INTRODUCTION

The field trip today will concentrate mostly on the metamorphic effects on the Biwabik Iron Formation, at the Peter Mitchell mine of eastern Mesabi Iron Range, caused by intrusion of the nearby Mesoproterozoic Duluth Complex (1.1 Ga). The stratigraphy of the iron-formation that is used at this mine, and nearby mines, was mainly developed by Gundersen and Schwartz (1962) and is depicted in Figure 3-1. This stratigraphy has since been modified by Bonnichsen (1968) in nearby Dunka Pit, and by mine personnel at the nearby Erie/LTV mine (now referred to as the Cliffs Erie site in Figure 3-1). While the stratigraphy is important as an ore control it will take a backseat in this portion of the trip in order to more fully concentrate on metamorphism of the iron-formation.

Metamorphic effects in easternmost Mesabi Iron Range have greatly modified the mineralogy of the iron-formation through progressive devolatilization reactions, and near obliteration of primary textures, especially as the contact of the Duluth Complex is approached. Recrystallization and replacement of primary iron minerals and granules during diagenesis and metamorphism have been extensive, and consisted of a number of discrete events. The mineralogy of the Eastern Mesabi Range is reviewed in detail by Gundersen and Schwartz (1962) and that of the Dunka Pit area by Bonnichsen (1975). The following discussion serves to compliment the work of these researchers with work performed to date by Cliffs Natural Resources geologists in the area of Northshore Mining’s Peter Mitchell Mine. In contrast to the iron-formation of the Western and Central Mesabi Range, which is dominated by very low greenschist metamorphic facies assemblages, rocks of the eastern Mesabi have been subjected to middle greenschist through upper amphibolite facies metamorphic conditions. Hornblende and pyroxene hornfels facies are also observed at the contact of iron-formation with the Duluth Complex. Progressive effects of contact metamorphism toward the contact of the Duluth Complex have produced distinct mineral assemblages that document changing metamorphic conditions and concomitant changes in mineralogy. These changes are readily apparent in the highly reactive mineral assemblages of the Biwabik Iron Formation.

MINERALOGY

The Biwabik Iron Formation in the vicinity of the Peter Mitchell Mine consists of higher grade metamorphic assemblages that include magnetite, iron-rich chain silicates, and quartz. Minerals found to occur in the Biwabik Iron Formation from both the Peter Mitchell Mine and nearby Dunka Pit are given in Table 3-1 below. The overlying argillaceous sedimentary rocks of the Virginia Formation are generally quartz-muscovite-biotite-microcline-plagioclase+-chlorite schist with local zones of carbonaceous+/-pyrite+/-pyrrhotite phyllite. Minerals found in the
Virginia Formation in the area of the Peter Mitchell Mine are provided in Table 3-2. Excluding Cu-Ni PGE mineralization, the mineralogy of gabbroic rocks of the Duluth Complex in this area is relatively simple: labradorite, anorthite, augite, orthopyroxene, olivine group minerals, with accessory magnetite, ilmenite, and apatite.

**Figure 3-1:** Submember nomenclature for the Biwabik Iron Formation as used at the various taconite mines and idled mine sites that will be visited on this field trip. Submembers from Gundersen and Schwartz (1962) and Bonnichsen (1968). Mined horizons are shown by red bars on the sides of the columns. Note that the G submember is positioned in either the Upper Slaty or Upper Cherty depending on the mine site.
Table 3-1: Minerals found in the Biwabik Iron Formation in the area of the Peter Mitchell Mine and Dunka Pit.

