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Bureau of Mines Report of Investigations/1983

Mineralogy and Liberation Characteristics of Western Mesabi Range Oxidized Taconites

By Rolland L. Blake



UNITED STATES DEPARTMENT OF THE INTERIOR

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Library of Congress Cataloging in Publication Data:

Blake, Rolland Laws

Mineralogy and liberation characteristics of Western Mesabi Range oxidized taconite.

(Report of investigations ; 8813)

Bibliography: p. 25-26.

Supt. of Docs. no.: I 28.23:8813.

I. Taconite--Minnesota--Mesabi Range. I. Title. II. Series: Report of investigations (United States. Bureau of Mines) ; 8813.

TN23.U43 [QE390.2.176] 622s [549'.23] 83-600235

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	μm	micrometer
cm	centimeter	mlt	million long tons
ft	foot	mm	millimeter
ft ³ /lt	cubic foot per long ton	pct	percent
km	kilometer	ppm	parts per million
m	meter	wt pct	weight percent
mi	mile		

MINERALOGY AND LIBERATION CHARACTERISTICS OF WESTERN MESABI RANGE OXIDIZED TACONITES

By Rolland L. Blake¹

ABSTRACT

The Bureau of Mines investigated the mineralogy, tonnage, and beneficiating characteristics of oxidized (nonmagnetic) taconite iron resources of the Western Mesabi Range as part of its program to insure adequate future domestic mineral supplies. Magnetic taconite currently provides about 95 pct of Mesabi production, but the large tonnages of oxidized taconite between the magnetic deposits will be needed to help meet future domestic demand for iron ore. Three bulk samples that represent large tonnages from the Western Mesabi Range were selected to determine their mineral composition and liberation by light optical microscopy and to test their beneficiating response.

This report describes the mineralogy and liberation characteristics of the three samples of the Biwabik Iron-Formation for 26.5 mi (42.7 km) from Keewatin to Grand Rapids, MN. (Details of response to beneficiation were reported previously.) The samples represent mostly material from the Lower Cherty Member of the Biwabik Iron Formation, although one sample included some Upper Cherty Member. Minerals of all three samples were quartz (chert), hematite, goethite, and minor to trace amounts of magnetite, iron carbonate, and iron silicates.

It was concluded that the oxidized taconites of the Western Mesabi Range represent a subeconomic indicated resource that can be selectively mined and beneficiated as a future large source of iron feed for steelmaking.

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INTRODUCTION

OBJECTIVE

This report describes the geology, mineralogy, tonnage potential, and microscopically observed liberation characteristics of oxidized taconite on the Western Mesabi Range (WMR). Six previous Reports of Investigations have described

the beneficiation testing and response (1-6).² Table 1 lists these publications under the area sampled and type of beneficiation.

²Underlined numbers in parentheses refer to items in the list of references at the end of this report.

TABLE 1. - Bureau of Mines published results of beneficiation tests on bulk samples of WMR nonmagnetic taconite¹

	WMR-1	WMR-2	WRM-3
Flotation.....	RI 8482 (3)	RI 8505 (4)	RI 8552 (2).
Reduction roasting.....	RI 8549 (5)	RI 8572 (6)	None.
WHIMS ²	None.....	RI 8325 (1)	None.

¹See figures 1 and 2 for location of WMR areas 1, 2, and 3.

²Wet high-intensity magnetic separation.

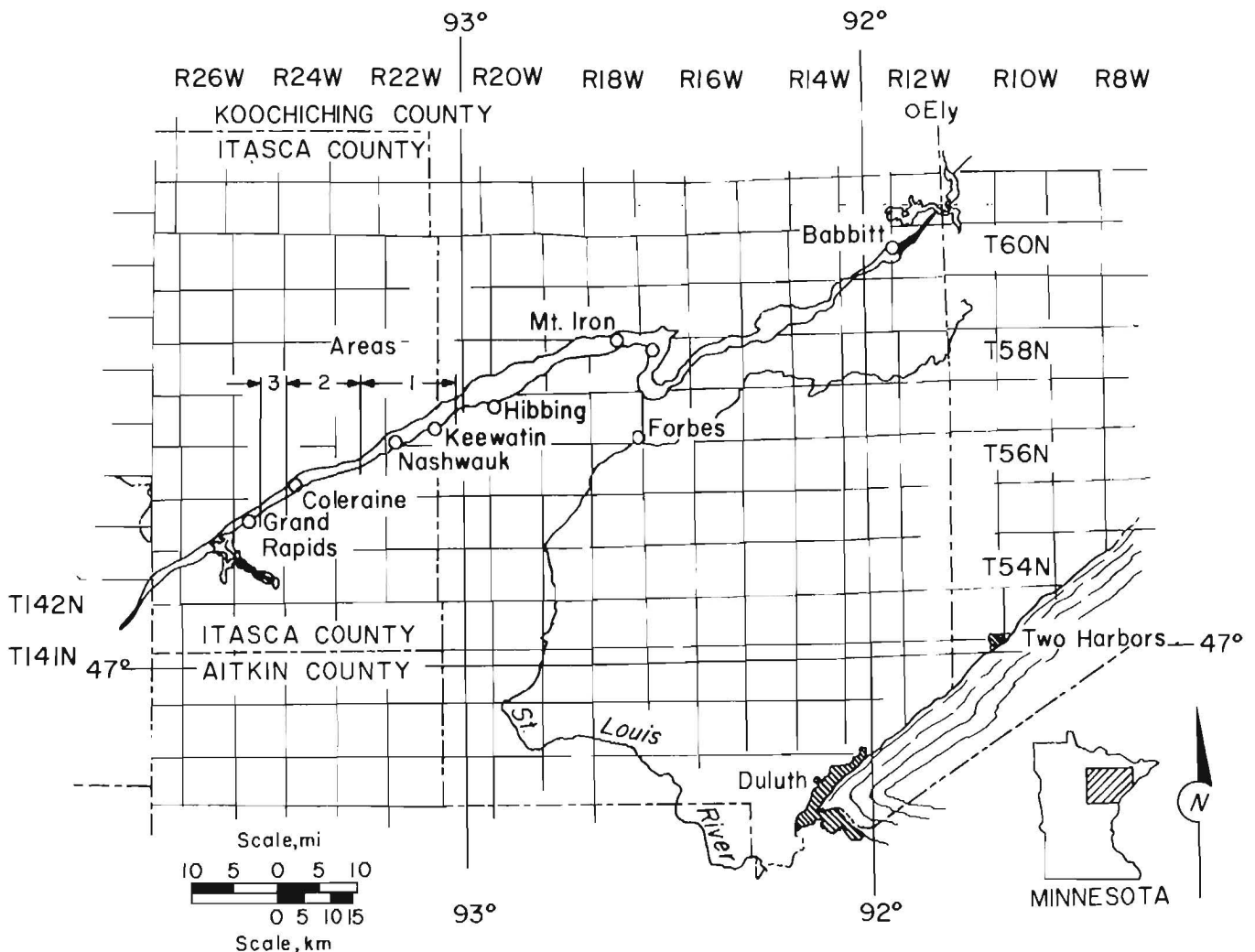


FIGURE 1. - Location of Western Mesabi Range, MN, and oxidized taconite areas 1, 2, and 3.

BACKGROUND

To expand the U.S. iron reserve base, the Bureau of Mines has undertaken research to develop beneficiation processes for the oxidized taconites of the WMR (4). In 1980 domestic production of 69.6 mlt (million long tons) of iron ore supplied 70 pct of U.S. requirements (98.9 mlt) (7). The Mesabi Range (fig. 1), the only producing iron ore district of the three (Mesabi, Cuyuna, and Vermilion) in Minnesota, supplied 45.2 mlt (65 pct) of 1980 domestic iron ore (7). Each year magnetic taconite (first produced in 1952) supplies more and more (about 95 pct in 1980 (7)) of Mesabi Range production because pellets made from taconite concentrates have superior grade and structure for blast furnace feed compared with natural iron ores, wash ores, and gravity concentrates. Although the open pit Mesabi Range magnetic taconite deposits are limited, surrounding or between them are the oxidized (nonmagnetic) taconite resources.

For this report, oxidized taconite is Biwabik Iron-Formation material that has been altered enough that the dominant iron minerals are now hematite and/or goethite, but alteration has not proceeded far enough to have produced the natural iron ores. Oxidized taconite was formed from (1) magnetite taconite in which most to all magnetite has been altered to hematite and/or goethite or (2) iron carbonate-iron silicate taconite in which most to all of the iron carbonate-iron silicate has been altered to goethite and/or hematite. Oxidation refers to the fact that most of the Fe^{2+} has been oxidized to Fe^{3+} . One objection to the term "oxidized taconite" is that it excludes primary hematite taconite, such as the Red Basal Taconite of the Mesabi Range or metamorphic hematite of some other iron ranges. As used here, oxidized taconite is similar to that defined by Bleifuss (8), except that he acknowledged only a little secondary ferric oxide enrichment, whereas the present author recognizes somewhat more. This may be a moot point because when oxidized taconites are utilized in the future,

even material that would formerly be classified as one of the natural ores will be found in small to large amounts and included as feed to the plant.

Oxidized taconite is presently uneconomical to treat, but it is readily accessible in the subglacial outcrop area of the WMR. The tonnage and beneficiating characteristics of this material were not well known. Recently, oxidized taconites at Tilden, MI, have been treated successfully by the selective flocculation-desliming-cationic-flotation process that was developed jointly by the Bureau's Twin Cities Research Center and The Cleveland-Cliffs Iron Co. (9). Tilden oxidized taconite, in general, contains mostly hematite and little goethite, whereas Mesabi oxidized taconite contains hematite plus considerable goethite. Both ores contain fairly coarse quartz, and some slime problems are caused by earthy hematite from Tilden and also by earthy goethite from the WMR. The concentrate produced in the jointly developed process makes pellets of chemical quality equal to that of pellets made from magnetic taconite concentrate. However, more thermal energy is required for heat-hardening of pellets made from the hematite-rich Tilden concentrate, and they are of lesser physical quality than those from magnetic taconite concentrate.

The area examined in this study extends 26.5 mi (42.7 km) from Keewatin to Grand Rapids, MN (fig. 2). Most work was done on samples from the Lower Cherty and some from the Upper Cherty Members of the Biwabik Iron-Formation³ (fig. 3). This part of the range was divided into three blocks (fig. 2) for sampling based on apparent differences in mineralogy and on availability of bulk samples representing large tonnages of taconite. Area WMR-1 extends for 13 mi (20.9 km) along the strike of the Biwabik Iron-Formation

³The material studied here was oxidized taconite involved mostly in early stages of alteration rather than taconite involved with more extensive alteration that formed semitaconites, or wash and heavy-media ores.

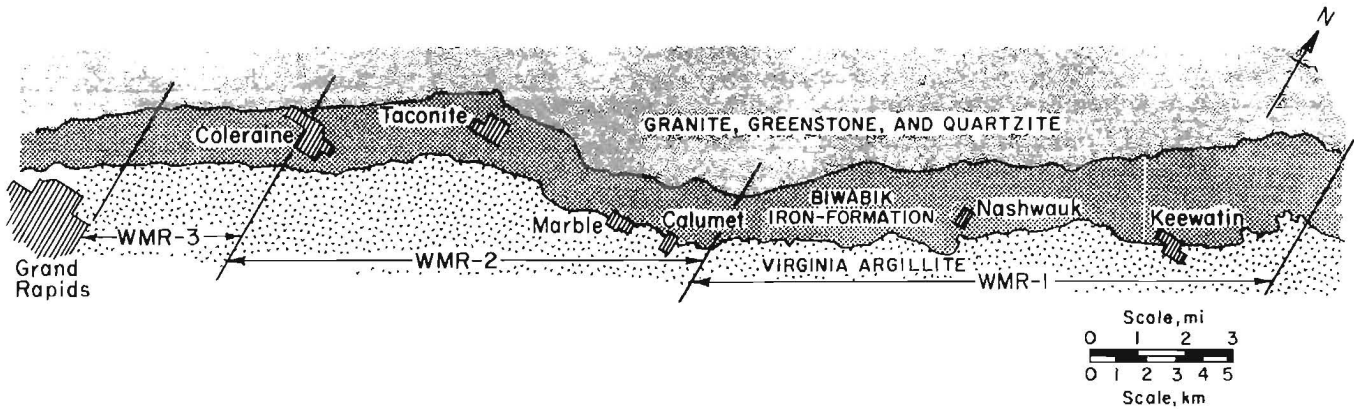


FIGURE 2. - Outcrop map of Biwabik Iron-Formation in areas 1, 2, and 3.

