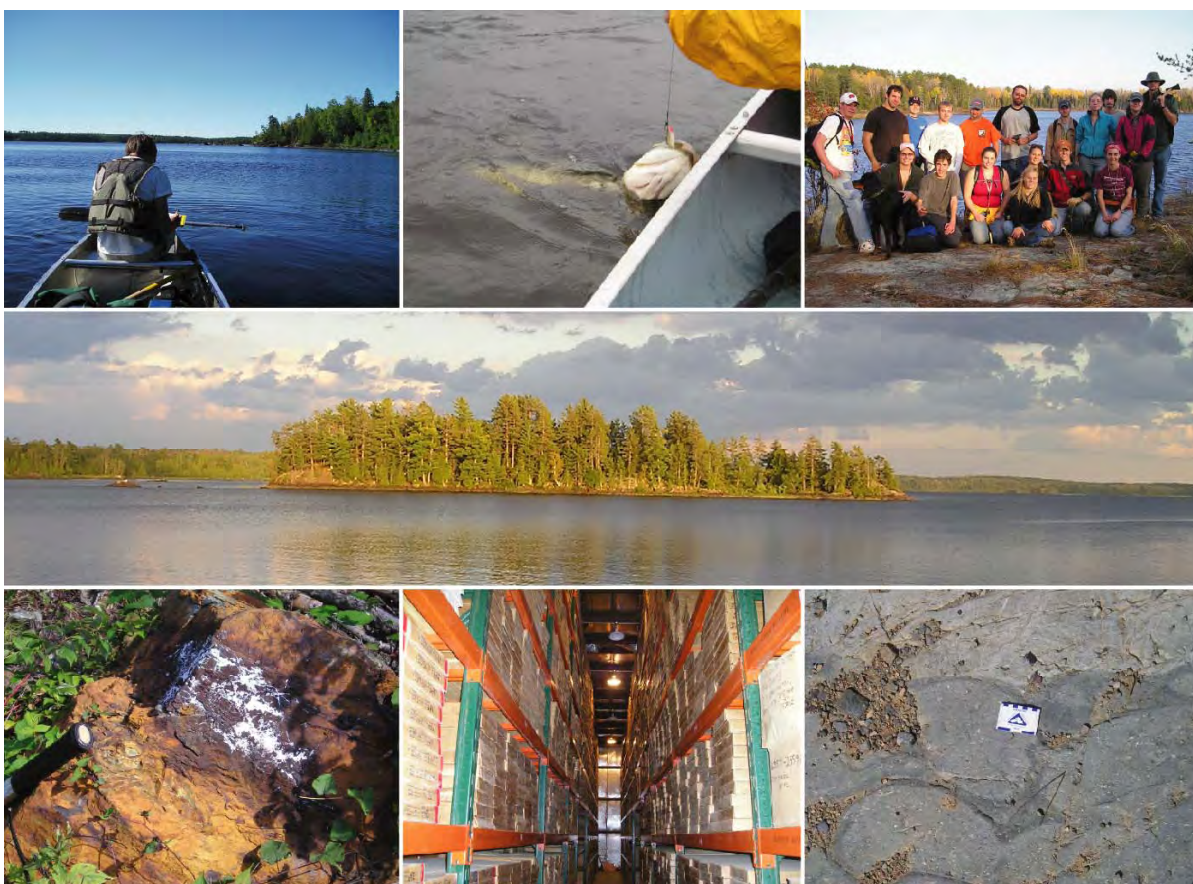


55TH ANNUAL MEETING



INSTITUTE ON LAKE SUPERIOR GEOLOGY
ELY, MINNESOTA, MAY 5 – 12, 2009



PROCEEDINGS VOLUME 55
PART 2 – FIELD TRIP GUIDEBOOK



INSTITUTE ON LAKE SUPERIOR GEOLOGY

**55TH ANNUAL MEETING
MAY 5-10, 2009
ELY, MINNESOTA**

**HOSTED BY:
Precambrian Research Center, UMD**

**JAMES D. MILLER, GEORGE J. HUDAK AND DEAN M. PETERSON
Co-Chairs**

**Proceedings Volume 55
Part 2 – FieldTrip Guidebook**

EDITED BY DEAN M. PETERSON

DULUTH METALS LIMITED AND THE PRECAMBRIAN RESEARCH CENTER

Cover Photo: Photographs taken in recent years during geological mapping, ore deposit research, fishing for dinner, and educational activities for undergraduate geology students in northeastern Minnesota.
(photographs by Dean Peterson)

55TH INSTITUTE ON LAKE SUPERIOR GEOLOGY

PROCEEDINGS VOLUME 55 CONSISTS OF:

PART 1: PROGRAM AND ABSTRACTS

PART 2: FIELD TRIP GUIDEBOOK

TRIP 1: CU-NI DEPOSITS OF THE DULUTH COMPLEX

TRIP 2: GLACIAL GEOLOGY OF THE VERMILION MORaine

TRIP 3: SOUDAN IRON MINE AND PHYSICS LAB TOUR

TRIP 4: PIONEER MINE CANOE EXCURSION

TRIP 5: GEOLOGY & METAMORPHISM OF THE EASTERN MESABI RANGE

TRIP 6: GEOLOGY OF THE LAKE ONE TROCTOLITE BY CANOE

TRIP 7: ARCHITECTURE OF AN ARCHEAN GREENSTONE BELT

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Peter Hollings
Department of Geology
Lakehead University
Thunder Bay, ON
P7B 5E1
CANADA
peter.hollings@lakeheadu.ca

ILSG website: <http://www.lakesuperiorgeology.org>

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The editor (Dean M. Peterson) wishes to thank the field trip guidebook authors for their contributions to the 55th Annual ILSG conference Field Trip Guidebook tome. This annual meeting is especially built around excellent field trips for ILSG participants that mineral industry companies and local geologists in the Lake Superior region provide to the Institute. I believe that this field guide continues that tradition, and will be useful for professional geologists and students of geology for many decades to come.

The editor also wishes to tell the authors of the guidebook that some of the text and figures have been edited for clarity (which I guess is the role of a compiler and editor), and I hope that such editing better conveys the message that the written descriptions and especially the rocks in the Lake Superior District are trying to tell us.

The institute wishes to thank Duluth Metals for their \$2,000 contribution to the 55th ILSG Field Trip Guidebook. These monies have been used to pay for the numerous color figures and thus lower the cost to participants of the printed version.

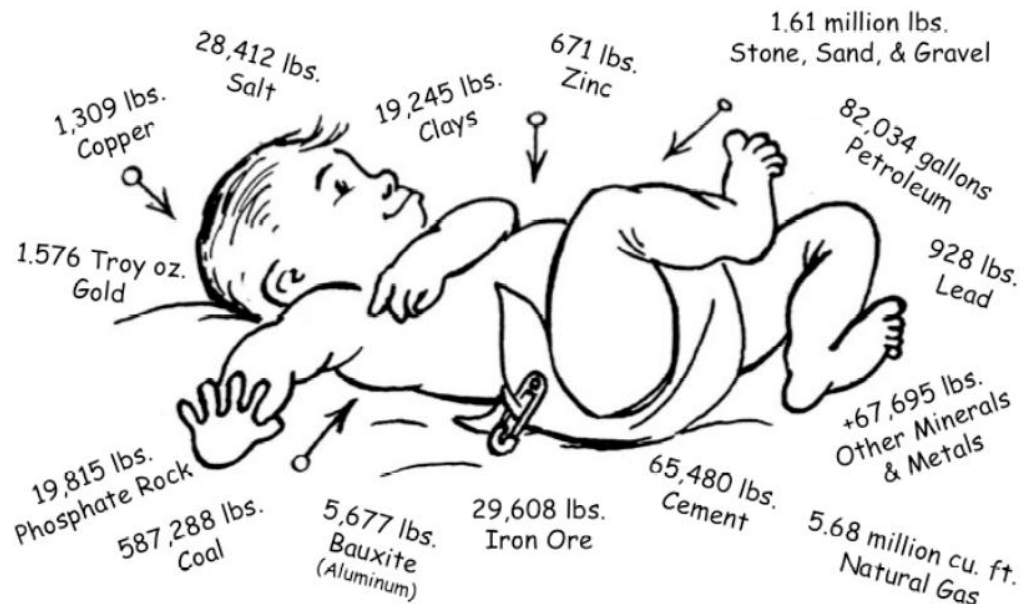


55th Annual Institute on Lake Superior Geology

Field Trip 1

CU-NI-PGE DEPOSITS OF THE DULUTH COMPLEX GEOLOGY AND DEVELOPMENT

Every American Born Will Need . . .



3.6 million pounds of minerals, metals, and fuels in their lifetime

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46,279 Pounds of Minerals for Every American Last Year

Rich Patelke (PolyMet Mining)

Dean Peterson (Duluth Metals Ltd. & PRC)

Mark Severson (Natural Resources Research Institute)

Tim Jefferson (Teck American)

Ernie Lehmann (Franconia Minerals)

COPPER-NICKEL-PGE PROJECTS

GEOLOGY PROGRESS AND DEVELOPMENT

INSTITUTE ON LAE SUPERIOR GEOLOGY, ELY MINNESOTA, MAY 2009

Field Trip Coordinator:

Dean Peterson

Field Guide Compiled By:

Richard Patelke

Written Contributions By:

Richard Patelke-PolyMet

Steve Geerts-PolyMet

Mark Severson-Natural Resources Research Institute

Tim Jefferson-Teck American

Dean Peterson-Duluth Metals

Richard Routledge-Scott Wilson RPA for Franconia

Presenters of Introductory Talks:

Kevin Pylka-PolyMet

Dean Peterson-Duluth Metals

William Brice-Franconia

Paul MacRobbie-Teck American

Mark Severson-Natural Resources Research Institute

Richard Patelke-PolyMet

Field Trip Leaders:

Richard Patelke PolyMet

Mark Severson-Natural Resources Research Institute

Tim Jefferson-Teck American

Ernie Lehman-Franconia

Stuart Behling-Franconia

Dean Peterson-Duluth Metals

PART 1: INTRODUCTION, DEPOSITS, AND REGIONAL GEOLOGY OF THE FIELD TRIP AREA

By: Richard Patelke, Mark Severson, Tim Jefferson, and Dean Peterson

PURPOSE OF TRIP

Over time there have been many trips to drill sites, core sheds and outcrops of the mineralized parts of the Duluth Complex. As the current projects move toward development it becomes appropriate to visit the sites, assess the development potential, and see how that potential has changed over time. We will visit core displays for four of these projects, PolyMet's NorthMet project, Teck American's Mesaba deposit, Franconia's Birch Lake deposit, and Duluth Metals Nokomis deposit. PolyMet is in the permitting process with state and federal agencies; Franconia and Duluth Metals have commissioned scoping studies on their deposits and are on the cusp of proceeding to development. Teck does their assessment work internally and is taking a different and less public route through economic review and development. These write-ups are not core specific and are intended to give a sense of the general geology of these projects.

Besides the four companies whose projects we will visit, Encampment Resources, Cardero Resources, Prime Meridian Resources, and Kennecott have been active in the area. Technical reports from most of these companies are also available on "SEDAR" at <http://www.sedar.com>. These reports will give good background on the reserve and resource calculations, as well as development planning. Throughout these descriptions, the term "PGE" means platinum group elements (mostly platinum and palladium) and gold.

Since these deposits were first known in the 1950's and 1960's, market and technological changes have made older assessments of the projects obsolete. The big market change has been the rise of PGE as important products, providing about a fourth of the revenue for these projects. Technological change has included: the ability to routinely and inexpensively analyze for PGE; improvements in flotation processes that allow the capture of almost all sulfide (minimizing sulfur in tails as well as improving recoveries), allow for the production of saleable split (i.e., separate copper and nickel) concentrates; and the refinement of hydrometallurgical processes that are able to cleanly recover not just copper and nickel, but PGE, gold, cobalt, and silver. Better flotation and the polymetallic nature of these deposits have pushed the ore vs. waste cut-off much lower than in historic estimates.

The change in environmental aspects of these projects due to the recent market and technological changes cannot be overstated. Much of the research on these issues over the years has assumed metal and sulfur contents in waste rock and tailings far above expected ore versus waste cut-off grades for these deposits today, when hydrometallurgical processes are considered.

EXPLORATION AND DEVELOPMENT BACKGROUND

Large resources of low-grade copper-nickel sulfide ore that locally contain PGE concentrations are well documented by drilling in the basal zones of the Partridge River and South Kawishiwi intrusions. At least eleven occurrences of significant mineralization have been delineated in the basal 300 to 1000 feet of both intrusions. Of these eleven occurrences, three projects are currently undergoing deposit definition drilling, including the Mesaba (Teck American), Birch Lake (Franconia Minerals), and Nokomis (Duluth Metals Ltd.) deposits. A fourth project, the NorthMet deposit (PolyMet Mining) is currently undergoing environmental review and mine permitting. Overall, the copper-nickel mineralization consists predominantly of disseminated sulfides that collectively constitute over 4.4 billion tons of material

averaging 0.66% Cu and 0.20% Ni at a 0.5% Cu cut-off, according to an earlier study by Listerud and Meineke (1977).

Serious exploration for Cu-Ni deposits at the base of the Duluth Complex began in 1948, about 8 miles to the southeast of Ely, MN, when strongly mineralized rocks were uncovered in an excavation used to source road material for Spruce Road. Local prospector Fred S. Childers of Ely noted copper stains in the material and he, along with Roger V. Whiteside of Duluth, began searching along the basal contact in the vicinity of the Kawishiwi River. In 1951, they diamond drilled a 188 foot deep hole and intersected mineralized gabbro that averaged 0.36% Cu and 0.13% Ni. In 1952, both Bear Creek Mining Company (BMC) and the International Nickel Company (INCO) began intensive exploration efforts along a 38 mile-long zone that coincided with the basal contact. INCO eventually picked up the Childers-Whiteside properties (Spruce Road and Maturi deposits); whereas, BMC concentrated most of their effort near the town of Babbitt which resulted in the discoveries of the Babbitt (formerly called Minnamax and now known as Mesaba) and Serpentine deposits. By 1960, these exploration efforts indicated that very large tonnages of disseminated Cu-Ni mineralization were present; however, the low-grade nature of the deposits and the unavailability of state-owned mineral lands at the time led to suspension of activities.

In 1966, state mineral leases were offered by the Minnesota Department of Natural Resources (DNR) and were awarded to successful bidders, resulting in renewed exploration activity (including the return of BMC and INCO). Since 1966, over 20 companies have been actively involved in exploration for Cu-Ni and Fe-Ti-V deposits along the basal contact of the Complex. Over 2,000 holes, totaling over 2 million feet of core, have been drilled. Exploration efforts during this period also defined several more deposits including: Dunka Road (now NorthMet) and Wyman Creek (United States Steel Corp.), Birch Lake (Duval Corporation and Newmont Mining), South Filson Creek (Hanna Mining), Dunka Pit (Erie Mining, BMC, and Exxon), and Wetlegs (BMC and Exxon). AMAX Exploration Inc. leased the Babbitt deposit from BMC and renamed it the Minnamax deposit in 1973. During mid to late 1970s, the Spruce Road and Minnamax deposits came closest to development. Mining plans were submitted, test shafts were sunk (one each at the Maturi and Minnamax/Mesaba deposits), surface bulk samples were collected from three sites, and various land-use and water-use permits were requested from State and Federal agencies. In 1974, the Minnesota Environmental Quality Board required that a regional Environmental Impact Statement (EIS) be conducted prior to acceptance of any site-specific EIS mining-related proposals. The DNR discontinued lease sales of State lands (1974-1982) until completion of the regional EIS. However, by the time the regional EIS was submitted in 1979, development of the Cu-Ni deposits was put on hold by the most of the mining companies involved due to weakened copper and nickel markets and the inability to make marketable (i.e., "smeltable") separate copper and nickel concentrates. Amax abandoned their plans to develop an underground high grade ore zone within the Minnamax/Mesaba deposit (known as the Local Boy ore body) in late 1982.

Then starts the "PGE" era. During the early period of drilling (prior to 1980), all of the exploration companies recognized that the Cu-Ni deposits had some potential for hosting PGEs. Based on very limited sampling, the companies assumed that the typical Cu-Ni ore contained no more than a few hundred parts per billion (ppb) combined platinum and palladium. In 1985, the DNR and Minerals Resource Research Center (MRRC of the U of M) conducted a geochemical evaluation of portions of a Duval drill hole (DU-15), from the Birch Lake area, and found significant values of up to 9 parts per million (ppm) combined Pt and Pd (Sabelin and Iwasaki, 1985, 1986). This was at a time when demand for these elements was increasing due to their use in automotive catalysts. A short time later, Morton and Hauck (1987) compiled all of the known PGE data for the Complex and reported the presence of anomalous PGE values, often associated with high Cu values, at several other Cu-Ni deposits. These discoveries sparked renewed interest in the Cu-Ni deposits as potential polymetallic deposits (Miller et al., 2002; and references therein). E.K. Lehman and Associates of Minnesota obtained mineral leases from the state of Minnesota and began drilling wedges off the discovery hole (DU-15W) in the Birch

Lake area. These Lehmann leases were later incorporated into Franconia Minerals holdings. Additional drill holes were sampled and analyzed for PGEs by several other companies throughout the Duluth Complex, and as a result, significant PGEs were found at many deposits. The occurrences of PGE mineralization for each deposit will be more thoroughly discussed later in this guidebook.

Enter the “Hydromet” era. Early development of the deposits was hampered both by state leasing issues, complex metallurgy that resulted in an inability at the time to make marketable separate Cu and Ni concentrates, and by general environmental concerns regarding sulfide mining and conventional pyrometallurgical processes. In the mid to late 1990s, the potential of developing the Cu-Ni deposits using hydrometallurgical techniques once again sparked renewed activity in the Duluth Complex. PolyMet plans to use the PlatSol technique, developed and patented by SGS Lakefield on NorthMet ores, to recover Cu, Ni, Co, and PGE at the NorthMet deposit (Dunka Road). Teck American is conducting tests on Mesaba ore to utilize its patented Cominco Engineering Services Laboratory (CESL) process to recover metals. Both Duluth Metals and Franconia have PlatSol licenses. The PlatSol and CESL processes are of similar concept, both utilizing an autoclave (pressure oxidation) process wherein sulfides are converted to sulfates and metals put into, and then recovered from, solution. Thus the sulfur air emissions of conventional smelting are eliminated and an inert and potentially marketable by-product of gypsum (calcium sulfate) is produced. Other residues from the processes are easily isolated for landfill disposal or other containment.

REGIONAL GEOLOGIC SETTING, DULUTH COMPLEX

The Duluth Complex and associated intrusions of Keweenawan age (~1.1 billion years) in northeastern Minnesota constitute one of the largest mafic intrusive complexes in the world, second only to the Bushveld Complex of South Africa (Miller et al., 2002). These rocks cover a 2,200 square mile (5,700 square km) arcuate area associated with the two strongest gravity anomalies (+50 and +70 milligals) in North America, that imply intrusive roots more than 8 miles (13 km) deep (Allen and others, 1997). The comagmatic flood basalts and intrusive rocks underlying much of northeastern Minnesota were emplaced during the development of the Mesoproterozoic Midcontinent rift, which can be traced geophysically from exposures in the Lake Superior region along a 1250 mile (2,000 km) long, segmented, arcuate path to Kansas and Lower Michigan. The Duluth Complex is defined as the more or less continuous mass of mafic to felsic plutonic rocks that extends for >170 miles (275 km) in an arcuate fashion from Duluth nearly to Grand Portage (Fig. 1-1). It is bounded by a footwall of Paleoproterozoic sedimentary rocks and Archean granite-greenstone terranes (Peterson and Severson, 2002), and a hanging wall largely of comagmatic, rift related flood basalts and hypabyssal intrusions of the Beaver Bay Complex (Fig. 1-1). In genetic terms, the Duluth Complex is composed of multiple discrete intrusions of mafic to felsic tholeiitic magmas that were episodically emplaced into the base of a comagmatic volcanic edifice between 1108 and 1098 Ma.

The geology of the Duluth Complex and adjacent areas has recently been described in two major publications by the Minnesota Geological Survey (MGS). These include a 1:200,000 scale regional bedrock geological map of northeastern Minnesota (Miller et al., 2001), and a comprehensive written description of the geology depicted on this map (Miller et al., 2002), commonly referred to as the “bible” by geologists working on Duluth Complex geology. Readers’ interested in more detailed descriptions of the geologic setting of the Duluth Complex should begin their quest for knowledge by downloading these publications from the MGS website ([ftp://mgssun6.mnngs.umn.edu/pub2/](http://mgssun6.mnngs.umn.edu/pub2/)).

Within the nearly continuous mass of intrusive igneous rock forming the Duluth Complex, four general rock series are distinguished on the basis of age, dominant lithology, internal structure, and structural position within the complex.

Felsic series—Massive granophyric granite and smaller amounts of intermediate rock that occur as a semicontinuous mass of intrusions strung along the eastern and central roof zone of the complex, emplaced during an early stage magmatism (~1108 Ma).

Early gabbro series—Layered sequences of dominantly gabbroic cumulates that occur along the northeastern contact of the Duluth Complex, emplaced during early stage magmatism (~1108 Ma).

Anorthositic series—A structurally complex suite of foliated, but rarely layered, plagioclase-rich gabbroic cumulates emplaced throughout the complex during main stage magmatism (~1099 Ma).

Layered series—A suite of stratiform troctolitic intrusions that comprises at least 11 variably differentiated mafic layered intrusions that occur mostly along the base of the Duluth Complex. These intrusions were emplaced shortly after the Anorthositic series (~1099 Ma).

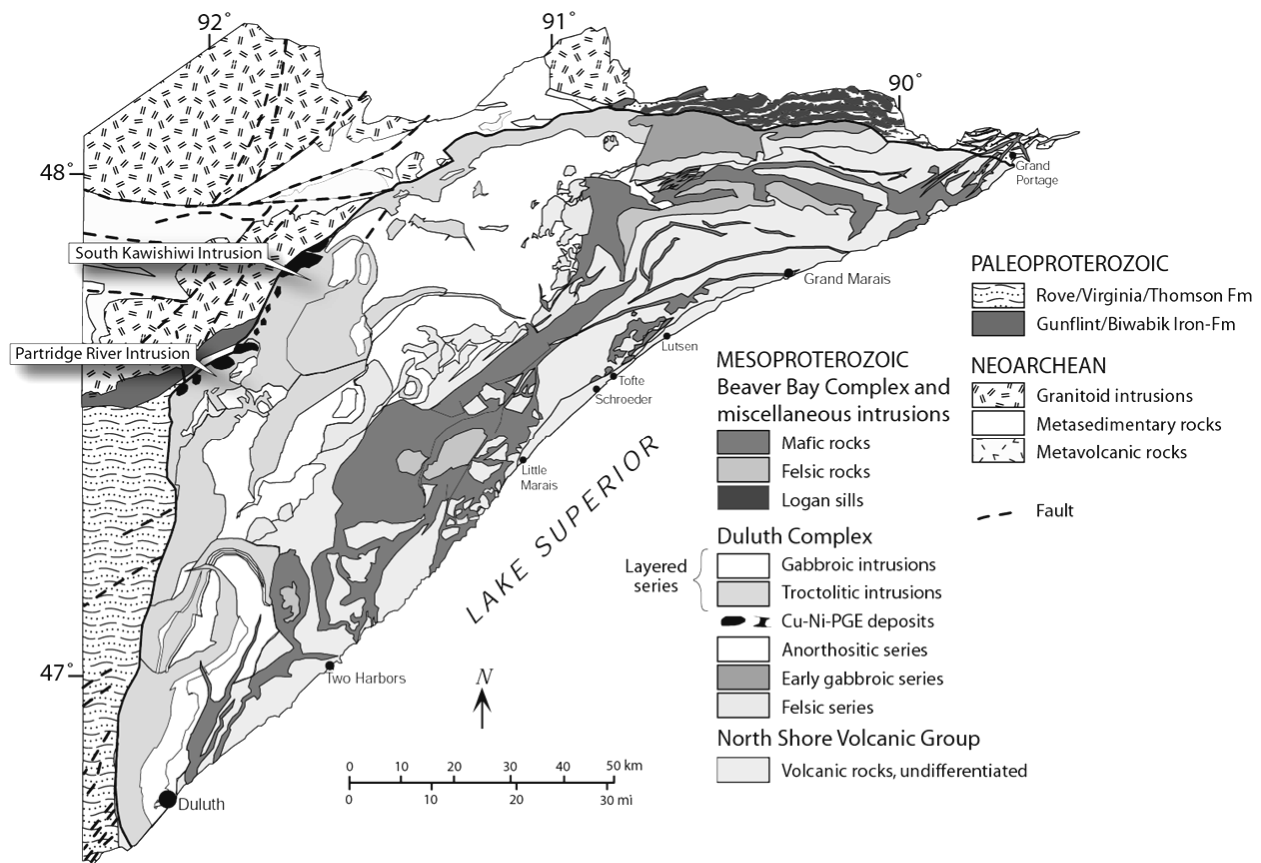


Figure 1-1. Generalized geologic map of northeastern Minnesota. (modified from Miller et al., 2002).

LOCAL GEOLOGIC SETTING-PARTRIDGE RIVER, SOUTH KAWISHIWI, AND BATHTUB INTRUSIONS

The four deposits under review for this trip are located in three of the oldest intrusions in the Complex. NorthMet and parts of the Mesaba deposit in the Partridge River intrusion, Parts of Mesaba in the newly defined Bathtub intrusion, and Birch Lake and Nokomis in the South Kawishiwi intrusion (Fig. 1-2).

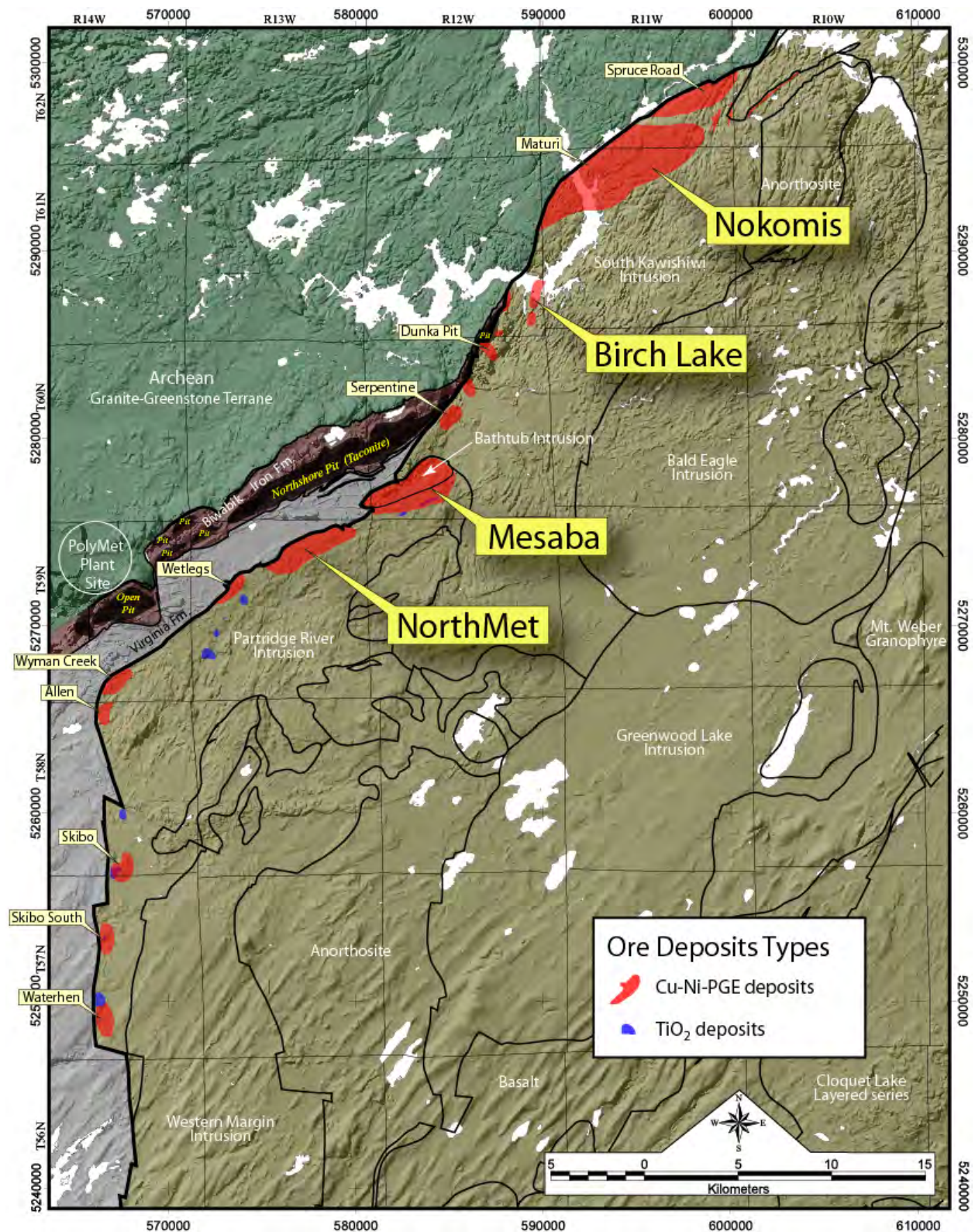


Figure 1-2. Location of Cu-Ni±PGE sulfide deposits, Fe-Ti±V oxide deposits (Oxide-bearing Ultramafic Intrusion - OUI), and other exploration areas along the western edge/base of the Duluth Complex. Note that the NorthMet deposit was referred to as the Dunka Road deposit and the Mesaba deposit was referred to as the Babbitt deposit; the most recent names for these two deposits are used in this guidebook.

Partridge River intrusion

The Partridge River intrusion (PRI) consists mainly of troctolitic cumulates, dips gently to the southeast, and is exposed in an arc-shaped area that extends from the Water Hen deposit, on the southwest, to the southern edge of the Mesaba/Babbitt deposit, on the northeast (Fig. 1-3). Footwall rocks include the Paleoproterozoic Virginia Formation and locally the Biwabik Iron Formation. The basal 3000 ft. (900 meters) are known in great detail from studies of abundant drill core (Severson and Hauck, 1990; Severson, 1988) and are subdivided into seven or more units that can be traced over a strike-length of 15 miles (24 kilometers).

The units of the Partridge River intrusion (PRI) are recently described in Miller and Severson (2002) and are depicted in Figure 1-3. At the base of the PRI is Unit I which consists of a suite of heterogeneous-textured troctolitic rocks that contain the vast majority of disseminated sulfide-mineralized zones. The top of Unit I is characterized by a fairly persistent ultramafic horizon, which in actuality is at the base of Unit II. Within Unit I are several laterally-discontinuous ultramafic horizons and abundant footwall sedimentary inclusions of the Virginia Formation. Noritic rocks are common at the basal contact and adjacent to the inclusions. Unit II consists of more homogenous-textured troctolitic rocks with minor sulfide-bearing zones. However, at the Wetlegs deposit, both Units I and II contain abundant laterally-discontinuous ultramafic horizons, interbedded with troctolitic rocks that are collectively referred to as the Wetlegs Layered Interval (Fig. 1-3).

Unit III is a major marker bed throughout much of the PRI (Wetlegs to Mesaba deposits - Fig. 1-3) in that it is characterized by a poikilitic leucotroctolite with olivine oikocrysts that are randomly dispersed throughout the rock giving it a mottled appearance. This mottled-appearance, and the relatively fine-grained nature of Unit III, give it a distinct appearance in drill core and it is easily identified. Unit III pinches out to the west of the Wetlegs deposit and is present on only the southern fringe of the Mesaba deposit. The rapid pinch-out of Unit III to the north within the Mesaba deposit appears to be related to emplacement of a distinctly different sub-intrusion herein referred to as the Bathtub intrusion (see discussion below).

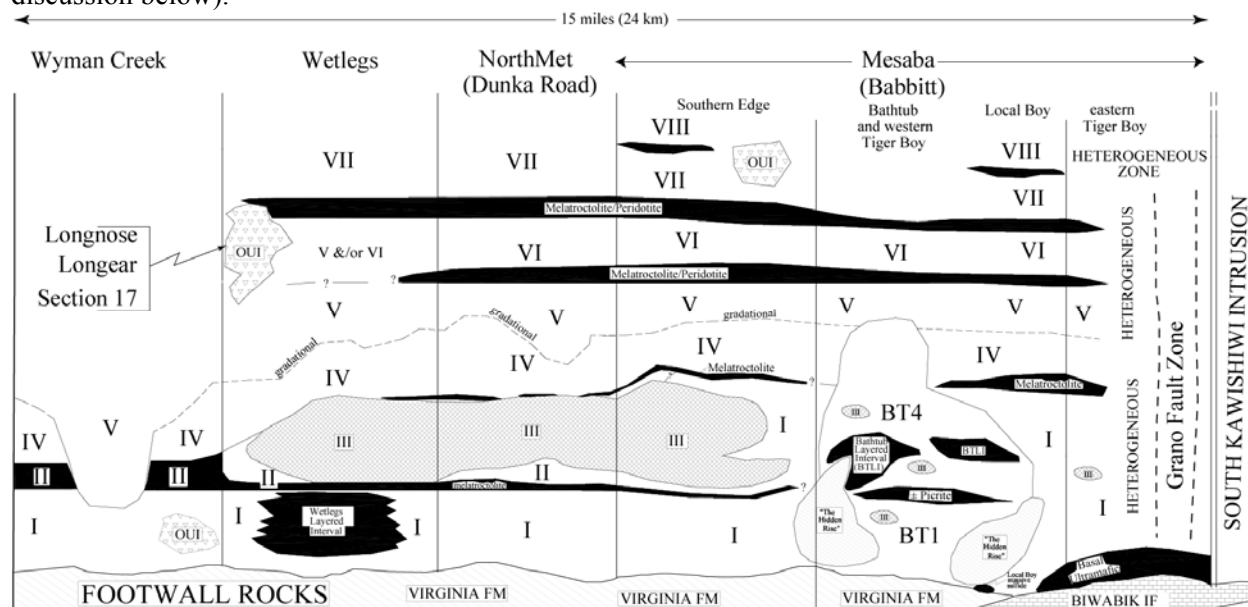


Figure 1-3. Generalized stratigraphy of the basal zone of the Partridge River intrusion (modified from Severson, 1994). Roman numerals (I through VIII) denote igneous units in the Partridge River intrusion; BT1 and BT4 denote igneous units in the Bathtub intrusion; and OUI denotes Oxide-bearing Ultramafic Intrusions.

Overlying Unit III in the PRI are units IV through VIII. Unit IV varies from a troctolite to augite troctolite, often contains an ultramafic base, and commonly grades upward into Unit V which is coarser-grained and varies from a troctolite to troctolitic anorthosite. Units VI and VII, and additional units above VII, are generally homogenous-textured troctolitic to anorthositic troctolitic rocks; each with a persistent ultramafic base that record magma injection events.

Bathtub intrusion

The Bathtub intrusion (BTI) is wholly contained in the central portion of the Mesaba (Babbitt) deposit. It has recently been singled out as a separate intrusion to explain the abrupt change from typical Partridge River intrusion stratigraphy in the southern part of the deposit to a completely different stratigraphy, to the north, in the remainder of the deposit. There are three structural features that are pertinent to understanding the intrusive history of the BTI that include (Fig. 1-4): 1) an east-west trending paired syncline and anticline in the footwall rocks referred to as the Bathtub Syncline and Local Boy Anticline; 2) a zone that is closely associated with the Local Boy Anticline, referred to as “The Hidden Rise,” that separates the PRI and BTI; and 3) a north-trending zone fault zone, referred to as the Grano Fault, that has been postulated to have been the feeder zone for the BTI and footwall-injected massive sulfides of the Local Boy ore zone.

The “Hidden Rise” is a loosely-defined zone wherein scattered hornfels inclusions, and associated noritic rocks, are fairly common. When viewed collectively, the inclusions in “The Hidden Rise” define an east-west trending “ridge” that is roughly positioned at the contact between the PRI and BTI. Thus, “The Hidden Rise” is used to both define this hornfels-bearing “ridge” and to artistically, and conveniently, divide the BTI from the PRI. The morphology of this feature suggests that it may have originally served as the floor and/or north edge of an earlier intruded PRI and later served as a wall along the south edge of the BTI as it was emplaced. The BTI has been subdivided into two main units, BT1 and BT4, each of which contain several internal subunits (Fig. 1-4). In the vicinity of the Bathtub Syncline, ultramafic layers and modally-bedded rocks are extremely common within the BT4 Unit and have been collectively referred to as the Bathtub Layered Interval (BTLI).

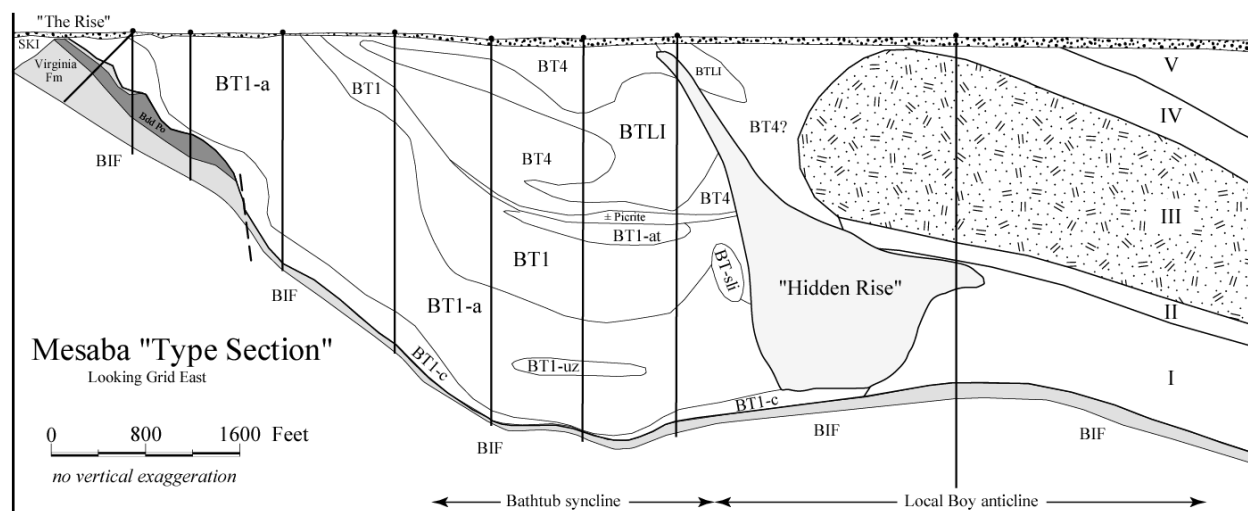


Figure 1-4. Schematic “type-section” cross-section, looking east, through the Mesaba deposit that crudely displays the spatial distribution of most of the igneous units in the Bathtub intrusion and pertinent structural features. Note that not all of the PRI units are shown on the right side of the figure.

Cu-rich massive sulfides are locally present at the Mesaba deposit in a small zone referred to as the Local Boy ore zone. Local Boy is positioned along the crest of the Local Boy Anticline, in close to proximity to “The Hidden Rise,” and just west of the Grano Fault. Most of the massive sulfides are associated with

either hornfelsed sedimentary inclusions above the basal contact or with footwall rocks below the contact while the interfingering intrusive rocks are relatively barren of massive sulfides (Severson and Barnes, 1991). This suggests that the massive sulfide ores were not formed by the gravitational settling of sulfides, but rather, the ores formed by injection of an immiscible sulfide melt into structurally prepared areas within the footwall rocks along the Local Boy anticline in a vein-like setting. A possible feeder vent for the sulfide injection event may have been the Grano Fault, which was repeatedly reactivated during emplacement of the Complex. West-directed increases in Cu and PGE, associated with the massive sulfides at Local Boy, suggest that the immiscible sulfide melt fractionally crystallized and became progressively enriched in Cu and PGE as it was deposited in an east-to-west direction.

Partridge River and Bathtub intrusion footwall rocks

Because the footwall at NorthMet and Mesaba is so similar, following is a generic description appropriate to both deposits. The drilled footwall rock types at Mesaba and NorthMet consist mainly of the Virginia Formation and Biwabik Iron Formation. Both are Paleoproterozoic in age (approximately 1.9-1.8 Ga) and are the two upper units of the Animikie Group. Any discussion on these two formations must include a description of their type-section on the Mesabi Range, as well as, a description of them as related to the metamorphism and partial melting that was produced during emplacement of the Complex. Lying beneath the Biwabik Iron Formation, but encountered only in a few drill holes are the Paleoproterozoic Pokegama quartzite (also of the Animikie Group), along with granites and gneisses of the Archean Giant's Range Batholith.

Biwabik Iron Formation

The Biwabik Iron Formation (BIF) exposed on the nearby Mesabi Range has typically been subdivided into four informal lithostratigraphic members (Wolff, 1917) that are, from the bottom up: Lower Cherty, Lower Slaty, Upper Cherty, and Upper Slaty. Diamond drill holes at Mesaba and NorthMet generally pierce the top submembers of the Upper Slaty, and end in submember C or D: Submember A is comprised of a pale to white chert and marble, submember B is characterized by alternating bands of green diopside and chert, and submember C is a green to gray thin-bedded rock consisting of chert-fayalite-ferrohypersthene with wispy black bands of magnetite (taconite). The upper contact of the BIF is gradational with the overlying Virginia Formation.

Virginia Formation Below the PRI and BTI

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 (180 meters) thick and contains common intervals wherein black, thin-bedded, carbonaceous argillite is the dominant rock type (Lucente and Morey, 1983); visible sulfides are locally present. The lower lithosome is the unit which underlies the Mesaba deposit, and the base of the Virginia Formation is what is most commonly intersected below the Bathtub intrusive, prior to reaching the Biwabik Iron Formation.

In close proximity to the Duluth Complex, the Virginia Formation is described as being a hornfels that, as defined by Turner (1968), is a nonfoliated rock composed of a mosaic of equidimensional grains. In reality, many of the “hornfels” textures exhibited by the metamorphosed Virginia Formation do not meet this criterion, but as the term has been widely used in descriptions of the Virginia Formation in the vicinity of the Complex, it is retained in this guidebook. Mineral assemblages in the hornfels, in both the footwall and in inclusions within the Complex, consist of varying mixtures of cordierite, quartz, K-spar, and biotite with lesser amounts of chlorite, muscovite, plagioclase, orthopyroxene, and minor graphite and sulfides.

The effects of partial melting are profound and portions of the hornfelsed Virginia Formation no longer even remotely resemble a sedimentary rock. Severson et al. (1994a) subdivided the hornfelsed Virginia Formation, in both the footwall and in inclusions within the Duluth Complex, into at least five informal units based largely on metamorphic attributes, which are each related to varying degrees of partial melting. These members, and a pre-Duluth Complex sill, are described below and are schematically portrayed in Figure 1-5 - although in real occurrence, this idealized metamorphic progression is more erratic, often with rapid lateral and vertical changes between the four metamorphic units discussed below.

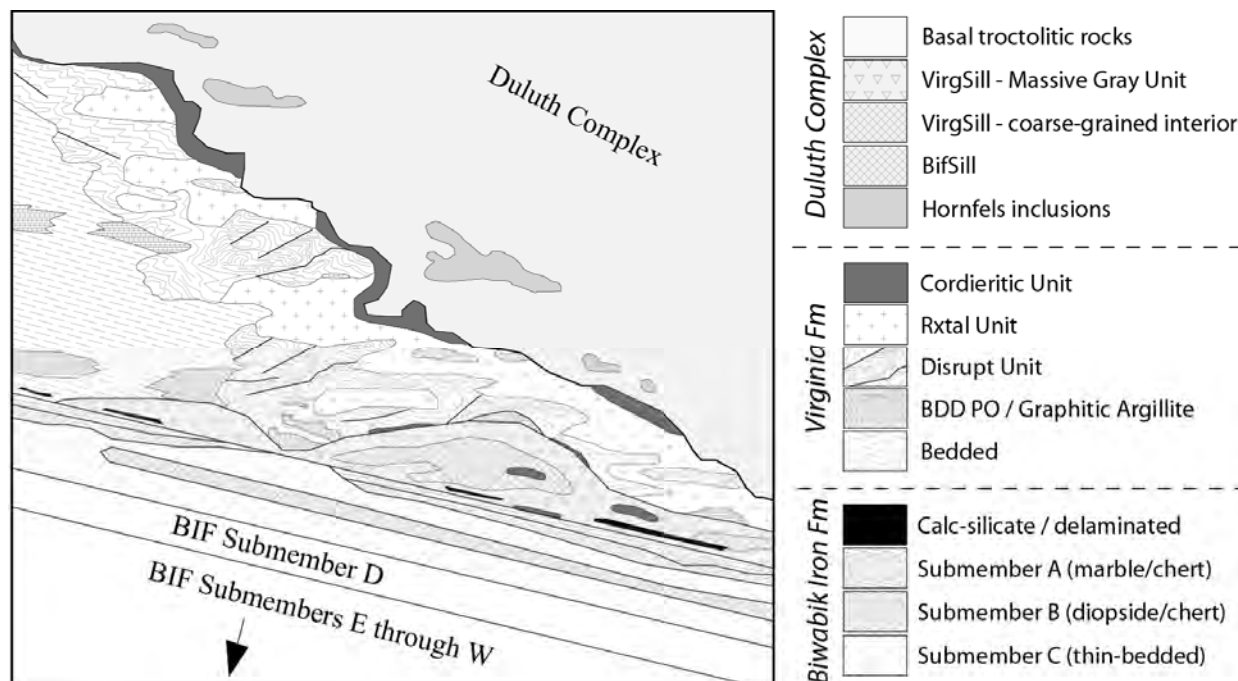


Figure 1-5. Schematic cross-section showing the general relationships of the metamorphosed footwall rocks beneath the Duluth Complex at the Mesaba, NorthMet, Wetlegs, and Serpentine deposits.

Cordieritic hornfels

Directly beneath the basal contact of the Duluth Complex, the adjacent Virginia Formation typically consists of massive/nonfoliated, cordierite-rich hornfels that display a bluish-gray color in drill core. The rock is generally fine-grained, granoblastic, and biotite-poor (due to loss of water into the Complex) and locally may contain porphyroblastic and/or poikiloblastic cordierite. Original bedding planes are preserved in some localities, but mostly the bedding planes have been obliterated by contact metamorphism.

Recrystallized unit (RXTAL)

Beneath the cordieritic “capping” the next metamorphic variant of the Virginia Formation nearest to the Duluth Complex is a rock that is referred to as the RXTAL unit. The RXTAL unit is properly classed as a diatexite and is characterized by fine- to medium-grained cordierite, plagioclase, biotite, quartz, and K-spar with lesser amounts of Opx and opaques. Bedding planes of the original argillaceous rocks are obliterated and what remains is a massive recrystallized rock with decussate biotite that contains enclaves (blocks and folded boudins) of more structurally competent calc-silicate hornfels and thin-bedded siltstone

Disrupted unit (DISRUPT)

With increased distance from the Complex, the RXTAL unit progressively grades into the DISRUPT unit which is a thin-bedded rock that is visibly deformed and underwent less degrees of partial melting.

Textures that characterize the DISRUPT unit are bedding planes that are extremely chaotic and random in orientation due to pervasive small-scale folding, faulting, and brecciation. Superimposed on this chaotic pattern are abundant zones of leucocratic partial melts that are also chaotic and folded. The rock consists of varying amounts of quartz, cordierite, K-spar, biotite, plagioclase, and muscovite with leucosome veins and patches containing quartz, K-spar (microperthite), plagioclase, and muscovite (Duchesne, 2004). The DISRUPT unit is properly classed as a metatexite.

Graphitic argillite and Bedded Pyrrhotite (BDD PO) units

Carbonaceous argillite of the lower lithosome of the Virginia Formation is commonly preserved as either the BDD PO unit, or graphitic argillite, in close proximity to the Duluth Complex. This rock commonly contains over 5% disseminated pyrrhotite and/or extremely thin-bedded pyrrhotite laminae (hairline-thick), and variable amounts of graphite, staurolite(?) and sillimanite. Wherever the unit contains conspicuous and regularly-spaced laminae of pyrrhotite (0.5-3.0 mm thick at 1-20 mm spacings) it is informally referred to as the bedded pyrrhotite unit (BDD PO unit).

VirgSill

The VirgSill is generally present in the bottom 0.5-130 feet of the Virginia Formation, and as local apophyses into the top of the Biwabik Iron Formation. The VirgSill was intruded along the contact between the Virginia Formation and Biwabik Iron Formation and exhibits a granoblastic texture indicating that it was metamorphosed by the Duluth Complex (and thus the VirgSill is pre-Duluth Complex in age). On this basis, the VirgSill is inferred to be equivalent to the Logan sills (circa 1,109 Ma); as is another sill, the BIFSill, in the C submember of the Biwabik Iron Formation (Hauck et al., 1997). However, the VirgSill and BIFSill are different chemical entities (the VirgSill is much more Cr-enriched), and thus, these two sills may be related to at least two different intrusive events. When present, the VirgSill ranges from a few centimeters to several meters thick. Identification of the VirgSill in drill core is hampered by the fine-grained granoblastic texture that makes it difficult to distinguish from the enclosing hornfelsed Virginia Formation rocks; both were metamorphosed by the Duluth Complex. The VirgSill is subdivided into two textural varieties (Severson et al., 1994a; Park et al., 1999):

1. MG unit – fine-grained, massive, gray-colored unit (massive gray unit or MG unit) that appears to be a border phase or chill zone - albeit quite thick at some localities (up to 200 feet-thick in drill hole B1-264). In some drill holes the entire interval of the VirgSill consists of the MG unit.
2. Coarser-grained interior – medium- to coarse-grained, green- to brown-colored, olivine- and hornblende-bearing interior of the sill that is easily identified as an intrusive rock in drill core. The coarse-grained interior is not always present, and when present, may be up to 80 feet thick, and occurs as either a single lense within a thick MG unit or as several vertically-stacked lenses within the MG unit.

Both the MG unit and coarser-grained interior of the VirgSill contain variable amounts of plagioclase, olivine, hornblende, clinopyroxene, orthopyroxene, and biotite with local sulfides (pyrrhotite, chalcopyrite, and bornite). The presence and metamorphic effect of this sill has caused an “armoring” wherein previously metamorphosed Virginia Formation has resisted assimilation by the Duluth Complex. Across much of the lower parts of the NorthMet and Mesaba deposits there is a persistent thin (<10ft.) rind of Virginia Formation associated with this sill.

South Kawishiwi intrusion

The South Kawishiwi intrusion (SKI) consists mainly of troctolitic cumulates and dips gently to the southeast. The SKI is exposed in an arc-shaped area that extends from the Serpentine deposit, on the southwest, to the Spruce Road deposit, on the northeast (Fig. 1-2). Footwall rocks include the Paleoproterozoic Virginia Formation, Biwabik Iron Formation and Archean Giants Range Batholith, the latter is the dominant footwall rock type. The presence of Biwabik Iron Formation as inclusions, from the

Birch Lake deposit to as far north as the Spruce Road deposit, indicates that the majority of Paleoproterozoic units were assimilated and removed from the footwall during emplacement of the South Kawishiwi intrusion (Severson et al., 2002). The basal stratigraphic section is known in great detail from studies of abundant drill core and is subdivided into 17 different units (Fig. 1-6) that are present over a strike-length of 19 miles (31 kilometers). The lowermost units are unevenly distributed along the strike length of the intrusion in a “compartmentalized” fashion, suggesting a complicated intrusive history (Miller and Severson, 2002). A few salient features to keep in mind regarding the igneous stratigraphy of the SKI include:

- The vast majority of sulfide mineralization is confined to the BH (**B**asal **H**eterogeneous Unit), BAN (**B**asal **A**ugite Troctolite and **N**orite Unit), UW (**U**pdip **W**edge Unit), and U3 (**U**ltramafic **3** Unit);
- Major marker beds include three horizons that contain abundant cyclic ultramafic layers (U1, U2, and U3 Units) and a pegmatite-bearing unit (PEG Unit - originally recognized by Foose, 1984). The U1, U2 and U3 Units represent periods of rapid and continuous magma replenishment that crystallized more primitive ultramafic layers before mixing with the resident magma (Severson et al., 2002);
- The U3 Unit is unique in that it contains several massive oxide pods (titanomagnetite-rich), as well as, recognizable inclusions of bedded Biwabik Iron Formation. The spatial correspondence between the U3 Unit and footwall iron-formation suggests that most of the massive oxide pods are iron-rich “restite” produced by assimilation and partial melting of the iron-formation (Muhich, 1993; Severson, 1994; Severson et al., 2002);
- The U3 Unit contains the vast majority of high PGE values, especially within the Birch Lake area and possibly at the Nokomis deposit. However, high PGE values are also present in the PEG Unit (Birch Lake area and Nokomis deposit), the top of the BH Unit (Maturi deposit and Nokomis deposit), and in very locally in troctolitic rocks situated well above the basal contact (South Filson Creek deposit); and
- A large inclusion/pillar of anorthosite is present at the Nokomis deposit. This pillar, and possible proximity to a vent area and magma flow paths (see discussion for Nokomis deposit) are the inferred reasons for high PGE values at the Nokomis deposit.

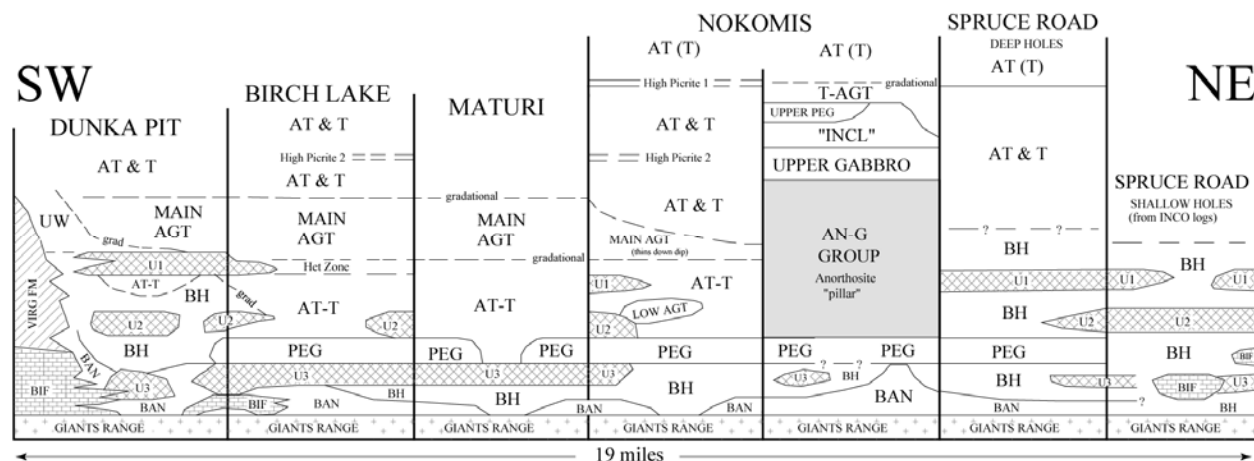


Figure 1-6. Generalized stratigraphy of the basal zone of the South Kawishiwi intrusion (modified from Severson, 1994; and included in Miller and Severson, 2002). The lowermost igneous units are: BAN = Basal Augite Troctolite and Norite; BH = Basal Heterogeneous; U3 = Ultramafic 3; PEG = Pegmatitic unit of Foose (1984); U2 = Ultramafic 2; U1 = Ultramafic 1; AT-T = Anorthositic Troctolite to Troctolite; UW = Updip Wedge; Main AGT = Main Augite Troctolite.

REGIONAL ECONOMIC GEOLOGY

While Minnesota is home to the United States iron ore industry, development of its known non-ferrous deposits has been hampered by industry downturns, remoteness from the rest of the base metals industry, a complex land situation, and a (wrongly) perceived environmental risk. The state has done much to support non-ferrous exploration, in particular maintaining an impressive drill core and data library in Hibbing, and sponsoring extensive mapping and sampling projects. Research arms of the MDNR and the University have contributed much knowledge to mineral processing methods for these ores. In general this work has not been well publicized. This short discussion on regional mineral potential focuses on rocks in the north part of the state, but there has been recent exploration for nickel and diamonds throughout the state. For detailed discussion of potential in Archean rocks see Peterson (2001a) and for Duluth Complex rocks see Miller et al., 2002.

Mesabi Range Iron Mines-Status

There are six operating iron mines employing about 3,500 people in the region. They all produce taconite pellets from low grade magnetic ore. Four are captive to steel companies, two produce pellets for market, generally through long term contracts. Product shipping is largely by rail to one of four ports on Lake Superior, then by boat to mills on the lower lakes. About thirty eight million tons of pellets were produced in 2007. Total material movement (ore and stripping) was on the order of two hundred million tons. The one-hundred plus year history of this world class mining district means that there is an extensive developed infrastructure and service industry for these mines.

Two iron related projects are in development in 2009: Mesabi Nugget, located near the PolyMet plant site, will initially use purchased concentrate to produce iron nuggets suitable for electric furnace production of steel, the company has submitted plans to the state to re-open some of the LTV pits and produce their own concentrate; and Essar Steel (Minnesota Steel Industries, formerly Minnesota Iron & Steel) plans to re-open a closed taconite mine (Butler Taconite) at the western end of the Mesabi Range and produce direct reduced iron from taconite pellets on site. That direct reduced iron will in turn be used to make steel slab for shipment. This will be the only mine to steel, single-site production facility in North America. Both of these projects are under construction.

Other Regional Economic Geology

Two broad age groups dominate the other rocks with mineral potential in northern Minnesota. Archean rocks represent possible hosts for lode gold, Volcanogenic Massive Sulfide (VMS), and diamond prospects. North of the Duluth Complex is extensive terrane of exposed Archean rock, similar to that in Ontario (Wawa and Quetico subprovinces). Over the years various prospects for gold and base metals have been delineated, but follow up work has been sporadic and generally short lived. These prospects include, for gold: Raspberry, Murray Shear zone, Spaulding Bay, Mud Lake, Pac Man Pond, and Section 6, investigated by Goldfields, Newmont, Kerr McGee, and Noranda among others. For base metals the deposits include: Clear Lake, Skeleton Lake, Fivemile Lake, and Purvis Road worked by the above companies as well as Exxon, Teck, Rendrag, and Lehmann. A 2001 PhD. thesis (Peterson, 2001a) is an excellent review of the Archean mineral potential of the region. That report makes detailed analytical comparisons between producing gold and base metals camps in Canada and prospects in Minnesota. Diamond work in Archean age rock of Minnesota includes Exmin (DeBeers), WMC, and others; as well as the Minnesota Geologic Survey.

Proterozoic rocks in northern Minnesota include Animikian Basin (Paleoproterozoic, ~1.8 Ga) sedimentary rocks (Pokegama Quartzite, Biwabik Iron-Formation, and the Virginia Formation). Besides current iron ore production, past exploration has focused mostly on zinc and other base metals in the Virginia. Anomalous mineralization (sphalerite, molybdenite) has been found in the Virginia, but no prospects have been defined.

Titanium and Other Oxide Mineral Potential in the Duluth Complex

There are at least four titanium deposits within 12 miles (19 kilometers) of PolyMet's Hoyt Lakes plant site (out of 13 known titanium deposits in the area). They are all located in the Duluth Complex and locally called "OUI's" for "Oxide Ultramafic Intrusions". These are titanium rich plugs which cross-cut the rocks of the Complex. All are greatly undersampled, especially for PGE and other oxides besides titanium (chromium, vanadium, etc.)

Bulk samples have been processed from two of these titanium prospects. The titanium in these deposits is in magnesium-rich ilmenite which is not easily processed by current commercial methods. BHP, Coleraine Minerals Research Laboratory of the NRRI, and others have done extensive process testing towards adding value to these prospects. All 13 have been drilled, but generally not to a point where a legitimate (i.e., NI43-101 compliant) resource can be declared. Two OUI's with reasonable historical resource estimates are Longnose, with 50 million tons averaging 21% TiO₂ based on 11 drill holes and Water Hen, with 62 million tons averaging 14% TiO₂, based on 37 drill holes. At present, Cardero Resources has leased Longnose, as well as the Section 34 deposit about halfway between Duluth and the Iron Range.

This group of deposits represents great potential for undiscovered copper-nickel-PGE, silver, as well as oxide rich "plug-like" intrusions with known titanium resources and possibilities for chromium, vanadium, etc. It is obviously unknown what is undiscovered, but historic exploration on the Duluth Complex and associated rocks has focused almost exclusively on the large copper-nickel deposits along the northwestern contact with virtually no work done on the interior of the Complex. There is a large collection of core available for all of these projects, and in general a good collection of related data stored at the Minnesota Department of Natural Resources in Hibbing. NRRI has logged most of this core, and consolidated whatever assay data is available (Patelke, 2003).

PART 2: POLYMET NORTHMET DEPOSIT

By: Richard Patelke, Steve Geerts, Mark Severson

NORTHMET PROJECT SUMMARY

NorthMet, located in the Partridge River intrusion of the Duluth Complex, is a large, disseminated sulfide deposit in heterogeneous troctolitic rocks associated with the 1,100 million year old Mid-Continent rift. Metals of interest are copper, nickel, cobalt, platinum, palladium, and gold. The majority of the metals are concentrated in four sulfide minerals: chalcopyrite, cubanite, pentlandite, and pyrrhotite, with platinum, palladium and gold also found in bismuthides, tellurides, and alloys. NorthMet is one of eleven copper-nickel-PGE deposits along the northern margin of the Complex (PGE: platinum, palladium, gold). All of these share grossly similar geologic settings—disseminated sulfides with minor local massive sulfides in heterogeneous rocks forming the basal unit of the Duluth Complex along the contact with older rocks.

The deposit is on the southern flank of the Mesabi Iron Range, which is host to six large operating taconite mines, the closest of which is less than two miles (3.2 km) north of the planned NorthMet pits (Figure 1-7). Ore from NorthMet will be processed at a rate of 32,000 short tons per day through the former LTV Steel Mining Company iron ore concentration plant (“Erie Plant”) with new facilities for processing of the NorthMet copper-nickel-PGE concentrates through a hydrometallurgical method day to produce copper metal and various hydroxide and concentrate products of nickel-cobalt-PGE (Figure 1-8).

EXPLORATION and DEVELOPMENT

There have been four major drilling programs since 1969, re-sampling for PGE began in 1989, three PolyMet joint ventures were pursued and dissolved in the 1990's, processing technology was developed in the late 1990's, the former LTV Steel Mining Company concentrator and other property was optioned in 2003, and the metallurgical process was refined in 2005-2008.

Drilling programs have been conducted by United States Steel (USS, 1969-1974) and PolyMet Mining Inc. (Reverse Circulation or “RC” drilling and core drilling in 1998-2000 & two phases of core drilling in 2005 and 2007), plus two (actually two pairs of twins) holes by NERCO Minerals Company in 1991. This drilling encompasses 285,756 feet over 371 holes as of May 2008. Over 35,973 acceptable assays have been taken from this drilling (216,344 feet assayed). Table 1-1 gives a breakdown of years, footages, and number of assays for all project drilling.

United States Steel (USS) began core drilling at NorthMet (as the Dunka Road project) in 1969. Drilling targeted a conductor that turned out to be in the footwall metasedimentary rocks, but the first drill hole hit massive sulfide in the Duluth Complex. Drilling continued over five years for 112 holes with 133,716 feet of intercept. The working assumption was to mine the deposit from underground, sampling was limited to the most continuous zones with strong visible copper-nickel mineralization, and only about 2,200 samples representing about 22,000 feet were taken. USS assayed only for copper, nickel, sulfur, and iron. PGE presence was known from sampling on concentrates, but the economics of PGE recovery were apparently not pursued. Project work stopped while apparently incomplete and was not restarted.

USS did not do much follow-up, but kept their land ownership, core, pulps, coarse rejects, and records for the project. In the mid 1980's the Minnesota Department of Natural Resources (MDNR) began sampling various historic drill core intervals in the Duluth Complex for PGE and got some good, but localized, results. In 1989 Fleck Resources (Fleck) leased the Dunka Road property from USS and began a program of re-assaying USS pulps and coarse rejects with a much more extensive multi-element suite, as well as

adding in some new samples from existing core through cooperative work with the Natural Resources Research Institute (NRRI), associated with the University of Minnesota Duluth. The results were very positive in showing elevated PGE values in the deposit and confirming the previous copper-nickel assays.

Fleck partnered with NERCO in 1991 for some bulk sample work, mine plans, environmental reviews etc., done through Fluor Daniel Wright engineers, but the partnership was eventually dissolved. In 1995 Fleck joined with Argosy Mining Corp. to do more work on the project, again with no major progress towards production. In June 1998, Fleck became PolyMet and focused their resources on Dunka Road, which was renamed NorthMet. Without partners, except for a brief venture with North Mining (North), PolyMet drilled and sampled 87 holes in 1998-2001, and sent two large bulk metallurgical samples to Lakefield Laboratories (now SGS) in Lakefield, Ontario for development and refinement of the PlatSol hydrometallurgical process and began some environmental background work.

In the summer of 2000, North was taken over by Rio Tinto. The joint venture agreement was terminated by PolyMet upon consideration that NorthMet appeared to be a low priority to Rio Tinto. The main concern was that other partnership opportunities might be missed during the time that Rio Tinto assessed and prioritized the ongoing North projects. However, much of the North funding was already in place and was used to partially finance the 2001 pre-feasibility study. After release of the pre-feasibility study (2001), a brief hiatus, and a major re-evaluation of how the project should proceed, PolyMet became active again in 2003 with new management and a new development plan.

This plan involves integrating the former LTV Steel Mining Company iron ore concentration plant (“Erie Plant) with new facilities for processing of the NorthMet copper-nickel-PGE concentrates through a hydrometallurgical method at rate of 32,000 short tons of ore per day to produce copper metal and various hydroxide and concentrate products of nickel-cobalt-PGE. Geologic work towards this end began in 2004 and first focused on a careful and total re-compilation of the historic NorthMet project drill hole related data. This effort organized and verified all drilling metadata, location, downhole survey, lithology, and assay data, and cataloged all paper (and digital) records for the project. Of note is that this resulted in an increase in the number of acceptable assays from 12,000 to around 17,200 and an improved geologic picture from careful consolidation of existing records.

This work was used as background for a revised resource estimate in January 2005 and planning of a drill program for 2005. The 2005 program entailed drilling and sampling 109 holes (77,000 feet), collection of a forty ton metallurgical bulk sample for pilot scale testwork, geotechnical (oriented core) drilling, in-fill sampling of previously drilled core, and extensive collection of waste characterization data. The 2005 drilling program added 13,450 multi-element assay records to the existing database. A PolyMet report covers the details of historic drilling and assaying (Patelke & Geerts, 2006).

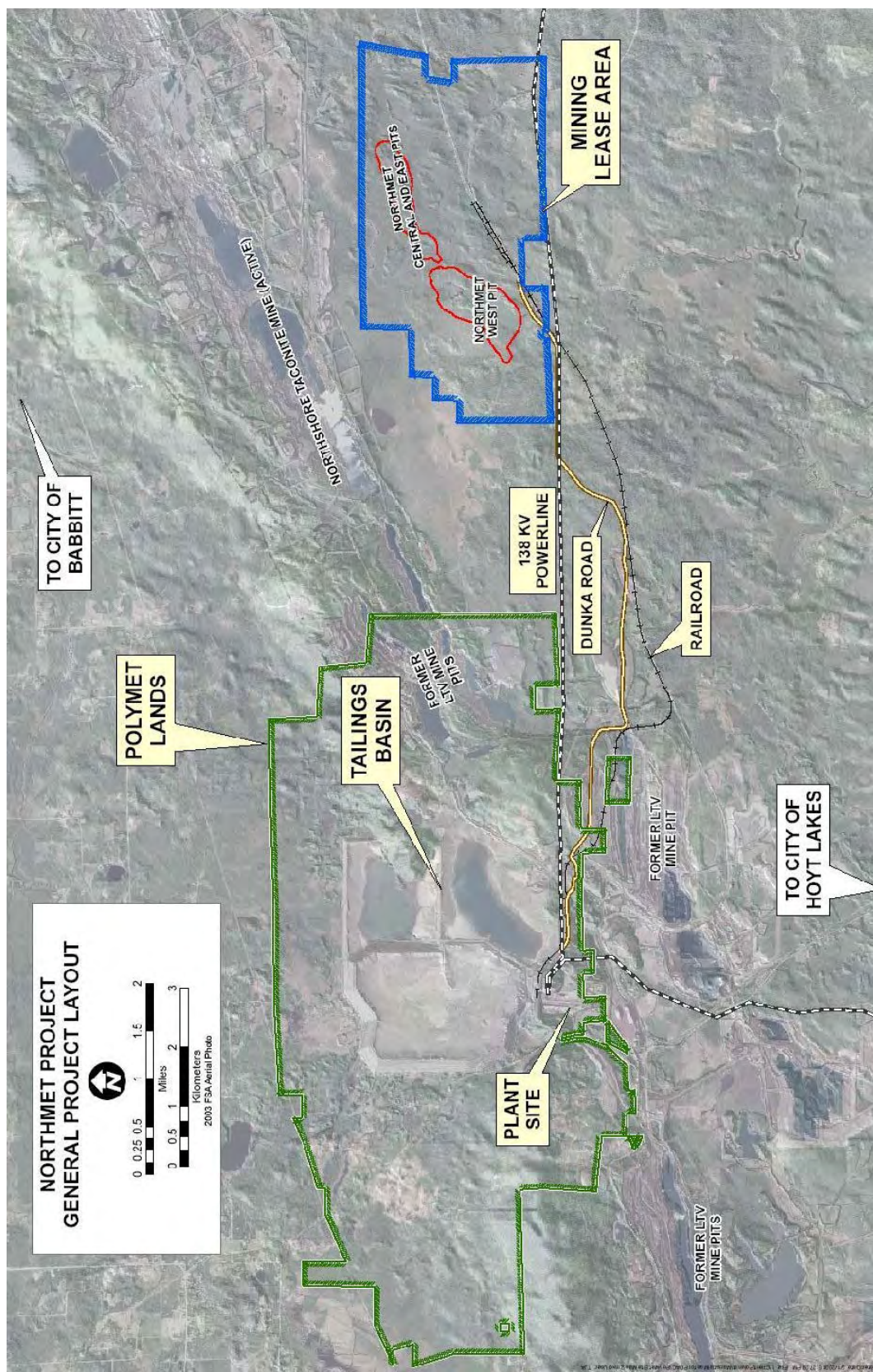


Figure 1-7. PolyMet NorthMet project site.