<table>
<thead>
<tr>
<th>Amphibole Group</th>
<th>Pyroxene Group</th>
<th>Olivine Group</th>
<th>Other Silicates</th>
<th>Oxides/Hydroxides</th>
<th>Carbonates</th>
<th>Phosphates</th>
<th>Other Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grunerite</td>
<td>Hedenbergite</td>
<td>Fayalite</td>
<td>Quartz</td>
<td>Magnetite</td>
<td>Siderite</td>
<td>Hydroxylapatite</td>
<td>Pyrrhotite</td>
</tr>
<tr>
<td>Ferro-actinolite (minor)</td>
<td>Ferro-hypersthene (minor)</td>
<td>Ferroan Clinohlorel</td>
<td>Hematite (minor)</td>
<td>Ankerite</td>
<td></td>
<td></td>
<td>Pyrite</td>
</tr>
<tr>
<td>Ferro-hornblende (minor)</td>
<td>Ferroselite</td>
<td>Biotite</td>
<td>Goethite</td>
<td>Rhodochrosite (minor)</td>
<td></td>
<td></td>
<td>“Anthraxolite”</td>
</tr>
<tr>
<td>Ferro-pigeonite</td>
<td>Diopside</td>
<td>Oligoclase</td>
<td>Ilmenite</td>
<td>Ferroan Dolomite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cummingtonite</td>
<td></td>
<td>Andesine</td>
<td>Ferroan Kutnahorite</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Almandite</td>
<td>Calcite</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Andradite</td>
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<td></td>
<td></td>
<td>Cordierite</td>
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<td></td>
<td>Sekaninaite?</td>
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<tr>
<td></td>
<td></td>
<td>Wollastonite</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Epidote</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Titanite</td>
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</tr>
</tbody>
</table>

Table 3-2: Mineralogy of the Virginia Formation in the vicinity of the Peter Mitchell Mine.

<table>
<thead>
<tr>
<th>Silicates</th>
<th>Other Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscovite</td>
<td>Ilmenite</td>
</tr>
<tr>
<td>Biotite</td>
<td>Pyrrhotite</td>
</tr>
<tr>
<td>Quartz</td>
<td>Pyrite</td>
</tr>
<tr>
<td>Microcline</td>
<td>Chalcopyrite</td>
</tr>
<tr>
<td>Anorthite</td>
<td>Rutile</td>
</tr>
<tr>
<td>Oligoclase</td>
<td>Ankerite</td>
</tr>
<tr>
<td>Andesine</td>
<td>Calcite</td>
</tr>
<tr>
<td>Anthophyllite</td>
<td>Graphite/Carbonaceous material</td>
</tr>
<tr>
<td>Cordierite</td>
<td></td>
</tr>
<tr>
<td>Staurolite</td>
<td></td>
</tr>
<tr>
<td>Wollastonite</td>
<td></td>
</tr>
<tr>
<td>Ferroan Clinohlorel</td>
<td></td>
</tr>
<tr>
<td>Andalusite</td>
<td></td>
</tr>
<tr>
<td>Sillimanite</td>
<td></td>
</tr>
<tr>
<td>Almandine</td>
<td></td>
</tr>
<tr>
<td>Epidote</td>
<td></td>
</tr>
<tr>
<td>Titanite</td>
<td></td>
</tr>
</tbody>
</table>

Quartz is the most abundant mineral in the metamorphosed Biwabik Iron Formation and constitutes layers of recrystallized chert. It also occurs pervasively in the matrix of the iron formation admixed with varying amounts of other fine-grained minerals such as magnetite, and minerals of the amphibole group. Quartz grains are equant to irregular and granoblastic. Fayalite also occurs as equant, granoblastic grains with quartz along with fine-grained magnetite, especially in the M, N, and O submembers. In addition to quartz, fayalite is commonly associated with ferrohypersthene, cummingtonite, grunerite, magnetite, and rarely cordierite. Sekaninaite,
the Fe-analogue of cordierite, has been tentatively identified in one sample by x-ray diffraction methods.

Magnetite is the second most abundant mineral in the Biwabik Iron Formation and is the ore mineral of interest in taconite units of the entire Mesabi Iron Range. The occurrence of magnetite in the Eastern Mesabi Iron Range is described in detail by Gundersen and Schwartz (1962) and Bonnichsen (1975) and will be only briefly reviewed here. In the Peter Mitchell Mine, and at Dunka Pit, magnetite is abundant in the F through O taconite submembers where it constitutes ore. Equant magnetite grains range from sub-millimeter to locally 5 mm in size and are invariably euhedral due to their high placement in the idioblastic series due to their high force of crystallization, similar to garnet group minerals. Magnetite occurs in distinct laminae and in thin to thick, planar to wavy layers of variable continuity that consist of profusely intergrown grains with minor amounts of fine-grained quartz. Many magnetite-rich layers in the Upper Cherty member exhibit parting surfaces containing coarse-grained aggregates of magnetite crystals. Magnetite is also found as fine- to coarse-grained isolated clusters or “granules” in recrystallized chert, and as fine-grained replacement of algal stromatolites and interbedded intraformational conglomerate clasts (I submember). Magnetite-rich layers alternate with quartz-rich (recrystallized chert) layers and amphibole-rich (generally cummingtonite-grunerite) layers. Poikiloblastic textures of magnetite are only seen upon microscopic examination of grains in polished thin section and reveals poikiloblasts enclosing quartz with very minor amounts of amphibole group minerals and fayalite.