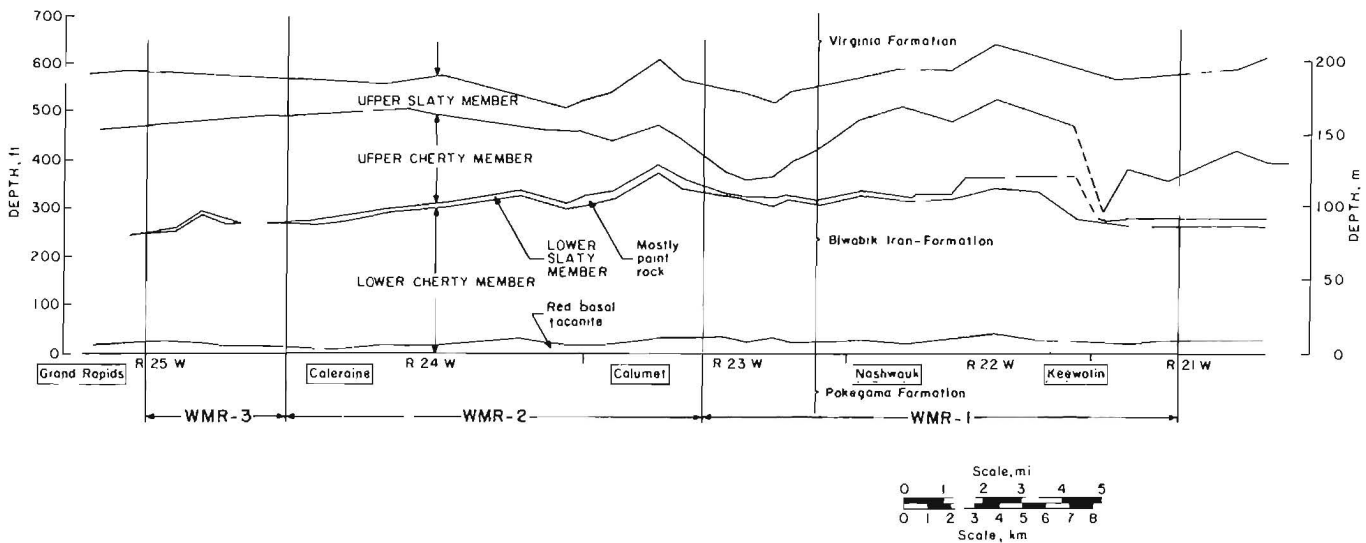


FIGURE 3. - Longitudinal section of Biwabik Iron-Formation in areas 1, 2, and 3 (modified from White (11)).

and within the subglacial outcrop. Area WMR-2 extends for 10 mi (16.1 km), and area WMR-3 is 3.5 mi (5.6 km) long. Petrographic samples were collected from drill core, from open pit bank samples, and from three representative bulk samples (several hundred tons each). Polished and thin sections were made for examination by light optical microscopy. Mineral and rock fragments were examined in refractive index oils; some minerals were identified by X-ray diffraction.

The mineralogy (10) and stratigraphy (11) of the Biwabik Iron-Formation and of the soft iron ores derived from these rocks were investigated by earlier workers. The Bureau has conducted fairly continuous sampling since about 1956,

plus bench-scale and pilot plant beneficiation experiments, and reported (12-17) on nonmagnetic taconite prior to the current series of tests. Gundersen and Schwartz (18) investigated the mineralogy, textures, and stratigraphy of the hard magnetic taconite from the Eastern Mesabi Range.

A comprehensive study of nonmagnetic oxidized taconite of the WMR from Hibbing to Coleraine, MN, a distance of 30 mi along the strike (fig. 1), was made by the GNR (Great Northern Railway),⁴ but their 1963 company report remains unpublished. Part of the GNR work was published by one of the investigators (8).

⁴Now Burlington-Northern.

A recent report by Marsden (19) tabulates estimated Mesabi Range iron ore reserves by ore class and by geographic range unit. The reserve estimate was designed to include all taconite material that can be produced to a no-loss situation. Iron ores are classed as natural iron ore, four grades of magnetic taconite ore based on weight recovery of magnetite and the iron content of the concentrates, and OXYBIF (pronounced

oxy-bif). "OXYBIF" refers only to the oxidized Biwabik Iron-Formation, the non-magnetic taconite that is considered to be potentially concentratable material and that may yield commercial-quality concentrates or pellets. OXYBIF is the hematitic or goethitic cherty iron-formation that was formed by the oxidation of the magnetite-rich, cherty, iron-formation and that, if unoxidized, should be taconite or taconite lean ore.

ACKNOWLEDGMENTS

This work was made possible by the cooperation and courtesy of employees of Mesabi Range iron mining companies. Geologists, mining engineers, and metallurgists discussed problems, guided sampling tours, provided bulk samples, and

aided in understanding the problems encountered. Helpful discussions are also acknowledged by personnel of the University of Minnesota and the Minnesota Geological Survey.

GENERAL GEOLOGY OF THE WESTERN MESABI RANGE

The WMR trends west-southwest (fig. 1); west of Grand Rapids, MN, it turns south and is suspected from drill core evidence to correlate with the Emily and Cuyuna districts (11). The iron ores and magnetic taconites are derived from the Biwabik Iron-Formation, a metasedimentary unit of the Animikie Group of Middle Precambrian age. The iron-formation dips gently southeast and is underlain conformably by the Pokegama Quartzite and overlain conformably by the Virginia Argillite Formation. The minerals and textures indicate that the Biwabik Iron-Formation was originally deposited mostly as a chemical precipitate (10), perhaps as a noncrystalline gel, high in silica, iron, and carbonate, and containing considerable water. The three sedimentary formations were involved in burial, lithification, and finally regional metamorphism, an event dated at about 1.76 billion years ago (20). The underlying sandstone was cemented to a quartzite, and the overlying shale was altered to an argillite. The Biwabik Iron-Formation lost much water and formed iron oxide (mostly magnetite), iron carbonate, and iron silicates stilpnomelane, minnesotaite, greenalite, and chamosite (10-11, 21). These minerals are found in the

unoxidized taconite. Most of the minor folding and gentle southerly dip are believed related to the regional metamorphism. A more recent event that affects mining was the deposition of Pleistocene glacial drift on the Western Mesabi Biwabik Iron-Formation outcrop area to a depth of about 40 ft at the north contact with the underlying quartzite and 160 to 200 ft at the south contact with the argillite (11). The drift must be removed for open pit mining of the taconite. Weathering of the iron formation to the present time has produced increasing amounts of iron ores and oxidized taconite by forming hematite and goethite at the expense of magnetite, iron carbonate, and iron silicates and by removal of silica.

Stratigraphically the Biwabik Iron-Formation was observed by Wolff (22) and confirmed by other geologists and mining engineers to contain four members, from oldest to youngest the Lower Cherty, Lower Slaty, Upper Cherty, and Upper Slaty (fig. 3). Each member contains both cherty and slaty layers, but the units are named for their predominant rock type. The term "cherty" refers to a dominance of chert as the matrix for

other minerals; "slaty" refers to iron silicate and carbonate-rich layers that may contain some chert. These rocks exhibit no slaty cleavage, only bedding parting and jointing, and are thus argillites and not slates.

Oxidation of the iron-formation to iron ore has been thought from early Mesabi mining days to be controlled by structures such as noses of folds, joint system intersections, and faults, because these more porous and permeable paths allow access of ground water to leach and otherwise alter the original minerals. Major structures were described by Gruner (10) for the entire range and by White (11) for the Western Mesabi. Both investigators found that vertical or steeply dipping joint systems are oriented in all directions, but three joint sets are predominant: N 10° E, N 45° W, and N 80° W.

AREA 1

Area 1 extends for 13 mi (20.9 km) along the strike of the Biwabik Iron-Formation and includes the western third of R 21 W, all of R 22 W, and the eastern half of R 23 W (figs. 2-3). This is from 2 mi (3 km) east of Keewatin, MN, to 1 mi (1.6 km) west of Snowball Lake, MN. The east and west limits of area 1 were selected because this block of the formation was believed to be fairly consistent throughout in containing substantial amounts of both magnetic and oxidized (nonmagnetic) taconite, whereas west of this block extensive oxidation has left very little magnetic taconite. The subglacial outcrop of the Biwabik Iron-Formation in area 1 (fig. 2) is between 1 and 2 mi (1.6 to 3.2 km) wide. Its north and south limits are irregular because of the shallow dip and minor folding. The average dip is 6° south, but local dip undulations and monoclines may reach 45° to 70°. Shallow reverse dips to the north are sometimes encountered in mining.

Figure 3 is a stratigraphic, longitudinal section, which shows thickness variations of the four members in the

study area. The section is drawn looking north, and information was projected to a plane along the subglacial south contact with the Virginia Formation. On the WMR the Lower Cherty is the thickest member, ranging from 225 to 330 ft (70 to 100 m), and contains most of the ore bodies and the most consistent magnetic taconite layer. The basal 20 to 30 ft (6 to 9 m) (10) of the Lower Cherty is called the "red basal taconite" layer from its original hematite content. This layer is usually too lean or does not liberate well enough to be considered an iron reserve or resource. The Lower Slaty Member usually ranges from a few feet to 40 ft (12 m) thick; the lower part is either unoxidized black shale or has been oxidized to paint rock, a slippery-feeling, red kaolinite-hematite and/or goethite-bearing material. It is usually too lean in Fe, too high in Al₂O₃, and/or too fine grained to be treatable.

Recent magnetic taconite exploration and mining in area 1 have enabled Owens, Trost, and Mattson (23) to study structural control of taconite oxidation and to guide mining operations to provide fairly homogeneous feed for two magnetic taconite beneficiating plants. Structures such as folds, joints, faults, and fracture zones have affected the iron resources, reserves, and mining in area 1 (fig. 4). These structures have controlled ground water circulation and therefore the location of higher iron grade areas where silica has been removed. These structures affect the mining process, partly by dictating where enriched material is located, but also by requiring careful mining operation planning to remove the valuable iron ore and taconite with the lowest cost of removing lean rock. This requires extensive development drilling, as well as field geologic mapping.

