FIELD TRIP 2
GEOLOGY AND STRATIGRAPHY OF THE CENTRAL MESABI IRON RANGE

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[Map of Minnesota showing geological formations and descriptions of Precambrian rock map units]
INTRODUCTION

Iron-formation was described as early as 1866 by Henry Eames on what was to become the Mesabi Iron Range. Several attempts were made by individuals to find ore on the Mesabi Range on their way north to the iron mines of the Vermilion Range (Soudan to Ely, Minnesota); however, it was not until November 16, 1890 that the first rich iron ore on the Mesabi Iron Range was discovered by the Merritt brothers near what is now Mountain Iron, Minnesota. In 1892, the first shipment from this mine was 4,245 tons of ore (White, 1954). Exploration for iron ore ensued and within the next few years, most of the productive parts of the Mesabi Iron Range were discovered.

The Mesabi Iron Range is the largest iron range in the United States and is one of the largest in the world. It is 0.25 to 3.0 miles wide and 120 miles long (Fig. 2-1). The Biwabik Iron Formation, as thick as 750 feet, in general dips gently to the southeast at an angle of about 7° to 15°. The iron-formation, called taconite, typically contains 30 to 40 percent iron and 40 to 50 percent SiO₂, plus other components (Morey, 1992). In numerous places along the length of the range, notably along fault zones, silica was leached out, thereby enriching the iron content to over 55 percent. These pockets became the high-grade natural ore mines; there were more than 500 individual mines prior to merging into larger mines as the ore between adjacent properties was removed. These were very important in making the United States an industrial giant, and were instrumental in providing raw material for World Wars I and II. As the high-grade ore was depleted, the taconite process was developed. In 1967, taconite production exceeded natural ore production. Currently, six taconite plants are in production (Fig. 2-2).

The name of Biwabik Iron Formation was chosen by Van Hise and Leith (1901, p. 356), "...because the word Biwabik is the Chippewa word for a piece or fragment of iron." The word taconite is also used in discussions pertaining to hard, unoxidized portions of the iron-formation. H.V. Winchell (1882, p. 135) originally called portions of the Biwabik Iron Formation "taconyte" because he thought the rocks correlated with lower Cambrian rocks in the Taconic Mountains in northern New England. Since that time, many geologists have used taconite in their descriptions of the iron-formation and it has thus become firmly established. Perhaps a more proper definition for taconite is an economic term for iron-formation from which iron can be profitably extracted after fine-grinding, followed by magnetic separation and pelletizing (Morey, 1993).

Figure 2-1: Generalized map of the Mesabi Iron Range (cross-hatched). Note the Duluth Complex (Keweenawan, 1.1 Ga) on the east side.
The peneplained Archean craton in the Lake Superior region formed a platform upon which a Paleoproterozoic continental margin assemblage was deposited in Minnesota, Michigan, and Wisconsin. Extension resulted in localized rifts that received thicker accumulations of sediments and volcanic rocks than did adjacent parts of the platform. Seas transgressed onto the continent one or more times and an ocean basin opened south of present-day Lake Superior. Island arcs that formed during southward subduction collided with the craton margin to the north as the ocean basin closed. A remnant of this oceanic crust is poorly preserved as a dismembered ophiolite sequence in Wisconsin (Schulz, 1987, 2003). The arc volcanics are preserved as the Wisconsin magmatic terranes. The collision resulted in a fold-and-thrust belt known as the Penokean orogen (1880-1830 Ma; Schulz and Cannon, 2007). To the north of the fold-and-thrust belt, a northward-migrating foreland basin—the Animikie basin—developed as the stacked thrusts weighed down the crust (Fig. 2-3). Thick turbidite successions were deposited along the basin axis, and terrigenous clastics and Lake Superior-type iron-formation were deposited on the shelf along the northern margin (the foreland or peripheral bulge) of the basin. See Ojakangas et al. (2001) and Severson et al. (2003) for more detailed summaries on Paleoproterozoic basin development in the Lake Superior region.

The development of the Midcontinent Rift System at 1.1 Ga severed the basin into northwestern and southeastern segments (Fig. 2-3). If the Midcontinent Rift System rocks are removed from the geologic map, the different portions of the Animikie basin become contiguous and the fold-and-thrust belt rocks of Minnesota, Wisconsin, and Michigan become continuous (Fig. 2-4).

Figure 2-5 is an interpretive cross-section of the Animikie basin during its formative stages, with sediments derived from the Archean basement to the north and from the fold-and-thrust belt to the south. The Paleoproterozoic supracrustal rocks in the northwestern segment, including east-central and northeastern Minnesota and the adjoining part of Ontario, are for the most part poorly exposed. However, mining of iron ore on the Mesabi and Cuyuna ranges and continued mining of taconite on the Mesabi Iron Range have resulted in excellent artificial exposures and an abundance of drill hole information. Geophysical surveys and stratigraphic test drilling by the Minnesota Geological Survey have also been major sources of information (e.g., Southwick et al., 1988).
Figure 2-2: Generalized map of the Mesabi Iron Range A) Aerial distribution of taconite pits and cities. B) A longitudinal section of the Biwabik Iron Formation showing: average thickness of the iron-formation at each taconite operation (along with the thickness of the various members at each operation), and mined taconite intervals (as black columns adjacent to the sections). From Severson et al. (2009).

Figure 2-3: Generalized geologic map showing the distribution of Precambrian rocks and structural elements of the Lake Superior region, modified from Ojakangas 1994 and references therein (from Ojakangas et al., 2001).
Figure 2-4: Schematic hypothesized paleogeography at the time of sedimentation of the Paleoproterozoic Animikie Group turbidites that overlie shelf deposits in the Animikie basin. The rocks of the 1,100 Ma Midcontinent Rift System have been removed from the map, and Michigan and Wisconsin are thus positioned 60 miles closer to Minnesota-Ontario than they were after the formation of the Midcontinent Rift System. Arrows denote generalized transportation directions of sediment from major source areas. Compare with Fig. 2-3. Modified from Ojakangas (1994) and references included therein (from Ojakangas, et al., 2001).

Figure 2-5: Schematic cross-section depicting deposition of the Animikie Group turbidites that overlie shelf deposits in the Animikie basin, with sediment derived from both the north south. The southern area, the fold-and-thrust belt, comprises a complex assemblage including: 1) accreted Paleoproterozoic volcanic and plutonic rocks and volcanic rocks of the Wisconsin magmatic terranes; 2) accreted Archean miniplatte terranes; 3) older Paleoproterozoic passive-margin sedimentary rocks and volcanic rocks produced during initial rifting of the continental margin, both scraped off the southward-subducting Archean Superior craton; and 4) recycled initial foredeep deposits, possibly including basal shallow water sandstones deposited in the transgressing sea of the northward-migrating foreland basin. The peripheral bulge comprises a source-rock assemblage of Archean granitic rocks and Archean volcanic-sedimentary (greenstone) belts. Scale is approximate. Compare with Fig. 2-4. Modified from Ojakangas (1994) and references included therein (from Ojakangas et al., 2001).
Animikie Group

The Paleoproterozoic Animikie Group unconformably overlies the Mille Lacs and North Range Groups to the south and the Archean basement to the north (see Fig. 2-6; Southwick and Morey, 1991). Magnetic data show North Range structures are present beneath Animikie strata to the east of the exposed North Range Group (Chandler, 1993).

The group consists of three conformable major formations on both the Mesabi and Gunflint ranges. The respective units on the two ranges are the Pokegama Formation and the Kakabeka Quartzite (the lowest units), the Biwabik and Gunflint Iron Formations (the middle units) and the Virginia and Rove Formations (the upper units, composed of graywacke and shale). The Thomson Formation in the northern part of east-central Minnesota is correlative with the Virginia and Rove Formations. The Biwabik and Gunflint Iron Formations are on strike with each other and were probably continuous prior to the intrusion of the Duluth Complex at about 1,100 Ma.

In the model presented here, the Animikie Group in Minnesota and Ontario on the Mesabi and Gunflint ranges and the Baraga Group of Michigan and Wisconsin on the Gogebic Range were both deposited in the Animikie foreland basin. The basal units comprised of siliciclastic sediment derived from the Archean basement, and the overlying iron-formation, were deposited in a shallow sea on the northern edge (the peripheral bulge or foreland) of the northward-migrating Animikie basin (for example Ojakangas, 1994). Additional details are provided below in the section titled "Environments of deposition, Animikie Group."

The siliciclastic and iron-formation units are exposed on the Gogebic Range of northern Michigan and Wisconsin (the Palms Quartzite and Ironwood Iron Formation), on the Mesabi Iron Range of northern Minnesota (the Pokegama Formation and the Biwabik Iron Formation), and on the Gunflint Range of northeast Minnesota and Ontario (the Kakabeka Quartzite and the Gunflint Iron Formation), and are lithostratigraphic equivalents. They probably were continuous from south to north prior to development of the Midcontinent Rift System in Mesoproterozoic time. A consequence of this model is that they are diachronous, with the units in Michigan and Wisconsin (located about 60 miles to the south of the Mesabi Iron Range during deposition). The thickest and uppermost units in the basin, essentially lithostratigraphic correlatives but probably differing somewhat in age, are the Michigamme, Tyler, and Copps Formations of the southeastern segment and the Thomson, Virginia, and Rove Formations of the northwestern segment. These are typical turbidite-shale (flysch) sequences, with graded beds and intercalated muddy "rain-out" sediment (Fig. 2-6).

Figure 2-6: Generalized correlation chart of Paleoproterozoic strata in the Lake Superior region. Note that recently obtained age dates are shown for the Gunflint Iron formation, Mahnomen Formation (detrital zircon), Hemlock Volcanics, and the Rove and Virginia Formations (sources listed in the references). The position of the Sudbury ejecta layer is from Cannon and Addison (2007).
Ages

Age constraints for deposition of all three formations of the Animikie Group range from roughly 2,125 Ma to 1,821 Ma. The Pokegama Formation rests unconformably on the northeast-trending Kabetogama dike swarm, dated at 2,125 ± 45 Ma (Rb-Sr isochron – Southwick and Day, 1983; Beck, 1988), which gives a maximum age for deposition. A minimum age of deposition for the Pokegama Formation is 1,930 ± 25 Ma (Pb/Pb), which was obtained from quartz veins that cut the Pokegama Formation (Hemming et al., 1990).