Minerals of the amphibole group are found throughout the iron-formation with grunerite and cummingtonite the most prevalent. These amphiboles range from very fine- to very coarse-grained and occur as subhedral, prismatic, isolated crystals. They may also occur as intergrown crystals forming divergent fascicles, rosettes, and radial acicular aggregates in the matrix or clustered in distinct bands of variable thickness. Poikiloblastic crystals of cummingtonite-grunerite can be observed macroscopically and microscopically to enclose grains of quartz and magnetite. Ferrohornblende and ferroactinolite, although relatively abundant, are difficult to distinguish from minerals of the cummingtonite-grunerite series macroscopically. Cummingtonite, grunerite, ferrohornblende, and ferroactinolite have all been observed replacing retrograded pyroxenes.

Minerals of the pyroxene group are dominated by ferrohypersthene and hedenbergite in most of the submembers. Bonnichsen (1975) reports ferro-pigeonite and diopside locally at Dunka Pit. All of the pyroxenes in iron formation are medium- to very-coarse-grained, subhedral, variably poikiloblastic and exhibit replacement by amphiboles locally. Pyroxenes increase in both modal abundance and grain size as the contact with the Duluth Complex is approached (west-northwest to east-southeast across the Peter Mitchell Mine). Bonnichsen (1975), and Cliffs Natural Resources observations, show that ferrohypersthene crystals are disproportionately large compared to other mineral species when the mineral is found in abundance. Ferrohypersthene crystals, from 2-7 cm, are not uncommon in close proximity to the Duluth Complex and can be coarsely poikiloblastic containing quartz, magnetite, fayalite, hydroxylapatite, and amphiboles. Growth of these pyroxenes is not encumbered by previously existing or slower growing crystals.

Almandine garnet occurs locally in the Biwabik Iron Formation, largely restricted to the Lower Slaty and Lower Cherty members, as 2 mm to 2 cm, red-brown subhedral to euhedral crystals generally associated with amphiboles, biotite, and ferroan clinochlore. Andradite garnet is commonly found in the A and G submember, in similar habit to almandine. Most of this garnet is a constituent of the silicate-rich bands, but it is also locally found in late-stage calcite-quartz veins with diopside and ferrohornblende.

Layer silicates are subhedral and more common in the “slaty” layers imparting a schistosity. Oligoclase, andesine, rare carbonate group minerals, ilmenite, epidote, and hydroxylapatite are generally very fine-grained and comprise matrix constituents.

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Contact metamorphism has affected the Biwabik Iron Formation and Virginia Formation disproportionately; assemblages in the iron-formation are very reactive and sensitive to more subtle changes in P-T compared to the Virginia Formation. The pelitic Virginia Formation lacks diverse mineral assemblages and records few reactions because many of the minerals are stable over large ranges in temperature and $f_{H_2O}$. In contrast, the Biwabik Iron Formation preserves prograde metamorphic reactions several kilometers west and north of the contact with the Duluth Complex; whereas, visual contact effects within the Virginia Formation, including partial melting, are limited to within 200 meters from the Duluth Complex. A very visual and pronounced example of the contact effects of the Duluth Complex is observed in the A submember at the top of the Biwabik Iron Formation. The A submember was originally a thin, “dirty” limestone-dolomite layer that was drastically transformed mineralogically into an off-white and dark-speckled rock with an assemblage containing typical calc-silicate contact metamorphic minerals that include wollastonite, diopside, andradite, ferrohornblende, titanite, andesine, epidote, fluorapatite, and recrystallized calcite and dolomite.

Profound thermal effects of the Duluth Complex on adjacent metasediments are largely due to its high emplacement temperature. Chalokwu et al. (1993) estimated emplacement temperatures of the Partridge River intrusion of the Duluth Complex to be approximately 1,150°C. Klein (1973), and subsequent researchers, have noted that olivine-bearing assemblages in iron-formation have largely been described from contact metamorphic occurrences involving high temperature intrusions.