AREA 2

Area 2 extends for 10 mi (16.1 km) along the strike of the Biwabik Iron-Formation and includes the western half of R 23 W and all of R 24 W from 1 mi (1.6 km) west of Snowball Lake to

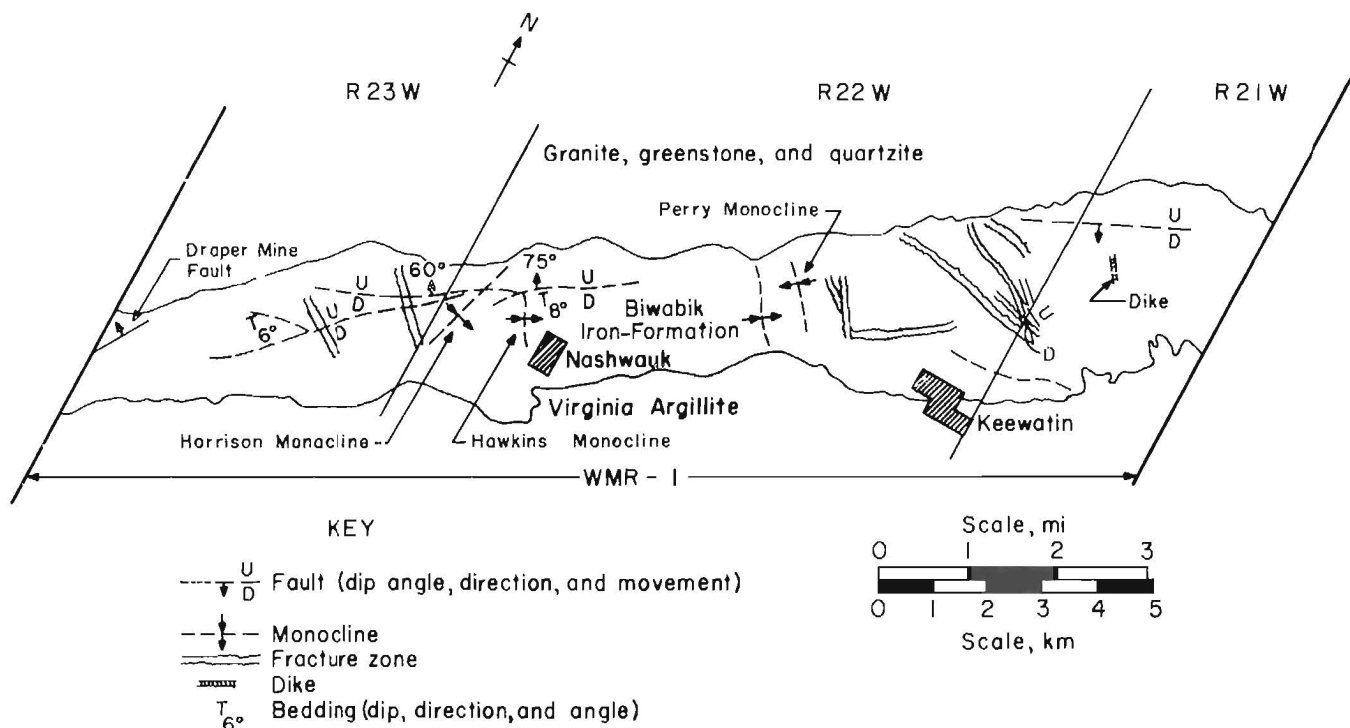


FIGURE 4. Structures that affect oxidation of taconite in area 1 (after Owens (23)).

Coleraine, MN (figs. 2-3). This block is composed mostly of oxidized (nonmagnetic) taconite; only very small amounts of magnetic silicate-carbonate iron-formation remnants occur west of the Draper Mine Fault, west end of figure 4 (23). The subglacial outcrop of the Biwabik Iron-Formation in area 2 (fig. 2) ranges from 1 to 1.5 mi (1.6 and 2.4 km) wide, and its north and south limits are somewhat more regular than in area 1 because of less structural deformation. The average dip of the beds is again about 6°. Only one monocline is known; it is north of Marble and Calumet, MN. Most structural information of area 2 is based on diamond drilling, whereas in area 1, it was supplemented by current mining of magnetic taconite; the most westerly taconite processing plant is near the west end of area 1. When future oxidized taconite mining proceeds in area 2, local structures similar to those observed in

area 1, but fewer and of lesser intensity, will probably be observed. Stratigraphically (fig. 3) area 2 is similar to area 1, and structure is again thought to be the major ore control.

AREA 3

Area 3 extends for 3.5 mi (5.6 km) along the strike of the Biwabik Iron-Formation and includes the eastern half of R 25 W. This block is composed mostly of oxidized (nonmagnetic) taconite, and most of the characteristics described in area 2 apply here also. Stratigraphically (fig. 3) the Lower Slaty Member starts to thin and pinch out in this interval; the Lower Cherty Member continues to thin slightly, a trend starting in area 2. The structure in area 3 is mainly the slight dip of the beds averaging about 6° SE, and no other structures have been reported.

BULK SAMPLING METHODOLOGY AND LOCATIONS

METHODOLOGY

Pilot plant testing of ores requires large samples to reach a steady state, operate at steady state, and shut down. Also, changes made to refine equipment and processes require additional testing on the same type of sample for valid comparison. Therefore, bulk samples of 350, 600, and 800 tons were collected from areas WMR 1, 2, and 3, respectively.

"Magnetic" taconite on the WMR for this study is Biwabik Iron-Formation rock that retains most or all of its original magnetite. It usually also retains its original iron carbonate and iron silicate minerals. "Oxidized" taconite is rock in which magnetite is absent or a minor constituent, either from lack of original magnetite or from oxidation that removed the original magnetite or replaced it with hematite and/or goethite. Oxidized taconite contains minor to trace, or none, of the original iron silicates and carbonates because the oxidation-alteration processes that replace magnetite by hematite or goethite also replace carbonates and silicates. Oxidized taconite may vary between being rich in, or devoid of, hematite and/or goethite based upon its original mineralogy and the degree and type of weathering it was exposed to. At the iron-rich end, oxidized taconite would approach the wash and heavy-media ores; richer still would be direct-shipping ores. At the lean end, oxidized taconite would approach an iron-free rock. Oxidized taconite amenable to beneficiation could be in the range of 25 to 40 pct Fe and with a texture such that the iron oxides could be separated from the gangue minerals. Satisfactory recovery and grade would result from processes other than magnetic separation or from those used on wash and heavy media ores.

Providing a large metallurgical sample that represents oxidized taconite in each area requires considerable knowledge of the Biwabik Iron-Formation. Drill cores could not furnish enough material, but their appearance and analyses provided

valuable information along with that obtained during open pit mining. One possible source of a large sample is the natural ore and taconite open pit mine banks. However, most material does not represent oxidized taconite between the richer ore bodies because the alteration that produced these deposits was gradational, and economical mining limits are determined by falloff in grade and recovery. Thus, the enriched halo that surrounds open pit mines usually would not represent the leaner material sought between the mines. However, it is possible to select a bank location at an open pit mine where mineralogy, texture, chemical analysis, and beneficiation tests have shown the oxidized taconite to be similar to the average material between open pits. The parameters of this material between pits would be known from drill core logging, chemical analysis, beneficiation tests on the core, and personal experience.

Iron-mining-company exploration geologists, mining engineers, and research laboratory metallurgists who have carried out exploration drilling and beneficiation testing of areas between mines are the best people to suggest where to find a representative sample of substantial tonnage of nonmagnetic taconite. Also, they can plan the mining of a large sample when weather is favorable and heavy equipment and access roads are available. Bulk samples for areas 1, 2, and 3 were obtained in this manner. The area 1 bulk sample is more representative of the material in that area than are the area 2 and 3 bulk samples for their areas. This is because considerable research to obtain such a sample had already been done before the Bureau asked the mining company for such a sample. However, the personnel at companies in areas 2 and 3 also worked hard to provide representative samples.

Hand specimens that represent the various macroscopically different types of rock comprising a bulk sample were selected with help from a company geologist. It was not possible to

estimate the weight or volume percent of each type of rock in the sample. When fine material was present in significant amounts, a separate sample was taken to compare with the hand specimen.

taken in accessible areas. Subject to this limitation, the samples consisted of the best mixture to represent the oxidized taconite based on extensive drilling, core analysis, and laboratory testing.

GEOGRAPHIC LOCATION

STRATIGRAPHIC LOCATION

Geographic location of bulk samples is limited by the fact that they had to be

Generalized stratigraphy of area 1 taconite is shown in figure 5. Geologists

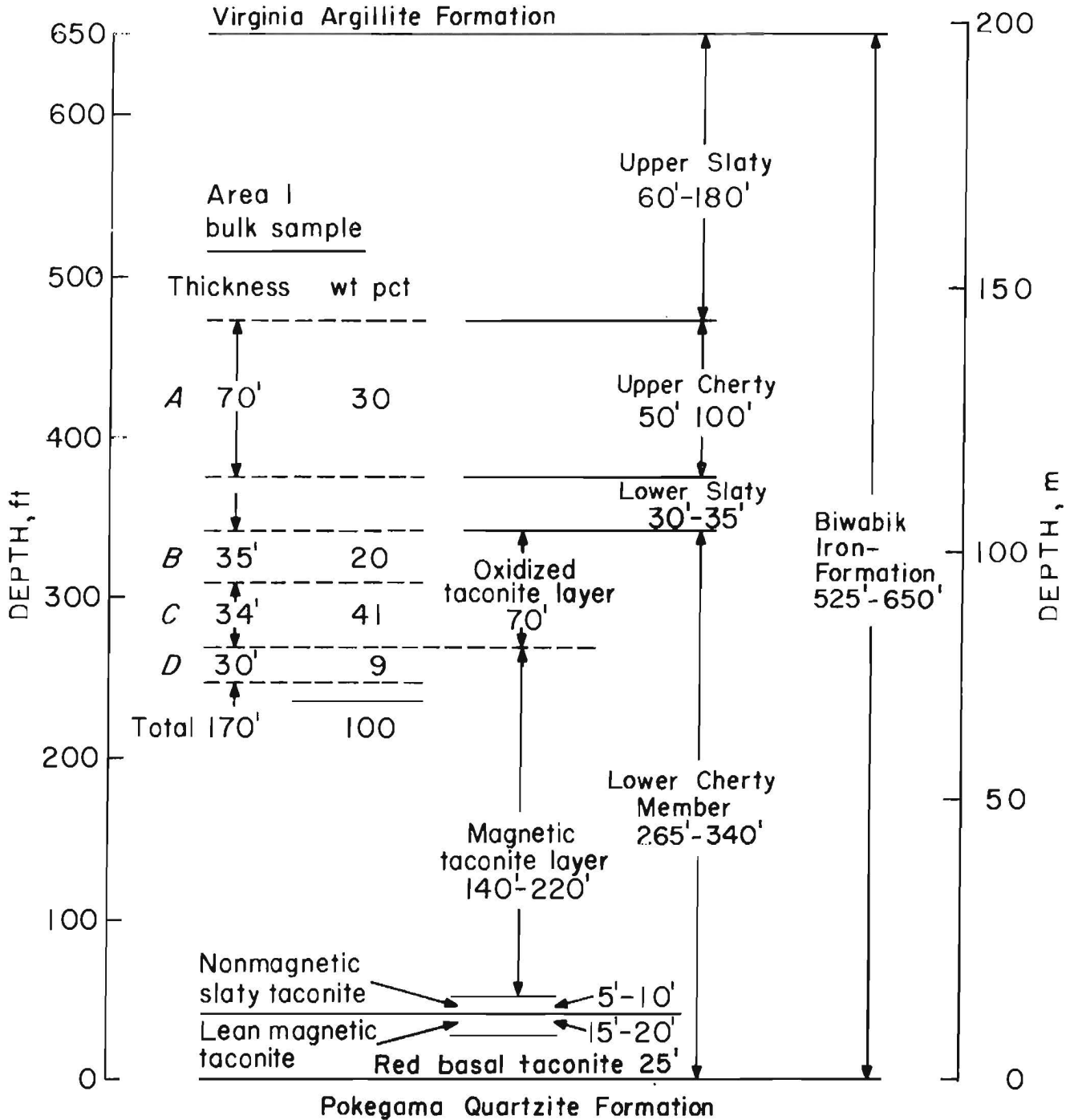


FIGURE 5. - Stratigraphic location of bulk sample of oxidized taconite from area 1.

and metallurgists have determined that the Lower Cherty Member is the most amenable of the four members to proposed processing of oxidized taconite because of its predominantly coarse texture and its moderate to extensive oxidation. In area 1 the magnetic layer is presently being mined where its magnetite content is sufficient for treatment by magnetic separation. Below that layer, the lean taconite and lean red basal taconite have low potential amenability. The upper part of the Lower Cherty, which is removed by stripping to expose the magnetic taconite, is of primary interest for non-magnetic processing. The Upper Cherty Member has some potential amenability, but the two slaty members are normally too fine grained, too high in Al_2O_3 , or too unoxidized (contain iron carbonate and iron silicates) to be of interest.

The area 1 bulk sample is a 350-ton composite of material selected to consist

of 70 wt pct from the Lower Cherty horizons plus 30 wt pct from the Upper Cherty horizon as shown in figure 5. These weight proportions were chosen by mining company geologists and engineers as an accurate blend of Upper and Lower Cherty Members that represents the amenable materials above the currently mined magnetic layer. By design the weight percent figures are not proportional to the vertical interval. Typical hand specimens were selected from the separate stockpiles before the materials were mixed to form the composite sample.