An age of 1,878 ± 2 Ma (U/Pb on euhedral zircons) has been obtained from an ash layer in the upper Gunflint Iron Formation (Fralick and Kissin, 1998; Fralick et al., 2002). An ejecta layer, related to the 1,850 Ma Sudbury impact event, has been found near the top of the Biwabik Iron Formation and at the top of the Gunflint Iron Formation (Addison et al., 2005). Zircon ages from ash layers near the base of the Virginia Formation have yielded 1,850 Ma (Hemming et al., 1996) and 1,832 ± 3 Ma (Addison et al., 2005 – the latter sample was collected a few inches above the base of the Virginia Formation in drill hole VHD-00-1). Zircon ages from ash layers positioned at the base of the Rove Formation, and about 70 meters above the base of the Rove Formation, have yielded ages of 1,836 ± 5 Ma (Addison et al., 2005) and 1,821 ± 16 Ma (Kissin et al., 2003), respectively.

Schulz and Cannon (2007) have proposed that the age differences between the bottom of the Rove Formation (1,836 Ma) and top of the Gunflint Formation (1,878 Ma) are indicative of a previously unrecognized disconformity and that a significant hiatus in sedimentary deposition separates the two formations. They further suggest that this hiatus represents a period of emergence between deposition of the iron-formation and the overlying clastic rocks – whether this emergence extended into the Mesabi Iron Range is unresolved at this time. Furthermore, detrital zircons with U/Pb ages of 1,780 Ma (Heaman and Easton, 2005) have been obtained from a sandstone bed about 400 meters above the base of the Rove Formation, suggesting that deposition in the northern part of the Animikie basin outlasted Penokean deformation (1880-1830 Ma) in the southern part of the basin (Schulz and Cannon, 2007).

Pokegama Formation

This formation has long been called the Pokegama Quartzite, but because it contains appreciable argillite and siltstone, the name Pokegama Formation is more appropriate. It has been studied by several workers since it was named by Winchell (1893) for exposures at the western end of the Mesabi Iron Range. Much of the previous work has been summarized by Morey (1972, 1973, 2003).

Few natural exposures exist, as thick glacial drift generally covers the formation. Outcrops, road cuts, and mine cuts occur at a few places along the length of the range, but most exposures are in the central portion of the range. A few drill holes have penetrated the entire formation. One is located just south of Eveleth (T. 57 N., R. 17 W., sec. 5, NE, NE) and another is southwest of Mountain Iron (T. 58 N., R. 18 W., sec. 8, SE, SE); the thicknesses are 167 feet and 85 feet, respectively (Fig. 2-7). Other drill cores have not yet been studied in detail. Numerous drill holes have penetrated only the upper few feet of the formation, as the drilling was generally undertaken in relation to iron ore exploration and development. The Pokegama Formation is thin at the eastern end of the range and thickens to the western end where it may be more than 300 feet thick.

The formation is composed of three main rock types—argillite, siltstone, and quartzite. The quartzite is generally silica-cemented quartz sandstone, and is therefore an orthoquartzite rather than a metaquartzite. Morey (2003) determined that mineralological changes in the Pokegama Formation and the Biwabik Iron Formation are the result of diageneric rather than metamorphic, except at the eastern end of the range adjacent to the Duluth Complex. These three rock types make up three gradational members—lower, middle, and upper—respectively, as shown in Figure 2-7. Minor thin conglomerates occur at the base of the formation, and seem to represent a weathered residuum on the surface of Archean rocks, perhaps reworked by fluval processes.

The Pokegama Formation unconformably overlies Archean metavolcanic, metasedimentary, and plutonic rocks. There may be as much as 100 feet of relief on the Archean surface (Grout and Broderick, 1919), but the surface was, nevertheless, essentially a peneplain. Some Archean "knobs" were islands.
when the Pokegama Formation was being deposited, and are present in the wooded areas between Eveleth and Virginia where they have been re-exhumed. The Pokegama Formation–Biwabik Iron Formation contact is gradational, with some cherty horizons in the upper Pokegama Formation and some sand grains of quartz in the lowest bed of the Biwabik Iron Formation. Various geologists have placed the contact at different stratigraphic levels.

**Figure 2-7**: Measured sections from two drill holes that penetrate the entire Pokegama Formation. Dark shading represents shale, thin blank units represent siltstone, the slanted pattern represents sandstone and siltstone, and the dotted pattern represents sandstone. Modified from Ojakangas (1983).

**Biwabik Iron Formation**

The Biwabik Iron Formation is around 175-300 feet thick in the extreme eastern end of the Mesabi Iron Range at Dunka Pit (Bonnichsen, 1968), 730-780 feet thick in the central Mesabi Iron Range/Virginia Horn area near Eveleth, around 500 feet thick in the western Mesabi Iron Range near Coleraine, and eventually exhibits a “nebulous ending about 15 miles southwest of Grand Rapids” (Marsden et al., 1968) on the extreme western end of the Mesabi Iron Range.

Since the early 20th century, the Biwabik Iron Formation has been subdivided into four informal members referred to as (from bottom to top): Lower Cherty member, Lower Slaty member, Upper Cherty member, and Upper Slaty member (Wolff, 1917). The cherty members are typically characterized by a granular (sand-sized) texture and thick-bedding (beds ≥ several inches thick); whereas, the slaty members are typically fine-grained (mud-sized) and thin-bedded (≤1 cm thick beds). [Note that slaty is a miner’s term to denote parting parallel to bedding in these thin-bedded rocks, and the name is not indicative of metamorphism or slaty cleavage.] The cherty members are largely composed of chert and iron oxides (with zones rich in iron silicates), while the slaty members are generally composed of iron silicates and iron carbonates with local chert beds. Both cherty and slaty iron-formation types are interlayered at all scales, but one rock type or the other predominates in each of the four informal members, and they are so-named for this dominance. The slaty members are envisioned to have been deposited on the outer shelf as an iron-rich chemical mud in a deep-water/low-energy environment (below storm wave base) as a result of either the warming of upwelling iron-rich waters (Morey, 1993), or mixing of a stratified water column
due to storm events (Pufahl and Fralick, 2004). Shoreward-moving tidal currents and storm events are envisioned to have disrupted this chemical mud and generated granules that were transported shoreward and reworked in a shallow-water, high-energy environment to form the cherty members (Pufahl and Fralick, 2004; Ojakangas et al., 2005). Thus, the granules that comprise the cherty members are interpreted as intraclasts derived from within the basin. The repetition of the major cherty and slaty members was first interpreted by White (1954) as being the result of transgressive and regressive ocean events.

There are some diagnostic marker units within the formation. Two stromatolite-bearing intervals several feet thick are present, one at the base of the Lower Cherty member and the other in the middle of the Upper Cherty member. The black "Intermediate Slate" at the base of the Lower Slaty member is reportedly an ash-fall tuff containing about 4 to 5.5 percent aluminum oxide (Morey, 1992). At the top of the Upper Slaty member are several feet of limestone and dolomite. Most of these marker units, which are prominent in the eastern and central parts of the range, pinch out to zero in the vicinity of Hibbing, about 60 miles from the west end of the range (Severson et al., 2009). The Lower Slaty member is not present at the far western end of the range.

Virginia Formation

There are rare exposures of the Virginia Formation in mines at the east end of the Mesabi Iron Range, and a few scattered outcrops, where it has been metamorphosed by the mafic intrusions of the Mesoproterozoic Duluth Complex. Several holes drilled south of the range to study the underlying iron-formation have been drilled through the Pleistocene cover and have intersected as much as 1,443 feet of the pr The Virginia Formation is a thick sequence of argillite, siltstone, and graywacke at the top of the Animikie Group.

On the basis of lithotypes present in five drill holes, Lucente and Morey (1983) divided the Virginia Formation into two informal members – a lower argillaceous lithosome and an upper silty and sandy lithosome. The lower lithosome is approximately 600 feet thick and contains common intervals wherein black, thin-bedded, carbonaceous argillite is the dominant rock type; visible sulfides are locally present – especially in the eastern Mesabi Iron Range. These carbonaceous argillites indicate that deposition of the lower lithosome occurred by slow accumulation of black mud in deep water under anoxic conditions (Lucente and Morey, 1983). The distribution of specific packages of carbonaceous argillite layers within the lower lithosome are staggered and overlapped at different horizons. This relationship indicates that deposition of the carbonaceous argillite packages took place in small, restricted basins, e.g., 3rd order basins. Fine-grained, sericite-rich tuffaceous beds are locally present within the lower lithosome, and in some locales these beds are up to five feet thick. Also, chert and limestone beds (and/or carbonate concretions) may be present near the base of the Virginia Formation.

The upper lithosome also consists dominantly of argillite, but it generally lacks carbonaceous argillite, and instead, contains abundant interbeds of siltstone and fine-grained feldspathic graywacke comprising thickening- and coarsening-upward turbidite sequences that were deposited via turbidity currents in a prograding submarine fan complex (Lucente and Morey, 1983). All varieties of Bouma sequences, A through D, are exhibited by the graywacke beds.

The contact with the Biwabik Iron Formation varies from sharp to highly gradational, depending on the locality. Over much of the Mesabi Iron Range, clastic argillaceous sediments are in sharp contact with a carbonate horizon at the top of the iron-formation. The clastic rocks of the Virginia Formation were largely derived from Archean rocks to the north, with some contributions from older Paleoproterozoic rocks to the south (Lucente and Morey, 1983). However, limited neodymium and lead isotope data suggest that detritus in the Virginia Formation was derived mainly from a Paleoproterozoic source (2.32-1.86 Ga; Hemming et al., 1995) that was presumably located to the south in the Fold-and-Thrust Belt.