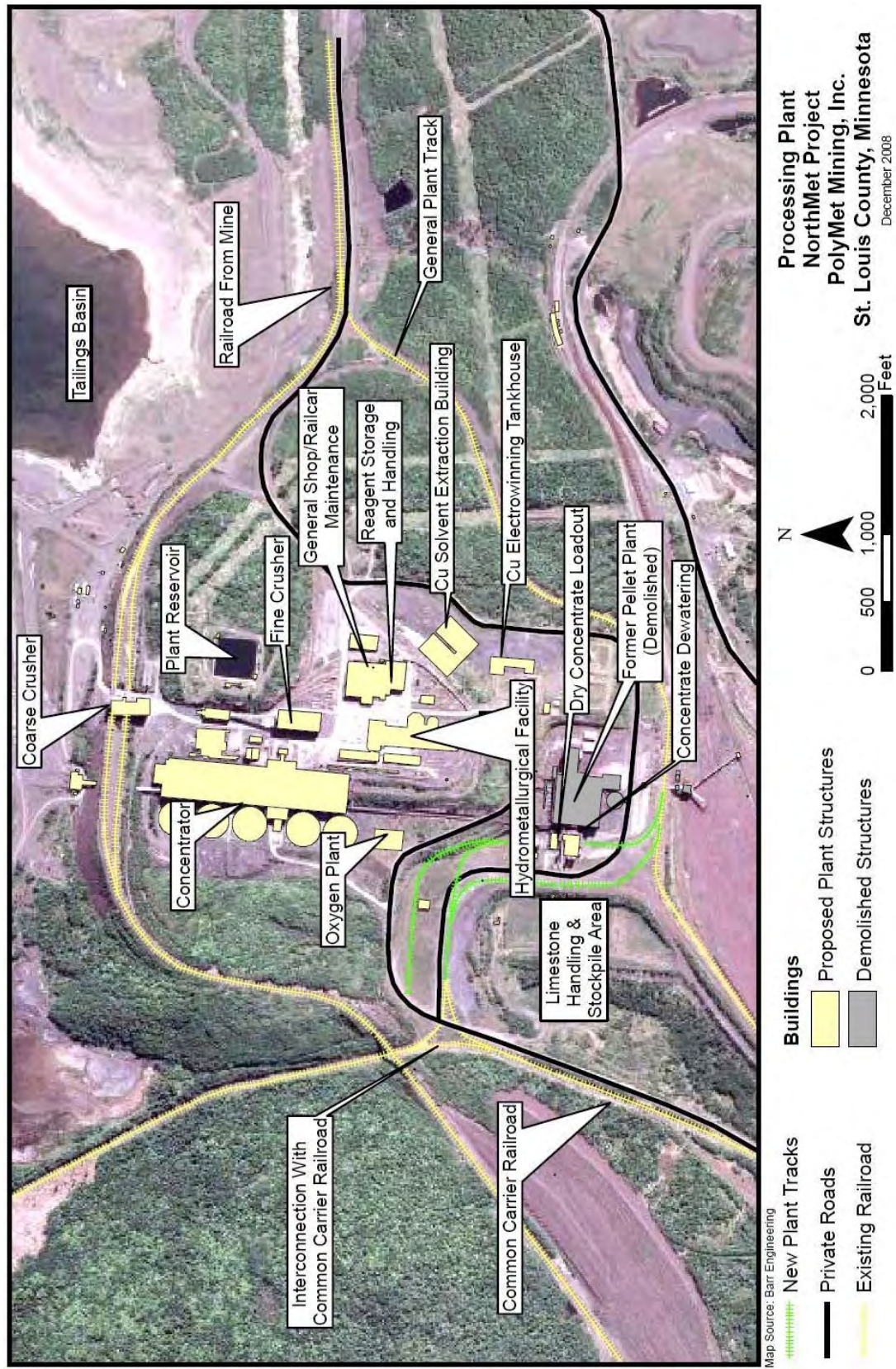


Figure 1-8. Detail of Erie Plant site showing existing facility and new construction.

Drilling in 2007 for 24,530 feet with 3,546 assays concentrated on defining mineralization in the upper units in the west part of the deposit (the “Magenta Zone”). This drilling and the subsequent re-modeling of the deposit turned about 50 million tons of material previously classed as waste to ore. There is also over 34,000 feet of hydrogeology drilling and “stratigraphic holes” (drilling by other companies not done as part of the NorthMet project). No assays are in use from these 44 holes which are used for geologic control. Approximately 89.5% of Unit 1 and about 57% of the upper units have been sampled across the deposit. The sampled percentages are higher in the anticipated area of mining.

Table 1-1. Total drilling and assaying for NorthMet project

Company	Drilling years	Assaying years	No. of drill holes	Total footage for group	No. of assay intervals used in “accepted values” tables	Assayed footage used in final database	Assay Laboratories
US Steel	1969-1974	1969-1974, 1989-1991, 1999-2001, 2005-2006, 2008	112	133,716	11,259	73,303	USS, ACME, ALS-Chemex
NERCO	1991	1991	2 (4)	842	165	822	ACME
PolyMet reverse circulation drilling	1998-2000	1998-2000	52	24,650	4,765	23,767	ACME
PolyMet core drilling	1999-2000	2000-2001, few in	32	22,156	4,058	20,727	ALS-Chemex
PolyMet RC drilling deepened with AQ core tail	2000	2000	3	2,696	524	2,610	ALS-Chemex
PolyMet core drilling	2005	2005-2006	109	77,166	11,656	71,896	ALS-Chemex
PolyMet core drilling	2007	2007	61	24,530	3,456	23,310	ALS-Chemex
Totals for Exploration Drilling:			371	285,756	35,973	216,344	
US Steel stratigraphic holes	1970's?	none	6	9,647	none	none	
INCO	1956	none	3	2,015	none	none	
Humble Oil / Exxon	1968-1969	none	3	9,912	none	none	
Bear Creek / AMAX	1967-1977	none	11	8,893	none	none	
PolyMet / Barr Engineering (hydrologic testing)	2005-2007	none	21+	3,459+	none	none	

Table 1-2. Large metallurgical samples collected at NorthMet

Bulk Sample	Year	Tons	Location of sample
USS Bulk sample pit No. 1	1971	Unknown, but small	Pit in center of property
USS Bulk sample pit No. 2	1971	300	Pit at east end of property
USS Bulk sample pit No. 3	1971	20	Pit at east end of property
NERCO PQ drill core	1991	Estimated at 4.5 tons or less by drill core size	One PQ drill hole from each end of property
Argosy Mining	1995	Unknown, but small	Composited from USS coarse rejects
PolyMet RC drill cuttings	1998	26	One composite, mostly from what is now considered east part of 10 year pits
PolyMet RC drill cuttings	2000	33	One composite, mostly from what is now considered east part of 10 year pits
PolyMet 4 inch and PQ core and coarse reject	2005	10.5, 21.5, and 10.7	Three composites from within ten year pits across property
PolyMet coarse reject	2006	4.2 and 4.94	One composite from 10 year east pit, one from 20 year pit across property
PolyMet ¼ core from 2005 and 2007 Drilling	2007	500 kg	One composite, from east and west pit areas
PolyMet ¼ core from 2005 and 2007 Drilling	2008	4.44	One composite, from east and west pit areas
PolyMet ¼ core from 2005 and 2007 Drilling	2008	4.48	One composite, from east and west pit areas

Sampling in Unit 1 (the main mineralized zone) is now mostly continuous through the zone for all generations of drilling. The PolyMet RC and core holes have continuous sample through the upper waste zones (which do have some intercepts of economic mineralization). Work in 2005 through 2008 essentially completed the sampling of historic USS core within the area likely to be mined. This broad sampling limits the possibility of location bias in the sample set. While not all of the USS core has been sampled, there is no known unsampled mineralized core.

There have been numerous bulk samples taken at NorthMet (Table 1-2). Samples have been representative by Unit and rock type. Agreement between calculated grades (based on core sampling) and analyzed grades of final sample has been excellent. Earlier bulk samples represented the first ten years of production, more recent samples used material from across the deposit. Each bulk sample has built upon the previous, and work has progressed to the point where PolyMet has confirmed the ability to make separate, saleable, copper and nickel concentrates. This will allow the company to develop cash flow from sales much earlier in production while completing construction of the hydrometallurgical facility.

The planned hydrometallurgical process (PlatSol) was developed on NorthMet ores. The process uses pressure oxidation (225°C, over 30 atmospheres) in the presence of chloride to capture all base and precious metals in the concentrate. Hydromet process recoveries are all over 98%. Other geologic data collected includes: recovery and RQD measurements on all core, over 7,000 specific gravity measurements, over 900 whole rock analyses, over 300 Rare Earth Element packages and a large amount of microprobe data collected for waste characterization purposes.

GEOLOGY OF THE NORTHMET DEPOSIT

NorthMet consists of seven igneous units that dip southeast, with most economic sulfide mineralization in the top parts of the lowermost unit (Unit 1). The following is a summarized description of the geology of the deposit, based on observations from drill core and limited outcrop mapping.

Quaternary Geology

In general the Quaternary geology of the region is a thin (0-30 feet or 0-10 meters., but locally thicker) blanket of glacial deposits including till, lacustrine materials, and outwash. Low spots are usually peat bog or open wetland. Topography is subdued and drainage is poor. Site specific geologic studies of the drift have not been done, though a series of geophysical soundings were carried out in 2006 to better define drift thickness outside the area to be mined (Ikola, 2006). Lehr and Hobbs (1992) mapped the area as part of the Wampus Lake Moraine. Minnesota Geologic Survey map 164 (Jennings and Reynolds, 2005, includes GIS database) categorizes all drift materials as Rainy Lobe till and re-sedimented glacial deposits, overlain locally by post glacial peat.

Test pits for preliminary PolyMet engineering studies and informal observations of sumps and other small excavations bear this out. Most areas consist of unsorted sand / silt / clay with cobbles and boulders. Boulders on surface can be greater than 10 feet in size and there may be a boulder lag horizon just below the ground surface in some areas. As measured from drill holes, thickness of the drift ranges from 0 to 50 feet (mostly less than 20 feet) and averages about 12 feet. The 2006 geophysical soundings measured thicknesses up to 60 feet past the western margins of the drilled area.

Structural Geology

The general structure of the NorthMet deposit, as defined by igneous contact dips, foliation in serpentinized zones, bedding trends in the Biwabik Iron Formation (BIF) and in the Virginia Formation, is dominated by an overall dip ranging from 15-25° to the southeast, striking about N56°E. Dips in the seven igneous units are grossly similar, but dips of the mineralized zone are up to 60° in the east pit area. Dips in both the Animikian and the Duluth Complex rocks can be attributed to crustal loading, associated with the input of large volumes of magma originating from the Mid-continent Rift System (Sims and Morey, 1972).

Numerous faults have been proposed across the NorthMet Deposit, based largely on reconciling dips in the footwall rocks. Unfortunately, not enough evidence has been established through drilling to indicate with certainty the exact location of major offsets or faulting within the igneous rock units or the footwall rocks on a hole-to-hole basis. This definition difficulty is compounded by the fact that over time the fault representations have been extended vertically from ground surface to footwall, though many were originally thought to only show offset in the footwall, or were based solely on limited outcrop evidence.

Clearly however, offset or faulting exists, at least within the footwall rocks, due to substantial offsets in the BIF (assuming an average 20° dip) as evidenced between drill holes portrayed in cross-sections. Many of these same offsets can be correlated in adjacent cross-sections. Fault zones are apparent in drill core and show up as brecciated intervals (up to several feet thick), including gouge mineralization (clay, calcite, quartz, etc.), slickensides on serpentinized fracture faces, and/or severely broken (rubble) core. However, the exact location of all faults/offsets at the NorthMet Deposit on a hole to hole basis has only been approximated, due to the sparse structural information as so far provided by drilling. Extensive angle drilling in 2005 and 2007 (142 of 170 holes) brought no great clarity to this issue (virtually all previous drilling was vertical). The current geological model and working cross-sections are therefore constructed with minimal faulting influence, especially within the igneous rock units of the Partridge River intrusion, until more evidence clarifies this issue.

Logging and Mapping Units

A summary of the general stratigraphy of the NorthMet Deposit is outlined below. Rock units and formations are listed in descending order, as would be observed from top to bottom in drill hole. NorthMet units are labeled as Units 1 through 7 (Units I through VII in Severson's terminology), bottom to top. Unit 3 is probably the oldest, the intrusion sequence of the other units is not clear.

The broad picture is of a regular stratigraphy of troctolitic to anorthositic rock units, dipping southeast at 20° to 25°, with basal ultramafic units defining the boundaries of some of these units. The basal ultramafic zones tend to have diffuse tops, sharp bases, and are commonly serpentinized and foliated. Geologists have generally picked the unit boundaries at the base of these ultramafics though there are local exceptions. Economic sulfide mineralization is ubiquitous in the basal igneous unit (Unit 1) and is locally present, but restricted, in the upper units.

Rock Type and Unit Classification

Igneous rock types in the Complex are classified at NorthMet by visually estimating the modal percentages of plagioclase, olivine, and pyroxene, using a rock classification scheme (Figure 1-9) modified from Phinney (1972). Due to subtle changes in the percentages of these minerals, a variation in the defined rock types within the rock units may be present from interval to interval or hole to hole. This is especially true for Unit 1.

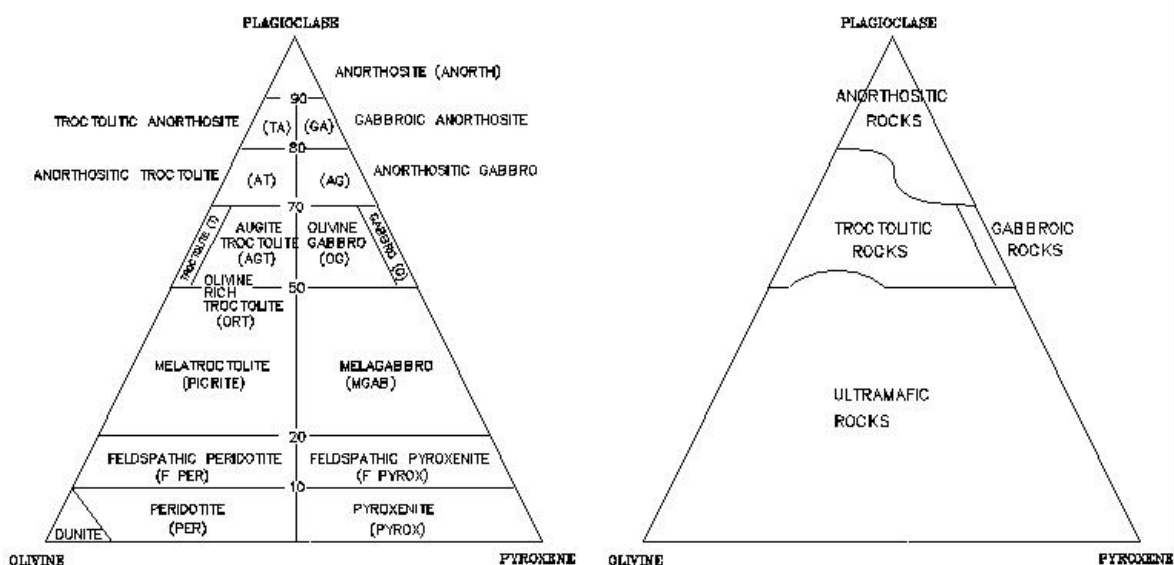


Figure 1-9. Modified Phinney (1972) diagram for rock type classification

Unit definitions are based on: overall texture of a rocktype package; mineralogy; sulfide content; and context with respect to bounding surfaces (i.e., ultramafic horizons, oxide-rich horizons). Unit definitions are not always immediately clear in logging, but usually clarified when drill holes are plotted on cross-sections. In other words, to correctly identify a particular stratigraphic unit, the context of the units directly above and below should also be considered. Based on drill hole logging, the generalized rock type distribution at NorthMet is about 83% troctolitic, 6% anorthositic, 4% ultramafic, 4% sedimentary inclusions, 2% noritic and gabbroic rocks, and minor pegmatite, breccia, basalt inclusions, and others.

Unit Definitions and Descriptions

Descriptions of the general igneous Stratigraphy for the NorthMet deposit is described below and presented in a stratigraphic column in Figure 1-9.

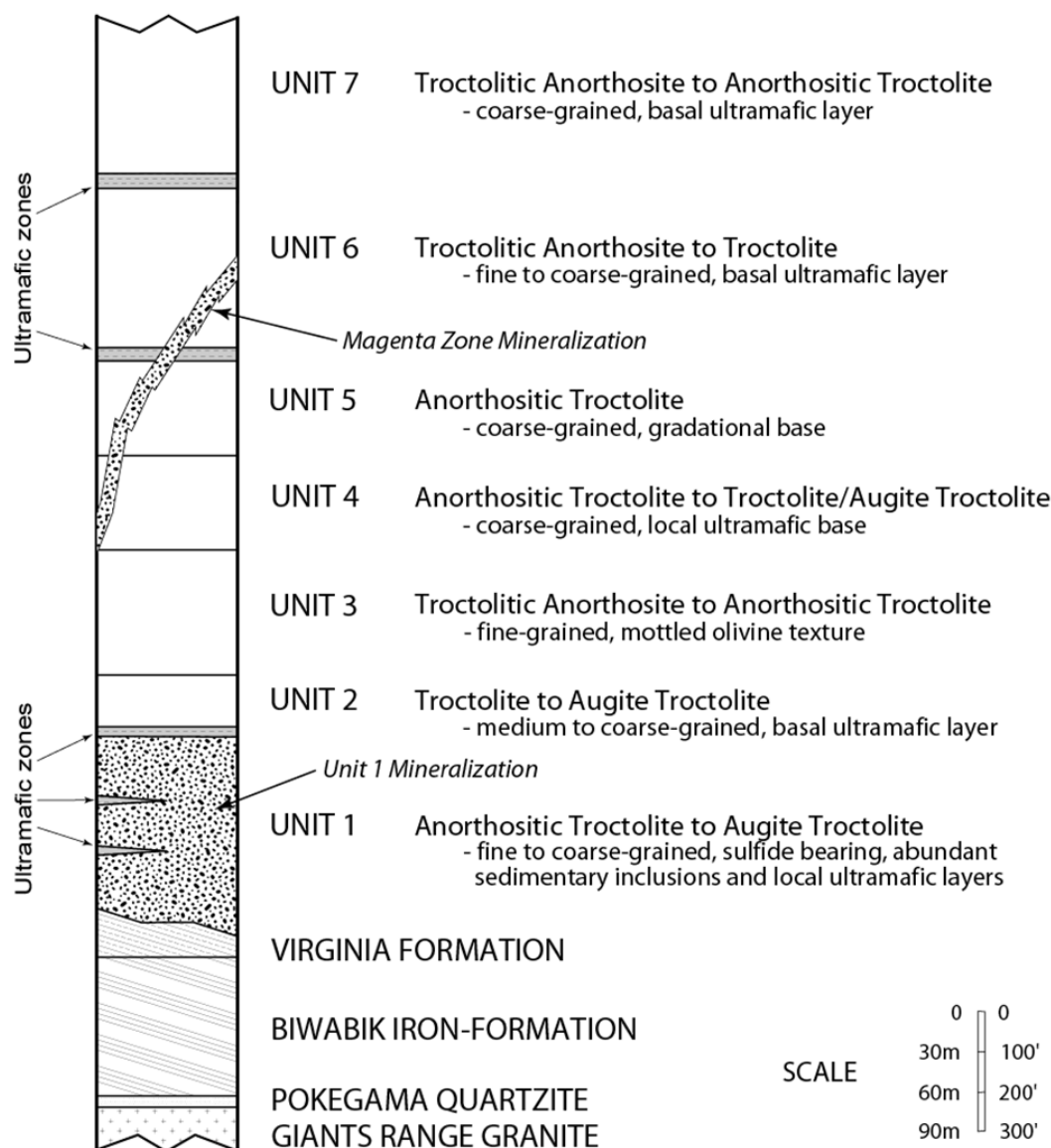


Figure 1-9. Generalized stratigraphic column for NorthMet units (modified after Geerts, 1994)

Unit 7

Unit 7 (Figures 1-9, 1-10, and 1-11) is the uppermost unit intersected in drill holes at the NorthMet Deposit. It consists predominantly of homogeneous, coarse-grained anorthositic troctolite and troctolitic anorthosite, characterized by a continuous basal ultramafic subunit that averages 20 ft. thick. The ultramafic consists of fine- to medium-grained melatroctolite to peridotite and minor dunite. The average thickness of Unit 7 is unknown due to erosion removing the upper parts. Unit 7 is generally not mineralized.

Unit 6

Very similar to Unit 7, Unit 6 is composed of homogeneous, fine- to coarse-grained, troctolitic anorthosite to troctolite. It averages 400 ft. thick and has a continuous basal ultramafic subunit that averages 15 ft. thick. Overall, sulfide mineralization is minimal, although a number of drill holes in the southwestern portion of the NorthMet Deposit contain significant sulfides and associated elevated PGEs

(Geerts 1991, 1994). Sulfides within Unit 6 generally occur as disseminated chalcopyrite/cubanite with minimal pyrrhotite. This mineralized occurrence, the “Magenta Zone”, transitions into Units 3, 4, and 5, and is discussed in greater detail below.

Unit 5

Unit 5 exhibits an average thickness of 250 ft. and is composed primarily of homogeneous, equigranular-textured, coarse-grained anorthositic troctolite. Anorthositic troctolite is the predominant rock type, but can locally grade into troctolite and augite troctolite towards the base of the unit. The lower contact of Unit 5 is gradational and lacks any ultramafic subunit, therefore the transition into Unit 4 is a somewhat arbitrary pick. Due to the ambiguity of this contact, thicknesses of both units vary dramatically. However, when Units 5 and 4 are combined, the thickness is fairly consistent deposit-wide. Aside from Magenta Zone mineralization in the west, Unit 5 is not mineralized.

Unit 4

Being somewhat more mafic than Unit 5, Unit 4 is characterized by homogeneous, coarse-grained, ophitic augite troctolite with some anorthositic troctolite. Unit 4 averages about 250 ft. thick. At its base, Unit 4 may contain a local thin (usually no more than 6 inch) ultramafic layer or oxide-rich zone. The lower contact with Unit 3 is generally sharp. Unit 4 is rarely mineralized outside the Magenta Zone.

Unit 3

Unit 3 is used as the major “marker bed” in determining stratigraphic position in the PRI. It is composed of fine- to medium-grained, poikilitic and/or ophitic, troctolitic anorthosite to anorthositic troctolite. Characteristic poikilitic olivine gives the rock an overall mottled appearance. On average Unit 3 is 300 ft. thick. As with Units 4 and 5, the thickness of Units 2 and 3 tend to be highly variable, whereas if combined into one unit, it is more consistent deposit-wide (though not as consistent as Units 4 & 5).

Unit 2

Unit 2 is characterized by homogeneous, medium- to coarse-grained troctolite and augite troctolite with a consistent basal ultramafic subunit. The continuity of the basal ultramafic subunit, in addition to the relatively uniform grain size and homogeneity of the troctolite, makes this unit distinguishable from Units 1 and 3. Unit 2 has an average thickness of 100 ft. The ultramafic subunit at the base of Unit 2 is the lowermost continuous basal ultramafic horizon at the NorthMet Deposit, averages 25 ft. thick, and is composed of melatroctolite to peridotite and minor dunite.

In some ways the characteristics of Unit 2 and how it fits into the stratigraphy are ambiguous. It can be interpreted as the lower part of Unit 3, the upper part of Unit 1, or a separate unit. Based on continuity of the ultramafic boundary it seems to be a lower, more mafic, counterpart to Unit 3 or a separate unit. However, even though Unit 2 has been historically described as barren, in the western part of the deposit it appears to have mineralization grossly continuous with that at the top of Unit 1. The general lack of footwall inclusions would argue against Unit 2 being older than Unit 1.

Unit 1

Of the seven igneous rock units represented within the NorthMet Deposit, Unit 1 is the only unit that contains significant deposit-wide sulfide mineralization. Sulfides occur primarily as disseminated interstitial grains between a dominant silicate framework and are chalcopyrite > pyrrhotite > cubanite > pentlandite. Unit 1 is also the most complex unit, with internal ultramafic subunits, increasing and decreasing quantities of mineralization, complex textural relations and varying grain sizes, and abundant sedimentary inclusions. It averages 450 ft. thick, but is locally 1,000 feet thick and is characterized lithologically by fine- to coarse-grained heterogeneous rock ranging from anorthositic troctolite (more abundant in the upper half of Unit 1) to augite troctolite with lesser amounts of gabbro-norite and norite (becoming increasingly more abundant towards the basal contact) and numerous sedimentary inclusions.

By far the dominant rock type in Unit 1 is medium-grained ophitic augite troctolite, but the textures can vary wildly. Two internal ultramafic subunits occur in drill holes in the southwest, and have an average thickness of 10 ft.

Footwall rocks are covered in the Partridge River intrusion description.

Inclusions

Two broad populations of inclusions occur at NorthMet: hanging wall metabasalts (Keweenawan) and footwall metasedimentary rocks. Basalts are fine-grained, generally gabbroic, with no apparent relation to any mineralization. Footwall inclusions may carry substantial sulfide (pyrrhotite) and often appear to contribute to the local sulfur content. Footwall inclusions are all Virginia Formation, no iron-formation, Pokegama Quartzite, or older granitic rock has been recognized as an inclusion at NorthMet. Sedimentary inclusions make up about 4% of the logged rocktypes, and basalt inclusions sum to less than 1% of the drilling footage.

Inclusions and Timing

Generally, hanging wall inclusions are restricted to Unit 3 and the units above, while footwall inclusions are most abundant in Unit 1. This zoned distribution of inclusions indicates that one possible scenario for order of intrusion is that Unit 3 intruded first, created space between the basalt and the Virginia Formation, then portions of the hanging wall basalts collapsed into the Unit 3, but for some reason Unit 3 was not able to disaggregate or assimilate much of the footwall rock (due to temperature, viscosity of magma or ductility of the footwall). Unit 1 however, intruded between Unit 3 and the footwall and was able to assimilate large portions of the footwall and thus contaminate itself with both sulfur and silica. In this scenario Unit 2 is intruded after Unit 1, between Units 1 and 3, as Unit 2 has limited footwall inclusions. Unit 3's intrusion would have separated the footwall and Unit 1 from later Units 4 through 7, which never reacted with the footwall at the NorthMet site. Therefore, any footwall inclusions seen in Units 4 through 7 (and probably those seen in Unit 2) can be interpreted as being carried in from some other part of the magmatic system. Note that basalt overlies and is in direct contact with the Virginia Formation at the Wetlegs deposit to the west of NorthMet, implying that the starting conditions for this chain of events are plausible.

Other Igneous Units

Quadrangle scale outcrop mapping indicates that other igneous stratigraphic units are present above Unit 7. These units are similar to Units 6 and 7 in that they consist of homogeneous-textured troctolitic rocks with basal ultramafic members.

There are minor, unmineralized, pre-Complex sills in both the Virginia Formation and Biwabik Iron Formation at NorthMet (VirgSill and BIF Sill in footwall descriptions above). In neither case is there any apparent relation to Duluth Complex mineralization. Early sills in the Virginia probably metamorphosed the Virginia, forming a zone that resisted assimilation during later intrusion of the Complex—hence leading to the thin “rind” of metamorphosed Virginia on top of the BIF seen in the deeper downdip drill holes at NorthMet.

Alteration

The vast majority of rock within the NorthMet Deposit would be considered fresh and is unaltered or only weakly altered. Types of alteration most commonly observed in NorthMet rocks are serpentinization / chloritization of olivine, sericitization and saussuritization of plagioclase, and uraltization of pyroxenes. Most alteration is related to close proximity of fractures and/or joints that cross-cut the troctolitic rocks. Likewise, on a microscopic level the center of alteration is focused around microfractures. This pattern suggests that both fracturing and accompanying alteration of the rock occur as a result of the migration of late-stage deuteric fluids during the cooling phase. The vast majority of sulfide mineralization is

independent of alteration.

Nickel in Silicates (Lab Assay Nickel vs. Recoverable Nickel)

It has been characteristic of NorthMet and other Duluth Complex deposits to show lower nickel recoveries in process test work than would be expected from laboratory assays on drill core. Generally there is a loss of about 25-35% of the nickel compared to drill core assays when concentrating sulfides. From previous work, it is known that small amounts of unrecoverable nickel occur as a magnesium-iron-nickel silicate $[(\text{Mg,Fe,Ni})_2 \text{SiO}_4]$ that is tied up in the mineral olivine, which is one of three significant gangue minerals that occur across the NorthMet deposit. Testwork has shown that most of the very small amount of nickel contained in silicates would not be recovered during the autoclaving process proposed.

For example, mineralogical studies show that approximately 25% to 35% of the rock in NorthMet is composed of olivine. Previous microprobe study, plus work by PolyMet in 2006, has shown an average of about 0.10% nickel in olivine. The approximate nickel grade of the PolyMet metallurgical bulk samples is 0.10%. Because the average nickel in the olivine is the same as the average nickel in the bulk samples, the unrecoverable nickel in the olivine would be expected to reduce nickel recovery by the amount of olivine in the bulk sample - 25% to 35%. Nickel recoveries on the six PolyMet metallurgical bulk samples have ranged from 69% to 77%. This is in line with an approximate 25% to 35% loss of nickel to silicate.

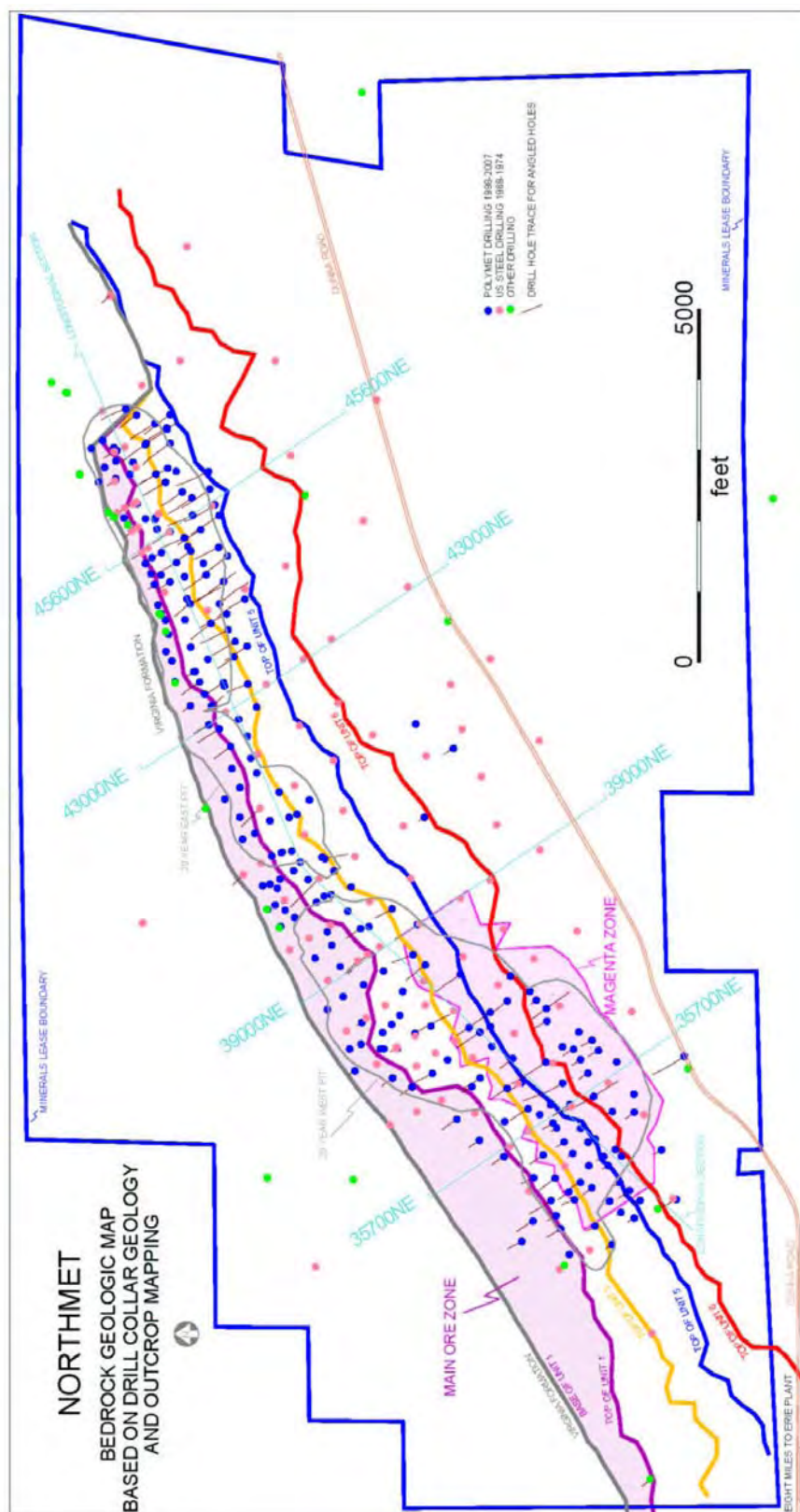


Figure 1-10. Geologic map of NorthMet Deposit, all units dip southeast, Magenta Zone is projected upward, does not actually subcrop

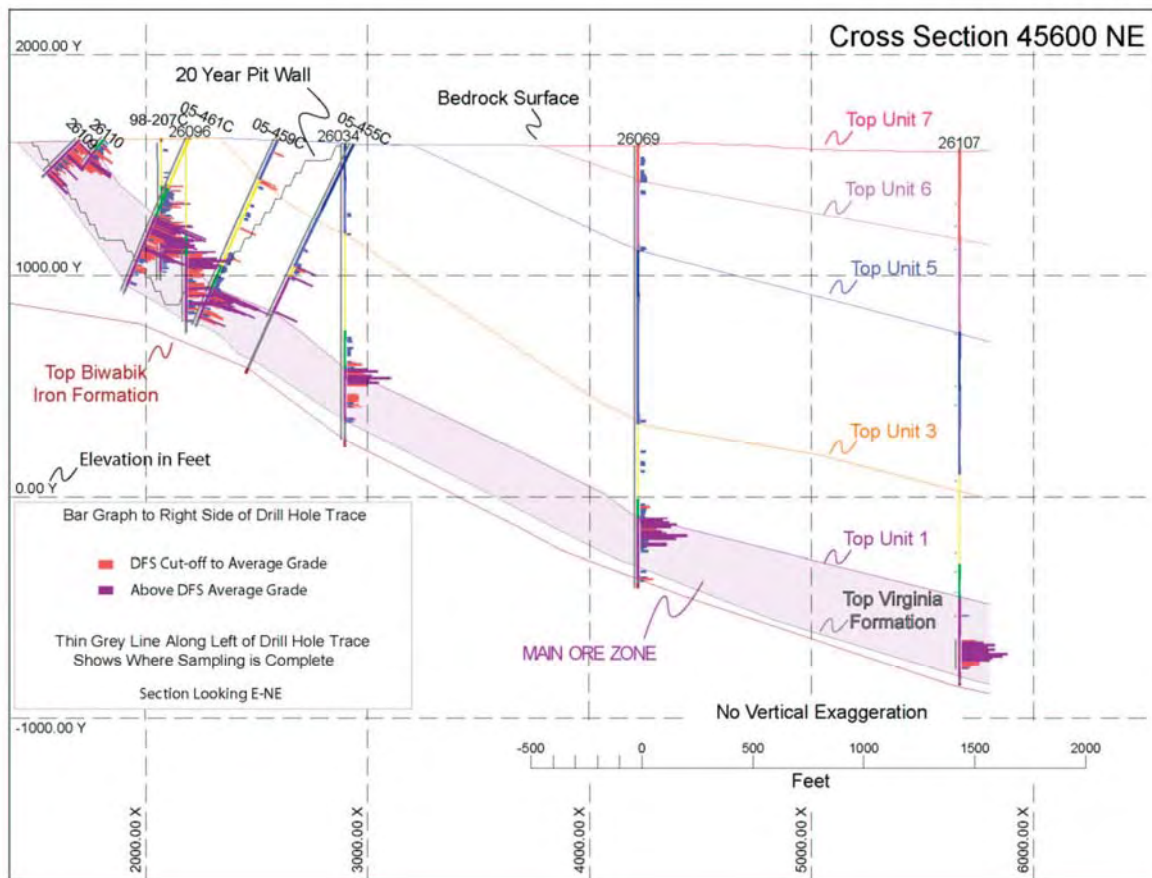
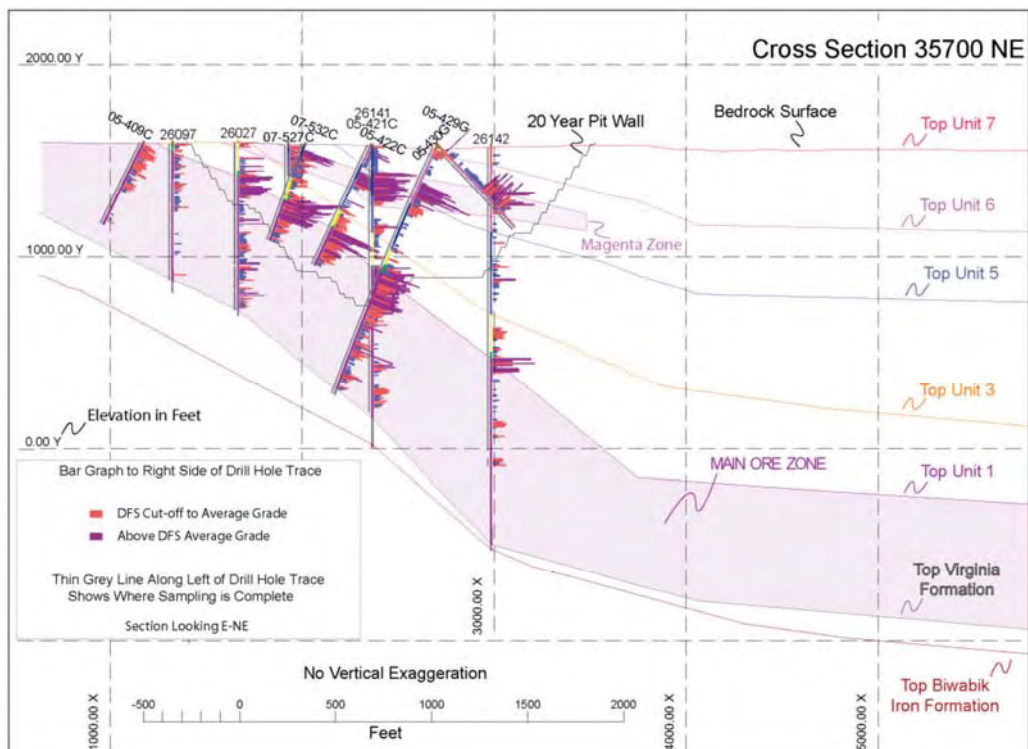


Figure 1-11. Cross section 35700 at west end of property and 45600 at east end. Purple shading indicated ore zones, bar graphs along holes indicate grades expressed as dollar values, where red = \$7.42 cut-off to average grade (~\$14.39), and purple shows above average grade, blue are zones of potential lean ore should metals prices rise.

ECONOMIC MINERALIZATION

The majority of economic mineralization (copper, nickel, cobalt, platinum, palladium, and gold) at NorthMet occurs in the upper parts of basal Unit 1, with copper and nickel in chalcopyrite, cubanite, and pentlandite, all in the presence of pyrrhotite. Cobalt is contained in sulfides. Platinum, palladium, and gold, while showing good correlation with sulfur and the other metals, are also in a variety of tellurides, bismuthides, and alloys, as well as associated with the major and minor sulfides. Table 1-3 shows correlation of metals values in drill core data.

Table 1-3. Simple correlation ® table for economic metals and sulfur

	Cu %	Ni %	S %	Pt ppb	Pd ppb	Au ppb	Pt+Pd+Au	Co ppm	Zn ppm
Cu %	1.000								
Ni %	0.860	1.000							
S %	0.541	0.572	1.000						
Pt ppb	0.568	0.508	0.195	1.000					
Pd ppb	0.750	0.635	0.292	0.673	1.000				
Au ppb	0.591	0.472	0.250	0.482	0.699	1.000			
Pt+Pd+Au	0.760	0.645	0.292	0.778	0.983	0.755	1.000		
Co ppm	0.544	0.704	0.621	0.217	0.281	0.241	0.288	1.000	
Zn ppm	-0.021	-0.004	0.286	-0.041	-0.037	-0.017	-0.039	0.093	1

The simple correlation table above (number of samples=19,516) shows the strong relation of copper, nickel, and palladium, and a somewhat surprising relation of cobalt to sulfur. Zinc's low factor is probably related to its multiple origins as either magmatic or derived from assimilation of footwall rock, hence representing two populations of data. The sulfur vs. metal correlation is probably greatly affected by iron, the presence of which is not shown here, but is in excess in all rocks.

Grades are highest at the top of Unit 1 and fade going down hole. Grades appear to be higher down-dip though this may be an artifact of less dense sampling. There is a smaller zone of economic mineralization (about 50 million tons) at the western end of the property in the upper units, known as the "Magenta Zone." This zone is generally copper and PGE-rich (sulfur-poor relative to metals) and of "average" reserve grade.

The minerals of interest from a waste characterization perspective are the same as above, but pyrrhotite is expected to be the main mineral affecting water quality in regards to waste rock, though the traces of chalcopyrite, cubanite and pentlandite will require study for waste rock storage. Trace pyrite and pyrrhotite are the main sulfide minerals found in the tailings. Pyrite is largely from joint faces and other secondary sources-it is rarely seen in polished section or core.

Most sulfide mineralization at NorthMet is of a distant source (but sedimentary?), some is locally modified by sulfur derived from footwall metasedimentary rocks (Virginia Formation). Minor veins and other cross-cutting relations indicate some movement of sulfides within the deposit, but there is no evidence recognized for large scale relocation of sulfides, nor any macroscopic evidence for any hydrothermal event that may have remobilized PGE's or sulfides.

Virtually all sulfide mineralization at NorthMet moved in with magmatic pulses, and metal enrichment of the magma happened in a deeper chamber. Therefore, the main controls on the location of mineralization within the deposit may be the specific magmatic pulse or pulses making up the individual units. While textures in Unit 1 are described as heterogeneous, there is also a broad homogeneity in regards to mineral

occurrence, mineral chemistry, whole rock and REE chemistry, and gross rock type that all reinforce the view of a large system of magma pulses replenishing the resident magma at the NorthMet site.

The exception to this is that some sulfur, particularly in Unit 1, was derived locally from assimilation of footwall rocks (evidenced by high pyrrhotite content nearer footwall inclusions). The main effect of this assimilation has been to dilute the sulfide grade with additional pyrrhotite in Unit 1, rather than this sulfur scavenging more base metals from the magma.

RESOURCE

The PolyMet resource and reserve (Table 1.4) models have been done in cooperation with several consultants, most recently PEG Mining of Toronto. PolyMet supplies the geologic solids model, database, and block model geometry. Geostatistics and population of the block model, and hence the resource estimate, are done in consultation, with finalized resource block models then sent forward to engineers for reserve calculation and mine planning. Resource geologic modeling treats the NorthMet deposit as five separate domains:

1. Virginia Formation footwall rocks;
2. a domain including the upper, higher grade parts of Unit 1, locally merged with the higher grade zones at the base of Unit 2;
3. the remainder (lower part) of Unit 1;
4. the Magenta zone in Units 3, 4, 5, & 6 in the western part of the deposit;
5. and the remaining, less mineralized, parts of Units 2 through 7.

Unit 1 is mineralized throughout the deposit area, with other units (2 through 6) showing some economic mineralization in the western and central parts of the deposit, but essentially no continuous zones in the east. There is no known economic mineralization in the footwall rocks. Deposit wide, Unit 1 has the highest grades near its top.

Though grades vary, Unit 1 is also mineralized to the east of the deposit, down-dip (south) to depths of at least 2,500 feet, and past the limits of expected pit development in the west. The development of waste rock stockpiles over these areas in the east and south is not expected to encumber any material that could reasonably be classed as ore because the upper units are barren and the Unit 1 mineralization is from 1,700 to over 2,500 feet below ground surface.

For modeling purposes, Unit 1 is bounded by both “hard” and “soft” geologic surfaces. A “hard” boundary is one where the interpolation of drill hole data into the block model does not cross geological surfaces, a soft boundary is one where interpolation crosses geological boundaries. The top of Unit 1 (i.e., the ultramafic at the base of Unit 2) is a soft boundary for mineralization estimation as the mineralized domain model crosses from Unit 1 into Unit 2. The base of Unit 1, where it contacts the Virginia Formation, is a hard boundary for estimation and metals values, with virtually all sulfide in the Virginia Formation below as pyrrhotite. No data from Unit 1 is used in estimating grades in the Virginia Formation, or vice versa.

In the up-dip, west half of the deposit there is an arbitrary and diffuse geologic boundary within Unit 1 that vanishes to the east. This is roughly equal to the top of a petrological contamination zone where large quantities of the footwall metasedimentary rocks have been assimilated. This zone is informally called the “front” or “norite zone” by PolyMet geologists. Precious metals values drop off in this zone and pyrrhotite becomes the dominant sulfide. Moderate copper values may persist below this line, but this is essentially a lower physical limit to combined polymetallic grades above the likely project cut-offs.

Table 1-4. NorthMet resource and reserve values. Work done by Wardrop Engineering 2007. Cut-off based on “Net Metals Value” per ton, accounting for grade, average flotation and hydromet recovery, realization costs, metal prices, and other factors. See Desautels and Patelke, 2008 for resource calculation details. Enough reserve has been shown for 24 years of production.

RESERVES-2007

	Cut-off value	Million Tons	Cu %	Ni %	Co ppm	Pt ppb	Pd ppb	Au ppb
Proven	\$7.42	118.1	0.30	0.09	75	75	275	38
Probable	\$7.42	156.5	0.27	0.08	72	75	248	37
Proven and Probable	\$7.42	274.6	0.28	0.08	73	75	260	37

RESOURCES-2007

	Cut-off value	Million Tons	Cu %	Ni %	Co ppm	Pt ppb	Pd ppb	Au ppb
Measured	\$7.42	202.5	0.285	0.083	74	71	258	36
Indicated	\$7.42	491.7	0.256	0.075	70	66	231	34
Measured & Indicated	\$7.42	694.2	0.265	0.077	71	68	239	35
Inferred	\$7.42	229.7	0.273	0.079	56	73	263	37

ASSUMPTIONS

Metal and Units	Cu %	Ni %	Co ppm	Pt ppb	Pd ppb	Au ppb
Assumed Metal Price	\$1.25 lb	\$5.60 lb	\$15.25 lb	\$800 oz	\$210 oz	\$400 oz
Average % recovery, as used in DFS	92.33	70.34	40.75	75.74	72.69	67.04

In the center of the deposit the highest, near surface, Unit 1 grades transition into the middle of the unit, while in the east, mineralization is strong and vertically persistent throughout the unit. The top of the merged Unit 1 and Unit 2 mineralized domain (domain 1) forms a hard boundary that, combined with the bedrock ledge (depth to bedrock) surface, forms the bottom and top estimation boundaries for the upper units (exclusive of the “Magenta Zone”, which is internal to this domain). There is no conclusive relation between specific Unit 1 specific rock type and presence or grade of mineralization except that noritic rocks are generally of lower grade.

Units 2 and 3: These units are treated as one unit in the geologic model, with PolyMet geologists considering them as a single package grading from an ultramafic base to an anorthositic top for modelling purposes. The thickness of the package stays relatively constant, though the thickness of the two individual units varies, primarily due to Unit 2 locally thinning.

While generally barren, Unit 2 has mineralization at its base in the western half of the deposit. These zones may not be strictly equivalent to Unit 1 type mineralization. Copper and nickel values are lower, as is pyrrhotite, but behavior of other metals is inconsistent, with PGE (Pt + Pd +Au) content varying locally relative to nearby grades at the top of Unit 1. Above the basal zone of Unit 2 it is usually barren, medium-grained, and homogenous in texture. Average PGE in Unit 2 is slightly above that of Unit 1.

Unit 3 shows mineralization in the west, in the middle of the unit and near the top. This occurrence is merged into the Magenta Zone.

Units 4 and 5 are also modeled as a geologic package. There is no compelling geologic reason to fully separate these units, the boundary between them being an arbitrary pick based on overall changes in texture from homogenous to heterogeneous, grain size, and plagioclase content, but without a well defined

bounding horizon. The top boundary of Unit 5 is the basal ultramafic of Unit 6, which is an unused hard boundary in grade modelling. The bottom boundary of Unit 4 is a discontinuous ultramafic horizon. There are also discontinuous oxide-rich zones along the contact between Units 3 and 4.

Metals and sulfur grades in Unit 4 are proportional to Unit 1, but consistently lower. Unit 4 has few high copper or sulfur assay intervals. There is some near surface mineralization, modelled as a part of the Magenta Zone, described below. Otherwise there is only low grade, discontinuous material at the base.

Unit 6 and Unit 7: These units are very similar in nature. Both are homogenous anorthositic troctolites with well defined ultramafic bases. No top for Unit 7 has been seen in drill hole.

Units 3, 4, 5 and 6 host a zone of mineralization, modeled as the Magenta Zone. Unit 6 material was described by Geerts (1994) as the “Magenta Horizon” when originally found in six drill holes. Further drilling has extended these copper rich, sulfur poor zones (of moderate overall grade) into more than fifty drill holes in Units 3, 4, 5, and 6. The zone transitions across the ultramafic base of Unit 6 and into Units 3, 4 and 5, (i.e., does cross the igneous stratigraphy) which is problematic if the emplacement model of these units representing individual pulses of magma is correct. There is no gross evidence for this mineralization being hydrothermal, which could cross boundaries, but would presumably alter large masses of rock.

Unit 7 has a few good assay intercepts, but no apparent continuity for sulfides.

Table 1-5. Average values for assays by unit after removal of the less than 0.05% copper intervals (drill core samples). Unsampld zones not accounted for here. Data complete through 2006.

	Cu %	Ni %	S %	Pt+Pd+Au ppb	Co ppm	Cu+Ni %	Cu/Ni	Cu/S	Total % of unit sampled	Average sample length-feet
Unit 1	0.3	0.09	0.83	349	76	0.39	3.35	0.43	90	5.3
Unit 2	0.2	0.07	0.39	365	73	0.27	2.74	0.61	80	5.6
Unit 3	0.19	0.05	0.5	286	62	0.25	3.19	0.53	71	7.2
Unit 4	0.21	0.06	0.58	269	66	0.28	3.40	0.44	51	7.6
Unit 5	0.27	0.07	0.54	398	65	0.35	3.64	0.54	41	7.8
Unit 6	0.33	0.08	0.48	532	69	0.41	3.74	0.69	27	7.2
Unit 7	0.2	0.06	0.32	330	83	0.26	3.60	0.72	11	8.4

Copper, nickel, and sulfur values in Table 1-5 are calculated after removing samples with less than 0.05% copper. Samples removed are generally those collected for waste characterization purposes, many well outside the expected mining area, and these low values can somewhat obscure the ore chemistry / mineralogy relations in the “ore.” Ratios are calculated on all raw data, not on the copper-nickel-sulfur values shown here.

- No lateral or vertical zonation has been recognized in sulfide or silicate mineral Chemistry;
- Gatehouse (North Mining) did report some geochemical cyclicity in unit 1, but this has not been revisited with the larger data set;
- Poor assay grades in the noritic rocks are related to footwall assimilation and contamination, otherwise there is little connection between grades and specific rock type. About 83% of the igneous rocks at NorthMet are troctolites, 6% anorthositic rocks, 4% ultramafic rocks, and 4% footwall inclusions. The remainder are norites, gabbros, and other;
- Within Unit 1 copper:sulfur ratio tends to be highest at top, then diminishes with depth, following the pattern of PGE’s;

- The upper units have higher copper:sulfur ratios than Unit 1 (i.e., more chalcopyrite rich), but lower overall copper values;
- Ratio of PGE to copper is lowest in Unit 1, but Unit 1 has greatest quantities of both;
- Chalcopyrite is the dominant sulfide in the upper units regardless of total sulfur content;

Sulfide (Ore) Mineral Proportions

Various metallurgical test programs have been conducted on NorthMet ores since the 1970's. Reported sulfide mineral proportions have not been entirely consistent between these tests. Table 1-6 shows well characterized sulfide mineral proportions for waste rock from studies done by PolyMet in 2006 and results from various previous studies.

Sulfide mineralogy within the NorthMet Deposit has been described in detail through petrographic observations and microprobe analysis. Approximately 95-98% of all sulfide mineralization consists of 4 predominant species, in decreasing order of abundance: chalcopyrite (cp) > pyrrhotite (po) > cubanite (cb) > pentlandite (pn). In general, Po:Cp+Cb ratios increase towards the basal contact or in proximity to sedimentary inclusions. Likewise, Cp:Cb ratios increase with increased distance away from the footwall rocks. In core logging and other work, chalcopyrite is often not distinguished from cubanite.

The results show a fairly wide range of values, which may not be totally representative of the deposit as a whole. It is important to note that these discrepancies may be the results of differences in composites, mixed intervals from multiple units including both waste rock and ore, or variations in petrography or laboratory procedures. Some of the composite samples submitted for metallurgical studies were prepared from relatively limited representative core (NERCO samples from 2 drill hole locations), while others were prepared from multiple locations evenly distributed across the deposit.

Table 1-6. Sulfide Average Percentage (recalculated to 100 % Sulfide)

METALLURGICAL STUDIES:	Chalcopyrite %	Cubanite %	Cp:Cb ratio	Pyrrhotite %	Pentlandite %
SGS Lakefield 1991 (NERCO L1)	44	12	4:1	2	9
SGS Lakefield 1991 (NERCO H1)	36	18	2:1	3	8
SGS Lakefield 2000 (PolyMet Conc.)	32	14	2:1	27	7
SGS Lakefield 2005 (Comp. 1)	37	9	4:1	38	16
SGS Lakefield 2005 (Comp. 2)	42	7	6:1	36	15
SGS Lakefield 2005 (Comp. 3)	36	7	5:1	41	16
INDEPENDENT STUDIES:	-	-	-	-	-
Geerts 1994 (Unit 1 – Ore)	54	15	4:1	21	3
POLYMET WASTE ROCK STUDY 2006:	-	-	-	-	-
Unit 6	76	6	12:1	5	4
Unit 5	55	3	17:1	17	5
Unit 4	41	5	8:1	32	16
Unit 3	48	6	9:1	35	5
Unit 2	52	13	4:1	24	9
Unit 1	39	7	6:1	44	9

Mining

Mining (Figure 1-12) at NorthMet will begin with contractor clearing and overburden stripping of the pit and stockpile areas. Engineered stockpile bases and liner systems must be in place before mining begins,

as does the overall water collection system for treatment and pumping to the tailings basin. Ore and waste production will start in the east pit, with production from the west pit ramping up soon afterwards. Up through about year 11 or 12 production from both pits will be equal until the east pit is mined out. At that point, backfilling of the east pit will begin, with the ultimate goal of constructing a wetland in that pit. The central pit area will be mined last.

Ore will be moved at a rate of 32,000 tons per day. Waste to ore strip ratio will be about 1.46:1. Ore will be moved by truck to the “superpocket” and loaded to 100 ton capacity side dump rail cars by pan feeder. There will be twenty trains per day of 16 cars each. Trains will go to the crushers via the existing rail line parallel to the Dunka Road and a short run of new track through the former LTV pits. The equipment fleet is expected to be eight 240 ton haul trucks, two electric hydraulic shovels, one large wheel loader, two rotary blasthole drills, plus bulldozers, rubber tired dozers, road graders, water trucks, and smaller fleet vehicles. GPS control for dispatch is planned for all equipment, with high precision GPS planned for the shovels and drills. High precision GPS may also be installed on the haul trucks.

Bench heights will be forty feet. Ore blast patterns will have blasthole burden and spacing of 25' by 28', and the holes will have 5' of subdrilling and 17' of stemming. Waste rock blast patterns will have blasthole burden and spacing of 29' by 34', 6' of subdrilling and 20' of stemming. ANFO and emulsion blends will be the explosives used.

Ore and waste categorization (“ore control”) will be by assay of core and / or blast holes and careful pit mapping. Waste material will be sorted to stockpiles, and stockpile liners will be built, according to the sulfur and metals content of the waste rock. Over 80% of the waste rock will never produce acid drainage, and about 4% will produce acid drainage within one year. Safe final disposition of this rock will be a permit condition, but as yet the state has not concluded what that condition will be. PolyMet has proposed to place some under capping systems, and to place some underwater.

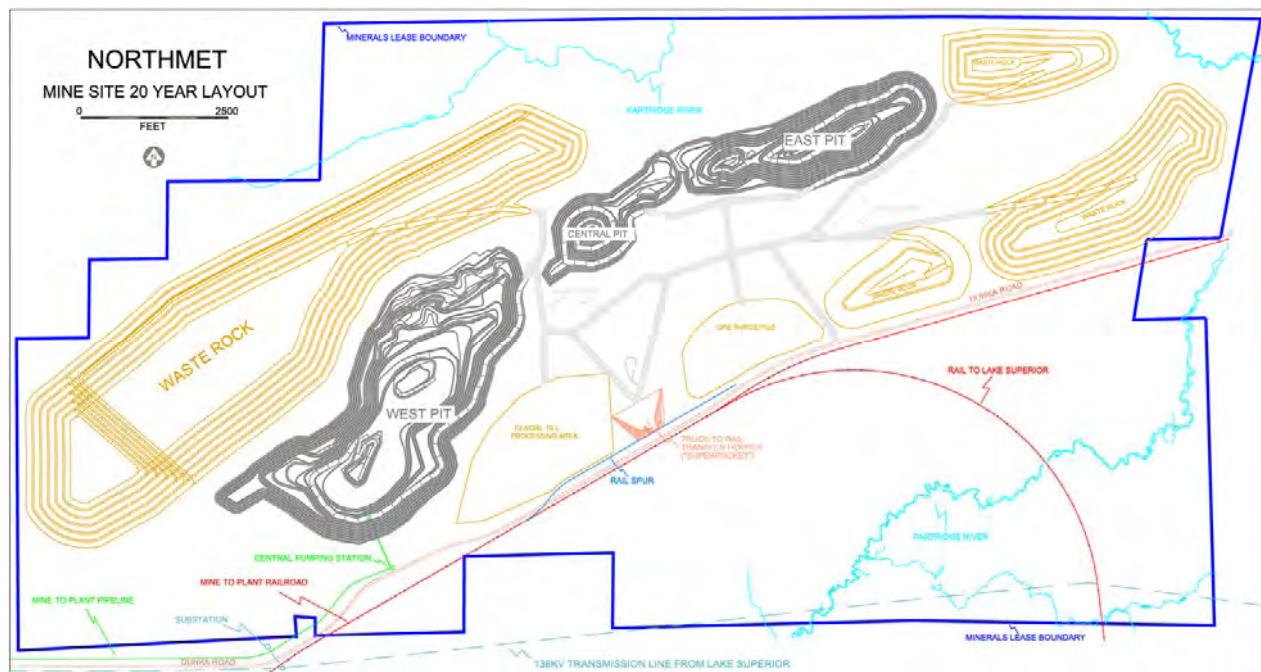


Figure 1-12. Layout of mine site showing 20 year pits, stockpiles for various waste categories, haul roads, railroad, pipelines, lease boundary, and loadout.

PolyMet Process Plant

The Plant Site consists of three areas:

- Process Plant - discussed in this section – beneficiation and hydrometallurgical processing facility including Tailings Basin and Hydrometallurgical Residue Facility
- Area 1 Shop – mine mobile equipment major repair facility
- Area 2 Shop – base of mine and railroad operations, locomotive service facility, rail car maintenance facility

The Process Plant design is based on key parameters determined by the characteristics of the deposit to be mined and the beneficiation and hydrometallurgical processes that will extract the metals from the ore. On average, 32,000 short tons of ore will be processed each day. This results in annual metal production of 38,821 short tons of copper, 9,037 short tons of nickel, 400 short tons of cobalt, 22,184 ounces of platinum, 87,129 ounces of palladium and 13,824 ounces of gold.

The process plant is located at the LTVSMC plant site. The entire Process Plant is in an area that was previously disturbed by mining operations. The Beneficiation Plant will use the Coarse Crusher Building, Fine Crusher Building and Concentrator Building that were part of the LTVSMC taconite plant. The Hydrometallurgical Plant will be located in the three new buildings constructed at the LTVSMC site - the Hydrometallurgical Facility, the Cu Solvent Extraction Building and the Cu Electrowinning Tank House.

The Beneficiation Plant consists of the following processing steps:

- Ore Crushing – reducing 48” ore from the mine to 2.5” in the Coarse Crusher Building and from 2.5” to 0.315” in the Fine Crusher Building
- Ore Grinding – reducing the 0.315” ore from the Fine Crusher Building to 120 microns in the Concentrator Building
 - Flotation – separating the ore into
 - Concentrate containing the minerals with the metals to be extracted in the Hydrometallurgical Plant
 - Tailings containing the rock in the ore that is not valuable to be pumped to the Tailings Basin
- Concentrate Regrinding – reducing the size of the concentrate particles from 120 micron to 15 micron

The flotation process has been designed to recover virtually all of the sulfide minerals to the concentrate and minimize the amount of sulfide minerals remaining with the tailings. This process has been tested with ore samples representing the NorthMet ore in a pilot plant set up to represent the proposed grinding and flotation process. The flotation tailings generated by this work has been subjected to rigorous waste characterization. Collectively this has demonstrated that the flotation tailings can be placed in the LTVSMC Tailings Basin.

The Hydrometallurgical Plant consists of the following processing steps:

- High Pressure Oxidation Autoclave.
 - Oxidize the copper, nickel, cobalt, iron sulfides and the gold and platinum group minerals (AuPGMs) contained in the concentrate to liberate the contained metal and drive those metals into a leach solution.
 - Generate a leach residue containing the portions of the concentrate that did not dissolve.
- AuPGM Precipitation – precipitate the AuPGMs from the leach solution and filter the precipitated solids to be sold as a product for further refining.

- Solution Neutralization – neutralize the leach solution (minus AuPGMs) by adding limestone and generating a solution neutralization residue.
- Copper Solvent Extraction – separate the leach solution (minus AuPGMs) into two components.
 - A strip solution containing the copper.
 - A raffinate solution containing the non copper portions of the leach solution plus residual copper.
- Copper Electrowinning – transfer the copper from the strip solution onto plates as a very pure final product.
- Raffinate Neutralization with Iron and Aluminum Removal.
 - Neutralize the raffinate solution (minus AuPGMs and copper) by adding limestone and generating a raffinate neutralization residue.
 - Precipitate iron and aluminum (which behave as impurities in downstream processing) with the raffinate neutralization residue.
- Residual Copper Removal – precipitate residual copper from raffinate solution and recycle.
- Mixed Hydroxide Precipitation – precipitate the nickel, cobalt and zinc from the raffinate solution and filter the precipitated solids to be sold as a product for further refining.
- Magnesium Removal – precipitate magnesium from the raffinate solution and pump the precipitated solids to the Hydrometallurgical Residue Facility along with the leach residue, solution neutralization residue, and raffinate neutralization residue. These residues are not hazardous waste individually or combined. The total annual residue generation is 794,000 short tons.
- The Hydrometallurgical Residue Facility will be located within the LTVSMC Tailings Basin. The facility will have engineered lined containment areas designed for the residues to be disposed.

Water management at the Plant Site will:

- Segregate water that has contacted hydrometallurgical residues in the Hydrometallurgical Plant and the lined Hydrometallurgical Residue Facility and recycle it to the Hydrometallurgical Plant.
- Collect water that has seeped from the Tailings Basin and return it to the Tailings Basin for reuse.
- Use treated water from the Mine Site (via the Tailings Basin) as make-up water.
- Supplement the Mine Site make-up water with new water from Colby Lake.

The result is that there is no surface discharge of process water at the Plant Site and that the requirement for make-up water via water appropriation from Colby Lake is minimized.

The Plant Site already has required service infrastructure available:

- County Road 666 ends at the Main Gate for the industrial area that included the NorthMet Process Plant, Area 1 Shop and Area 2 Shop.
- The Canadian National Railroad serves the industrial area that included the NorthMet Process Plant, and existing PolyMet track connects to the Area 1 Shop and the Area 2 Shop.
- Three Minnesota Power 138Kv transmission lines serve the NorthMet substation.
- Access to railroad line from mine to plant site

The closure plan for the Plant Site consists of standard mineland reclamation practices and landfill closure practices (for the Hydrometallurgical Residue Facility). Original watersheds will be restored to the extent practicable. Structures will be removed and the structure areas covered with soil and revegetated.

PART 3: DUNKA ROAD FIELD TRIP STOPS

By: Mark Severson

INTRODUCTION

In transiting from the PolyMet plant site to Babbitt, we will follow the Dunka Road, a private mine road originally used as a service road for the LTV railroad and to access the Dunka Pit iron mine east of the Northshore mine. The road is now controlled by PolyMet, Cliffs Erie, and Minnesota Power. Access is restricted. Note that UTM locations given for the field trip stops (Fig. 1-13) are estimates.

NORTHMET AND MESABA DEPOSITS

As the bus proceeds to Babbitt, we will make a few stops, time and weather permitting, and traverse across the southernmost limits of the NorthMet deposit and the Mesaba deposit. There is very little to see in the way of mineralized exposures for either of these deposits. However, one point to keep in mind is the immense size of these low-grade deposits. The NorthMet deposit extends for about 3 miles (4.8 km) along the road, and the Mesaba deposit extends for another 2.5 miles (4 km) along the road. The deposits are separated by undrilled and untested area along the Partridge River that is about 1 mile (1.6 km) wide. Most of the undrilled area is within the PolyMet lease area.

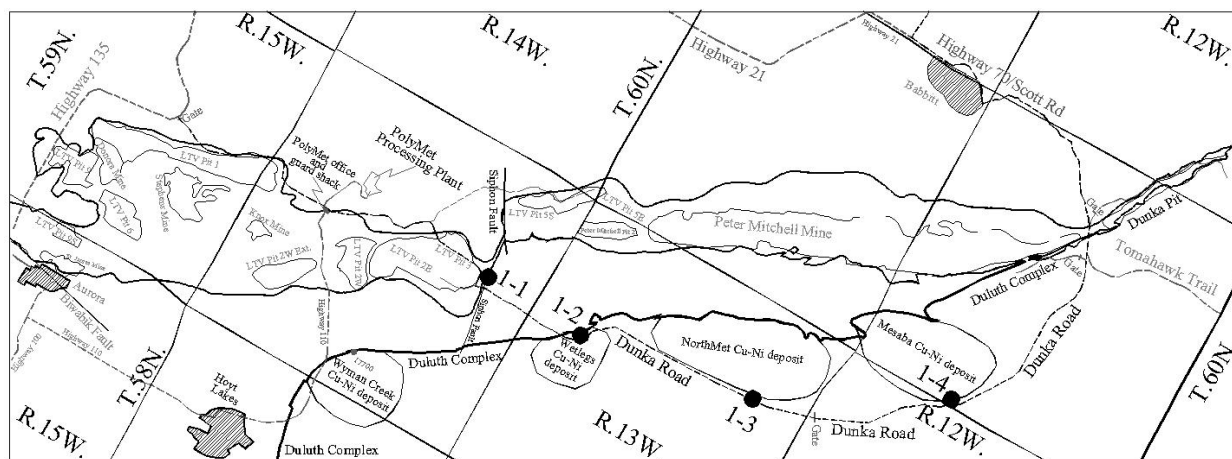


Figure 1-13. Locations of field trip stops along Dunka Road.

LTV Mine

Just outside the town of Hoyt Lakes, the bus will enter and proceed east through the now inactive LTV taconite mine. 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 in the Paleoproterozoic Biwabik Iron Formation. At least four horizons were mined: one from the Upper Slaty Member (submembers D and E); two from the Upper Cherty Member (submembers G-H-I-J, and submembers L-M); and one from the Lower Cherty Member (submembers S-T-U).

Crude ore, which contains about 30% iron, was typically crushed and ground to a powder-like consistency and passed through several stages of magnetic separation and silica flotation to form a magnetite concentrate with 67% iron content. It was then mixed with a bentonite binder and rolled in balling drums to produce “green pellets” (or balls about the size of a marble). The pellets were then conveyed to a furnace where they were heat-hardened at about 2,400° Fahrenheit (1,300° C). After the pellets were

hardened they were able to be easily handled and transported by rail to the Taconite Harbor Pier, and shipped via the Great Lakes to iron mills. In 1973, a record high of 13,104,000 tons of pellets was shipped from Taconite Harbor. 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 bought the concentrator and tailings basin from Cliffs for use in processing Cu-Ni material from the NorthMet Deposit.

As the bus progresses down the Dunka Road (a private mine-related road) through the mine area note the undulating nature of bedding planes in the iron-formation (LTV Area 3 where iron ore was mined from the Lower Cherty member). This area is located near the base of the Biwabik Iron Formation and it does not take much imagination to envision deposition of the gently undulating beds in shallow waters along the shores of the Animikie Basin. To the north (left side of bus), the iron-formation conformably overlies beach sands of the Pokegama Quartzite (bottom of the Animikie sediment package). To the south, the iron-formation is conformably overlain by deep water sediments and turbidites of the Virginia Formation (top of the Animikie sediments).

After going through Area 3 the road takes a sharp jog to the south (right). At this locale, the surface trace Siphon Fault approximates the road and iron-formation is present to the west of the road and the Virginia Formation is present across the swamp on the east side of the road. Just before the road curves back to the east to climb a low hill, take the immediate left and go down a secondary mining road for about 500 feet (150 meters). Proceed to the north on foot along a flagged trail to the next stop.

STOP 1-1: Virginia Formation near Siphon fault

No hammering please!

Location: Cliffs-Erie site, T. 59 N., R. 14 W., sec. 26, SE of SE of NE
Allen quadrangle; UTM: 569,505E/5,271,610N (NAD 83)

Description: This is the only natural exposure of the Virginia Formation on the Mesabi Iron Range. Unfortunately, it is only a few feet thick. A total of 1,443 feet (440 meters) of the formation is present in drill cores from holes drilled south of the range. Note the graded beds, mud chips, concretions, and loading at the bases of these beds. The bedding is near vertical in this location due to proximity to the north-trending Siphon fault—an inferred growth fault (Graber, 1993) wherein the iron-formation decreases in thickness to the east (across the fault) by about 100 feet (30 meters).