The area 2 bulk sample was 600 tons of material taken from a 20-ft layer at the top of a 185-ft-thick section of Lower Cherty material. As shown in figure 6, the 185-ft section was above the red basal taconite (which does not liberate iron oxides well and contains undesirable Al_2O_3) and does not include the top 60 ft which varies from wash ore to retreat ore

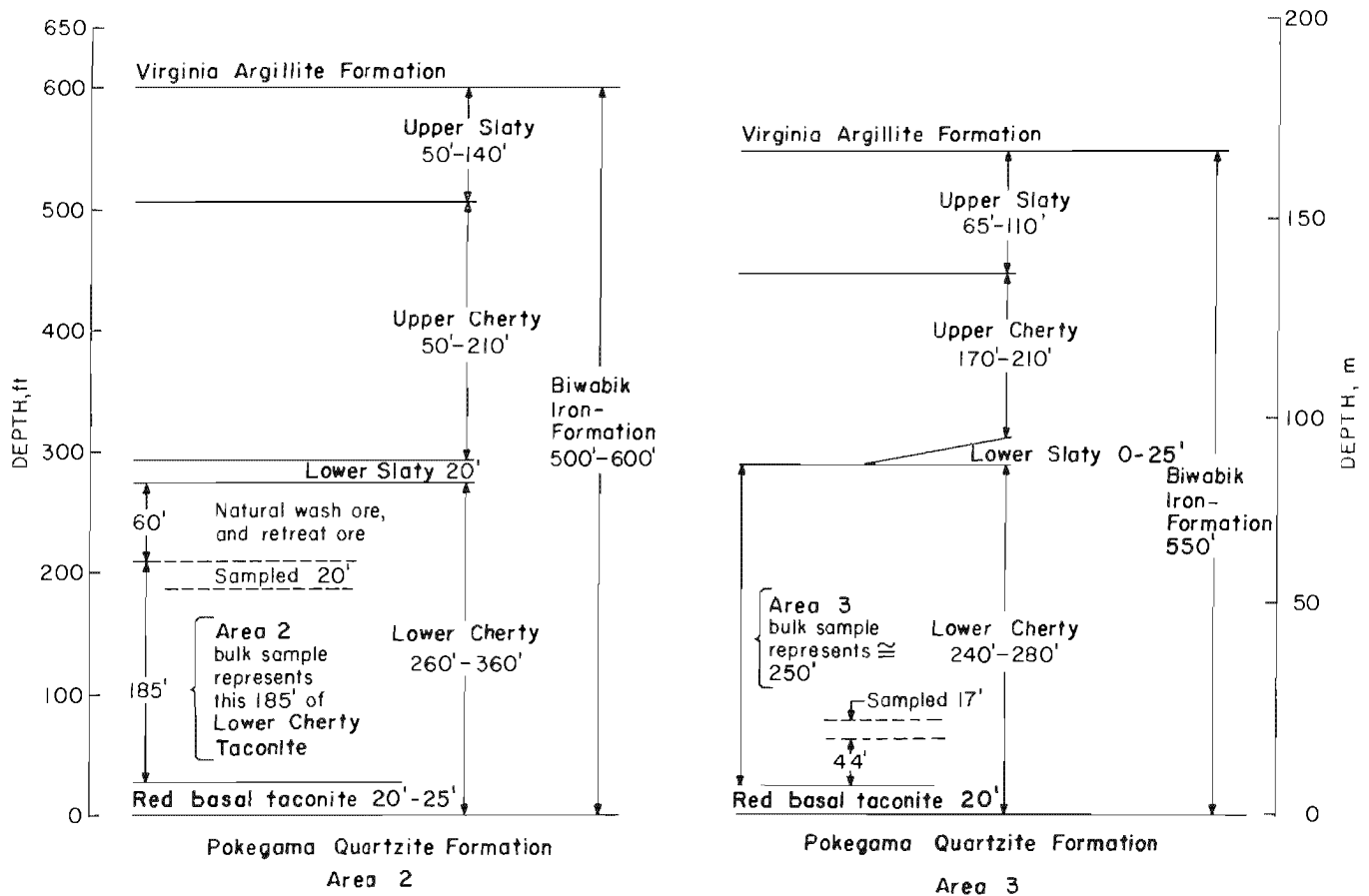


FIGURE 6. Stratigraphic location of bulk samples of oxidized taconite from areas 2 and 3.

to lean sand. The Upper cherty material in area 2 was not considered because it is leaner and is not expected to yield an acceptable recovery. The area 2 Lower Cherty stratigraphic equivalence of the magnetic taconite layer of area 1 is mostly oxidized and so is represented by the bulk sample WMR-2. Although the sampling interval was only 20 ft based on accessibility, drill core analyses and testing of core indicated to the mining company personnel that this material was fairly representative of the 185-ft section. There are leaner and richer layers and zones within the strata, but these are also present in the 20-ft sampling interval.

The area 3 bulk sample consisted of 800 tons taken from a 17-ft-thick layer between 44 and 61 ft above the red basal

taconite. The sample represents 250 ft of Lower Cherty Member, except for 20 ft of red basal taconite (fig. 6). Fewer drill holes in this area resulted in less certainty as to how well the sample represents the entire strata, but it is the best sample available from area 3, which has had little mining activity. As shown by Bleifuss (8) (fig. 1), some strata in the Lower Cherty Member of the WMR originally contained carbonate-chert or silicate-chert and no magnetite, while other strata contained magnetite which mostly altered to martite (hematite). The carbonate-chert and silicate-chert strata altered so as to contain goethite as the dominant iron oxide. Westward the amount of original magnetite diminished until in area 3 it was almost insignificant.

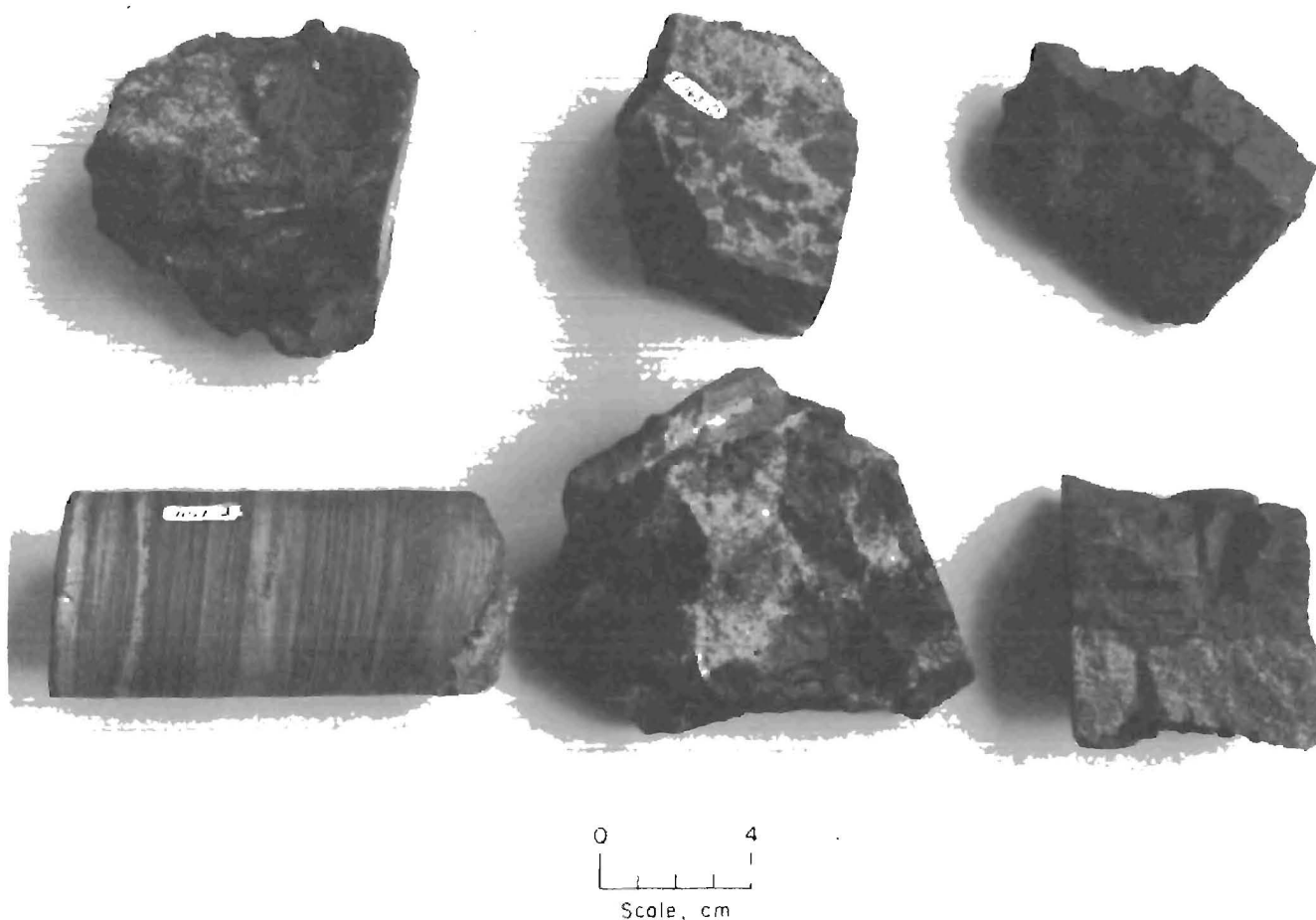


FIGURE 7. - Hand specimens of area 1 showing variations in textures and structures.

CHARACTERIZATION OF BULK SAMPLES

Macroscopic and microscopic examination of the specimens selected from each stockpile for the bulk sample of area 1 showed almost as much variation in mineralogy, texture, alteration, and liberation rock types in any one stockpile as among stockpiles (fig. 7). Typical sample differences within a stockpile included varying proportions of hematite, of goethite, and of total iron oxides to quartz. Other differences included the thickness and continuity of chert-rich versus iron oxide-rich layers. Further differences include the range in degree of weathering that resulted in removal of silica and migration of small amounts of iron to form lean and porous rocks at one place, enriched concentration of iron oxides nearby, and almost unweathered taconite at another place.

MACROSCOPIC TEXTURE AND GRAIN SIZE

The macroscopic appearance of unoxidized taconite usually reveals cherty and slaty layers that are interbedded (figs. 7-9). Each layer or lamina consists of rather specific proportions of two or more of the minerals already mentioned. Slaty layers usually range in thickness from less than 1 to 10 mm. Cherty taconite layers are usually from 2 mm to over 10 cm in thickness. The lateral extent of the layers ranges from a few centimeters to several tens of meters. Layers are frequently parallel, but many cherty layers are wavy, some pinch out, and a few bifurcate and may rejoin around nodules that formed during lithification. Minerals in cherty layers commonly occur as separate grains within granules in a