The Virginia Formation is correlated with the Thomson Formation (Morey and Ojakangas, 1970) that is exposed 60 miles to the south in the vicinity of Carlton and Cloquet, Minnesota, and also with the Rove Formation in northeast Minnesota and adjacent Ontario (Morey, 1967).
ENVIROMENTS OF DEPOSITION, ANIMIKIE GROUP

The Pokegama Formation is interpreted to have been deposited in a tidally influenced shallow marine setting near the shoreline, having received clastics from the Archean basement to the north (Ojakangas, 1983). In this model of a transgressing sea, the lower (argillaceous) member was deposited at the shoreline in the upper tidal flat, the middle member of intercalated argillaceous and silty sediment was deposited seaward in the middle tidal flat, and the upper member of quartz sand was deposited still further seaward in a lower tidal flat/subtidal environment. This is illustrated in Figure 2-8. Walther's Law is applicable here, with the vertical facies showing the relationships of the lateral facies. The lowermost Pokegama Formation contains siltstone beds that contain alternating thicker and thinner laminae that have been interpreted as evidence of the diurnal inequality, and are being investigated further for possible clues to the Paleoproterozoic lunar orbit (Ojakangas, 1996).

The Biwabik Iron Formation is interpreted to have been deposited seaward of the Pokegama Formation on a shallow marine, tidally dominated shelf (Fig. 2-8). Precipitation of iron minerals including iron carbonate, iron silicate, chert, and perhaps some hematite, occurred on the outer shelf in waters below wave base, giving rise to the mud-textured (slaty) iron-formation. These minerals were likely related to upwelling waters from the deeper part of the basin.

Figure 2-8: Sedimentation model showing lateral relationships of the siliciclastic tidal facies of the Pokegama Formation, the two main facies of the Biwabik Iron Formation, and the Virginia Formation (on the slope?). Thicknesses and geography are not to scale; modified from Ojakangas (1983).

The two sand-textured members (Lower Cherty and Upper Cherty) formed in a shallow-water, high-energy environment, as indicated by stromatolites, cross-bedding, and rounded (locally oolitic) grains of iron minerals and chert. Shoreward-moving tidal currents (flood tides) and/or storms may have disrupted the mud-textured sediment (precipitates) and transported sand-sized aggregates into shallower water where they were altered by seafloor processes and early diagenetic processes. Thus these granules are interpreted as "intraclasts" derived from within the basin.

Shallow channels up to a mile wide and tens of feet deep were cut into the Lower Slaty member and filled with sand-textured grains of iron minerals and chert in the Virginia horn area. These grains apparently were derived from shallow water and carried seaward into the deeper water environment in
which the iron minerals were precipitating. Ebb-flow tidal currents, or offshore flowing storm-generated currents, are interpreted as the erosion and transportation agent.

A plot of 102 cross-bed measurements in the Minorca Mine (Fig. 2-9) on the northeast edge of the Virginia horn shows 90 percent of the readings making a very prominent mode to the north–northeast and a minor, broader mode to the south (Fig. 2-9). This distribution is interpreted as the product of a strong flood tide toward the paleogeographically determined northern shoreline and a much weaker ebb tide.

A study of the orientations of stromatolite mounds in the stromatolite horizon within the Upper Cherty member was conducted by Boerst (1999). His map is presented in Figure 2-10. A paleocurrent plot of mound elongation (Fig. 2-10) is interpreted as the result of shore-normal tidal currents and shore-parallel longshore currents in shallow water.

Figure 2-9:
A. Paleocurrent rose diagram of 102 cross-bed measurements from the Lower Cherty member (LC-4 submember) in the Minorca Mine.
B. Photo of cross-bedding in the Minorca Mine.
C. Photo of herringbone cross-beds in the Minorca Mine
Figure 2-10: Mapped stromatolite mounds in the algal submember (I submember) in the Upper Cherty of the LTV 2E pit. The rose diagram represents the elongation of the mounds, with each elongate mound plotted on both sides of the rose diagram. From unpublished work by Kevin Boerst (1999).

Fluctuations in sea level, in response to episodic tectonic processes associated with the Fold-and-Thrust Belt to the south (Southwick et al., 1988), were responsible for repeated deposition of the various slaty and cherty members during periods of regression and transgression, as was first proposed by White (1954).

The Virginia Formation was deposited seaward of the iron-formation, probably in a slope-type environment (Fig. 6-8) where episodic turbidity currents deposited graded beds. Some volcanic ash fall evidently settled into the basin forming graded beds with a totally volcanic composition. The dominance of black, fissile shale suggests the "raining out" of clay (such as settling through the water column) and deposition in deep, anoxic water below the wave base. Minor, thin, sandstone lenses were deposited by bottom currents (Lucente and Morey, 1983).

IRON FORMATION MINERALOGY

The detailed origins of the various iron minerals that constitute the Biwabik Iron Formation are beyond the scope of this field guide. In fact, there is controversy about which of the minerals in any Lake-Superior type iron-formation represents original precipitates as opposed to diagenetic phases (Simonson, 2003). Replacement of the granules found in the iron-formation during diagenesis has been extensive. Eh and pH are major controls on the stability of the iron minerals in both the depositional and diagenetic environments (Ojakangas et al., 2005). Klein (2005) has suggested that the original precipitate materials that were deposited were probably: hydrous Fe-silicate gels of a greenalite type composition; Na-, K- and Al-containing gels approximating stilpnomelane compositions; SiO₂ gels; Fe(OH)₂ and Fe(OH)₃ precipitates; and very fine-grained carbonate oozes. A variety of other primary chemical precipitates for iron-formation in general have also been postulated by an assortment of authors and include siderite, iron hydroxide/oxyhydroxide, iron silicates (Konhauser et al., 2002; Rajan et al., 1996), nontronite and iron oxides (Hiemenz, 1997), and colloidal iron silicates (Lascelles, 2007). The Biwabik Iron Formation throughout the western and central Mesabi Iron Range is comprised of various minerals as listed in Table 2-1.

Morey (1992) reports, that on average, the cherty members contain more silica than the slaty members. In turn, the slaty members contain more CaO, MgO, and CO₂, indicating the importance of carbonate in the fine-grained thin-bedded rocks (Morey, 1992). The slaty members also contain more Al₂O₃, reflecting increases in stilpnomelane (Morey, 1992). Morey and Morey (1990) suggested that the stilpnomelane may be titanium-bearing based on a positive correlation between TiO₂ and Al₂O₃. These relationships suggest that the slaty members may, in part, be due to a volcanic contribution (Schmidt,
Shard-like features associated with stilpnomelane have been reported to be present in the carbonaceous-rich “intermediate slate” at the base of the Lower Slaty (Morey et al., 1972; Perry et al., 1973).

Table 2-1. Common mineral names and formulas associated with the Biwabik Iron Formation (excluding the more highly metamorphosed eastern Mesabi Iron Range in proximity to the Duluth Complex).

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
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<tbody>
<tr>
<td>Chert</td>
<td>SiO₂</td>
</tr>
<tr>
<td>Chalcedony</td>
<td>SiO₂</td>
</tr>
<tr>
<td>Microcrystalline Quartz</td>
<td>SiO₂</td>
</tr>
<tr>
<td>Magnetite</td>
<td>Fe₃O₄</td>
</tr>
<tr>
<td>Hematite</td>
<td>Fe₂O₃</td>
</tr>
<tr>
<td>Goethite</td>
<td>HFeO₂</td>
</tr>
<tr>
<td>Siderite</td>
<td>FeCO₃</td>
</tr>
<tr>
<td>Ankerite</td>
<td>Ca(Fe₃,Mg)(CO₃)₂</td>
</tr>
<tr>
<td>Stilpnomelane</td>
<td>K(Fe²⁺, Fe³⁺,Al)₁₀Si₂O₃₉(OH)₁₂</td>
</tr>
<tr>
<td>Minnesotaite</td>
<td>Fe₇Si₉O₁₀(OH)₁₂</td>
</tr>
<tr>
<td>Greenalite</td>
<td>Fe₈Si₉O₁₀(OH)₅</td>
</tr>
<tr>
<td>Chamosite (iron-chlorite w/significant Al)</td>
<td>Fe₆(Al,Si)₆O₁₀(OH)₆</td>
</tr>
<tr>
<td>Talc</td>
<td>Mg₃Si₄O₁₀(OH)₂</td>
</tr>
<tr>
<td>Calcite</td>
<td>CaCO₃</td>
</tr>
<tr>
<td>Dolomite</td>
<td>CaMg(CO₃)₂</td>
</tr>
</tbody>
</table>

Greenalite is a mineral that is commonly reported to be primary/early diagenetic in that it exhibits no detectable replacement of any pre-existing phase (French, 1973; LaBerge et al., 1987; Simonson, 1987; Klein, 2005). Greenalite most often occurs as round-shaped granules that are <1 mm in diameter. Siderite is also reported to be early diagenetic (LaBerge et al., 1987).

Stilpnomelane is a secondary mineral that commonly replaces early iron silicates, most commonly greenalite (French, 1973). French (1973) suggests that stilpnomelane formed under conditions ranging from diagenesis to low-grade metamorphism. A few occurrences of both chamosite and talc were reported by French (1973), but more recently, McSwiggen and Morey (2008) show that both minerals are common throughout portions of the Biwabik Iron Formation. Minnesotaite, the iron analogue of talc, generally occurs as sheaves or needles that replace greenalite (French, 1973), and is a diagenetic product.

Fine-grained magnetite is probably early, but numerous researchers have come to the conclusion that the majority of magnetite grains, which are relatively coarse-grained and commonly euhedral, are late diagenetic in origin (LaBerge, 1964; LaBerge et al., 1987; Zanko et al., 2003) and form by the replacement of pre-existing iron silicates and iron carbonates (French, 1973). With increasing metamorphic grade to the east, contact metamorphic effects of the Duluth Complex have increased magnetite grain size due to recrystallization.

Stilpnomelane is a secondary mineral that commonly replaces early iron silicates, most commonly greenalite (French, 1973). French (1973) suggests that stilpnomelane formed under conditions ranging from diagenesis to low-grade metamorphism.

Fine-grained siderite and ankerite are probably primary, but coarser-grained variants of both minerals are secondary, as they replace earlier minerals. Ankerite mottles are a good example of this secondary replacement.