Taconite units of the Biwabik Iron Formation are characterized by regular interlayering of magnetite-rich and quartz-rich layers ranging from <1cm up to 12 cm thick, locally. Outcrops farthest from the Duluth Complex display prominent banding with sharp contacts between magnetite, quartz, and quartz-amphibole layers. Boudining of quartz-rich layers, re-healed structural discontinuities, and intraformational conglomerate clasts are observed locally within taconite submembers. The degree of metamorphism and deformation increases with proximity to the Complex. Outcrops nearest the Complex lack pronounced banding compared to exposures that are more distal in the aureole. Exposures in close proximity to the Complex exhibit larger grain size, increased reaction band thickness, and more diverse mineral assemblages that can include quartz, magnetite, ferrohypersthene, hedenbergite, ferroselite, ferrohornblende, ferroactinolite, cummingtonite, grunerite, oligoclase-andesine, ilmenite, titanite, and pyrrhotite. Magnetite grain size is essentially unaffected by increased metamorphic grade, but does exhibit coarsening locally near the contact with the Duluth Complex along with increased Ti content.

In the relative close proximity to the Duluth Complex, French (1968) delineated four zones of progressively metamorphosed iron-formation (Fig. 3-2) as follows.

1. Zone 1 = “Unaltered” taconite with quartz, magnetite, hematite, siderite, ankerite, talc, chamosite, greenalite, minnesotaite, and stilpnomelane. Contrary to French (1968) and McSwiggen and Morey (2008), Cliffs NR personnel believe that “unmetamorphosed iron-formation” in the Mesabi Iron Range does not exist. All rocks have been subjected to diagenetic effects as well as burial and/or regional metamorphism.

2. Zone 2 = Transitional taconite with the above minerals but with extensive replacement by quartz and ankerite. French (Fig. 23; 1968) portrays zone 2 as occurring 2.8-10.0 miles from the Duluth Complex but notes that the first widespread metamorphic affects to the iron-formation occur three miles from the Duluth Complex.

3. Zone 3 = Moderately metamorphosed taconite marked by the appearance of iron-rich amphibole (grunerite) at the expense of original iron carbonates (ankerite and siderite) and iron silicates (minnesotaite and stilpnomelane). Zone 3 is present 1.7-3.0 miles from the contact with the Duluth Complex and the maxium temperature was probably 300-400°C.
4. Zone 4 = Highly metamorphosed taconite (sillimanite grade) is well expressed by the appearance of iron pyroxenes and complete recrystallization of the taconite. The taconite consists of quartz, iron amphiboles (cummingtonite and blue-green hornblende), iron pyroxenes (hedenbergite, and ferrohypersthene), and magnetite, with variable amounts of fayalite, garnet, and calcite. Zone 4 occurs within 1.7 miles of the contact with a minimum temperature of formation around 600°C (as indicated by the presence of wollastonite in the A submember).

Morey et al. (1972) agreed with French (1968) but show the divisions between the four zones to be positioned much closer to the Duluth Complex (see Fig. 5-11). Griffin and Morey (1969) found that hedenbergite is the dominant pyroxene phase in the Zone 3 / Zone 4 transition. Frost et al. (2007) have since revised and expanded these zones/isograds to specifically include the formation of ferrohypersthene with crystalline graphite, hedenbergite, fayalite, and orthopyroxene. The reader is referred to this reference for details as well as an extensive list of possible metamorphic reactions in the Biwabik Iron Formation.

French (1968) found that metamorphism of the iron-formation was largely isochemical with a progressive loss of H2O and CO2 towards the Duluth Complex; with no change in the siderite and ankerite compositions towards the Complex. Possible reactions in Zone 4 (French, 1968) include:

1. hedenbergite formed by grunerite+calcite=hedenbergite+quartz+H2O+CO2;
2. hedenbergite formed by ankerite+quartz=hedenbergite+CO2;
3. ferrohypersthene formed by grunerite=ferrohypersthene+quartz+H2O;
4. fayalite formed by grunerite=fayalite+quartz+H2O; and
5. fayalite formed by magnetite+quartz=fayalite+O2.