STOP 1-2: Wetlegs Cu-Ni Prospect / Partridge River Intrusion

Location: Rail tracks just south of Dunka Road T. 59 N., R. 13 W., sec. 18, NE of SE of SE
Allen quadrangle; UTM: 572,72E/5,271,178N (NAD 83)

A west to east traverse along the LTV railroad tracks will be conducted at this field stop. The traverse, approximately 0.5 miles (0.8 km) long, will start at the basal contact and progress upwards through the igneous stratigraphy of the Partridge River intrusion. Outcrops of Units I and III will be viewed. A generalized geologic map of the Wetlegs prospect is shown in Figure 1.13. Detailed descriptions of the railroad cuts are listed in Table 1-7 below.

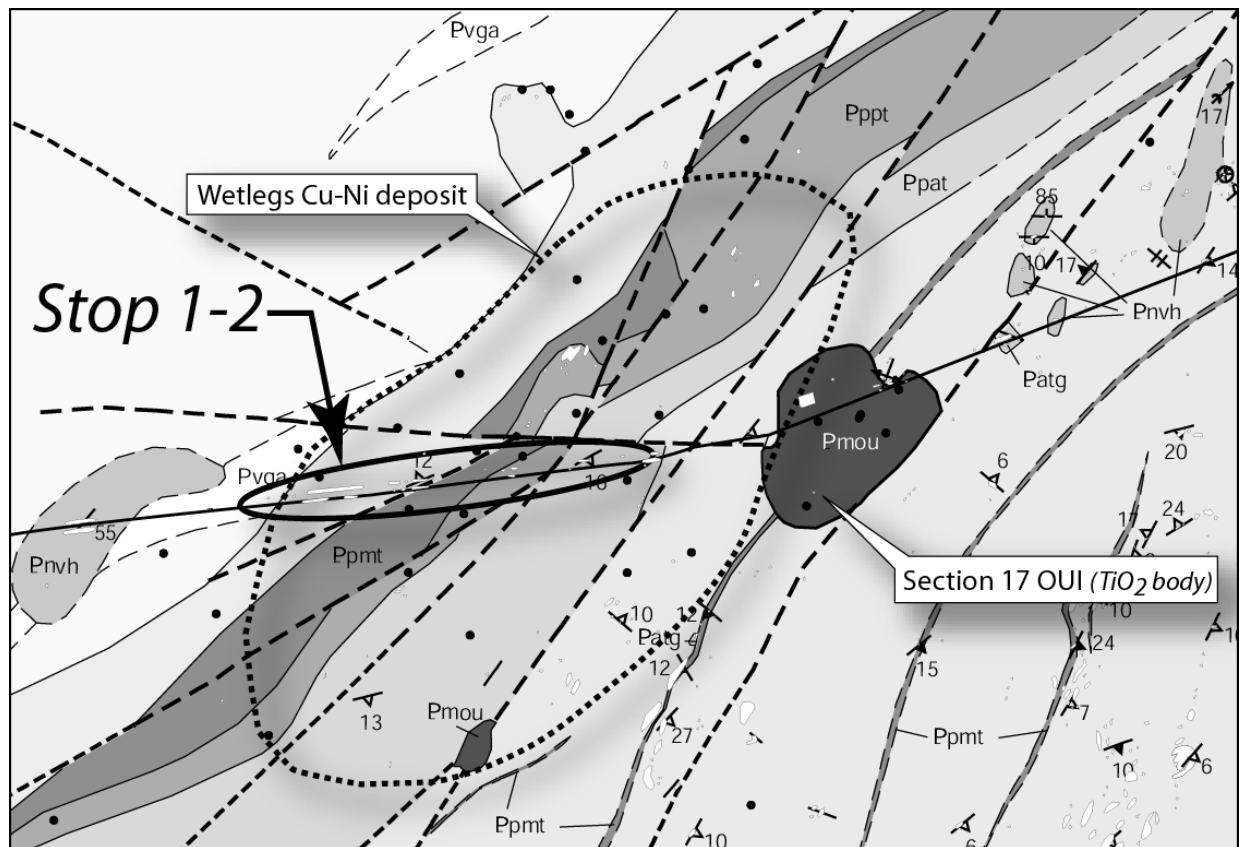


Figure 1-13. Geology of the Wetlegs Cu-Ni deposit area and the location of Stop 1-2 (Severson and Miller, 1999).

Table 1.7. Wetlegs Prospect outcrop descriptions of Stop 1-2.

Feet (W to E)	Description of Outcrops
0 ft.	Railroad culvert – Longnose Creek
100-110 ft. (left side of tracks)	Sulfide/gossan-cemented till consisting mostly of large boulders of a pyrrhotite- and graphite-rich member of the Virginia Formation (the BDD PO unit). Note the rounded granite cobbles beneath the BDD PO boulders. Drilling indicates that the BDD PO subcrops very close to this location.
337-355 ft. (left side of tracks)	Very fine-grained (chilled) gabbro at basal contact with 60% plagioclase, 30% orthopyroxene, 5 % clinopyroxene, trace to 2 % biotite, and 3 % oxides. The outcrop contains well assimilated “streaks” of Virginia Formation inclusions (very hard to see recently).
400-1025 ft. (both sides of tracks)	Unit I – taxitic medium- to coarse-grained ophitic augite troctolite (POcf) to olivine gabbro (PcOf) with patches and lenses of augite-rich pegmatite. The outcrops are sulfide-bearing with the sulfides unevenly distributed along patches, spots, lenses, and joint faces (at numerous orientations!). Trace amounts to 5% uraltite due to pervasive deuteric alteration is present.
1245-1355 ft. (two outcrops on north side of tracks)	Unit I – taxitic, pervasively uraltitized, medium- to coarse-grained ophitic olivine gabbro (PcOf) to augite troctolite (POcf) with trace to 1% sulfides. Also present within these outcrops are very coarse-grained anorthosite inclusions that vary from 10 cm across to 3x5 meter blocks. The edges of the inclusions are sharp, and straight to highly lobate. Within the inclusions, the plagioclase foliation is subvertical and highly variable.
1385-1685 ft. (many outcrops on both sides of tracks)	Unit I – taxitic, medium- to coarse-grained ophitic augitic troctolite (POcf) with abundant irregular pegmatitic patches and lenses. The pegmatites contain variable amounts of saussurized plagioclase, clinopyroxene, oxides, biotite, and uraltite, with minor quartz, k-feldspar, graphic granite, and sulfides. Most of the sulfides are either within or adjacent to the pegmatites. Uralite is common throughout the outcrops as pervasive replacement products in irregular patches and along joints.
2355-2480 ft. (four outcrops on both sides of the tracks)	Unit III – mottled, poikilitic/ophitic troctolite (Po(cf)) to augite troctolite (Pocf). This is a major marker bed due to the presence of medium- to high-density olivine oikocrysts up to 10 cm across. This unit is easily recognized in drill core due to the mottled texture, and the relatively finer-grained plagioclase (1-5 mm).

STOP 1-3: Dunka Railroad Junction-PolyMet Discussion Stop

Location: Where rail line splits along Dunka Road, T. 59 N., R. 13 W., sec. 13, NW of NE Babbitt SW quadrangle; UTM: 578,358E/5,273,795N (NAD 83)

Weather permitting we will stop here to look across a clear cut where some of the PolyMet facility will be located, talk about development plans, note Dunka Junction as a landmark on most regional maps and air photos, and look at outcrops of the upper units of the PRI (Unit VIII or 8?), barren of sulfides, but very typical. Some basalt inclusions are in the flat outcrop to the south of the road.

STOP 1-4: Dunka Railroad Hornfels and Late OUIs

Location: Abandoned rail grade, south and parallel to the Dunka Road T. 60 N., R. 12 W., sec. 33, NE of SW, Babbitt SE quadrangle; UTM: 584,808E/5,276,122N (NAD 83)

The Dunka Railroad hornfels is a large mafic volcanic inclusion located near the eastern margin of the Partridge River intrusion and just south of the Mesaba deposit. Outcrops and drill hole information indicates that the inclusion is about 900 x 1,500 meters across. The hornfels is a fine-grained, granoblastic to poikiloblastic basaltic hornfels that contains variable amounts of plagioclase, augite, hypersthene, inverted pigeonite, and olivine. Both massive and meta-amygdaloidal varieties are present.

In addition to the basaltic hornfels, several small bodies of late intrusive OUIs (Oxide Ultramafic Intrusions-cross-cutting plugs of oxide-rich rock) are also present in the railroad cuts. The abundance of OUI at this locality is related to proximity to the north-trending Grano Fault, which may have served as a feeder vent for the massive sulfides at the Local Boy area of the Babbitt/Mesaba deposit. These OUIs, and a wide variety of granitic rocks, occur as lenses and bodies that cut the troctolitic rocks of the Partridge River intrusion. They are extremely common in drill holes, within a 1,300- 1,900 foot (400-580 meter) wide zone, on the west side of the Grano Fault. The OUIs at this locality are characterized by medium- to coarse-grained clinopyroxenite with 75-80% augite, 0-15% olivine, <5% interstitial plagioclase, and 5-15% oxides (ilmenite is dominant). Contact relationships with the basaltic hornfels are sharp but highly irregular and lobate. Granitic dikes and veins, present within a NNE-trending zone, are also evident in the exposures. They are rarely observed in close proximity to the OUI, but where they are, the dikes crosscut the OUI. Four sites, shown on Figure 1-14, can be observed at this locality.

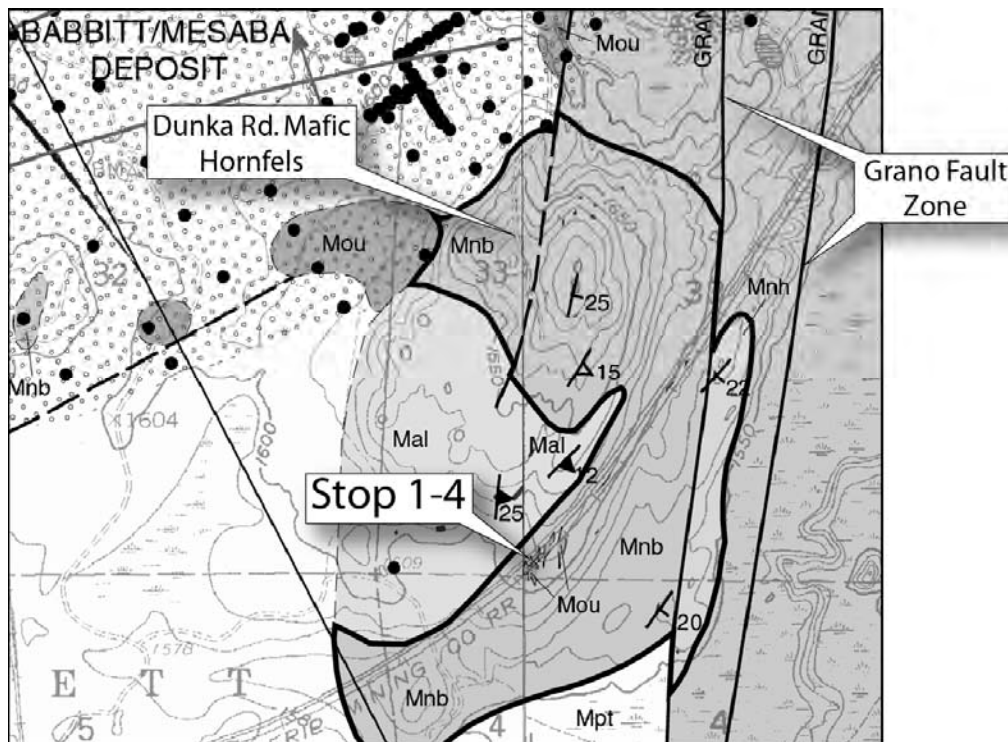


Figure 1-14. Geology of the Dunka Railroad hornfels and the location of Stop 1-4. (From Miller, Severson, and Foote, 2002).

PART 4: MESABA DEPOSIT – TECK AMERICAN INCORPORATED

By: Tim Jefferson and Mark Severson

BACKGROUND

Previous exploration and development work

The Mesaba deposit was first discovered along the base of the Duluth Complex in 1958 by Bear Creek Mining Company (BMC) which targeted a geophysical anomaly. Between 1958 and 1960 BMC completed 55 shallow drill holes for 43,000 feet (13,952 meters) on their discovery located 5 miles (8 km) south of Babbitt. BMC renewed drilling activities in 1967-1971 completing 149 additional holes. Drill hole B1-105 intersected substantial amounts of semi massive to massive sulfide mineralization between 1,400 and 1,800 feet (425 and 550 meters) below surface in footwall rock. Subsequent drilling defined a high grade zone appropriately named the Local Boy deposit after BCM geologist Stuart Behling, the “local boy,” who encouraged BMC to continue drilling this site. Bear Creek defined the overall tonnage and grade for the deposit to be 851 million tons (772 million tonnes) grading 0.46% Cu, 0.12% Ni at 0.25% Cu cut-off.

In late 1973, AMAX Exploration, Inc. agreed to take over BMC’s state and private leases. During the next four years (1974-1978) AMAX continued drilling over the entire deposit (completing 228 drill holes), and evaluated whether an underground operation was feasible (Watowich, 1978). In particular their focus was drawn to the Local Boy ore body, and following successful permitting, they sank a shaft in 1976-1977. Four drifts totaling 3,800 feet (1,160 meters) were developed and 218 underground holes were completed. This detailed definition resulted in an overall underground resource of 364 million tons (330.2 million tonnes) averaging 0.84% Cu and 0.19% Ni, with a Local Boy-only resource of 5 million tons (4.54 million tonnes) grading 1.89% Cu, 0.36% Ni. Both underground resources were estimated based on a 0.60% Cu cut-off. Due to weakening copper and nickel markets and the inability to produce separate high grade Cu and Ni concentrates, Amax abandoned their plans to develop the deposit in late 1981. Rhude and Fryberger obtained leases and evaluated the Local Boy deposit circa 1990.

Arimetco Inc, picked up the Babbitt deposit leases, renamed the Mesaba deposit, and evaluated the property circa 1994-1996. They did not complete any drilling but collected two bulk samples for metallurgical test work. Arimetco upgraded the resource estimate to 3,300 million tons (2,993.7 million tonnes) grading 0.46% Cu, 0.12% Ni, cut-off 0.38% Cu (Miller et al, 2002). Arimetco Inc. declared bankruptcy in late 1996.

Present exploration and development work

Teck American Incorporated picked up a package of state and private leases covering the Mesaba deposit in 1997. In 2001 the evaluation of the resource included collection of a 5,511 ton (5,000 tonnes) bulk sample. Sulfide concentrates were made from this bulk sample and tested at their Cominco Engineering Services Lab near Vancouver, BC, using their patented CESL hydrometallurgical pressure oxidation process. New definition drilling began in the fall of 2007 and continued until June, 2008 for a total of 67,430 feet (20,560 meters) in 64 drill holes (Fig. 1.15). This drilling was concentrated on the western portion of the deposit to complete a 400 foot (120 meter) grid infill program. In addition to this work, a new 4,409 ton (4,000 tonnes) bulk sample was mined in the fall of 2008. Sulfide concentrates from this ore were made at NRRI’s Coleraine Mineral Research Laboratory. The concentrates were shipped to the CESL facilities for a new round of hydrometallurgical tests, including the successful recovery of an intermediate mixed nickel-cobalt hydroxide. While Teck has not released a new reserve estimate pending completion of additional definition drilling, they are continuing their evaluation of the deposit on several fronts, including baseline environmental studies, geophysical surveys, and flotation and ore beneficiation /

recovery test work at their Applied Research and Technology division at Trail, BC, along with other engineering studies.

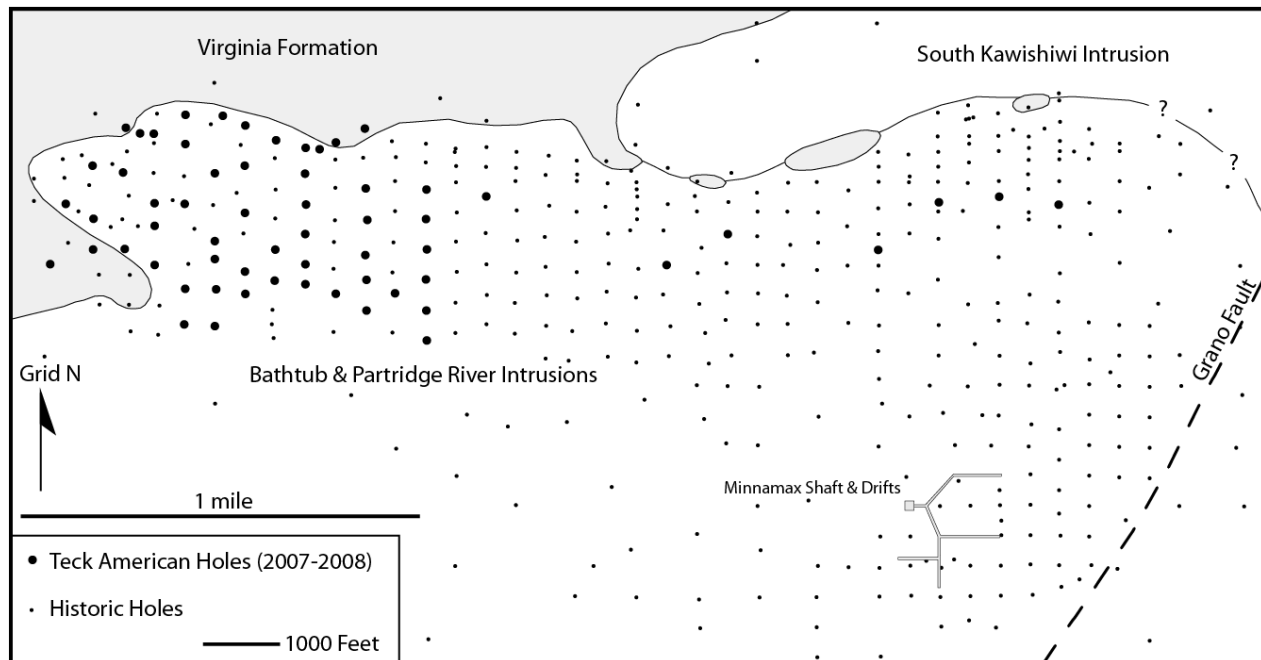


Figure 1-15. Drill hole location map for Mesaba Deposit. Grid north is about 33° west of north.

Recent re-logging of historic holes at the Mesaba deposit, in addition to information gained from logging of holes completed in 2007-2008 by Teck American geologists and Mark Severson (NRRI), indicates that the deposit is primarily hosted by a previously unrecognized intrusion within the Duluth Complex (Severson and Hauck, 2008). It is believed that this intrusion, informally named the Bathtub intrusion (BTI), lies between the Partridge River intrusion (PRI), to the south, and the South Kawishiwi intrusion (SKI) to the north and east. This intrusion is believed to have been fed by a vent in the Grano Fault area on the east side of the Mesaba deposit. The BTI is believed to pre-date the South Kawishiwi intrusion, and is coeval in age to the Partridge River Intrusion. It is further believed, based on drill hole evidence, that igneous units of the PRI and BTI overlap and co-mingle, with the upper units of the PRI overlying BTI units. Supporting evidence for this new interpretation is based on igneous units that are unique to either the PRI or BTI, and different styles of sulfide mineralization between the two. The following geologic discussion is largely based on the work of Severson and Hauck (2008) but is condensed and summarized.

The reader is referred to the regional geology section for further description of the Partridge River and South Kawishiwi intrusions.

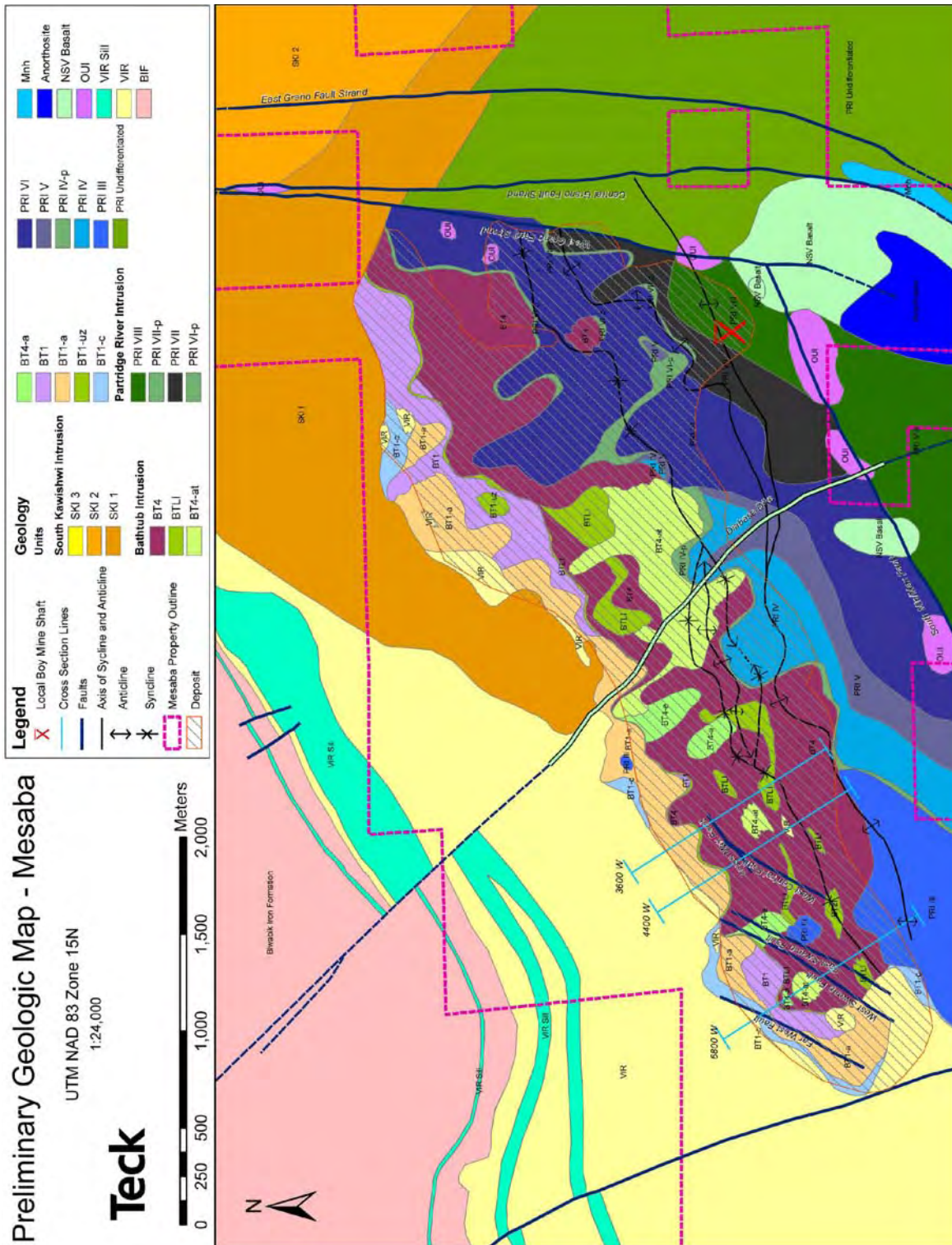


Figure 1-16. Preliminary geologic map of the Mesaba deposit showing major geologic units of the Bathtub, Partridge River, and South Kawishiwi intrusions. Major structural features associated with the deposit are also shown. Outline of ore deposit and Teck property boundaries are indicated.

GEOLOGIC SETTING

Footwall Rocks

As there is great commonality between the footwall rocks at the NorthMet Deposit and the Mesaba Deposit, they are discussed in the regional geology section for the PRI

Structure

There are three structural features that are pertinent to understanding the intrusive history of the BTI that include (Fig. 1.16): 1. an east-west trending paired syncline and anticline in the footwall rocks referred to as the Bathtub Syncline and Local Boy Anticline; 2. a zone that is closely associated with the Local Boy Anticline, referred to as “The Hidden Rise,” that separates the PRI and BTI; and 3. a north-trending fault zone, referred to as the Grano Fault, that has been postulated to have been the feeder zone for the BTI and footwall-injected massive sulfides of the Local Boy ore zone.

The paired Local Boy Anticline and Bathtub Syncline have been determined to be pre-complex, and pre-or syn-deposition of the BIF and Virginia formations by the following evidence:

1) BIF submembers A and B are notably thin or absent along the trough of the syncline. There is always a thin layer of Virginia Formation between the BIF and the overlying Bathtub intrusion in the synclinal trough (indicating that the Duluth Complex has not assimilated BIF A and B in the syncline).

2) The VirgSill also is thickest along the axis of the anticline and limbs of the syncline, and thins or is absent in the trough of the syncline. This attests to a more open structural setting along anticlinal folding for injection of the sill.

It is thus interpreted that the thinning of BIF within the trough is due to lack of deposition of these more calcareous units in deeper water (Severson et al., 1994a).

The “Hidden Rise” is a loosely-defined zone wherein scattered hornfels inclusions of footwall Virginia Formation, and associated noritic rocks, are fairly common. When viewed collectively, the inclusions in “The Hidden Rise” define an east-west trending “ridge” that is roughly positioned at the contact between the PRI and BTI. Thus, “The Hidden Rise” is used to both define this hornfels-bearing “ridge” and to artistically, and conveniently, divide the BTI from the PRI. The morphology of this feature suggests that it may have originally served as the floor and/or north edge of an earlier intruded PRI and later served as a wall along the south edge of the BTI as it was emplaced.

Along the far eastern edge of the Mesaba deposit is the north-trending Grano Fault, so named for the abundant and sometimes voluminous amounts of late granitoid and oxide rich pyroxenitic lenses (OUIs) associated with the fault zone (Severson, 1994). The late intrusive lenses are interpreted to have vertical configurations. They were injected along subsidiary fault zones parallel to, and immediately west of, the Grano Fault. The late intrusives cut the troctolitic rocks and thus, demonstrate that the fault was active during and after emplacement of the PRI, BTI and SKI and may represent a rift related transform fault. Other features that are associated with the Grano Fault include:

- a steep drop in the basal contact (down to the east);
- abundant pre-Complex sills are common within the Biwabik Iron Formation in a limited area at the Serpentine deposit - the localized increase in the sills outlines the fault trace at Serpentine and suggests that the fault was activated prior to emplacement of the SKI and PRI (see also Zanko et al., 1994); and
- a well-defined topographical lineament occurs along the trace of the fault to the south of the Mesaba deposit. Along the eastern edge of Mesaba, a buried valley, defined by contouring the top

of the ledge (Plate IV, Severson et al., 1994b), is also present on the northern extension of the same topographical lineament.

BATHTUB INTRUSION

The newly named Bathtub intrusion (BTI) is wholly contained in the central portion of the Mesaba (Babbitt) deposit. The BTI has recently been singled out as a separate intrusion to explain the abrupt change from typical Partridge River intrusion (PRI) stratigraphy, in the southern part of the deposit, to a completely different stratigraphy to the north in the remainder of the deposit. The BTI has been divided into two major units, BT1 and BT4, each of which contain several subunits. These units, in addition to footwall rocks, and structural features, are portrayed in Fig. 1.17.

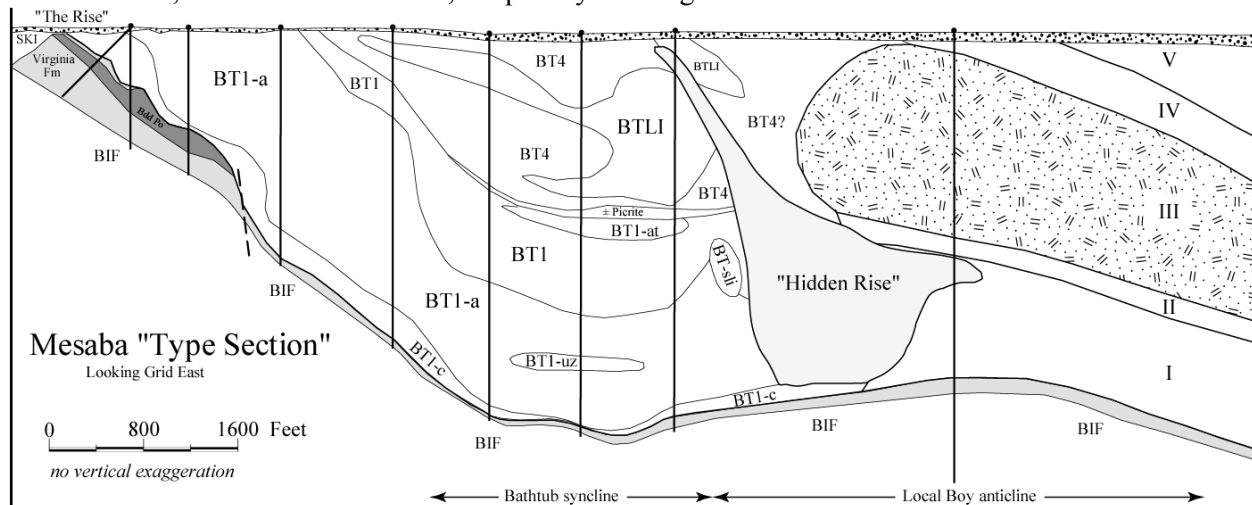


Figure 1-17. Schematic “type-section” cross-section, looking east, through the Mesaba deposit that crudely displays the spatial distribution of most of the igneous units in the Bathtub intrusion. Note that not all of the PRI units are shown on the right side of the figure.

BT1 Unit

The lowermost unit of the BTI is referred to as the BT1 Unit. It is very similar to Unit I of the nearby PRI in that it is heterogeneous-textured at all scales, contains abundant hornfels inclusions near the basal contact, and is the main sulfide-bearing unit at Mesaba. However, there are some important differences between Units I and BT1 that include:

- Augite troctolite is the dominant rock type in the bottom half of BT1 (as is also the case for Unit I) but in many of the cross-sections the entire up-dip portion of BT1 consists of augite troctolite;
- Massive sulfide occurrences are more common near the basal contact in the BT1 than in Unit I (excluding the unique Local Boy ore zone) indicating that sulfide settling may have been a more important mineralization mechanism in the BTI;
- Coarse- to very coarse-grained disseminated sulfides (up to several centimeters across) are exceedingly common in the lowermost portions of BT1; whereas, this same relationship is not so obvious in Unit I – this again implies the importance of a sulfide settling origin, and;
- Ultramafic horizons and patches are very common in portions of the BT1; whereas, similar ultramafic horizons are not as common in Unit I of the PRI.

The BT1 Unit has been further subdivided into several internal subunits that are discussed below.

BT1-a

This subunit of the BT1 is a heterogeneous-textured augite troctolite grading to olivine gabbro. The BT1-a subunit is more common in the bottom half of the BT1 Unit and increases up dip (to the north) at the expense of most other subunits of the BT1.

BT1-c

At the base of the BT1 there is significant silica contamination of the magma, due to assimilation of the footwall rocks, and noritic rocks (norite to gabbro norite), with common hornfels inclusions, are the dominant rock types with lesser amounts of augite troctolite. The BT1-c subunit spatially occurs as a rind or coating along the basal contact of the BT1.

BT1-uz

Wherever olivine-rich ultramafic rocks are common over appreciable intervals in the BT1 Unit this subunit is used to designate ultramafic zones. The morphology of the ultramafic rocks in these zones ranges from well-defined layers to zones where irregular ultramafic patches are presumably peppered throughout a troctolitic host rock.

BT1-at

This subunit of the BT1 is used to denote areas where anorthositic troctolite is the dominant rock type. The BT1-at zone is located at the very top of the BT1 Unit in the cross-sections of this report. It is a small unit that is locally present in only the central portion of the Bathtub ore zone.

BT-sli

A few holes in the extreme western end of the BTI exhibit well-defined modally-bedded rocks consisting of alternating troctolitic and olivine-enriched ultramafic rocks. These intervals are designated as BT-sli for the Bathtub Side Layered Interval (Figures 8 and 9a). The BT-sli subunit occurs about in the center of BT1 unit where it comes in close proximity to "The Hidden Rise." While the BT-sli can be readily mapped out and correlated between cross-sections, it is difficult to tell if this subunit is a downward continuation of the BTLI or "± Picrite" (as depicted in Fig. 1.17).

BT4 Unit

The uppermost unit of the BTI is referred to as the BT4 Unit. It was originally correlated with Unit IV of the PRI. However, the BT4 Unit is distinctly different from Unit IV in that the BT4 Unit at Mesaba is:

- heterogeneous-textured at all scales and composed of many alternating rock types;
- sulfide-bearing whereas Unit IV is mostly sulfide-barren – the sulfides in BT4 are generally, finer-grained and generally of lower ore grade tenor in comparison to sulfide-bearing zones in the underlying BT1 Unit;
- floored by a semi-persistent ultramafic layer termed the "± Picrite" (see discussion below) in the central portion of the Bathtub ore zone; and
- ultramafic layers and modally-bedded zones, termed the Bathtub Layered Interval (BTLI), are common in the central portion of the Bathtub ore zone.

The BT4 Unit has been further subdivided into several internal subunits based on the presence of a dominant rock type. The various subdivisions of the BT4 Unit are briefly discussed below.

BT4-a

This subunit of the BT4 on the cross-sections denotes areas where heterogeneous-textured augite troctolite is the dominant rock type.

BT4-at

This subunit of the BT4 is used to denote areas where anorthositic troctolite is the dominant rock type. Thick zones of BT4-at are common to some cross-sections through the Mesaba deposit and show relatively good correlation and predictability with similar zones in adjacent cross-sections..

"± Picrite"

At the base of BT4 is a semi-persistent olivine-enriched ultramafic horizon referred to as the "± Picrite." It is present in about 70% of the drill holes in the BTI-portion of the Mesaba deposit. The "± Picrite" is generally absent in the up dip direction (to the north) and is variably present to the south in the contact zone between the PRI and BTI. Where present, the "± Picrite" is about 1-15 feet thick, but exceptions are locally present. In some areas, the "± Picrite" consists of several stacked ultramafic horizons, or modal beds, that are interlayered with troctolitic rocks, and thus, the zone represents a collection of several cyclic layers. In other areas of the Mesaba deposit, the "± Picrite" is not always easily singled out as it occurs in close proximity to a downward thickening BTLI with similar ultramafic layers and modal beds. Therefore, in some instances it is difficult to pick the "± Picrite" out of a myriad of ultramafic horizons associated with either the BTLI or BT-sli.

Bathtub Layered Interval (BTLI)

In the vicinity of the Bathtub Syncline, ultramafic layers are extremely common within the BT4 Unit. The ultramafic layers may represent repetitious cyclic layers and can be correlated in drill holes as an overall rock package. This package of abundant cyclic layers, present in the BT4 Unit, is referred to as the Bathtub Layered Interval (BTLI). In the eastern half of the Mesaba deposit the BTLI appears to be present in a subhorizontal saucer-shaped morphology. Conversely, in the western half of the deposit, the BTLI is confined to one or two cylinder-shaped zones, albeit with irregular edges, that are positioned in close proximity to "The Hidden Rise."

Overall, the ultramafic rock types of the BTLI are characterized by alternating assemblages of either/or: melatroctolite (picrite), feldspathic peridotite, peridotite, dunite (minor), olivine-rich troctolite, and troctolite with modal beds of olivine-rich layers. One or more of these rock types may be stacked above the other in no particular order, and the thickness of this assortment may be highly variable between drill holes. The number of individual ultramafic layers present within the BTLI for any particular drill hole varies drastically. In some holes, over 75 individual ultramafic layers and modal beds are intersected, whereas in other holes only a few scattered ultramafic beds are encountered. The range in thickness for each of the individual ultramafic beds also shows considerable variation, ranging from a few inches to over tens of feet thick. Although the BTLI can be correlated as a package of alternating troctolitic and ultramafic layers, each of the individual ultramafic layers cannot be correlated on a hole by hole basis. This situation indicates that the ultramafic layers either: 1) commonly bifurcate - thick ultramafic layers may divide into many thin ultramafic layers; 2) some may actually represent dike-like features (filter pressed?); 3) some may pinch out or have very limited spatial extent due to localized crystallization or other deposition-related origins; or 4) combinations of the above.

Gradational tops and sharp bases are commonly present, indicating that crystal settling may have been important (this is especially true in the eastern half of the Mesaba deposit). However, the reverse (gradational bottoms and sharp tops) is also locally present. In addition, the inclination of contacts and modal bedding associated with the ultramafic layers are highly variable, ranging from 5°-80° (with localized overturned beds). This variation in inclinations can even be present in even a single drill hole. For the most part, the bedding and contact inclinations in the BTLI are steeper higher up in the drill hole and gradually shallow with depth. The shallow to steep angles exhibited by the BTLI may reflect that the ultramafic layers originated via a variety of mechanisms that include: 1) crystal settling to form subhorizontal layers (dominant in the eastern half of the deposit); 2) filter-pressing to form localized dike-like morphologies; 3) slumpage and folding of the beds took place before they were fully crystallized to form highly irregular and overturned beds; 4) compaction differences took place during lithostatic loading of the crystal pile to form steep and irregular beds; 5) cooling and crystallization took place along, and parallel to, the southern wall of the BTI (up against "The Hidden Rise"); or 6) combinations of all of these mechanisms. Whatever their origin, the steep beds displayed by the BTLI in the western half of the Mesaba deposit are inordinately associated with "The Hidden Rise."

PARTRIDGE RIVER INTRUSIVE (PRI) AT MESABA

Many of the igneous rock units that are present at the nearby NorthMet deposit are also present along the southern edge of the Mesaba deposit and are believed to represent units of the Partridge River Intrusion (see previous geologic setting discussion). Additionally, Units IV through VI of the PRI appear to extend northward and overlie the heterogeneous-textured BT4 Unit. This relationship, also depicted in Figure 1.17, suggests that the BTI was eventually over-ridden/overlain by the upper units of the PRI. The overall timing of emplacement for the PRI versus the BTI is unknown but correlations in the cross-sections crudely suggest the following:

- Units I through III were intruded first along the southern edge of the Mesaba deposit with a vent area located somewhere to the southwest. “The Hidden Rise” generally marks the northern extent of this intrusive activity and originally formed as part of the floor to these units. Unit III may have been intruded as thin lenses across and north of “The Hidden Rise” – this may explain the local presence of Unit III-like inclusions in the BTI.
- Concurrent with or after the above activity, the BT1 Unit was intruded from a vent area located somewhere to the east, possibly from the Grano Fault area. “The Hidden Rise” formed the southern wall of this particular magma chamber.
- The BT4 Unit was intruded into the same magma chamber but was emplaced above the BT1 Unit.
- Concurrent with or after the above activity, Units IV through VII+ of the PRI were intruded from a vent area located somewhere to the southeast. These upper units were emplaced over the BT4 Unit.

MINERALIZATION AT MESABA

The Mesaba deposit is characterized by disseminated sulfide mineralization, which occurs most commonly as intercumulus accumulations of chalcopyrite, cubanite, and pyrrhotite. Pentlandite crystals are less commonly identified megascopically. Additionally, less common occurrences of talnakite and bornite have been noted. Short intercepts of semi-massive to massive sulfide mineralization are often encountered in drill core in the Virginia footwall rocks immediately adjacent to noritic intrusive rock. Sulfur isotope analyses have indicated that the source of the sulfur used in the formation of the sulfides of the Mesaba deposit is the pelitic sediments of the Virginia Formation (Ripley, 1986). The model of sulfide deposition entails turbulent injection of units of the BTI wherein immiscible sulfide droplets coalesce within the silicate melts and attract the chalcophile elements (chiefly copper and nickel) through magma mixing. Thus, the most contaminated magma (from assimilation of footwall Virginia formation) hosts basal sulfides that contain excess sulfur relative to intrusive units higher above the footwall. The sulfide content of the rock increases, often dramatically as the footwall is approached. This sulfide content increase is accompanied by the increasing presence of pyrrhotite and a subsequent change in the copper bearing sulfides (cubanite is dominant over chalcopyrite). The disseminated mineralization is generally composed of 1-4% sulfides, but can reach upwards of 8-12 % sulfides as the footwall is approached. In addition to the interstitial disseminated sulfide and semi-massive to massive sulfide mineralization, sulfides may locally occur as clots up to several cm in diameter, and are seen occasionally as chalcopyrite rich vein fillings indicative of a late sulfide-rich fluid origin.

The most important mineralized zone at Mesaba is the basal zone, starting at the footwall Virginia Formation contact, that commonly ranges between 200 and 400 feet thick (60 and 125 meters thick). Higher up in the intrusive package, often overlapping the BT1-BT4 unit boundary, is a second zone of disseminated sulfide mineralization which is more erratic and discontinuous in nature.

The Mesaba deposit (hosted by the BTI) displays significant differences with the nearby NorthMet deposit (hosted by the PRI). At NorthMet, the ore zone lower in the deposit is more stratiform and near the top of PRI Unit I, while at Mesaba the main mineralized zone starts immediately at the footwall contact zone. As noted in earlier discussions, units of the BTI are more erratic and chaotic than those of the adjoining PRI intrusion. This is also true of the sulfide distribution which is often locally quite chaotic, and variable but overall the basal zone is tied together by adjacent drill holes to define a strongly mineralized ore body of considerable extent. The footprint of the Mesaba deposit is an oblong to arcuate shape, 3,000 by 13,000 feet (925 by 4,000 meters) in approximate dimension, cropping out to surface on the northern/up-dip side and extending to approximately 1,650 feet (500 meters) below surface in the southern/down-dip direction. The strongest basal mineralization is often localized within the Bathtub Syncline. Here, concentration of sulfides by gravitational settling into the footwall depression has likely occurred. Teck American has not released any new reserve/resource estimates, and the reader is referred to historic reserve numbers as reported at the start of the Mesaba section.

Three geologic cross sections from the western half of the Mesaba deposit depicting composited Cu-Ni grades from historic and recent drilling are displayed below (Figures 1.18, 1.19, and 1.20).

PGE Mineralization at Mesaba

Platinum group metal mineralization (PGE) occurs at Mesaba and the other Duluth Complex copper-nickel deposits. Along with analyzing all new drill core for precious metals (Pt-Pd-Au), Teck American is in the process of cataloging and analyzing pulps from historic drill holes (BMC, AMAX) for precious metals at this time as well. Analytical results of this data collection (in progress) have not been released to the public. As a general statement, the western side of the Mesaba deposit (hosted by the BTI) generally contains very low PGE values, while there are occurrences of anomalous PGE values in the eastern half of the Mesaba deposit. It is postulated that the higher values to the east may be dependent on a more proximal distance from the hypothesized vent area of the BTI.

Analytical results of limited analysis of historic pulps for PGEs from the Local Boy ore body and pulps from historic drill holes intersecting upper portions of Unit I of the PRI in the southern portions of the Mesaba lease have been previously published and are summarized below:

Local Boy PGE Occurrences

Numerous anomalous PGE and precious metal values are confirmed to be present within the massive sulfide ores (Severson and Barnes, 1991; Hauck and Severson, 2000). Maximum values include: Pd – 11,100 ppb, Pt – 8,300 ppb, Au – 13,100 ppb, and Ag – 62 ppm (note that these values are present in sampled intervals that range from 5 feet to 15 feet thick). The majority of the anomalous PGE values are spatially distributed along the axis of the Local Boy anticline with the highest Cu and PGE values occurring in the west half of Local Boy. The Grano Fault may have served as a feeder zone to the massive sulfides that were injected into the footwall rocks along the Local Boy Anticline as an immiscible sulfide melt. This melt fractionally crystallized in an east-to-west direction and progressively became enriched in PGE towards the west (see discussion below).

PGE Mineralization at the Top of PRI Unit I (along the Southern Margin of the Mesaba Deposit)

Drill holes along the southern margin of the Mesaba deposit intersect an igneous stratigraphic section similar to the section present at the nearby NorthMet deposit. Limited sampling for PGE at the top of Unit I (the equivalent of the Red Horizon of Geerts (1991, 1994) at NorthMet) has taken place in a few holes at the Mesaba deposit (Severson and Hauck, 2003). For the most part, the Pd contents at the top of Unit I in the sampled holes are similar to Pd contents of the Red Horizon at the NorthMet deposit. Publicly available data indicates a maximum of 1,267 ppb Pd is present at the top of Unit I in the southern portion of the Mesaba deposit (Severson and Hauck, 2008).

MASSIVE SULFIDES AT THE LOCAL BOY ORE ZONE OF THE MESABA DEPOSIT

Cu-rich massive sulfides near the basal contact of the Complex are locally present at the Mesaba deposit in a small zone referred to as the Local Boy ore zone. In 1976, AMAX Inc. completed a 1,700-foot-deep exploratory shaft (Minnamax shaft) down to massive sulfides of the Local Boy ore zone and, in 1977, completed four drifts (A, B, C, and D; Figures 1.21 through 1.24). Underground Fan drilling (217 holes) was completed in 1978 to further define the massive sulfide distribution. Sulfide minerals include pyrrhotite, pentlandite, chalcopyrite, talnakhite, cubanite, maucherite (nickel arsenide), sphalerite, bornite and late mackinawite, chalcocite, covellite, godlevskite, and native silver. A more detailed description of these minerals, along with microprobe compositions, microphotographs, and possible paragenetic sequence, are presented in Severson and Barnes (1991).

The Grano Fault may have served as a feeder zone to both the BTI and to massive sulfides of the Local Boy ore zone. Severson and Hauck (2003) speculated that magma that issued from the Grano Fault may have been initially enriched in PGE, forming the PGE-enriched massive sulfides at the base of the PRI in the Local Boy ore zone, but as the magma intruded in an east-to-west direction [to form the BTI] it became progressively impoverished with respect to PGE in such a manner that rocks at the extreme western end of the Bathtub ore zone contain very little PGE.

Footwall Structures in the Local Boy Ore Zone

Several investigators have recognized that pre-existing structural conditions in the footwall rocks strongly influenced the basal contact of the Duluth Complex (Mancuso and Dolence, 1970; Watowich, 1978; Holst et al., 1986; Martineau, 1989; Severson and Barnes, 1991). Major irregularities in the basal contact are generally related to folds in the underlying country rock indicating that intrusion proceeded more or less along bedding planes in the footwall rocks (Holst et al., 1986). This is readily expressed by a major east-west -trending trough and ridge in the basal contact at Mesaba that coincides exactly with a syncline-anticline that is defined by the top of the Biwabik Iron Formation (BIF). The thickness of preserved Virginia Formation between the Complex and the BIF is variable due to the amount of material assimilated by the Complex.

The Local Boy ore zone is also situated over this anticlinal ridge. The majority of massive sulfide ore zones, hosted mainly by the Virginia Formation (Severson and Barnes, 1991), are broadly coincident with the axis of the anticline. The contoured top of the BIF in the Local Boy area is shown in Figure 1.21. Similar anticline geometries are also present for the basal contact as shown in Figure 1.21. All the data indicate that an EW-trending anticline is the major structural feature present within the footwall rocks of the Local Boy area.

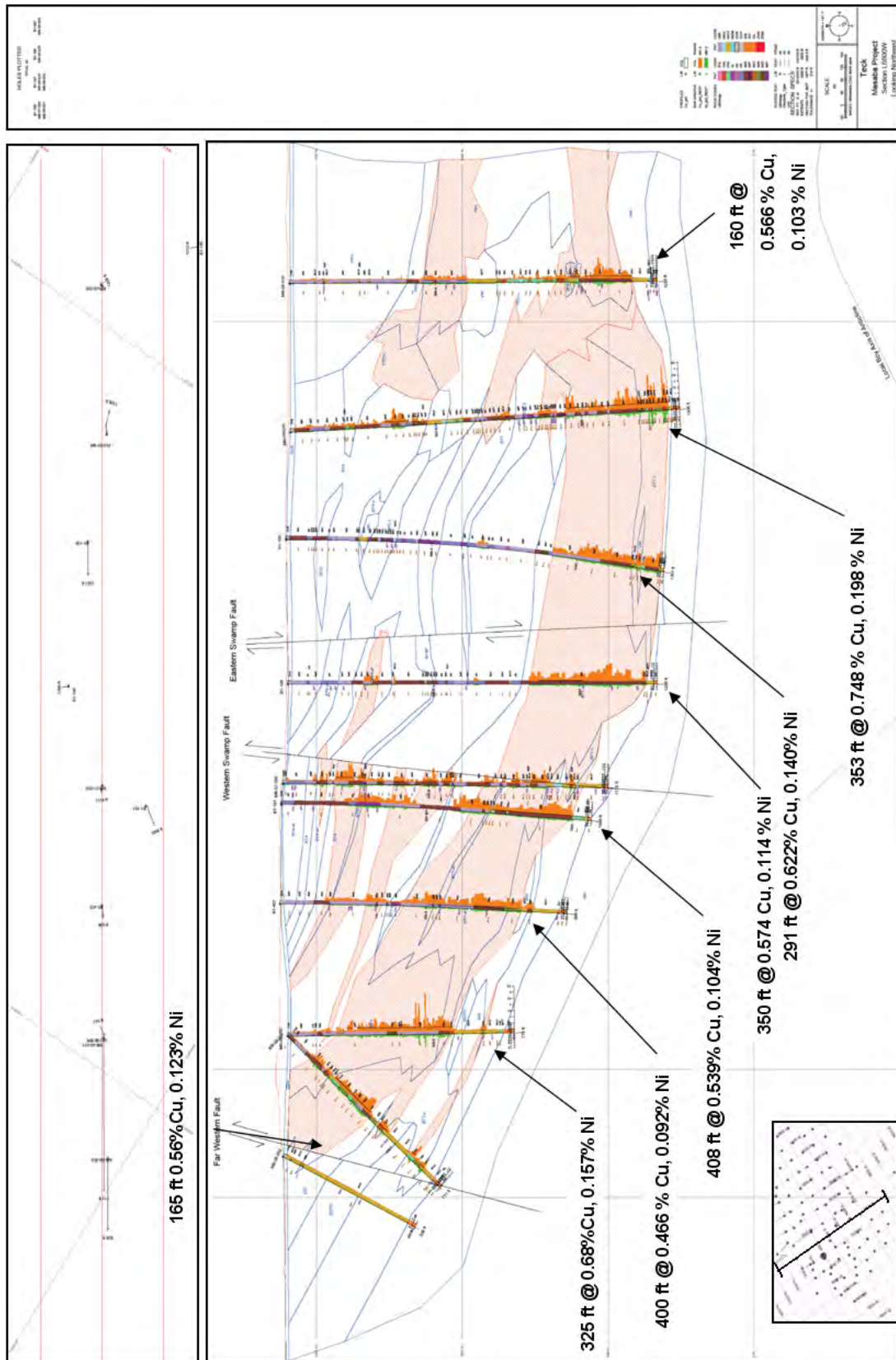
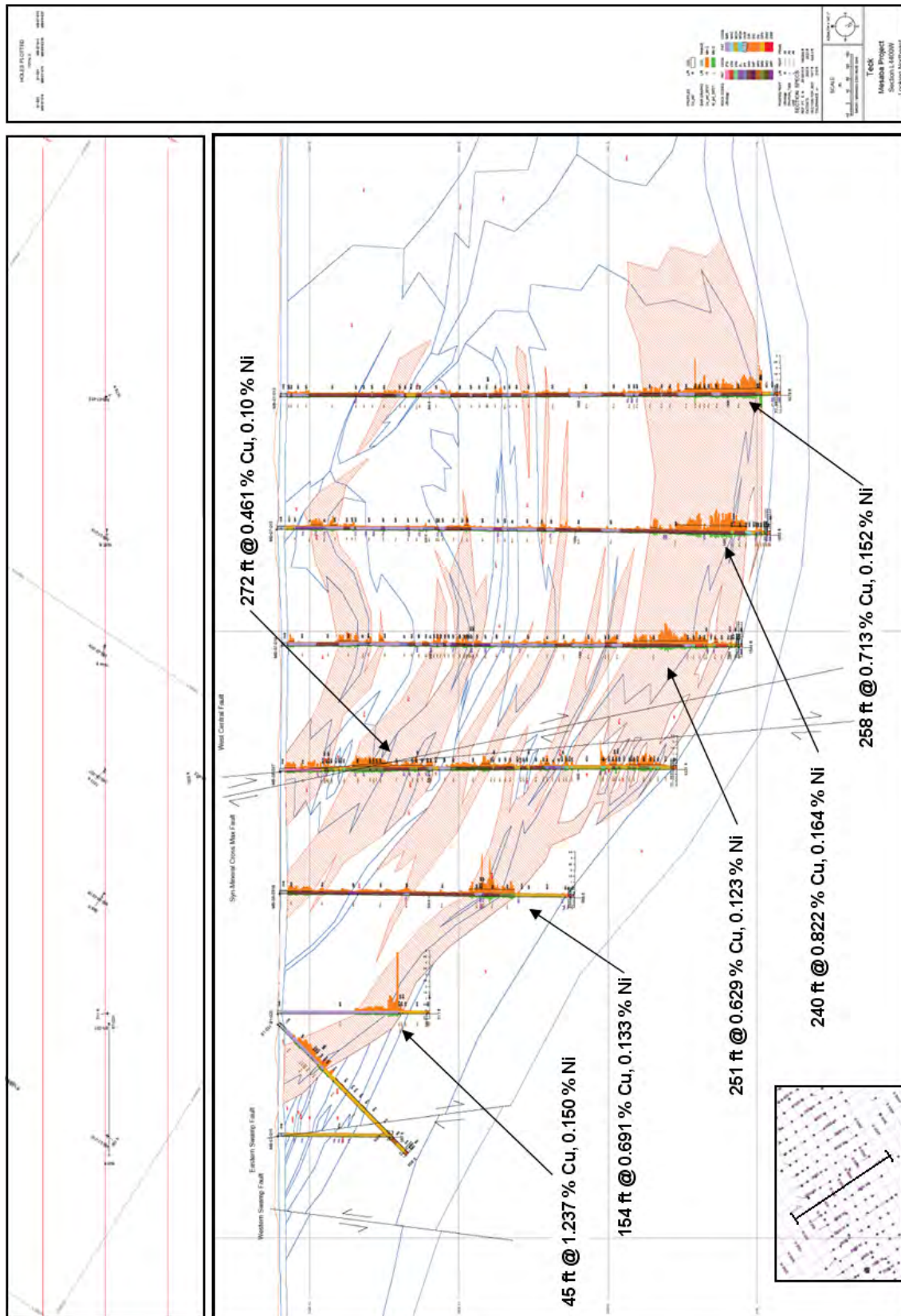


Figure 1-18. Cross-section 68+00W through the west end of the Mesaba deposit showing grades of significant intervals. Drill holes MB-08-38 from this cross-section will be on display at Teck's core shack.



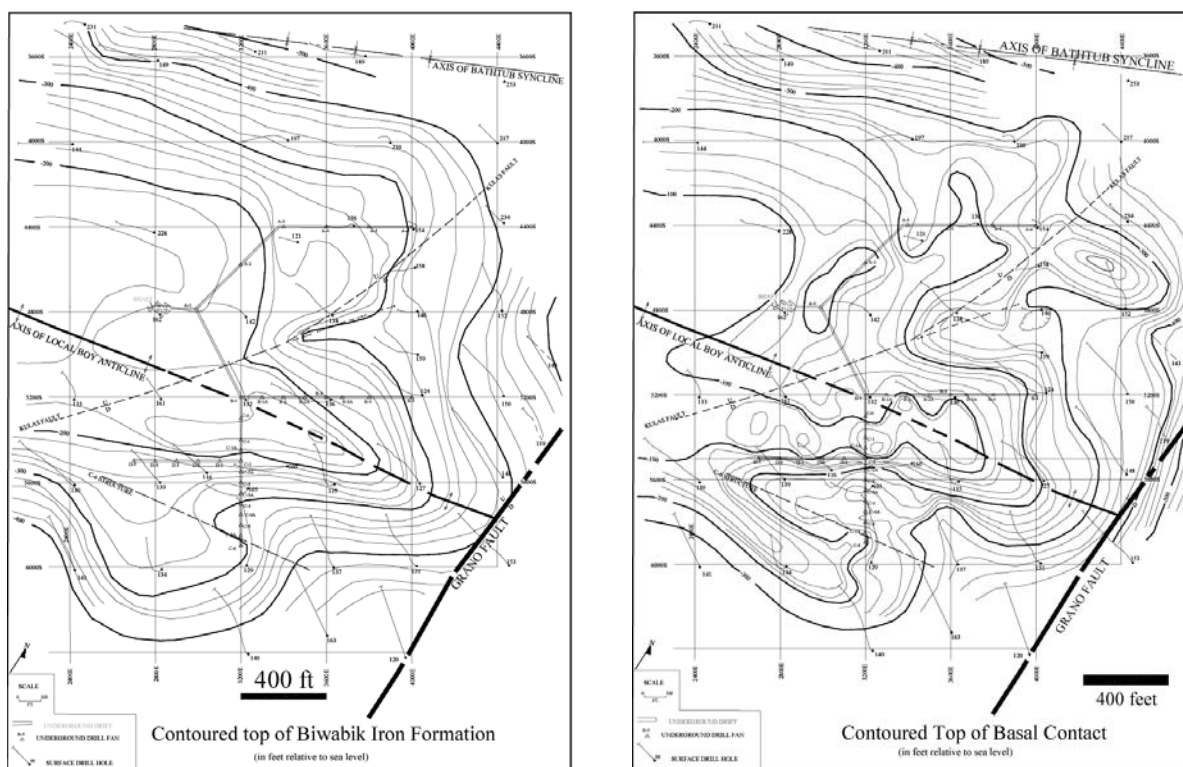


Figure 1-21. Contoured top of the Biwabik Iron Formation at Local Boy (left), and the contoured top of the basal contact between the footwall Virginia Formation and the Partridge River intrusion at Local Boy (right).

The spacing of the contours in Figure 1.21 suggests that the anticline is asymmetrical with a steeper flank to the immediate south of the anticlinal crest. Also, fault zones in drill core, as well as recognizable fault offsets of correlative units, are most commonly present on the south flank of the anticline. Taken collectively, all these data suggest that additional structural features, in the form of increased faulting and shearing, are more important on the south flank of the anticline in the Local Boy area. The northeast-trending Kulas Fault is also shown in the Figure 1.21. This fault was initially mapped by Jim Kulas in the underground drifts at Local Boy. The cross-sections included in Severson and Hauck (2008) also recognized the fault, with an offset of 10-20 feet, and named the fault after Kulas.

Mineralization Trends in the Massive Sulfide at the Local Boy Ore Zone

The vast majority of massive sulfides at Local Boy are contained within the Paleoproterozoic Virginia Formation. Even though the massive sulfides straddle the basal contact, most of the massive sulfides are associated with either hornfelsed sedimentary inclusions above the contact or with footwall rocks below the contact while the interfingering intrusive rocks are relatively barren of massive sulfides (Severson and Barnes, 1991). This suggests that the massive sulfide ores were not formed in this area by the gravitational settling of sulfides, but rather, the ores formed by injection of an immiscible sulfide melt into structurally prepared areas within the footwall rocks along the Local Boy anticline in a vein-like setting. A similar mechanism is proposed for the Norilsk-Talnakh deposits in Russia.

Even though the basal contact of the Complex with the Virginia Formation is highly undulatory, the massive sulfides exhibit a definite top and bottom. The ore is distributed such that most of it is contained within a zone between 20 feet and 300 feet above the top of the Biwabik Iron Formation. The geologic constraint for the bottom of the ore zone generally corresponds to the top of the VirgSill. The constraints for the upper portion of the ore zone are unknown and may have been obliterated during emplacement of

the Complex. Figure 1.22 is an attempt to show, in a plan view, where massive sulfide zones are present. Also shown in the figure are the different massive sulfide types (ranging from pyrrhotite-dominant to Cu-rich) relative to structural features. The relationships shown in Figure 1.22 indicate that: 1) semi-continuous massive sulfide zones are present, mainly to the south of the Kulas Fault; and most important 2) the massive sulfides show a progressive change in an east-to-west direction from Cu-poor massive sulfides to Cu-rich massive sulfides in the vicinity of the Local Boy anticline. These relationships suggest that the injected immiscible sulfide melt underwent fractional crystallization and progressively became more Cu and PGE enriched as it moved through the footwall rocks in an east-to-west direction.

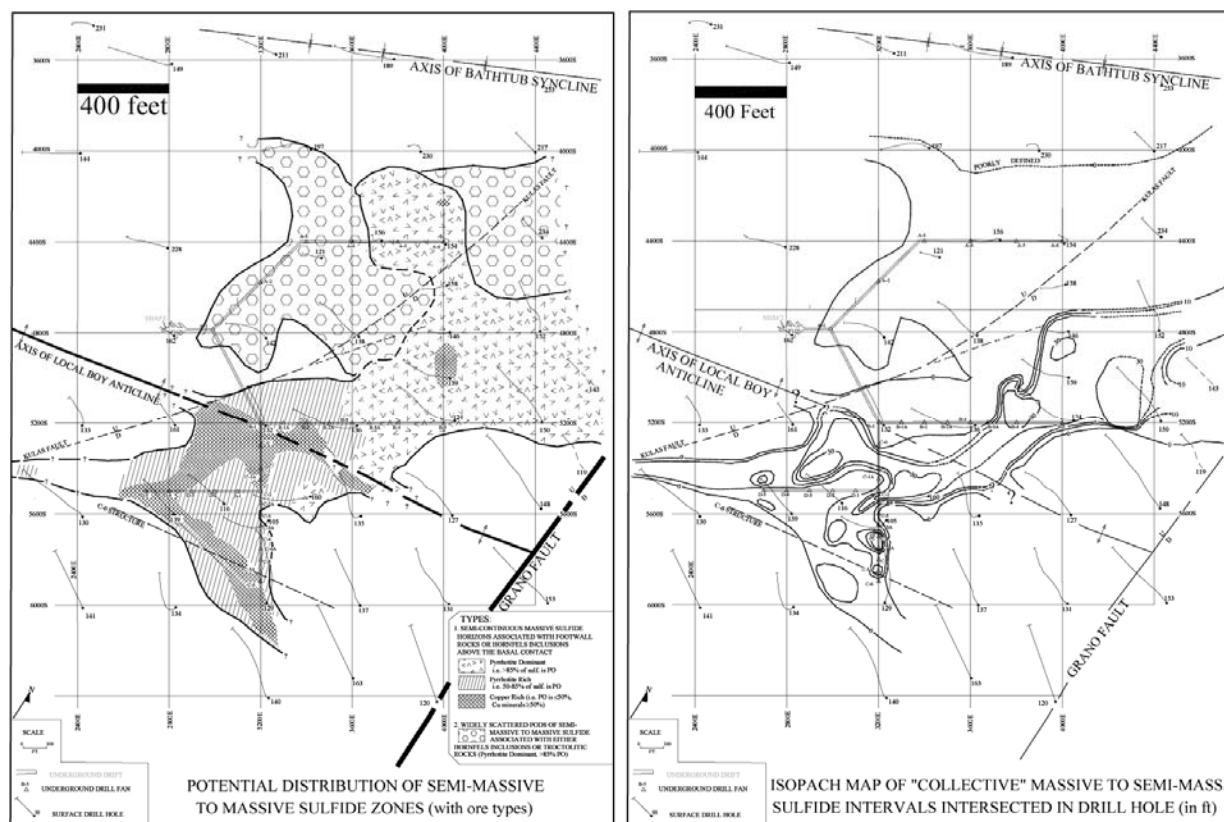


Figure 1-22. Potential distribution of semi-massive to massive sulfide types (Cu-poor versus Cu-rich) at the Local Boy ore zone (left); and an isopach map of the cumulative thickness of the massive sulfide zones at the Local Boy ore zone (right). Note that the massive sulfides are not present as a continuous blanket, but rather, as one or more stacked disjointed/separated multiple horizons near the basal contact.

A possible feeder vent for the sulfide injection event may have been the Grano Fault, which was repeatedly reactivated during emplacement of the Complex. Other data that indicates that the Grano Fault was a potential feeder vent include: 1) the massive sulfides are more common, and thicker (Figure 1.22), close to the Grano Fault (feeder) and along the axis of the Local Boy anticline (structurally-prepared site); 2) the VirgSill rarely contains significant amounts of disseminated sulfides – except near the Grano Fault; and 3) the Biwabik Iron Formation rarely contains sulfides – except near the Grano Fault. In summary, the massive sulfides at the Local Boy ore zone are interpreted to be structurally controlled in that they are situated along the axis of the Local Boy anticline. The massive sulfides are Cu-rich (5-25% Cu) and are almost exclusively hosted by the Virginia Formation. Sulfide textures suggest that the massive sulfides were injected as an immiscible sulfide melt into the footwall rocks. The overall pattern of sulfide types and PGE contents suggest that the sulfides formed via a process of fractional crystallization of an immiscible sulfide melt as it migrated into the footwall rocks. The Grano Fault is inferred to represent the potential feeder zone in this scenario.

PART 5: FRANCONIA BIRCH LAKE PROJECT

Extracted from Routledge, 2004; some contribution by Mark Severson

Birch Lake Deposit

A few widely-spaced holes were drilled in the Birch Lake area by Duval Corporation in the 1970s. Some Cu-Ni mineralization was intersected at great depths in many of these holes; however, exploration companies were not impressed with the Cu-Ni grades and largely abandoned the area - the potential for PGE mineralization was never considered. In the mid-1980s, the MDNR and Mineral Resources Research Center (MRRC) conducted analyses of iron-rich intervals in the basal portion of drill hole Du-15. PGE values as high as 9,123 ppm Pd+Pd, associated with high Cr₂O₃ contents (5.3%) were documented (Sabelin and Iwasaki, 1985; 1986). This discovery marked the start of serious PGE exploration in the Duluth Complex and a multitude of holes and wedges have since been drilled at Birch Lake.

Property Geology

The Birch Lake property is entirely underlain by the South Kawishiwi intrusion (SKI) that is itself bordered on the southwest by the Partridge River body and on the southeast by the Bald Eagle pluton. The SKI extends approximately 25 miles (40 km) northeast-southwest and is up to 4.5 miles (7 km) wide. The footwall Middle Precambrian metasediments outcrop less than a kilometer west of the property boundary in the area of the Birch Lake deposit, and are best exposed in the Dunka pit area. Figure 1.23 shows the property geology. On the Birch Lake property, the SKI ranges in vertical thickness from 1150 feet to 4,420 feet as interpreted from 34 pilot hole drill intercepts of the footwall metasedimentary rocks or Giants Range monzonite. The lithology and igneous stratigraphy of the SKI (Fig. 1-6) has been simplified to seven principal units found on the property as summarized in Table 1.8.

The Cu-Ni bearing sulfides and associated PGE mineralization at Birch Lake occur consistently in the upper portion of the "U3" ultramafic unit below its contact with pegmatitic phases of sulfide-barren, hanging wall troctolites, gabbros, and anorthosites. The U3 unit is mainly troctolite phases with compositions ranging to anorthosite. It is variable in modal mineralogy, composition and texture over short distances but can be distinguished by the presence of sulfides, cumulus olivine with interstitial plagioclase, and olivine rich ultramafic intervals (dunites, melatroctolites, picrites) ranging from less than 1 foot to tens of feet (0.3 m to tens of meters). Late granitic and felsic dikes cut the SKI and U3 unit.

The U3 unit has been intersected at depths as shallow as 1,125 feet (343 m) and up to 3000 feet (915 m) deep in 31 pilot holes on the property. Intercept thicknesses of the U3 range from 48 feet to 375 feet (14.6 m to 114.3 m) and vertical thickness averages 175 feet (53 m) based on statistics for 31 pilot holes.

Strong PGE enrichment is associated with late stage Cu-Ni sulfides, particularly with chalcopyrite, talnakhite, and bornite where they occur as replacement mineralization. Weaker PGEs are found where chalcopyrite and pyrrhotite are the primary sulfides. Saussuritization and serpentinization are common deuteric alteration in the U3 unit. Retrograde alteration and schistosity accompany the east west and northwest faults.

The Complex has not been significantly deformed since magma consolidation, but it has been subjected to displacements along reactivated basement faults as well as cross faults. Mapped structures are mostly sub-vertical north-northeasterly faults and fault zones that are evident as linears on airphotos and topographic maps. Rowell (2002) believes that these faults have been active pre-, syn- and post-emplacement of the SKI and offset the mineralized U3 unit. Where exposed in parts of the SKI and footwall rocks, movement on these faults ranges from 10 feet to 400 feet (3 m to 120 m).

Table 1.8. Stratigraphic Section for South Kawishiwi intrusion at Birch Lake.

Unit	Thickness	Remarks
<u>Hanging Wall Rocks</u>		
AT&T	Thick	Thin picrite units at top or middle of unit
Main AGT	Averages 275 m	
AT-T	21 m to 365 m; average 115 m	
<u>Cu-Ni-PGE Mineralized Units</u>		
PEG	3 m to 80 m; averages 28 m	Sulfides first appear near base
U3	1 m to 125 m; averages 30 m	Up to 20 ; Cu-Ni-PGEs-oxides enriched
BH	Extremely variable	Primary host for Cu-Ni sulfides in intrusion
BAN	3m to 115 m; averages 38 m	
<u>Footwall Rocks:</u>		
BIF	120 m	Contact metamorphosed to pyroxene hornfels
GRB		Melted and recrystallized

West-northwest trending faults cut the northeasterly faults and show left lateral displacements in the south portion of the property and right lateral offsets under Birch Lake (Rowell, 2001). These late faults have vertical displacements in the order of 10m and may be akin to transform faults that accompany rifting elsewhere. The Bob Bay Fault zone trends north through Bob Bay but northeasterly south and north of Bob Bay. The faulting appears to have influenced the localization of sulfides and higher PGEs and it effectively cuts off the Birch Lake deposit on the west. Drill holes in this fault zone commonly intersect massive and disseminated sulfides in the footwall rocks and/or felsic dikes that cross-cut the intrusion. The sense of displacement between holes 88-1 and DU-15 is in the order of 200 to 300 feet (60 m to 90 m) down on the east side.

A regional west-northwest fault diminishes mineralization and metal grades along its length and divides the deposit into a north, main segment and a small south segment. The spatial distribution of faults on the property is such that the Birch Lake deposit is displaced laterally and vertically by the sub-vertical fault sets. However, at the relatively wide spacing of the mostly vertical drill holes that test the deposit, the location of most of the interpreted faults is not known with the degree of confidence generally required for reserve estimation and mine planning.

Deposit Types

The Duluth Complex hosts four types of magmatic mineralization at or near its footwall:

- Large, low grade disseminated Cu-Ni sulfide deposits that are locally enriched in PGEs.
- Localized high grade zones of massive Ni-Cu sulfides, which maybe enriched in PGEs.
- Disseminated, PGE enriched, Cu-Ni sulfides associated with specific types of phase-layer transitions, and in this sense are stratabound deposits.
- Titanium and vanadium oxides-rich ultramafic plugs that are, in some cases, potentially deposits.