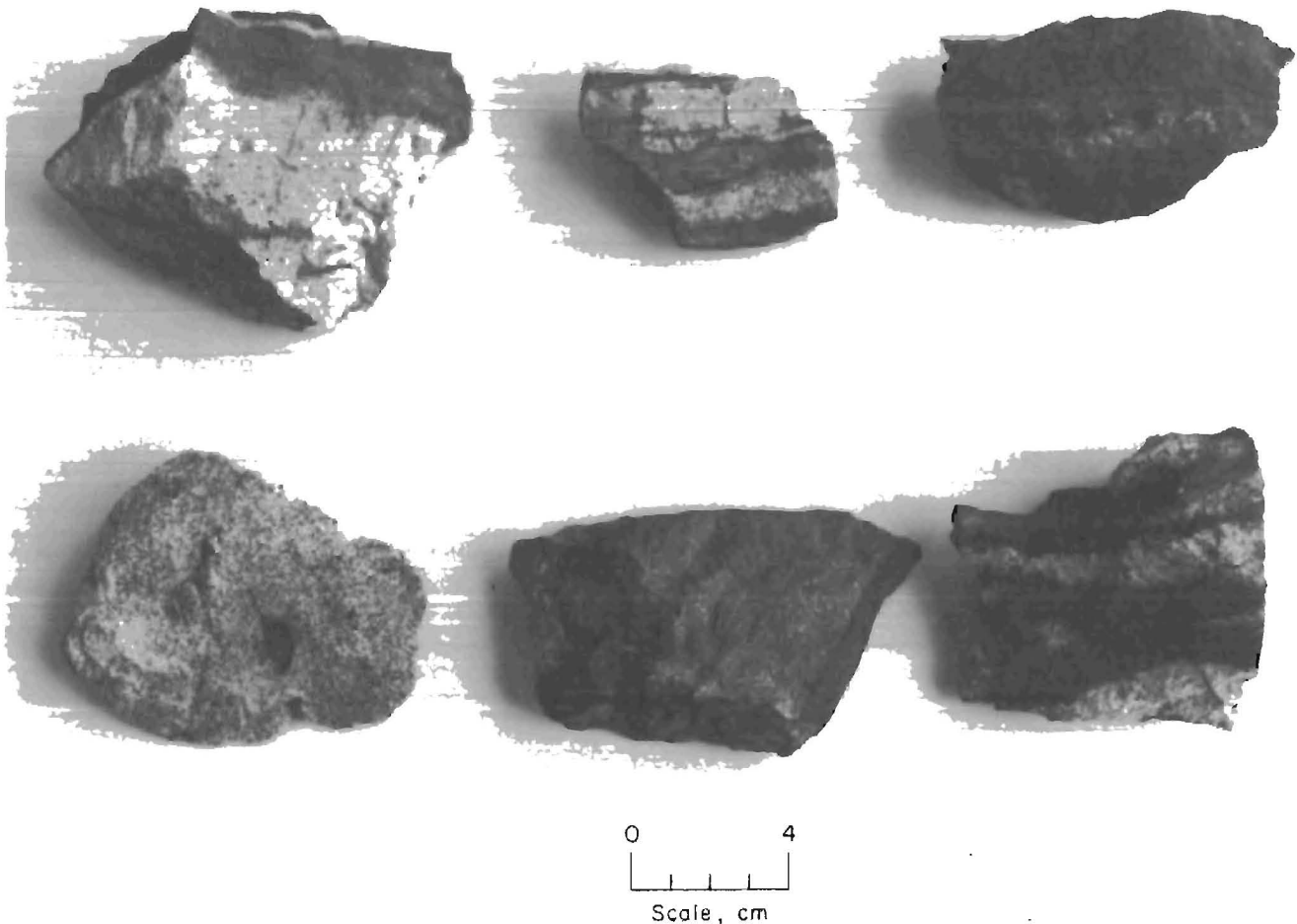


FIGURE 8. - Hand specimens of area 2 showing variations in textures and structures.

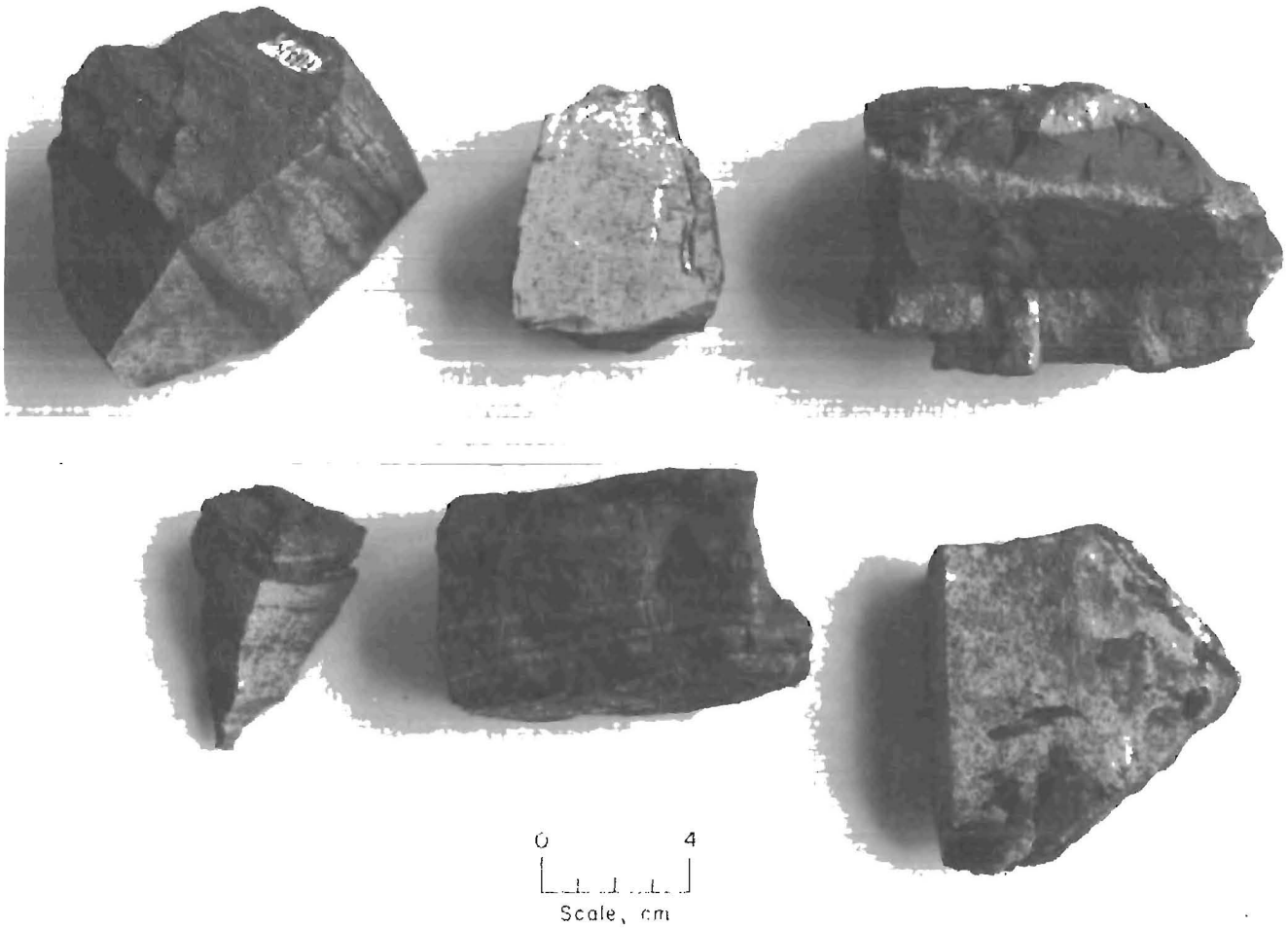


FIGURE 9. - Hand specimens of area 3 showing variations in textures and structures.

matrix of finer mineral grains. Granules are 0.2 to 2 mm in longest dimension, and ovoid to elliptical to distorted in shape. Minerals in slaty taconite are too fine grained to be observed with the unaided eye, and these layers are usually devoid of granules.

Area 1

Three (A, B, and C) of the four stockpiles (excluding D of fig. 5) of area 1 sample showed similarity in their overall degree of oxidation and contained only trace amounts of magnetite, iron carbonate, and iron silicate, indicating that the original minerals were either replaced or leached. The fourth stockpile (D of fig. 5) appeared more like the underlying magnetic taconite. It varied from an unoxidized to a partly oxidized condition.

The Upper Cherty (A of fig. 5) stockpile sample showed macroscopically that some rocks had a cherty matrix with scattered or clustered 0.1- to 1.0-mm grains of goethite and/or hematite. Taconite coherency ranged from hard, unleached material to extensively leached and friable rock, the latter containing earthy goethite. Some oxidized taconite showed a cherty matrix with partly decomposed products from iron silicate and iron carbonate. Some taconite is massive, hard goethite with either scattered quartz inclusions or frequent cavities.

The upper 35-ft layer (B of fig. 5) of the Lower Cherty Member is an oxidized taconite derived from a carbonate-chert material containing only small to trace amounts of magnetite. This layer usually is lean (23 pct Fe) and contains some wash ore and retreat ore. The oxidized

taconite contains hard goethite and a small amount of hematite as scattered small grains to irregular networks with a cherty matrix. Some goethite occurs in solid layers up to 5 cm thick. Rock coherency ranges from hard to friable.

The middle layer (C in fig. 5) of the Lower Cherty sample of area 1 is composed of mostly oxidized taconite with a cherty matrix containing goethite and/or hematite. Most iron oxide is in scattered small grains, while some forms an interconnecting network through the cherty matrix, and some occurs as solid iron oxide layers from 0.5 to 2 cm thick. Most of the oxidized taconite is hard and coherent, but some is leached and friable. Occasionally, thin layers that are magnetite-rich occur between granule taconite and a solid goethite layer.

The lowermost layer (D of fig. 5) is a magnetic taconite with olive green iron silicate and buff-colored iron carbonate matrix containing magnetite as scattered grains and rarely as layers. Where oxidized, the taconite shows that goethite and hematite (brown and red, respectively) have replaced the magnetite. Sedimentary layering (bedding) is well preserved in the less oxidized parts, whereas it is partly destroyed in the oxidized material.

Area 2

Macroscopically the area 2 taconite sample is partly coherent rock with a white cherty matrix containing scattered iron oxide, mostly hematite and partly goethite, and trace amounts of magnetite (fig. 8). The iron oxide occurs mostly as irregular clusters of subhedral to euhedral grains, the clusters ranging from 0.2 to 1.5 mm in diameter. Scattered through the cherty matrix are small amounts of earthy goethite and hematite that would be lost during beneficiation. This sample is fairly homogeneous when compared to the highly variable area 1

sample. Original layering has been partly destroyed by weathering.

Area 3

Macroscopically the area 3 taconite sample (fig. 9) is similar to the area 2 sample (fig. 8) in that it has a white cherty matrix with disseminated iron oxides, hematite, and goethite. Some iron oxide occurs as clusters or isolated grains from 0.5 to 10 mm in diameter. A small amount of iron oxide occurs in solid layers from 0.25 to 3 cm thick. Original layering is preserved in some of the rocks.

MINERAL COMPOSITION

Area 1

The mineral content of bulk sample WMR-1 is based on a point count of sized fractions briquetted and polished and on chemical analyses of three different head samples, plus other analyses on selected size fractions. Quartz is the most abundant mineral at nearly 45 wt pct (table 2). Magnetite is present in the overall bulk sample at 4 pct, while iron carbonate is 2 pct and iron silicates are only 0.3 pct. The low iron carbonate, iron silicate, and magnetite content results from the more oxidized nature of 91 pct of the sample (A, B, and C of fig. 5). Most of the magnetite, iron carbonate, and iron silicate are found in the lean oxidized 9 pct of the sample (D of fig. 5). Figure 10 shows the distribution of these minerals in various size fractions screened from minus 10-mesh pilot plant feed after the sample had been partly ground. The three most abundant minerals are present in nearly uniform amounts for the three coarsest size fractions. Below 100 mesh, quartz content increases, which suggests that goethite and hematite are more readily broken to finer sizes. Below 10 μm , quartz and the ferrous oxides are present in the same amounts.

TABLE 2. - Mineral distribution of WMR bulk samples, weight percent

Mineral	WMR-1		WMR-2: Petrographic ³	WMR-3: Petrographic ⁴
	Petrographic ¹	Chemical analysis calculations ²		
Quartz.....	44.8	44.8	40.0	49.0
Hematite.....	25.9	23.0	41	34
Goethite.....	22.8	25	16	14
Subtotal.....	48.7	48.0	57.0	48.0
Magnetite.....	4.1	5.5	.9	1
Carbonate.....	2.1	1.6	.7	Trace
Iron silicate.....	.3	.1	1.0	2
Total.....	100.0	100.0	100.0	100.0

¹Based on point count of sized fractions briquetted and polished and an average of 3 chemical analyses.

²Based on chemical analysis totaling 97.6 pct and normalized to 100 pct.

³Based on average of 2 chemical analyses and visual estimate of polished briquets of screened fractions.

⁴Based on point count.

Area 2

Minerals of area 2 sample (table 2) show about equal amounts of quartz (40 pct) and hematite (41 pct), 16 pct goethite, and about 1 pct each of magnetite, iron carbonate, and iron silicate. The extensive oxidation of area 2 sample is indicated by this low magnetite, iron silicate, and iron carbonate content.

Area 3

The area 3 sample shows a mineral content (table 2) of 49 pct quartz, 34 pct hematite, and 14 pct goethite. As in area 2, the iron carbonate and iron silicate are nearly destroyed because of extensive oxidation.