Bonnichsen (1968) felt that the metamorphism at Dunka Pit was also isochemical. He suggested that all of the CO2 was driven from the iron-formation; whereas, a portion of the H2O remained behind, although a mechanism of this partial segregation of volatiles was not proposed. Bonnichsen (1968) indicated this water reacted with the various pyroxenes and fayalite to form hydrous minerals, mainly amphiboles, until the supply of H2O was exhausted. However, textural evidence indicating recrystallization of siderite, and some greenalite, directly to hedenbergite and fayalite suggests the overstepping of intermediate minnesotaite and grunerite producing reactions. This indicates a steep thermal gradient over a protracted time interval during emplacement of the Duluth Complex and the local occurrence of pigeonite indicates temperatures of at least 800°C (Vocke, 1981). A rapid rise in temperature during emplacement of the Duluth Complex and overstepping of lower temperature metamorphic reactions would result in a virtually complete devolatilization of the iron formation. Dehydration and decarbonation reactions during prograde metamorphism of iron formation are responsible for a 10-50% volume reduction of the original lithology, depending on the original bulk chemistry (Floran and Papike 1975; Caddey et al., 1991). Volume loss in the Biwabik Iron Formation due to metamorphic devolatilization has enhanced the thinning of this unit eastward across the Mesabi Iron Range.

Closer to the Duluth Complex, Bonnichsen (1968) found that the metamorphic grade of the Biwabik Iron Formation reached pyroxene hornfels facies in the Dunka Pit area. At this locale, the iron-formation is positioned ≤¼ mile from the Duluth Complex. It is mainly composed of recrystallized quartz, magnetite, and orthopyroxene – the orthopyroxene is mostly ferrohypersthene with inverted pigeonite (characterized by ferrohypersthene with hedenbergite lamellae). Also present are lesser and variable amounts of Ca pyroxene (hedenbergite, diopside), fayalite, cummingtonite, talc, and hornblende±actinolite (mostly formed during retrograde metamorphism). Bonnichsen (1968) describe poikilitic textured minerals (ferrohypersthene, fayalite, and cummingtonite) in the iron-formation enclosing quartz and magnetite.
Figure 3-2: Approximate boundaries of four zones of metamorphosed iron-formation after French (1968) and Morey et al. (1972).

Perry and Bonnichsen (1966) estimated the maximum temperature of metamorphism at Dunka Pit, as determined by $\text{O}^{18}/\text{O}^{16}$ ratios of quartz and magnetite, to be 700-750°C. This was confirmed by Hyslop et al. (2008) in their recent O and Fe isotope study of the Biwabik Iron Formation. They showed that isotopically determined temperatures decreased from about 700°C at the contact of the Duluth Complex, to 375°C at a distance of 2.6 km from the contact.

Pigeonite in iron-formation in contact with the Partridge River intrusion of the Duluth Complex suggests peak metamorphic temperatures in excess of 825°C, as determined by Chalokwu et al. (1993). At the Wyman Creek Cu-Ni deposit, Perry and Bonnichsen (1966) estimated a temperature range of 400-650°C for metamorphism of the iron-formation in drill hole #17700 (Fig. 3-2), in which the top of the iron-formation is located 525 feet below the Duluth Complex.

A more recent study by Muhich (1993) at Dunka Pit, found that where the Biwabik Iron Formation is in direct contact with the Duluth Complex (the intervening Virginia Formation is absent), metamorphism was not isochemical and that some metasomatic transfer of elements took place in a thin zone that spans the contact. This transfer is illustrated by significant gains in titanium in the iron-formation. Overall, within a 25 foot wide zone on one side of the contact, Muhich (1993) found that the iron-formation showed gains in TiO$_2$, V, Al$_2$O$_3$, CaO, Na$_2$O, K$_2$O, Ba, Rb, Sr, MgO, Cu, Ni, and H$_2$O; and a loss of SiO$_2$ and P$_2$O$_5$. On the other side of the contact, also in a 25 foot wide zone, the Duluth Complex showed gains in K$_2$O, Rb, S, Fe$_2$O$_3$, and H$_2$O; with a loss of TiO$_2$ and MnO. A temperature of metamorphism for the iron-formation, as determined from coexisting titanomagnetite/ilmenite pairs, was found to be in the range of 651-689°C.