The Birch Lake deposit is an example of the third- type of mineralization: 1% to 5% disseminated copper and nickel sulfides bearing significant palladium, platinum, and gold values with lesser silver, cobalt and rhodium. The mineralization is stratabound in that it is consistently associated with the top of the U3 unit and pegmatite marker horizon that is traceable hole to hole as the deposit hanging wall. Palladium and platinum enrichment and the Pt:Pd ratio is greater near top of the U3 unit; copper and nickel grades are variable as is the Ni:Cu ratio. The base of the deposit within the U3 unit is determined by assay cut-off.

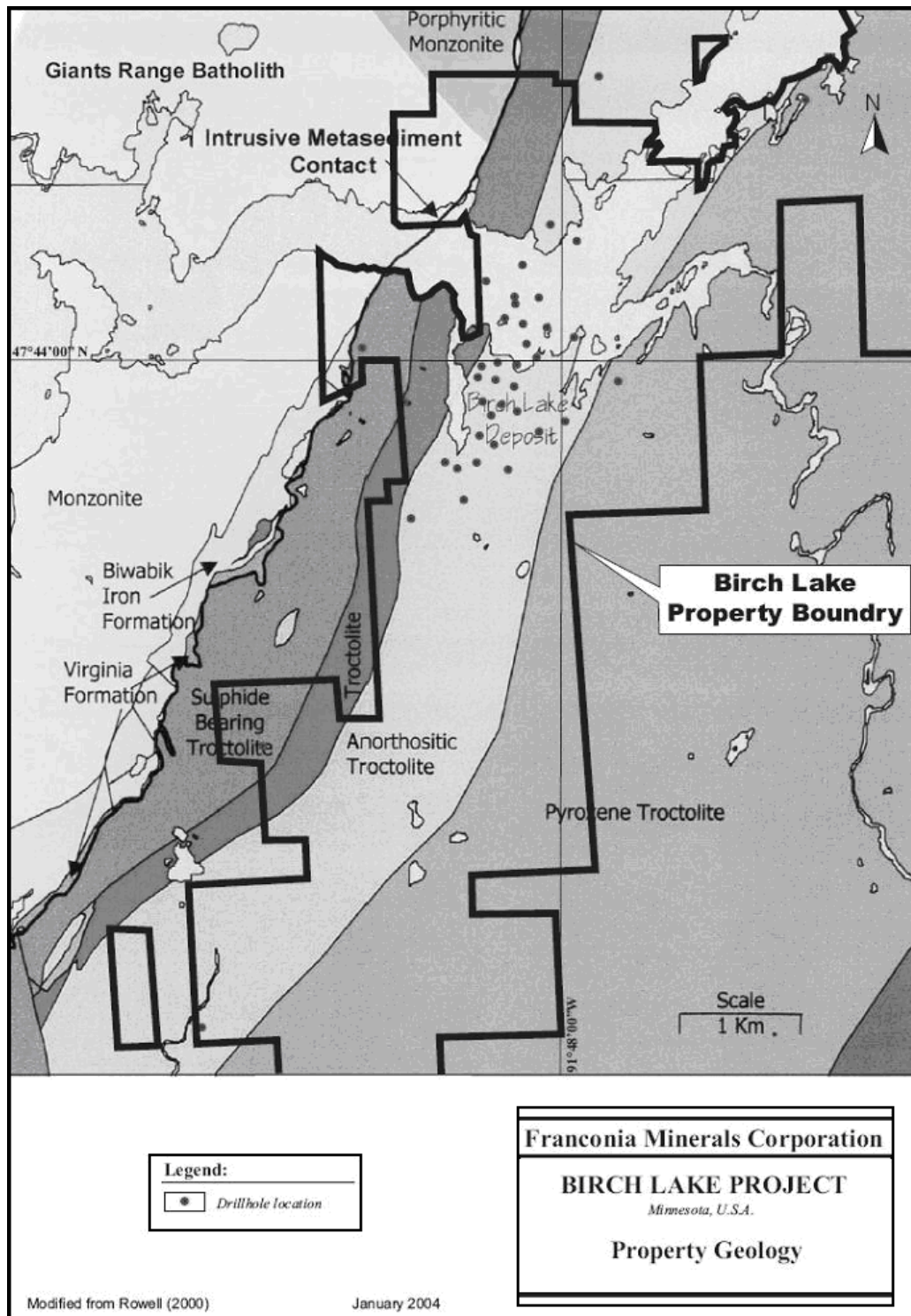


Figure 1-23. Birch Lake property geology (from Routledge, 2004).

Mineralization

Information on mineralization has been obtained from core logging by personnel of the BBJV, its partners and State geologists, laboratory analysis and the detailed mineralogical investigation of five core samples from five drill holes. The latter consisted of reflecting light microscope and scanning electron microscope

study of polished thin sections prepared from heavy minerals concentrated by heavy liquid separation of crushed and ground core (Cabri, 2002). These samples had relatively high PGE grades. Detailed petrography and electron microprobe work on drill core from four holes has also been done by the UMN and the NRRI (Marma et al., 2002).

Sulfides are disseminated interstitially in the rock matrix and mirror the size of rock forming mineral grains: coarser sulfides with coarse grained to pegmatoid fabrics, finer sulfides with medium grained rocks. The sulfides occur:

- intergrown as eutectic and replacement textures
- as triple point exsolution between rock mineral grains
- intergrown with silicates
- rarely as sulfide seams or veinlets

Microscope study by Cabri (2002) has identified the major ore minerals to be chalcopyrite and undefined members of the chalcopyrite family, possibly one or more of talnakhite, mooihoekite, putoranite and haycockite; the oxide minerals chromian spinel, ilmenite, magnetite, chromite and native copper and troilite. Common minerals found are the copper sulfides bornite, chalcocite, and cubanite as well as nickel sulfide minerals heazlewoodite and pentlandite. Trace amounts identified are altaite, digenite, frobergite, galena, mackinawite, millerite, sphalerite and nine different PGM-bearing minerals, native silver, silver telluride and alloys of silver and gold. Cobalt is analyzed from pentlandite up to 2.12 wt%. Iron sulfide gangue is pyrrhotite and troilite.

The PGEs occur as various fine grained Pd tellurides with other Pt, Os, Ru, Au, Ag, Te and B minerals. Ninety percent of the PGMs are associated with copper sulfides (Cabri, 2002) as discrete grains attached to sulfides, as sulfide inclusions and at the margins between sulfides and gangue silicates. The PGMs may form halos around, or be included in, interstitial copper sulfides, pyroxenes, secondary amphiboles and biotite. PGEs are also remobilized in chlorite, serpentine or secondary magnetite. High PGE values were first analyzed from an interval characterized by poikilitic chromite in plagioclase feldspar known as "2 in one texture". Pd minerals occur at twice the frequency of Pt minerals and this is reflected in drill core analyses. Native silver is generally occluded in sulfides with Ag and Au-Ag alloys found as discrete grains and inclusions.

Geologic controls on spatial distribution of metals and mineralization are not fully understood (Lehmann, 2002b). Lehmann (2002a) suggests that partially crystallized ultramafic magma was injected into the crystallizing SKI from vents associated with faults at the base of the Duluth Complex. This produced thick localized piles of dunites and melatroctolites in the SKI along the margin of the Duluth basin. Metal enriched residual fluids introduced with the ultramafic magma migrated upwards and laterally to be trapped and precipitate sulfide mineralization where permeability was disrupted horizontally, such as elevation changes and changes in magma composition. An initial pulse of mineralization introduced widespread chalcopyrite and cubanite and pyrrhotite with low, but anomalous, PGE values at the base of the Complex. A subsequent more localized mineralization event precipitated sulphur deficient copper-iron sulfides and troilite accompanied by low grade PGEs that were trapped stratigraphically higher in the SKI at the pegmatite hanging wall unit at the Birch Lake deposit. PGEs and copper may have been redistributed by cooler, late stage, magmatic fluids that caused the deuteric alteration of the ultramafic host rocks.

Further complicating this picture, the presence of chlorine-rich drops (formed by a deliquescent process) on the drill core suggests that a hydrothermal model of concentrating the PGEs could also be invoked.

PART 6: DULUTH METALS DRILL CORE REVIEW

Dean M. Peterson - Duluth Metals Limited

INTRODUCTION AND COMPANY HISTORY

Wallbridge Mining Company Limited began active mineral exploration in the Duluth Complex in 1998 when it reviewed data on the adjacent Maturi and Spruce Road deposits. The company completed limited field work including geological mapping, geophysical surveys and a three hole drill program. A review of existing data allowed an estimation of an underground Inferred Resource of copper, nickel, cobalt and PGE of the Maturi deposit and its extension to the east. Based on this initial work, the company elected to proceed to acquire properties immediately to the east of the Maturi Deposit, previously referred to as the Maturi Extension Property but currently referred to as the Nokomis Property.

Duluth Metals was incorporated under the laws of the State of Delaware on January 18, 2000 under the name of Wallbridge America Corporation. During 2000 and 2001 Duluth Metals acquired four state leases and two federal prospecting permits within the Nokomis Property for future exploration. The initial exploration work in 2001 and 2002 included contracting a 3D computer model of the geology (completed by individuals at the Natural Resources Research Institute or NRRI) and reviewing the exploration potential of Duluth Metals' holdings on the basis of this new 3D geological model. Resampling was done on drill core from seven holes on the property and one hole immediately adjacent to the property stored at the core storage facility in Hibbing, Minnesota. Results of this new geochemical data provided the foundation of the initial magma flow model for the deposit (Peterson, 2001b). During 2003 and 2004 Duluth Metals conducted no significant exploration and merely maintained its properties in good standing.

Increased development activity in the area and increasing commodity prices in 2005 resulted in Wallbridge activating Duluth Metals. Also in that year Wallbridge concluded that the most effective way to finance the exploration and possible development of these properties was to "spin off" Duluth Metals by vending it into a free standing company to be run independently. In early 2006 a fully equipped field office was set up in Ely, Minnesota located approximately 15 minutes drive from the project site. Facilities including three bedroom accommodation, computerized data handling, core analysis and storage have been organized at the Ely field office. A seven hole drill program completed in the spring of 2006 extended the mineralization to the east into the property acquired in January 2006 from a private party. The results of the drilling also confirmed the grade and consistency of the mineralization located beneath a very large anorthosite block in the middle of the Nokomis Property. Through sound geologic analysis of the public domain data and the fortuitous open properties available between the known Maturi and Spruce Road deposits, the foundation for a world-class Cu-Ni-PGE discovery was put into place.

However, it requires more than a bit of well positioned property to make a world-class discovery. The favorable alignment of world metals demand, increasing metals prices, new hydrometallurgical extractive technologies, and a bit of luck provided the strong market conditions facilitating the successful Initial Public Offering (IPO) of Duluth Metals stock in October of 2006. The financial underpinnings of the IPO provided the fuel for a systematic exploration drilling of the property. This approximately 500,000 foot drill program was incredibly successful, with every one of the 155 drill holes intersecting Cu-Ni-PGE mineralization. This extensive drill program provided the cornerstone of the development of the giant Nokomis Cu-Ni-PGE deposit. In tandem with the drilling efforts were property acquisition efforts (still ongoing), resulting in the purchase of private surface lands, leasing of additional State lands, and the optioning of the Dunka Pit property as a potential process and tailings site (Fig. 1-24).

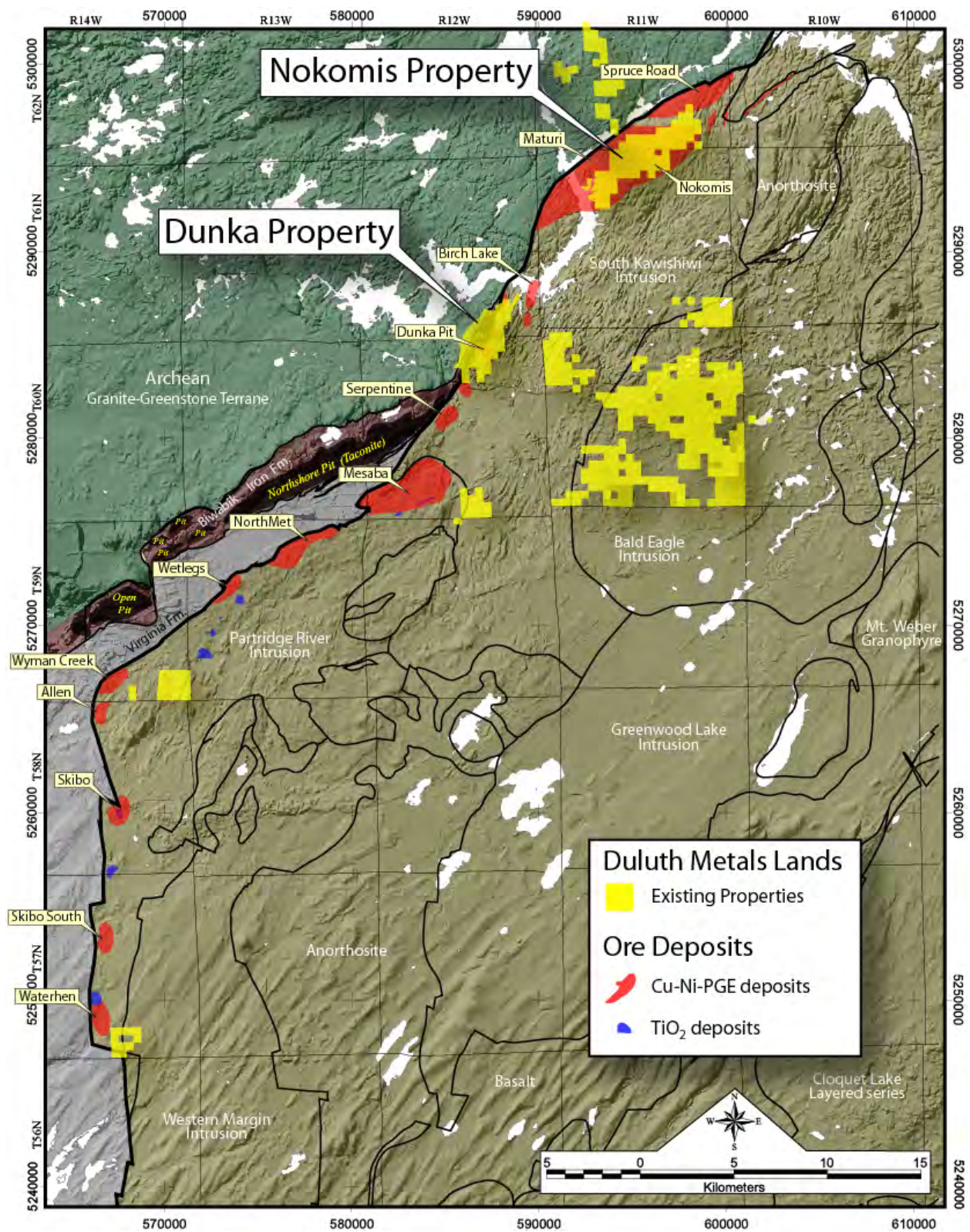


Figure 1-24. Simplified terrain and geology map with overlays of identified Cu-Ni-PGE & TiO₂ deposits and Duluth Metals properties.

NOKOMIS DEPOSIT MILESTONES

With the success of drilling efforts (Fig. 1-25) came National Instrument 43-101 (NI 43-101) compliant resource calculations, showing that within the Duluth Complex the Nokomis stands out with its continuity of grade and overall dimensions. NI 43-101 is a mineral resource classification scheme used for the public disclosure of information relating to mineral properties owned by, or explored by, companies which report these results on stock exchanges within Canada.

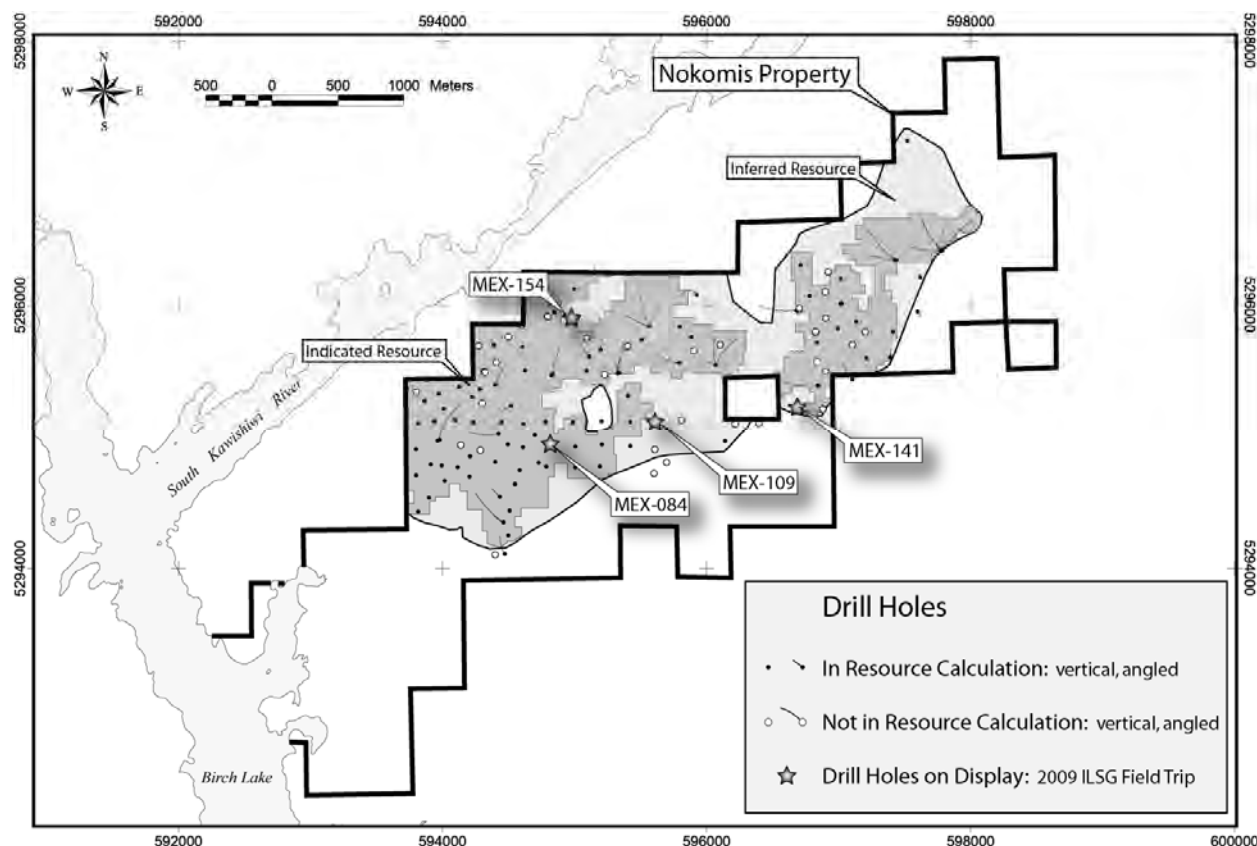


Figure 1-25. Defined resource blocks categorized as Indicated and Inferred, Duluth Metals drill holes, and the location of selected drill holes on display for this field trip (ILSG, 2009).

With the positive resource picture, metallurgical testing was warranted on the Nokomis data and a study was contracted with SGS Lakefield. Here again the Nokomis deposit proved itself by demonstrating exceptionally high recoveries of Cu, Ni, and precious metals (Table 1-9). These high recoveries are above typical metal recoveries of conventional smelting, therefore a technology agreement was signed by Duluth Metals for the use of the patented Platsol process.

Table 1-9. Nokomis metallurgical test results, completed by SGS Lakefield.

Metal / Recovery	Cu	Ni	Pt	Pd	Au
Flotation / Concentration Recovery	95.3%	72.4%	86.0%	87.0%	73.0%
Hydrometallurgical (Platsol) Recovery	99.6%	99.2%	97.6%	98.1%	84.1%
Combined Recovery	94.9%	71.2%	83.9%	85.4%	61.3%

With the positive metallurgical testing, two scoping studies were completed on the Nokomis Project by the consulting firm Scott Wilson Roscoe Postle Associates Incorporated (SWRPA) resulting in very positive outcomes. Based on indicated and inferred resources, the Nokomis Deposit ranks as one of the largest combined base and precious metal resources discovered in North America in decades. For comparison, the Nokomis deposit contains a higher than average grade for deposits within the Duluth Complex. Specifically, the Nokomis Deposit contains significantly higher grade zones of copper, nickel, platinum, palladium, gold and silver zones in large coherent portions of the deposit. One of the main objectives of the Company is to quantify these higher grade zones and appraise the potentially positive impact on future mining scenarios.

An updated interim resource estimate was received on June 4, 2008 from SWRPA based on drilling completed through April 2008 (Fig 1-25). The increased resource estimate update at a 1% copper equivalent cut-off and various copper cut-off grades is shown in Table 1-10. Based on SWRPA review of metal prices, process recoveries, refining costs and underground mine operating costs likely to apply at the Nokomis deposit site, the 1.0% copper equivalent cut-off grade is reasonable for the statement of indicated and inferred resources at this time.

Table 1-10. Indicated and inferred resource estimate for the Nokomis Deposit.

Indicated Resources									
Cut-off	Tonnes (000's)	Cu %	Ni %	Co %	Au g/t	Pt g/t	Pd g/t	TPM g/t	CuEq %
1.0% CuEq	449,413	0.624	0.199	0.010	0.084	0.159	0.358	0.600	1.46
0.5% Cu	376,306	0.658	0.206	0.011	0.090	0.172	0.390	0.653	1.54
0.6% Cu	247,149	0.714	0.216	0.011	0.103	0.199	0.452	0.753	1.66
0.7% Cu	112,035	0.794	0.233	0.011	0.123	0.240	0.549	0.912	1.86
0.8% Cu	41,078	0.883	0.255	0.011	0.152	0.293	0.679	1.124	2.09

Inferred Resources									
Cut-off Grade	Tonnes (000's)	Cu %	Ni %	Co %	Au g/t	Pt g/t	Pd g/t	TPM g/t	CuEq %
1.0% CuEq	284,230	0.627	0.194	0.01	0.096	0.191	0.431	0.718	1.50
0.5% Cu	236,102	0.667	0.198	0.01	0.105	0.210	0.475	0.790	1.58
0.6% Cu	155,743	0.725	0.201	0.01	0.120	0.239	0.542	0.902	1.69
0.7% Cu	72,418	0.817	0.214	0.01	0.144	0.280	0.640	1.065	1.88
0.8% Cu	33,292	0.900	0.215	0.01	0.173	0.320	0.739	1.231	2.03

Note:

1. CIM definitions were followed for Mineral Resource estimation and classification.
2. Mineral Resources are estimated at a zone definition (wireframe) cut-off grade of approximately 1.0% Cu equivalent grade (CuEq).
3. The approximately 1.0% CuEq cut-off grade includes all material in the wireframed zones.
4. Bulk density is 3.01 t/m³
5. Resources were estimated to a maximum depth of approximately 1,350 m.
6. Copper equivalent (CuEq%) is based on Net Smelter Return Factors as determined for the Preliminary Economic Assessment by Scott Wilson RPA dated January 18, 2008.
7. Metal Prices used were \$1.75/lb copper, \$7.00/lb nickel, \$10.00/lb Co, \$600/oz Au, \$1100/oz Pt and \$350/oz Pd.
8. Copper equivalent (CuEq%) = Cu% + 3.03 x Ni% + 0.63 x Co% + 0.30 x Au g/t + 0.76 x Pt g/t + 0.24 x Pd g/t based on expected metal prices and process recovery and refining charges.
9. TPM is Au g/t + Pt g/t + Pd g/t.
10. Co, Au, Pt, Pd grades, that are lacking in historic drill holes, have been entered in the resource database based on regression of assay grades from DML drill hole assays

The indicated and inferred resource estimates for base and precious metal content in the Nokomis deposit truly are enormous (Table 1-11). It is perhaps more revealing to compare these Nokomis numbers on the world stage of magmatic Cu-Ni-PGE sulfide deposits. This comparison (Fig. 1-26) is based on two types of data for this class of ore deposit. Historic metal contents for mining camps and individual deposits are taken from Anthony Naldrett's book titled "*Magmatic Sulphide Deposits: Geology, geochemistry, and exploration*" published in 2004. Publically reported metal contents for these same mining camps and deposits, as well as the Nokomis deposit, are from SEC filings, NI 43-101 reports, and related audits available online. Review of this figure clearly displays the size and importance of the Nokomis deposit on the world stage. For example, a simple comparison of the publically reported data for the Sudbury mining camp versus Nokomis shows that the Nokomis deposit contains more copper and PGE than is left in all of the active and developing mines in Sudbury.

Table 1-11. Calculated base and precious metal content of the Nokomis Deposit.

	Metal	Indicated	Inferred
Base	Copper	6.18 Billion lbs.	3.93 Billion lbs.
	Nickel	1.97 Billion lbs.	1.21 Billion lbs.
	Cobalt	103.00 Million lbs.	62.80 Million lbs.
Precious	Platinum	2.30 Million ozs.	1.75 Million ozs.
	Palladium	5.17 Million ozs.	3.94 Million ozs.
	Gold	1.21 Million ozs.	0.88 Million ozs.
	TPM (Pt+Pd+Au)	8.68 Million ozs.	6.57 Million ozs.

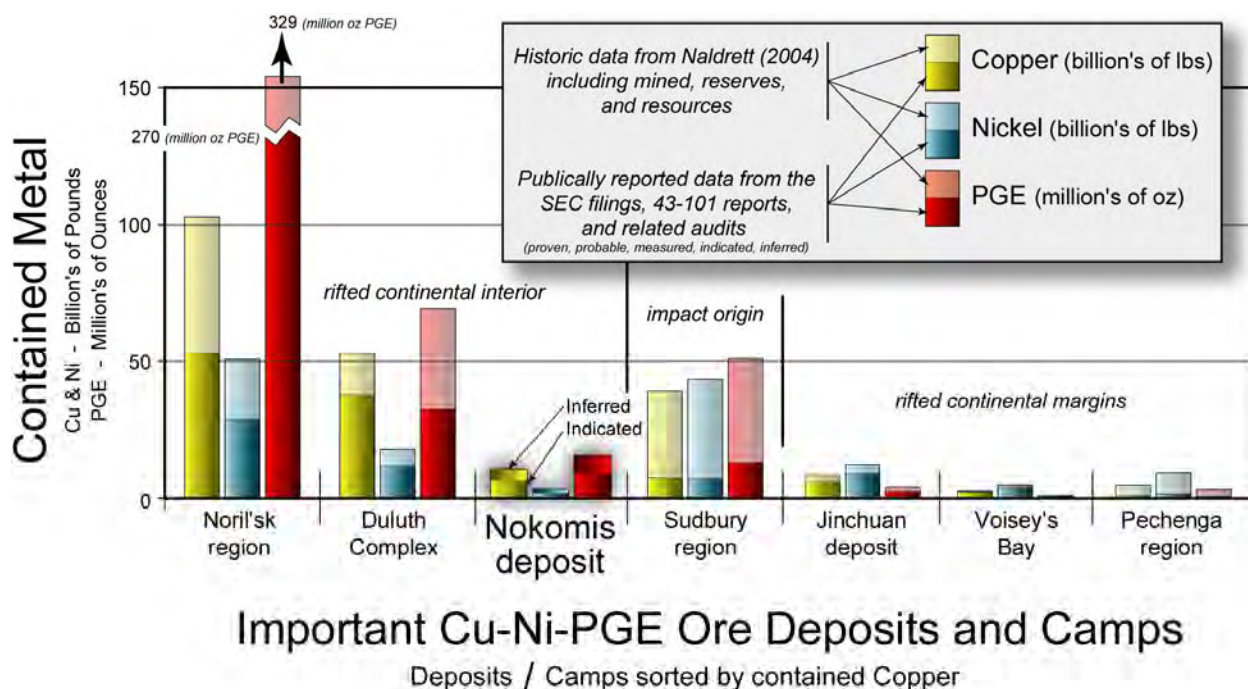


Figure 1-26. Chart of the contained base and precious metals in world class Cu-Ni-PGE mining camps and deposits.

On January 12, 2009, Duluth Metals announced the receipt of a new independent NI 43-101 Preliminary Assessment ("PA" or Scoping Study) on its Nokomis Project from SWRPA. This report (available online at SEDAR) provides an updated preliminary assessment of the Nokomis Project, based on the June 2008 mineral resource estimate. This PA is based on an expanded 40,000 tonne per day ("tpd") production rate scenario which doubles the January 2008 PA production rate. The report confirms positive economics for the Nokomis Deposit even at today's lower metal prices with the potential to be one of the world's low cost copper-nickel producers (Table 1-12).

Table 1-12. Nokomis production rate scenarios.

Base Case¹ Scenarios	Production Rate² @ 20,000 tpd	Production Rate³ @ 40,000 tpd
Undiscounted Net Present Value	\$4.328 Billion	\$8.214 Billion
Net Present Value @ 10%	\$792 Million	\$1.598 Billion
Average Annual Cash Flow	\$205 Million	\$434 Million
Internal Rate of Return (IRR)	21.0%	23.0%
Capital Cost	\$795 Million	\$1.332 Billion
Payback Period	4 years	4 years
Annual Metal Production	102.1 million lbs Cu	181.7 million lbs Cu
	23.8 million lbs Ni	42.3 million lbs Ni
	121,000 ozs TPM	251,000 ozs TPM

Note, all monetary units are in \$US:

¹ Scott Wilson RPA: Base Case Prices of \$1.75/lb Cu; \$7.00/lb Ni; \$10.00/lb Co; \$1,100/oz Pt; \$350/oz Pd; \$600/oz Au

² January 18, 2008 Scott Wilson RPA Preliminary Assessment on the Nokomis Project, Minnesota, U.S.A.

³ January 8, 2009 Scott Wilson RPA Preliminary Assessment on the Nokomis Project, Minnesota, U.S.A.

The new PA for the Nokomis Project envisions and includes costing for a fully integrated mining and processing facility that encompasses the following general process flow: Ore production rate of 40,000 tonnes per day (14 million tonnes per year); Underground mining by blasthole open stoping with partially recoverable pillars; Underground access by shaft and ramp; Underground ore handling by conveyor systems; Underground primary crushing, further crushing and grinding on surface; Transfer from mine to concentrator via 10 km slurry line; Agitated holding tanks at mill with a minimum capacity of 11,000 m³; Flotation concentration, producing a bulk copper-nickel-cobalt-PGM-gold concentrate; Hydrometallurgical processing using PLATSOL™ process; Production of saleable copper and nickel metal via standard electrowinning and production of cobalt and PGM-gold products to shipped to refineries for final processing to metal; and a brownfields tailings disposal facility within three kilometers of the processing site.

Table 1-13 shows unit cash costs (operating and capital), calculated for either nickel or copper. This measure provides a means to compare costs in dollars per pound of metal to individual metal prices (also in dollars per pound of metal). SWRPA notes that the calculation is net of byproduct credits, which in this case amount to approximately 60% of revenue. Since no single metal is a dominant contributor, unit cash costs calculated in this manner appear very low, or negative in most cases.

Table 1-13. Unit cash costing chart for evaluating the Nokomis deposit as a Copper or Nickel mine with all other metals as byproducts.

Assumptions	Low Case	Base Case	Market Case
Key Variable - Cu Price (\$/lb)	\$1.55 /lb.	\$1.75 /lb.	\$3.31 /lb.
Key Variable - Ni Price (\$/lb)	\$4.90 /lb.	\$7.00 /lb.	\$12.70 /lb.
Capital Cost, including Contingency (Billion \$)	\$1.332	\$1.332	\$1.332
Conceptual Projected Mine Life	22 years	22 years	22 years

Nokomis as a Copper Mine

Unit Cash Costs - Operating (\$/lb Cu)	\$(0.09) /lb.	\$(0.72) /lb.	\$(2.36) /lb.
Unit Cash Costs - Capital (\$/lb Cu)	\$0.42 /lb.	\$0.42 /lb.	\$0.42 /lb.
Total Unit Cash Costs - Operating + Capital (\$/lb Cu)	\$0.32 /lb.	\$(0.30) /lb.	\$(1.94) /lb.

Nokomis as a Nickel Mine

Unit Cash Costs - Operating (\$/lb Ni)	\$(2.15) /lb.	\$(3.61) /lb.	\$(11.62) /lb.
Unit Cash Costs - Capital (\$/lb Ni)	\$1.79 /lb.	\$1.79 /lb.	\$1.79 /lb.
Total Unit Cash Costs - Operating + Capital (\$/lb Ni)	\$(0.36) /lb.	\$(1.82) /lb.	\$(9.83) /lb.

Low Case - reflecting recent low metal prices of 1.55/lb Cu; \$4.90/lb Ni; \$10.00/lb Co; \$795/oz Pt; \$295/oz Pd; \$600/oz Au.

Base Case - same base case prices used in the previous Technical Report (January 2008 PA), based on long-term average price forecasts of the past several years. (\$1.75/lb Cu; \$7.00/lb Ni; \$10.00/lb Co; \$1,100/oz Pt; \$350/oz Pd; \$600/oz Au).

Market Case - prices as of January 13, 2008*, for direct comparison to the previously-reported 20,000 tpd scenario contained in the January 2008 PA.

ENVIRONMENTAL STUDIES

With the scoping studies completed, Duluth Metals initiated baseline and preliminary Environmental Studies. Duluth Metals recognizes environmental guardianship as an important corporate priority, and is working closely with State and Federal agencies to establish policies, programs and practices for conducting its business in an environmentally sound manner. Our company realizes its long-term success depends on the well being of the environment and the community as a whole. Duluth Metals goal is to not only remain in compliance with all State and Federal regulations governing their operations but to exceed them. Duluth Metals has an environmental policy under which it has made a number of commitments consistent with responsible environmental stewardship. The Company is committed to:

1. Retain qualified, professional employees and consultants to design and implement their field programs;
2. Develop, design and operate facilities in a socially and environmentally friendly manner in order to mitigate environmental impacts;
3. Support research to advance understanding of industry's impact on the environment and to reduce harmful effects through improved practices and technologies;
4. Contribute to the dissemination of environmentally sound technology and management methods;
5. Work with government and the public to develop effective, efficient, and equitable measures to protect the environment based on sound science;
6. Require contractors to comply with our Company's environmental policy requirements;
7. Encourage dialogue on environmental issues with employees and the concerned public groups and to be responsive to their concerns;
8. Ensure that all employees understand and are able to fulfill their environmental responsibilities; and,
9. Reclaim work sites in accordance with site specific criteria in a planned and timely manner.

The numerous studies need to be completed (over a number of years) in order for Duluth Metals to gain the right to mine the deposit in an environmentally sound manner is perhaps best viewed in a graphical form (Fig. 1-27). This chart clearly displays the complex interplay of geology, geoengineering, metallurgy, mine planning and design, and extensive environmental studies that must mesh together into a coherent plan to put the Nokomis Deposit into production. Duluth Metals has initiated baseline environmental and engineering studies in support of the Nokomis environmental review and permitting process. Examples of baseline environmental studies completed include: Wetlands Delineations and Functional Assessments; Stream Morphology Assessments; Wildlife Habitat Surveys; Sensitive Plant Species Surveys; and, Phase 1a Cultural Resources Searches. In addition, several preliminary environmental engineering studies have been completed to help with siting potential facilities.

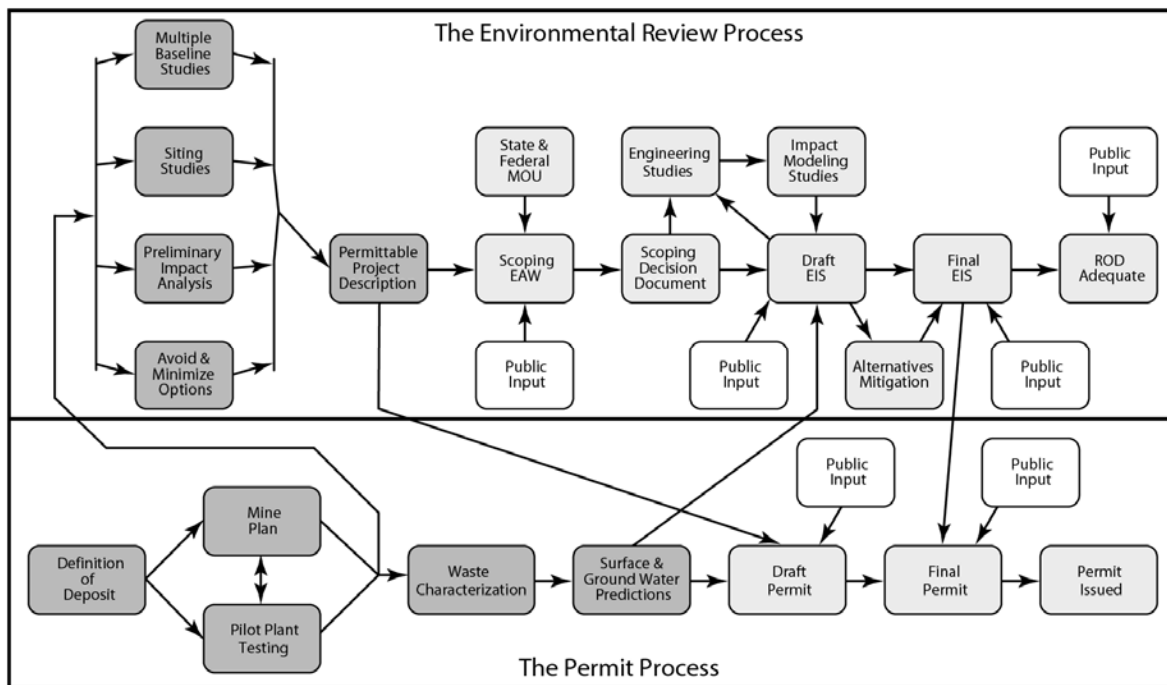


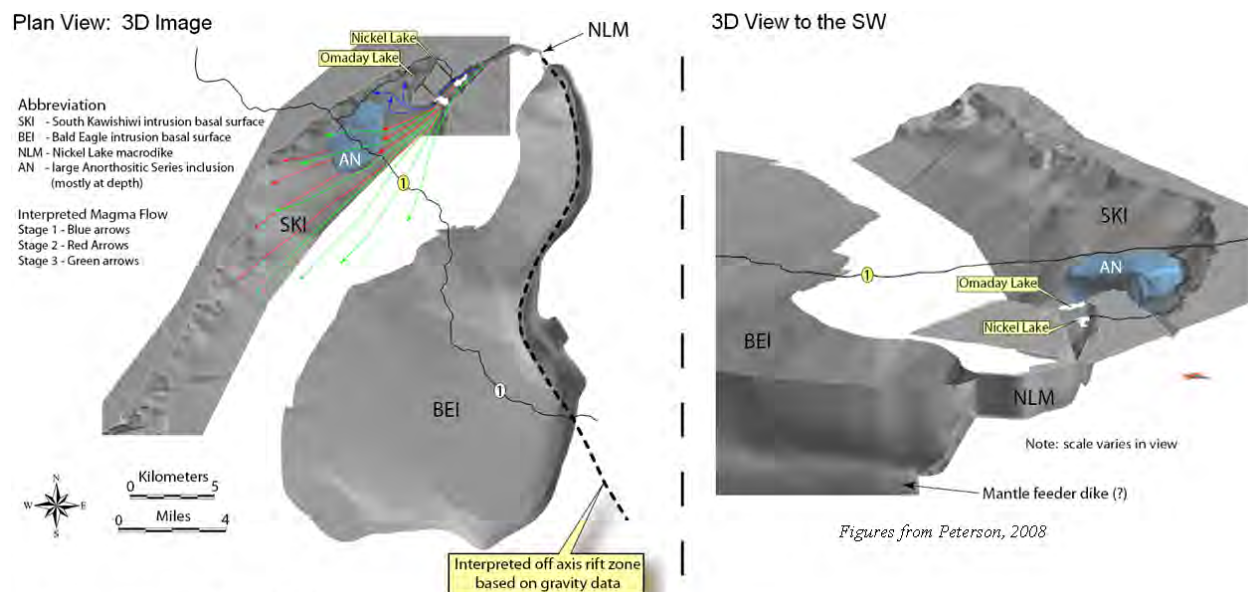
Figure 1-27. The environmental review and permit process utilized in Minnesota for the Cu-Ni-PGE projects in the Duluth Complex. Dark grey boxes represents work that the company has to complete, light grey boxes are completed by the state and federal agencies, and white boxes represent times the public has input into the process.

GEOLOGY OF THE NOKOMIS DEPOSIT

Duluth Metals Limited's Nokomis deposit is the most recently discovered Cu-Ni-PGE deposit in the 1.1 Ga. Duluth Complex of northeastern Minnesota. The deposit is located near the north end of the South Kawishiwi intrusion (SKI) west-southwest of the junction of the Nickel Lake Macrodiike (NLM) and the SKI (Peterson et al., 2006; Peterson and Albers, 2007; Tharlason et al., 2007; Peterson, 2008; White, in prep; Gal, 2008). The deposit was discovered utilizing a genetic ore deposit model that identified channelized magma flow within the SKI under a large xenolith/pillar of anorthosite. The model led to exploratory drilling in 2006, deposit discovery and initial resource estimation in 2007, and significant resource expansion in 2008, all in a period of 18 months. The regional scale magma flow model that is being used by Duluth Metals to interpret the origin of the Nokomis Deposit is presented in Figure 1-28.

Duluth Metals has come to the realization that the initial basaltic composition SKI magmas that ultimately created the Nokomis deposit intruded as sulfide-bearing, crystal-laden slurries (olivine and plagioclase crystals). Therefore the company has reinterpreted the regional basal stratigraphy (PEG, U3, BH, BAN) of the SKI (Fig. 1-6) at Nokomis into the Basal Mineralized Zone, or BMZ. The company believes that

the geometry of the system (sill-like sub-horizontal intrusion) led to crystal sorting and melting the footwall granitic rocks to create the heterogeneous lithologies of the BMZ (Fig. 1-29).



Idealized Magma Flow Model

- 1) Magma ascends through a mantle feeder dike
- 2) Sulfide saturation occurs while magma incorporates sedimentary rocks (Virginia Fm sulfidic argillites)
- 3) Rift-parallel faulting opens a sub-horizontal space (the Nickel Lake Macrodike, NLM) that magma traverses to the SW along
- 4) Subhorizontal sill intersects an active transform fault and magma sills out (to NNW) to form the Spruce Road Deposit
- 5) Continued flow lifts the hangingwall Anorthosite as sill-like magma fingers traverse to the WSW forming the Nokomis Deposit
- 6) Much Later – The Bald Eagle Intrusion intrudes in a “Trap Door” fashion structurally higher than the SKI

Figure 1-28. Regional scale magmatic flow model for the northern SKI. Modified after Peterson, 2008.

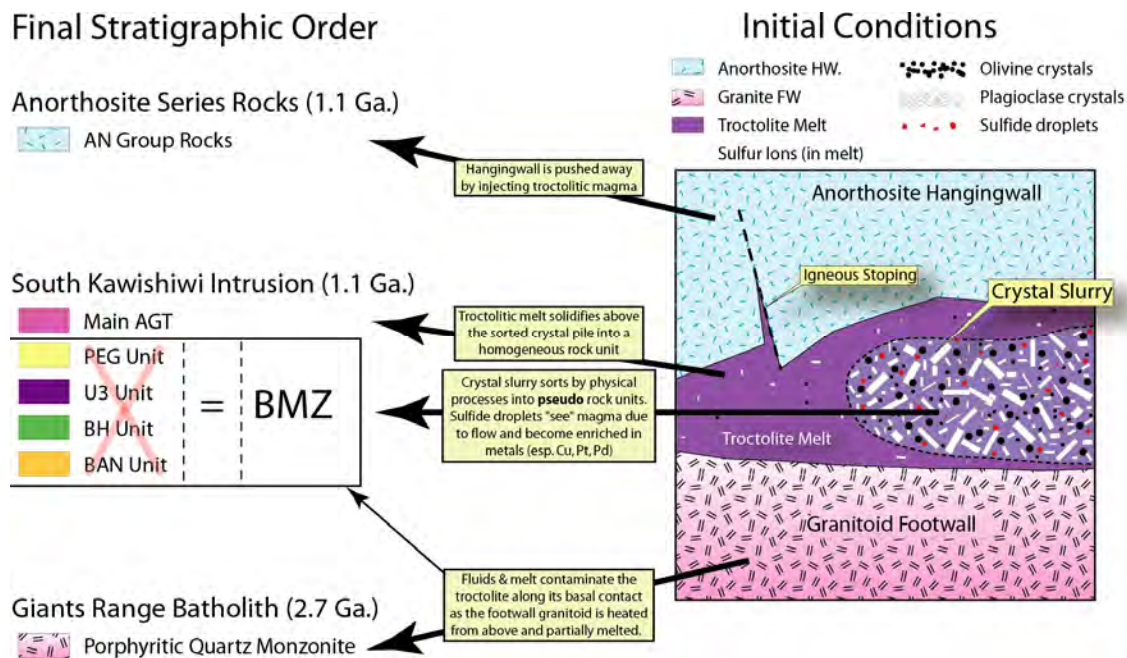


Figure 1-29. Simplified crystal-liquid slurry model for the SKI in the Nokomis area.

The SKI is a shallow dipping (~24° east-southeast) sill-like troctolitic intrusion exposed in an 8- x 32-kilometer arcuate band along the northwestern margin of the Duluth Complex. Lithologic units within the Nokomis deposit include Mesoproterozoic rocks of the SKI and Anorthositic Series of the Duluth Complex as well as basalt xenoliths of the North Shore Volcanic Group. At Nokomis, SKI magmas intruded between hangingwall anorthositic rocks and footwall granitic rocks of the Neoarchean Giants Range batholith (Fig. 1-29). Brief descriptions of the map units that Duluth Metals recognizes on the property are given in Table 1-14.

Table 1-14. Lithostratigraphic units within the Nokomis deposit.

Duluth Complex and related rocks (1.1 Ga.)	
SKI	Anorthositic troctolite to troctolite (ATA Series) - Medium to coarse-grained, homogeneous, well-foliated and locally layered anorthositic troctolite, troctolite, and ophitic troctolitic rocks. In the field, this unit is commonly referred to as the “sea of troctolite”.
	Augite-bearing troctolite (Main AGT) - Heterogeneous, coarse-grained, subophitic to ophitic, poorly foliated augite troctolite characterized by scattered augite-rich pegmatitic clots and patches. Commonly capped by hanging wall inclusions (HB & Ai) and interpreted to be the solidified basaltic liquid that carries the crystals and sulfides of the BMZ.
	Sulfide-bearing troctolite (BMZ) - Heterogeneous, sulfide-bearing, vari-textured troctolite, augite troctolite, anorthositic troctolite, and olivine gabbro with 0.5 - 5% disseminated chalcopyrite, cubanite, pentlandite and pyrrhotite.
Xenoliths in the SKI	Anorthosite (AN-G & Ai) - Undifferentiated Anorthositic Series inclusions. Includes well-foliated anorthosite, troctolitic-anorthosite, poikilitic troctolitic anorthosite, gabbroic anorthosite, and rarely gabbro and troctolite. Inclusions range from a few cm’s to elongate bodies measured in km’s.
	Anorthositic gabbro to gabbro (Upper Gabbro) - Mixed group of Anorthositic Series rocks that occur in the central portion of the map area. Includes well-foliated anorthositic gabbro, gabbro, anorthosite, hornfelsed basalt, and augite troctolite.
	Basaltic hornfels (Upper Basalt, HB) - Fine-grained, granoblastic to poikiloblastic basaltic hornfels; consists of variable amounts of plagioclase, augite, olivine, hypersthene, and inverted pigeonite. Commonly associated with Anorthosite xenoliths (unit Ai).
Giants Range Batholith (2.68 Ga.)	
Footwall	Porphyritic quartz monzonite (GRB) - Pink, coarse-grained, hornblende-phyric, quartz monzonite with large (1-2 cm) orthoclase phenocrysts. Also contains irregular zones of aplite and supracrustal xenoliths. Strongly recrystallized and partially melted locally along the contact with the SKI.

Two detailed geologic cross sections through the Nokomis Deposit are presented in Figure 1-30. These sections display the continuity of the basal mineralization as well as the differences in the hangingwall stratigraphy from west to east through the deposit (see Fig. 1-6). In the east, the deposit is located under an extremely thick (>1000m) pillar of Anorthosite Series rocks, and in essence the basal SKI can be viewed as a thin sill-like body. To the west, the anorthosite pillar ends and the immediate hangingwall rocks to the deposit are troctolites of the Main AGT unit. We interpret that the Main AGT as the

solidified troctolite melt (see Fig. 1-29) that carried the crystals and sulfide droplets of the magmatic slurry.

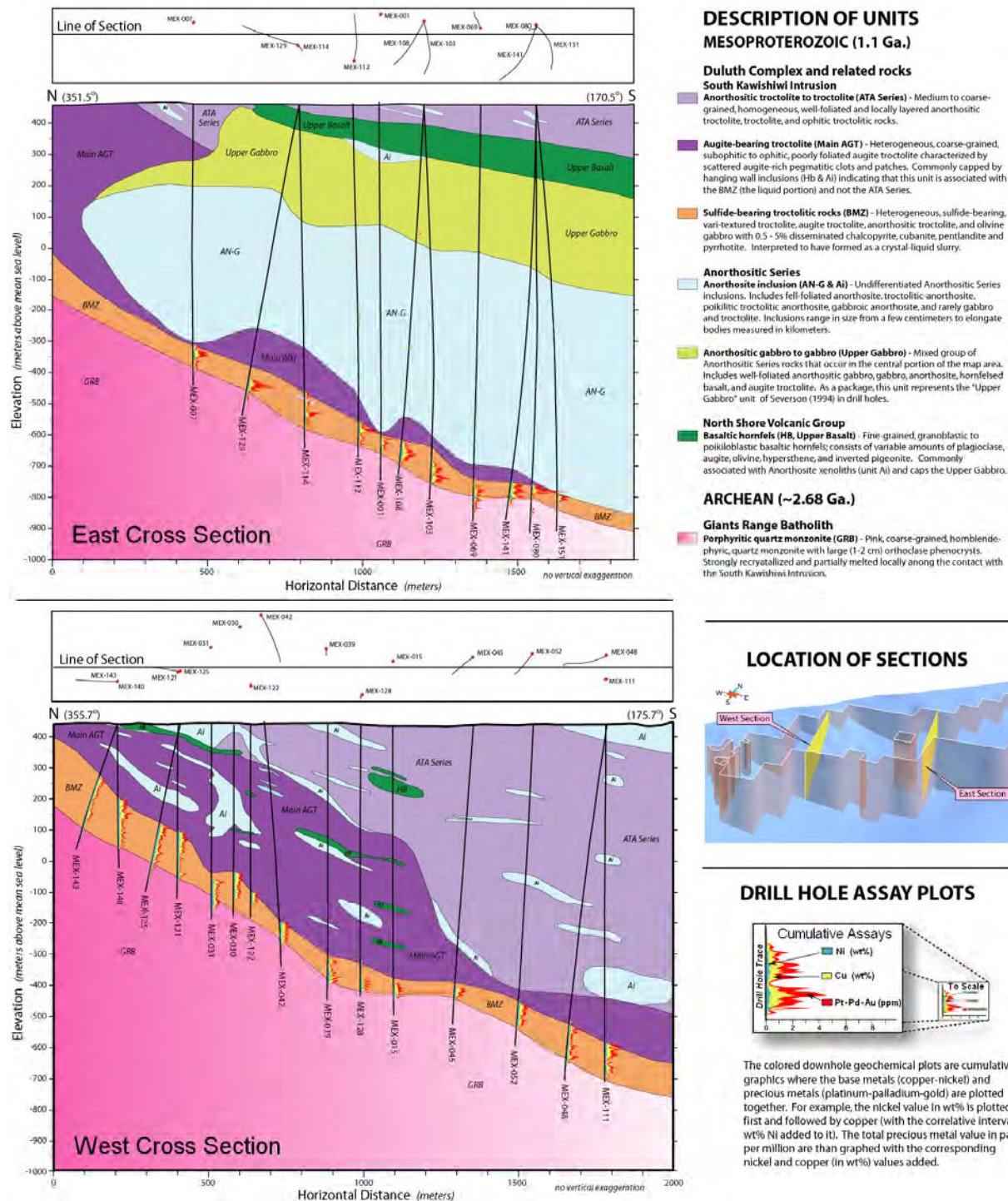


Figure 1-30. Geologic cross sections through the Nokomis Deposit.

NOKOMIS ORE DEPOSIT MODEL

Duluth Metals is utilizing advanced geological modeling and analysis of the Nokomis deposit to identify and characterize higher grade copper, nickel, platinum, palladium and gold zones within the deposit. This same modeling defines contiguous, large tonnage, higher grade zones that will be important in the evaluation of future mining scenarios. The geologic modeling also provides an innovative way to understand the origin of, and the controls on, grade distribution within the deposit. As well, the model will assist on directional search parameters and variography of subsequent block models and grade - tonnage estimates. Duluth Metals is commissioning a new 43-101 resource estimate which will include 155 drill holes and 63 wedges as part of its higher grade zone targeting effort.

The results of our models show four distinct types of higher-grade Cu-Ni-PGE mineralization within the Nokomis Deposit. These four distinct types of mineralization are briefly described below and are presented graphically in Figure 1-31.

1) PGE- rich disseminated mineralization on the Eastern side of the Nokomis Property.

This area is known as the Eastern High Grade Corridor (21 drill holes as press released October 27, 2008). This large coherent zone of significantly higher grade PGE mineralization is the result of the initial constriction of the magma channel beneath a large block of older Anorthositic Series rocks within the Nokomis Deposit. Such a blockage impedes the flow of crystals and sulfide droplets. However, the liquid portion of the magma continues to flow along with its dissolved Platinum Group Elements ("PGE"). Once these dissolved and flowing PGE's come in contact with a stuck sulfide droplet, they dissolve into the sulfide droplets and increase the PGE tenor of the sulfide.

2) Ni-Co enriched semi-massive sulfides at, or immediately below the base of the magma channel.

This mineralization is believed to have formed by continuous flushing of hot magma through the channelway which melted footwall granitic rocks. These granitic melts were incorporated into the magma and induced the formation of new sulfide minerals beneath the crystal slurry. These new sulfides scrubbed the melt of nickel and cobalt and settled to the bottom of the system.

3) Cu-PGE enriched disseminated mineralization deep in the footwall below the magma channel.

The ever-deepening (into the melting footwall) magma channel induced and pinned hydrothermal convection cells in the footwall beneath the magma channel. The water in the system was released from the footwall granitoids by thermal metamorphism and circulated Cu-PGE downwards beneath the channelway.

4) Cu-PGE enriched disseminated mineralization at the top of the mineralized zone (Top-Loaded).

To the sides of the magma channelway, the sulfide-bearing crystal-liquid slurry was intruded as batches of magma out and to the sides of the channel. Since these highly crystalline magmas are distal to the very hot main magma channel, they solidified quickly into sulfide-bearing troctolite. Once the silicates (olivine+plagioclase) are solid, buoyant fractionated sulfide (Cu-PGE) liquid and magmatic waters moved upwards through the solidifying crystal pile and precipitated Cu-PGE sulfide and hydrous silicate minerals beneath the overlying crystal-poor, liquid silicate magma.

Company sponsored and internal research on many aspects of the mineralization within the Nokomis Deposit is continuing. Models based on normative mineralogical compositions have shown that the composition of Cu-Ni-PGE mineralization reflects local segregation and fractionation of the sulfide liquid as well as processes involved in the transportation upwards and/or downwards of the evolved sulfide liquid through the solidified host rock (Figs. 1-32 and 1-33). Further details of segregation-fractionation-infiltration and transportation processes of evolved Cu-Ni-PGE sulfide liquids/fluids are currently being explored by Duluth Metals. Such studies include detailed petrography, fluid inclusion studies, research-grade total PGE analyses, whole-rock analyses, and stable isotope geochemical studies.

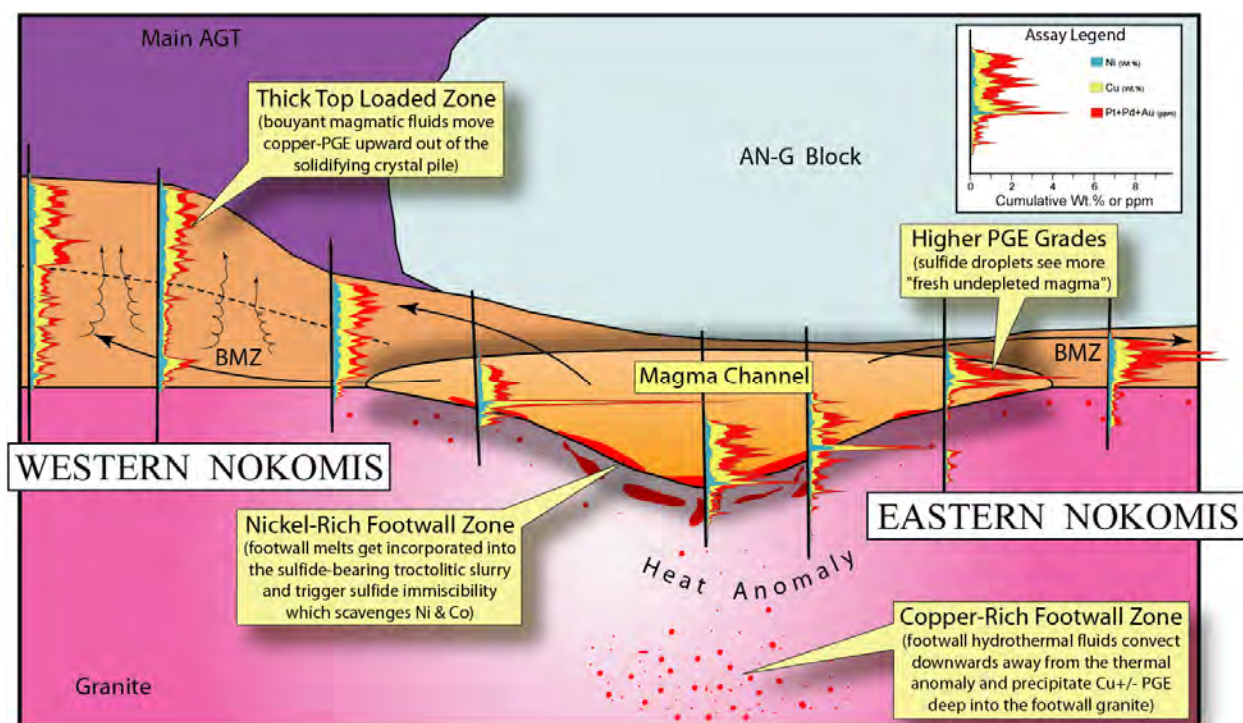


Figure 1-31. The integrated ore deposit model for the Nokomis deposit.

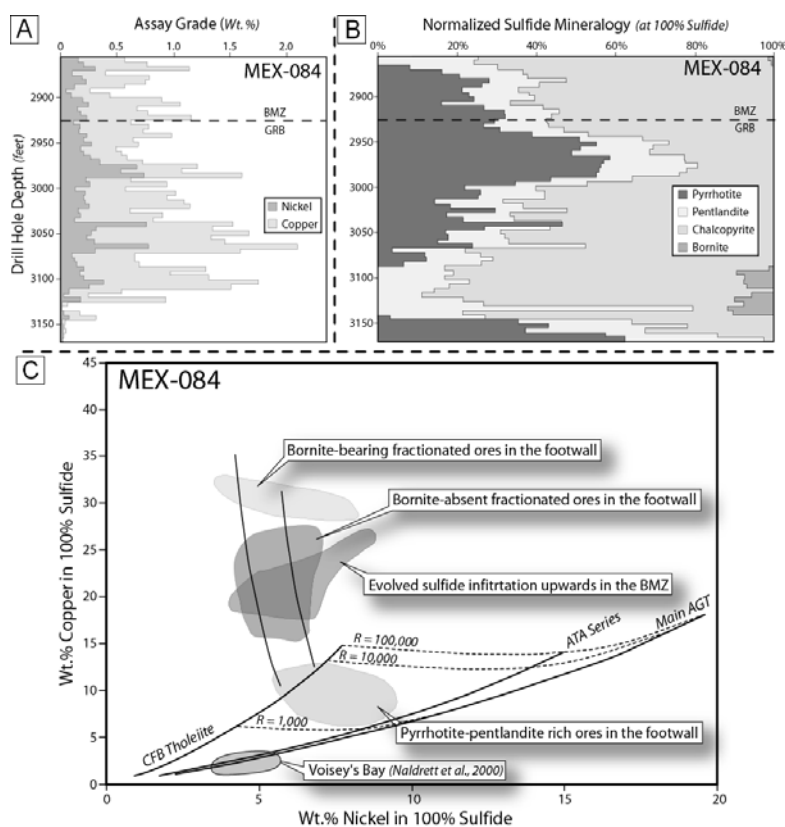


Figure 1-32. Copper-Nickel assays (A), normalized sulfide mineralogy calculated at 100% sulfide (B), and sulfide fractionation model for Nokomis drill hole MEX-084.

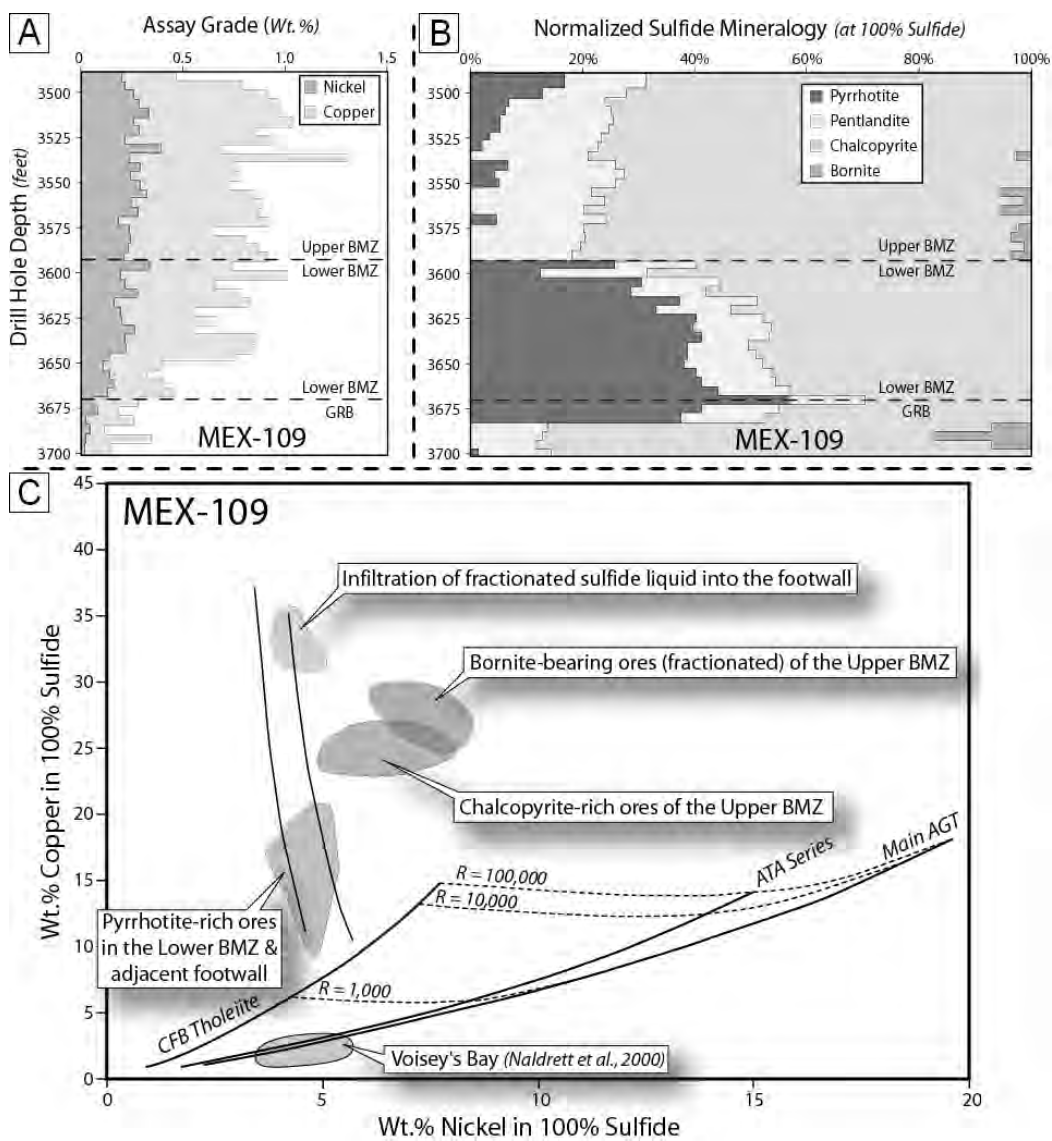


Figure 1-33. Copper-Nickel assays (A), normalized sulfide mineralogy calculated at 100% sulfide (B), and sulfide fractionation model for Nokomis drill hole MEX-109.

DRILL CORE DISPLAY

Intervals from four drill holes will be on display in the Duluth Metals drill core logging shed in Ely Minnesota. These holes were chosen to display typical aspects of the four styles of mineralization outlined above that occur throughout the deposit. The locations of the four holes (MEX-084, MEX-109, MEX-141, and MEX-154) are given in Figure 1.25 and press released assay data for these holes are given in Table 1-15. The only drill hole on display that has exceptional textures and/or Cu-Ni-PGE grades for the defined style of mineralization (Fig. 1-31) is MEX-084, which is perhaps the finest example of mineralization in the footwall Giants Range batholith ever drilled in the Duluth Complex. The other drill holes (MEX-109, MEX-141, MEX-154), display typical textures and Cu-Ni-PGE grades (Table 1-15) within the Nokomis Deposit.

We at Duluth metals invite you to examine these drill hole intervals and think about the physical and chemical processes that came together to create truly one of the world's largest resources of Cu-Ni-PGE (Fig. 1-26). Herein at the Nokomis deposit, a channelized and crystal-laden (plagioclase and olivine phenocrysts) basaltic melt containing sulfide droplets intruding sub-horizontally as a sill-like body between a granitoid footwall and anorthosite hangingwall. The physical magmatic processes that the system underwent imparted discrete thermal and chemical processes onto the system. Many of these combined processes can be seen as snapshots in time and place in the drill hole intervals presented.

Table 1-15. Composite assays from the four selected Duluth Metals drill holes on display.

Details of the Interval	From (ft)	To (ft)	Int. (ft)	Cu (%)	Ni (%)	Au (g/t)	Pt (g/t)	Pd (g/t)	TPM (g/t)	Ag (g/t)
<i>MEX-141 Drill hole in the magma channel in the PGE-rich Eastern High Grade Zone</i>										
0.3% Cu cut-off	4032.0	4202.0	170.0	0.779	0.246	0.131	0.296	0.718	1.146	2.981
0.5% Cu cut-off	4032.0	4192.0	160.0	0.809	0.251	0.136	0.309	0.747	1.192	3.152
including	4147.0	4182.0	35.0	1.201	0.436	0.158	0.352	0.957	1.468	3.907
including	4177.0	4182.0	5.0	2.050	1.280	0.134	0.700	2.080	2.914	5.300
<i>MEX-84 Drill hole beneath the magma channel with abundant footwall mineralization</i>										
0.3% Cu cut-off	2849.7	3115.4	265.7	0.691	0.250	0.097	0.184	0.423	0.704	2.452
0.5% Cu cut-off	2859.6	3110.4	250.8	0.705	0.258	0.100	0.187	0.433	0.720	2.515
including	3041.5	3110.4	68.9	1.033	0.270	0.146	0.286	0.637	1.068	4.082
including	3041.5	3071.0	29.5	1.209	0.367	0.188	0.334	0.670	1.192	4.559
<i>MEX-109 Drill hole into Top-Loaded mineralization in the center of the property</i>										
0.3% Cu cut-off	3483.0	3668.0	185.0	0.760	0.227	0.130	0.260	0.602	0.991	2.903
0.5% Cu cut-off	3493.0	3648.0	155.0	0.828	0.247	0.143	0.286	0.660	1.089	3.150
including	3498.0	3538.0	40.0	0.955	0.278	0.213	0.414	0.901	1.527	3.863
<i>MEX-154 Drill hole into thick Top-Loaded mineralization in the Western portion of the property</i>										
0.3% Cu cut-off	1627.0	1937.0	310.0	0.609	0.179	0.065	0.117	0.260	0.443	2.408
0.5% Cu cut-off	1627.0	1797.0	170.0	0.690	0.196	0.073	0.129	0.287	0.490	2.757
including	1667.0	1682.0	15.0	1.020	0.289	0.156	0.188	0.446	0.790	3.833
0.5% Cu cut-off	1882.0	1937.0	55.0	0.582	0.166	0.072	0.120	0.268	0.460	2.141

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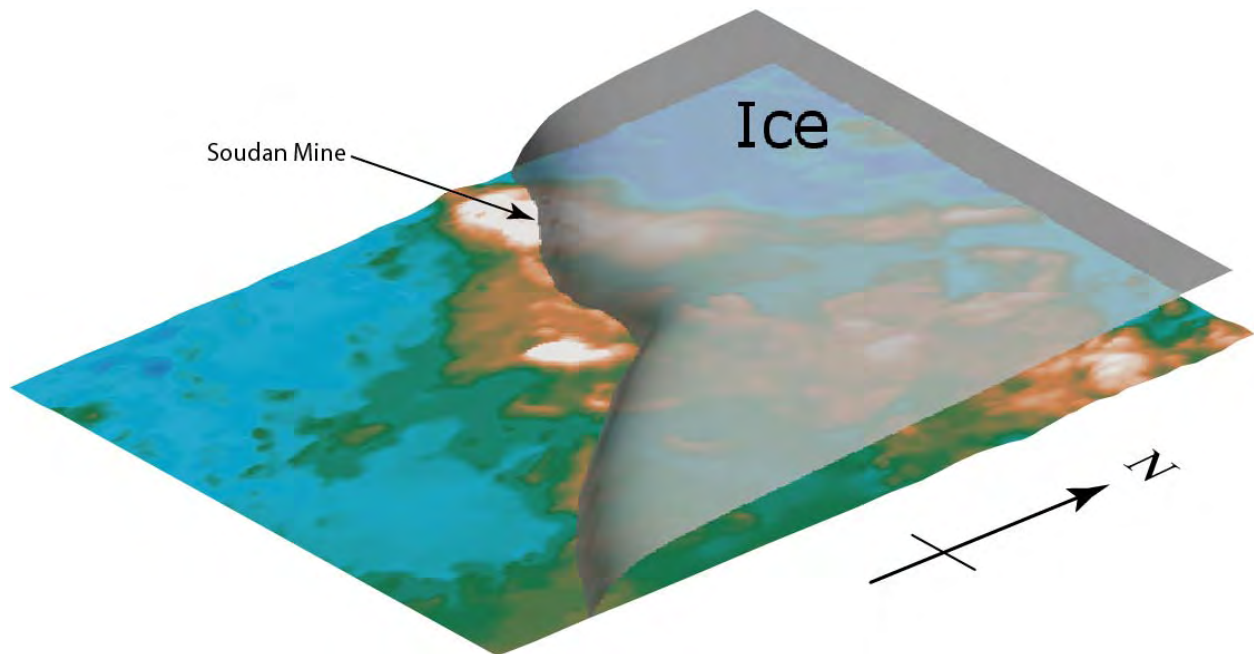
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55th Annual Institute on Lake Superior Geology

Field Trip 2

GLACIAL GEOLOGY OF THE VERMILION MORaine



3D interpretation of the location of the Laurentide ice sheet in the Soudan Mine area at the time of the development of the Vermilion Moraine (modified from Peterson and Patelke, 2003).