Earlier work on the oxidized taconites of the western Mesabi Iron Range was accomplished by Bleifuss (1964). He showed that late hematite was developed by the oxidation and pseudomorph replacement of magnetite octahedra, that layers of goethite were precipitated from solutions likely derived from the oxidation of siderite, and that some goethite formed by the oxidation of acicular iron silicate minerals. Additional work was done by Ojakangas in Zanko et al. (2003).
DIRECT-SHIPPING ORES

The genesis of the high-grade (natural) ore bodies that occur as pockets along fault zones in the Biwabik Iron Formation has long been debated. It is clear that a major hydrologic event removed 40 to 60 percent of the silica and oxidized the iron minerals to hematite and goethite. However, it is unknown whether these fluids were descending, cool, meteoric waters or ascending hydrothermal waters related to igneous activity. Did this event occur during the Cretaceous (the age of conglomerates that contain clasts of high-grade hematite), or prior to that time? Morey (1999) provided an excellent review of the arguments. He then proposed that a large-scale, topography-driven, hydrothermal ground-water system moved waters northward, during the Paleoproterozoic, through the sands of the underlying Pokegama Formation, from the vicinity of the regional Penokean orogenic uplift in northern Wisconsin and east-central Minnesota. Graber and Strandlie (1999) questioned this concept and pointed out that the lack of metamorphosed natural ore bodies in the eastern Mesabi Iron Range proves that they were formed long after emplacement of the Duluth Complex rather than during the Paleoproterozoic.

PRODUCTION FIGURES—IRON ORE AND TACONITE

The annual amounts of direct-shipped ore and taconite produced from the Mesabi Iron Range are shown in Figure 2-11. Production and shipping of direct ore started in 1892 and rose steadily until 1953 when a maximum 76 million tons were produced in one year (note the precipitous drop in direct ore production corresponding to the Great Depression). At around 1955, there was a dramatic decrease in the amount of direct ore as the various mines became depleted. This also corresponds to the initial start-up of taconite mining, using a concentrating and pelletizing method developed by E.W. Davis of the University of Minnesota. Reserve Mining opened the first taconite operations in 1955 (Peter Mitchell Mine) and was shortly followed by Erie Mining in 1957 (the old LTV site). Six more taconite operations were added in the 1960s, and by 1967, annual taconite production exceeded direct ore production. The mid-1980s marked a serious depression in the iron ore and steel industry that resulted in the closure of one operation (Butler Taconite) and the bankruptcies of two other taconite producers including Reserve Mining Company – the former operator of the Peter Mitchell Mine. The Peter Mitchell Mine reopened as Cyprus Northshore Mining in 1989. It was subsequently purchased by Cleveland-Cliffs in 1994 and has been operated as Northshore Mining since that time. More recently, LTV Steel and Eveleth Taconite have closed; Evtac has since reopened as United Taconite.

![Mesabi Range Taconite/Iron Ore](image)

**Figure 2-11:** Annual production figures for direct ore (includes all forms of direct ore) and taconite for the period 1892-2008. Data and graph from James Sellner, Minnesota Department of Natural Resources, Lands and Minerals Division, Hibbing, MN.
The four-fold stratigraphy of Lower and Upper Cherty and Lower and Upper Slaty members (Wolff, 1917) is still used at each of the currently operating (and inactive) taconite mines on the Mesabi Iron Range. However, each of the mining companies further subdivides the Biwabik Iron Formation into several submembers based on bedding types seen in drill core (Fig. 2-12) and mineral assemblages. It is at this point that the Biwabik Iron Formation stratigraphy becomes very complicated due to the following reasons:

- There are localized lateral facies changes between mines (and even within a single mine).
- Not all mines use the same numbering system—some use abbreviations (for example LC—Lower Cherty member) followed by a number (as in LC-5 at the top of the Lower Cherty member). However, other mines use an alphabet system, devised by Gundersen and Schwartz (1962), starting with the A submember at the top of the Upper Slaty member (in this system the top of the Lower Cherty member corresponds to the R submember). And further still, another mine refers to the Lower Cherty member as the number 1 unit and subdivides it into eight submembers, with 1-8 at the top of the Lower Cherty member.
- Some mines label downward in their numbering system, whereas other mines label upward in their numbering system.

Figure 2-12: Textural characteristics of the Biwabik Iron Formation (from Severson et al., 2009 – modified from Pfleider et al., 1968). Dark bands shown in this figure are typically magnetite-rich.

Geologists at the Natural Resources Research Institute (Severson et al., 2009) have recently logged drill core from all but one of the mines in the central and western Mesabi Iron Range – 152,000 feet of core were logging in over 380 drill holes that are spread out along 75 miles of strike length. Their investigation established the presence of at least 25 major “Rosetta Stone” units, depicted in Figure 2-13,
Figure 2-13: Summary of the 25 major “Rosetta” units in the Biwabik Iron Formation that were identified and described in Severson et al. (2009). Most of these units have corresponding submember designations at each of the taconite mines that can be seen in Figures 2-14 through 2-17.
that comprise the Biwabik Iron Formation. Most of these “Rosetta” units have long been recognized by
the various taconite mines on the Mesabi Iron Range, but they have been called such a variety of
submember names that it is often difficult to keep one straight from the other. Not only does one have to
remember each of the submember names, but one has to also remember which submember applies to
which mine. The naming of the 25 major “Rosetta” units, as defined by the bedding type that is dominant
in that submember, helps to avoid this confusion. In the NRRI report (Severson et al., 2009), the 25
“Rosetta” units were carefully correlated in hung stratigraphic sections, and the units were named for the
bedding types that each represents.

A brief description of the 25 major “Rosetta” units, as presented in Figure 2-13, are presented in the
next few pages (starting from the base of the iron-formation and progressing upwards). Also, correlation
charts that show the various mine submember nomenclatures relative to each other, and the “Rosetta”
units, are shown in Figures 2-14 through 2-17 for the Lower Cherty, Lower Slaty, Upper Cherty, and
Upper Slaty members, respectively.

Figure 2-14: Correlation chart of Lower Cherty submembers at the various taconite mines/areas along the Mesabi
Iron Range. Vertical red bars represent portions of the Lower Cherty that are mined at the various taconite
operations. No scale implied; looking north (from Severson et al., 2009

Lower Cherty member — the Lower Cherty member is the most remarkable of all of the members of the
Biwabik Iron Formation in that it displays a fairly consistent pattern of submembers throughout the
western, central, and a portion of the eastern Mesabi Iron Range that consist of:

- **Basal Contact Unit** — includes five interbedded rocks types: Algal Chert unit, Conglomerate unit,
  hematite-stained siltstone with detrital quartz grains (SLTST unit), Ooidal Jasper unit, and Thin-
  Bedded unit;
- **Basal Red Unit** — thin-bedded iron-formation;
- **Regular-Bedded Unit** — magnetic, granular iron-formation with regular-spaced, planar, bedding
  planes;
- **Local Thin-Bedded Unit** — thin-bedded iron-formation that is present in a restricted area of the
  Mesabi Iron Range that issuggestive of a localized transgressive event as recorded in the re-
  appearance of a thin-bedded “slaty” iron-formation that is similar to the Basal Red Unit;
o Weak Wavy-Bedded to Regular-Bedded Unit – transition zone between the Regular-bedded Unit and the overlying Wavy-Bedded Unit;

o Wavy-Bedded Unit – magnetic, granular iron-formation with magnetite concentrated in bands that pinch, swell, terminate, and bifurcate in a semi-random pattern. Both cross-bedded zones and magnetite-coated stylolites, indicating some volume reduction during diagenesis, are fairly common to this unit. The unit is often further broken down into the following types at many of the taconite mines as follows:
  - Wavy-Bedded;
  - Wavy-Bedded with salt-and-pepper texture (S&P texture);
  - Wispy Wavy-Bedded with S&P texture;
  - Wavy-Bedded with scattered, but common, wavy-bands up to three inches thick; and
  - Silicate Taconite bodies characterized by magnetite-poor, thicker-bedded zones of iron silicate-rich, granular chert;

o Variably-Bedded and/or Mottled Unit – magnetic, granular, silicate-rich iron-formation exhibiting a multitude of bedding types (including intraformational conglomerates and disarticulated beds in various stages of forming conglomerates) that contain variable amounts of superimposed late diagenetic iron-carbonate mottles (most often pink ankerite);

o Bold Striped Unit – consists of alternating: 1) green-colored, iron silicate-rich bands (both greenalite- and minnesotaite-rich varieties are present); 2) brown-colored, internally thin-bedded, iron carbonate-rich sets; and 3) dark-gray to black magnetite-rich bands that gives the rock a “boldly-striped” appearance; magnetite content decreases to nil with height in this unit and carbon-coated stylolites are common;

o Mesabi Select Unit – non-magnetic, medium- to thick-bedded, greenalite-rich, granular chert.

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**Figure 2-15**: Correlation chart of Lower Slaty submembers at the various taconite mines/areas on the Mesabi Range. Red bars represent portions of the Lower Slaty that are mined at the various taconite operations. No scale implied; looking north (from Severson et al., 2009). Note the three optional contacts for the top of the Lower Slaty. The upper “alternative contact” is used here.
**Lower Slaty member** – the GIF-type iron-formation of the Lower Cherty member is overlain by a package of BIF-type iron-formation, or thin-bedded iron-formation, that is characteristic of most of the Lower Slaty member. The basal contact of the Lower Slaty member is abrupt everywhere, indicating a rapid change from shallow water deposition of the Lower Cherty to deeper water deposition of the Lower Slaty. Perhaps this abrupt change is tectonic in nature, and it is related to a series of thrust plate collisions that took place in the Fold-and-Thrust belt to the south of the Animikie Basin. While the basal contact of the Lower Slaty member is abrupt and easily defined, the upper contact of this member is often highly gradational and less well defined. This transition is especially true in the Virginia Horn area where there are several lense-shaped bodies/channels of GIF-type iron-formation that are present within a dominantly thin-bedded rock package. Historically, the placement of the upper contact of the Lower Slaty in the Virginia Horn area has been controversial and subject to change. Gruner (1924, p. 20) first described this placement as “somewhat arbitrary” due to the repeated alternations of cherty and slaty rocks, and he later decided (Gruner, 1946, p. 45) that the cherty alternations were lensoidal and placed these lenses in the Lower Slaty. However, White (1954) included these same lenses in the Upper Cherty. Even the mining companies have oscillated in their lithologic picks of the upper contact of the Lower Slaty. In the end, the placement of the upper contact of the Lower Slaty member in the Virginia Horn area becomes more of an academic problem. It is more important to remember that both cherty and slaty rocks show a pronounced interfingering relationship in the contact zone between the Lower Slaty and Upper Cherty. “Rosetta” units in the Lower Slaty member consist of:

- **Intermediate Slate** – thin-bedded, black, carbonaceous argillite that is most often at the very base of the Lower Slaty member;
- **Lowermost Thin-Bedded Unit** – weakly- to non-magnetic, thin-bedded, fine-grained iron-formation;
- **Lower IBC Unit** (IBC = “interbedded chert”) – magnetic, granular iron-formation that is present as small lensoidal, channel-like bodies in the lower portion of the Lower Slaty member in the Virginia Horn area;
- **Middle Thin-Bedded Unit** – variably-magnetic, thin-bedded iron-formation that contains a localized, but laterally extensive, **Middle IBC Unit** in the southern Virginia Horn area;
- **Upper IBC Unit** – variably-magnetic, granular iron-formation that is locally present as large, lensoidal, channel-like bodies in the upper portion of the Lower Slaty member in the Virginia Horn area; and
- **Uppermost Thin-Bedded Unit** – variably-magnetic, thin-bedded iron-formation at the top of the Lower Slaty member in the Virginia Horn area;

**Upper Cherty member** – the Upper Cherty member is vastly different from the Lower Cherty member in that the Upper Cherty contains very few consistent submembers that are equally present along the entire length of the Mesabi Iron Range. There are also profound differences in the dominant bedding types in the Upper Cherty in the eastern Mesabi Iron Range, versus bedding types in the central and western Mesabi Iron Range, that are not fully understood at this time. The Upper Cherty member in the west and central Mesabi Iron Range consists of the following “Rosetta” units:

- **Bottom Alternating-Bedded Unit** – consists of alternating thick- and thin-bedded sets indicating deposition in progressively shallowing water at the base of the Upper Cherty member (not present everywhere along the Mesabi Iron Range, but very common in the Virginia Horn area);
Figure 2-16: Correlation chart of Upper Cherty submembers at various taconite mines/areas along the Mesabi Iron Range. The vertical red bars represent portions of the Upper Cherty that are mined as taconite ore. Note that the Upper Cherty thins drastically in the central portion of the Keetac area in a valley-like morphology. Note also the distinct change in bedding types that constitute the Upper Cherty in the eastern Mesabi Iron Range. Upper Cherty submembers at Coleraine are based solely on oxidized characteristics that have been described in Zanko et al. (2003). No scale implied; looking north (from Severson et al., 2009).

- **Lower Regular-Beded Unit** – magnetic, granular iron-formation with regular-spaced, planar, bedding planes (more common in the western Mesabi Iron Range, e.g., west of Minntac);

- **Algal Unit** – stromatolite-rich and conglomeratic unit (often referred to as either the “I horizon” or “Mary Ellen Jasper”) that consists of the following morphologies:
  - Algal columns with associated intraformational conglomerates are exceedingly common from Dunka Pit to Gilbert,
  - Oncolites with associated intraformational conglomerate and lesser algal mat material are more common in the Eveleth (Utac) to Buhl (Minntac – west pit) area,
  - Further to the west, in the Buhl to Hibbing area, algal mats and conglomerate are dominant with rare oncolites; and
  - The algal unit cannot be traced in drill holes to the west of Hibbing.

- **Upper Alternating-Beded Unit** – similar to the Bottom Alternating-Beded Unit, but positioned above the Algal Unit (only present at Minntac); and

- **Upper Regular-Beded Unit** – magnetic, granular iron-formation with regular-spaced, planar, bedding planes.

It is interesting to note that the Upper Cherty thins appreciably to the south of the Keetac mine (see Fig. 2-16) in a valley-like morphology that has been infilled by thin-bedded iron-formation correlative with the Upper Slaty submember.
Correlation chart of Upper Slaty submembers at various taconite mines/areas on the Mesabi Range. Vertical red bars represent portions of the Upper Slaty that are mined as taconite ore. Note that the Upper Slaty exhibits drastic changes in thickness across the Mesabi Iron Range. Submembers at the Northshore and Dunka Pit mines are similar to the submembers at the Cliffs-Erie site with some differences. The general position of layers containing material related to the Sudbury impact event (1,850 Ma) are shown for the Utac area (Addison et al., 2005) and the Coleraine area (Cannon and Schulz, 2009). No scale implied, looking north (from Severson et al., 2009).

Upper Slaty member – the Upper Slaty is characterized by dominantly thin-bedded rocks in all locations along the Mesabi Iron Range. One exception is a carbonate horizon at the very top of the Upper Slaty to the east of Hibbing. Another exception is the presence of lense-shaped bodies of regular-bedded chert that are locally present and may represent interbedded chert “channels,” as are present as IBCs in the Lower Slaty member. “Rosetta” units in the Upper Slaty member, which is rarely drilled, in the western and central Mesabi Iron Range consist of the following:

- **Thin-Bedded Unit** – dominant rock type of the Upper Slaty member characterized by variably-magnetic, fine-grained, thin-bedded iron-formation;
- **Alternating-Bedded Unit** – consists of alternating thick- and thin-bedded sets indicating deposition in progressively deepening water at the base of the Upper Slaty member (only locally present at Minntac – especially in the East Pit);
- **Regular-Bedded Unit** – magnetic, granular iron-formation with regular-spaced bedding planes that occur as channel-like bodies (?) in the Upper Slaty; and
- **Dolomite/Limestone Unit** – iron-poor carbonate rocks (often referred to as the “A horizon”), with interbedded chert and minor argillite beds, at the very top of the Upper Slaty member and locally contains ejecta material from the 1,850 Ma Sudbury impact event near the base of this unit.

Definition of the 25 “Rosetta” units can also be used as starting points for more detailed sequence stratigraphy studies and basin analysis. There are clearly variances in some of the units, and the four iron-formation members, that are related to facies changes. Good examples of these differences, as put forth in Severson et al. (2009) are the following:
1. The Lower Cherty is remarkably consistent throughout most of the Mesabi Iron Range, and it exhibits a procession of units that could be related to reworking of materials in a siliciclastic environment (Fig. 2-18); whereas, most of the Upper Cherty is vastly different, and it is suggestive of an entirely different depositional environment;

2. The rapid thinning of the Lower Cherty in the eastern Mesabi Iron Range, across the Siphon Fault (which is inferred to be a growth fault), suggests a unique change in the depositional environment from the rest of the Mesabi Iron Range;

3. The Lower Slaty is uniquely thicker in the Virginia Horn area, possibly related to reactivation of Archean-age structures (M. Jirsa, pers. comm., 2006), and contains several “interbedded chert” lenses that were either deposited as individual parasequences or, more likely, as “cut and fill” channels;

4. The possible presence of slumped bodies of “Mesabi Select equivalent” in the Lower Slaty at the East Reserve/ McKinley Extension mine suggest unique localized responses to earthquake induced seismicity that occur only at this locality and may be related to proximity to the Siphon Fault (17 miles to the east) and/or proximity to other mapped or unmapped faults;

5. The Upper Cherty is unique in that there is increased biogenic involvement in its genesis, as suggested by increased stromatolite occurrences that in some areas form extensive “fields”;

6. There is a profound difference in the Upper Cherty in the eastern Mesabi Iron Range, wherein wavy-bedded rocks are more common, versus the central and western Mesabi Iron Range, where regular- to medium-bedded rocks dominate;

7. The various forms of the stromatolites (columns, mats, and oncites) associated with the Algal Unit suggest changes in specific areas along the shore in regards to shoreline morphology, water depth, and current strength/direction;

8. The unique presence of a submarine valley in the Upper Cherty, near Keewatin, which was filled with Upper Slaty materials; and

9. The change in the nature of the Upper Slaty in the eastern Mesabi Iron Range (with some wavy-bedded zones) in regard to the same member in the central and western Mesabi Iron Range (no wavy-bedded zones).

As the list above indicates, there are several unique differences in the stratigraphy of the iron-formation that could give an impression of overall heterogeneity. In fact, Morey (1992) mentions this heterogeneity several times in his discussion on the chemistry of the Biwabik Iron Formation. This heterogeneity, in part, stems from the multitude of submembers used by each of the different mines, and also from previous concepts of the iron-formation stratigraphy that were based on a handful of widely-spaced drill holes that were available to the public at the time. Rather, the investigation of Severson et al. (2009) shows that there are gradual lateral facies changes that can be traced in numerous drill holes. This change is a reasonable relationship when one remembers that shorelines along continental shelves are not static, and the rocks deposited on them reflect changes in water depth, current strength, and changes in the morphology of the shoreline, e.g., the presence of bays, beaches, mudflats, estuaries, submarine valleys, etc. Thus, Severson et al. (2009) found that the iron-formation is remarkably homogenous with reasonable local facies changes that take place progressively in a series of drill holes positioned along the strike of the Mesabi Iron Range.
Figure 2-18: Possible siliciclastic environment for deposition of portions of the Biwabik Iron Formation in cross-sectional view (facies division in a shallow sea). Compiled, and drawn, by Marsha Patelke (in Severson et al., 2009) from sources including Boggs (2001), Leeder (1999), Nichols (1999), and Pratt et al. (1992).

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Klein, C., 2005, Some Precambrian banded iron-formations (BIFs) from around the world: Their age, geologic setting, mineralogy, metamorphism, geochemistry, and origin: American Mineralogist, v. 90, p. 1473-1499.


STOP DESCRIPTIONS

[Note that some of these descriptions, and the text above, are modified from a GSA field trip in 2005 (Ojakangas et al., 2005), and Institute of Lake Superior Geology field trip (Ojakangas et al., 2009), and a recently released report by Severson et al. (2009).]

Figure 2-19: Generalized location map of all stops on the Mesabi Iron Range during Field Trips #2 and #3. Note that in order to observe Stops 2-1, 2-2, and 2-3 in stratigraphic order, we will be backtracking for short distances.