Discussion of Mineral Composition and Element Distribution

Referring to table 2 for mineral composition and to table 3 for chemical analyses of the bulk samples, quartz content is 45, 40, and 49 wt pct for bulk samples 1, 2, and 3, respectively, a moderate variation indicating that sample 2 should be richest in iron oxide as evidenced by its combined ferric oxide (hematite and goethite) content at 57 pct. Areas 1 and 3 each have 48 pct combined

ferric oxide (table 2). The area 1 sample also contains about 5 pct magnetite for a combined iron oxide content of about 53 pct. The area 3 sample contains the least combined iron oxide (49 pct). The ratio of hematite to goethite in each bulk sample is of interest. Early in the

TABLE 3. - Chemical analyses of WMR 1, 2, and 3 bulk samples, percent

Chemical	WMR-1	WMR-2	WMR-3
SiO ₂	43.7	44.5	49.0
Al ₂ O ₃.....	.65	.64	.45
FeO.....	2.9	.7	1.5
Fe ₂ O ₃	47.4	50.9	44.6
TiO ₂.....	.25	.26	.14
MgO.....	.19	.26	.14
CaO.....	.52	.41	.19
K ₂ O.....	.03	.05	.1
Na ₂ O.....	.03	.05	.1
MnO.....	.61	.10	.10
Sulfur.....	.018	.01	.012
Phosphorus.....	.039	.013	.01
Carbon.....	.17	.11	.23
LOI at 400° C..	2.26	1.6	2.8
LOI at 1,000° C	3.17	2.4	3.4
Total.....	101.94	99.00	102.77

¹Jacobs and Colombo (3).

²Jacobs and Colombo (4).

³Jacobs (2), modified by eliminating 11 trace elements.

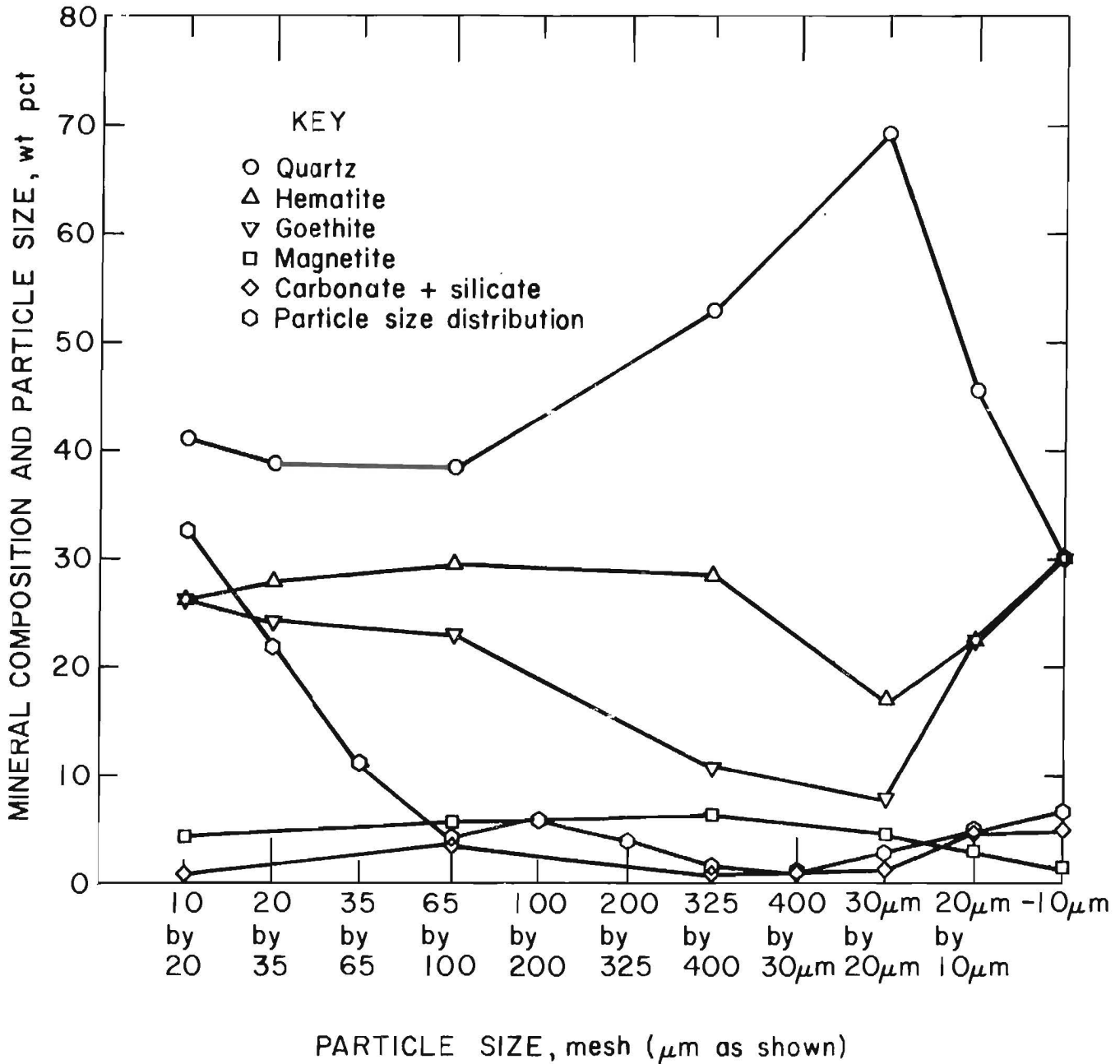


FIGURE 10. - Mineral composition versus size distribution of area 1 bulk sample as minus 10-mesh feed to flotation grinding circuit.

study, it was believed that area 1 sample would have considerably more hematite than goethite, that area 2 sample would have more goethite than hematite, and that area 3 sample would have

considerably more goethite than hematite. These ideas were based on the predominating color of the samples (red for hematite and brown to yellow for goethite). Also oxidation and hydroxylation that

would favor goethite formation over hematite was thought to increase westerly. The area 1 bulk sample contained about equal amounts of hematite and goethite. The area 2 sample contained 2.6 times as much hematite as goethite, and the area 3 sample contained 2.4 times as much hematite as goethite. When these ratios were observed by light optical microscopy, there was concern that softer goethite might pluck out of the polished section more readily than hematite, thus giving a falsely low goethite content. However, chemical analyses supported the ratios indicated. Earthy goethite and earthy hematite do not polish well, and some is lost during sample preparation. The amounts of hematite and goethite are important because hematite is richer in iron (70 pct) than goethite (63 pct) and a concentrate grade is thus richer if it contains more hematite. Also, the mineral beneficiation response may be different. The slime problem during beneficiation is greater with goethite and earthy hematite since they appear to break down more readily to finer particles than the coarser crystalline hematite.

The various chemical constituents of the bulk samples (tables 2 and 3) are considered to be associated with the minerals as follows: Ferrous iron is distributed among magnetite, siderite, and iron silicates, and ferric iron among hematite, goethite, and magnetite. (Two-thirds of the iron in magnetite is Fe^{3+} .) SiO_2 is present mostly as quartz or chert, with a very small amount (0.1 wt pct) attributed to iron silicates. A small amount of the Al_2O_3 is present in the iron silicate stilpnomelane. Probably most of the Al_2O_3 is present as small quantities of painty material such as kaolinite stained with fine hematite and/or goethite. The kaolinite is a weathering product of stilpnomelane. The small amounts of CaO , MgO , and Mn are present in both carbonate and silicates substituting for Fe . The small amount of sulfur probably results from weathering of trace amounts of pyrite and possibly

arsenopyrite. Phosphorus is probably from apatite or related phosphates, which are difficult to recognize in the taconite. LOI up to $400^\circ C$ represents water adsorbed on mineral surfaces and (OH) in the goethite crystal structure. LOI between $400^\circ C$ and $1,000^\circ C$ represents both CO_2 from carbonate and (OH) from iron silicate structures, as these minerals were thermally decomposed.

MICROSCOPIC TEXTURES, ALTERATION, AND LIBERATION

Petrographic examination of taconite is carried out with light optical microscopy using polished briquets, occasional thin sections, and fragments in refractive index oils. Mineral identification, grain size, texture (grain-to-grain relationships), alteration, and liberation characteristics (size and type of locking of ore to gangue minerals) can be determined by these techniques. Concentrates, middlings, and tailings can be observed to let the mineral beneficiation process engineer know if liberation has been achieved and if the separation process was successful. Most of the process problems were related to separation efficiency; few resulted from lack of liberation.

Unoxidized and partly oxidized taconite contains iron silicates (minnesotaite, stilpnomelane, and possibly greenalite), siderite, and magnetite. Some of this magnetite is partly replaced by hematite (martite) along magnetite grain boundaries and along crystallographic planes within magnetite. Most of this magnetite occurs in clusters of grains with overall size ranging from 30 to $300 \mu m$ in diameter and averaging about $100 \mu m$. Individual magnetite grains range from about $100 \mu m$ to just visible (several μm). Liberation of most magnetite would be about 30 to $40 \mu m$ because the magnetite breaks easily through the clusters and less easily at magnetite-gangue grain boundaries. Figures 11-13 show typical textures in samples from areas 1, 2, and 3.

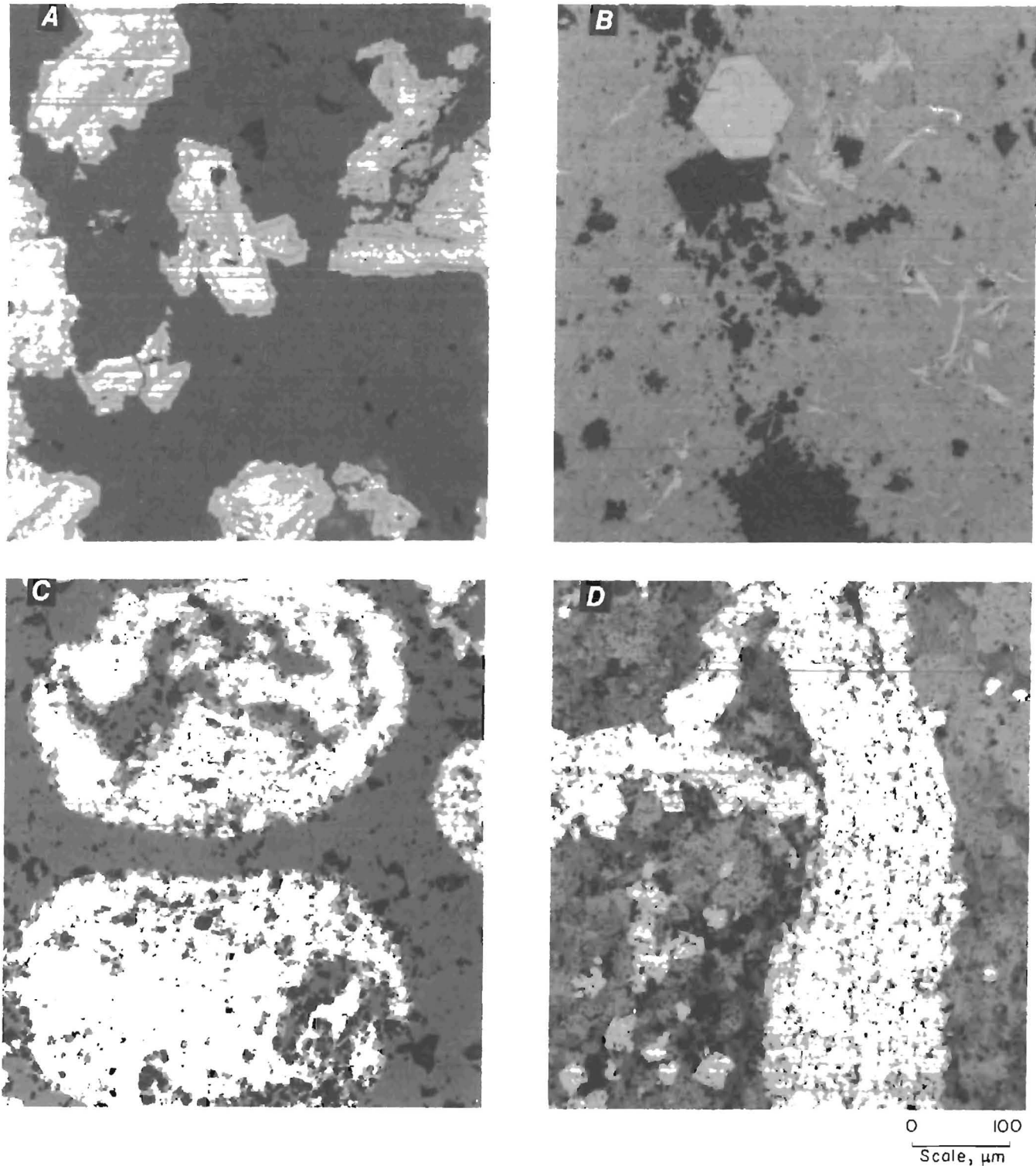


FIGURE 11. - Photomicrographs of polished surfaces of area 1 bulk sample taconite. *A*, Light-gray hematite and medium-gray goethite replacing magnetite euhedra. Dark gray is quartz or chert matrix, black spots are cavities in the surface. *B*, Light-gray hematite in coarse crystals replacing magnetite and in irregular blades replacing iron silicates surrounded by massive goethite (medium gray) that partly filled cavities. Present cavities in surface are dark gray to black. *C*, Hematite (white) and goethite (light gray) replacing granules that were magnetite. Medium gray is quartz matrix, and black is cavities in surface. *D*, Light-gray, fresh magnetite in a thin layer, along a fracture, and in isolated euhedra in a mottled gray matrix of iron carbonate, iron silicate, and quartz. Black is cavities in surface. White is hematite in initial stage of replacing magnetite.