Phil Larson (Cliffs Natural Resources)

Howard Mooers (Department of Geological Sciences, UMD)

FIELD TRIP 2

GLACIAL GEOLOGY OF THE VERMILION GREENSTONE BELT

Phillip C. Larson (Cliffs Natural Resources)

Howard D. Mooers (Department of Geological Sciences, University of Minnesota-Duluth)

INTRODUCTION

This field trip provides an introduction to the glacial geology and glacial sedimentary environments of the Vermilion district of northeastern Minnesota. The bedrock geology and topography of this area are characteristic of millions of square km of glaciated Precambrian shield terranes in Canada, Scandinavia, and the United States. Overlying bedrock in the belt is an assemblage of glacial sediments characteristic of a great portion of the glaciated shields on earth. In recent years, these characteristics have allowed the glaciated Vermilion greenstone belt to serve as a virtual laboratory for investigating the nature and scale glacial erosion and entrainment, and transport processes.

Metavolcanic and metasedimentary rocks of the Vermilion district are also notably prospective for volcanogenic massive sulphide and shear-hosted lode gold deposits (Peterson and Jirsa 1999; Peterson, 2001; Peterson and Patelke 2004). Mineralized clasts and geochemical anomalies related to such deposits are evident in glacial deposits overlying and down-ice of the greenstone belt. The presence of anomalous mineralization, combined with the well-described nature of glacial sediment dispersal, in the district provides a unique opportunity to demonstrate the techniques by which till geochemical and mineralogical data can be incorporated into an integrated mineral exploration program.

This field trip visits a selection of sites that illustrate the range of glacial sediment types present in this typical glaciated shield terrane, as well as their compositional heterogeneity. A second theme of the trip is the collection and manipulation of the types of data useful to mineral exploration in glaciated terranes.

REGIONAL BEDROCK GEOLOGY

(The following overview of regional bedrock geology is largely taken from Peterson, Jirsa, and Hudak (2009), included in this guidebook.)

Supracrustal rocks in the Vermilion district consist of volcanic-dominated stratigraphic sequences of the Wawa subprovince of the Superior Province of the Canadian Shield (Fig. 2-1). Rocks of the Wawa subprovince in northern Minnesota are divided on the basis of stratigraphic and structural setting into: (1) the Soudan belt, to the south, and (2) the Newton belt, to the north (Jirsa et al., 1992; Southwick et al., 1998). The two belts are fault-bounded, and the relationship between stratigraphic units within each belt is largely conformable, although faults obscure contacts locally. The boundary between these contrasting structural panels occurs along the Mud Creek shear zone (Hudleston et al., 1988), small segments of the Vermilion and Wolf Lake faults (Sims and Southwick, 1985), and the Bear River fault (Jirsa et al., 1992).

The Soudan belt contains large, broad folds involving calc-alkalic and tholeiitic volcanic strata overlain by, and locally interdigitated with, turbiditic rocks. In contrast, the Newton belt consists of elongate, northeast-trending, and mostly northward-younging volcanic and volcanoclastic sequences. Volcanic rocks of the Newton belt differ from those of the Soudan belt in containing locally abundant komatiitic flows and peridotitic sills.

To the south, supracrustal rocks of the Soudan belt are intruded by syn- to post-tectonic granitoid rocks of the Giants Range batholith. At the northern edge of the Vermilion district, the Vermilion fault marks the boundary with granite, granite-rich migmatites, migmatites, paragneisses, and biotite schists of the Quetico subprovince of the Superior Province of the Canadian Shield (Jirsa and Boerboom, 2003).

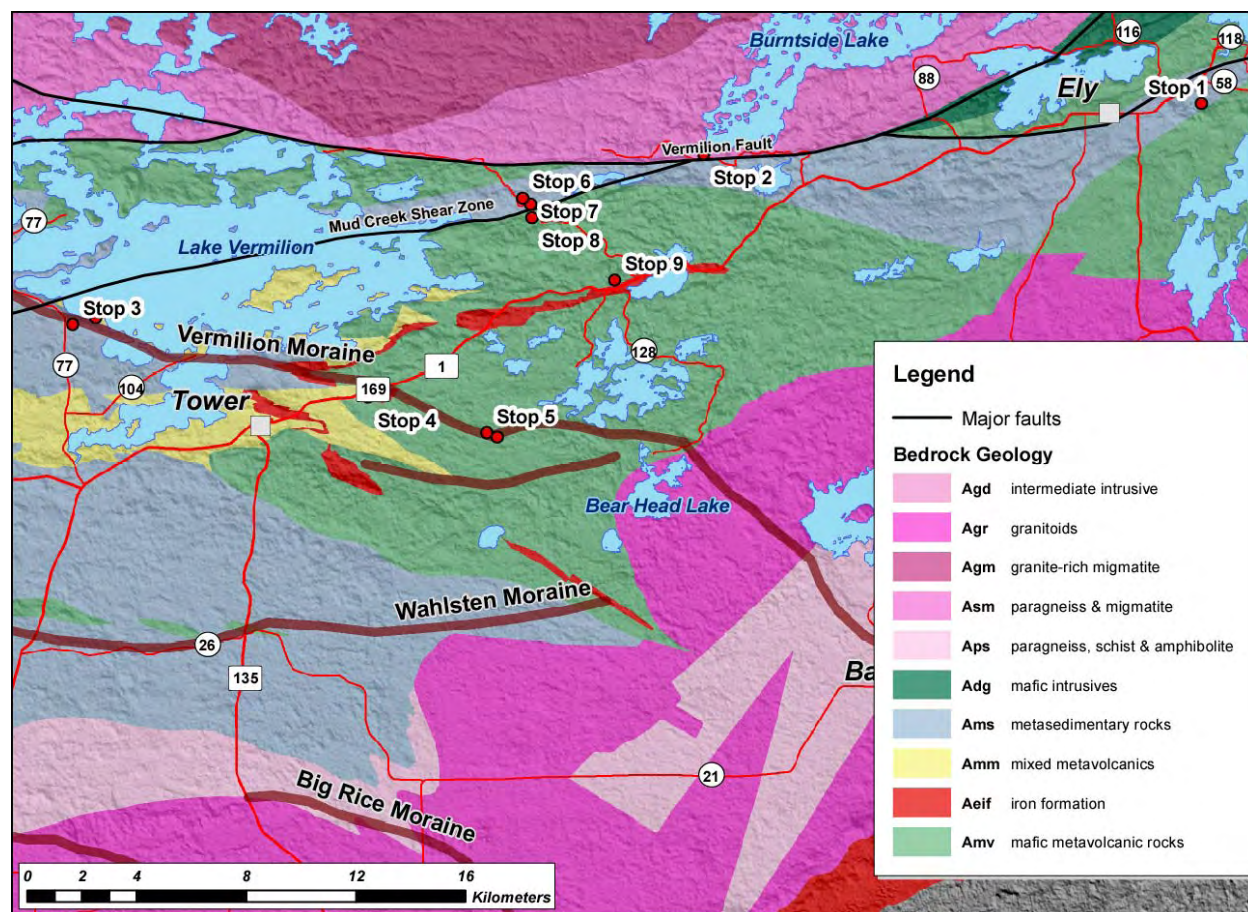


Figure 2-1. Bedrock geology of the Vermilion district, modified from Morey and Meints, 2000.

GLACIAL HISTORY OF THE VERMILION DISTRICT

In common with most of the high latitude regions of North America, the Vermilion district was repeatedly glaciated during the ice ages of the Pleistocene Epoch. Glacigenic sediments and landforms in the Vermilion district are associated with the Rainy Lobe of the Laurentide ice sheet. While there are a number of possible definitions of what constitutes the Rainy Lobe – sedimentological, textural, compositional, and association with particular geomorphic features – a definition rooted in glacial dynamics perhaps works best. In this sense, the Rainy Lobe refers to that portion of the Laurentide ice sheet lying northwest of Lake Superior (occupied by the Superior Lobe), and east of the Winnipeg Basin and Red River Valley (occupied by the Red River Lobe). In common, Rainy Lobe landforms and glacigenic sediments reflect a general northeast to southwest ice flow direction, and a Labradoran (northeastern) sediment provenance.

Preglacial Environment

In common with much the Canadian Shield, glacial erosion has nearly completely stripped preglacial regolith from bedrock in the Vermilion district. However, preglacial saprolites are a common occurrence

underlying glacial sediments in central and western Minnesota; the nearest such occurrences are exposed in open pit mines of the Mesabi Range, on the south flank of the Giant's Range.

Massive iron oxide mineralization exposed in surface workings of the Consolidated Vermilion mine (near Stops 2-6 and 2-7) contains voids lined by botryoidal goethite. The botryoidal goethite occurs as dripstone-like structures, suggesting that it precipitated in open spaces in the vadose zone. Inasmuch as the water table of the preglacial peneplained Canadian Shield was likely similar to the modern, this occurrence supports the hypothesis that little erosion of unweathered bedrock was accomplished by multiple glaciations through the course of the Pleistocene. The topography observed in the Vermilion district today therefore likely represents that of the base of the preglacial weathering regolith.

Pre-Late Wisconsinan

Throughout the field trip area, no till or glaciofluvial sediments older than those deposited during the Late Wisconsinan retreat of the Laurentide ice sheet have been described. However, circumstantial evidence of the past existence of pre-Late Wisconsinan glacial sediments are present, and pre-Late Wisconsinan glacial sediments are preserved a few 10s of km to the south.

Winter (1971) and Winter and others (1973) described a dark-colored, sandy-silty calcareous till in exposures in open pit mines on the Mesabi Iron Range. Inasmuch as this till, where present, occurred immediately above bedrock, they referred to it as the "basal till". Stark (1977) and Lehr and Hobbs (1992) described occurrences of Winter's basal till in exposures in the Dunka Mine, approximately 20 km south of the area encompassed by the current field trip.

The matrix of Winter's basal till is calcareous, and the pebble fraction contains carbonate clasts in addition to the granitic and metamorphic lithologies typical of Rainy Lobe tills. A northeast-southwest pebble fabric in Winter's basal till strongly supports a northeastern provenance for this till. In this case, carbonate in pebbles and till matrix is derived from Paleozoic carbonates in the Hudson Bay Lowlands.

Surficial Rainy Lobe tills in the region are typically non-calcareous, leading some workers to suggest that calcareous tills in the region must have a Keewatin (northwestern) provenance. However, it is more likely that calcareous Labradoran (northeastern) provenance tills are the norm in northeastern Minnesota, with the relatively thin, noncalcareous tills deposited during the Late Wisconsinan the exception (Mooers and Lehr 1997, Larson and Mooers 2005, Larson and Mooers 2008). Mooers and Lehr (1997) and Larson and Mooers (2008) noted the close association between carbonate and distinctive clasts of Paleoproterozoic greywacke in HBL provenance tills. In many cases, the greywacke clasts are able to survive englacial comminution and weathering better than the carbonates, and only greywacke clasts remain. The presence of greywacke clasts in till is therefore strong evidence that the material forming the till was once calcareous.

The presence of calcareous Labradoran provenance tills to the southwest (Mooers and Lehr 1997), and to the northeast (northwestern Ontario) (Karrow and Geddes 1987), suggests that a continuous sheet of calcareous till once extended across the Vermilion greenstone belt. However, by Late Wisconsinan time, much of this calcareous till had been remobilized and removed from the Canadian Shield, including the field trip area (Larson and Mooers 2008).

Late Wisconsinan

By no earlier than 15 ka, the Rainy and Superior Lobes began to retreat from the St. Croix Moraine in central Minnesota (Clayton and Moran 1982). By the time the St. Louis Sublobe advanced from the northwest into the basins of Glacial Lake Upham I and Aitkin I, the southern margin of the LIS was roughly coincident with the Giant's Range (Fig. 2-2).

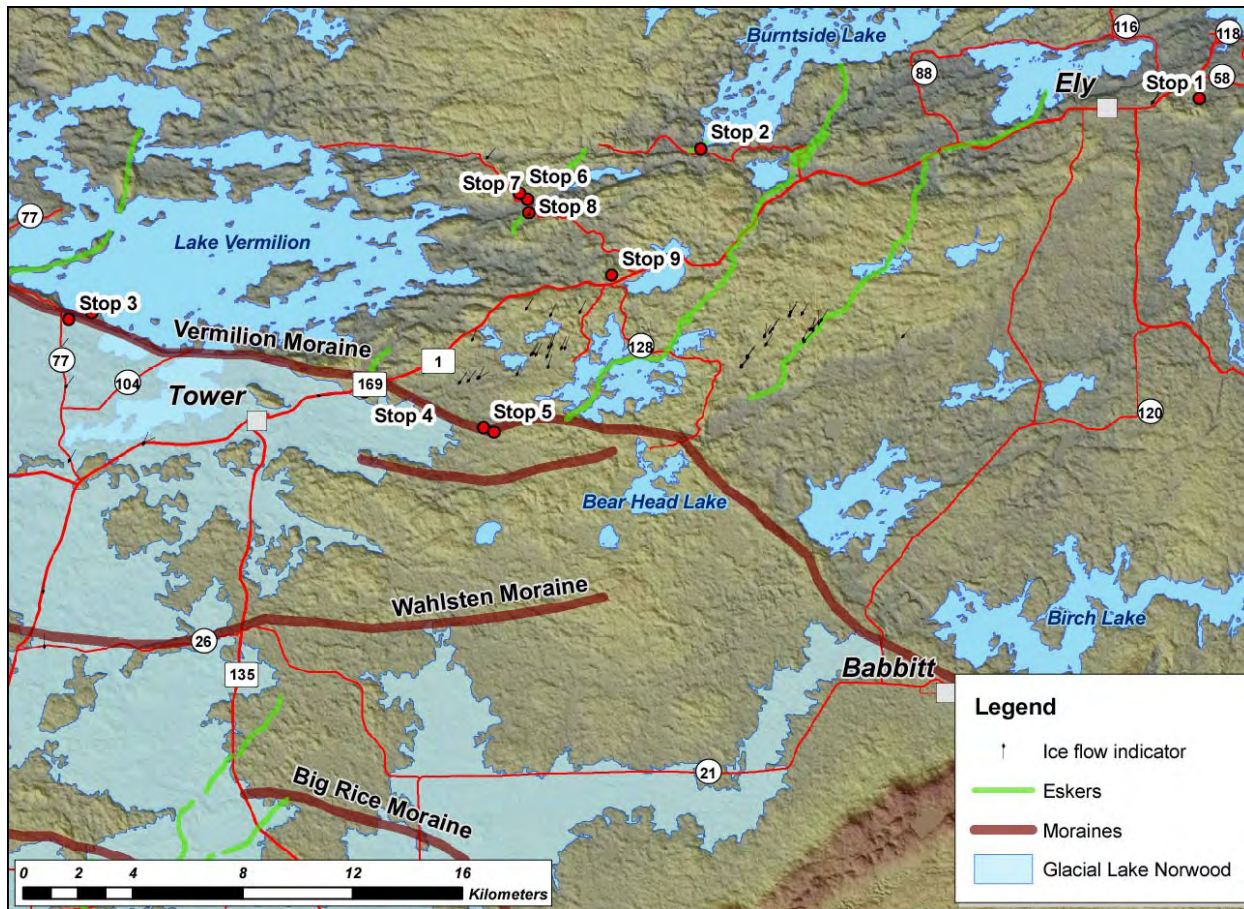


Figure 2-2. Surficial geology of the Vermilion district.

Prior to retreating to the Giant's Range and the Laurentian divide, the topography generally sloped away from the margin of the LIS. Consequently, meltwater tended to be efficiently channeled away from the ice margin. However, once the margin retreated to the north of the height of land, meltwater ponded in front of the ice sheet, forming proglacial lakes, with the surface elevation of these lakes controlled by the elevation of the outlet spilling over the height of land. The first proglacial lake formed north of the Giant's Range – Glacial Lake Norwood – was the first in a succession of lakes and lake stages that characterized the margin of the LIS until the final drainage of Glacial Lake Ojibwe.

The retreat of the LIS margin north of the height-of-land marked a momentous change in the nature of sediment and landforms associated with the ice margin. South of the height-of-land, ice margin sediment-landform assemblages are dominantly hummocky moraines composed of till and outwash channels, fans, and plains composed of glaciofluvial sediment. North of the height-of-land, ice margin sediment-landform assemblages are dominantly sharp-crested moraines composed of glaciofluvial sediments and proglacial plains composed of glaciolacustrine sediment.

Glacial Lake Norwood

Once the margin of the LIS retreated north of the Giant's Range, meltwater ponded to form Glacial Lake Norwood (GLN) (Winchell 1901), which drained to the south through the Embarrass Gap. The initial level of GLN was approximately 1475 feet, indicating that the area south and west of Big Rice Lake was

still occupied by ice (Lehr and Hobbs 1992). This stage of the lake likely corresponds to the ice marginal position marked by the Big Rice moraine.

Retreat of the LIS from the Big Rice moraine to the Wahlsten moraine roughly coincided with a drop in the level of GLN to 1450 feet (Lehr and Hobbs 1992). The drop in lake level was triggered in part by downcutting of the outlet through the Embarrass Gap. Further downcutting of the Embarrass Gap outlet was prevented since the outlet was draining into Glacial Lake Upham II at the time, also at roughly 1450' elevation. Continued outflow through the Embarrass Gap indicates the presence of glacial ice in the area north of Nashwauk and Hibbing.

GLN persisted at the 1450 foot level during the retreat and re-advance of the LIS to the Vermilion moraine. As ice and debris covered ice melted north of the Giant's Range the lake expanded to the west. This larger lake is referred to as Glacial Lake Koochiching (GLK) (Hobbs 1983), in reference to its being fronted by Keewatin (northwestern) provenance ice in southern Koochiching County. The highest level of GLK (Mizpah stage) formed strandlines at 1430 feet elevation as far west as southwestern Koochiching County (Hobbs 1983). Lowering of the level of Glacial Lake Upham II allowed continued downcutting of the Embarrass Gap outlet to 1430 feet, and later to 1400 feet (Lehr and Hobbs 1992).

Melting of stagnant ice and debris-cored ice in northeastern Itasca County ultimately opened a new outlet to GLN/GLK southward through the Prairie River. Opening and downcutting of the Prairie River outlet rapidly lowered GLK to about 1350 feet elevation (Gemmell stage) (Hobbs 1983). The LIS probably did not retreat from the Vermilion moraine prior to opening of the Prairie River outlet, as glaciolacustrine sediments are not found north of the moraine.

Persistence of a proglacial lake draining through the Embarrass Gap resulted in much of the area between the Vermilion moraine and the Giant's Range being wave-washed, or mantled by glaciolacustrine sediment.

Big Rice moraine

The first moraine to the north of the Giant's Range is the Big Rice moraine. The moraine orientation is roughly east-west, indicating ice flow was from north to south (180°). The LIS margin was for the most part subaerial while this moraine formed, as GLN was of limited extent. Consequently, most of this moraine is comprised of hummocky meltout till. Björck (1990) radiocarbon dated basal organic sediment from Heikkila Lake at $12,100 \pm 150$ ka (LU-2556) (14.1 ± 0.5 ka cal yr bp). Heikkila Lake is a kettle lake hosted in the moraine, so this date represents a minimum age on moraine stabilization.

Wahlsten moraine

The second moraine to the north of the Giant's Range is the Wahlsten moraine. Similar to the Big Rice moraine, the Wahlsten moraine's orientation is roughly east-west, indicating continued ice flow to the south (180°). The Wahlsten moraine is generally lower in elevation is lower than the Big Rice, so a significantly greater portion of the LIS margin fronted GLN. To the west, where the ice margin fronted the lake, the moraine is composed of coalescing ice-contact deltas. Here the moraine has a sharp, symmetrical cross sectional profile, and is composed predominantly of glaciofluvial sands and gravels. To the east, the moraine is composed of hummocky meltout till, fronted by proglacial outwash fans. Basal organic radiocarbon dates from Lempia Lake, a kettle lake immediately south of the moraine, are $12,050 \pm 240$ ka (Lu-2555) and $11,550 \pm 550$ ka (Lu-2502) (14.1 ± 0.7 ka cal yr bp) (Björck 1990). As with the Heikkila Lake date, this like represents a minimum age of landscape stabilization.

Vermilion moraine

The Vermilion moraine is the third prominent moraine to the north of the Giant's Range. Unlike the Big Rice and Wahlsten moraines, Vermilion moraine orientation is roughly west-northwest to east-southeast.

This change in moraine orientation is reflected in a change in ice flow direction, to approximately 210°. Reorientation of the ice flow direction was possibly triggered in part by faster recession of the LIS from the Wahlsten moraine in the area fronted by GLN.

Asymmetric retreat and re-advance to the Vermilion moraine resulted in a slight inflection in the ice margin orientation in the vicinity of Bear Head Lake. This inflection in turn produced a slight trough in the surface of the LIS, extending in the up-ice direction from Bear Head Lake, including past the general vicinity of Ely. This slight trough in the LIS resulted in enormous volumes of surface meltwater and glacial debris, captured from a disproportionately large area of the ice sheet, being channeled to a single discharge point. A large sediment fan, composed of sandy, pebbly, cobble, and boulder gravel was deposited in front of the Vermilion moraine (Lehr and Hobbs 1992), in part by evacuating stagnant ice north of the Wahlsten moraine, and a segment of the Wahlsten moraine itself.

West of Soudan, the LIS margin fronted GLN, and the moraine is composed predominantly of coalescing ice-contact deltas. In this area, the moraine has a sharp, symmetrical cross-sectional profile, and is composed primarily of glaciofluvial sands and gravels. East of Soudan, the LIS margin was subaerial, and the moraine is composed of hummocky meltout till and associated small, proglacial outwash fans.

The age of the Vermilion moraine is poorly constrained, however a basal radiocarbon date on woody material from a kettle lake in the Vermilion moraine southeast of Ely is 12,000±85 ka (ETH-29845) (13.8±0.1 ka cal yr bp) (Lowell and others, in press), placing a minimum age on moraine stabilization.

The next prominent moraine set formed by the LIS after the Vermilion greenstone belt are the Eagle-Finallyson-Steep Rock moraines of northwestern Ontario, 100 km to the northeast (Zoltai 1965). Björck (1985) dated obtained a bulk sediment radiocarbon date of 11,100±110 ka (WIS-1375) (13.0±0.2 ka cal yr BP) from a lake on the down-ice of these moraines, suggesting the area to the north of the Vermilion moraine was deglaciated by that time.

GLACIGENIC SEDIMENT IN THE VERMILION DISTRICT

In the Vermilion district, Rainy Lobe tills are pebble- and boulder-rich, with a sandy matrix. The lithologic and geochemical composition of tills and associated glaciofluvial sediments is highly heterogeneous, reflecting the similarly heterogeneous regional bedrock composition. Tills generally lack a significant component of clay-size grains, or clay minerals. The coarse-grained nature of tills, and lack of clay-size material, result in high permeability and poor compaction – even in lodgment tills.

Spatially, the distribution of glacial sediment is quite variable, with till, glaciofluvial, and even glaciolacustrine sediment widely distributed through the region. Sediment cover is patchy, with abundant bedrock outcrop, particularly in the areas north of the Vermilion moraine and above the level of Glacial Lake Norwood. Although glacial sediment may locally be several meters thick, it typically averages ~1 m.

Rainy Lobe provenance tills in the Vermilion district are essentially non-calcareous, and have a very low acid buffering capacity. This, combined with their high permeability, results in deep weathering, particularly of labile sulphide minerals. The spruce, fir, and pine forests common to the area favor formation of podzolic soils. Most soil profiles evidence an Of horizon overlying a bleached Ae horizon. Even the thickest soil profiles in till lack a true C horizon, with most displaying weak iron oxide staining (presumably due to weathering of iron sulphide minerals). In many cases, a C horizon is completely absent, with a vibrant red Bf horizon resting directly on bedrock. When sampling till for geochemical

analysis, the weathered C horizon is the preferred sampling media. Where the C horizon is absent or inaccessible, care is taken to sample the Bf horizon.

Erosion rates

Larson and Mooers (2004) estimated a bedrock erosion and entrainment rate of $\sim 10 \text{ mm}\cdot\text{a}^{-1}$ during the period the Laurentide ice sheet was actively eroding, entraining, and transporting sediment to the Vermilion moraine, a rate comparable to that of modern temperate glaciers in Alaska (Hallet et al. 2006). Assuming active erosion and entrainment occurred at that rate over a modest mean flowline length of 10 km, as much as 300 tons of debris per meter length per year were delivered to the Vermilion moraine. This debris delivery rate is sufficient to construct the observed Vermilion moraine in as little as 100 years.

Clearly, such high erosion and entrainment, and sediment delivery rates could not have acted over either a large area of the ice sheet's bed, or over a long period of time. This provides strong support to the hypothesis that till and glaciofluvial sediment deposits and landforms associated with the Vermilion moraine formed over a relatively short period of the history of the Laurentide ice sheet – likely only a few centuries. In this sense, surficial sediments in the VGB and elsewhere on glaciated shield terranes represent a snapshot in time in the long history of both the Pleistocene

CHARACTERIZATION OF GLACIGENIC SEDIMENTS FOR DRIFT EXPLORATION

Incorporation of geochemical and mineralogical data collected from glacial sediments into an integrated mineral exploration program is a key to successful exploration in glaciated terranes. In common with surficial sediment sampling programs in other geomorphic environments, the three critical questions an explorer seeks to answer over the course of a drift exploration program are:

- What is the significance of a particular anomaly?
- How far has the material been transported?
- What direction was the material transported?

The answers to these questions can be more systematically determined in a glaciated terrane than in any other surficial environment. In this sense glaciation, far from obscuring bedrock mineralization, provides an important tool for detecting and vectoring to bedrock mineralization.

Mean transport length

Till in the VGB is characterized by extreme compositional variability, reflecting the composition of local bedrock. A useful concept for quantifying this variability is the concept of a mean transport length – the distance from within which 50% of the material in the till has been derived.

Mean transport length has been characterized for the VGB on two different size fractions of till. This is accomplished by plotting the concentration of a till component derived from a known source (indicator) against the distance along a glacial flow line down-ice of the source. In the case of the VGB, the extreme contrast in composition between granitoid and high-grade metamorphic rocks of the Vermilion Batholith to the north of the Vermilion fault, and the greenschist grade metavolcanic and metasedimentary rocks of the VGB to the south of the Vermilion fault provides a widespread, but easily recognizable, indicator in the form of the lithic and geochemical components derived from the Vermilion Batholith. In particular, potassium feldspar-bearing coarse-grained granitoid clasts in tills from the VGB are uniquely derived from north of the Vermilion fault. In addition, rocks of the Vermilion Batholith are characterized by relatively high potassium content ($\sim 3.4\% \text{ K}_2\text{O}$) relative to those of the VGB ($\sim 1.7\% \text{ K}_2\text{O}$).

The concentration of both indicators in till decrease systematically with distance from the Vermilion fault; this decrease can be mathematically approximated using the equation:

$$c_i^{T>0} = c_i^{T=0} e^{-aT}, \quad (1)$$

Where c_i is the indicator concentration, T is the transport length, and a is a dimensionless constant. Solving for T at the point at which $c_i^{T>0} = 0.5c_i^{T=0}$ gives an estimate of the transport length from within which 50% of the material in the till is derived. In the case of K_2O in the -63 micron fraction of till, this relationship is:

$$K_2O = 1.73 + 1.66e^{-0.225T}, \quad (2)$$

where T is transport length in km, indicating a mean transport length for the -63 micron fraction of ~ 3.0 km (Fig. 2-3) (Larson 2004). (The factor 1.73 is the apparent mean K_2O concentration in weight percent of rocks of the greenstone belt.)

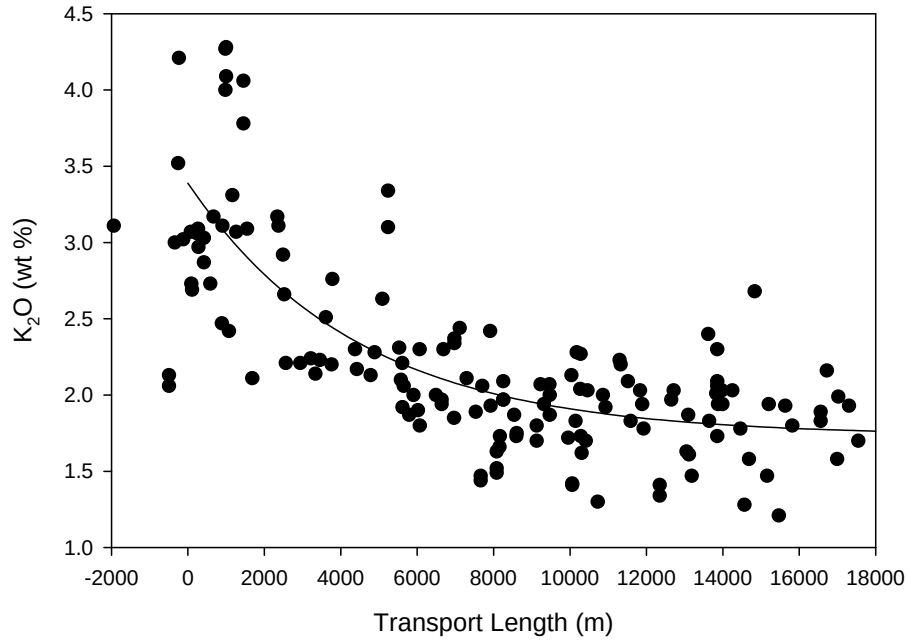


Figure 2-3. K_2O concentration in the -63 micron fraction of tills in the VGB, plotted against distance in the ice-flow direction from the Vermilion fault. (Larson 2004.)

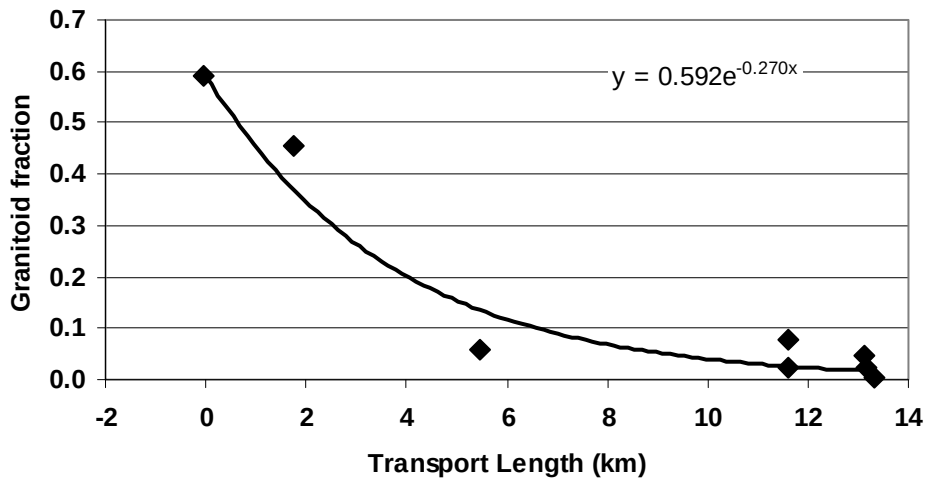


Figure 2-4. Granitoid concentration in the 2-4 mm fraction of tills in the VGB, plotted against distance in the ice-flow direction from the Vermilion fault. (unpublished data from 2008 PRC Field Camp students)

In the case of granitoid clasts in the 2-4 mm fraction of till:

$$c_{gran} = 0.592e^{-0.270T}, \quad (3)$$

where the background granitoid fraction of tills in the greenstone belt is 0.0, indicating a mean transport length for 2-4 mm pebbles of ~2.6 km (Fig. 2-4) (unpublished data from 2008 PRC field camp students). These two independently derived estimates provide a robust assessment of the mean transport length of till-forming material in the Vermilion district.

Ice flow direction

Measurements of striae and grooves in bedrock indicate preservation of a number of predominant orientations, corresponding to a number of paleo ice flow directions. Between the Vermilion and Wahlsten moraines, striae cluster between 180-185°, roughly normal to the east-west orientation of the Wahlsten moraine. Immediately south and to the north of the Vermilion moraine, striae cluster between 200-225°, with a predominant mode between 210-215°; this orientation is roughly normal to the WNW to ESE orientation of the Vermilion moraine. Scattered throughout the area, a very few striae have been measured oriented ~240°; where present, these striae orientations are overprinted by the 180-185° and 210-215° striae sets (Fig. 2-5).

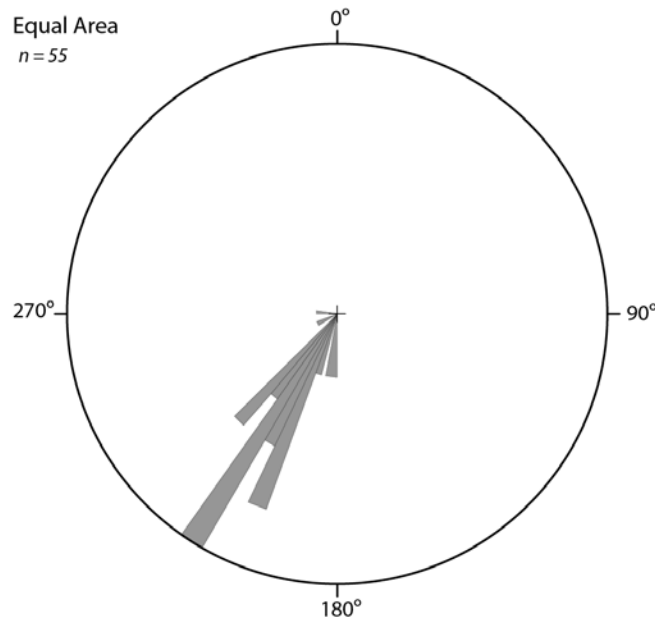


Figure 2-5. Rose diagram of ice flow indicator (striae and grooves) orientations in the Vermilion district.

The multiple ice flow directions recorded in striae and moraine orientations are interpreted to record changing ice flow directions during retreat of the Rainy Lobe. The older 240° orientation is interpreted to represent ice flow direction when the area was completely covered by the Laurentide ice sheet, and the ice margin was located a significant distance to the southwest. The 180° orientation reflects the ice flow direction when the ice margin was located at the Big Rice and Wahlsten moraines, while the 210° orientation reflects the ice flow direction during the readvance to the Vermilion moraine.

North of the Vermilion moraine, striae in the 200-225° cluster varies. At a given outcrop, or cluster of outcrops, individual striae orientations typically vary over a range of ~5°. However, over length scales of ~1 km, striae cluster orientations may vary up to ~20°. This may be the product of spatial and temporal variation in erosion rates as ice flow direction changed during retreat and re-advance of the Rainy Lobe to the Vermilion moraine.

Mineral endowment

Considered at a sufficiently large scale, the composition of till broadly reflects that of the substrate underlying the ice sheet. In the case of a system where mean transport length is relatively short, till composition reflects that of the local bedrock. A sufficiently large sample of till compositional data from such an area therefore represents a statistically meaningful characterization of bedrock composition. In addition to providing important information regarding threshold values for background and anomalous concentrations, comparison of a sample population from a particular area to a reference population may provide information regarding the relative endowment of elements of economic interest.

Rencz and others (2006) present a useful compendium of the statistical characteristics of a number of geochemical variables for the -63 micron fraction of tills in Canada. They included in excess of 13,000 till samples compiled from over 50 separate surveys. Bajc (1999, 2000) collected nearly 700 -63 micron till geochemical samples from the Shebandowan greenstone belt, a Wawa subprovince supracrustal sequence located 150 km northeast of the Vermilion district. Larson (2004) reported 150 -63 micron till geochemical analyses collected in the Vermilion district. Comparison of these three data sets provides an assessment of the relative thresholds for background and anomalous geochemical values of tills in the Vermilion district.

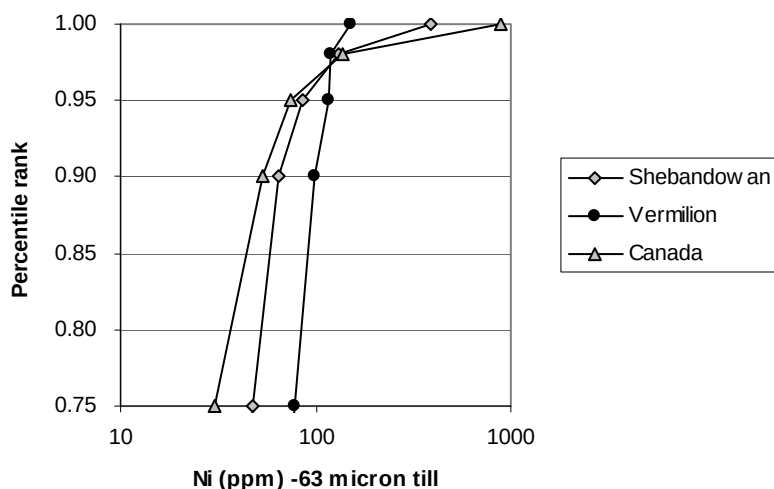


Figure 2-6. Relative abundance of nickel in the -63 micron fraction of till. Data from Rencz and others (2006), Bajc (1999,2000), and Larson (2004).

Nickel displays high abundance in the fine fraction of Vermilion district tills relative to both the larger Canadian data set (Rencz et al., 2006) and the Shebandowan greenstone belt (Bajc 1999, 2000) (Fig. 2-6). However, in both the Canadian and Shebandowan datasets, the 98th percentile values are higher than in the Vermilion dataset. This suggests that while tills in the Vermilion district are characterized by high background nickel values, no truly anomalous samples indicative of potential economic nickel mineralization have been collected.

Copper displays a slightly elevated abundance in the fine fraction of Vermilion district tills relative to both the larger Canadian data set (Rencz et al., 2006) and the Shebandowan greenstone belt (Bajc 1999, 2000) (Fig. 2-7). In both the Canadian and Shebandowan datasets, only the maximum values are higher than in the Vermilion dataset. This suggests that tills in both the Vermilion district and Shebandowan belt are characterized by similar background values somewhat higher than Canada as a whole. However, the highest copper values in the Vermilion district are lower than both other data sets, suggesting somewhat lower potential for economic copper mineralization than in the Shebandowan belt, or Canada as a whole.

Zinc displays high abundance in the fine fraction of Vermilion district tills relative to both the larger Canadian data set (Rencz et al., 2006) and the Shebandowan greenstone belt (Bajc 1999, 2000) (Fig. 2-7). In both the Canadian and Shebandowan datasets, only the maximum values are higher than in the Vermilion district. This suggests that tills in the Vermilion district belt are characterized by background zinc values higher than the Shebandowan belt and Canada as a whole. The significantly higher 98th percentile zinc values in the Vermilion district are significantly higher than for both other data sets, suggesting higher potential for economic zinc mineralization than in the Shebandowan belt, or Canada as a whole.

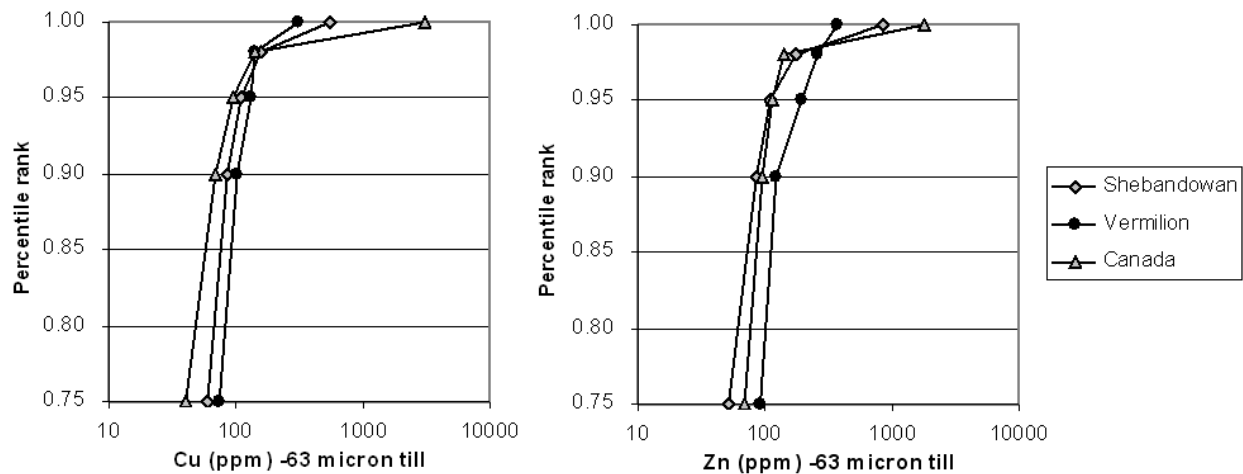


Figure 2-7. Relative abundance of copper (left) and zinc (right) in the -63 micron fraction of till. Data from Rencz and others (2006), Bajc (1999,2000), and Larson (2004).

Integrating ice flow directions, mean transport length, and geochemical data: The Probability Window

Integration of the three parameters can serve as a powerful tool for vectoring to economic mineralization in glaciated terrane. When a mineralized clast or anomalous geochemical sample is found in till or other glacial sediment, the only statement that can be said with any confidence about its origin is that it did *not* come from bedrock underlying the sample site. However, careful observation of ice flow direction indicators, calculation of mean transport length, and assessment of the significance of anomalies can be used to constrain the potential source to a probability window.

The probability window (a polygon) is constructed by extending side lines in the general up-ice direction of a sample location. The exact orientations of the lines are opposite the limits of the potential range of ice flow directions determined for the area in question. The up-ice limit to the probability window is imposed by constructing a third line at a distance equal to the mean transport length. The polygon thus defined represents an area within which there is theoretically a 50% probability of the anomalous sample originating (Fig. 2-8).

Clearly, given the inherently heterogeneous nature of till composition, relatively low confidence can be placed in any single such determination of a potential source area for an anomalous sample. However, multiple probability windows calculated from multiple anomalous samples, augmented by iterative sampling, offer to provide increasing confidence in identifying potential source areas. This information, when integrated with geologic and geophysical data, can provide a powerful tool for vectoring toward economic mineralization in glaciated terrane.

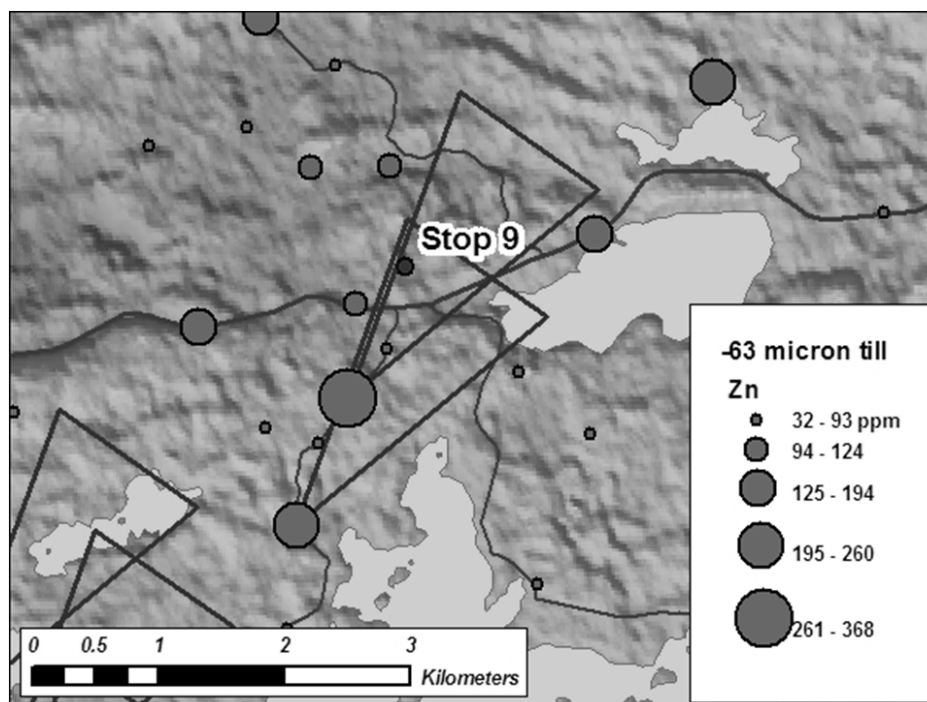


Figure 2-8. Illustration of the use of probability windows to constrain the potential source area of mineralized clasts or anomalous till geochemical samples(data from Larson 2004).

FIELD TRIP STOPS

Note: All location coordinates are given as UTM Zone 15, NAD 83 datum

STOP 2-1.

Hidden Valley Recreation Area

Location: 588490E, 5306530N

Ice-contact glaciofluvial deposits.

The Hidden Valley exposure reveals poorly sorted coarse gravel glaciofluvial sediments of the Rainy lobe. In this vicinity, the lithologic composition of the sediment reflects a predominance of granitoid rocks eroded from the Quetico subprovince of the Canadian Shield. This deposit is part of a broad zone of voluminous glaciofluvial deposits extending northeast from Bear Head Lake, likely deposited in a subtle trough in the surface of the ice sheet extending up-ice of an inflection point in the orientation of the ice margin. The enormous quantity of glaciofluvial sediment deposited on this trend is a reflection of the enormous surface meltwater discharge captured by the trough in the ice sheet.

STOP 2-2.

Wolf Creek Road gravel pit

Location: 570310E, 5304700N

Ice-contact glaciofluvial deposits.

The Wolf Creek gravel pit reveals 40 feet of glaciofluvial sediment deposited subglacially as an esker. On the flanks of the esker, a stony diamict is exposed; this may be a till deposited by the LIS during the re-advance to the Vermilion moraine. This locality lies essentially on the Vermilion fault, and the

lithologic composition of the sediment is overwhelmingly dominated by granitoid and high-grade metasedimentary rocks of the Vermilion Granitic Complex. This lithologic composition represents the composition of sediment in transport by glacier ice as the Rainy Lobe begins flowing across greenschist-grade metasedimentary and metavolcanic rocks of the greenstone belt. The concentration of greenstone lithologies in tills down-ice of this locality provides a quantitative assessment of the rate at which greenstone rocks are eroded and entrained by the Rainy Lobe.

STOP 2-3.

Vermilion moraine (subaqueous segment)

In this vicinity, the Vermilion moraine is characterized by a proximal (northeast) ice-contact scarp and a distal subaqueously-deposited outwash apron. The crest of moraine is generally ~1450' elevation, corresponding to the level of Glacial Lake Norwood. The bulk of the moraine at this location is composed of well-sorted sand and gravel, suggesting much of the sediment was deposited in water, either directly from supra- and englacial meltwater, or from resedimented ice-contact debris. Pinching and swelling of the moraine along its length reflects the spacing of meltwater drainage channels on the ice surface. Locally, where the crest of the moraine exceeds 1450' elevation, sediment at the moraine crest is composed of diamict, presumably meltout till, formed by release of englacial debris on the surface of the ice sheet. This suggests a significant fraction of the sediment delivered to the ice margin was englacial debris.

STOP 2-3A.

Forest Lane Resort

Location: 548090E, 5298730N

Ice-proximal scarp of moraine.

The area on the up-ice side of the scarp is characterized by an abundance of large boulders. Large boulders are common in deposits of the Rainy Lobe, and result from the isotropic nature of the granitoid bedrock and widely spaced fractures, which favors glacial quarrying of large boulders. The boulders were of sufficient size that meltwater draining from the ice surface was unable to transport them beyond the ice margin.

STOP 2-3B.

Holmes Excavating Gravel Pit

Location: 547250E, 5298480N

Ice-distal slope of moraine.

At this locality, the Vermilion moraine is composed of subaqueously-deposited sand and gravel representing a system of prograding deltas along the ice margin. Sediment size range from silt to coarse sand and gravel indicating a variety of depositional energies, and the sediments are often highly deformed. The deformation suggests that the deposition was rapid. Loading was apparently fast enough that finer-grained sediments were not efficiently dewatered whereas coarser sediments dewatered effectively. The strength of soft sediment is a function of water content; consequently, deformation of the coarser gravel lenses tends to be brittle in character (Fig. 2-9), while in the finer grained sediment deformation tends to be ductile in character. Deformation of the sediments ranges from small-scale faults and folds to large-scale (10s of meters) folds and detachment structures (Fig. 2-10).



Figure 2-9. View of brittle deformation features in sand and gravel of Vermilion moraine, Holmes Excavating Gravel Pit. (photo from fall of 2002) Note that the coarser gravel beds behave as rigid blocks, while the interbedded silts and sands deform in a ductile fashion.



Figure 2-10. View of nappe structure and recumbent fold nose in sand and gravel of Vermilion moraine, Holmes Excavating Gravel Pit. (photo from fall of 2002).

STOP 2-4.

Breitung Township gravel pit

Location: 558020E, 5295840N

Vermilion moraine at strandline of Glacial Lake Norwood.

At this location on the Vermilion moraine, the margin of the ice sheet was positioned roughly at the level of Glacial Lake Norwood. Rather than building a steep-crested moraine, sediment delivered to the margin by meltwater formed a prograding flat-topped fan delta. Visible in the walls of the pit are channel scour-and-fill structures. Not coincidentally, this particular fan delta is located at the discharge point of an esker system traceable for several km up-ice (see Stop 2-8).

STOP 2-5.

Murray Road

Location: 562380E, 5294540N

Vermilion moraine (subaerial segment)

At this location on the Vermilion moraine, the ice margin was position well above the level of Glacial Lake Norwood, and a relatively steep subaerial moraine formed. Here the moraine is composed of a complex association of sand, gravel, and meltout till. Large boulders are common in the moraine. One boulder in particular is a felsic tuff, correlative with felsic Metavolcanic bedrock mapped only a few km up-ice. On subaerial segments such as this, the moraine is fronted by small outwash fans and aprons on the distal side.

STOP 2-6.

Mud Creek Road

Location 563680E, 5303070N

Till on bedrock.

This exposure provides an opportunity to examine basal till of the Rainy lobe. It is difficult to determine the nature of the till deposition, however, the sediments and the local geomorphic expression suggest a lodgment origin. The lithologic composition of the till is a direct reflection of the local bedrock, and the till has a sandy loam texture with a slightly higher proportion of silt than typical exposures.

STOP 2-7.

Mud Creek Road

Location: 563970E, 5302860N

Thick till.

At this location, a relatively thick sequence of till is exposed in a roadcut. Its position in the lee side of an east-west trending bedrock ridge may be responsible for its preservation. The lithologic composition of the till varies along the exposure and directly reflects the lithology of local bedrock immediately beneath the till. At the eastern end of the exposure, the till is composed of a predominance of iron formation, incorporated from bedrock immediately underlying the till. Also at this location, a single clast of Hudson Bay-provenance Paleoproterozoic greywacke was recovered. Its occurrence lends further support to the idea that a continuous sheet of carbonate-greywacke bearing drift at one time extended over the Vermilion district. It also suggests that a drift sheet deposited early in the Wisconsin glacial cycle was largely removed by remobilization later in the glacial cycle.

STOP 2-8.

Mud Creek Road

Location: 564020E, 5302360N

Esker.

This gravel pit contains the remnants of an esker; the same esker system responsible for deposition of the fan delta at Stop 2. This esker system, like most of those associated with the Vermilion Moraine, is discontinuous. Scour and polish are visible on striated bedrock, suggesting sediment-laden meltwater may have been eroding bedrock.

STOP 2-9.

Trygg Road gravel pit

Location 567060E, 5300080N

Sulphide mineralized clasts in glacial sediment.

The Trygg Road pit exposes glaciofluvial sediment and basal till of the Rainy Lobe, and lies approximately 5 kilometers downglacier from the Vermilion fault. This gravel pit is notable in that the till and glaciofluvial sediments exposed here contain an abundance of sulphide mineralized metasedimentary clasts, ranging in size up to boulders. These clasts are likely derived from cherty metasediments hosted by the Gafvert Lake felsic complex. Both the size of the largest mineralized clasts, as well as their abundance, reflect their relative short transport distance from their bedrock source, perhaps no more than 1 km up-ice. Therefore this pit offers an opportunity to visualize clearly the rapid rate of entrainment of local lithologies and the concept of calculation of the *mean transport length* from the ratio of locally derived lithologies to those derived north of the Vermilion fault.

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55th Annual Institute on Lake Superior Geology

Field Trip 3

SOUDAN IRON MINE AND PHYSICS LAB



Rail depot at the Soudan Mine circa 1925, © Minnesota Historical Society/CORBIS.

Dean Peterson (Duluth Metals Ltd. & PRC)

James Pointer (MN Dept of Natural Resources, Parks and Trails)

Marvin Marshak (Department of Physics, Univ. of Minnesota)

FIELD TRIP 3

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INTRODUCTION

The Soudan Mine was the first iron ore mine in Minnesota when it opened in 1882. Since then the Minnesota Iron Range's have contributed billions of tons of iron ore to the industrialization of America and the world. Iron mining at Soudan began in surface pits but due to the rock formation, the miners quickly went underground. By 1892 the entire mining operation was underground. The mine remained open for 80 years, but technology changes caused the mine to cease production in 1962. The Soudan Mine, a registered National Historic Landmark, is currently owned and operated by the State of Minnesota, Department of Natural Resources, Division of State Parks and Trails. Each year approximately 30,000 visitors go underground at Soudan, mostly during the summer season from Memorial Day weekend through the end of September and the first three weekends in October. This figure includes over 5,000 K-12, college, and other formal groups that visit the mine throughout the year.

In February 2004, Dr. Michael Turner, Assistant Director of the National Science Foundation (NSF), announced the NSF's intent to pursue a three-phase process leading to the establishment of a Deep Underground Science and Engineering Laboratory (DUSEL) in the United States (see Bachall et al., 2001). DUSEL would provide a program and one or more locations to study the deep (to depths of ~2.5 km) underground geological and biological environment and use the isolation of that environment to frontier physical science and engineering initiatives. The goals of NSF's deep underground geological and biological science initiative were outlined in the 2003 document "*EARTHLAB: A Subterranean Laboratory and Observatory to Study Microbial Life, Fluid Flow, and Rock Deformation*" (McPherson et al., 2003).

The Soudan Mine in northeastern Minnesota was one of eight sites under consideration by the NSF for hosting DUSEL under the leadership of Dr. Marvin Marshak of the University of Minnesota (Marshak et al., 2003, 2005, 2007). Although the University of Minnesota's three proposals for the Soudan Mine ultimately did not win the competition for hosting the DUSEL, the collaboration between the universities' School of Physics & Astronomy in Minneapolis and the Natural Resources Research Institute in Duluth laid the foundation for this field trip.

SOUDAN UNDERGROUND MINE STATE PARK

The promise of gold brought the early settlers to the Vermilion Iron Range in 1865. These early pioneers discovered economical quantities of iron ore while prospecting. One of these prospectors was George Stuntz, a government surveyor. Stuntz discovered the existence of commercial value iron ore on the South shore of what is now known as Stuntz Bay on Lake Vermilion. From 1865-75 Stuntz made many trips back to the Lake Vermilion area collecting numerous samples. Some of these specimens were shown to George C. Stone, a Duluth banker and Minnesota legislator. He became interested in the prospect of iron mining on the Vermilion. George Stone convinced Charlemagne Tower, a lawyer in Pennsylvania, that the mining operation would be a good business venture. At the time a new steel making process, known as the Bessemer process, was being introduced in the United States, creating a need for high grade iron ore. Tower dispatched Professor Albert Chester, a renowned geologist, to the Lake Vermilion region

as head of an exploring expedition. Chester returned with a detailed account of the mineral lands. In his report Chester mentioned large quantities of iron ore and little or no gold, thus ending Minnesota's brief and dramatic gold rush.

When the mine opened in 1882, the miners used a rock quarrying method of mining. The basic tools were hand drills, pry bars, black powder and bare hands. The railroad finally reached Tower in 1884, allowing the first shipment of ore from the Soudan Mine to be made on July 31st. The ore was railed to Two Harbors, Minnesota, where it was shipped to the steel mills in the East. As the ore was removed and the mine pits were sunk deeper into the hill, it became necessary to send the miners, equipment, and supplies down ropes hung over the side of the pit. Like all mining, the work was dangerous. Masses of earth and rock kept caving in, which resulted in heavy losses of lives and halts in production. These tragic incidents prompted the decision to work the mine by underground methods. By 1892, the entire operation had been moved underground.

Of the thirteen shafts on property, eventually only two shafts remained: the No. 8, which is in use today for tours, and the Alaska shaft, which is about 1700 feet to the east. The No. 8 reaches a depth of almost 2,400 feet with horizontal drifts extending more than three-fourths of a mile east and west to various ore bodies. It connects with the Alaska shaft on a variety of levels.

The year 1924, marked the end of an era for the Soudan Mine, because the mine was changed from a "mule and man-powered mine" to a modern electrified operation. At this time a new head frame and hoisting system were constructed, which is the equipment that is in use today. After World War II, the Soudan Mine, like other underground operations on the Vermilion Range, started to slow down. The 27th level was the last to be opened for mining. The level was never fully developed because of the advancement of the new taconite process and changes in smelting methods detracted from the usefulness of Soudan ores.

In the early 1960's, increasing costs of production began to reduce profits. Soon the Vermilion ores could not compete economically with the newly developed pelletized taconite ores of the giant Mesabi Range, just to the south. The Soudan Mine ceased operations on December 15, 1962. The last shipment from the stockpile was made in August 1963. The United States Steel Corporation generously donated the mine to the State of Minnesota for creation of the Soudan Underground Mine State Park. The Department of Natural Resources, Parks and Trails Division, administers the park. The park is a testimonial to the men who labored for us all.

The Park maintains the entire underground tour route, which includes the No. 8 shaft, the west section of the 27th level, the physics lab, and the rescue chamber. In addition there are pumping stations at the 12th, 22nd and 27th levels, and a reservoir for a sprinkler system on the 25th level. The remaining areas of the mine are monitored and research is conducted in a variety of these areas. Researchers are taking water samples, soil samples, and gas samples in hopes of learning more about their properties. Bat research is also conducted in the mine, since the mine is a large hibernacula for bats. The State Park also has a number of historic surface buildings, many of which are open for public visitation. These buildings include the "dry house", the engine house, the drill shop, and the crusher. The historic "dry house" includes exhibit space and a gathering area for the tours.

The State Park's Historic Underground Mine Tour leads visitors through the world of underground mining. Visitors don hard hats and enter a "cage" for the descent into the mine. The typical 90-minute mine tour takes visitors nearly half a mile down into the Earth to the 27th level of the mine. Once underground, a 3/4 mile train ride takes visitors to the Montana ore body, the last and deepest area mined at Soudan. Public tours run daily from Memorial Day weekend through the end of September and the first three weekends in October. The park offers group tours to schools, colleges, organizations and

businesses. In addition to the traditional underground mine tour, the Park is working to offer a geology tour for groups that includes a walking tour of the 27th level drift. The historic underground mine tour was made ADA accessible in 2008, with the addition of ramps and a new elevator. There is a charge for the underground mine tours.

SOUDAN UNDERGROUND LABORATORY

The University of Minnesota has operated the Soudan Underground Laboratory since 1980. Soudan's existing laboratories are 710 m deep and include two caverns (MINOS and Soudan 2), each 15 m wide by 15 to 16 m high. About 250 scientists and engineers and a support staff of 9 members now work on experiments at the Soudan Laboratory.

Neutrinos and WIMPS

Neutrinos are elementary particles that often travel close to the speed of light, lack an electric charge, are able to pass through ordinary matter almost undisturbed and are thus extremely difficult to detect. Neutrinos have a minuscule, but nonzero mass. They are usually denoted by the Greek letter ν (nu). Neutrinos are created as a result of certain types of radioactive decay or nuclear reactions such as those that take place in the Sun, in nuclear reactors, or when cosmic rays hit atoms. There are three types, or "flavors", of neutrinos: electron neutrinos, muon neutrinos and tau neutrinos; each type also has an antimatter partner, called an antineutrino. Electron neutrinos or antineutrinos are generated whenever neutrons change into protons or vice versa, the two forms of beta decay. Interactions involving neutrinos are generally mediated by the weak force. Most neutrinos passing through the Earth emanate from the Sun, and more than 50 trillion solar electron neutrinos pass through the human body every second.

Observations of the large-scale structure of the universe show that matter is aggregated into very large structures that would not have time to have formed under the force of their own self-gravitation. It is generally believed that some form of missing mass is responsible for increasing the gravitational force at these scales, although this mass has not been directly observed. This is a problem; normal matter in space will heat up until it gives off light, so if this missing mass exists, it is generally assumed to be in a form that is not commonly observed on earth. A number of proposed candidates for the missing mass have been put forward over time. Early candidates included heavy baryons that would have had to be created in the big bang, but more recent work on nucleosynthesis seems to have ruled most of these out. Another candidate are new types of particles known as weakly interacting massive particles, or "WIMP"s. As the name implies, WIMPs interact weakly with normal matter, which explains why they are not easily visible. Detecting WIMPs thus presents a problem; if the WIMPs are very weakly interacting, detecting them will be extremely difficult. Detectors like CDMS at Soudan and similar experiments measure huge numbers of interactions within their detector volume in order to find the extremely rare WIMP events.

MINOS Experiment

The Main Injector Neutrino Oscillation Search (MINOS) Far Detector Laboratory is 82 m long and houses the 5,500 tonne MINOS Far Detector. The MINOS detector at Soudan is the target of the 735 km Fermilab Neutrinos at the Main Injector (NuMI) beamline. The \$125 million NuMI beam first produced neutrinos in January 2005. A deeper understanding of lepton physics is the goal of a multi-decade program using the NuMI beam line, the MINOS Detector to measure 2-3 neutrino oscillations, the NOvA Off-Axis Detector to study 1-3 neutrino oscillations and a Proton Driver, to significantly upgrade the NuMI intensity.

MINOS is a particle physics experiment designed to study the phenomena of neutrino oscillations, first discovered by Super-Kamiokande experiment in 1998. Neutrinos produced at Fermilab by the NuMI (Neutrinos at Main Injector) beamline are observed at two detectors, one very close to where the beam is

produced (the near detector), and another much larger detector 735 km away in northern Minnesota (the far detector). Both MINOS detectors are steel-scintillator sampling calorimeters made out of alternating planes of magnetized steel and plastic scintillator. The magnetic field causes the path of a muon produced in a muon neutrino interaction to bend, making it possible to separate neutrino and antineutrino interactions. This feature of the MINOS detectors allows MINOS to search for CPT violation with atmospheric neutrinos and anti-neutrinos. The MINOS experiment started detecting neutrinos from the NuMI beam in February 2005. On March 30, 2006, the MINOS collaboration announced that the analysis of the initial data, collected in 2005, is consistent with neutrino oscillations, with the oscillation parameters which are consistent with Super-K measurements.

The NuMI beam is the only long baseline neutrino beam in the United States and one of only three such beams in the world. NuMI and the CERN-Gran Sasso beam are both >700 km in length. The K2K and T2K beams in Japan are less than 300 km long. NuMI has the highest flux of any of the three beams at the energy required for the first maximum of 2-3 neutrino oscillations. The NuMI beam represents a substantial functioning asset to neutrino physics in both the United States and the world.

To produce the NuMI beamline, 120 GeV Main Injector proton pulses hit a water-cooled graphite target. The resulting interactions of protons with the target material produce pions and kaons, which are focused by a system of magnetic horns. The neutrinos from subsequent decays of pions and kaons form the neutrino beam. Most of these are muon neutrinos, with a small electron neutrino contamination. Neutrino interactions in the near detector are used to measure the initial neutrino flux and energy spectrum. Because they are so weakly interacting, the vast majority of the neutrinos travel through the near detector and the 735 km of rock, then through the far detector and off into space. On the way toward Soudan, about half of the muon neutrinos oscillate into other flavors.

CDMS II Experiment

The Cryogenic Dark Matter Search (CDMS), housed in the 70 meter long Soudan 2 laboratory, is a series of experiments designed to directly detect particle dark matter in the form of WIMPs. Using an array of semiconductor detectors (silicon and germanium) at near absolute zero temperatures, CDMS has set the most sensitive limits to date on the interactions of WIMP dark matter with terrestrial materials. The first experiment, CDMS 1, was run in a tunnel under the Stanford University campus. The current dark matter search experiment at Soudan (CDMS 2) has been recently upgraded with almost double the detector mass and is now called SUPER CDMS.

NOvA Experiment

The University of Minnesota will receive a grant of \$40.1 million for the NOvA neutrino experiment construction. Funds are part of \$1.2 billion from Recovery Act to be disbursed by Department of Energy's Office of Science. The NOvA funding for Minnesota will generate an estimated 60-plus construction jobs and procurements for concrete, steel, road-building materials and mechanical and electrical equipment from U.S. firms. The NOvA Experiment will construct a detector optimized for electron neutrino detection in the existing NuMI neutrino beam. The primary goal of the experiment is to search for evidence of muon to electron neutrino oscillations. This oscillation, if it occurs, holds the key to many of the unanswered questions in neutrino oscillation physics.

The NOvA far detector will be located in northern Minnesota between Orr and International Falls. The groundbreaking for construction will take place on May 1, 2009. The NOvA detectors will be constructed from liquid scintillator contained inside extruded PVC modules. The far detector will have a total mass of 15 kilotons and be 15.7 meters wide, 15.7 meters tall, and 78 meters long. A smaller copy of the far detector will be constructed in the NuMI beam on the Fermilab site to measure the neutrino event rates prior to oscillation.

SOUDAN GEOLOGY

The Soudan mine is located in the Neoproterozoic (~2.7 Ga) Vermilion Greenstone Belt of the Wawa subprovince of the Superior Province of the Canadian Shield. Supracrustal rocks in the greenstone belt consist of volcanic-dominated stratigraphic sequences that are divided on the basis of stratigraphic and structural setting into: (1) the southern Soudan belt and (2) the northern Newton belt (Jirsa et al., 1992; Southwick et al., 1998). The boundary between these contrasting structural panels can be traced geophysically across the width of Minnesota, and was designated informally as the Leech Lake structural discontinuity (Jirsa et al., 1992). In the Soudan Mine area, this discontinuity occurs along the Mud Creek shear zone (Hudleston et al., 1988), immediately north of the Soudan Mine (Fig. 3-1).

The Soudan belt, which hosts the Soudan Mine contains large, broad folds involving calc-alkalic and tholeiitic volcanic strata overlain by, and locally interdigitated with, turbiditic rocks. In contrast, the Newton belt consists of elongate, northeast-trending, and mostly northward-younging volcanic and volcanoclastic sequences that locally contain komatiitic flows and peridotitic sills. The two belts are fault-bounded, and the relationship between stratigraphic units within each belt is largely conformable, although faults obscure contacts locally. To the east, the Soudan belt is continuous with the Saganagons assemblage in Ontario and terminates against the Saganaga pluton and Northern Light Gneiss.

The Newton belt extends discontinuously eastward into the Shebandowan District of Ontario to form the Greenwater and Burchell assemblages. Intrusive rocks in both belts vary from gabbroic and felsic porphyries demonstrably related to volcanism, to large plutons emplaced posttectonically. Both districts contain unconformable, Timiskaming-type sequences composed of calcalkalic volcanic rocks, conglomerates, and finer grained sedimentary rocks. A simplified regional geological map of the Neoproterozoic terranes of northeastern Minnesota and adjacent Ontario is presented in Figure 3-1.

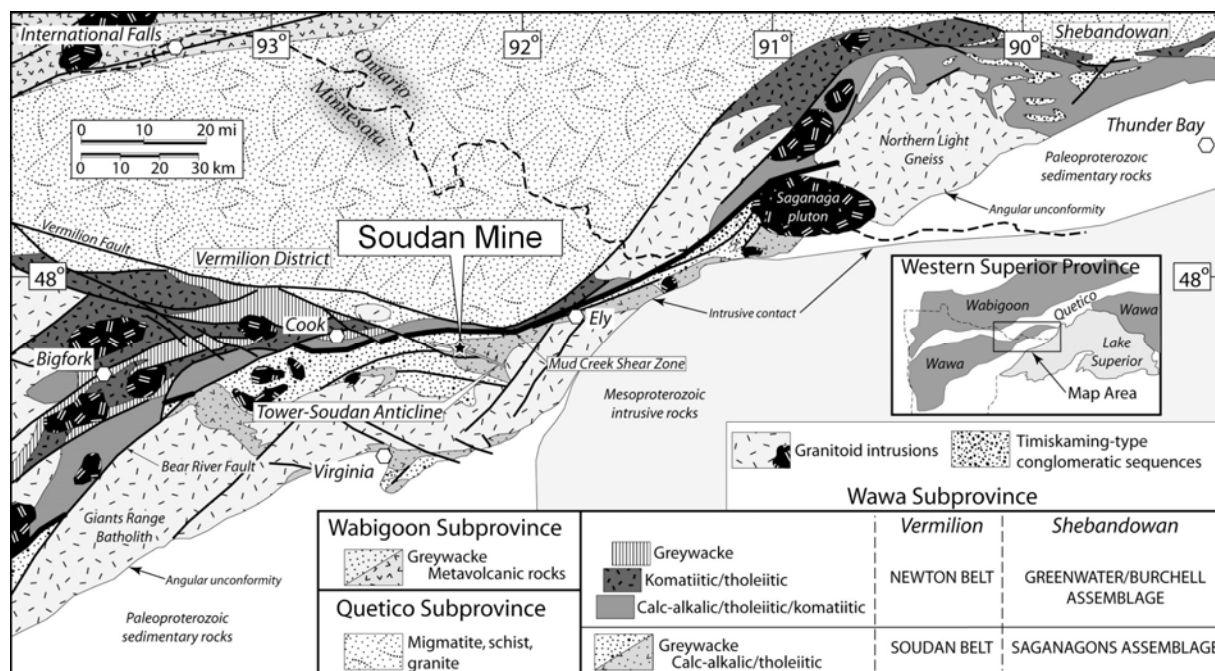


Figure 3-1. Simplified correlation map of Neo-Archean assemblages across the U.S. - Canadian border, modified from Peterson et al., 2001). Inset shows major subprovinces of the southwestern Superior Province.