Figure 2-20: Location map of stops 2-1 through 2-10 in the Virginia Horn area and United Taconite of the central Mesabi Iron Range.
**STOP 2-1:** Argillaceous lower member and silty middle member of the Pokegama Formation

Proceed north from Duluth on Highway 53 toward Eveleth. In Eveleth, there is a stoplight at Grant/Industrial Avenue. Go northward past the stoplight for about 1 mile and make a U-turn at the Dairy Queen. Head back south on highway 53 for a few hundred feet to a series of rock outcrops on the right side. Eveleth 7.5’ quadrangle, T.58N., R.17W, Sec 20, NW of SW of SE; 535380E, 5259555N (NAD83 UTM).

**Description:** This roadcut is about 500 feet long and 5-10 ft high, and is the only exposure of the lower argillaceous member. It consists largely of shale and siltstone with minor fine-grained sandstone. It has been interpreted as having been deposited in a low-energy upper tidal flat environment in a sea that transgressed onto the peneplaned surface of Archean rocks (Ojakangas, 1983). Minor channeling is common at the bases of the thicker sandstone beds, and at one spot, 0.5 m of section has been eroded. Small-scale cross-bedding is present in some siltstone beds, and elongated sole marks are visible on the bottoms of some sandstone and siltstone beds. A total of 57 of these paleocurrent indicators show that the currents were generally oriented in a north-south direction, parallel to the presumed paleoshoreline that was located immediately to the east. A few concretions as large as 6 inches in diameter are present, as is soft-sediment deformation. Hemming et al. (1991) illustrated the soft-sediment folding and interpreted it as evidence that the Animikie basin was tectonically active during deposition of the Pokegama and the Biwabik. Alternatively, it is interpreted herein as soft-sediment slumping into tidal channels. Fine laminations and sequences of laminations in the sandstone beds have been interpreted as tidal rhythmites (G. Ojakangas, 1996).

Above this roadcut, in the brush and trees on the hillside, the middle silty member is exposed in artificial cuts along an ATV trail. A short walk to the south (rather than clambering uphill through the brush) provides easy access to the trail. Blocks of the more massive upper sandy member are present higher on the hillside above the trail.

**STOP 2-2:** Upper sandy member of the Pokegama Formation

Continue southbound on Highway 53 and drive past the U.S. Hockey Hall of Fame on the right, and stop along the highway near the Rustic Rock Inn. VERY CAREFULLY cross the highway to view exposures on the east side near the Lutheran Church. Eveleth 7.5’ quadrangle, T.58N., R.17W, Sec 32, E ½ of SE; 536055E, 5256775N (NAD83 UTM).

**Description:** This is the upper sandy member of the Pokegama Formation, composed of silica-cemented quartz sandstone. It is the rock type found immediately beneath the Biwabik Iron Formation; it was penetrated by countless drill holes during mining and exploration, and resulted in the formation being originally named the Pokegama Quartzite. Note the massive beds separated by thin beds of shale or siltstone. Silica cementation likely obscured some original cross-bedding. This member was interpreted by Ojakangas (1983) as having been deposited in a high-energy, lower tidal or subtidal environment.

**STOP 2-3:** Weakly Wavy-Bedded unit of Lower Cherty member, Biwabik Iron Formation

Proceed south on Highway 53 for 0.6 miles (passing over an overpass) to a left-turn lane. Make a U-turn and proceed north on the highway for about 0.2 miles to the off-ramp for Highway 37 – rock exposures are on the beginning of this ramp (right side). Eveleth 7.5’ quadrangle, T.57N., R.17W, Sec 3, E ½ of NE of NE; 536230E, 5256285N (NAD83 UTM).

**Description:** Note that this member of the Biwabik Iron Formation overlies the sandy member of the Pokegama Formation of the last stop, and that both units dip gently to the southeast. Observe
the thick wavy bedding, the trough cross-bedding, and the sandy texture of the iron minerals and chert grains. The cross-beds are best observed in this eastern roadcut, but are also present at both ends of the longer cut on the other side of the highway. Cross-bedding measurements (Fig. 2-21), although not definitive, are suggestive of a tidally-influenced marine environment (also see Figure 2-9). This, coupled with Walther’s law of succession of sedimentary facies (i.e., the facies observed vertically are also similarly related laterally), places the deposition of the iron-formation seaward of the Pokegama Formation.

STOPS 2-4 through 2-9: Stratigraphic section of the Biwabik Iron Formation in the United Taconite Thunderbird North Mine

Continue down the off ramp and turn left on highway 37 and follow the detour signs northward through downtown Eveleth to the Thunderbird North Mine of United Taconite (formerly Eveleth Taconite, or Evtac). Eveleth 7.5° quadrangle T.58N., R.17W., Sec 20, 535290E, 5260255N (NAD 83 UTMS).

Historical Overview (from Phil Larson) – Material mined at the Thunderbird North Mine consists of taconite ore horizons from the Lower Cherty, Lower Slaty, and Upper Cherty members. Direct-shipping ore, also referred to a natural ore, was originally mined in the immediate vicinity from the Auburn (1894-2002), Virginia (1910-1953), and Gross-Nelson (1944-1977) deposits. Exploration for magnetic taconite at this site began in earnest in 1960, after the opening of pioneering taconite operations at the Reserve Mining Company (now Northshore Mining) and Erie Mining Company (now Cliffs Erie site) in the mid-1950s. Drilling by Oglebay Norton Company identified a substantial magnetic taconite deposit in the area and the property was jointly developed with the Ford Motor Company – groundbreaking occurred in June, 1964.

The Thunderbird North mine and Fairlane plant began producing in November, 1965, with an initial rated capacity of 1.6 million tons of iron ore pellets per year. In 1977, addition of a second concentrating and pelletizing line, and the opening of the adjacent Thunderbird South mine, increased rated capacity to 6.0 million tons of pellets. The Thunderbird South mine closed in 1992, and in 1996, ownership of the operation was transferred to Eveleth Mines LLC. Eveleth Mines closed the concentrating and pelletizing Line 1 in May, 1999, reducing capacity to 4.2 million tons of pellets. The remaining operation was idled in May, 2003.

The idled facility was purchased and re-opened by United Taconite LLC in December, 2003 (now owned 100% by Cliffs Natural Resources). They subsequently refurbished and reactivated Line 1 in December, 2004, which increased the annual rated capacity to 5.2 million tons of pellets.
Thunderbird North Mine Stratigraphy: The drilled thickness of the Biwabik Iron Formation in the vicinity of the Thunderbird North Deposit is approximately 685’. Average thicknesses of the four members, as recognized at Thunderbird North, are:

<table>
<thead>
<tr>
<th>Member</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Slaty</td>
<td>51 feet (15.5 meters)</td>
</tr>
<tr>
<td>Upper Cherty</td>
<td>347 feet (121 meters)</td>
</tr>
<tr>
<td>Lower Slaty</td>
<td>52 feet (16 meters)</td>
</tr>
<tr>
<td>Lower Cherty</td>
<td>236 feet (72 meters)</td>
</tr>
</tbody>
</table>

In addition to the subdivisions recognized throughout the Mesabi District, Thunderbird Mine geological staff have further subdivided the iron formation into 23 subunits based on lithologic, metallurgical, and mineralogical characteristics. These subunits form the basis for both resource estimation and grade control at the mine and are described below. [Note that the unit name (in parentheses) that follows the Utac submember name corresponds to NRRI “Rosetta” units – this is not the terminology used by the Thunderbird North Mine geological staff.] **Stops 2-4 through 2-9** will all be within the Thunderbird North mine and will be associated with some of the described submembers listed below. As the stops will be dependant on accessibility due to mining activities it is impossible to pre-determine the exact location of the stops at the time of this writing.

**Lower Cherty Member**
The Lower Cherty member is approximately 236 feet thick in the Thunderbird North deposit. It has been subdivided into the following eight subunits.

**LC-1 Submember (Basal Red Unit)**
The LC-1 submember is a pink-green-gray heterogeneous unit comprised of interbedded thin-bedded slaty and thin-bedded cherty carbonate-silicate(minnesotaite-talc-stilpnomelane) iron-formation. LC-1 comprises the basal 64 feet of the iron formation. It is defined as the footwall thickness of the iron formation, the magnetite grade of which is subeconomic. It is in general poorly described since the majority of exploration and development drilling terminates in the upper few feet of this unit.

**LC-2 Submember (Regular-Bedded Unit)**
The LC-2 submember is a gray thin-bedded cherty carbonate-silicate(minnesotaite-talc) iron-formation. Magnetite occurs as disseminated and diffuse idiomorphic granules and as replacement of thin slaty laminae and early burial styolites. Magnetite (slaty) laminae often have thin stringers of white talc. LC-2 averages 16 feet in thickness, but varies across the extent of the Thunderbird North Deposit, being thinner in the southwest extent of the deposit and thicker in the northeast extent. In the northeast portion of the deposit, the unit is of sufficient thickness and grade to warrant mining despite dilution by the overlying LC-3 waste unit.

**LC-3 Submember (Regular-Bedded Unit)**
Rocks of the LC-3 submember are characterized by interbedded greenish-gray thin-bedded cherty and green medium-laminated slaty iron-formation. The unit is weakly magnetic, with the cherty beds conspicuously low in magnetite. The unit averages 13 feet thick, but varies across the deposit. In the southwestern extent of the deposit, the unit is up to 30 feet thick and predominantly composed of slaty iron formation. In the northeastern extent of the deposit, the unit is consistently 10 feet thick and composed predominantly of thin bedded non-magnetic granular chert.
LC-4 SUBMEMBER (WAVY-BEDDED UNIT)
The LC-4 submember is composed of gray medium-bedded cherty oxide-carbonate(ankerite)-silicate(minnesotaite-talc) iron-formation with minor thin irregular thin beds of slaty (magnetite) iron formation. Magnetite occurs as disseminated idiomorphic granules, patchy haloes cored by coarse slaty intraclasts, and replacement of thin slaty laminae. LC-4 varies from 40-50 feet thick at Thunderbird North, thickening to the southwest. A notable feature of LC-4 is the presence of wispy laminae of magnetite, likely a later diagenetic overprint of early burial stylolites. The LC-4 and its equivalents are widespread across the Mesabi District, and perhaps the most economically significant subunit, having a high iron weight recovery (36%) and being capable of producing a low silica concentrate (~2.0%).