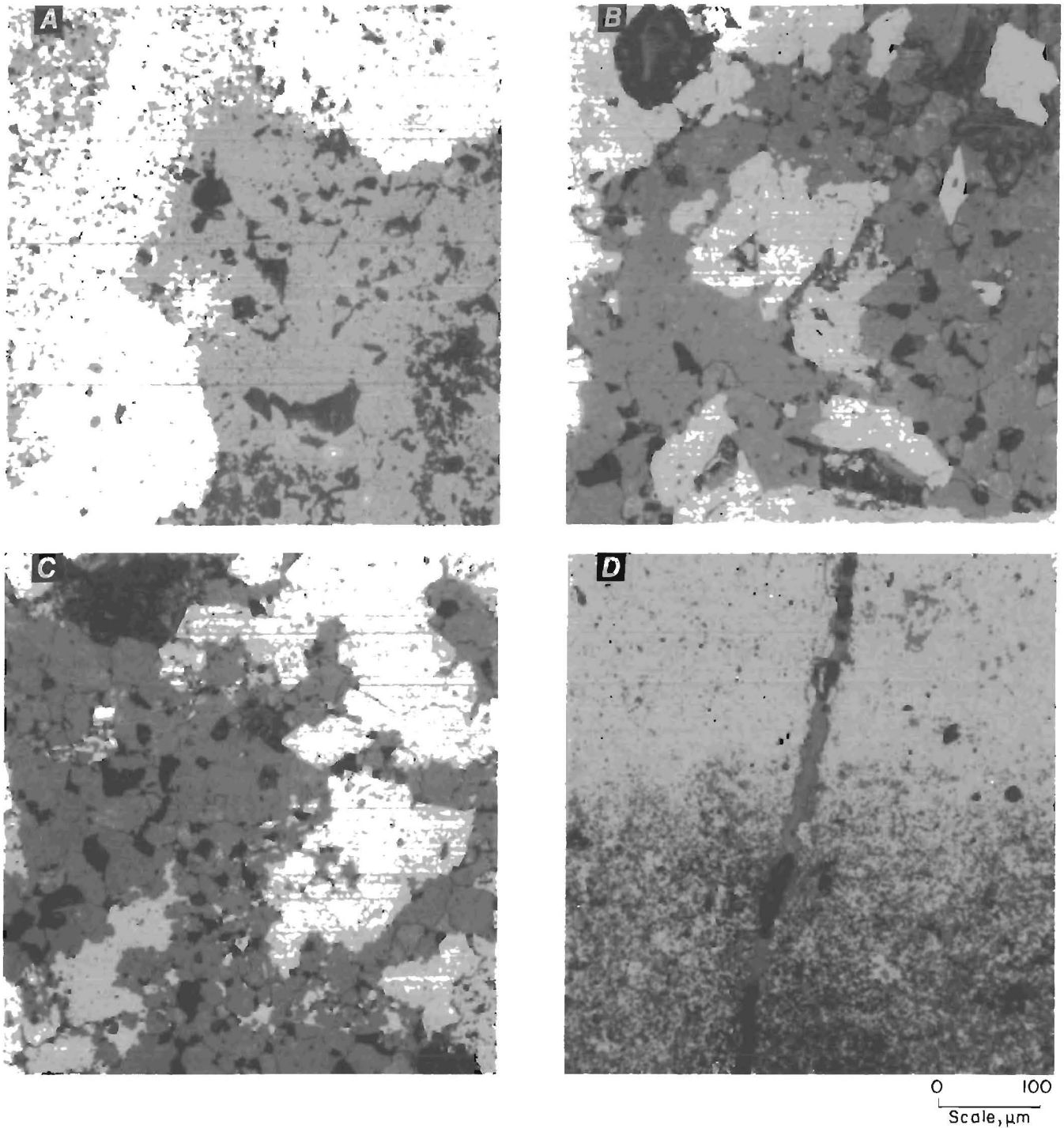


FIGURE 12. - Photomicrographs of polished surfaces of area 2 bulk sample taconite. *A*, White hematite has replaced magnetite euhedra in granule texture. Light-gray goethite contains coarse and minute cavities and has poor liberation. Medium-gray quartz shows moderate alteration by solution along grain boundaries that in places leaves coarse cavities (black to dark gray). *B*, White hematite and light-gray goethite replace magnetite clusters of anhedral to euhedral. Magnetite relics may be seen as lightest gray in centers of several coarse clusters of hematite and goethite. Gray quartz matrix shows black cavities. *C*, White hematite and light-gray goethite have replaced magnetite. Goethite also occurs in irregular shapes filling cavities in the gray gangue that is mostly quartz, itself containing black cavities in the surface. *D*, Medium-gray goethite in a solid layer (upper half) containing a few small gray quartz inclusions. Lower half shows leaner goethite layer with more disseminated quartz and very poor liberation characteristics. A fracture across the layers is partly filled with chert and iron carbonate. Black to dark gray is cavities in prepared surface.

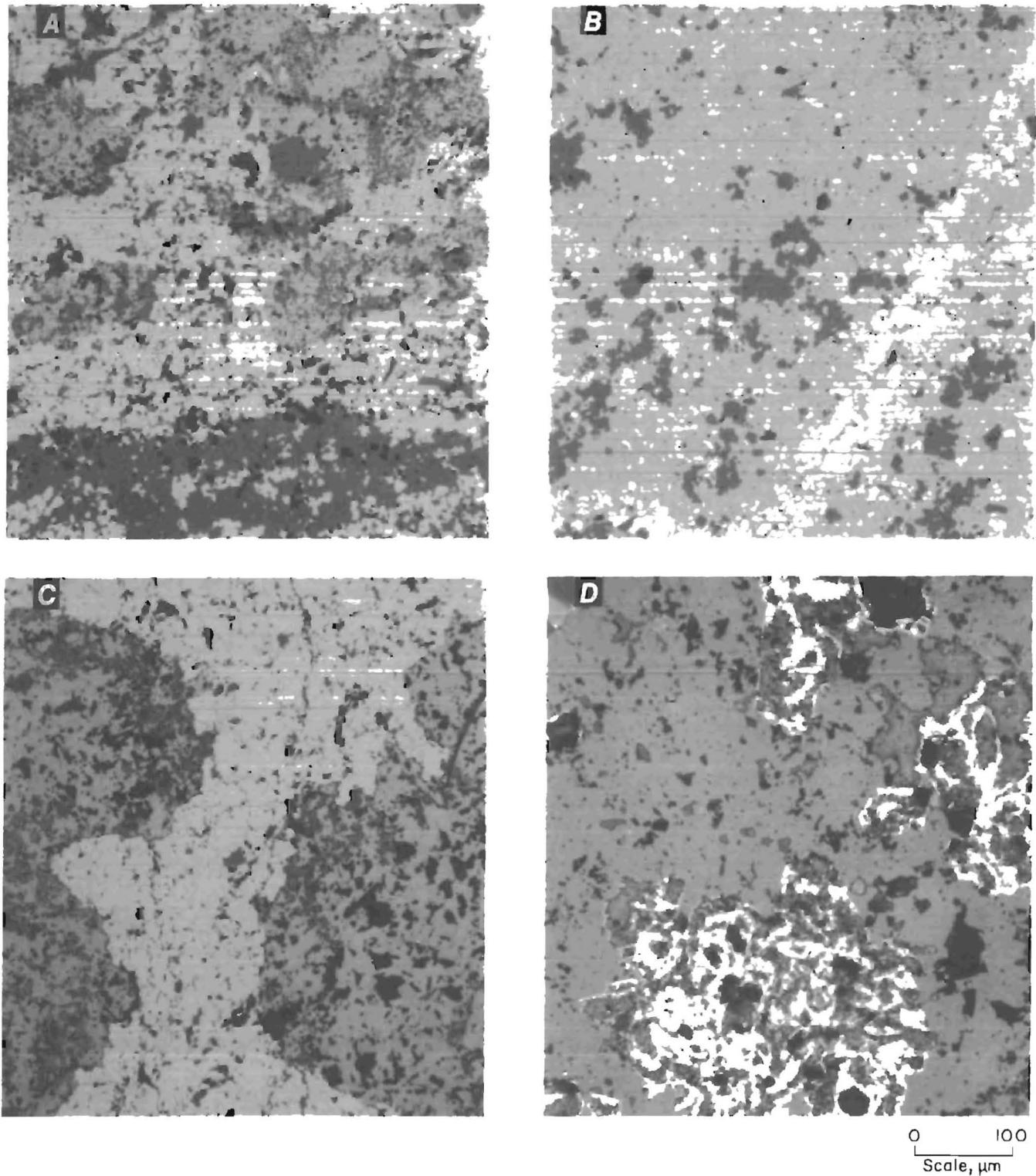


FIGURE 13. - Photomicrographs of polished surfaces of area 3 bulk sample taconite. *A*, White hematite in medium to fine grains replacing magnetite. Light-gray goethite mostly filling cavities. Hematite has better liberation characteristics than goethite in this texture. Dark gray is quartz or chert, and black is holes in the polished surface. *B*, Light-gray massive goethite contains minute hematite (white) inclusions and fine to coarse gangue (medium gray). Cavities in surface are black. *C*, Coarse hematite (light gray) is matrix for coarse goethite (medium gray). Black spots are cavities, and dark-gray areas are iron carbonates and/or iron silicates. *D*, White hematite has poor liberation characteristics in this quartz and iron silicate gray matrix. Black spots are surface cavities.

Increasing oxidation causes magnetite to be pseudomorphously replaced, mostly by hematite and partly by goethite, thus preserving the original shape and size of the octahedral magnetite. The last remnants of magnetite occur as a central core within grains or clusters of grains. Iron carbonate is occasionally replaced pseudomorphously, but more often it is leached away and the cavity is filled by goethite and occasionally by hematite in an irregular massive form. Iron silicates are replaced by goethite more frequently than by hematite. Much of the taconite appears to be good ore macroscopically, but microscopy shows a cherty matrix with disseminated goethite and/or hematite replacing scattered iron carbonate or silicate. Such material is too lean and would have an extremely small liberation size. Other layers altered from iron silicates are painty; they contain the clay minerals nontronite and kaolinite. Therefore, a large percentage of the oxidized taconite would either be left in place or removed as lean rock stripping.

Alteration of the original taconite also includes leaching of SiO_2 from



FIGURE 14. - Photomicrograph showing alteration of taconite by weathering, including solution, redeposition in cavities, and direct replacement.

quartz or chert and iron silicates, leaving cavities. Some cavities are left open, giving the rock a porous and friable texture. Some cavities are filled with redeposited SiO_2 , and some are filled with iron oxide, mostly goethite and a small amount of hematite. The degree of oxidation and alteration is fairly obvious both macroscopically (fig. 14) and microscopically. Microscopically both oxidation and leaching occur first along grain boundaries and then work, somewhat irregularly, deeper into grains. Various degrees of alteration recognized microscopically are summarized in table 4 and illustrated in figure 15.