Local Geological Setting

A detailed geological study of the Soudan DUSEL area was recently completed by Peterson and Patelke (2003) and is available online at <http://www.nrri.umn.edu/egg/REPORTS/TR200329/TR200329.html>. Detailed field mapping ranging from 1:100 to 1:2000 scale (Peterson and Patelke, 2003; Hudak et al., 2002, 2003), petrographic studies (Hudak et al., 2002, 2003), whole rock lithogeochemical studies (Hudak et al., 2002, 2003), and electron microprobe investigations (Hocker et al., 2003) have led to a more complete understanding of the tectonic environment, stratigraphy, structure, hydrothermal processes and mineralization episodes associated with the diverse strata in the Soudan Mine vicinity.

The local geological setting has been subdivided into three stratigraphic sequences (Fig. 3-2). The older Fivemile Lake Sequence is composed dominantly of coherent and volcanoclastic, dominantly calc-alkaline to transitional basalts and andesites, minor intercalated coherent and volcanoclastic rhyodacite and rhyolite, associated chemical exhalites (including subeconomic VMS horizons) and epiclastic strata. Facies analysis indicates the FLS formed within a relatively shallow submarine arc environment.

The younger Central Basalt Sequence (CBS) comprises an extremely texturally well-preserved sequence of sparsely amygdaloidal calc-alkaline, transitional, and tholeiitic basalt and andesite pillowed and massive lava flows; in-situ and resedimented rhyodacite to rhyolite lava flows, lava domes, and tuffs; as well as volcanic-derived mudstones, sandstones and breccias intercalated with chert, exhalites, and Algoma-type iron formations. Facies analysis indicates the CBS formed in a deeper water submarine environment which, based on lithogeochemical data, may be transitional between a volcanic arc and the opening of a back-arc rift.

Overlying the CBS are sedimentary-dominated rocks of the Upper Sequence (US), which in the Soudan DUSEL area consists dominantly of Algoma-type iron-formation; dacitic epiclastic rocks, crystal tuff and tuff breccia; mixed basaltic rocks and iron-formation; and greywacke. The contact between the CBS and the overlying US is transitional over approximately 100-150 meters, and marks a stratigraphically upward increase in the proportion of chemical sediments and decrease in volcanic rocks. The supracrustal strata in the immediate area have been intruded by numerous synvolcanic – diorite and gabbro sills, diabase and feldspar-porphyry dikes – and post-tectonic – lamprophyre dikes – intrusions. A simplified geologic map of the Soudan DUSEL area is presented in Figure 3-2.

Periods of generally N-S directed compression resulted in three Neoarchean deformation events in the Soudan area. The earliest deformation (D_1) produced the Tower-Soudan Anticline (Fig. 3-1), which is a west-plunging anticline within which the axis and plunge changes orientation along strike from nearly vertical in basalts to shallow NE plunging in the western sedimentary rocks. Axial-planar cleavage associated with this early fold typically is lacking, although Bauer (1985), Hooper and Ojakangas (1971), Hudleston (1976), and Jirsa et al. (1992) have described early cleavage (S_1) locally, and Peterson and Patelke (2003) have described D_1 flexural-slip shear zones immediately north of the Soudan Mine. A second deformation (D_2) associated with synchronous regional metamorphism resulted in foliation development and shear zones having largely dextral asymmetry. D_2 is constrained in the Vermilion greenstone belt to the time period 2674 to 2685 Ma (Boerboom and Zartman, 1993). The relationship between S_2 fabric and shear structures indicates that most shearing occurred relatively late in the D_2 event (Jirsa et al., 1992). Major shearing that produced the Mud Creek and related shear zones, e.g., the Murray, Mine Trend, and Linking shear zones in the Soudan Mine area (Fig. 3-2), is attributed to the late stages of D_2 dextral transpression. Structures related to the third deformation (D_3) include abundant NE- and NW-trending faults (Fig. 3-2).

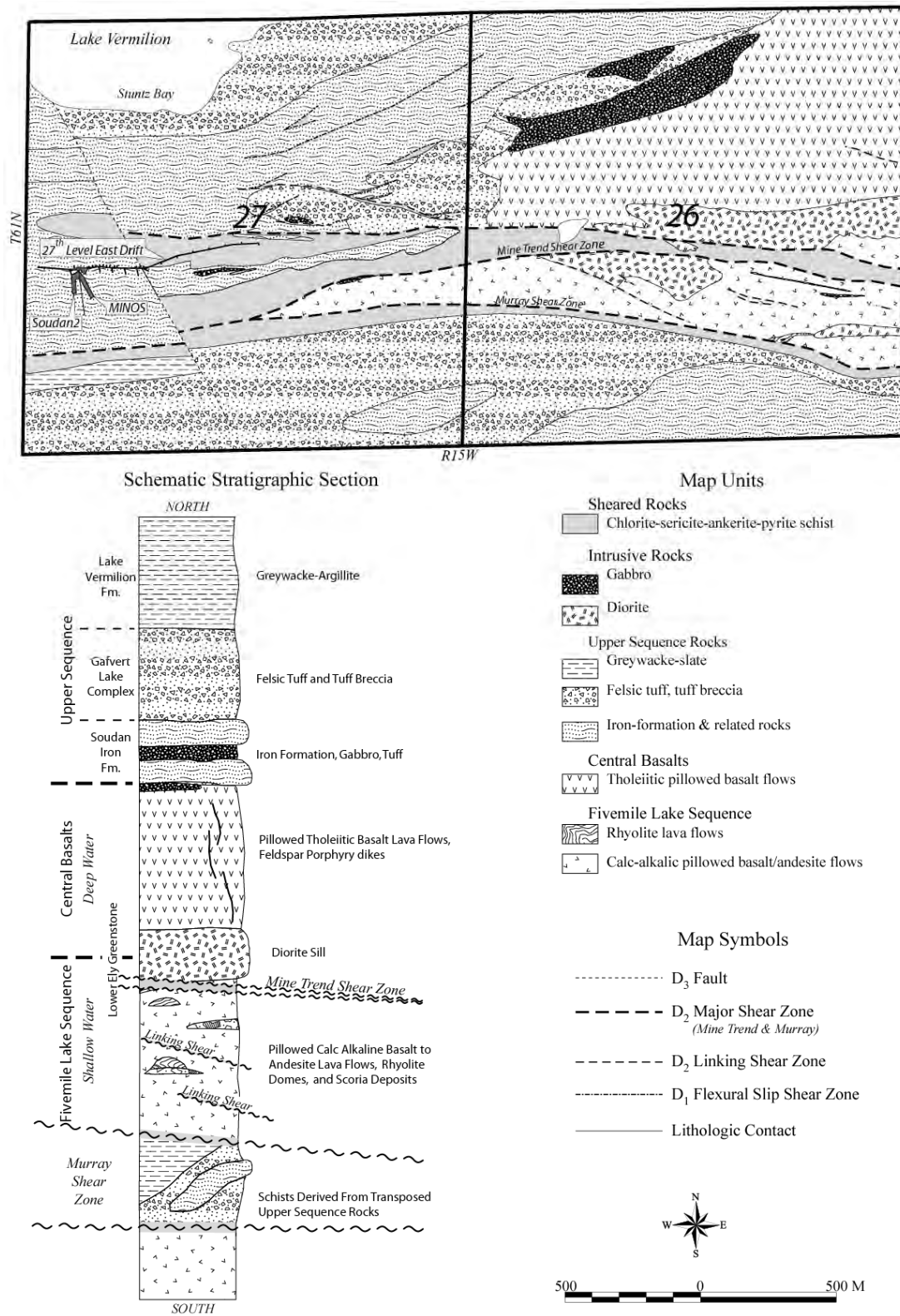


Figure 3-2. Simplified bedrock geologic map and stratigraphic section of the Soudan Mine area, Sections 26 and 27, T62N, R15W. Modified from Peterson and Patelke, 2003.

SOUDAN FIELD TRIP

The short time-frame of the 2009 ILSG field trip to the Soudan Mine only allows for quick tours of the facility and the scientific treasures it holds. The excursion begins at the surface of the Soudan Mine and will include a quick overview of the local geology based on geologic maps and observations of the region from the head frame vista.

The three minute trip underground in the inclined shaft will take us 2,341 feet underground. We will gather in the main hall of the MINOS cavern for brief PowerPoint presentations about the Soudan Mine from our field trip leaders. The presentations will pertain to the following topics: the State Park (James Pointer), geology of the area (Dean Peterson), and the various physics experiments (Marvin Marshak).

The group will be split in half and rotate through a tour of the Underground Physics Laboratory and a historic mine tour, which takes us via a 3/4 mile train ride to the Montana ore body, the last and deepest area mined at Soudan.

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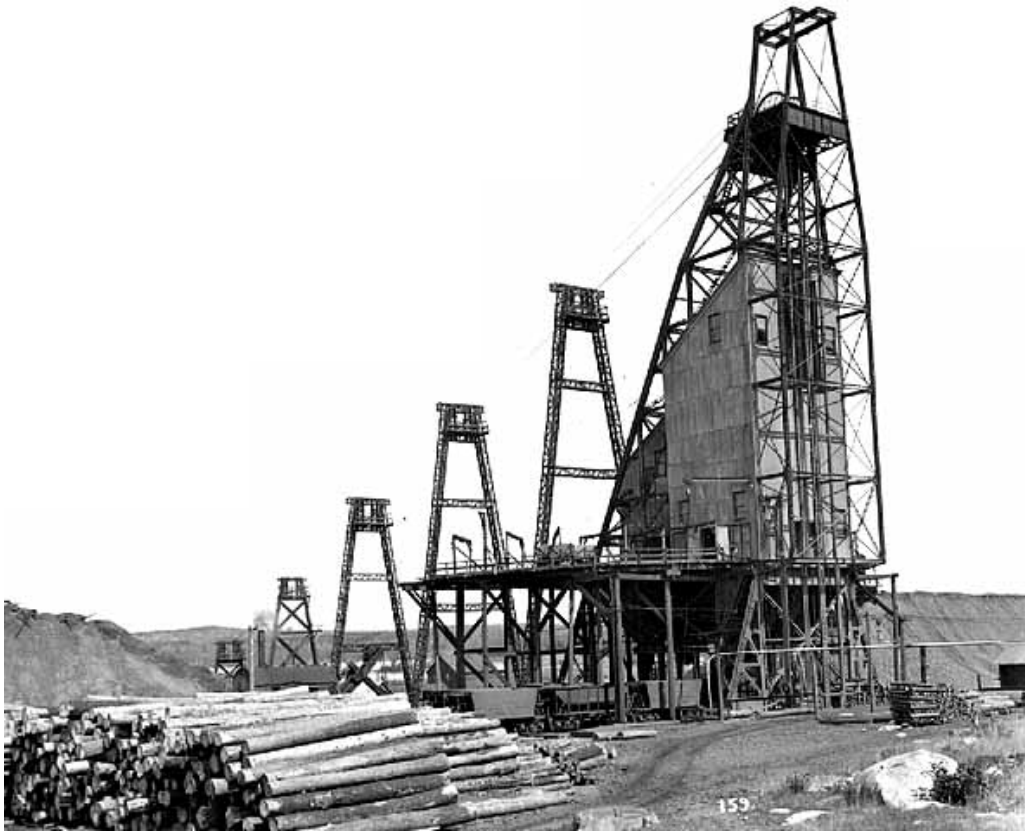
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Field Trip 4

PIONEER MINE CANOE EXCURSION



Sibley Mine headframe, Ely Minnesota 1905, Minnesota Historical Society.

Mark Jirsa (Minnesota Geological Survey)

Mike Hillman (Ely Historian)

FIELD TRIP 4

PIONEER MINE (Miners Lake) CANOE EXCURSION

Mark Jirsa—Minnesota Geological Survey,
Mike Hillman—Ely historian

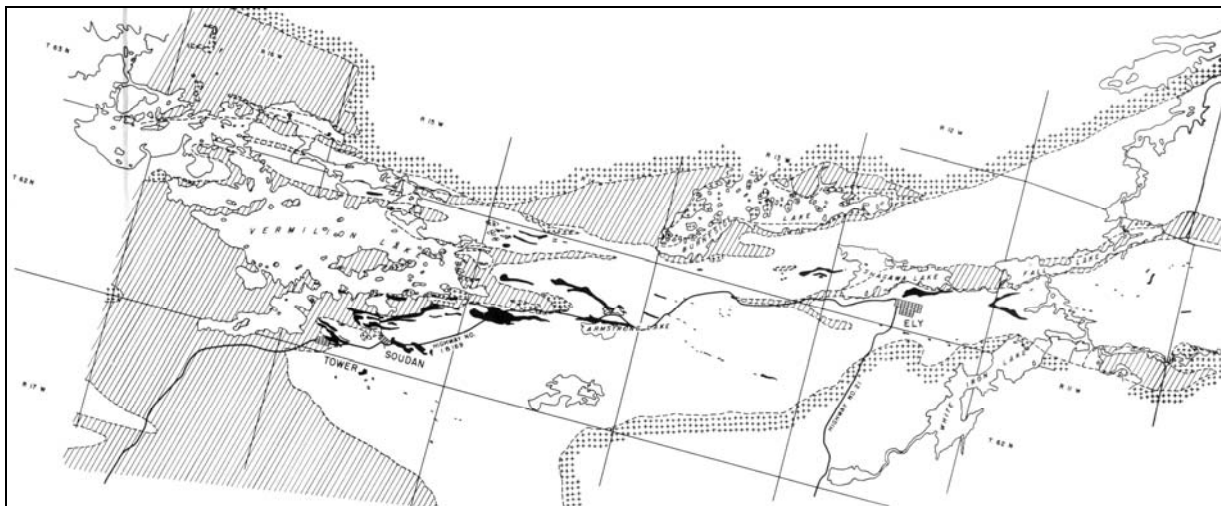


Figure 4-1. General geology of Archean rocks in the western half of the Vermilion district (after Clements, 1903). Black= iron-formation; diagonal rule=metasedimentary rocks; white=metavolcanic rocks (and lakes); plus symbol=intrusions.

MINERS LAKE (*information from Minnesota Department of Natural Resources website*)

Miners Lake was formed by the flooding of the open pit portion of a series of mostly underground iron mines after mining was discontinued in 1967. The lake has a maximum depth of about 140 feet. The flooded basin of Miners Lake includes the formerly mined area and a shallow bay to the east that was not mined. Brook and Rainbow trout are stocked at the rate of about 3000/year. Bass, pan fish, and white suckers are also present. The 2009 fishing season starts May 9.

INTRODUCTION

The Pioneer Mine was one of the richest underground mines on the Vermilion Iron Range from its opening in 1888, until closure in 1967. Mining extracted crystalline hematite from jaspilitic iron-formation, and the underground workings eventually attained a depth of more than 1500 feet. The iron-formation occurs as discontinuous layers and lenses within the Neoarchean Ely Greenstone along the Vermilion Iron Range or Vermilion district, as it was known (Fig. 4.1). The geology at Pioneer Mine is much like that at other mines of the district, including the Soudan Mine about 20 miles to the west. The Pioneer Mine and the adjacent Chandler, Sibley, Savoy, and Zenith mines (Fig. 4.2) lie within a complex isoclinal fold—known as the Ely Trough—having steeply dipping limbs. The brief geologic description presented here is based on historical records, primarily from mining company geologists of what was then the Oliver Iron Mining Division, U.S. Steel Corporation.

This trip starts with a visit to the Pioneer Mine Dry with local historian “Iron-Mike” Hillman. We then embark on a short canoe trip down the axis of the trough, exploring exposures along the mine walls.

Steeply dipping, pillowed metabasalt flows, lean and brecciated iron-formation, and a complex array of intrusions are visible from the gunnels.

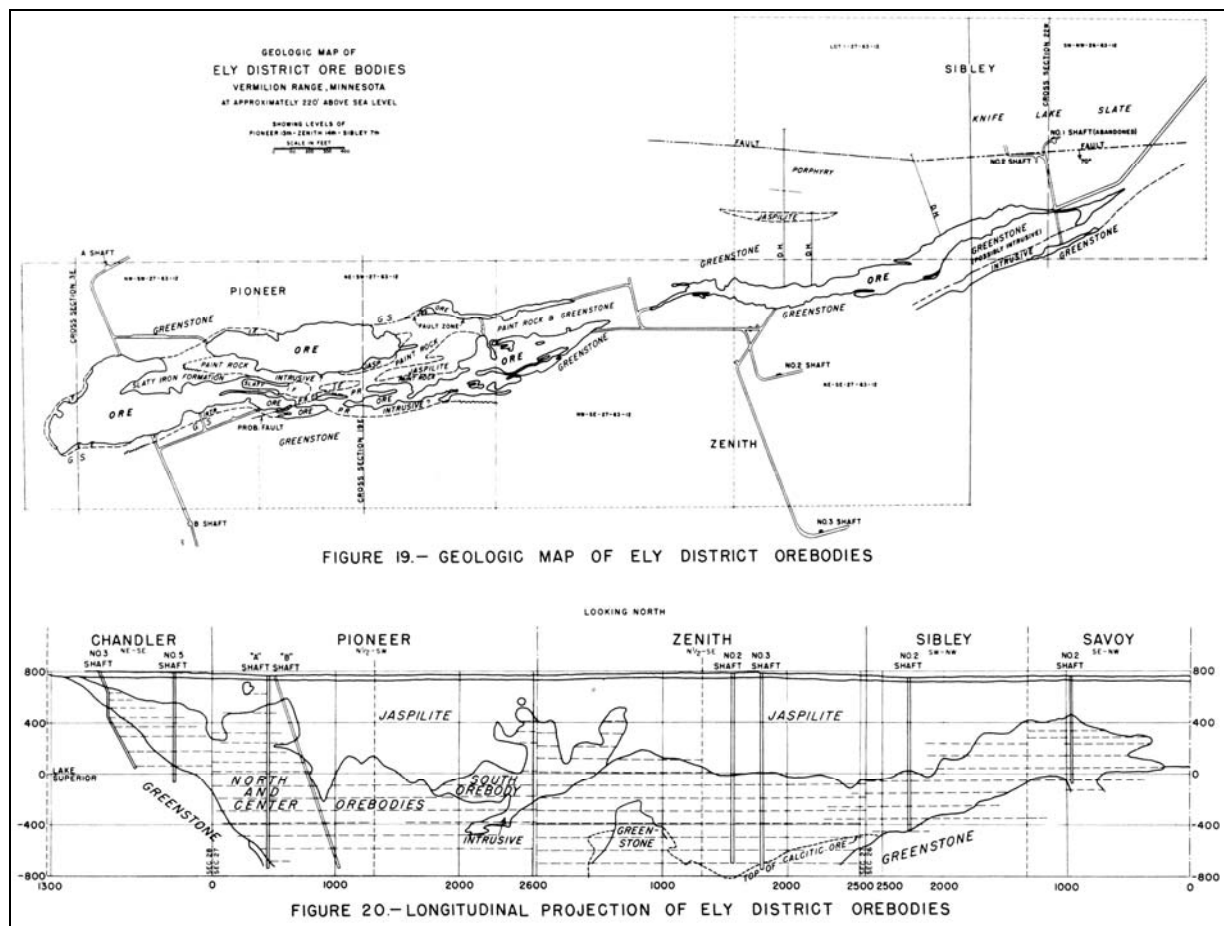


Figure 4-2. Geology of Ely trough mines (from Reid, 1956).

EXPOSURES

No descriptions of individual field “stops” are given here—instead, participants are encouraged to paddle along at a safe distance from the shoreline and observe, using the following general information as a guide. Bedding trends more or less parallel to the long axis (E-W) of the lake and dips steeply. Exposures at the west end of the lake show layered jaspilitic and slaty iron-formation capping pillowed, fragmental, and amygdaloidal metabasalt; overlain to the north by massive metabasalt. This is the west edge of the Chandler Mine. The south shore presents dip-slope exposures of pillowed metabasalt, mafic intrusions, and lenses and layers of lean iron-formation, all trending subparallel to the shoreline. These exposures lie within the Chandler and Pioneer Mines. Stratigraphic younging based on pillow morphology is northward, consistent with the interpretation that this shoreline exposes the south limb of the Ely trough. Easternmost exposures the north shore are within the Zenith Mine, and show liesegang-banded, altered (leached, oxidized) iron-formation.

CAUTION should be taken to avoid disturbing the metastable wall rocks!

LOCAL MINING HISTORY

Time-line for development of the Vermilion Iron Range (modified from Skillings, 2004)

1865 Iron ore discovered at Soudan by George R. Stuntz

1883 Iron ore discovered at Ely by H.R. Harvey

1884 Completion of Duluth and Iron Range Railroad line to Tower

1884 First shipment of ore from Soudan mine

1888 First shipment from Chandler and Pioneer Mines

1901 Largest annual shipment of >2 million tons

1967 Last shipment from Vermilion (at Pioneer Mine—289,000 tons of gravity concentrate)

1884-1967 Total iron ore shipped from Vermilion = 103,752,604 tons

Last iron ore reserve estimate calculated in 1985 for the Vermilion Iron Range = 6,237,076 tons.

Ely Trough mining and production (Skillings, 2004):

Mine Name	Operation Yrs.	~Total (million tons)
Chandler N	1891-1942	9
Chandler S	1888-1957	2
Pioneer	1888-1967	41
Zenith	1892-1964	21
Sibley	1899-1954	10
Savoy	1899-1916	2

GEOLOGY

The main rock types in the mine, as described in previous literature (Reid, 1956) include:

Greenstone (pillowed and massive metabasalt, minor hyaloclastite and mafic tuff)

Porphyry intrusions (plagioclase and quartz phenocrysts)

Basaltic intrusions (metagabbro, metadiabase)

Jaspilite

Slaty iron-formation

Graphitic and sericitic schist

“Paint rock” (an alteration product, apparently of any of the rocks types above)

The large deposit of iron ore at Ely is found in the basal part of a trough-like lens of iron-formation about 1.75 miles long and .25 miles wide at the surface. Mines within the trough structure included the Chandler North and South, Pioneer, Zenith, Sibley, and Savoy. The structure is blunt U shape at the west end (Chandler) and narrows to the east. The ore body plunges eastward from the Chandler into the Pioneer mine, and is abruptly split by a broad mass of paint rock. The ore continues along both N and S limbs of the trough, but the north limb ore pinches out eastward into the Zenith. Most of the Zenith, and all of the Sibley and Savoy ore bodies lie within the south limb of the trough, and the north limb is presumably truncated by a fault. The ore is fragmental hematite, cemented to varying degrees that increase with depth by secondary hematite. The limbs of the trough, as defined by iron-formation, converge at about 1500 depth, and the ore-bearing structure is less than 500 feet wide. The trough roughly parallels the east-northeast-trending regional strike of the Vermilion district. Its axis is warped, with a steep north to vertical dip on the west, and a steep southerly dip on the east. Footwall rocks surrounding the trough consist of metabasalt of the Ely Greenstone and several types of intrusive rocks. Least-altered metabasalt exposed outside of the mines consists of actinolite, epidote, chlorite, quartz, and albite.

Near the ore bodies, the rocks contain a more pronounced cleavage and consist of chlorite, fine-grained muscovite (sericite), and quartz. The trough interior is composed largely of jaspilite (alternating layers of hematite and chert), with lesser amounts of argillaceous iron-formation, mafic sill-like intrusions, irregular plagioclase-quartz porphyries, and lenses of graphitic and sericitic schist. Felsic porphyry intrusions were encountered during mining, and mafic sills and dikes were reported to cut iron-formation locally. Both of these rock types are common in the regional geology.

The precise age of folding responsible for the Ely trough is unknown. Jirsa and Miller (2004) speculate that the Ely trough and other similarly trending structures were deformed during D_1 , much like the deformation that formed the Tower-Soudan anticline to the southwest. This is largely based on the observation that fold axes near Ely are truncated by D_2 structures related to deformation along the Knife Lake-Burntside Lake trend.

ORE DEPOSITS

The major hematite ore bodies occur near the base of the trough. It was considered a “rubble ore,” because the bulk of it consisted of small angular fragments of hard blue hematite. The ore was relatively soft in the upper parts of the mine, but hardness increased with depth as it became partially to completely cemented by secondary hematite. In many places the ore was as hard as the “lump” ores at Soudan. The high grade ore bodies are more or less conformable with layering in jaspilite and greenstone, implying that the ores occupy the stratigraphic position of lean iron-formation. The ores contained 55-65 percent iron, low silica, P, Mn, and Al_2O_3 . An increase in pyrite content with depth was observed, and carbonate minerals increased eastward within the trough. Alteration is more intense than at any other deposits in the Vermilion district. The alteration includes oxidation and leaching, and involves the loss of silica, lime, magnesia, soda, and potash, and the addition of iron and oxygen. “Paint rock” is the ultimate extent of that alteration, resulting locally in material consisting almost entirely of kaolin and ferric oxide.

The origin of hematite ores on the Vermilion Range is controversial. Three scenarios have been speculated historically:

- 1) Leaching of silica from the primary iron-formation resulted in the formation of a residual hematite body, which was later compacted, hardened, and fractured by deformation and metamorphism;
- 2) Post-metamorphic leaching of silica and introduction of iron by downward-moving surface water;
- 3) Post-metamorphic leaching of silica and simultaneous introduction of iron by rising heated waters

A detailed study of mineralogy and structure at the Zenith Mine, which lies just east of the Pioneer, produced the following conclusions (Machamer, 1968):

- 1) The ore deposits are post-metamorphic;
- 2) They formed by the replacement of silica in iron-formation by iron oxides;
- 3) The replacement resulted from rising hydrothermal fluids, most likely generated from higher metamorphic grades at depth.

REGIONAL MINING HISTORY

Although the 6 mines described here were by far the most productive, at least 12 iron mines were explored and developed in the area from Ely; westward to Armstrong Lake and Mud Creek Road; and eastward along the Fernberg Road (Stenlund, 1988). Only 3 of these mines actually shipped ore, and their life-spans were short due to high costs in this rugged terrane and low tonnage. The local mining and

logging history is displayed in the Vermilion Interpretive and History Museum of the Ely-Winton Historical Society, housed on the campus of Vermilion Community College.

Overall the Soudan iron-formation member and other iron-formations in the Ely Greenstone consist of lens shaped bodies interleaved with volcanic strata. The most productive mines occur at Tower-Soudan and Ely. It is interesting to note that these are the two localities along the Vermilion range where iron-formation is “doubled” by folding. At the least, the folding consolidated otherwise attenuated iron-rich units. It is also likely that deformation played an important role in the alteration of the iron-bearing units to high-grade hematite deposits.

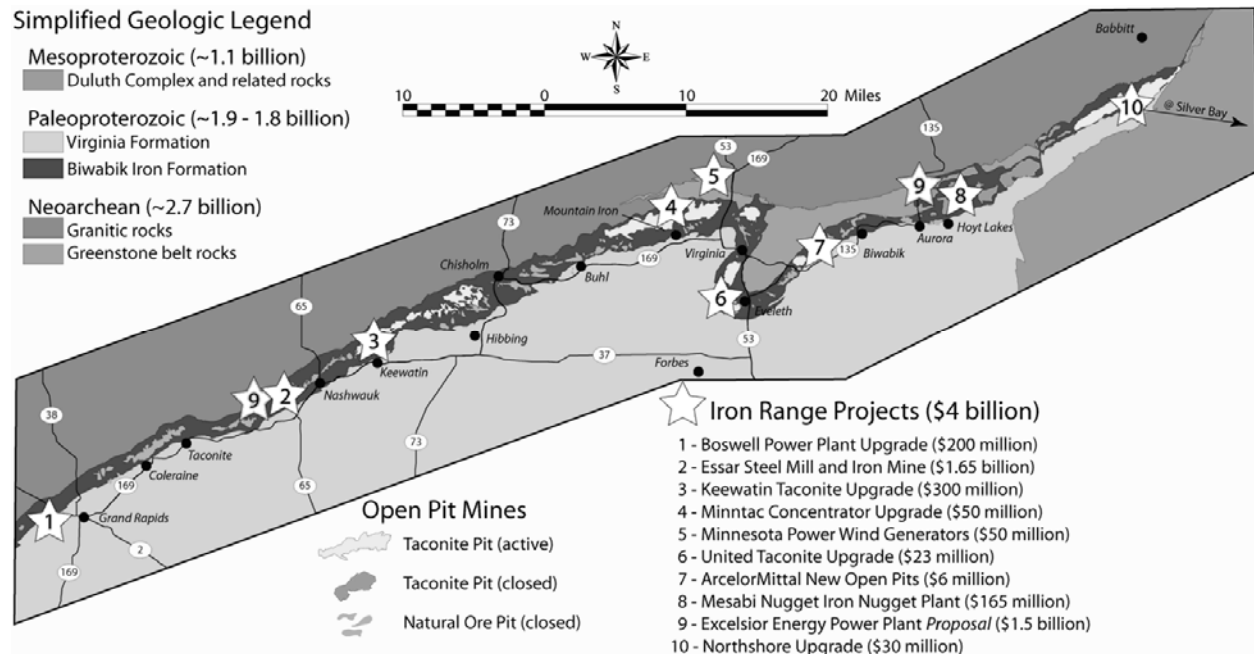
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Field Trip 5

GEOLOGY & METAMORPHISM OF THE EASTERN MESABI RANGE



Dick Ojakangas (Dept. of Geological Sciences, UMD)

Mark Severson (Natural Resources Research Institute)

Doug Halverson (Cliffs Natural Resources)

Jeff Bird (Cliffs Natural Resources)

Tom Campbell (Cliffs Natural Resources)

Jared Lubben (Cliffs Natural Resources)

Peter Jongewaard (Cliffs Natural Resources)

William Everett (Mesabi Nugget)

FIELD TRIP 5

GEOLOGY AND METAMORPHISM OF THE EASTERN MESABI IRON RANGE

Richard W. Ojakangas, Professor Emeritus, University of Minnesota Duluth
Mark J. Severson, Natural Resources Research Institute,
Thomas J. Campbell, Cliffs Technical Group, Cliffs Natural Resources
Jared D. Lubben, Cliffs Technical Group, Cliffs Natural Resources
Peter K. Jongewaard, Cliffs Technical Group, Cliffs Natural Resources
Douglas G. Halverson, Northshore Mining/Cliffs Natural Resources
Jeff Bird, Northshore Mining/Cliffs Natural Resources
William Everett, Mesabi Mining

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 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 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. 5-1). 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, 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. 5-2).

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).

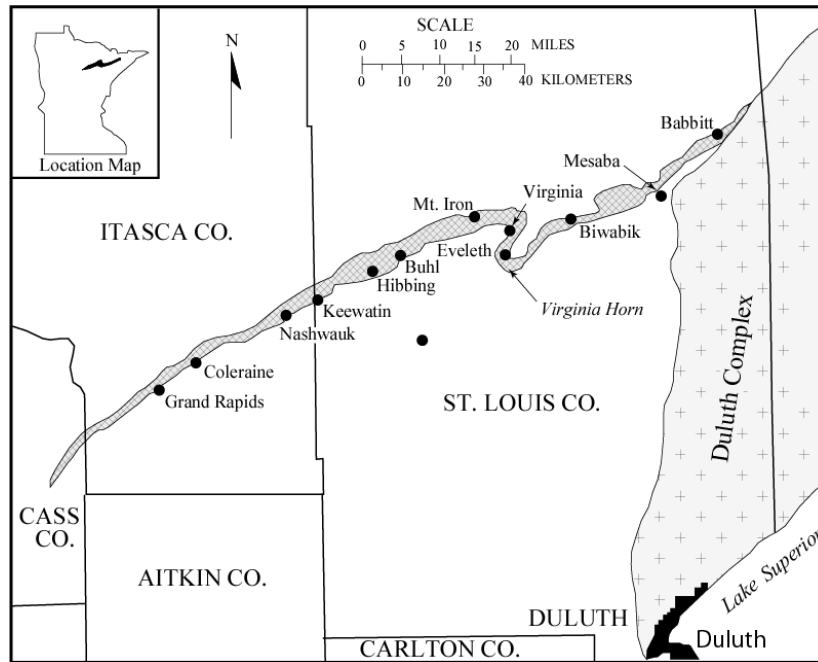


Figure 5-1: Generalized map of the Mesabi Iron Range (cross-hatched). Note the Duluth Complex (Keweenawan, 1.1 Ga) on the east side.

REGIONAL GEOLOGY

The peneplaned 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. 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. 5-3). 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 and others (2001) and Severson and others (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. 5-3). 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. 5-4).

Figure 5-5 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 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 (for example Southwick and others, 1988).

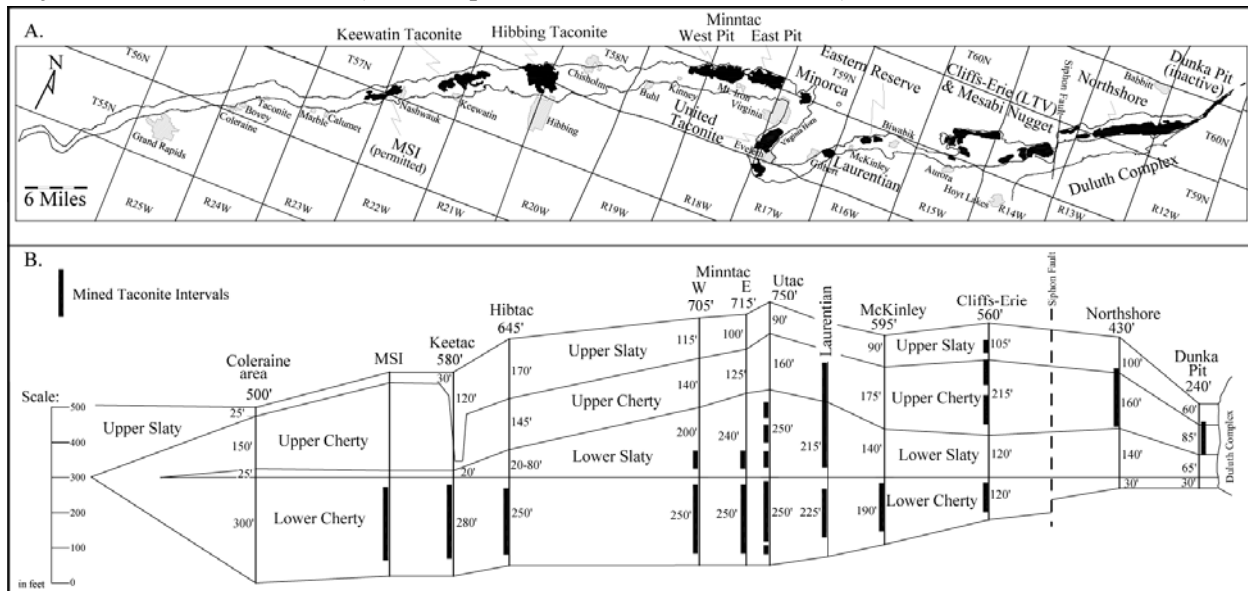


Figure 5-2: Generalized map of the Mesabi Iron Range. Inset A - Aerial distribution of taconite pits and cities. Inset B - Longitudinal section of the Biwabik Iron Formation showing: average thickness of the iron-formation at each taconite operation (along with the thickness of the various submembers at each operation), and mined taconite intervals (as black columns adjacent to the sections). From Severson and others (in prep.)

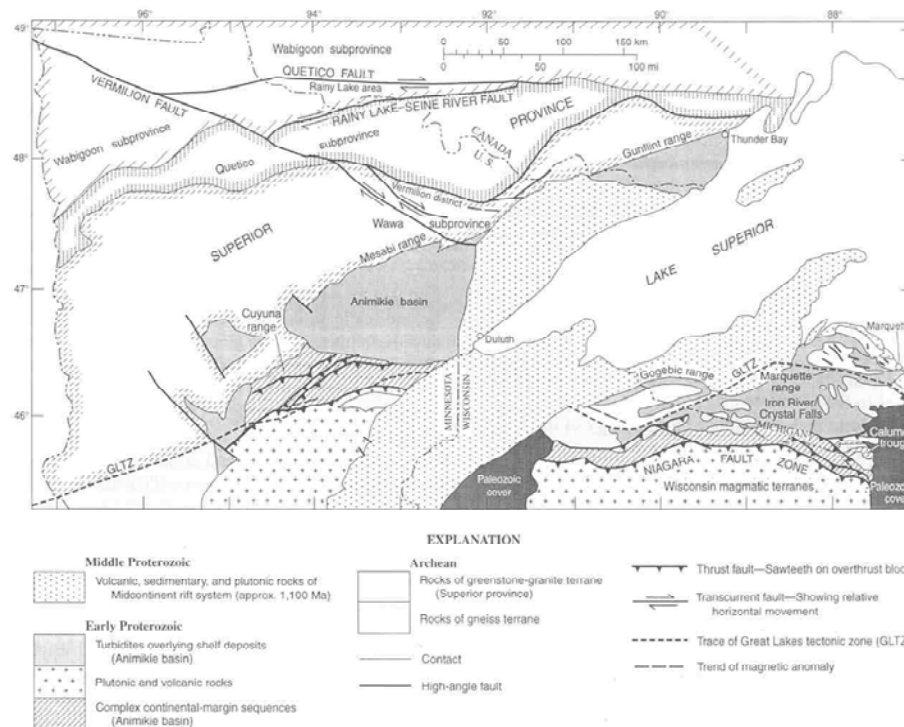


Figure 5-3: Generalized geologic map showing the distribution of Precambrian rocks and structural elements of the Lake Superior region, modified from Ojakangas 1994 and references therein (from Ojakangas and others, 2001).

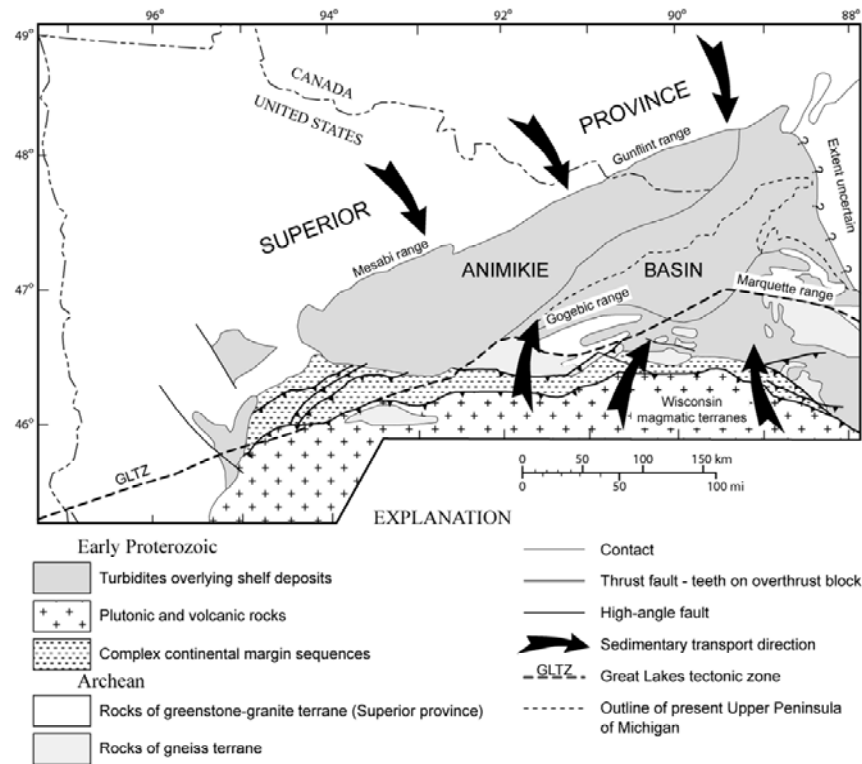


Figure 5-4: Schematic hypothesized paleogeography at the time of sedimentation of the Paleoproterozoic Animikie Group turbidites that overlie shelf deposits in the Animikie basin. The rocks of the 1,100 Ma Midcontinent Rift System have been removed from the map, and Michigan and Wisconsin are thus positioned 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. 5-3. Modified from Ojakangas (1994) and references included therein (from Ojakangas, et al., 2001).

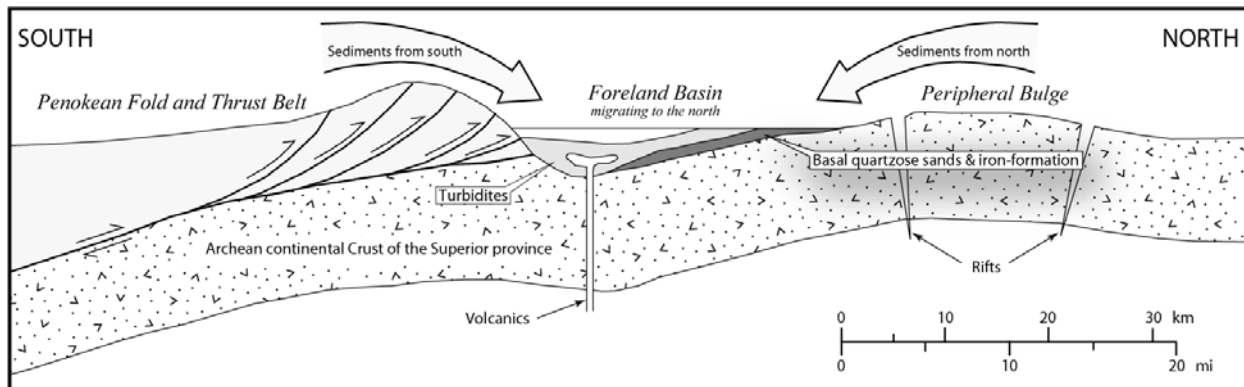


Figure 5-5: Schematic cross-section depicting deposition of the Animikie Group turbidites that overlie shelf deposits in the Animikie basin, with sediment derived from both the north and south. The southern area, the fold-and-thrust belt, comprises a complex assemblage including: 1) accreted Paleoproterozoic volcanic and plutonic rocks and volcanic rocks of the Wisconsin magmatic terranes; 2) accreted Archean miniplate 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. 5-4. Modified from Ojakangas (1994) and references included therein (from Ojakangas and others, 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. 5-6; 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 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 Range during deposition) thus somewhat older than those in Minnesota and Ontario. 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. 5-6).

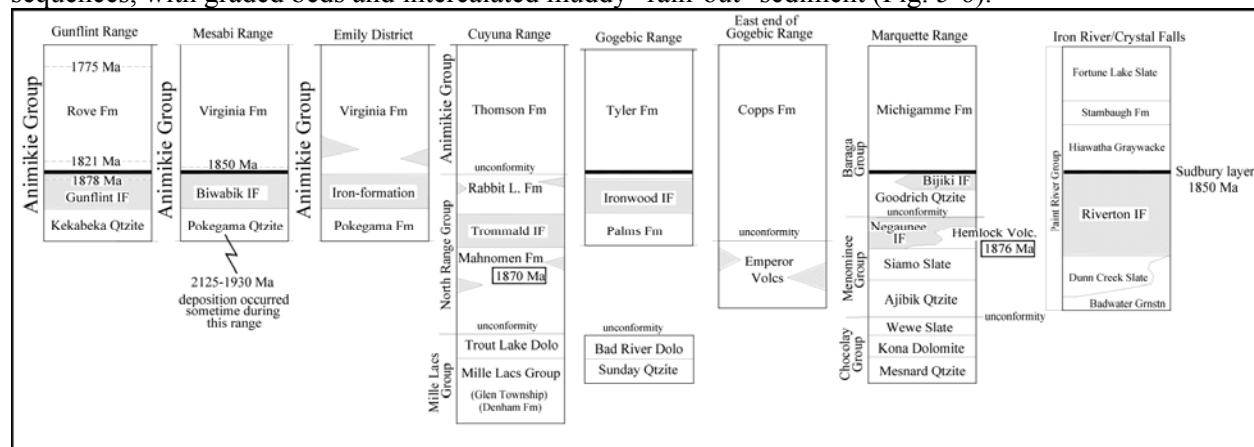


Figure 5-6: Generalized correlation chart of Paleoproterozoic strata in the Lake Superior region. Note that recently obtained age dates are shown for the Gunflint Iron formation, Mahnomen Formation, Hemlock Volcanics, and the Rove and Virginia Formations (sources listed in the references). The position of the Sudbury layer is from Cannon and Addison (2007).

Ages

Along the Mesabi Range, the Pokegama Formation rests unconformably on diabase dikes of the Kenora–Kabetogama dike swarm that give a Rb-Sr isochron age of $2,125 \pm 45$ Ma (Southwick and Day, 1983; Beck, 1988), and this provides a maximum age for deposition of the Pokegama Formation. A minimum age of $1,930 \pm 25$ Ma (Pb/Pb) for the Pokegama Formation was obtained by Hemming and others (1990) from quartz veins that cut the Pokegama Formation. A U/Pb age on euhedral zircons from an ash layer in the upper Gunflint Iron Formation of Ontario is $1,878 \pm 2$ Ma (Fralick and Kissin, 1998; Fralick and others, 2002). A similar age of $1,874 \pm 9$ Ma was obtained on zircon from rhyolite in the Hemlock Formation that is adjacent to (and is possibly interlayered with) the Negaunee Iron Formation in the Marquette Range Supergroup of Michigan (Schneider and others, 2002). A zircon age from an ash layer near the base of the Virginia Formation is 1,850 Ma (Hemming and others, 1996), and an age of $1,821 \pm 16$ Ma has been obtained from an ash layer in the Rove Formation about 70 meters above the Gunflint Iron Formation (Kissin and others, 2003). Several of these ages are shown on Figure 5-6.

It has been recently postulated that deposition of the iron-formations in the Lake Superior region was affected by the Sudbury impact event at 1850 Ma (Cannon and Addison, 2007; Jirsa, 2008). Field and petrographic evidence for this event are clear in the Gunflint Iron Formation (Addison and others 2005; Jirsa, 2008) and the iron-formations of Michigan (Cannon and Addison, 2007). However, an indication of this event in the top of the Biwabik Iron Formation is more subtle (Addison and others, 2007), possibly due to deeper water conditions that are recorded in the presently mined and drilled stratigraphic section on the Mesabi Range.

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. 5-7). Other drill cores, some recently rediscovered and some recently drilled, 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 mineralogical changes in the Pokegama Formation and the Biwabik Iron Formation are the result of diagenesis rather than metamorphism, 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 6-7. 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 fluvial 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.

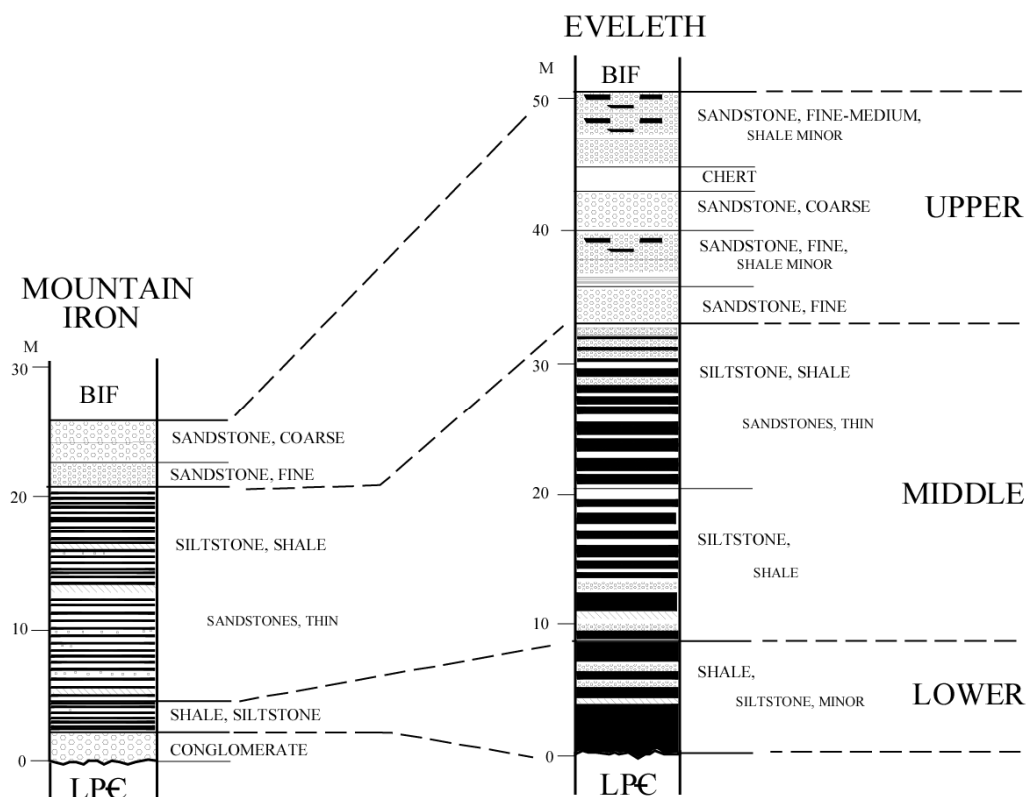


Figure 5-7: Measured sections from two drill holes that penetrate the entire Pokegama Formation. Dark shading represents shale, thin blank units represent siltstone, the slanted pattern represents sandstone and siltstone, and the dotted pattern represents sandstone. Modified from Ojakangas (1983).

Biwabik Iron Formation

This is one of the world's major iron-formations, and the largest in the United States. The formation is 200 to 750 feet thick and consists of four divisions as defined by Wolff (1917). These lithostratigraphic units, now informal members, are from the bottom up, the Lower Cherty, the Lower Slaty, the Upper Cherty, and the Upper Slaty (these are miners' terms, and do not indicate metamorphism; Fig. 5-2). The cherty members are dominantly granular (sand-textured), thick-bedded (several inches to a few feet), and are largely composed of chert and iron oxides. The slaty members are dominantly fine-grained (mud-textured), thin-bedded (less than 1 inch), and composed mostly of iron silicate and iron carbonate with local chert beds. However, these two rock types are interbedded on all scales and are generally gradational. They contain about the same high quantities of silica, 42 to 47 percent (Morey, 1992). The Lower Slaty member is not present at the far western end of the range.

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 and others, in press).

Virginia Formation

There are rare exposures of the Virginia Formation in mines at the east end of the Mesabi Range 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 preserved lower part of the formation (Lucente and Morey, 1983).

The lower portion of the formation in the drill holes is dominantly black shale. The upper portion of the drill core, while still dominantly shale, contains beds of siltstone and fine-grained feldspathic graywacke comprising thickening- and coarsening-upward turbidite sequences. Ash-fall tuff, cherty sideritic iron-formation, chert, and limestone are minor rock types low in the formation. The contact with the underlying Biwabik Iron Formation is gradational. The clastic rocks were largely derived from the Archean rocks to the north, with some contributions from lower Proterozoic rocks to the south (Lucente and Morey, 1983).

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).

ENVIRONMENTS 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 5-8. 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. 5-8). 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.

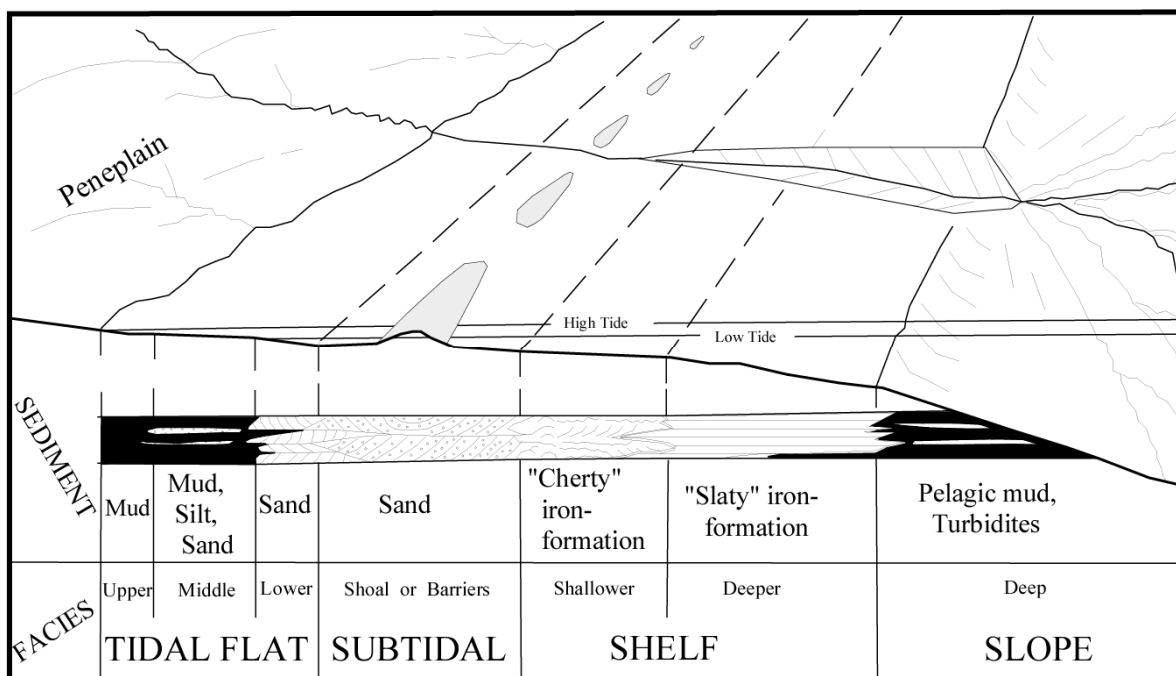


Figure 5-8: Sedimentation model showing lateral relationships of the siliciclastic tidal facies of the Pokegama Formation, the two main facies of the Biwabik Iron Formation, and the Virginia Formation (on the slope?). Thicknesses and geography are not to scale; modified from Ojakangas (1983).

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. 5-9) 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. 5-9). 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 5-10. A paleocurrent plot of mound elongation (Fig. 5-10) is interpreted as the result of shore-normal tidal currents and shore-parallel longshore currents in shallow water. The repetition of the cherty and slaty members has long been interpreted as the result of transgression and regression (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 falls

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).

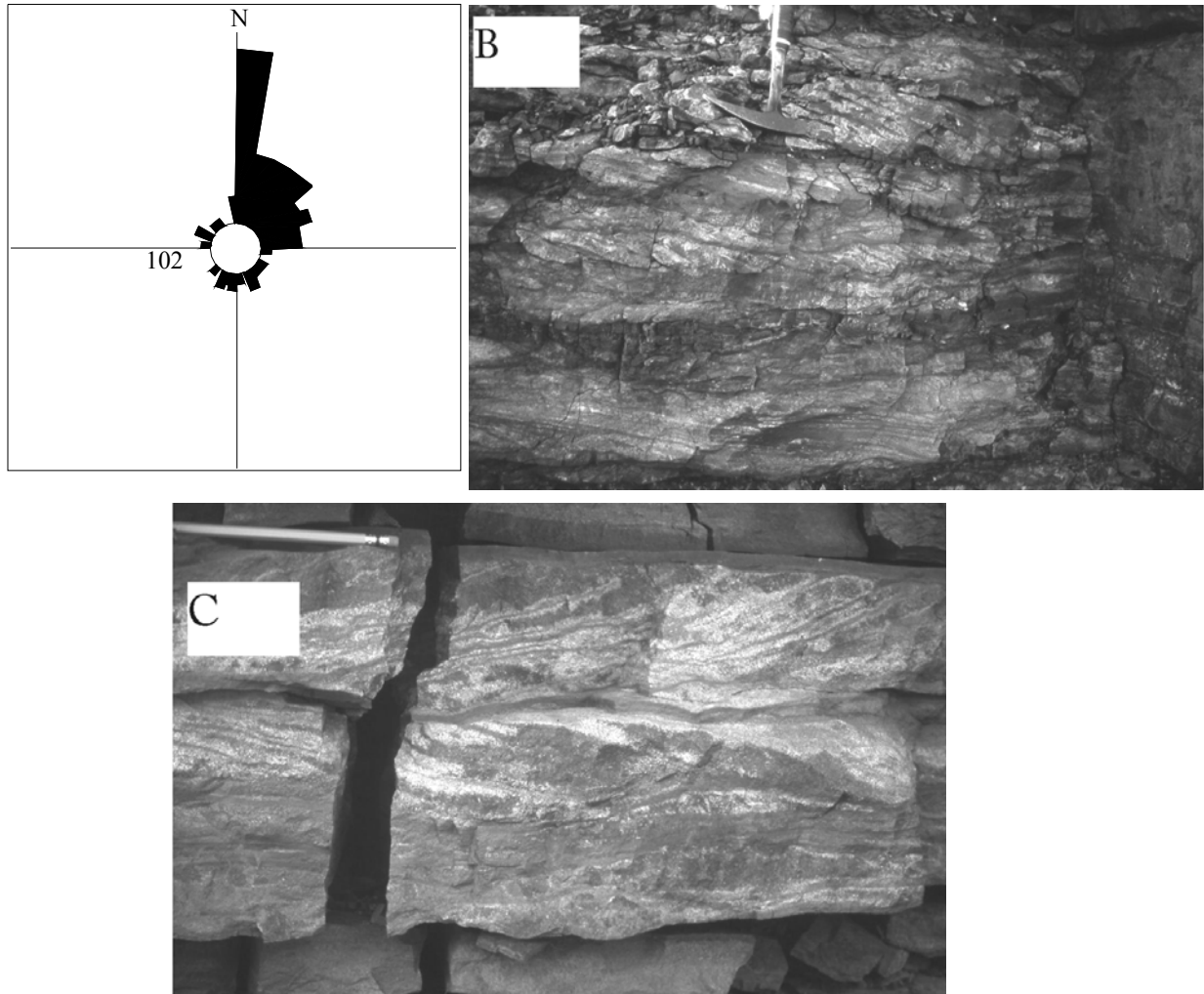


Figure 5-9: A. Paleocurrent rose diagram of 102 cross-bed measurements from the Lower Cherty member (LC-4 submember) in the Minorca Mine. Inset B - Photo of cross-bedding in the Minorca Mine. Inset C - Photo of herringbone cross-beds in the Minorca Mine

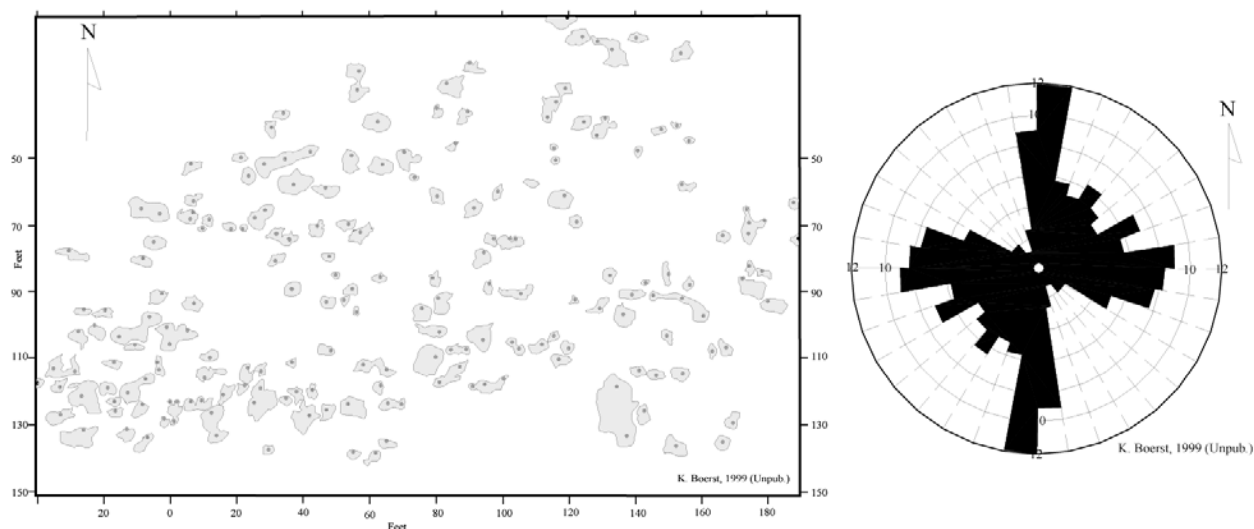


Figure 5-10: Mapped stromatolite mounds in the algal submember (I submember) in the Upper Cherty of the LTV 2E pit. The rose diagram represents the elongation of the mounds, with each elongate mound plotted on both sides of the rose diagram. From unpublished work by Kevin Boerst (1999).

MINERALOGY

Details on the origin of the primary iron minerals of the Biwabik Iron Formation, or any BIF, are exceedingly complex and controversial and are beyond the scope of this guidebook. In brief, Eh and pH are major controls on the stability of the various iron minerals and possible colloidal precipitates in the depositional environment and subsequent diagenetic environment. A variety of primary chemical precipitates for iron-formation in general have 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). Metamorphic effects, especially in the easternmost Mesabi Range, modified the mineralogy through progressive devolatilization reactions and modification or 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 has been extensive, and consisted of a number of discrete events.

Earlier work on the oxidized taconites of the western Mesabi Range was accomplished by Bleifuss (1964). He showed that late hematite was developed by the oxidation and pseudomorphic 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 and others (2003).

All of the magnetite grains are euhedral and are interpreted as late diagenetic in origin. Some of the hematite inclusions and crystals in magnetite are similar to those illustrated by Han (1982). He proposed that much of the magnetite formed by the replacement of, and overgrowth on, pre-existing hematite that served as nuclei. Han further suggested that ionic diffusion of ferrous iron was a key process in the formation of the magnetite. Organic carbon may have acted as a reductant in this process. Some of the magnetite may also originate from replacement of precursor siderite as observed in many examples in drill core and polished thin section from the western and central Mesabi Range.

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 Range proves that they were formed long after emplacement of the Duluth Complex rather than during the Paleoproterozoic.

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 iron formation of the Western Mesabi Range, which is dominated by 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. 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 the Peter Mitchell Mine and Dunka Pit are given in Table 5-1 below. The overlying pelites 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 5-2. Excluding Cu-Ni PGE mineralization, the mineralogy of gabbroic rocks of the Duluth Complex in this area is relatively simple: labradorite, anorthite, augite, olivine group minerals, with accessory magnetite, ilmenite, and apatite.

Table 5-1. Minerals found in the Biwabik Iron Formation in the area of the Peter Mitchell Mine and Dunka Pit.

Amphibole Group	Pyroxene Group	Olivine Group	Other Silicates	Oxides/ Hydroxides	Carbonates	Phosphates	Other Minerals
Grunerite	Hedenbergite (minor)	Fayalite	Quartz	Magnetite	Siderite	Hydroxyl-apatite	Pyrrhotite
Ferro-actinolite (minor)	Ferro-hypersthene (minor)		Ferroan Clinoclase	Hematite (minor)	Ankerite		Pyrite
Ferro-hornblende (minor)	Ferroselite		Biotite	Goethite	Rhodocrosite (minor)		"Anthrax-olite"
Ferro-pigeonite	Diopside		Oligoclase	Ilmenite	Ferroan Dolomite		
Cummingtonite			Andesine		Ferroan Kutnahorite		
			Almandite		Calcite		
			Andradite				
			Cordierite				
			Sekaninaite?				
			Wollastonite				
			Epidote				
			Titanite				

Table 5-2: Mineralogy of the Virginia Formation in the vicinity of the Peter Mitchell Mine.

Silicates	Other Minerals
Muscovite	Ilmenite
Biotite	Pyrrhotite
Quartz	Pyrite
Microcline	Chalcopyrite
Anorthite	Rutile
Oligoclase	Ankerite
Andesine	Calcite
Anthophyllite	Graphite/Carbonaceous material
Cordierite	
Staurolite	
Wollastonite	
Ferroan Clinocllore	
Andalusite	
Sillimanite	
Almandine	
Epidote	
Titanite	

Quartz is the most abundant mineral in the 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 (see later discussions on submembers of the iron-formation). 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 Range. The occurrence of magnetite in the Eastern Mesabi 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 idiomorphic 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 also is found as fine- to coarse-grained isolated clusters or “granules” in recrystallized chert, and as fine-grained replacement of algal stromatolites (I submember) and intraformational conglomerate clasts. 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 formation with grunerite and cummingtonite most prevalent. These amphiboles are very fine- to very coarse-grained, subhedral, prismatic, isolated

crystals or occur as intergrown crystals forming divergent fascicles, rosettes and radial, acicular aggregates in the matrix or 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. Bonnicksen (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). Bonnicksen (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 clinocllore. Andradite garnet is commonly found in the A and G submember, in similar habit to almandine, at the Peter Mitchell Mine. 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.

METAMORPHISM

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 fH_2O . In contrast, the Biwabik Iron Formation preserves prograde metamorphic reactions several kilometers west and north of the contact with the Duluth Complex; whereas, 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 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 and others (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 are characterized by regular interlayering of magnetite-rich and quartz-rich layers ranging from <1cm up to 12cm 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, ferropseudobrookite, hedenbergite, ferrosilite, ferropseudobrookite, 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. 5-11) as follows.

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), “unmetamorphosed iron-formation” in the Mesabi Range does not exist. All rocks have been subjected to diagenetic effects as well as burial and/or regional metamorphism, not to mention contact metamorphic effects due to the Duluth Complex in the Eastern Mesabi Range.

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 effects to the iron-formation occur three miles from the Duluth Complex.

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 temperature of formation was probably 300-400° C.

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 ferropseudobrookite), 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 and others (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 and others (2007) have since revised and expanded these zones/isograds to specifically include the formation of ferropseudobrookite 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.

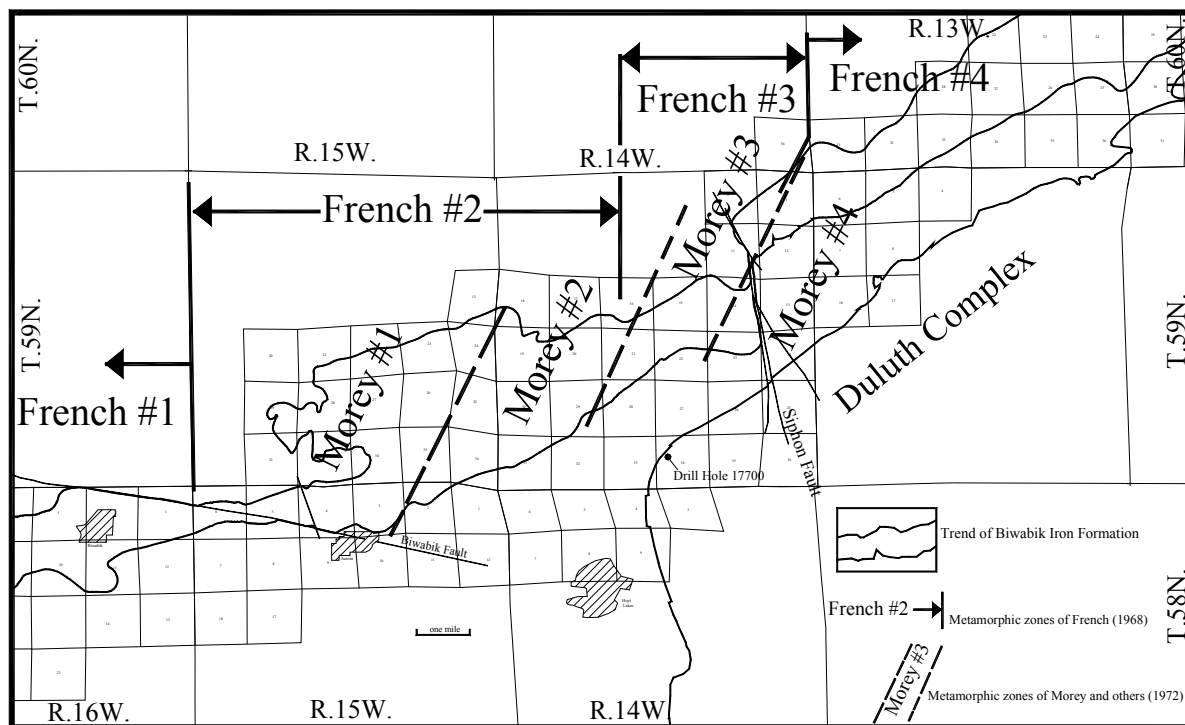


Figure 5-11: Approximate boundaries of four zones of metamorphosed iron-formation after French (1968) and Morey and others (1972).

French (1968) found that metamorphism of the iron-formation was largely isochemical with a progressive loss of H_2O and CO_2 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+ H_2O + CO_2 ;
2. hedenbergite formed by ankerite+quartz=hedenbergite+ CO_2 ;
3. ferrohypersthene formed by grunerite=ferrohypersthene+quartz+ H_2O ;
4. fayalite formed by grunerite=fayalite+quartz+ H_2O ; and
5. fayalite formed by magnetite+quartz=fayalite+ O_2 .

Bonnichsen (1968) felt that the metamorphism at Dunka Pit was also isochemical. He suggested that all of the CO_2 was driven from the iron-formation; whereas, a portion of the H_2O 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 H_2O 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 $800^\circ C$ (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, 1975; Caddey and others., 1990). Volume loss in the Biwabik Iron Formation due to metamorphic devolatilization has enhanced the thinning of this unit eastward across the Mesabi Range.

Closer to the Duluth Complex, Bonnicksen (1968) found that metamorphic grade of the Biwabik Iron Formation reached pyroxene hornfels facies in the Dunka Pit area. At this locale, the iron-formation is positioned $\leq 1/4$ 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). Bonnicksen (1968) describe poikilitic textured minerals (ferrohypersthene, fayalite, and cummingtonite) in the iron-formation enclosing quartz and magnetite.

Perry and Bonnicksen (1966) determined the maximum temperature of metamorphism at Dunka Pit, as determined by O^{18}/O^{16} ratios of quartz and magnetite, was estimated to be 700-750° C. This was confirmed by Hyslop and others (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 and others (1993). At the Wyman Creek Cu-Ni deposit, Perry and Bonnicksen (1971) estimated a temperature range of 400-650° C for metamorphism of the iron-formation in drill hole #17700 (Fig. 5-11), 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_2O_3 , CaO, Na_2O , K_2O , Ba, Rb, Sr, MgO, Cu, Ni, and H_2O ; and a loss of SiO_2 and P_2O_5 . On the other side of the contact, also in a 25 foot wide zone, the Duluth Complex showed gains in K_2O , Rb, S, Fe_2O_3 , and H_2O ; 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.