LC-5 SUBMEMBER (WAVY-BEDDED UNIT)
LC-5 is composed of pink-gray medium- to thick-bedded cherty oxide-chert-carbonate(ankerite) iron-formation. Magnetite occurs as disseminated grains and in mottles. The unit is notable for its high carbonate content, containing up to 3.0% CaO in ankerite. LC-5 varies from 40-50 feet thick at Thunderbird North, thickening to the southwest. LC-5 contains a small but variable amount of ‘primary’ (e.g. pre-supergene oxidation) hematite. LC-5 has appreciably more matrix chert than the underlying LC-4, and produces a significantly higher silica concentrate (~6.0%).

LC-6 SUBMEMBER (VARIABLY-BEDDED AND/OR MOTTLED UNIT)
The LC-6, averages seven feet thick, and consists of a pink massive- to thick-bedded cherty oxide-chert-carbonate(kutnahorite) iron-formation with conspicuous pink iron-carbonate mottles. The unit is composed principally of coarse grained intraclasts, reflecting a relatively high energy depositional environment. The unit also contains an appreciable content of ‘primary’ hematite, and has relatively low magnetite recovery. The unit is remarkably tough, and poses a challenge to mining in that it resists fragmentation during blasting and tends to produce large chunks.

LC-7 SUBMEMBER (BOLD STRIPED UNIT)
LC-7 is a composed of interbedded thick irregular magnetite-carbonate-silicate slaty and green thin- to medium-bedded cherty carbonate(siderite)-silicate(greenalite) iron-formation. The unit averages 13 feet thick. The unit is remarkable in that magnetite occurs predominantly in the thick slaty laminae, resulting in a boldly-striped appearance in drill core. Green LC-7 sharply overlies the pink LC-6, and the contact is a highly visible stratigraphic marker throughout the Virginia Horn area. The transition upward from thick-bedded coarse-grained to thin-bedded fine-grained iron-formation, as well as the contrasting mineralogical assemblages at the LC-6/LC-7 contact, suggests an abrupt transition in the depositional environment.

LC-8 SUBMEMBER (MESABI SELECT UNIT)
LC-8 is visually similar to LC-7, consisting of a interbedded green medium- to thick-laminar massive slaty and greenish-gray thin-bedded granular cherty carbonate(siderite)-silicate(greenalite) iron-formation. However, the unit contains little or no magnetite and is a waste product that makes excellent aggregate material. The LC-8 averages 21 feet in thickness. LC-8 from the Thunderbird North Mine is the type material for “Mesabi Select” crushed aggregate currently being marketed regionally for road construction, noted for its high specific gravity and angular fragmentation.

Lower Slaty Member
The Lower Slaty member, as defined at Thunderbird North, averages 52 feet thick and is characterized by non-magnetic and thin-bedded waste rock between the Lower Cherty and Upper
Cherty member ore horizons. Other interpretations (Severson et al., 2009) of the Lower Slaty in the Virginia Horn area extend it to up to the top of the UC-4 submember, and up to 309 feet thick.

**LS-1 SUBMEMBER (INTERMEDIATE SLATE UNIT)**
LS-1 is composed of predominantly black massive- to thinly-laminated slaty carbonate(siderite)-silicate(stilpnomelane-minnesotaite)-sulfide iron formation. The LS-1 averages 17 feet in total thickness, and is divisible into a lower half composed of a composed of thick bedded massive intraformational debris flow breccias and an upper half composed of thinly-laminated planar-bedded slaty iron-formation. Locally, thin to medium bedded black flinty cherts are present in the lower portion; these flinty cherts typically occur in pod-like bodies extending a few 100s of feet along strike. The upper portion of LS-1 has undergone extensive bedding-parallel deformation; essentially the entire horizon served as a low-angle fault plane. Small-scale folds are common, as are bedding-parallel syntectonic quartz-carbonate(ankerite-siderite) veins. The thinly-laminated planar-bedded slaty iron-formation in the upper portion is the so-called Intermediate Slate, a district-scale marker horizon. LS-1 is notable in that it contains a very high percentage of Al₂O₃ (1.86%) and other elements indicative of clastic input, suggesting the basin was experiencing either an influx of clastic detritus, or a sharp reduction in the rate of iron formation deposition.

**LS-2 SUBMEMBER (LOWERMOST THIN-BEDDED UNIT)**
LS-2 is composed of a green to greenish-gray well-cemented very thinly-laminated slaty carbonate-silicate(minnesotaite) iron-formation. The unit averages 35 feet thick. The top of the LS-2 is defined by the appearance of significant magnetic slaty iron-formation. Commonly, this corresponds to the first appearance of thin-bedded intraclast breccias. These breccias commonly have a magnetite-rich matrix.

**Upper Cherty Member**
The Upper Cherty member at Thunderbird North contains all potential ore horizons situated above the Lower Slaty waste horizons. This comprises 347 feet in thickness and the remainder of the thickness of the iron-formation exposed in the present workings. The lowermost 257 feet of the Upper Cherty, as defined at Thunderbird North, consists of alternating horizons of dominantly slaty- and cherty-iron-formation; these horizons have been included in the Lower Slaty by other workers (Severson et al., 2009) including US Steel (see Figure 2-15). The Upper Cherty has been subdivided into eleven subunits at Thunderbird North.

**LUC-1 SUBMEMBER (ORE ZONE OF LOWERMOST THIN-BEDDED UNIT)**
The LUC-1 is composed of gray laminar thin-bedded slaty chert-silicate(stilpnomelane) iron-formation. The unit averages 18 feet in thickness and is notable for producing only a very high silica concentrate (up to ~10% SiO₂). This unit, in common with the other slaty iron-formation horizons in the Upper Cherty member, has a relatively high Al₂O₃ content (~0.56%).

**LUC-2 SUBMEMBER (LOWER IBC UNIT)**
The LUC-2 is a heterogeneous unit, composed variously of green-gray thin-bedded slaty iron-formation, interbedded green-gray thin-bedded slaty iron-formation, thin-bedded cherty iron-formation, and gray thick-bedded cherty iron-formation. The unit as a whole averages 46 feet thick. For the unit as a whole, thin-bedded granular cherty horizons predominate over thin- to medium-laminated shales. The abundance and frequency of cherty horizons generally increases upsection within the unit. Locally, pink massive- to thick-bedded, coarse-grained, magnetite-bearing granular cherts, upwards of 20 feet thick, are present within the unit. These beds are characterized by significantly higher weight recovery, and significantly lower concentrate silica grades than the unit as a whole.
LUC-3 SUBMEMBER (MIDDLE THIN-BEDDED UNIT)
The LUC-3 is composed of dark reddish-brown thin/planar-bedded slaty chert-silicate iron-formation. The unit averages 19 feet thick. Nodules and beds of chert are increasingly abundant upsection, culminating in the presence of a 1-2 foot thick horizon containing thin bedded flinty chert.

UC-1 SUBMEMBER (MIDDLE IBC UNIT)
The UC-1 is composed of pinkish-gray thick-bedded cherty oxide-chert-silicate iron-formation. The unit averages 29 feet thick; however, it is not extensive through the deposit. The overall aspect of UC-1 is of a lenticular body on the order of several km in extent. UC-1 is notable in that it contains an appreciable content of ‘primary’ hematite; this hematite is intimately intergrown with magnetite, and thus, is recovered in the Fairlane concentrator circuit.

UC-2 (MIDDLE THIN-BEDDED UNIT)
The UC-2 is a dark reddish-brown thin-bedded slaty chert-silicate iron-formation, averaging 46 feet in thickness. UC-2 is generally characterized by low weight recovery and a high concentrate silica, and thus, is marginal ore at best.

UC-3 AND UC-3A SUBMEMBERS (UPPER IBC UNIT)
The UC-3 and UC-3A are gray thick-bedded cherty iron-formation. Combined, they average 91 feet in thickness. Similar to UC-1, these units are not laterally extensive, and have the overall aspect of lenticular bodies on the order of several km in extent. The two units comprise a single depositional package; however, the lower half (UC-3) is generally characterized by low weight recovery, while the upper half (UC-3A) is characterized by higher carbonate and magnetite content. UC-3A was historically one of the primary ore units at the Thunderbird North Mine; however, it is not now being mined and is only poorly exposed in the pit. UC-3A is notable for an abundance of coarse-grained jasper intraclasts; the vivid colors of these intraclasts have resulted in the name ‘confetti ore’ being attached to UC-3A.

UC-4 SUBMEMBER (UPPERMOST THIN-BEDDED UNIT)
The UC-4 is a dark reddish-brown thin-bedded slaty silicate iron-formation, averaging 18 feet in thickness. In areas where UC-1, UC-3 and UC-3A are absent, UC-4 is the upward continuation of UC-2. The unit typically has a very low weight recovery. The uppermost 1-5 feet of the subunit is commonly a black, thin-bedded non-magnetic slaty silicate iron-formation. This has been recognized as an important marker horizon, and for some workers (Figure 2-15), marks the top of the Lower Slaty member.

UC-5 SUBMEMBER (ALTERNATING-BEDDED UNIT – FIGURE 2-16)
The UC-5 consists of interbedded reddish-brown thin-bedded slaty silicate iron-formation and thin-bedded cherty iron-formation. The unit averages 15 feet thick. The thin cherty beds commonly contain abundant coarse-grained jasper intraclasts.

UC-6 SUBMEMBER (ALGAL/CONGLOMERATE UNIT)
The UC-6 is very distinct in that it is composed of red medium- to thick-bedded coarse-grained intraclast conglomerates. Clasts in the conglomerate are composed predominantly of resedimented cherty algal stromatolites (oncolites). The conglomeratic matrix is commonly composed predominantly of manganiferous carbonates. UC-6 is notable in having the highest manganese content in the Biwabik Iron Formation, averaging ~6.0% Mn.
UC-7 SUBMEMBER (REGULAR/MEDIUM-BEDDED UNIT)
The UC-7 is composed of gray to red thick-bedded oolitic cherty oxide-chert-carbonate iron-formation. The unit averages 37 feet thick in the Thunderbird North Mine area, and is known mostly from oxidized drill hole intercepts. The unit appears to consist of a lower red hematitic oolitic cherty iron-formation and an upper gray magnetite-bearing oolitic chert-carbonate(ankerite) cherty iron-formation. The upper gray horizon contains abundant coarse poikiloblasts of ankerite; commonly these are weathered away, leaving vesicle-like vugs in the oolitic cherts.

