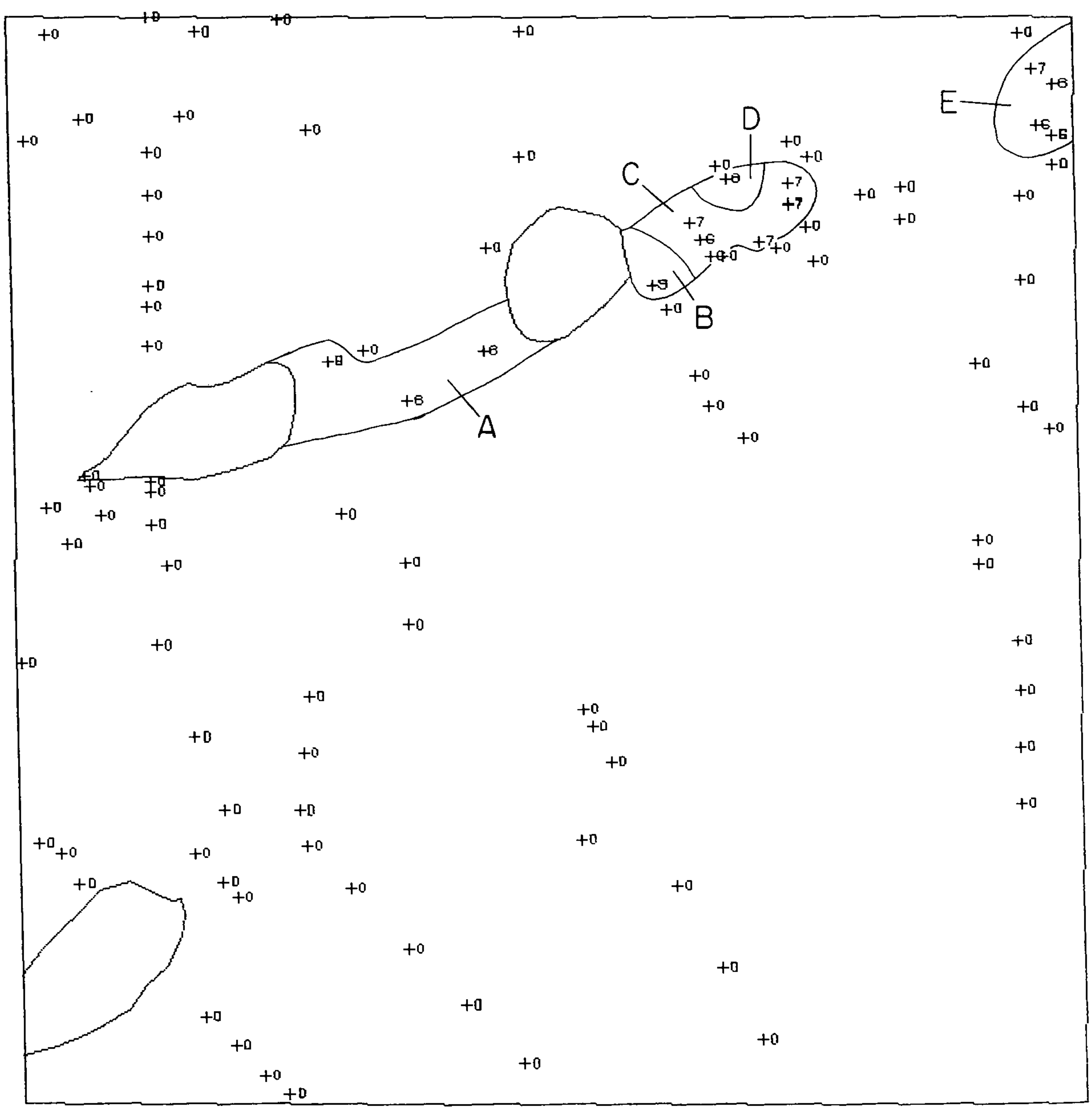


Figure C-2 -- Manganese-rich bodies (A, B, C, D and E) delineated on the computer-generated map shown in Figure C-1.