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 5-12. 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.

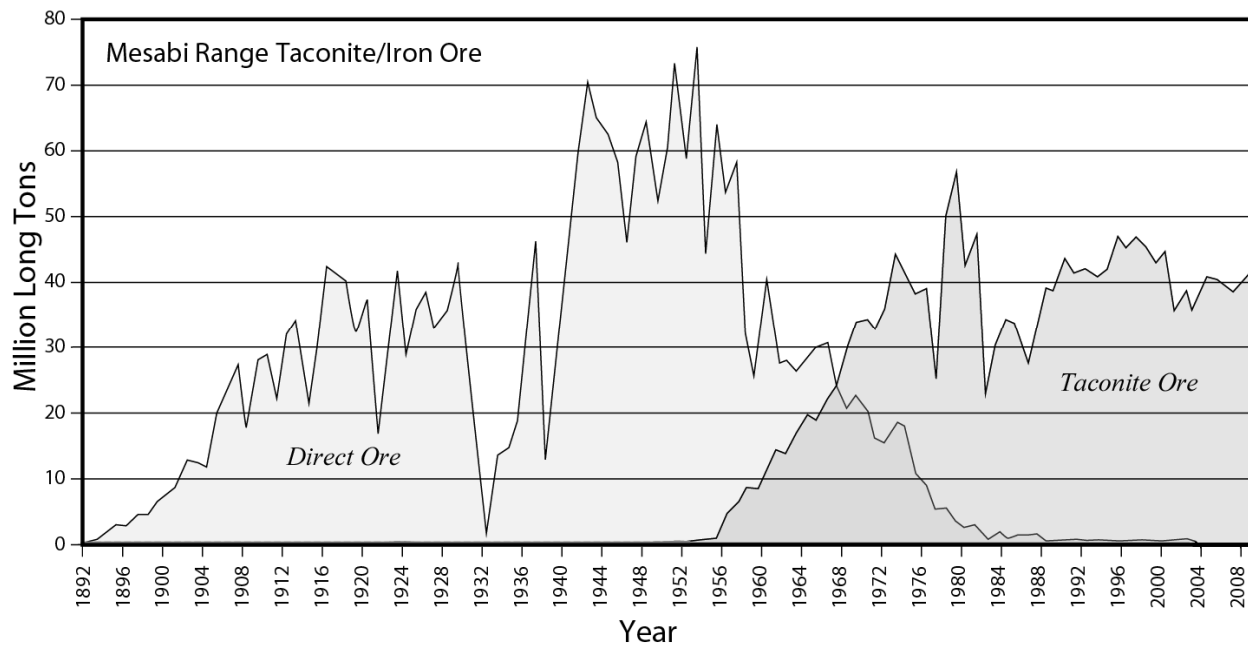


Figure 5-12: Annual production figures for direct ore (includes all forms of direct ore) and taconite for the period 1892-2008. Data and graph from James Sellner, Minnesota Department of Natural Resources, Lands and Minerals Division, Hibbing, MN

WHAT'S IN A NAME? (THOSE CONFUSING IRON-FORMATION SUBMEMBERS)

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 (Fig. 5-13) and mineral assemblages. It is at this point that the Biwabik Iron Formation stratigraphy becomes very complicated and at times confusing. This is mainly due to the following reasons:

- There are localized lateral facies changes between mines (and even within a single mine). Some mines reconcile these differences by splitting out numerous submembers (each with a distinct bedding type, texture, ore grade, and/or mineral assemblage), whereas other mines lump many of these same differences within a single submember.
- There are significant lateral facies changes over several miles between mines. For example, a particular horizon may be massive-bedded at one location but is regular-bedded a few miles away. This is particularly troublesome within the Upper Cherty member in the western two thirds of the Mesabi range.
- 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.

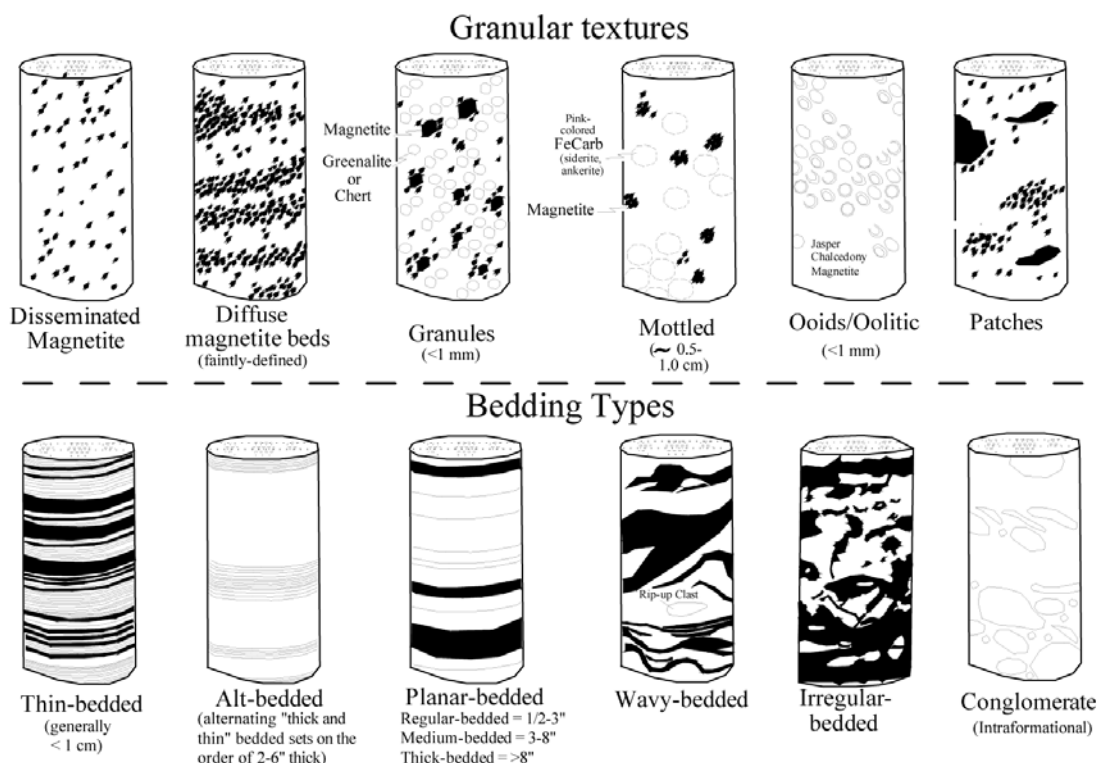


Figure 5-13: Textural characteristics of the Biwabik Iron Formation (from Severson and others, in prep. – modified from Pfleider and others, 1968).

The submember nomenclature that is used at each of the mines is summarized in Figures 5-15 through 5-18. It can readily be seen on these summary charts that submember names change nomenclature from one mine to the next. This is because there are few good marker horizons within the Biwabik Iron Formation, and even these can exhibit gradual lateral facies changes or pinch-and-swell relationships to each other. A few of the potential marker horizons within the Biwabik Iron Formation are presented below.

- Top contact of the Biwabik Iron Formation with the Virginia Formation—In the eastern half of the Mesabi Iron Range a carbonate horizon is present at the very top of the Upper Slaty member and the contact between the Biwabik Iron Formation and Virginia Formation is easily recognized (Gruner, 1924). However, to the west of Hibbing, the carbonate layer is absent and lenses of thin-bedded iron carbonate iron-formation are present in the Virginia Formation, and the top of the Biwabik Iron Formation is not easily discerned.
- Algal horizon (submember I) – A thin unit containing algal stromatolites and jasper-bearing intraformational conglomerate is present near the top of the Upper Cherty member. This submember is easily recognized but is not present west of Hibbing.
- Lower Cherty member - The Lower Cherty member is remarkably homogeneous over most of the Mesabi Range. The major units that are present, depicted in Figure 5-15, range from thin-bedded rocks at the base (Basal Red Unit of Figure 5-15) that is overlain successively by Regular-Bedded, Wavy-Bedded, and Irregular-Bedded & Mottled units respectively. Each of these units have been recently correlated in over 380 drill holes along the Mesabi Range and are so named for the bedding type that is dominant (Severson and others, in prep.). These major units (left side of Figure 5-15) are suggestive of a transgressive period at the beginning of iron-formation deposition (Basal Red Unit) followed by a regressive period wherein the overlying units were deposited in progressively shallower water. As can also be seen in Figure 5-15, each of these units has been called a plethora of submember names by each of the various taconite mines.

- Base of the Biwabik Iron Formation—The base of the Lower Cherty member is generally characterized by thin-bedded iron-formation (also called the Basal Red Unit - Fig. 5-15) with localized algal stromatolite and basal conglomerate horizons. However, at many localities the base of the Biwabik Iron Formation exhibits a gradational contact with the underlying Pokegama Formation. In the Virginia horn area, the base of the Biwabik Iron Formation contains an iron-bearing sandstone (White, 1954) that some mines include with the iron-formation, whereas others lump this type of material with the Pokegama Formation.

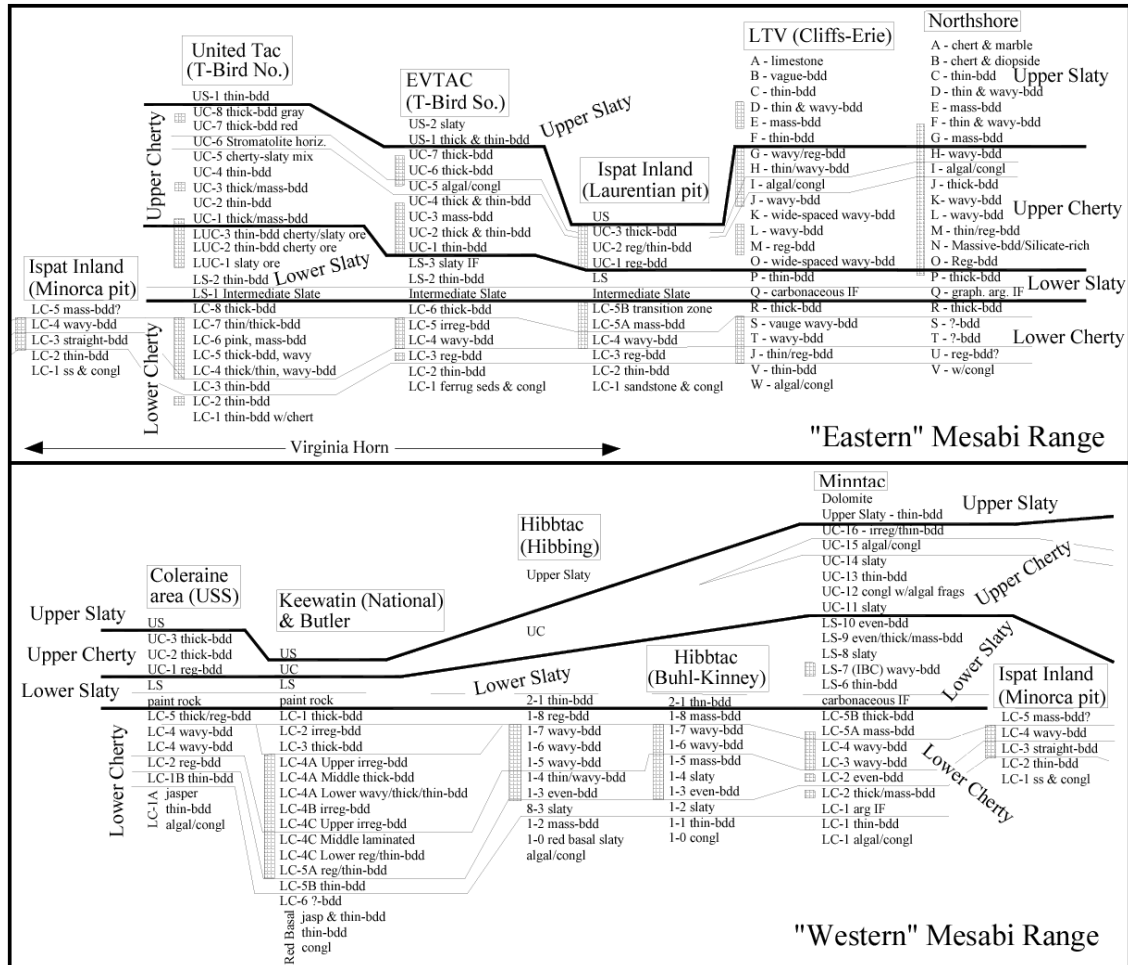


Figure 5-14: Correlation chart of submembers at each of the mines/areas within the Biwabik Iron Formation (correlations from Severson and others, in prep., except for the Evtac and Butler mines). All columns are hung on the base of the Lower Slaty member. Bars to the left of the columns indicate mined taconite ore zones. Note that correlations at the Thunderbird South Mine (Evtac) and the MSI mine (MSI-Mesabi Steel and Iron) are tenuous.

From the above description it is evident that there are few good marker horizons within the upper portions of the iron-formation. Even the top and bottom contacts of the iron-formation are gradational and subject to various interpretations. The "Intermediate Slate," the algal horizon in the Upper Cherty member, and most of the units in the Lower Cherty member are the only easily recognizable marker units. However, even using these horizons as markers, one can see from the correlation charts that there are problems.

Clearly, much additional work needs to be done to understand how submembers at one mine correlate with submembers at an adjacent mine. These types of studies could inevitably be important in determining why ore grades, and waste rock characteristics, change between mines and even within a

single mine. Such studies have been initiated by geologists at the Natural Resources Research Institute (Severson and others, in prep.) and over 380 drill holes have been logged and correlated in an area extending from Biwabik to Coleraine, MN.

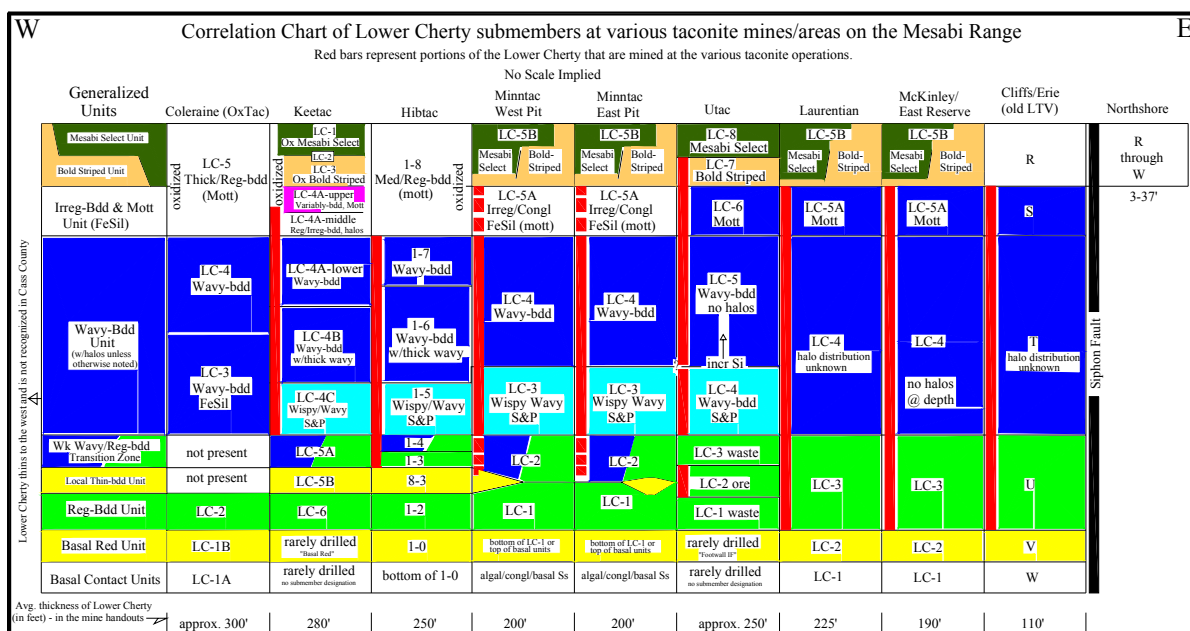


Figure 5-15: Correlation chart of Lower Cherty submembers at the various taconite mines/areas along the Mesabi Range. Contacts between all submembers are transitional/gradational! Note that the MSI mine area (old Butler mine) is not portrayed on this figure; however, the submembers are similar to those at Keetac. "S&P"= salt-and-pepper texture due to disseminated magnetite in chert. From Severson and others (in prep.).

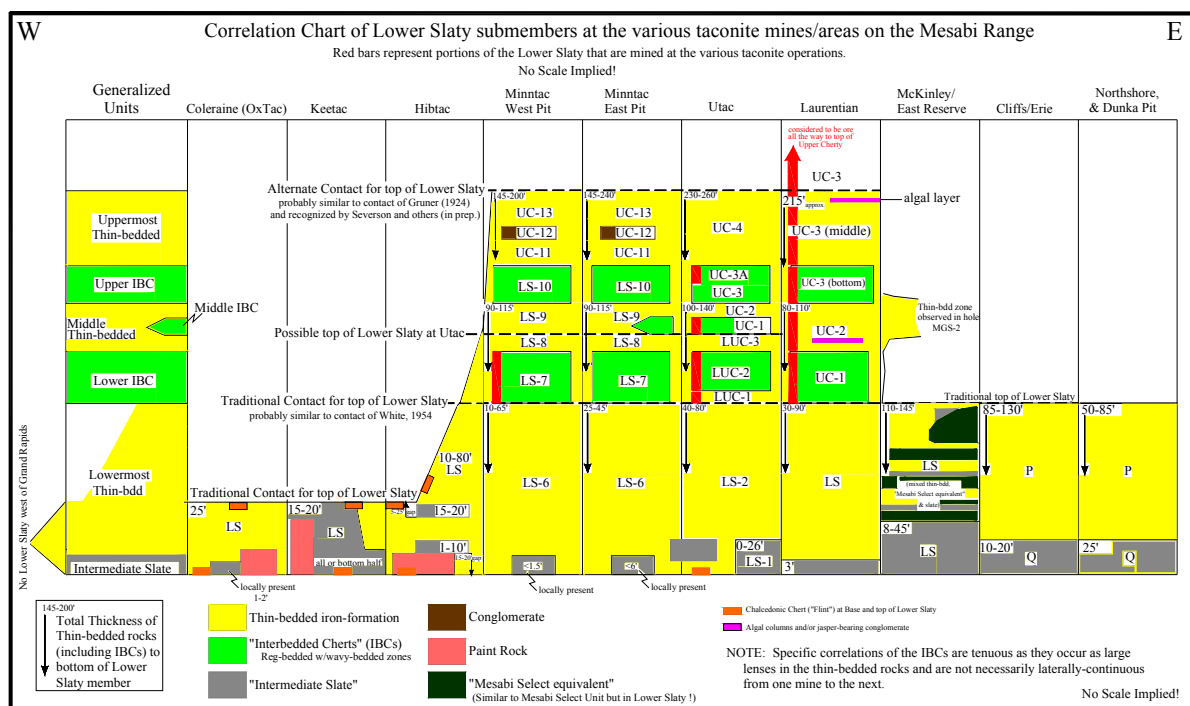


Figure 5-16: Correlation chart of Lower Slaty submembers at the various taconite mines/areas along the Mesabi Range. Note the three optional contacts for the top of the Lower Slaty. From Severson and others (in prep.).

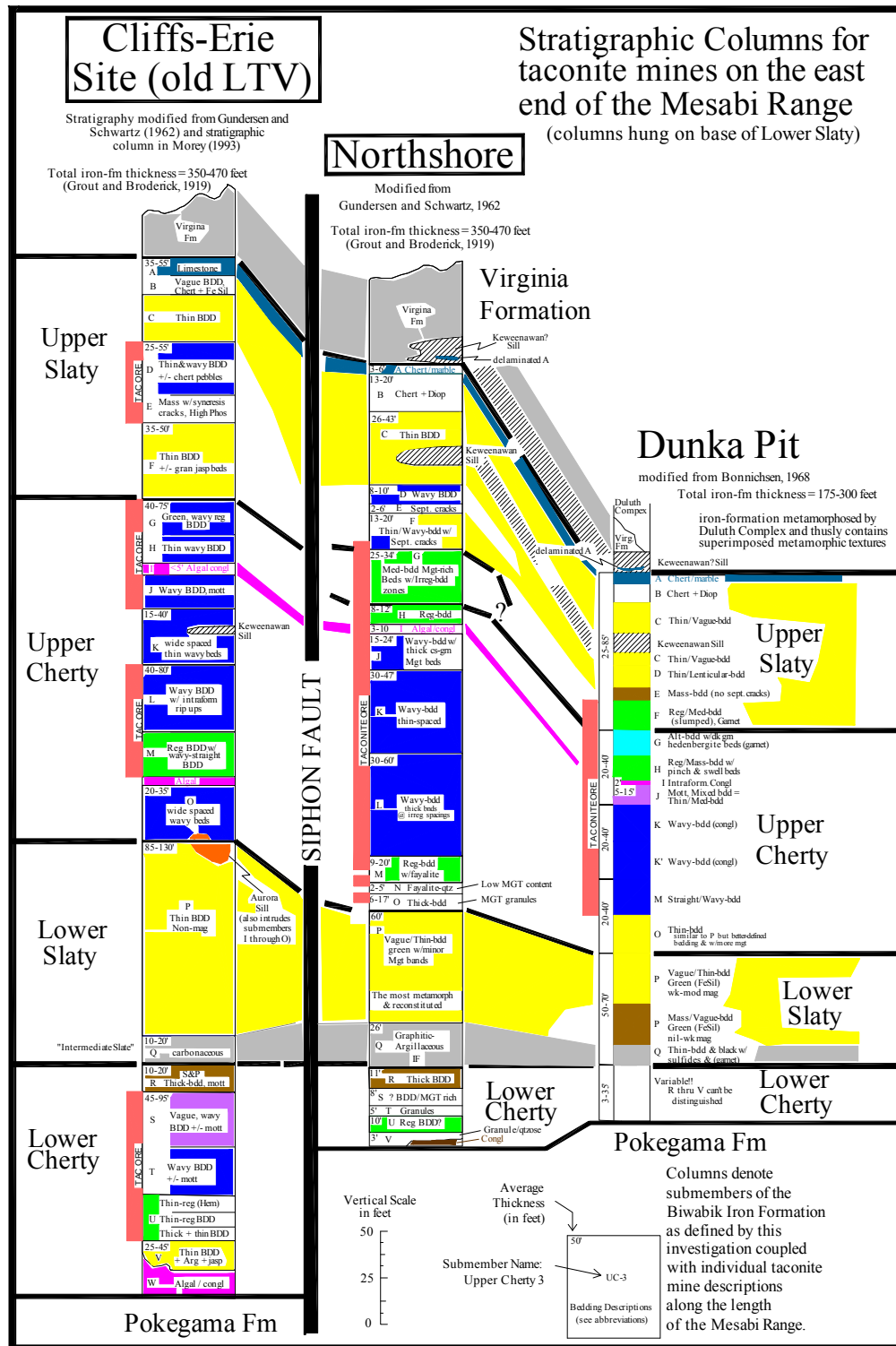


Figure 5-19: Submember nomenclature for the Biwabik Iron Formation as used at the various taconite mines and idled mine sites that will be visited on this field trip. Modified from Plate II in Severson and others (in prep.). Mined horizons are shown by a bar on the side of the column.

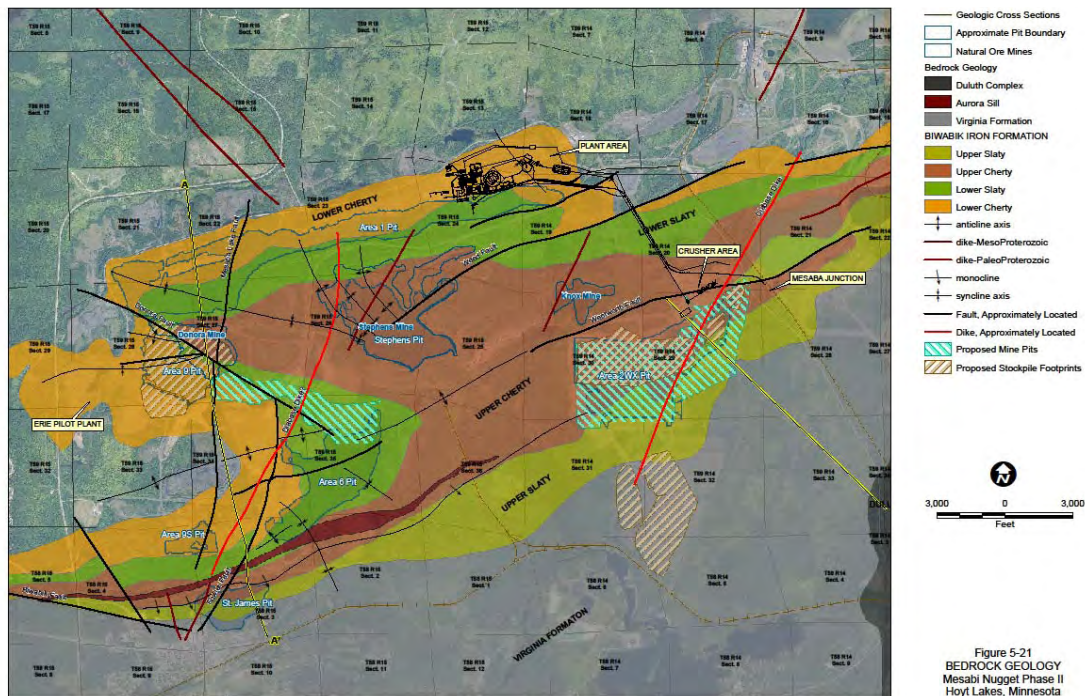


Figure 5-20: Bedrock geology at the Mesabi Nugget project. Note the locations of two cross-sections (shown in yellow) that are portrayed in Figures 5-21 and 5-22.

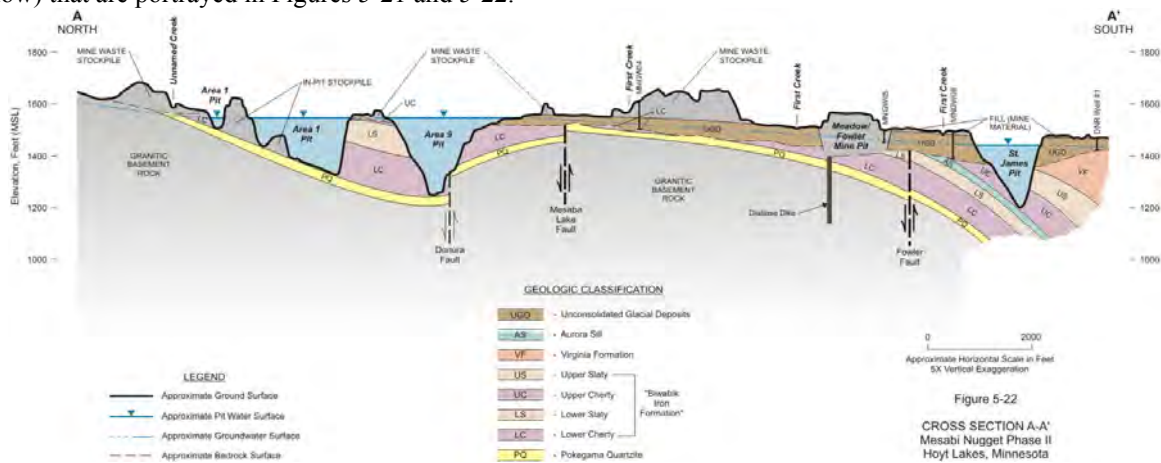


Figure 5-21: Cross-section A-A' at the Mesabi Nugget project.

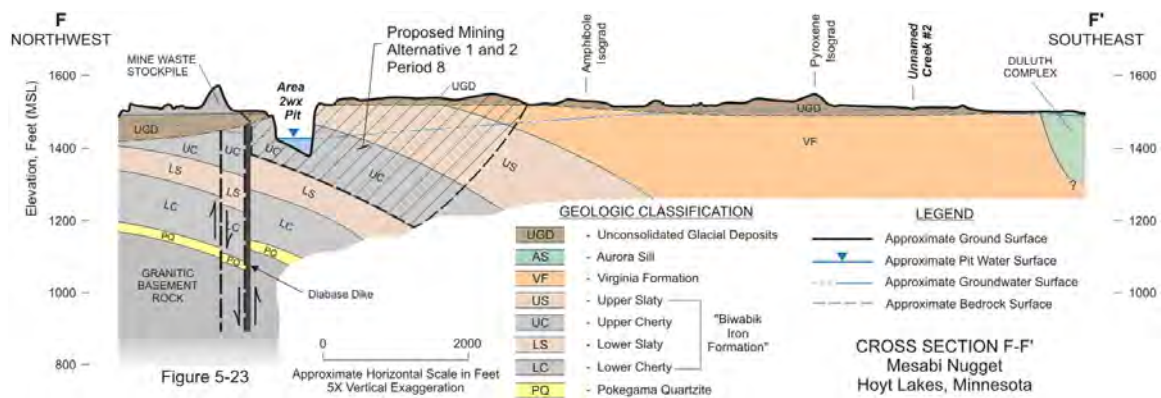


Figure 5-22: Cross-section F-F' at the Mesabi Nugget project.

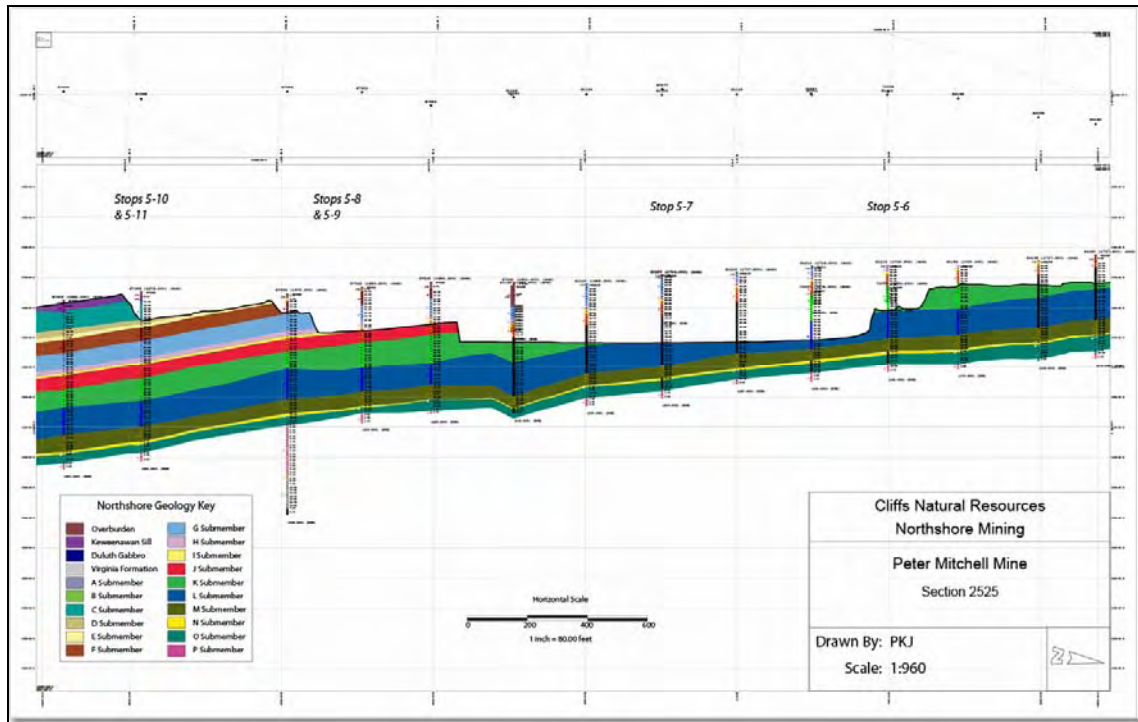


Figure 5-23: Modeled geologic section of Northshore Block 21. Diamond drill hole traces and relative unit thickness are illustrated on the section. The general geology of rocks seen at stops 5-6 through 5-11 is shown.

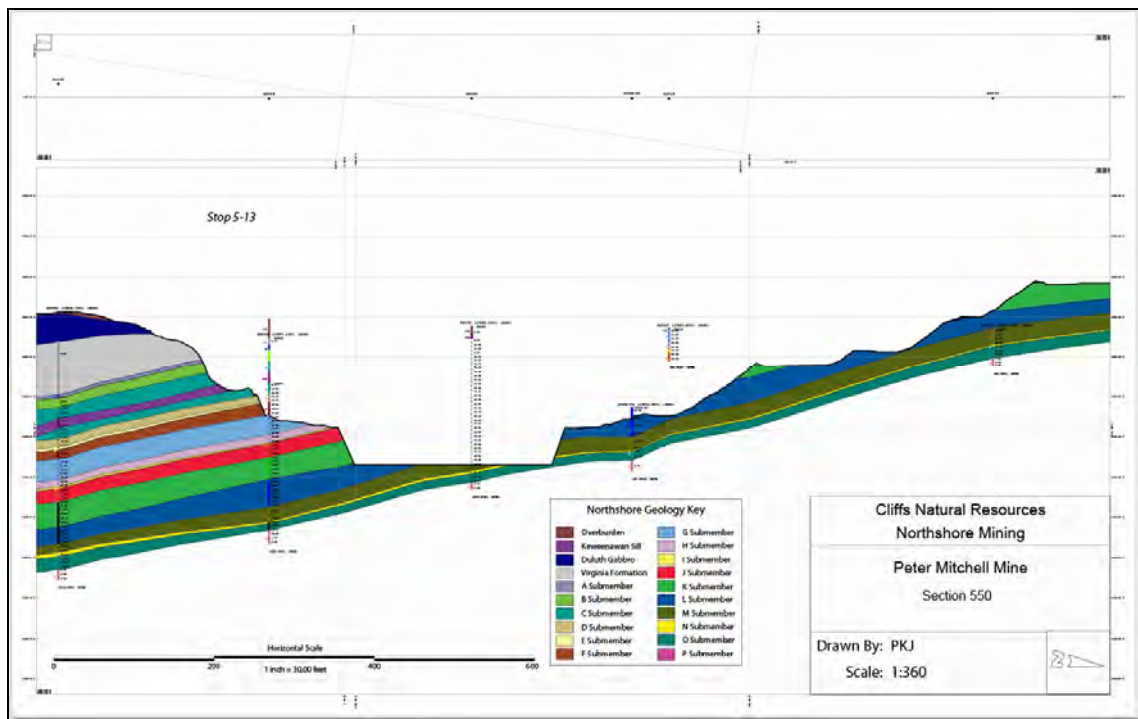


Figure 5-24: Modeled geologic section of Northshore Block 1E. Submember thickness is illustrated on the section. The overlying Virginia Formation (VF) and intruding Duluth Complex (GB) are viewed along the south end of the section.

FIELD TRIP STOPS

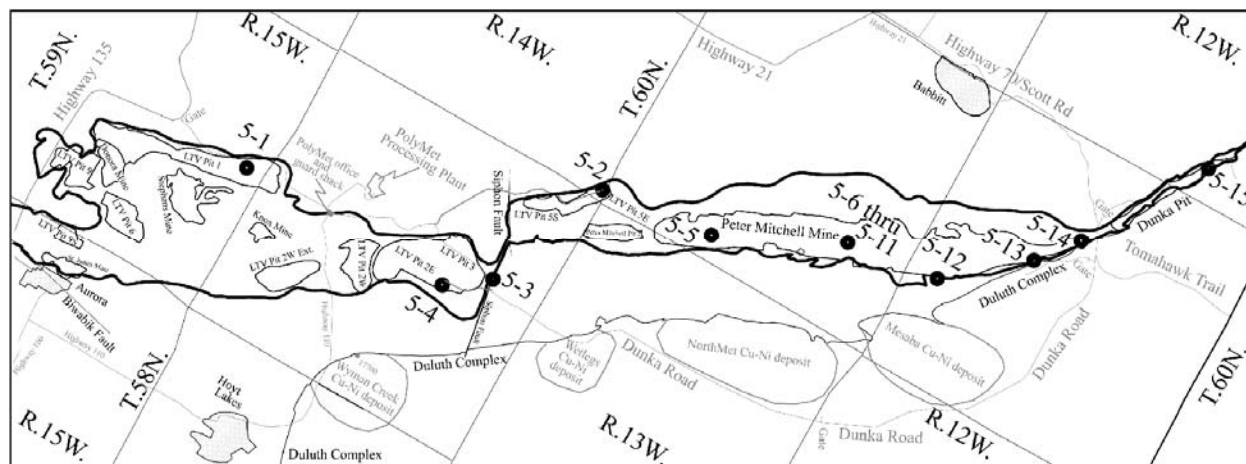


Figure 5-25: Location of field trip stops in the eastern Mesabi Iron Range of northeastern Minnesota. Dark black lines outline the margins of the Biwabik Iron Formation.

DIRECTIONS: Drive south from Ely on highway 21 through Babbitt (take a right at the T intersection at Babbitt) and Embarrass to the Four Corners intersection. Take a left at the intersection and go south on 135 about 5.3 miles to a gated entrance for PolyMet Mining and Mesabi Nugget (also known as the Cliffs-Erie site or old LTV mine). Continue down this private drive about one mile to the construction entrance to the Mesabi Nugget plant and turn right – proceed down this road and check in at the guard shack.

STOP 5-1: Mesabi Nugget Project Site

Location: T. 59 N., R. 15 W., Sections 13 and 24, Allen quadrangle

Description: Steel Dynamics Inc. and Kobe Steel Ltd. have jointly partnered in the Mesabi Nugget Project to construct and operate the world's first large scale Rotary Hearth Furnace (RHF) on the Mesabi Iron Range. The Mesabi Nugget Project is under construction on a portion of the former Erie Mining Company / LTV Steel Mining Company property. The construction site is located on the footwall of the old Area 1 mine site. The ITmk3 RHF technology was developed by Kobe Steel and will be used to produce a domestic supply of high-quality iron nuggets for Steel Dynamics' electric arc furnace facility in Butler, Indiana. The technology will combine iron concentrates and non-coking coal into a simple one-step process that reduces and melts the iron concentrate within the rotary furnace, producing a 97 percent pure iron nugget. The second phase of the project involves permitting and reactivation of several taconite pits adjacent to the construction site to extract iron ore for the nugget process.

The Mesabi Iron Range was initially identified by the first Minnesota State Geologist, Henry Eames, in 1866 at the northeast end of Embarrass Lake, roughly two miles to the west of this project site, at a point where the Biwabik Iron Formation intersected the Embarrass River. The eastern end of the Biwabik Iron Formation was first mapped from Embarrass Lake to Birch Lake by the Minnesota Geological Survey during the years of 1879 and 1881. By 1884 the Duluth & Iron Range Railroad had been built to provide access to the newly discovered Vermilion Iron Range at the southeastern end of Lake Vermilion. The railroad provided access for iron ore shipments from Tower to Lake Superior. The original rail route runs north-south along the eastern boundary of the Mesabi Nugget project site. The Village of Mesaba, shown in Figure 5-21, was the first incorporated community on the Mesabi Range. The village's rail station,

Mesaba Junction, provided a departure point for the early mineral exploration and new arrivals to the region. Today the rail access into the Mesabi Nugget plant intersects the Canadian National rail line near the site of the original Mesaba Junction.

The structural geology and outline of the four informal members of the Biwabik Iron Formation are shown in Figure 5-21 overlying a current aerial photograph of the project area. Four mining areas of the former Erie/LTVSMC comprise the Mesabi Nugget project area: Area 1 to the north, Area 6 & 9 to the west, and Area 2wx to the south. The western mining area is dominated by the northwest striking Donora fault and several northeast trending faults. To the south the Aurora Sill was intruded into the lower portion of the Upper Cherty member and caused a pronounced steepening of the dip in Area 6, as shown in Figure 5-22. The structural complexity of the area has resulted in a diverse and long history of both natural ore and taconite mining. By the early 1900's there were eight underground and open-pit mining operations within the boundary of the Mesabi Nugget project. The early mining operations extracted natural ore from oxidized zones in the Upper Cherty member associated with the fault structures of the region. The prominent mining operations are shown in Figure 5-21. Figure 5-23 is a cross-section through the Area 2wx mining area. It identifies the gently sloping Biwabik Iron Formation, the Wentworth Fault, a diabase dike intersecting Area 2wx, and the Duluth Complex to the south with associated metamorphic isograds.

In the early 1950's Pickands Mather & Co. constructed and operated a taconite pilot plant adjacent to the present Area 9 pit on the western edge of the project area. During the ensuing years Erie Mining Company was constructed to utilize the extensive ore reserves of high grade taconite of the eastern end of the Mesabi Iron Range. Figure 5-19 is a generalized geologic column of the Biwabik Iron Formation in the Aurora area.

NEXT: Return to private drive and proceed approximately 2.5 miles east to the guard shack near the office buildings of PolyMet Mining Corp. After receiving permission to enter the property, go straight and follow this road about 2.3 miles to a T-intersection with Dunka Road (another private company road). Continue north (left) at this intersection and drive about 3.5 miles along various mining company roads to the Pit 5E location. The stratigraphic nomenclature for the Biwabik Iron Formation at the Cliffs-Erie site is presented in Figure 5-19.

STOP 5-2: Lower Cherty and Lower Slaty members

Location: Pit 5E, Cliffs-Erie site, T. 60 N., R. 14 W., sec. 36, SE, SE Allen quadrangle; UTM: 571,040E/5,275,876N (NAD-83)

Description: At this inactive mine pit the entire stratigraphic section of the Lower Cherty and Lower Slaty members can be viewed. Also present at this site are localized exposures of the underlying Pokegama Formation and granitic rocks of the Archean Giants Range Batholith. Both are exposed in the floor of the mine where they are present as several small domal features giving the overall impression of an egg-carton morphology. The Giants Range Batholith at this site is characterized by a porphyritic quartz monzonite that contains an unusual amount of chlorite.

The Lower Cherty member at this site is about 80 feet thick. Most of the units are regular- to medium-bedded and constitute taconite ore. At the bottom of the mine bench, the W submember that is characterized by interfingering conglomerate, algal stromatolite horizons, and pale gray chalcidonic chert bands with quartz-filled syneresis cracks; all three can occur in direct contact with either the underlying Pokegama Formation or granitic rocks of the Giants Range Batholith. The stromatolites are recognized by bright red jasper columns. The conglomerate contains a variety of iron-formation clasts (cherty and

thin-bedded iron carbonate) in a chalcedonic matrix with detrital quartz grains. Above the W submember is the V submember which is typically thin-bedded, locally contains chalcedonic chert bands (up to a few inches thick), and appears to be less than one foot thick. The V submember is not exposed in the mine walls (covered by mining rock debris) but can be found as loose pieces on the mine floor in close proximity the first stromatolite horizon that will be visited. These pieces are typically thin-bedded, non-magnetic, and exhibit fine-scale cross-beds that could be likened to hummocky cross-stratification (HCS).

At the bottom of the mine face is a Regular-Bedded Unit that is correlative with the U submember. A one foot thick imbricated conglomerate is present about three feet above the stromatolite horizon in the U submember. This unit transitions upward into a Wavy-Bedded Unit (the T submember), which in turn, grades upward into the Mottled Unit (submember S). Both are similar in that they exhibit magnetite-rich wavy beds that terminate, bifurcate, and pinch and swell in a semi-random manner. The S submember contains conspicuous iron carbonate mottles (ankerite?) that are pink and <1 cm across. The Wavy-Bedded Unit (submember T) at this locality is identical to all of the other wavy-bedded units at all of the taconite mines in the Mesabi Range. Within the T submember the magnetite is in: 1. the wavy beds, 2. disseminated throughout the cherty bands, and 3. within mottles that are generally less than 1 centimeter in diameter and cored by iron-carbonate. The T submember is about 50 feet-thick and is easily recognized in drill core due to the wavy beds and a salt-and-pepper texture that is defined by disseminated magnetite. Cross-beds are observed in some of the fallen blocks that are associated with this unit. Cross-bedding measurements taken elsewhere (Ojakangas and others, 2005), although not definitive, are suggestive of a tidally-influenced marine environment. This, coupled with Walther's law of succession of sedimentary facies (the facies observed vertically are also similarly related laterally), places the deposition of the iron-formation seaward of the Pokegama Formation.

The Lower Slaty member at this site is 80 feet thick and consists entirely of thin-bedded, weakly to moderately magnetic rock. At the base of the Lower Slaty member is the "Intermediate Slate" which is characterized by thin-bedded, black, organic-rich mudstone that is about five feet thick at this locality. The "Intermediate Slate" is extremely fissile and locally exhibits bright, shiny graphitic surfaces with bedding-parallel slickensides. Pyrite is common to this submember and is present as both disseminated fine- to medium-grained cubes and as thin disks (marcasite/pyrrhotite) along bedding planes. All of the Lower Slaty member constitutes waste rock at this mine.

Note that the name "slate" has been applied to all thin-bedded rocks in the Biwabik Iron Formation, but this term is a misnomer, because these rocks are essentially unmetamorphosed and do not have the cleavage of a true slate but merely a parting parallel to bedding (White, 1954). Morey (1992, 1993) reported that the "Intermediate Slate" possibly contains an ash-fall component. It has the highest Al_2O_3 content of any analyzed sample of the Biwabik Iron Formation.

NEXT: From Stop 5-2, return to the south to the intersection with Dunka Road. Take a left and head east along Dunka Road about 1.8 miles. While continuing to the next stop the bus will go through Pit 3 where ore was mined from the Lower Cherty member. Note that the undulating floor of this pit was exposed during striping by following the bedding trends of one or two bed forms. Imagine that this roll-and-swell topography may mimic the original bedding surface of the unlithified iron-formation as it was deposited in shallow water. After going through Pit 3 the road takes a sharp jog to the south. At this locale, the surface trace Siphon Fault is present along the east side of the road. Iron-formation is present to the west of the road and the Virginia Formation is present across the swamp on the east side of the road. Just before Dunka Road curves back to the east take the immediate left and go down a secondary mining road for about 500 feet. Proceed to the north on foot along a flagged trail to the next stop.

STOP 5-3: Virginia Formation near Siphon fault

No hammering please!

Location: Cliffs-Erie site, T. 59 N., R. 14 W., sec. 26, SE, SE, NE
Allen quadrangle; UTM: 569,505E/5,271,610N (NAD 83)

Description: This is the only natural exposure of the Virginia Formation on the Mesabi Iron Range. Unfortunately, it is only a few feet thick. A total of 1,443 feet of the formation is present in drill cores from holes drilled south of the range. Note the graded beds, mud chips, concretions, and loading at the bases of these beds. The bedding is near vertical in this location due to proximity to the north-trending Siphon fault—an inferred growth fault (Graber, 1993) wherein the iron-formation decreases in thickness to the east (across the fault) by about 100 feet.

NEXT: From Stop 5-3, proceed back to, and angle across Dunka Road to a gated entrance (not locked). Go down this secondary mine road about 0.5 miles. Park and walk about 300 feet to the south.

STOP 5-4: Algal submember (I submember) near the top of the Upper Cherty member

Location: Pit 2E, Cliffs-Erie site, T. 59 N., R. 14 W., sec. 23, N 1/2, NW
Access to this site is via Dunka Road, which is a private mining company road.
Allen quadrangle; UTM: 568,202E/5,2706,25N (NAD 83)

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 member consists of mounds of fossilized algal colonies that are separated by jasper-bearing intraformational conglomerate; the overall thickness of this unit is 2 to 20 feet. This horizon occurs only in the eastern half of the range (not present west of Hibbing). However, there is some ambiguity in the positioning of this unit within the Upper Cherty member. In the Virginia Horn area, this horizon is positioned near the base of the Upper Cherty and can be traced upwards in a series of drill holes (Severson and others, in prep.) to a position near the top of the Upper Cherty near Hibbing (see Fig. 5-17). To the east of the Virginia Horn, the horizon can be traced at the base of the Upper Cherty to a position near Biwabik, MN, where two algal horizons are reported (in drill hole MGS-2 and in the old LTV submember nomenclature). These two horizons occur in the bottom and top of the Upper Cherty member. It is difficult to tell which of these algal horizons is the one that was traced eastward from the Virginia Horn. The lower algal horizon pinches out further east and the upper horizon can be traced as far east as Dunka Pit. The algal horizon that will be visited on this trip occurs near the top of the Upper Cherty member.

This locality is an excellent place to view a nearly horizontal portion of the iron-formation that contains abundant individual mounds of algal stromatolites. Stripping of glacial overburden in this area once revealed a dip slope the size of a football field that contained stromatolite mounds (Graber, 1993). Figure 5-10 illustrates a large portion of that exposure that has since been mined. The present stop is at an area 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° to the vertical; unfortunately, that site has also been removed by mining.

At the extreme eastern edge of this exposure are the J and H submembers. Both of these submembers

contain rare anthraxolite, which is an organic bitumen containing 95 percent or more carbon that is black with a vitreous luster and conchoidal fracture and resembles obsidian (Morey, 1994). Morey (1994) reported that anthraxolite is present throughout the iron-formation but is most common beneath the carbon-rich Intermediate Slate. Furthermore, he suggested it formed via a mechanism of concentrating carbon from a mass-kill phenomenon, followed by later migration of a carbon-rich liquid to form the anthraxolite.

NEXT: Return to Dunka Road and proceed eastward about 14.6 miles (through a locked gate about midway down the road) to the entrance and guard shack of the Peter Mitchell Mine. After receiving permission to enter the property, proceed down the road to the offices of Northshore Mining. The next ten stops are on the mine property. The stratigraphic nomenclature of submembers in the Peter Mitchell Mine is portrayed on Figure 5-20.

STOP 5-5: Submembers I and G (and lunch)

Location: Peter Mitchell Mine, Block 35, T.60N, R.13W., Section 33
Babbitt quadrangle; UTM 574,773E/5,276,403 (NAD-83)

Description: This site was chosen as an excellent area to collect unique garnets, up to several inches across, from the G submember (located at the top of the mine bench) and to take another look at the I submember (exposed at the base of the bench near the water). At this locale, the I submember is 3-5 feet thick and consists almost entirely of intraformational conglomerate, often with bright red jasper clasts, and rare algal stromatolites. The G submember contains coarse-grained, brown to brown-red, euhedral andradite garnet. The garnets occur as single crystals and as clusters of crystals. Both exhibit dodecahedral forms – especially when associated with patches that are rich in calcite, quartz, and actinolite.

NEXT: The following series of stops offer a review of several submembers of the Upper Slaty and Upper Cherty members. The samples examined to date from these stops exhibit middle to upper greenschist facies metamorphism based on the identified gangue mineralogy. Thin sections reveal gangue mineralogy mostly consisting of quartz-cummingtonite-grunerite. Reflected light studies of ore from these stops indicate a wide range of magnetite grain size and liberation characteristics, which are important parameters for ore grading and classifying. It is important to note that rocks from most of these stops are lower metamorphic grade when compared to the metamorphic grades in the extreme northeast end of the Peter Mitchell Mine and Dunka Pit.

STOP 5-6: Submembers K and L

Location: Peter Mitchell Mine, Block 21, T. 60 N., R. 13 W., sec. 26, NE, NW
Babbitt quadrangle; 578,337E/5,278,665N (NAD-83)

Description: Both the K and L submembers of the Upper Cherty member constitute taconite ore. Both are wavy-bedded and contain isolated black chert intraclasts. The K submember is slightly different in that the wavy beds are thinner and more closely-spaced than the wavy beds of the L submember.

Petrographic review 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 assemblages of euhedral grains ranging up to 200 microns in diameter. The assemblages are randomly distributed within the matrix; however, diffuse bands of magnetite assemblages are observed. X-ray 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 5-7: Submembers I, J, and K (all constitute taconite ore)

Location: Peter Mitchell Mine, Block 21, T.60N., R.13W., section 24, S ½, NE Babbitt Quadrangle; UTM 578,505E/5,278,416N (NAD-83)

Description: Submember K (described above), as well as, submembers J and I, are viewed at this site. The I submember is present at the top of the mine bench but can be readily spotted in loose pieces in the floor of the mine where it is distinguished by: 1. pink coloration; 2. conglomeratic nature; and 3. the presence of ribbon-like stringers of quartz veins that parallel bedding. Metamorphism is higher in this area relative to the previous stops and the I submember does not display the striking algal features, but rather a more “washed-out” appearance. The J submember is typically regular-bedded to weakly wavy-bedded with close-spaced magnetite-rich beds. A northeast-trending fault is present in this area and is characterized by chloritic breccia. Some weak oxidation (brown-stained zones) is associated with the fault; however, these zones are still strongly magnetic.

STOP 5-8: Submembers G, H, and I (all constitute taconite ore)

Location: Peter Mitchell Mine, Block 21, T.60N., R.13W., Section 24, N ½, NE Babbitt Quadrangle; UTM 578,617E/5,278,464N (NAD-83)

Stay away from the steep wall (loose blocks above)!

Description: Submember H at this location displays thin-bedded to weakly wavy-bedded quartz taconite with abundant magnetite. Along with large accumulations of magnetite, a gangue assemblage of quartz-grunerite-ferroactinolite is also displayed within the exposure. The top of the H can host a thin (~1 foot) intraformational conglomerate that separates the H and G submembers (not seen at this location). This feature can be used to map the contact between the Upper Slaty and Upper Cherty members. Note that Gundersen and Schwartz (1962) interpret the G submember as occurring in bottom of the Upper Slaty; whereas the G submember is considered to be at the top of the Upper Cherty at the Cliffs-Erie site and Dunka Pit mine (Figure 5-19). The G submember differs from H in that it is wavy-bedded and contains lensoidal chert bands that often exhibit bulb-shaped pinch-and-swell margins.

Reflected light analysis of this exposure displays well-defined bands of coarse magnetite (>50 microns), which also follow the wavy bedded nature of the iron formation typically associated with the H submember. The I submember is subtly noticed as you walk to the north and displays several examples of jasper-bearing algal quartz taconite. Magnetite grains range between fine (<5 microns) and coarse (> 50 microns) mostly occurring as disseminations within the matrix of the unit. Both submembers are typically classified as ore at the Peter Mitchell Mine.

Within the G submember, medium to coarse-grained andradite is observed. Bedding in the G submember

is significantly thicker than other submembers at the Peter Mitchell Mine and shows well-developed pinch and swell characteristics.

STOP 5-9: Submembers F (waste at this site but ore to the east) and G (taconite ore)

Location: Peter Mitchell Mine, Block 21, T.60N., R.13W, Section 24, NE, NE Babbitt Quadrangle; UTM 578,818E/5,278,516N (NAD-83)

Description: The F and G submembers of the geologic section at the Peter Mitchell mine can be viewed at this stop. The G submember is described above. The F submember typically consists of alternating magnetite-rich, thin-bedded sets, and thicker-bedded cherty sets (alternating bedding of Figure 5-13). Locally present in the F submember are small septaria-like structures, or syneresis cracks, that consist of whitish quartz-filled subvertical circular and radial fractures in the granular cherty layers. As can be seen at this location, contacts between submembers are typically gradational and are best determined in drill core where changes in bedding characteristics and mineralogy can be readily observed.

The F submember can contain appreciable magnetite; however, it is typically classified as waste due to the fine grain size making it difficult to liberate the iron. Magnetite grains observed under reflected light range between <5 microns to 50+ microns in submember F while analysis of submember G identifies a coarser magnetite grain size range of 10 – 50+ microns occurring in easy-to-liberate assemblages.

Further micro-examination of the F and G at this location confirm the presence of quartz and ferroactinolite, while common gangue minerals can also include the andradite, cummingtonite, and hedenbergite. At this location in particular, thin zones of cummingtonite crystal growth interrupt the thicker cherty beds within the iron formation.

STOP 5-10: Submembers C and D (waste)

Location: Peter Mitchell Mine, Block 21, T.60N., R.13W, Section 24, S1/2, NE Babbitt Quadrangle; UTM 578,681E/5,278,133N (NAD-83)

Description: The contact between submembers C and D of the Upper Slaty member can be viewed at this location. Both the C and D submembers are thin-bedded units of the Upper Slaty member; however, the D submember is different in that it contains slightly thicker beds and lenses of chert. A 20-foot-thick Keweenawan sill is also present near this stop (see Stop 5-11) and is positioned towards the top of the C submember.

Petrographic review of samples from this area display minor magnetite with a gangue mineralogy of cummingtonite-grunerite series amphiboles as well as cordierite and ferroactinolite. The C submember also contains magnetite, fayalite, ferropseudobrookite, and chert. X-ray analysis of submember D at this location indicates gangue mineralogy of quartz, cummingtonite, and hedenbergite.

Magnetite, although scarce in the C submember, is fine-grained (5-10 microns) and confined to fractures and open-spaces within the matrix of the recrystallized slaty beds. Magnetite grains identified within the D submember are very-fine grained (~5 microns) and disseminated within the quartz-rich matrix of the rock. The C and D submembers are typically categorized as waste based mostly on low magnetic iron values, however, high phosphorous concentrations measured within both submembers also limits them as waste.

STOP 5-11: Keweenawan Sill in the C submember

Location: Peter Mitchell Mine, Block 21, T.60N., R.13W, Section 24, N1/2, SE Babbitt Quadrangle; UTM 578,702E/5,278,080N (NAD-83)

Description: A 2- to 18-foot-thick sill is present towards the top of the C submember across most of the strike length of the Peter Mitchell Mine and Dunka Pit. A sill with identical chemistry and textures is present within the J submember much further to the west in Pit 2E at the Cliffs-Erie Site (Severson and Hauck, 1997). The sill at this locality, informally referred to as the BIFSill or C-Sill, is generally fine- to medium-grained with locally very coarse-grained plagioclase phenocrysts and vertical columnar jointing. A granoblastic texture is evident in thin-section, indicating that the sill was emplaced in the early Keweenawan and was later metamorphosed by intrusion of the Duluth Complex. Hauck and others (1997) noted that the BIFSill is chemically similar to the Logan sills to the northeast in the Rove Formation, and have informally called this sill a "Logan-type" sill.

X-ray diffraction data collected from samples of the sill at this site yield a mineral assemblage of quartz-albite-actinolite-antigorite-illite with magnetite. In reflected light, magnetite is abundant and occurs as randomly oriented lath-shaped crystals believed to represent the pseudomorphic replacement of pre-existing ilmenite crystals by magnetite.

STOP 5-12: Keweenawan Sill (in the Virginia Formation) and A and B submembers

Location: Peter Mitchell Mine, Block 11, T.60N., R.12W, Section 19, SW, SE Babbitt Quadrangle; UTM 581,691E/5,278,881N (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 half of the Mesabi 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. Magnetite grains are scarce within these beds and are very fine grained when present.

At the very base of the 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 and others (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, but this sill is decidedly different than the BIFSill and age dates are needed for both of these sills.

STOP 5-13: Duluth Complex and metamorphosed Virginia Formation (optional)

Location: Peter Mitchell Mine, Block 0, T.60N., R.12W, Section 16, SW, SW

Babbitt Quadrangle; UTM 584,266E/5,280,874N (NAD-83)

Description: In close proximity to the Duluth Complex, the well-bedded sediments of the Virginia Formation are typically transformed into a rock that at first appearance looks like an intrusive rock due to the presence of randomly oriented biotite. This rock is informally referred to as the "recrystallized unit," but is more properly classed as a diatexite (Sawyer, 1999). During emplacement of the Duluth Complex, the sediments of the Virginia Formation were heated, generating 20 to 40 percent pervasive partial melts, that enabled these rocks to literally flow in response to stresses that were applied during emplacement. All bedding planes are obliterated and what remains is a medium-grained recrystallized rock that contains plagioclase, cordierite, orthopyroxene, and randomly oriented biotite. Within this recrystallized matrix are blocks/boudins of more structurally competent siltstone and calc-silicate hornfels (originally limey layers).

Also at this locality are gabbroic rocks at the basal contact of the South Kawishiwi intrusion. The rocks exposed at this stop consist of weakly to moderately mineralized, fine- to medium-grained, ophitic augite troctolite to olivine gabbro. Copper-nickel values are unknown for this exposure.

As you walk to this site you will notice numerous blasted blocks of the C submember with shiny dark green faces along bedding planes and on joint faces. This coating is an iron silicate known as hisingerite ($\text{Fe}^{3+}_2\text{Si}_2\text{O}_5(\text{OH})_4\cdot 2\text{H}_2\text{O}$). Also present are blasted blocks with coarse-grained magnetite, and coarse-grained pyroxene that has grown along bedding planes during metamorphism by the Duluth Complex.

STOP 5-14: Submembers F-P (Blasted Rock)

Location: Peter Mitchell Mine, Block 3E-4E, T.60N., R.12W., Section 9, SW, SE
Babbitt Quadrangle; UTM 5282276N, 585022E (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, garnets, and coarse grained granular magnetite. The F and G submembers in this area of the pit are hard to distinguish in drill core and in broken form because the original bedding textures, primarily in the F, have been overprinted or altered by recrystallization of the iron formation. In situ, and in blasted form, the presence of red to brown-red garnet, which is abundant in the G, is the best indicator to use in distinguishing between the two submembers. The I submember in this area is a 1' to 2.5' thick quartzite conglomerate retaining no stromatolite textures due to overprinting caused by the intense recrystallization of the chert. In the J through M submembers little has changed with the banding characteristics of the magnetite allowing the submembers to be readily identified in the field. The biggest change seen 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 in part be explained by a decrease in the average thickness seen in the chert bands separating the magnetite bands. This gives each submember an overall condensed appearance as the magnetite bands become more closely spaced. The O and P submembers can be tough to identify in drill core and in the field due to their rather massive appearance. The best indicator to distinguish the two units is the abundant disseminated granular magnetite which occurs in the O.

NEXT: Leave the Peter Mitchell Mine and return to Dunka Road. Take a left after the guard shack and cross the Tomahawk Trail. Continue north to a locked gate (permission is needed to enter) and follow several mining roads to the next stop.

STOP 5-15: Dunka Pit (Optional)

Location: Dunka Pit T. 61 N., R. 12 W., section. 35, SE, NW
Babbitt NE quadrangle; UTM 587,337E/5,286,348N (NAD-83)

Description: At the extreme north end of the pit, the iron-formation is in fault contact with the Duluth Complex. The fault is near-vertical, north-trending, and juxtaposes iron-formation, west of the fault, against gabbroic rocks of the South Kawishiwi intrusion (SKI) to the east of the fault. The age of the fault is not easily determined, but faulting appears to have been initiated before emplacement of the SKI. In the immediate area of the fault, a westward change in the character of the iron-formation is obvious over a 20-25 foot wide zone. This change consists of well-bedded iron-formation grading into a banded plagioclase-magnetite rock, that in turn, grades into a troctolitic rock with magnetite lenses. Emplacement of the SKI induced upper-greenschist to middle-amphibolite facies metamorphism of the iron-formation resulting in coarse grain sizes that can be viewed within both ore and gangue minerals.

To the immediate west of the fault, the iron-formation contains high amounts of titanium due to the metasomatic transfer of Ti across the fault (Muhich, 1993). Due to its high titanium content, which is detrimental to making steel, the iron-formation immediately adjacent to the fault was discarded during mining.

END OF TRIP (return to Ely)

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55th Annual Institute on Lake Superior Geology

Field Trip 6

GEOLOGY OF THE LAKE ONE TROCTOLITE BY CANOE



Jim Miller (Department of Geological Sciences, UMD)

FIELD TRIP 6

GEOLOGY OF THE LAKE ONE TROCTOLITE (BY CANOE) NORTHWESTERN DULUTH COMPLEX

Jim Miller (University of Minnesota Duluth)

INTRODUCTION

The Duluth Complex and associated Keweenawan intrusions in northeastern Minnesota constitute one of the largest mafic intrusive complexes in the world, second only to the Bushveld Complex of South Africa. These rocks cover an arcuate area of over 5,000 km² (Fig. 6-1) and give rise to two strong gravity anomalies (+50 & +70 mgal) that imply intrusive roots to more than 13 kilometers depth (Allen and others, 1997). The intrusive rocks of northeastern Minnesota were emplaced into a comagmatic volcanic edifice during formation of the Midcontinent Rift between 1108 and 1095 Ma (Paces and Miller, 1993).

The Duluth Complex is physically defined as a more or less continuous mass of mafic to felsic plutonic rocks that extends in an arcuate fashion from Duluth to nearly Grand Portage (Fig. 6-1). It is bounded by a footwall of predominantly Paleoproterozoic and Archean rocks, a hanging wall of largely mafic volcanic rocks and hypabyssal intrusions, and internally, it contains scattered bodies of strongly recrystallized mafic volcanic and sedimentary hornfels. Defining the Duluth Complex more genetically, it is composed of multiple discrete intrusions of mafic to felsic tholeiitic magmas that were episodically emplaced into the base of a comagmatic volcanic edifice in two general stages - an early stage at about 1108 Ma and a main stage at 1099 Ma. Within the Duluth Complex, four general rock series are distinguished on the basis of age, dominant lithology, internal structure, and structural position.

Felsic Series – massive granophyric granite and smaller amounts of intermediate rock that occurs as a semi-continuous mass of intrusions strung along the eastern and central roof zone of the complex and was emplaced during early stage magmatism (~1108 Ma).

Early Gabbro Series – layered sequences of dominantly gabbroic cumulates that occur in two major intrusions along the northeastern contact of the Duluth Complex and were also emplaced during early stage magmatism (~1108 Ma)

Anorthositic Series – a structurally complex suite of foliated, but rarely layered, plagioclase-rich gabbroic cumulates that was emplaced throughout the complex during main stage magmatism (~1099 Ma).

Layered Series – a suite of stratiform troctolitic to ferrogabbroic cumulates that comprise at least 11 variably-differentiated mafic layered intrusions and occurs mostly along the base of the Duluth Complex. These intrusions were emplaced during main stage magmatism, but generally after the anorthositic series.

The Lake One troctolite refers to layered series rocks that occur along the base of the Duluth Complex in the Lake One area (Fig. 6-1). In contrast to most other layered series bodies, it is not designated as an “intrusion” because its eastern extent is not known because of inadequate mapping in the heart of the Boundary Waters Canoe Area (BWCA).

This trip will focus on three general aspects of the geology of the Lake One Troctolite: 1) the contact relationships between the Lake One troctolite and Archean rocks of the footwall and anorthositic series of the hanging wall; 2) the general lithostratigraphic variations in through the troctolite and 3) the characteristics of large volcanic hornfels inclusions within the troctolite. The descriptions of the Lake

One troctolite that follow are based largely on field mapping conducted in 1981, 1982, and 1984 as part of my PhD dissertation (Miller, 1986).

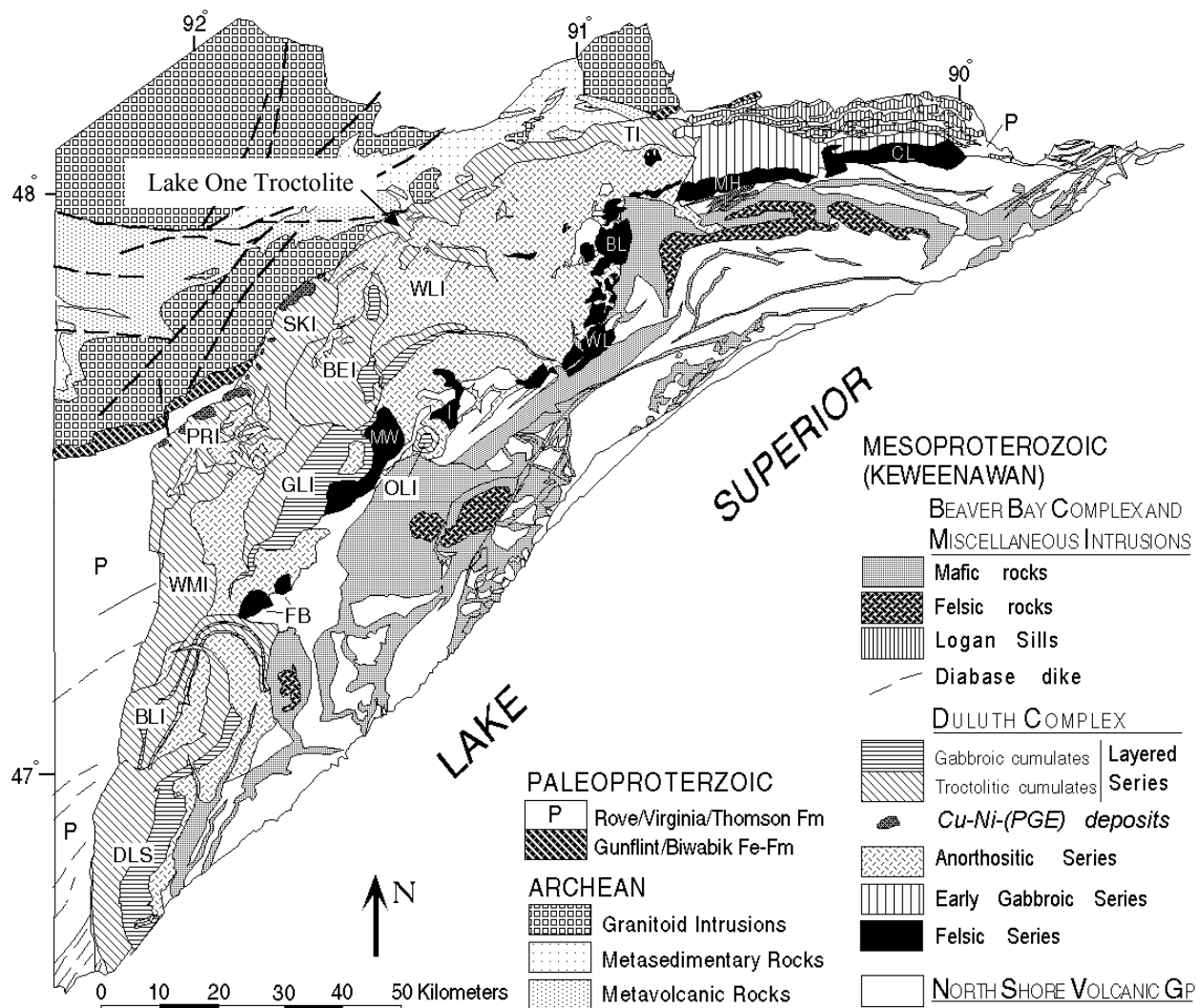


Figure 6-1. Generalized geology of the Duluth Complex and related Keweenaw rocks of northeastern Minnesota highlighting the location of the Lake One Troctolite. Other layered series intrusions are: TI – Tuscarora intrusion, WLI – Wilder Lake intrusion, SKI – South Kawishiwi intrusion, BEI – Bald Eagle intrusion, PRI – Partridge River intrusion, GLI – Greenwood Lake intrusion, OSI – Osier Lake intrusion, WMI – Western Margin intrusion, BLI – Boulder Lake intrusion, DLS – Layered Series at Duluth. Felsic Series intrusions are: CL – Cucumber Lake granophyre, MH – Misquah Hills granophyre, BL – Beth Lake granophyre (and Wine Lake monzodiorite), WL – Whitefish Lake granophyre, I – Isabella granophyre, MW – Mt. Weber granophyre, and FB – Fairbanks/Brimson granophyres. Geology modified from MGS Misc. Map M-119 (Miller et al., 2001).