Additional prograde metamorphic reactions that may have transpired in the Biwabik Iron Formation are listed in Table 3-3. Possible magnetite producing prograde reactions are given in Table 3-4.
Table 3-3: Prograde iron formation reactions that may have occurred in the Biwabik Iron Formation at the Peter Mitchell mine.

\[
\text{Fe}_3\text{Si}_2\text{O}_5(\text{OH})_4 + 4\text{SiO}_2 = 2\text{Fe}_3\text{Si}_6\text{O}_{10}(\text{OH})_2 + 2\text{H}_2\text{O}
\]

Greenalite  Quartz  Minnesotaite

\[
3\text{FeCO}_3 + 4\text{SiO}_2 + \text{H}_2\text{O} = \text{Fe}_7\text{Si}_4\text{O}_{10}(\text{OH})_2 + \text{CO}_2
\]

Siderite  Quartz  Minnesotaite

\[
7(\text{Fe,Mg})_7\text{Si}_4\text{O}_{10}(\text{OH})_2 = 3(\text{Fe,Mg})_7\text{Si}_8\text{O}_{22}(\text{OH}) + 4\text{SiO}_2 + 4\text{H}_2\text{O}
\]

Minnesotaite  Grunerite  Quartz

\[
\text{Fe}_3\text{Si}_2\text{O}_5(\text{OH})_4 + 3\text{CO}_2 + 3\text{FeCO}_3 + 2\text{SiO}_2 + 2\text{H}_2\text{O}
\]

Greenalite  Siderite  Quartz

\[
7\text{FeCO}_3 + 8\text{SiO}_2 + \text{H}_2\text{O} = \text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2 + 7\text{CO}_2
\]

Siderite  Quartz  Grunerite

\[
\text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH}) + 7\text{CaCO}_3 + 6\text{SiO}_2 = 7\text{CaFeSi}_2\text{O}_6 + \text{CO}_2
\]

Grunerite  Calcite  Quartz  Hedenbergite

\[
\text{CaFe(CO}_3)_2 + 2\text{SiO}_2 = \text{CaFeSi}_2\text{O}_6 + 2\text{CO}_2
\]

Ankerite  Quartz  Hedenbergite

\[
(\text{Fe,Mg})_2\text{SiO}_4 + \text{SiO}_2 = (\text{Fe,Mg})_2\text{SiO}_6
\]

Olivine  Quartz  Ferroselite

\[
(\text{Fe,Mg})_7\text{Si}_8\text{O}_{22}(\text{OH})_2 + \text{FeCO}_3 + (\text{Fe,Mg})_2\text{SiO}_6 + \text{CO}_2 + \text{H}_2\text{O}
\]

Grunerite  Siderite  Ferroselite

\[
2\text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2 = 7\text{Fe}_2\text{SiO}_4 + 9\text{SiO}_2 + 2\text{H}_2\text{O}
\]

Grunerite  Fayalite  Quartz

Table 3-4: Possible magnetite producing prograde iron formation reactions that may have occurred in the Biwabik Iron Formation at the Peter Mitchell mine.

\[
12\text{FeCO}_3 + 2\text{H}_2\text{O} = 4\text{Fe}_3\text{O}_4 + 11\text{CO}_2 + \text{CH}_4
\]

Siderite  Magnetite

\[
\text{FeCO}_3 + \text{Fe}_2\text{O}_3 = \text{Fe}_3\text{O}_4 + \text{CO}_2
\]

Siderite  Hematite  Magnetite

\[
\text{Fe}_3\text{Si}_2\text{O}_5(\text{OH})_4 + 3\text{Fe}_2\text{O}_3 = 3\text{Fe}_3\text{O}_4 + 2\text{SiO}_2 + 2\text{H}_2\text{O}
\]

Greenalite  Hematite  Magnetite  Quartz

\[
4\text{Fe}_3\text{Si}_2\text{O}_5(\text{OH})_4 + \text{CO}_2 = 4\text{Fe}_3\text{O}_4 + 8\text{SiO}_2 + 6\text{H}_2\text{O} + \text{CH}_4
\]

Greenalite  Magnetite  Quartz
With respect to magnetite, the ore mineral in taconite ores, contact metamorphism of the Biwabik Iron Formation by the Duluth Complex in the eastern Mesabi Range resulted in the following changes evident upon microscopic examination: 1) recrystallization of stable phases (quartz, and to a lesser extent magnetite), 2) reaction of preexisting minerals to form new minerals, and 3) formation of new textures. All of these factors affect the ore character at Northshore more profoundly than at any other Cliffs operation. In fact, contact metamorphism is the single-most influential factor affecting taconite and crude ore processing at the Northshore operation. Five basic magnetite textures/sizes have been identified in various submembers through reflected light microscopy:

1. Fine, subhedral grains: isolated or aggregated into bands (Figure 3-3).
2. Coarse, subhedral to euhedral, recrystallized grains: isolated or aggregated into bands.
3. Very fine, subhedral grains disseminated in grunerite (Figure 3-4).
4. Hiatal texture, or bimodal size distribution, of magnetite with varying degree and types of aggregation.
5. Fine (<5µ) silica/Fe silicate inclusions in cores of magnetite grains

These textures can observed in various submembers and ore types; however, numbers 2, 3, and 4 are most common in the taconite ores of the easternmost Peter Mitchell mine in proximity to the contact of the Duluth Complex. Numbers 1 and 2 produce ores that easily liberate magnetite from gangue minerals as shown in Figure 3-5. Number 3, however, results in ores that are problematic during concentration stages. During magnetic separation, the separators cannot differentiate between liberated magnetite and iron silicates that contain heavily disseminated magnetite, thus introducing additional gangue material into the plant.

Figure 3-3: Reflected light photomicrograph showing heavily aggregated fine-grained magnetite with interstitial quartz and iron silicates in the J submember. Scale located in lower right of photograph.
Figure 3-4: Transmitted light photomicrograph of a twinned grunerite crystal heavily laden with magnetite inclusions. The hiatal texture, or distinct disparity in magnetite grain size is apparent. Scale at lower right of photograph.

Figure 3-5: Scanning electron microscope photograph of concentrate produced from coarser grained, easily liberated magnetite ores produced from the K Submember from the eastern Peter Mitchell mine. Scale located in the bottom center for reference.
REFERENCES

**STOP DESCRIPTIONS**

**Figure 3-3:** Location of four field trip stops in the eastern Mesabi Iron Range of northeastern Minnesota. Dark black lines outline the margins of the Biwabik Iron Formation.

Depart Giants Ridge Resort and return south to Minnesota 135. Proceed east about 2 miles, where Minnesota 135 heads north (left turn). Go about 11 miles to the north to the “Four Corners” gas station/intersection and turn right (east) on highway 21 and head towards Babbitt. On the west side of Babbitt continue straight on highway 70 (highway 135 heads north at this point) and skirt Babbitt which is located immediately south of the road. Continue on this road about 6.3 miles to the entrance to the Peter Mitchell Mine. All of the stops in the first half of the day are at the Peter Mitchell Mine.

**Historical Overview:** The Peter Mitchell mine is located approximately three miles south of Babbitt, MN, just south of the Laurentian Divide. This taconite mine was initially developed by Reserve Mining Company in 1955 with a processing plant located on Lake Superior at Silver Bay, MN. Large-scale mining operations eventually resulted in a practically continuous pit that spanned some eight miles along the trend of the Mesabi Iron Range. Due to a variety of reasons, Reserve Mining filed for bankruptcy and closed the operation in 1986. Cyprus Northshore Mining acquired the property in 1989. In the fall of 1994, Cyprus Northshore Mining was sold to Cleveland Cliffs (now Cliffs NR). About 5.3 million tons of iron pellets are produced annually.
STOP 3-1: Submembers F through L – Amphibole grade metamorphism
Peter Mitchell Mine, Blocks 18 and 19, T. 60 N., R. 13 W., sections 24 and 25
Babbitt quadrangle; UTM 579072E, 5278720N (NAD-83)

Description: Taconite at this stop in the West Pit is representative of lower portions of the “high grade ores” that include the K submember as well as upper parts of the “footwall ore” that include the L submember. Ore microscopy of samples from the L submember at this stop indicate abundant subhedral magnetite grains (5-15 microns) mainly confined to well-defined bands parallel to bedding. Further contributing to the high-grade nature of this submember are coarse assemblages (granules and pebbles) of similar subhedral magnetite grains disseminated within the cherty beds of the rock. X-ray analysis of a sample from this location indicates gangue mineralogy of quartz, cummingtonite, and grunerite.

Magnetite grains in the overlying K submember typically occur as granules and aggregates of euhedral grains ranging up to 200 microns in diameter. The aggregates are randomly distributed within the matrix; however, diffuse bands of magnetite are ubiquitous. X-ray diffraction analyses of these samples indicate a gangue mineral suite of quartz, cummingtonite, and grunerite that is consistent with the suite identified for submember L.