The liberation size of goethite should vary considerably more than that of hematite because most hematite replaces

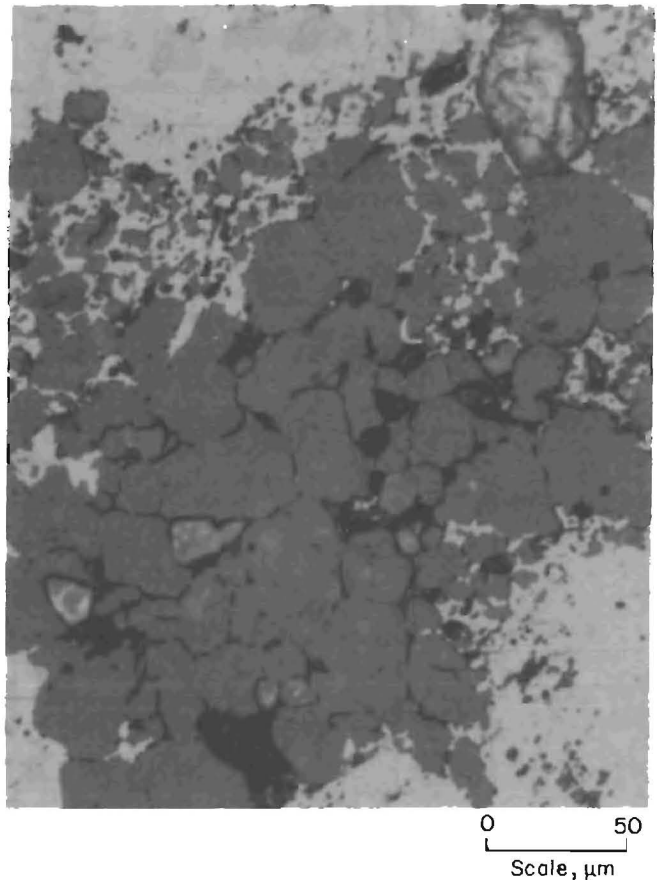


FIGURE 15. - Photomicrograph of polished surface showing extensive weathering along quartz grain boundaries. Medium-gray quartz has lighter gray goethite occurring both as fine and coarse cavity filling. Unfilled cavities are dark gray to black.

TABLE 4. - Degrees of taconite alteration recognized from microscopic analysis

Original taconite minerals and features	Alteration process	Initial	Moderate	Extensive	Pervasive
DEGREE OF TACONITE ALTERATION OBSERVED MICROSCOPICALLY					
Magnetite.....	Oxidation and pseudomorphic replacement.	Grain edges, cleavage planes alter to hematite.	Partly to mostly altered to hematite and/or goethite.	Magnetite relics at center of ferric oxide grains.	No magnetite.
Iron carbonates and iron silicates.	Solution of carbonate and leaching of silica.	Slight alteration to hematite and/or goethite if much carbonate or silicate.	Much alteration to hematite and/or goethite.	No relics.	
QUARTZ MATRIX SHOWING LEACHED QUARTZ-QUARTZ CONTACTS					
Quartz.....	Leaching of silica.	<10 pct.....	11 to 30 pct....	31 to 70 pct..	>70 pct.
Iron silicate.....	.....	If much iron silicate, SiO ₂ leached and the iron is oxidized.	If little iron silicate, SiO ₂ leached and the iron is oxidized.	No relics.	
Cavities, none.....	.....	Occasional.....	Few.....	Frequent.....	Many, interconnected.
Rock, coherent.....	.....	Coherent.....	Mostly coherent.	Moderately friable.	Very friable.
CAVITIES AND CAVITIES FILLED BY FERRIC OXIDES					
Cavities for filling by iron oxides, none.	Secondary enrichment of ferric oxide by filling cavities.	<10 pct.....	11 to 30 pct....	31 to 50 pct..	>50 pct.

magnetite in its original size and shape, whereas much goethite fills cavities in irregular shapes. Screened fractions of WMR-1 bulk sample were examined in polished briquets and as fragments in refractive index oils on a slide to estimate the percentage of each iron oxide liberated from gangue minerals (table 5). Liberation of the iron oxides from each other was not required, as all contribute positively to concentrate grade of iron. Results confirmed the expectation that goethite is more completely liberated than hematite or magnetite at coarser sizes. At finer sizes no real difference in the amount of liberation was apparent for the three iron oxides. Oxidized taconite from all three areas was essentially similar microscopically except for the increased amount of magnetite in area 1 sample. Oxidation and alteration effects and liberation were essentially similar in the three areas.

TABLE 5. - Liberation characteristics of iron oxides in bulk sample WMR-1

Screen fraction	Estimated liberation from gangue minerals in size fraction, pct ¹		
	Hematite	Goethite	Magnetite
10 by 20 mesh....	3	20	10
20 by 35 mesh....	10	25	15
35 by 65 mesh....	20	35	20
65 by 100 mesh...	25	40	30
100 by 200 mesh..	30	50	40
200 by 325 mesh..	50	60	70
325 by 400 mesh..	65	65	80
400 by 30 μ m.....	80	75	85
30 by 20 μ m.....	90	85	95
20 by 10 μ m.....	95	95	95
Minus 10 μ m.....	98	98	98

¹Estimated by visual observation using light optical microscopy of polished grains in briquets and as fragments in refractive index oils on glass slide.

BENEFICIATION RESULTS AND ESTIMATE OF WESTERN MESABI RANGE OXIDIZED TACONITE RESOURCES

Beneficiation results of pilot plant testing of WMR oxidized taconite are summarized in table 6 from three references (2-4). An estimated 3.25 billion long tons of oxidized taconite amenable to either cationic or anionic "selective-flocculation-desliming-flotation" is available in WMR areas 1, 2, and 3. The crude feed composite averaged 32 to 36 wt pct Fe. The cationic process is favored

over the anionic process on the basis of reagent costs. For areas 1, 2, and 3, respectively, the concentrates averaged 61.7, 63.5, and 62.8 wt pct Fe and 5.1, 4.3, and 4.7 wt pct SiO₂. The Fe recovery was 67, 85, and 72.3 wt pct, respectively, showing that area 2 sample responded best. Chemical treatment of process water resulted in recovery of about 85 pct of the total water used.

TABLE 6. - Beneficiation results for WMR oxidized taconite bulk samples

	Cationic flotation			Anionic flotation
	WMR-1	WMR-2	WMR-3	
Estimate of oxidized taconite resources ¹.....billion long tons..	2.0	0.75	0.5	Nap
Hematite-goethite ratio.....	1.1	2.6	2.4	Nap
Crude iron.....wt pct..	35.3	36.1	32.3	Nap
Concentrate, pct:				
Feed ²	38.5	48.1	37.2	37.7
Iron.....	61.7	63.5	62.8	63.0
SiO ₂	5.1	4.3	4.7	5.3
Iron recovery.....	67	85	72.3	73.5
Tails or slime + tails.....pct Fe..	18.8	10.7	14.2	13.7
Reclaimed water.....pct of total..	83	88	88	86

Nap Not applicable.

¹Jacobs (2); Jacobs and Colombo (3-4); sum = 3.25 billion long tons.

²Feed composite: 93 pct minus 400 mesh.

The poorest response of the three samples was for WMR-1 with 67 pct of the Fe in the feed recovered. Two factors may have entered here: The lower layer of partly magnetic taconite (layer D of fig. 5), mixed in with more oxidized layers above it, was probably not efficiently recovered by flotation. Also, WMR-1 was the first sample treated in the pilot plant, and process experience and refinements made during the study favored better conditions for recovery from WMR 2 and 3. Additional experiments to supplement flotation by reduction roasting (5-6) and/or WHIMS (wet high-intensity magnetic separation) (1) indicate that further improvements in beneficiation are possible over straight flotation treatment.

In table 6 the estimated amounts of oxidized taconite resource (2.0, 0.75, and 0.5 billion long tons for areas 1, 2, and 3, respectively) are based on the best judgment of mining company personnel as the amount of oxidized taconite that the bulk samples represented. Because these estimates do not cover the entire WMR areas 1, 2, and 3, they are conservative. In the present study an estimate was made of the amount of oxidized taconite available in these three areas based on the geology. It considered a 6° S average dip and material within the outcrop area to a vertical line at the south outcrop contact of the Biwabik Iron-Formation, and did not subtract the large amount of iron ore already removed in scattered underground mines and open

pits. All Lower Cherty material in areas 2 and 3, except the red basal taconite, was considered oxidized. In area 1 only Lower Cherty oxidized taconite above and below the magnetic layer was considered, and only some of the Upper Cherty taconite where it had been mixed in with bulk sample 1. A tonnage factor of 14 ft³ was used to convert volume to weight. No attempt was made to account for lean rock, poor liberation, or other problem material. According to the joint U.S. Bureau of Mines and U.S. Geological Survey Mineral Resource Classification System (24), this material would be considered a "subeconomic indicated resource." Table 7 lists these tonnages and compares them with the corresponding amounts from Marsden's (19) OXYBIF tonnages, which were modified to correspond to the same geographic range units.

TABLE 7. - WMR oxidized taconite tonnage estimate compared with Marsden's OXYBIF estimate

Area	Oxidized taconite, billion long tons ¹	OXYBIF, billion metric tons ²
1.....	3.2	2.9
2.....	3.2	2.9
3.....	1.5	1.1
Total...	7.9	6.9

¹Long ton = 2,240 lb.

²Marsden (19); metric ton = 2,204.6 lb; modified by corresponding geographic ranges.

SUMMARY

The geology and mineralogy of three bulk samples used for testing the selective-flocculation-flotation beneficiating response of oxidized taconite of the Western Mesabi Range have been studied. A strike distance of 26.5 mi (42.7 km) from just east of Keewatin, MN, to Grand Rapids, MN, was divided into three large blocks, and one bulk sample from each was tested in a pilot plant for amenability to flotation processes.

Within the outcrop area of the Biwabik Iron-Formation the area 1 rocks of the

Lower Cherty Member contain a magnetite-rich layer presently being mined and magnetically beneficiated. Above this magnetic layer is oxidized taconite which was mixed in a representative proportion with some of the Upper Cherty Member to provide the best sample for testing oxidized taconite response to flotation and/or magnetic roasting for future exploitation. In area 1, not all Upper Cherty oxidized taconite is amenable to beneficiation because the liberation size of iron oxides is too small and some areas are too lean for reasonable recovery.

In areas 2 and 3 extensive oxidation had changed most of the Lower Cherty Member to a nonmagnetic or oxidized taconite. In these areas, a large thickness of the Lower Cherty Member was selected on the basis of drill core and beneficiation testing as probably amenable to flotation processing. A large representative sample was chosen from each area. The Upper Cherty Member in areas 2 and 3 was considered too lean to be of interest at this time, but future testing may locate areas where its iron content could furnish enough recovery to be utilized. In all three bulk samples the major minerals were quartz (or chert), hematite, and goethite. Magnetite was a minor mineral in area 1 and recoverable with the ferric oxides. Iron silicates and iron carbonate were also present as minor to trace amounts in oxidized taconite and were usually rejected by the process. Liberation of all three iron oxides was found to be similar in the three bulk samples. Most problems with beneficiation processing were found to be with separation and not with liberation.

Petrographic analyses of the feed and products of selected separation stages are important in helping the mineral beneficiating engineer know the mineralogy, the type and degree of locking, and the behavior of the material in the process. Taconite mineralogy is fairly simple, but the variation in grade and in grain or particle size is closely related to its response. Some parts of the taconite have coarse layers or clusters of iron oxides, which liberate well; other parts of the taconite contain very fine, disseminated, or tightly locked minerals that cannot be economically separated physically. Flotation alone, or in combination with magnetic roasting and/or WHIMS of some products, has been found to produce concentrates of acceptable grade and recovery if advanced drilling, testing, and selective mining are utilized. Therefore, the oxidized taconites of the WMR represent a subeconomic indicated resource that can be selectively mined and beneficiated as a future large source of iron feed for steelmaking.

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