UC-8 SUBMEMBER (REGULAR/MEDIUM-BEDDED UNIT)
Similar to UC-5, the UC-8 consists of interbedded green-red thin-bedded slaty silicate iron-formation and thin-bedded cherty iron-formation. The unit averages 28 feet thick. UC-8 is known only from (commonly) oxidized drill hole intercepts. The thin cherty beds commonly contain abundant coarse-grained jasper intraclasts. The contact between UC-8 and the overlying US-1 is only poorly defined.

Upper Slaty Member / US-1 SUBMEMBER
The Upper Slaty member in the vicinity of the Thunderbird North Mine is only known from oxidized intercepts in a few drill holes, and is not exposed in outcrop. The unit is comprised predominantly of reddish-brown thin-bedded slaty iron-formation, and is about 50 feet thick.

STOP 2-10: Security Reserve/Fayal Complex Direct Shipping Ore
Proceed southward on company roads through the Thunderbird North Mine. Cross highway 7 (through two remote operated gates on either side of the highway) and continue south through the Thunderbird South Mine to the Fayal Pit. The site is an approximately 200 meters (650 feet) long exposure of iron-formation and direct shipping ore exposed along a northeast-trending access ramp into the flooded Fayal Mine complex. Eveleth 7.5’ quadrangle, SW¼SW¼, Section 5, T.57N., R.17W., UTM 535127E, 5255129N (NAD 83).

Description: The Fayal Mine (1895-1965; total production 44.5 million tons) was discovered in November, 1893 by David T Adams of Duluth. The mine site was initially explored by the McInnis Mining Company and was sold to the Minnesota Iron Company (a component of the 1901 United States Steel merger), after which the mine was operated by the Oliver Iron Mining Company.

Production of direct shipping ore began in 1895 and was initially extracted by shaft from underground operations. Open pit operations facilitated a rapid increase in production, reaching 1.9 million tons in 1902. Through the end of 1919, the complex had yielded an aggregate of 29.9 million tons – more than a million tons per year since 1895 (and two-thirds the ultimate production). The Fayal complex was closed in 1933, but was reopened on a smaller scale, as an open-pit truck operation, to recover lower grades of ore between 1944 and 1965. Final development plans included recovering approximately 794,000 tons of Lower Slaty- and lower Upper Cherty-hosted ores along the south side of the deposit (Security Reserve). However, by the time final mining was contemplated (ca. 2000), by Auburn Minerals LLC, the sulfur content of the reserve was deemed unacceptably high.

Included in the Security Reserve is an access ramp to the flooded Fayal Mine. Along this ramp, direct shipping ore is exposed in both the floor and wall of the ramp. This site is one of the few remaining locations on the Mesabi Iron Range to view in situ direct shipping ore.

All direct shipping ore in the Fayal deposit falls under the Soft Iron Ore Classification of Marsden (1968). The Fayal ore consists predominantly of hematite and goethite, with minor magnetite and manganese oxides, as is common with the other soft ore deposits of the Mesabi
Iron Range. Silica and clay minerals are the predominant gangue minerals. In 1901, Fayal direct shipping ore was reported to averaged 63.8% iron, 0.037% phosphorus, and 2.95% silica (dry basis; Leith, 1903). The direct shipping ore visible in the Fayal ramp occurs along the margin of the deposit and likely has lower iron and higher silica content than the typical higher grade ore shipped from the Fayal deposit for most of its life.

Ore formation and desilicification were accompanied by mass loss (as much as 50% by weight) and, to a variable extent, volume loss. Unaltered iron formation has a specific gravity of 3.3-3.4; Leith (1903) reported typical direct shipping ore specific gravities in the range of 2.6-3.1, with some ores as low as 2.0-2.1. Mass loss was typically accompanied by structural collapse and formation of a synclinal structure in the ore body. Commonly, the steepest dips in the bedded direct shipping ore were adjacent to the margins of the deposits. Iron formation exposed along the east side of the Fayal ramp parallels the contact of the direct shipping ore deposit. The ore is formed from predominantly slaty proto-ore, and displays varying degrees of desilicification and oxidation. Bedding in direct shipping ore on the north end of the ramp clearly displays a relatively steep dip to the west and the center of the trough.

Ore formation was evidently a multi-stage process. Early desilicification of the iron formation was accompanied by alteration of primary magnetite to hematite, and alteration of primary iron silicates and iron carbonates to goethite. Much direct shipping ore exhibits textures indicative of a second stage of enrichment. Secondary porosity induced during desilicification is often filled by paragenetically late iron hydroxides and hydrous iron oxides. Dripstone textures suggest at least some of these secondary iron hydroxides were precipitated in the vadose zone. Leith (1903) noted that hydrous minerals were more abundant in the shallower portions of the deposits, suggesting the presence of a supergene enrichment zone, perhaps coincident with a paleo-water table.

A common feature of the Biwabik Iron Formation are quartz-carbonate veins occupying vertical fractures and bedding-parallel slip planes. These veins postdate magnetite formation and diagenesis of the iron formation, but display textures indicative of syntectonic growth, suggesting they may be related to far-field deformation associated with the Penokean orogeny. In the vicinity of direct shipping ore deposits, these veins are commonly overprinted by: 1. complete or partial dissolution of carbonate minerals, 2. brecciation of the quartz (perhaps associated with volume loss collapse of the iron formation), and 3. recementing by secondary iron oxides and silica. The west side of the ramp parallels the northeast-trending Fayal fault, a high-angle, west-dipping normal fault, and one of the larger structures cross-cutting the Biwabik Iron Formation. The fault is occupied by a thick, brecciated, and re-cemented quartz±carbonate vein. Visible immediately adjacent to the large vein is drag folding in the footwall iron formation, indicating a hangingwall down sense of motion.

The nature and timing of ore formation has been the subject of much debate. The clear association of many deposits with fault and fracture zones, as well as the sharp wall contacts, has been cited as evidence in favor of a hydrothermal origin (Morey, 1999). In contrast, the clear association of the stratiform bodies with the paleosurface argues strongly in favor of a supergene origin. However, the complex paragenesis of the ores suggests that multiple events may ultimately be responsible for development of the ores.

STOP 2-10A (Optional): Drill Core Display
Proceed back north along the same route to the core shack within the Thunderbird North Mine. A drill hole (7N1001) cored through most of the Biwabik Iron Formation, and a portion of the upper Pokegama Formation, will be on display either inside the core shack, or weather permitting, will be laid outside. Submembers of the iron-formation will be labeled according to Utac’s classification scheme.
Hole 7N1001 was drilled west of the center of the current extent of the Thunderbird North Mine. Total depth of the hole is 211m (678 feet), and it penetrates ~190m (620 feet) of the ~210m (680 feet) thickness of the Biwabik Iron Formation in the Virginia Horn area.

STOP 2-11: Algal unit (I submember) of the Upper Cherty member, Cliffs-Erie site
Exit the Thunderbird North Mine by following the detour back through downtown Eveleth to highway 37. Turn left and proceed east down highway 37. Go under the highway 53 overpass and eventually go through Gilbert. At the intersection with highway 135 (on the north side of Gilbert) turn right and proceed east through Biwabik and towards Aurora. Just before Aurora highway 135 turns abruptly north – make this sharp left turn and continue down highway 135 for about 5.5 miles to the entrance to the PolyMet Mine and Mesaba Nugget Plant (private road). Turn right and go about 4 miles to the PolyMet guard shack and check in with their personnel. Continue down this same road for about another 2.3 miles to a junction with the Dunka Road. Turn right and go about 0.8 miles to the last stop of the day. Allen 7.5’ quadrangle T.59N., R.14W., Sec 23, N1/2 of NW; 568202E, 5270625N (NAD 83).

Historical Overview: Founded in 1957 by the Erie Mining Company, this mine was the second taconite production facility on the Mesabi Iron Range. Ore was mined from a series of pits that included mined portions of the Upper Slaty Member (submembers D and E); the Upper Cherty Member (submembers G-H-I-J, and submembers L-M); and the Lower Cherty Member (submembers S-T-U). In 1973, a record high of 13,104,000 tons of pellets was shipped from Taconite Harbor on Lake Superior. In its last years of full production, the LTV Mining Company produced about 8 million tons of taconite pellets annually. In May of 2000, the LTV Steel Corporation announced its intent to close the mine and facilities, including a power plant on Lake Superior. Over 1,400 people were laid off in January 2001. The mine, facilities, and tailings basin were acquired by Cliffs Management Services in late 2001. PolyMet Mining bought the concentrator and tailings basin from Cliffs for use in processing Cu-Ni material from the nearby NorthMet Deposit (in the intrusive Mesoproterozoic Duluth Complex).

Description: Algal structures were first described by Leith (1903) as “contorted bedding.” Grout and Broderick (1919) were the first who assigned an organic origin to them. The algal submember within the Upper Cherty consists of mounds of fossilized algal colonies that are separated by jasper-bearing intraformational conglomerate; both the algal and conglomerate units exhibit a combined thickness of 2-20 feet. This horizon occurs only in the eastern half of the range (not present west of Hibbing).

This locality is an excellent place to view a nearly horizontal portion of the iron-formation that contains abundant individual mounds of algal stromatolite. Stripping of glacial overburden in this area once revealed a dip slope the size of a football field that contained stromatolite mounds. See Figure 2-9 in this field guide, which illustrates a large portion of that exposure that has since been mined. The present stop is at an area is located several hundred feet west of that site. Internally, the mounds are characterized by many individual columnar finger-like structures that are convex upward. The mounds protrude up through a thin veneer of the overlying thin- to wavy-bedded H submember. Measurements on a nearby mine face in this horizon showed that all the columnar stromatolites were inclined at 30 degrees to the vertical; unfortunately, that site has also been removed by mining.

Return to the mine entrance along the same road system back to Minnesota 135 and proceed south towards Aurora and then west towards Biwabik. A few miles before reaching Biwabik turn right (north) on highway 138 and proceed to Giants Ridge Ski Resort.

OVERNIGHT AT GIANTS RIDGE RESORT