The magnetite textures in both submembers observed at this location can differ greatly from textures to the east where coarser assemblages are commonly observed closer to the Duluth Complex. These changes in texture can affect magnetite grade and the liberation/grindability performance of individual ores.

STOP 3-2: Submembers L through O – Mixed Amphibole and Pyroxene grade metamorphism
Peter Mitchell Mine, Blocks 1 and 2, T. 60 N., R. 13 W., sec. 17
Babbitt quadrangle; UTM 585145E, 5282509N (NAD-83)

Description: The L, M, N, and O submembers constitute “footwall ore“ at the mine and in this area (East Pit East), the ore has been subjected to upper amphibolite to pyroxene hornfels grade metamorphic conditions due to the contact influence of the Duluth Complex. Coarse grained iron pyroxenes and amphiboles are prevalent along with recrystallized magnetite that is coarser grained compared to occurrences in the Main and West pits. Quartz is also significantly recrystallized. Large porphyroblasts of hedenbergite, ferro-hornblende, ferro-actinolite, and almandine garnet are relatively common. Other gangue minerals in this area include fayalite, cordierite, sekaninaite (rare), anorthite, epidote, and apatite group minerals.

STOP 3-3: Submembers J through O – Mixed Amphibole and Pyroxene grade metamorphism
Peter Mitchell Mine, Block 4E, T. 60 N., R. 13 W., sections 9 and 16
Babbitt quadrangle; UTM 584088E, 5280975N (NAD-83)

Description: This stop was chosen to show the highly metamorphosed nature of the iron formation in close proximity to the Duluth Complex. The iron formation in this area of the pit contains abundant coarse grained iron pyroxenes, iron amphiboles, fine grained fayalite, garnet group minerals, and coarse grained granular magnetite. The most significant change observed in the J through M submembers, other than the increase in grain size, is the overall decrease in thickness of each unit. This change in thickness may be explained, in part, by a decrease in the average thickness seen in the chert bands separating the magnetite bands and increased metamorphic grade. This gives each submember an overall condensed appearance as the magnetite bands become more closely spaced.
STOP 3-4:  Keweenawan Sill (in the Virginia Formation) and A and B submembers of the Upper Slaty member  
Peter Mitchell Mine, Block 11, T.60N., R.12W, Section 19  
Babbitt Quadrangle; UTM 581691E, 5278881N (NAD-83)

Description:  At the very top of the Biwabik Iron Formation is a 2- to 6-foot-thick chert and marble unit (A submember) that corresponds to the carbonate horizon that is present in only the eastern and central portions of the Mesabi Iron Range.  This unit is locally absent in some areas (non-depositional unconformity) and extremely thick in other areas.  The B submember is characterized by alternating chert and diopside bands up to one foot thick; marble layers are locally present.  In some areas, pink granophyric veins locally cut the B submember.  These veins exhibit pinch-and-swell relationships in that the veins thicken within the diopside bands and pinch in the chert bands.

The mineralogy of the marble beds represents an assemblage of calcite-ankerite-wollastonite-quartz, while the B submember consists of a diopside-ankerite-wollastonite-magnetite mineral assemblage.

At the very base of the overlying Virginia Formation is a 2- to 100-foot-thick sill, informally called the VirgSill, that consists of a fine-grained, granoblastic rock with varying amounts of plagioclase, clinopyroxene, orthopyroxene, hornblende, olivine, and biotite.  The informal term of "Cr-bearing sill" was first used by Hauck et al. (1997) to highlight the relatively high chromium contents (600 to 1,200 parts per million) that are characteristic of this sill.  This sill exhibits two varieties:  1) a fine-grained, massive, gray-colored unit (this exposure) that is extremely difficult to distinguish from the hornfelsed Virginia Formation in drill core, and 2) a medium- to coarse-grained unit that is olivine- and/or hornblende-rich and is easily recognized.  A Keweenawan age is inferred for the VirgSill.

Leave the Peter Mitchell Mine and drive back to Babbitt and then back to the “Four Corners” intersection on highway 21.  Turn right on highway 135 at this intersection and proceed north to Tower.  Turn right on 169 and head towards Soudan.  Follow the state park signs to the Soudan Mine State Park.

END OF TRIP ON THE EASTERN MESABI IRON RANGE