PREVIOUS STUDIES OF THE LAKE ONE TROCTOLITE

The geology of the northwestern Duluth Complex was first examined during the early state geological survey conducted from 1875 – 1901. In the fourth volume of the final report, Winchell (1899) accurately showed the contact between gabbroic rocks and older greenstone, metasedimentary rocks, and granite in the Lake One-Snowbank Lake area (Chapter XXII, Winchell, 1899, p. 420). After the discovery of Cu-

Ni mineralization in the Spruce Road area of the basal Duluth Complex in 1948, exploration activity ensued all along the basal contact of the complex, including the Lake One area.

William Phinney (University of Minnesota), who was responsible for mapping most of the Duluth Complex in the Gabbro Lake 15' quadrangle in the early 1960's (Green et al., 1966), continued reconnaissance mapping to the east in the late 1960's into what is now the BWCA. Although geologic mapping in this area was conducted entirely by canoe, Phinney

+ was able to cover considerable ground with the aid of floatplane access to areas deep within the wilderness. (The present strict restrictions on motorized vehicles within the BWCA, which was established in 1978, make such easy access impossible today.) From 1966 to 1970, Phinney reconnaissance mapped parts of nine 7.5' quadrangles in that four year period: Snowbank Lake, Quagda Lake, Isabella Lake, and Lake Insula (all part of the Forest Center 15' quadrangle), Alice Lake, Lake Polly, Ensign Lake East, and Kekekabic Lake (Fig. 6-2). Unfortunately, no published or open file maps were produced from this effort. Rather, the only documentation of this mapping is a small figure included in Phinney's (1972) article on the northwestern part of the Duluth Complex contained in the Geology of Minnesota Centennial Volume (Fig. 6-2).

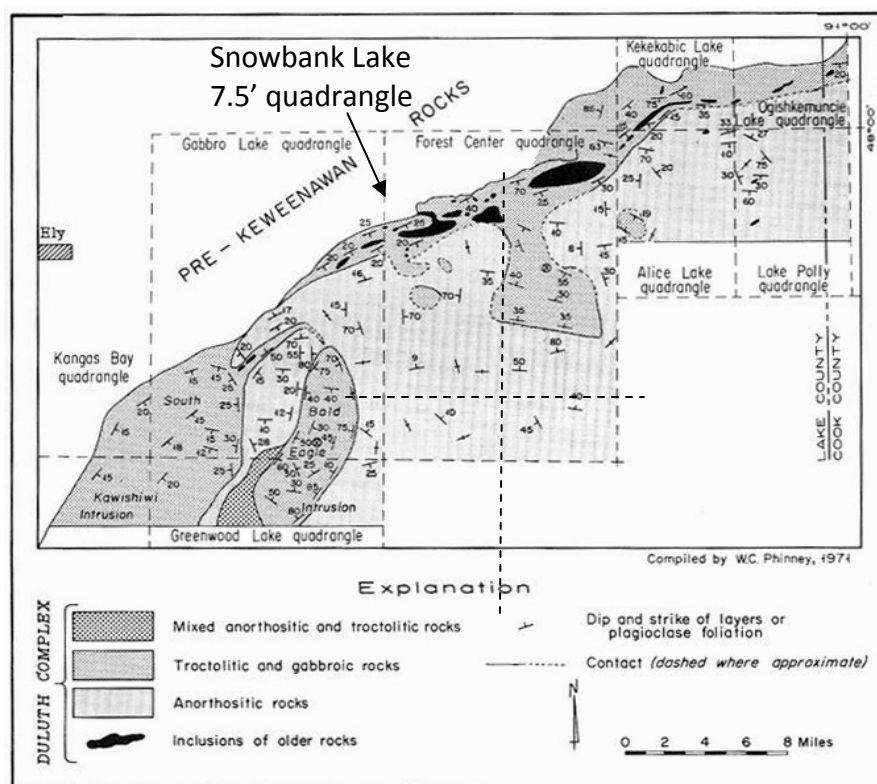


Figure 6-2. Generalized geology of the northwestern part of the Duluth Complex from detailed mapping in the Gabbro Lake 15' quadrangle (Green et al., 1966) and reconnaissance mapping elsewhere. Figure from Phinney (1972, figure V-26).

Detailed mapping the southern half of the Snowbank Lake quadrangle (NW quad of the Forest Center 15') was conducted by the author for his PhD dissertation (Miller, 1986). Although most of the mapping focused on the anorthositic series rocks in the quadrangle, the troctolitic rocks exposed between the basal contact and the anorthositic series hanging wall in the Lake One and Lake Two areas was also mapped in detail. This mapping showed the presence of a multiply emplaced suite of troctolitic cumulates centered

on Lake One, which were referred to as the Lake One troctolite in the thesis and in a subsequent paper written from the thesis research on the anorthositic series rocks (Miller and Weiblen, 1990). Although generally troctolitic rocks extend along the basal contact from the Lake One area to nearly the Gunflint Trail, it is not clear whether this is one continuous intrusion or several discrete bodies.

ROCK NOMENCLATURE

Rock names used in this guidebook will follow the modal rock classification scheme recommended by Miller, Severson, and Green (2002) and shown in Figure 6-3. The modal rock names will also commonly be modified with textural terms that indicate the general grain size and the intergrowth relationship between clinopyroxene and plagioclase, namely ophitic (pyroxene oikocrysts enclose many plagioclase chadacrysts), subophitic (pyroxene encloses only a few plagioclase), and intergranular (pyroxene and plagioclase are both anhedral to subhedral granular). The rock terms may also be modified to indicate the presence of minor or accessory mineral phases (e.g., biotitic, apatitic, olivine-bearing, ...).

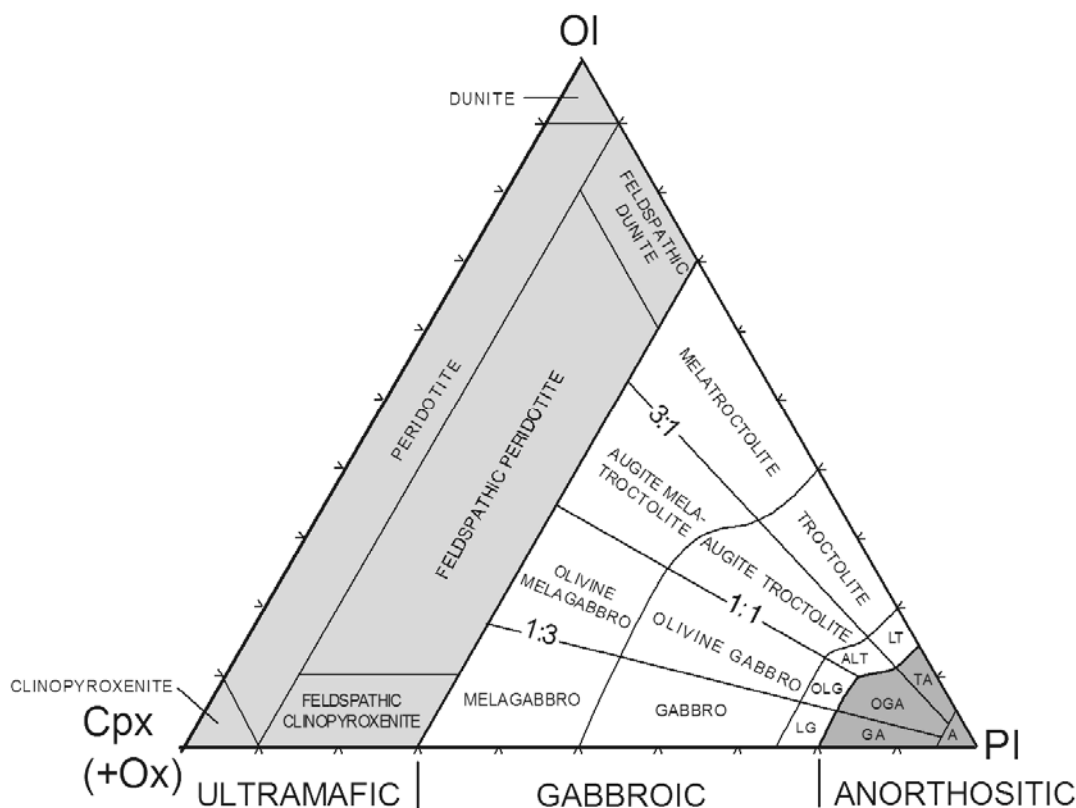


Figure 6-3. Modal classification scheme for gabbroic rocks of the Duluth Complex based on modal proportions of plagioclase (Pl), olivine (Ol), and clinopyroxene + Fe-Ti oxide (Cpx+Ox) (from Miller et al., 2002). Rock type abbreviations at the plagioclase-rich end are: LT – leucotroctolite, ALT – augite leucotroctolite, OLG – olivine leucogabbro, LG – leucogabbro, GA – gabbroic anorthosite, OGA – olivine gabbroic anorthosite, TA – troctolitic anorthosite, A – anorthosite.

An alternative, short-hand rock classification scheme is used here that incorporates both the mode and textures of the major minerals into a rock code. Basically, the scheme lists the minerals above 2 modal % in decreasing order of abundance. Uppercase abbreviations indicate a granular habit and lowercase abbreviations indicate an intergranular habit. This scheme is outlined in Table 6-1. Although based on non-genetic descriptions of mode and texture, one can interpret the rock code in terms of a cumulate rock

type whereby granular minerals may be inferred to be cumulus and intergranular minerals may be interpreted to be intercumulus.

Table 6-1. “Cumulate” Classification Scheme

Granular (Cumulus) / Interstitial (Intercumulus) Mineral Codes

PP*/P/p- plagioclase	F/f	- Fe-Ti oxide
O/o - olivine	A/a	- apatite
C/c - clinopyroxene (augite)	—/b	- biotite
I/i - inverted pigeonite	—/α	- amphibole
H/h - hypersthene, bronzite	—/g	- granophyre

** used with anorthositic group rocks*

Cumulate Code Translation of Some Common Rock Types in the Duluth Complex

Ophitic augite troctolite	POcf
Augite-bearing oxide troctolite	POFc
Olivine gabbroic anorthosite with poikilitic olivine	PPoc
Ophitic olivine gabbro	PcOf
Biotitic, feldspathic dunite with poikilitic plagioclase	Opb
Intergranular, apatitic oxide olivine gabbro	PCFOA
Ophitic biotitic augite leucotroctolite	POcb

ARCHEAN FOOTWALL ROCKS

The footwall of the Lake One troctolite in the Snowbank Lake quadrangle is composed of a variety of Archean rocks including granite, greenstone, and metasedimentary rocks (Gruner, 1941; Sims, 1985; Jirsa and Miller, 2004). In the Lake One area, the basal contact projects across the northern channel of Lake One where it outflows into the Kawishiwi River (Fig. 6-4). Along this stretch, calc-alkaline to tholeiitic metavolcanic and metavolcaniclastic rocks with a strong east-west penetrative foliation occur. These units have been interpreted to belong to the upper member of the Ely Greenstone (units Aeu and Aec, Fig. 6-4). Younger metasedimentary rocks including conglomerates, arkosic sandstones and siltstone of the Knife Lake Group lie unconformable on the Ely Greenstone units (unit Akc, Fig. 6-4) and are interpreted to be Timiskiming-equivalent sediments (Jirsa and Miller, 2004).

Another major feature of the footwall is the east-west-trending North Kawishiwi fault, which is a major splay of the regional transpressional Vermilion Fault system. The fault projects at an acute angle into the base of the Duluth Complex in the northern Lake One area (Fig. 6-4). That the fault appears to merge into the basal contact and does not obviously cut the Duluth Complex suggests that it may have been reactivated during emplacement of the Duluth Complex and thus controlled the shape of the basal contact.

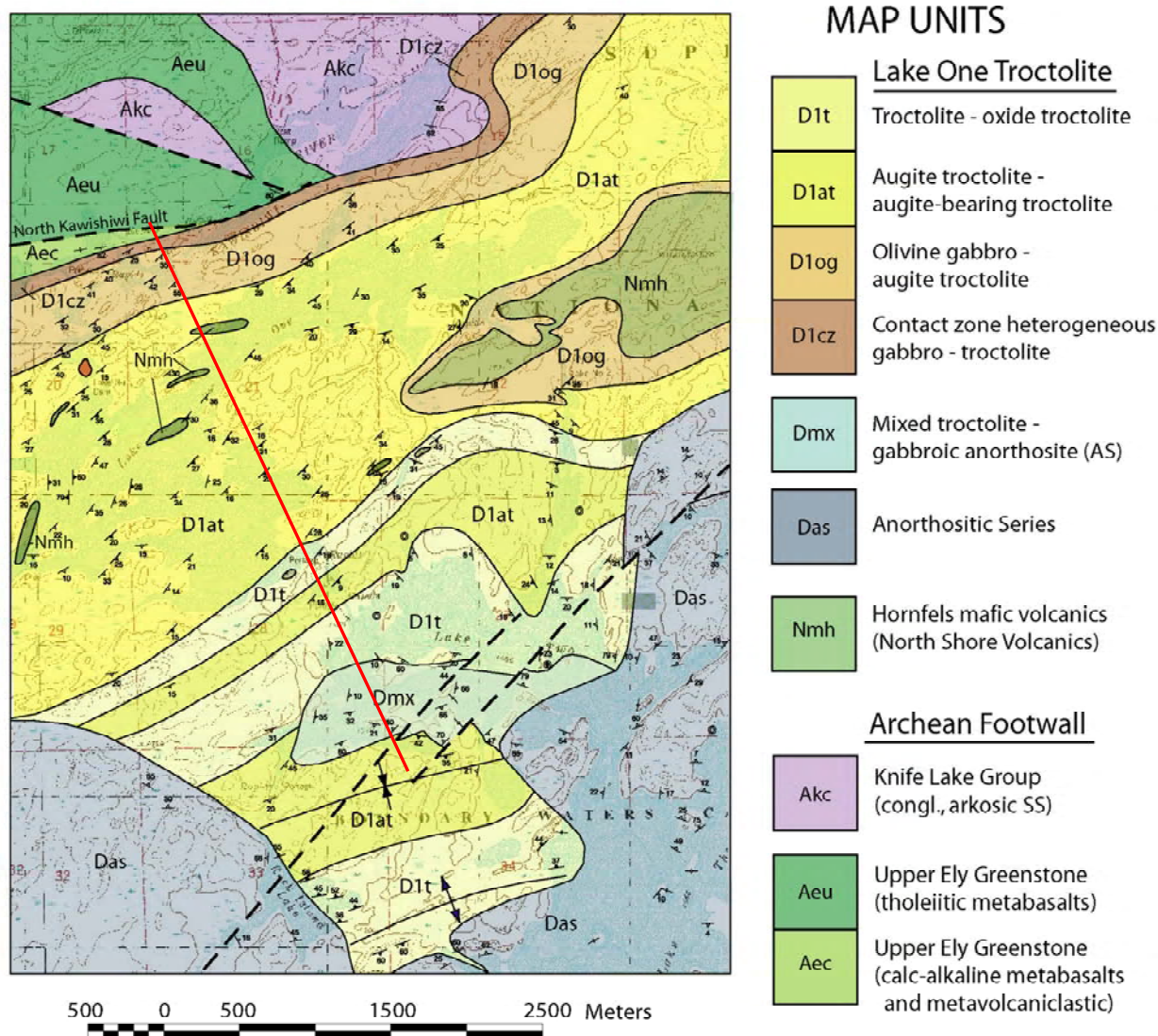


Figure 6-4. Geology of the Lake One troctolite in part of the Snowbank Lake quadrangle (after Miller, 1986). Geology of the Archean footwall taken from Jirsa and Miller (2004). The red line shows the approximate profile line along which the stratigraphic column in Figure 6-6 is constructed.

ANORTHOSITIC SERIES

The hanging wall of the Lake One troctolite is composed of various plagioclase-rich rock types of the anorthositic series. The contact between the troctolitic rocks and the anorthositic series is very irregular in shape and in character (Fig. 6-4). In the Snowbank Lake quadrangle, the contact curves southeast to Rock Island Lake and the western shore of Lake Three and then irregularly back to the north through Lake Two. From Lake Two, it curves to the east and more or less parallels the basal contact. Despite the irregular shape of the contact, the troctolitic rocks consistently strike to the northeast (i.e., roughly parallel to the basal contact) and dip to the southeast, except in the Rock Island Lake area where the dip locally reverses to the north to define a synform/antiform structure (Fig. 6-4). Where the contact between the Lake One troctolite and the anorthositic series is structurally disconformable, the change in lithology is abrupt but the two rocks are rarely observed to be in contact. This suggests possible fault contacts, especially in places where the troctolite strikes at high angles to the inferred contact. However, in a few places where the contact can be approximated to within a several meters, troctolitic rocks are observed to

be somewhat finer grained, nonfoliated and hosting scattered anorthosite inclusions, thus implying an intrusive contact. In one area of Lake Two, contacts are marked by zones of troctolite with abundant anorthosite inclusions (unit Dmx, Fig. 6-4). And in another area of Lake Two where the internal structure of the troctolite is semi-conformable to the contact, a more gradational contact relationship is observed. The anorthositic series of the Duluth Complex is composed of a structurally complex suite of medium- to coarse-grained, variably foliated, plagioclase-rich cumulates that occurs over the entire breadth of the complex from the western edge of the Poplar Lake intrusion of the early gabbro series to the southern terminus of the Duluth Complex at Duluth (Fig. 6-1). Over the entire exposure area of the anorthositic series, its lithologic character, internal structural, and contact relationships with adjacent rocks remain fundamentally constant. This is also true of its age of emplacement as two anorthositic series rocks from different parts of the complex have nearly identical U-Pb ages - 1099.1 ± 0.6 Ma and 1099.3 ± 0.6 Ma (Paces and Miller, 1993).

The average rock type of the anorthositic series is an altered, coarse-grained, moderately foliated, ophitic olivine leucogabbro composed of about 80% plagioclase. With the exception of some occurrences of granular olivine in sub-cotectic abundance, subhedral to euhedral plagioclase is the only cumulus phase in these rocks. An average rock type is somewhat misleading, however, since lithologic variability on a small (outcrop) scale is a ubiquitous feature of the anorthositic series (Miller and Weiblen, 1990). The range of the anorthositic series rock types results from variations in plagioclase mode from 70-99%; mafic mineral proportions; olivine texture from granular to poikilitic (oikocrysts up to 15 cm across); grain size from medium to very coarse; and abundance of felsic mesostasis up to 20%. Moreover, moderate to nearly complete hydrothermal alteration of olivine, pyroxene and, to a lesser degree, plagioclase is evident in many anorthositic series rocks.

Despite variations in texture and modal mineralogy and the complex zoning of individual crystals, one consistent feature of anorthositic series rocks is the constancy of average plagioclase compositions (An₆₅₋₆₂; Miller and Weiblen, 1990). This constant An content contrasts markedly with considerable variability in the mg# of mafic silicates and defines a distinct trend of An-Fo variation compared to layered series rocks, which more closely resemble normal gabbroic differentiation trends (Fig. 6-5). The An-Fo variations of anorthositic series rocks are similar in trend to anorthositic rocks of the Middle Banded Zone of the Stillwater Complex, though the latter have overall greater Fo and An contents (MBZ, Fig. 6-5). In general, mineralogical and chemical variations indicative of in situ fractional crystallization are generally lacking in anorthositic series rocks (Miller and Weiblen, 1990).

Complex internal structure is perhaps the most cogent feature of the anorthositic series in understanding its formation. Although rarely layered, anorthositic series rocks typically have some degree of plagioclase alignment. The attitude of this foliation, however, is extremely variable on an outcrop scale. Another structural complication is presented by changes in rock type that occur across sharp (but unchilled) to gradational boundaries. Discrete inclusions of one type of anorthositic rock (typically a more leucocratic composition) in another are common (Taylor, 1964; Miller and Weiblen, 1990). In the Snowbank Lake quadrangle, at least three intrusive episodes in the formation of anorthositic series rocks can be distinguished, with each successive episode producing less leucocratic compositions (Miller, 1986; Miller and Weiblen, 1990). Because of these outcrop-scale structural complexities, it is difficult to divide the anorthositic series into lithologic subunits. What is clear however, is that the anorthositic series was emplaced in multiple intrusive events.

Nearly all workers who have investigated the anorthositic series have come to the common conclusion that these rocks formed from the emplacement and static crystallization of plagioclase crystal mushes (Grout, 1918; Phinney, 1969; Davidson, 1972; Miller and Weiblen, 1990). Miller and Weiblen (1990) cited field, petrographic, and mineral chemical evidence to support the interpretation that the anorthositic

series was formed from multiple intrusions of variably differentiated basaltic magma physically enriched in intratelluric plagioclase of a near constant composition. However, because of their high viscosity, these mushes did not experience significant differentiation after being emplaced into the Duluth Complex. Rather, differentiation and the physical enrichment of plagioclase in anorthositic series parent magma/mushes was accomplished in a deeper staging chamber. Under higher pressures of the lower crust, plagioclase would be buoyant in basaltic magmas.

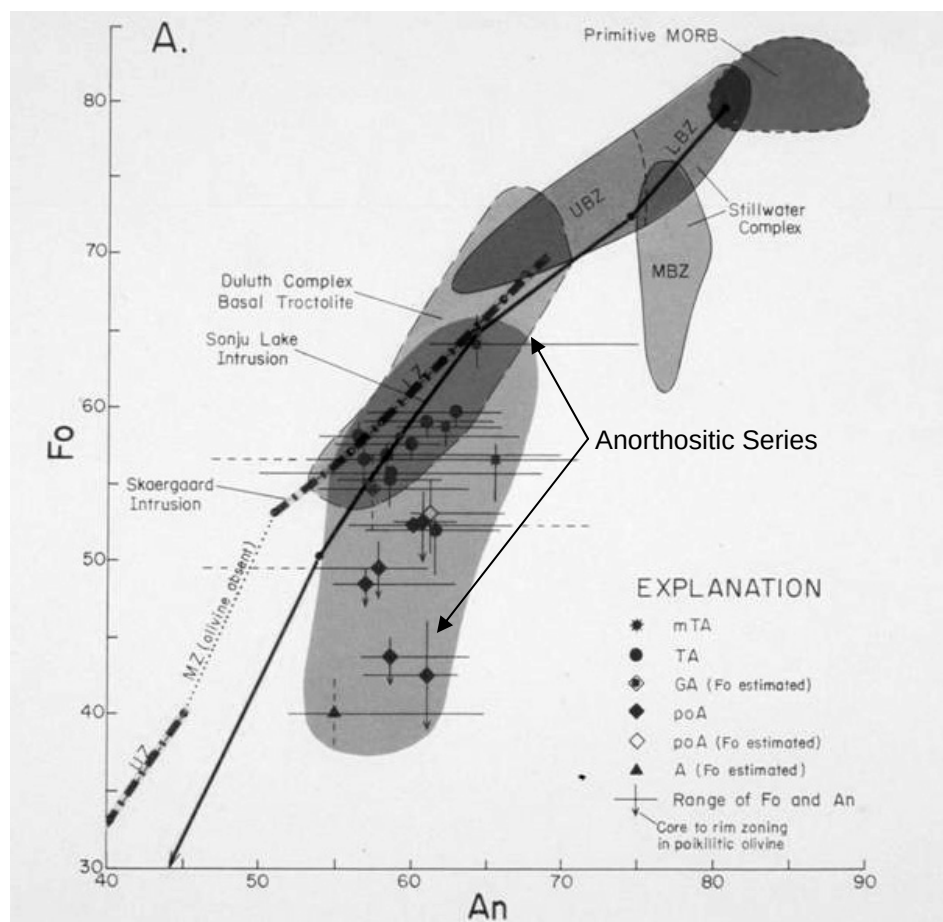


Figure 6-5. Fo-An variations of coexisting olivine and plagioclase in gabbroic and anorthositic rocks from the Duluth Complex and other mafic layered intrusions (Skaergaard and Stillwater). Plotted are the average (symbols) and range (lines) of Fo-An values determined from microprobe analyses of 21 anorthositic series rocks from Snowbank Lake quadrangle. (see Miller and Weiblen, 1990)

Most studies of the Duluth Complex interpreted the unique attributes of the anorthositic series as indicating an origin that was early, similarly unique, and unrelated to that of the layered series. In most areas of the complex, inclusions of anorthositic series rocks within the layered series abound as we will see in the Lake One area. In contrast, inclusions of troctolite have not been reported within anorthositic series rocks. These observations and a well-documented chilled margin of the layered series against the anorthositic series at Duluth (Taylor, 1964) seemed to imply that, in fact, anorthositic rocks were considerably older (and colder) than the layered series (Miller and Weiblen, 1990). However, this interpretation, which came to develop the status of a paradigm (Miller, 1992), was challenged by precise U-Pb ages that showed the anorthositic series and layered series to be essentially the same age of 1099 Ma (Paces and Miller, 1993).

Miller and Severson (2002) suggested that the anorthositic series and layered series were likely tapped in succession from a lower crustal chamber that was initially highly charged with suspended plagioclase. Whereas early extractions from this deep staging chamber was highly enriched in plagioclase, such crystal suspensions were progressively flushed out, resulting in successively less crystal-rich magmas. This model seems best able to explain the lithologic and structural attributes and contact relationships of the Duluth Complex at Duluth and along the northwestern contact area. Moreover, with the 1099 Ma age of the Duluth Complex approximately marking the transition from the latent stage to the main magmatic stage of Midcontinent Rift evolution, this model fits well with the latent stage being a period of extensive underplating of the crust (Miller and Vervoort, 1996; Vervoort et al., 2007).

LITHOSTRATIGRAPHY OF THE LAKE ONE TROCTOLITE

The Lake One troctolite is composed of a 1.5 kilometer-thick stratiform sequence of troctolitic cumulates exposed between the basal contact and the axis of the synformal structure in the vicinity of Rock Island Lake (Fig. 6-4). Within this stratigraphic section, seven stratiform map units can be distinguished (Figs. 6-4 and 6-6). Figure 6-6 shows the general modal variations across this stratigraphic section as well as map units originally defined by Miller (1986) and their equivalents in Figure 6-4.

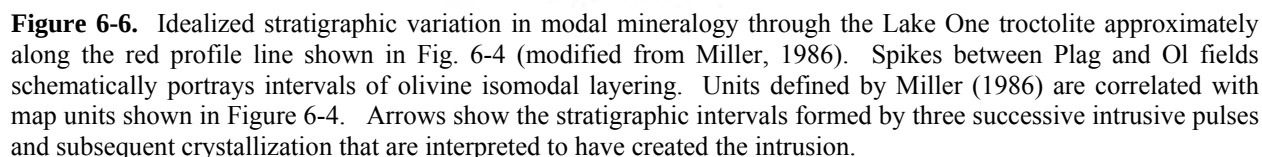
The basal unit (*D1cz*) is a texturally and modally heterogeneous (i.e. taxitic) unit that occurs in the lower 50 meters of the intrusion. Modal mineralogy varies from troctolite to olivine oxide gabbro that locally contains significant amounts of orthopyroxene and biotite. This is commonly interpreted as indicating contamination from the siliceous and volatile-rich footwall (Severson, 1994; Miller and Severson, 2002). Modal layering and igneous foliation is variably developed. This basal contact zone is similar to contact zones of other layered series intrusions in terms of its heterogeneity, however, it is notably poor in Cu-Ni sulfide which is the hallmark of the contact zones on the Partridge River and South Kawishiwi intrusions to the southwest (Fig. 6-1).

Between 50 and 300 m above the basal contact, the heterogeneous nature of the contact zone gives way to a more homogeneously textured zone of medium-grained ophitic olivine gabbro to augite troctolite (*PcOf* to *POcf* cumulates; unit *D1og*). The rocks are typically moderately to well foliated and show subtle modal layering. Biotite and orthopyroxene gradually decrease in abundance through the unit. The contact between the *D1og* and *D1at* unit is chosen where the augite to olivine ratio consistently drops below 1:2 and isomodal olivine layering becomes intermittently developed. This transition gives rise to a monotonous sequence of augite troctolite to troctolite.

The largest unit of the Lake One troctolite, *D1at*, is a consistently medium-grained, moderately to well foliated, ophitic troctolite to augite troctolite (*PO*, *POcf*) that is locally well layered. It is also rich in mafic hornfels inclusion as will be described below. Near the top of the unit exposed at the southeast end of Lake One, this unit becomes more consistently layered, enriched in ophitic augite, and coarser grained (Fig. 6-6). This augite troctolite abruptly gives way to a narrow interval of medium-grained troctolite with augite troctolite inclusions and then to rhythmically layered troctolite and melatroctolite (*PO/OP*). This unit is labeled the *D1t'* unit (Figs. 6-4 and 6-6). The abrupt transition between the *D1at* and *D1t'* units seems best explained as marking major recharge event of more primitive magma into the Lake One magma chamber.

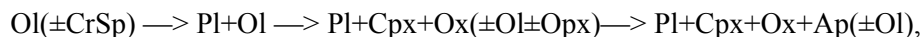
This *D1t'* troctolite unit (*D1t'*, Fig. 6-4) grades upward into a medium-grained, but coarsely ophitic augite troctolite (*POcf*) containing augite oikocrysts up to 15 centimeters across (unit *D1at'*). Together, the *D1t'* and *D1at'* units are about 150 m and may represent a differentiation cycle. The augite troctolite of the *D1at'* unit then abruptly gives way to a homogeneous, well foliated, locally oxide-bearing troctolite (*POf-PO* cumulate; unit *D1t''*), which likely represents another recharge event. Unlike the *D1t'* unit,

Foliation and intermittent layering in the *D1ta*" unit defines a synformal structure north of Rock Island Lake that trends to the NE (Fig. 6-6). The oxide troctolite that occurs on the south limb of this synformal structure is presumably the *D1t*" unit reappearing, however in this case, it displays a very well developed modal layering. Farther southeast of Rock Island Lake, the troctolite returns to a southeasterly dip, thus defining an anticlinal structure before descending below the anorthositic series cap.



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demonstrate a general sequence of cumulus mineral crystallization that is typical of complete fractional crystallization of tholeiitic magmas (Wager and Brown, 1968):



That the Lake One troctolite and its kindred intrusions only display the first part of this crystallization sequence is best explained as indicating that these were systems open to repeated and significant recharge of primitive magma. The cyclical changes in mode and texture in the Lake One troctolite, along with a limited range in mineral compositions (Miller, 1986), suggest that a least three major episodes of magma emplacement were responsible for its formation.

INCLUSIONS AND STYLE OF EMPLACEMENT

Two general types of inclusions occur in the Lake One troctolite – mafic hornfels inclusions and various types of anorthositic inclusions. Anorthositic series inclusions were described above. I will concentrate on the mafic hornfels inclusions here and discuss what the distribution of the inclusions implies about the emplacement of the Lake One troctolite.

The mafic hornfels inclusions range from meters to kilometers in size, but tend to be elongate in the plane of foliation and layering in the troctolite (unit *Nmh*, Fig. 6-4). The hornfels displays a fine-grained granoblastic texture and mineralogically ranges from troctolite to olivine gabbro. Oxide and orthopyroxene are also locally observed, but no systematic petrographic study of the inclusions has been conducted to determine the most common mineralogic types. Some inclusions contain well distributed coarse gabbroic knots that have been interpreted elsewhere (Miller and Severson, 2002) to represent meta-amygdules (some even show pipe amygdale shapes). Similar inclusions occur throughout the lower sections of layered series intrusions and are generally interpreted to be thermally metamorphosed basalt flows from the lower section of the North Shore Volcanic Group (NSVG).

The largest inclusion (or group of inclusions) in the map area occurs between the northeastern part of Lake One and the north arm of Lake Two (Fig. 6-4). Troctolitic rocks in the vicinity of inclusions are coarser and enriched in augite and iron oxide to create olivine gabbro to augite troctolite (mapped as unit *D1og*). Perhaps this gabbroic aureole formed from volatiles and partial melts driven off the large inclusion. Alternatively, perhaps it represents a fragment that was delaminated from a position originally closer to the lower contact.

Interestingly, mafic hornfels inclusions of significant size are almost exclusively contained within the lower two cycles of the troctolite (up to unit *D1at'*). The only exception to this is the mafic hornfels that will be investigated at Stop 6-13. Also, although anorthositic inclusions occur throughout the Lake One troctolite, large anorthositic series inclusions occur exclusively in the upper cycle (*D1t''* and *D1at''*). This strongly suggests that the anorthositic series was emplaced not directly at the unconformity between the Archean and basal lava flow, but instead some unknown distance up into the volcanic pile of NSVG. Interpreting the stratigraphy of the three successive cycles of the Lake One troctolite as indicating emplacement from bottom to top, implies that the first injection of Lake One troctolite magma was at the Archean-volcanic unconformity. This large scale intrusion effectively delaminated the basal lava flows that remained between the Archean footwall and the anorthositic series. The second recharge event was also largely into the basaltic flows, but the third cycle was emplaced into the base of the anorthositic series.

Recent mapping in the Tuscarora intrusion to the east shows a similar relationship (Costello et al., 2009). Two general troctolitic zones, comparable to the Lake One cycles, can be distinguished in the Tuscarora

with the lower one rich in mafic hornfels inclusions and the upper zone exclusively containing anorthositic series inclusions. This provides supporting evidence for the Lake One troctolite being the western extension of the Tuscarora intrusion.

STOP DESCRIPTIONS

DAY 1

GEOLOGY OF THE LOWER LAKE ONE TROCTOLITE

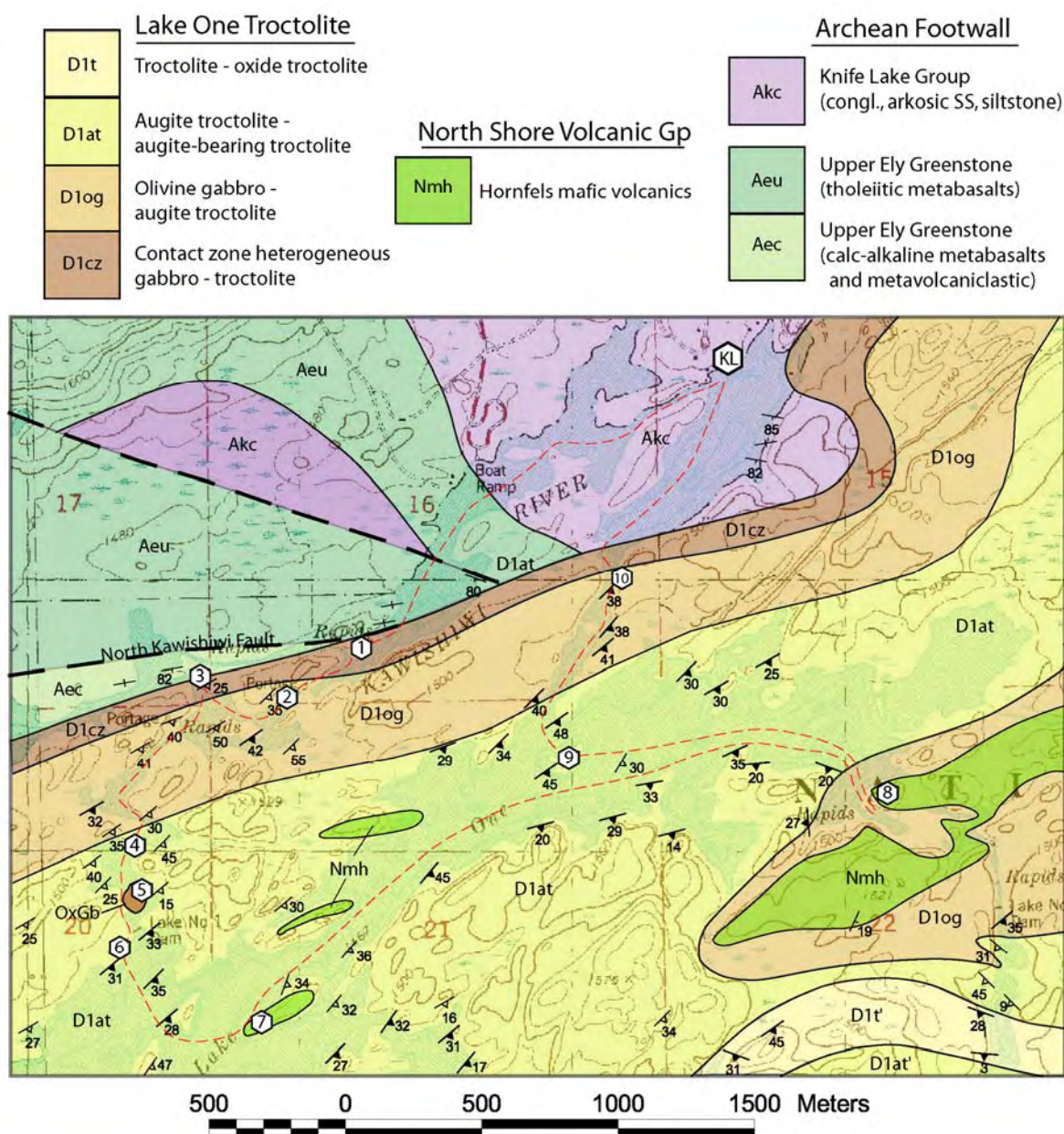


Figure 6-7. Geologic map of the lower Lake One troctolite showing the field stop locations for Day 1. Red dashed line shows the travel route to and from the Kawishiwi Lodge (KW).

Departing from the Kawishiwi Lodge, we will canoe west into the Kawishiwi River channel to the basal contact of the L1T. The geology between the lodge area and the BWCA canoe landing is dominantly metasedimentary rocks (conglomerates, arkosic sandstone and siltstone) of the Knife Lake Group. Downstream of the canoe landing, metavolcanics and metavolcaniclastics of the Upper Ely Greenstone predominate.

STOP 6-1: Contact of Lake One Troctolite (D1cz) and Archean Metavolcaniclastic Rocks (Aec)

Location: NW bank of Kawishiwi River (UTM83: 613225/5309950)

Exposed in outcrop forming the point to the southwest is a medium- to coarse-grained, poorly to moderately foliated, subophitic biotitic oxide olivine gabbro (PcOfb) with local patches of pegmatitic gabbro. An irregularly-shaped, meter-sized inclusion of gabbroic anorthosite is exposed in this area. Back to the northeast and inland about 5 meters is a ledge outcrop of a very dense, metasedimentary hornfels. Continuing NE back toward the shore, is more olivine gabbro. Here, the vari-textured nature of the basal contact zone is more evident with grain size ranging from fine to coarse. An interesting feature exposed here are spaced stringers of coarser gabbro at right angles to the moderately developed foliation. Perhaps this represents vapor streaming out of the footwall. At the far northeast end of the outcrop, the contact with metasedimentary hornfels is inferred within a meter of exposure.

Canoe SW to the portage. Cross over the portage and leave canoes. We will walk to the SW to view outcrops

STOP 6-2: Augite Troctolite of the Lower D1og Unit

Location: NW bank of Kawishiwi River at SW end of portage (UTM83: 612927/5309765)

Exposed in a pavement outcrop SW of the portage trailhead is a homogeneous medium- to medium coarse-grained, moderately to poorly foliated augite troctolite (POcf). This rock and more gabbroic varieties are typical of the D1og unit. Augite and oxide comprise about 8% of the rock here, but gradually increase in abundance to the NW to about 15%. About 1-2% biotite is also present.

Follow the north shore of the channel to the next portage.

STOP 6-3: Contact of Lake One Troctolite (D1cz) and Archean Metavolcaniclastic Rocks (Aec)

Location: NW bank of Kawishiwi River at E end of portage (UTM83: A – 612560/5309866; B - 612658/5309802)

Area A - Exposed in along the north bank of the rapids to the west of the portage is a strongly foliated, well-bedded metavolcaniclastic. Foliation and bedding are oriented ~N75E/80SE. The metasedimentary rock is cut by abundant quartz and chlorite veins. Granoblastic texture is locally evident.

Area B - Exposed in outcrop forming the point to southeast of the portage landing is a medium coarse-grained, poorly to moderately foliated, biotitic ophitic oxide olivine gabbro (PcOf) to augite troctolite (POcf). High density oxide oikocrysts (<1 cm) stand out in relief and augite oikocrysts are 1-2 cm across. This rock is unusually homogeneous for being so close to the basal contact. Note also that it is barren of sulfide.

Canoe SW to the portage at the west end of the bay. Cross over the portage and continue up the meandering channel about 600 m to an island in the channel.

STOP 6-4: Oxide Troctolite in the Lower D1at Unit

Location: Island in river channel (UTM83: 612348/5309210)

The exposures on this island are medium-grained, moderately foliated, augite-bearing oxide troctolite (POfc). Subpoikilitic to anhedral granular oxide is about as abundant as ophitic augite (each about 5%). Typically the augite:oxide ratio is 2-3:1. The greater abundance of oxide and its partially granular habit suggest that it is cumulus in part. Analyses of these granular oxide elsewhere indicate that they are complex Cr-Mg-Al-Ti spinels. Note that the rock is subtly plagioclase porphyritic. Also, subtle olivine layering is locally evident, especially on the NW corner of the island. All of these characteristics are common in rocks of the D1at unit.

Canoe S to the portage. Store canoes here while we explore the outcrop along the trail and exposures to the east.

STOP 6-5: Oxide-rich Melagabbro Intrusion/Inclusion? in the D1ta Unit

Location: North end of portage to Lake One (UTM83: 612387/5309040)

Outcrops on the west side of the portage trail are altered medium-grained augite troctolite. The mafic phases have been replaced by actinolite and chlorite and plagioclase is partially sericitized. The source of this alteration be related to the rock seen to the east along the river channel. Here we find a coarse-grained to pegmatitic amphibole-oxide-plagioclase rock. Unfortunately, a thin section was not made of this rock to determine whether the green amphibole is primary (hornblende?) or secondary (actinolite?) after pyroxene. Moreover, it is not clear whether this rock is an inclusion (perhaps of recrystallized iron formation) or is an oxide ultramafic intrusion (OUI's of Severson and Hauck, 1990). The alteration near the portage trail and the abundance of chloritic veins in the area suggest it may be a volatile-rich intrusion. However, the distortion of foliation to a dip of 70° in troctolite on the opposite shore suggests that it might be an inclusion. If the latter, it further implies that Paleoproterozoic strata existed on top of the Archean basement in this area when the Duluth Complex intruded. The last exposure of Biwabik Iron-formation observed in the footwall of the Duluth Complex occurs 30 km to the SE in the Dunka Pit area (Fig. 6-1).

Portage canoes to S end of the portage trail. Store canoes here while we explore the outcrop in the campsite area to the west.

STOP 6-6: Intermittently Layered Oxide Troctolite (D1ta Unit)

Location: Campsite west of south end of portage trail near Lake One Dam (UTM83: 612340/5308833)

This stop is mostly intended as a lunch stop. The pavement outcrops at the campsite are medium-grained, layered and moderately foliated oxide troctolite (POfc). Granular (cumulus?) iron oxide up to 3 modal% is present in greater abundance than interstitial augite (1-2%). Olivine-rich layers are common throughout the outcrop.

Canoe from portage past island to the S, then head E to SW end of large island.

STOP 6-7: Mafic Hornfels (Nmh) in the D1ta Unit

Location: Large island in central area of Lake One (UTM83: 612820/5308566)

Exposures on the SW end of this island show a mafic hornfels with a generally troctolitic modal composition. Locally, patches and stringers of coarse altered (amphibolitized) gabbro define crude layering that trends NE, roughly parallel to foliation and layering in the bounding troctolite. These

gabbroic areas are interpreted to be metamorphosed amygdaloidal zones of the original basalt flows. As is typical of mafic hornfels, they are cut by a network of chlorite-quartz veins.

Canoe into the northern basin of Lake One and head east to the outlet for the north arm of Lake Two.

STOP 6-8: Large Mafic Hornfels inclusion (Nmh) in Olivine Gabbro (D1og)

Location: Large outcrop knob north of outlet for the north arm of Lake Two (UTM83: 615090/5309395)

Exposures in the lower part of the slope are medium- to medium coarse-grained, non-foliated, subophitic olivine oxide gabbro. Progressing NE up the large knob, the gabbro coarsens and then a complex contact with mafic hornfels is encountered. The mafic hornfels is generally fine-grained, granoblastic and varies in mineralogy from olivine gabbro to troctolite. Crs clots of gabbro (meta-amygdules?) are dispersed throughout and the inclusion is cut by abundant chlorite veins. The inclusion on this knob is about 30 meters across, but it is probably part of a high concentration of hornfels inclusions in this area (greatly simplified in Fig. 6-7). Northeast of the inclusion is more olivine oxide gabbro that locally displays a plagioclase porphyritic texture. It is not clear whether this olivine oxide gabbro is a contamination halo affecting troctolitic rocks around the inclusions or whether it is “attached” to the hornfels that collectively comprise a larger inclusion mass included in the D1at unit.

Canoe west back into the northern basin of Lake One to an island near the entrance to the northern arm.

STOP 6-9: Well-layered Troctolite of the D1at unit

Location: Island near the entrance to the northern arm of Lake One (UTM83: 613938/5309517)

Exposed along a NE –trending ridge on northern side of this island is medium-grained, well-foliated augite-poor troctolite (PO) that commonly displays modal layering. Olivine enriched layers are 2-10 cm thick and contain 40-45% olivine compared to normal troctolite with 25-30% olivine. Low angle cross-bedding is noted locally. In one location, a small (<1 m) anorthositic inclusion is present. A similarly well layered troctolite is exposed on the northwestern projection of the island.

Canoe into the northern arm to exposure on E side of channel just before it opens into the northern bay.

STOP 6-10: Rhythmically-layered Augite Troctolite of the D1og unit

Location: Cliff face on east bank of channel (UTM83: 614164/5310251)

Exposed in the cliff face is a rhythmic layering in a medium-grained, poorly foliated, biotitic ophitic augite troctolite (POcfb). The layering is differentially weathered such that the more plagioclase-rich intervals stand out in relief. The dip of the layering is about 40° to the southeast. Some of the layering seems to be graded with olivine-rich intervals having sharp bases and gradational upper parts that grade to normal augite troctolite. Some subtle cross-bedding may also be recognized. Below this layered interval, the rock becomes considerably more gabbroic and vari-textured typical of the contact zone (D1cz).

If time permits, we may investigate the contact zone again which is exposed on the west side of the channel. It is similar to the relationships seen at stop 6-1.

DAY 2

GEOLOGY OF THE UPPER LAKE ONE TROCTOLITE

Departing from the Kawishiwi Lodge, we will canoe south down the northern arm of Lake One and into the southern basin of Lake One. There we head east toward to the portage to Lake Two.

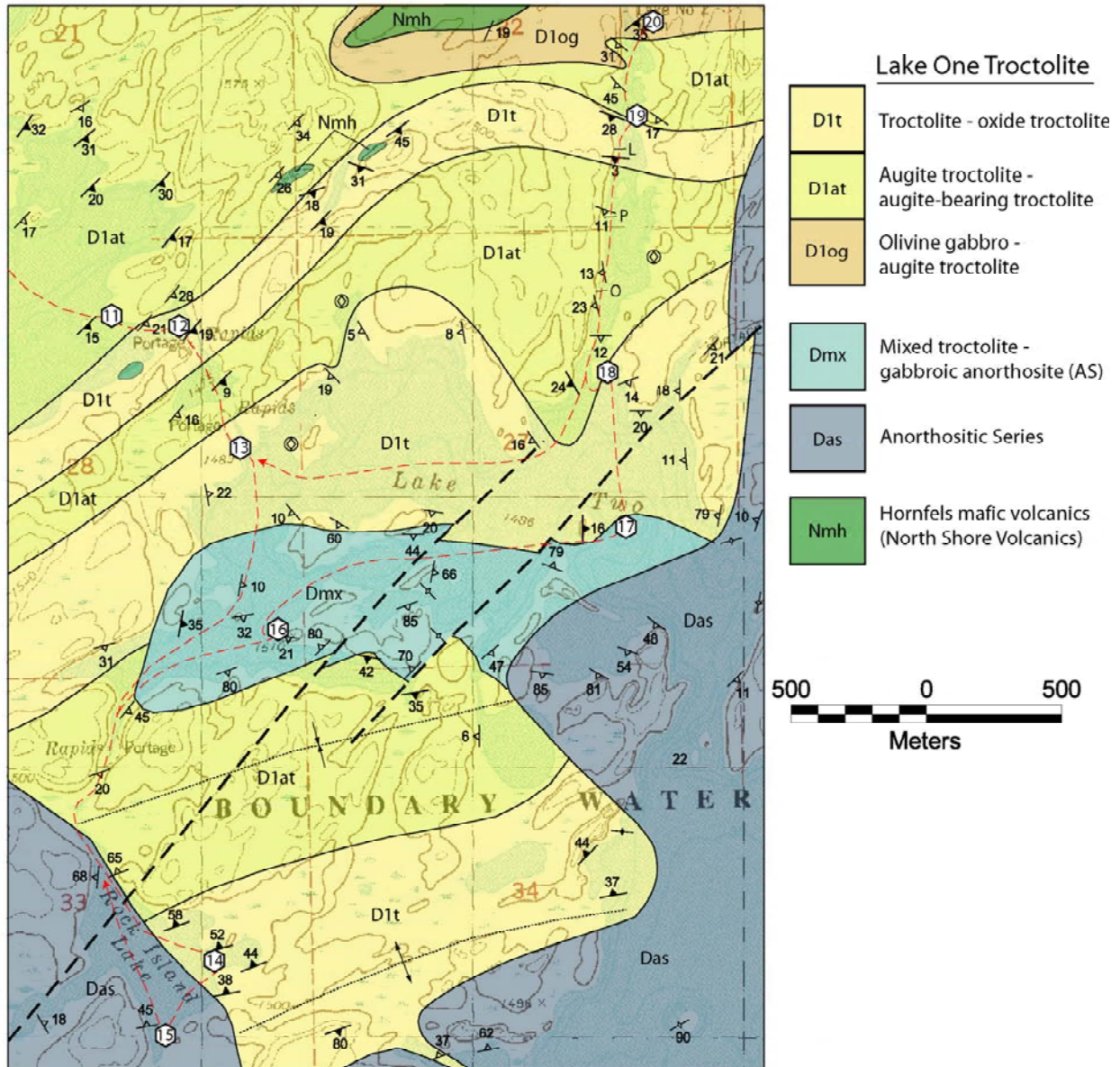


Figure 6-8. Geologic map of the upper Lake One troctolite showing the field stop locations for Day 2. Red dashed line shows the travel route.

STOP 6-11: Autolithic Inclusions near the D1t-D1t' Contact

Location: Small pavement outcrop at NE shore of southern basin of Lake One west of portage entry to Lake Two (UTM83: 613670/5307863)

In this small outcrop, four different blocks of troctolitic rock types are exposed in sharp contact with one another as shown in the sketch in Figure 6-9. Based on the cross-cutting relationships of foliation by sharp contacts, rock type 1 is the youngest and rock type 2 is the next oldest. Just to the east of this outcrop, a well layered oxide troctolite of the D1t' unit occurs that is interpreted to indicate an new magma recharge cycle. Perhaps this auto-brecciation represents the structural disruption that accompanied this recharge event.

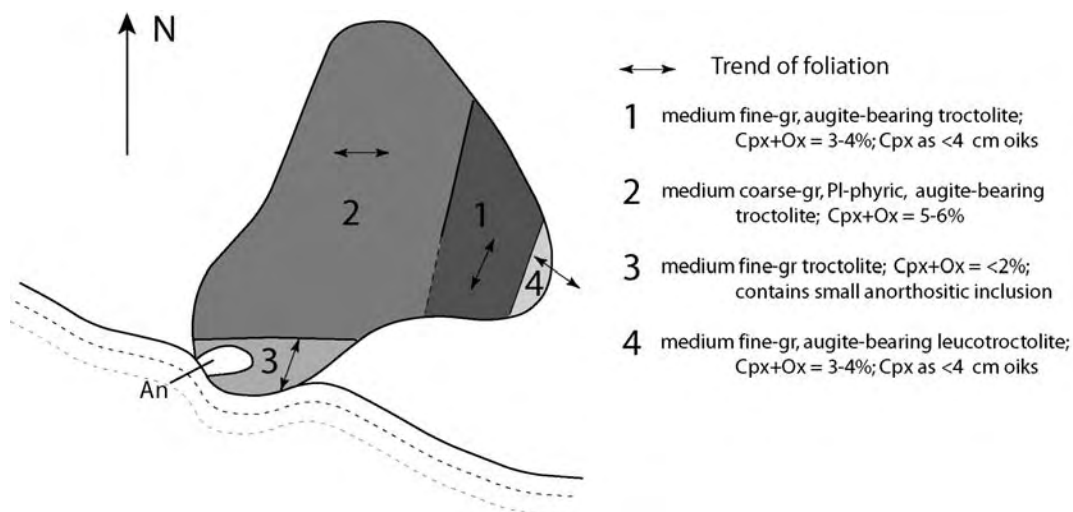


Figure 6-9. Sketch of contact relations among troctolitic rock types exposed at Stop 6-11 (from Miller field notes, Station 450, Aug. 8, 1981)

Head east to the portage to Lake Two. Store canoes and investigate outcrops in landing area.

STOP 6-12: Layered Troctolite of the D1t' Unit

Location: Outcrop at portage landing and in stream to the north of the portage. (UTM83: 613925/5307821)

The small outcrop at the landing is a medium-grained, augite-poor troctolite (PO) with very subhedral granular olivine. Progressing into the stream, the troctolite here shows rhythmic to intermittent isomodal olivine layering. Olivine layers range from 2 to 20 cm thick. Upstream, the rock gradually increases in augite and oxide mode. At the SE end of the portage, the rock is an augite troctolite (POcf) containing inclusions of mafic hornfels.

Head across the two small portages to Lake Two. The next stop will be at the SE end of the second portage.

STOP 6-13: Meta-amygdaloidal Mafic Hornfels Inclusions in Oxide Troctolite of the D1t' Unit

Location: Outcrop at portage landing and in stream to the north. (UTM83: 614126/5307391)

Pavement outcrops at the landing into Lake Two show a complex mix of mafic hornfels inclusions that locally display coarse clots and stringers of gabbro (meta-amygdules) hosted in a medium-grained, augite-bearing oxide troctolite (POFc). An anorthositic inclusion also is exposed in this outcrop. In the troctolite, oxide occurs as small subhedral grains and is equal to more abundant than augite. The troctolite is near the base of the D1t" unit. These mafic hornfels represent the highest stratigraphic occurrence of volcanic inclusions in the Lake One troctolite.

Head south from the portage to the SW arm of Lake Two and to the portage to Rock Island Lake. Cross the portage and canoe into the east corner of Rock Island Lake.

STOP 6-14: Northwest-dipping Layered Troctolite of the D1t" Unit

Location: Outcrop at the east end of Rock Island Lake. (UTM83: 614038/5305437)

Rhythmic isomodal olivine layering is exposed throughout the eastern end of Rock Island Lake. Olivine layers range are 1-10 cm thick. Small granular (cumulus) oxides are present in both the melatroctolite layers and the intervening troctolite. Pyroxene is rare throughout (<1%). The northwesterly dip of the layering here defines a synform structure in this area. The cause of this deformation is not clear (sag over a feeder?), but it likely occurred when the rocks were still semi-molten or at least at a high temperature since no deformation features are noted on a hand sample or thin section scale.

Canoe along SW along shoreline of Rock Island Lake to bay at south end.

STOP 6-15: Anorthositic Series (Das)

Location: Sloping pavement outcrop on east side of bay. (UTM83: 613847/5305200)

Three different anorthositic rock types are displayed on this outcrop. At the north end is a medium coarse-grained poikilitic olivine gabbroic anorthosite with 5-8 cm oikocrysts of olivine. Across an obscured, but presumably sharp contact is a coarse grained troctolitic anorthosite with large anhedral granular olivine, ophitic augite, and subpoikilitic oxide collectively totaling about 10% of the rock. Across a clearly sharp contact is a medium-grained leucotroctolite containing 15-20 % olivine and very little augite or oxide. This latter rock contains inclusions of the other varieties and is thus the younger intrusion. The outcrop scale variability in anorthositic rock types and the sharp unchilled contact relationships displayed here are typical of the anorthositic series.

Canoe and portage back into Lake Two. Head to the campsite on the eastern point of land that separates the SW arm of Lake Two from the main part of the lake.

STOP 6-16: Mixed Troctolitic and Anorthositic Rocks of the Dmx Unit

Location: Campsite in SW Lake Two (UTM83: 614250/5306703)

Exposed over the clean pavement surface at this campsite is a complex mix of anorthositic series rock types as inclusions in a fine- to medium-grained matrix. The anorthositic inclusions range from cm to tens of meters across and show a range of mineralogic and textural varieties typical of the anorthositic series. The intervening troctolite appears to be of two generations, an early finer grained troctolite that is locally Pl-phyric and a later medium-grained type. The contacts between the troctolite and anorthositic inclusions range from sharp to gradational over a several centimeters. This suggests that some of the anorthositic inclusions may have been partially molten when intruded by the troctolite and subsequently became disaggregated. A meter-sized mafic hornfels inclusion is exposed in one area of the outcrop.

Head east through the cluster of islands in southern Lake Two to an island in the east central part of the lake.

STOP 6-17: Mixed Troctolitic and Anorthositic Rocks of the Dmx Unit

Location: Island in east central Lake Two (UTM83: 615570/5307100)

Exposures around the margins of this small island provide another view of the scale and complexity of mixing between anorthositic and troctolitic rock types in the Dmx unit. Anorthositic varieties, which tend to be medium- to coarse-grained, include poikilitic olivine gabbroic anorthosite, granular troctolitic anorthosite, leucotroctolite and nearly pure anorthosite. The troctolite is variable in texture and mode as it locally seems to become hybridized with the anorthositic inclusions.

Head north to the entrance to the northern arm of Lake Two.

STOP 6-18: Contact between Augite Troctolite (D1ta') and Oxide Troctolite (D1t'')

Location: Point on east side of entrance to north arm of Lake Two (UTM83: 615488/5307646)

Shoreline outcrops here display medium-grained, moderately foliated oxide troctolite containing up to 3% anhedral granular to subpoikilitic oxide (POF-POf). Some subtle olivine layering is also evident. Progressing to the north, this rock abruptly transitions in to a coarsely ophitic augite troctolite with pyroxene oikocrysts up to 4 cm diameter (POcf). This transition is taken to define the D1ta'-D1t'' contact and is interpreted to represent the third major recharge event that created the Lake One troctolite.

Canoeing into north arm of Lake Two to the next stop, we can observe several interesting features in the outcrops lining the western side of the channel. Specific points of interest are labeled on Fig. 6-8. These include:

- O (615456/5307950) – coarsely ophitic augite troctolite w/ 5cm oikocrysts; also gabbroic pegmatite
- P (615473/5308241) – gabbroic pegmatite cutting augite troctolite.
- L (615596/5308493) – modal layering dipping S (sheet jointing dipping N); this is in the D1t' unit

STOP 6-19: Augite Troctolite of the Upper D1ta Unit

Location: Sloping pavement at campsite on east side of channel (UTM83: 615488/5307646)

Pavement outcrops here are medium-grained, moderately foliated, ophitic augite troctolite (POcf) corresponding to the upper part of the D1ta unit. Augite oikocrysts are present, but do not stand out as much as to the south at the previous stop (6-18).

Head north to the landing adjacent to the old dam. Investigate outcrop to the north.

STOP 6-20: Olivine Oxide Gabbro Aureole (D1og)

Location: Landing on east side channel at northern end of the north arm of Lake Two (UTM83: 615572/5308640)

Outcrop ledges along the east bank of the channel show a vari-textured (medium – pegmatitic), subophitic olivine? oxide gabbro similar to that seen yesterday at Stop 6-8. Some streaky textural layering is evident in some exposures. The occurrence of gabbro here demonstrates that the gabbro forms a complete

aureole around the mafic hornfels block (or blocks) that are abundant in this area. The gabbroic pegmatite cutting troctolitic rocks upsection from this (as seen in the channel exposures to the south) may also have emanated from the gabbroic aureole. If so, this would argue for the aureole having developed by contamination of volatile-rich partial melts driven from the hornfels inclusion(s).

Return to Kawishiwi Lodge. End of field trip.

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55th Annual Institute on Lake Superior Geology

Field Trip 7

ARCHITECTURE OF AN ARCHEAN GREENSTONE BELT: STRATIGRAPHY, STRUCTURE, MINERALIZATION



Graded bedding in greywacke of the Lake Vermilion Formation, Pike River dam (stop 7-14)

*"In the region occupied by these rocks are found immense bodies of magnetitic and hematitic iron ore.
In the talcose slates and primitive schistose rock are veins of quartz, carrying
auriferous and argenterous sulphides of iron and copper."*

Henry H. Eames, 1866

Dean Peterson (Duluth Metals Ltd. & PRC)

Mark Jirsa (Minnesota Geological Survey)

George Hudak (Dept. of Geology, UW-Oshkosh & PRC)

FIELD TRIP 7

ARCHITECTURE OF AN ARCHEAN GREENSTONE BELT: STRATIGRAPHY, STRUCTURE, AND MINERALIZATION

Dean M. Peterson (Duluth Metals Limited & PRC)

Mark A. Jirsa (Minnesota Geological Survey)

George J. Hudak (University of Wisconsin Oshkosh)

INTRODUCTION

Archean greenstone belts are one of the world's premier geological settings for hosting a variety of economically important mineral deposit types. These deposits include high-grade iron ore, lode-gold, volcanogenic massive sulfide, komatiite associated nickel, magnesite, and a number of others. The origin of these deposits are intrinsically linked to the architecture of the greenstone belt, namely the inter-relationships between stratigraphy, structural setting, and multiple generations of hydrothermal fluids.

The Vermilion district of northeastern Minnesota contains one of the classic granite-greenstone terranes in the United States. This district comprises the south-central part of the Wawa subprovince of the Superior Province of the Canadian Shield, and has been broadly correlated with the Saganagons Assemblage of the Wawa subprovince in northwestern Ontario (Peterson et al., 2001; Peterson and Patelke, 2003). In Canada, the Wawa subprovince hosts numerous lode gold (e.g. the Hemlo and Renabie districts) and volcanic-hosted massive sulfide (VMS) ore bodies (e.g. the Winston Lake, Willroy, Big Nama Creek, Willecho, and Geco deposits; Fyon et al., 1992). The Vermilion district is well known for its numerous, previously mined, massive hematitic iron ore deposits. These iron deposits were discovered in the early 1880s, and virtually all-subsequent exploration efforts in the region were targeted on similar iron-formation hosted hematite deposits. However, the discovery of world-class ore deposits in Ontario (the Kidd Creek VMS deposit in 1964 and the Hemlo gold deposit in 1980) led to short periods of both base metal and gold mineral exploration in the Vermilion district. To date, no lode gold and/or VMS ore bodies have been discovered in the Vermilion district, although abundant evidence exists that future exploration may result in the discovery of economically important deposits.

GREENSTONE BELTS

A strong debate continues on the origin, development, and architecture of Archean greenstone belts, particularly with regard to the roles of subduction, plume magmatism, rifting, diapirism and autochthonous vs allochthonous development (e.g. de Wit, 1998; Hamilton, 2003). Studies in the Superior and Slave Provinces of Canada indicate that strongly contrasting tectonic styles may have been in operation at the same time. For example at ca. 2.7 Ga, large diapiric batholiths and synclinal greenstone keels may suggest that diapirism was an important tectonic process in the Slave Province (Bleeker, 2002), whereas Stott (1997) suggests that the linear distribution of belts suggests that accretionary tectonics (i.e. plate tectonics) may have dominated in the Superior Province. Neither theory precludes the other, and in developing models for Archean tectonic evolution, no one model will be equally applicable to all areas. Hoffman (1990) presents a model of greenstone belt formation via arc-trench progradation as an application of the principle of lateral and temporal equivalence, also known to sedimentologists as "Walther's Law". In this model (Fig.7-1), accretion of the overriding plate in a subduction zone involves scraping of material off the downgoing plate and arc magmatism. The off-scraped material consists of sediment and the tops of igneous bathymetric highs (ie. island arcs, remnant arcs, seamounts, oceanic island chains, submarine plateaus, fracture zones and microcontinents).

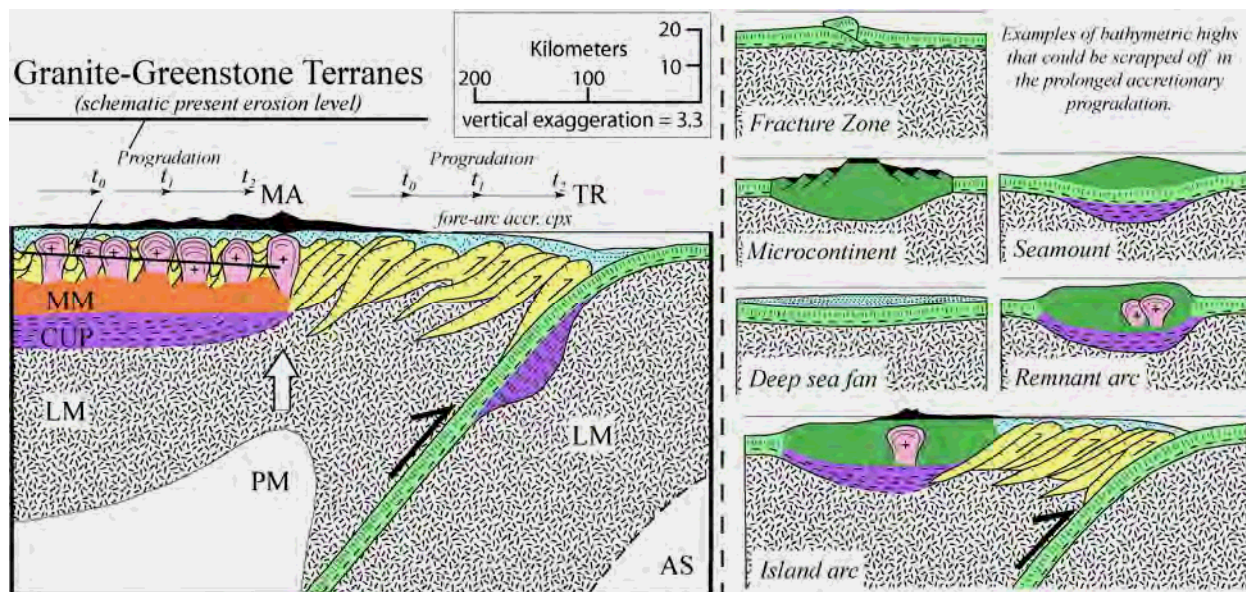


Figure 7-1. Prograding arc-trench model for the generation of granite-greenstone terranes. On the left is an idealized cross-section of an arc-trench system: AS, asthenosphere; CUP, cumulate underplating; LM, lithospheric mantle; MA, magmatic arc; MM, magma melting and mixing; PM, zone of partial melting; TR, subduction trench. Fore-arc accretion is achieved by scraping of sediment and topographic highs off of the downgoing plate. Examples of bathymetric highs that could be scraped off and eventually form greenstone belts are depicted on the right. Modified from Hoffman, 1990.

We hope to portray our present understanding of the Vermilion district in the context of its geological architecture—highlighting the interrelationships between stratigraphy, structure, and mineralization. The trip will revisit many outcrops on which so many historical discussions, many of them heated, pertaining to the regional geologic setting of the Archean occurred. Many of the stop descriptions in this field trip have been modified from the Field Trip Guidebook of the 50th Annual Meeting of the Institute on Lake Superior Geology, which was held in Duluth in May of 2004. In particular, volcanology and hydrothermal alteration within the Lower Ely Greenstone was described in detail by Hudak et al. (2004), gold mineralization north of the Mud Creek shear zone was described in detail by Peterson and Patelke (2004b), and classic outcrops in northeastern Minnesota were described by Jirsa et al (2004). Readers of this guidebook should review these documents for detailed descriptions.

REGIONAL GEOLOGICAL SETTING

Supracrustal rocks in the Vermilion district consist of volcanic-dominated stratigraphic sequences of the Wawa subprovince of the Superior Province of the Canadian Shield. Rocks of the Wawa subprovince in northern Minnesota are divided on the basis of stratigraphic and structural setting into: (1) the Soudan belt, to the south, and (2) the Newton belt, to the north (Jirsa et al., 1992; Southwick et al., 1998). The boundary between these contrasting structural panels can be traced geophysically across the width of Minnesota, and was designated informally as the Leech Lake structural discontinuity (Jirsa et al., 1992). In the region west and north of the Soudan Mine, the Leech Lake structural discontinuity occurs along the Mud Creek shear zone (Hudleston et al., 1988), small segments of the Vermilion and Wolf Lake faults (Sims and Southwick, 1985), and the Bear River fault (Jirsa et al., 1992).

The Soudan belt contains large, broad folds involving calc-alkalic and tholeiitic volcanic strata overlain by, and locally interdigitated with, turbiditic rocks. In contrast, the Newton belt consists of elongate, northeast-trending, and mostly northward-younging volcanic and volcanoclastic sequences. Volcanic

rocks of the Newton belt differ from those of the Soudan belt in containing locally abundant komatiitic flows and peridotitic sills. The two belts are fault-bounded, and the relationship between stratigraphic units within each belt is largely conformable, although faults obscure contacts locally. In its eastern extension, the Soudan belt is continuous with the Saganagons assemblage in Ontario and terminates against the Saganaga pluton and Northern Light Gneiss. The Newton belt extends discontinuously eastward into the Shebandowan District of Ontario to form the Greenwater and Burchell assemblages. Intrusive rocks in both belts vary from gabbroic and felsic porphyries demonstrably related to volcanism, to large plutons emplaced post-tectonically. Both districts contain unconformable, Timiskaming-type sequences composed of calc-alkalic volcanic rocks, conglomerates, and finer grained sedimentary rocks. A simplified regional geological map of the Neo-Archean terranes of northeastern Minnesota and adjacent Ontario is presented in Figure 7-2.

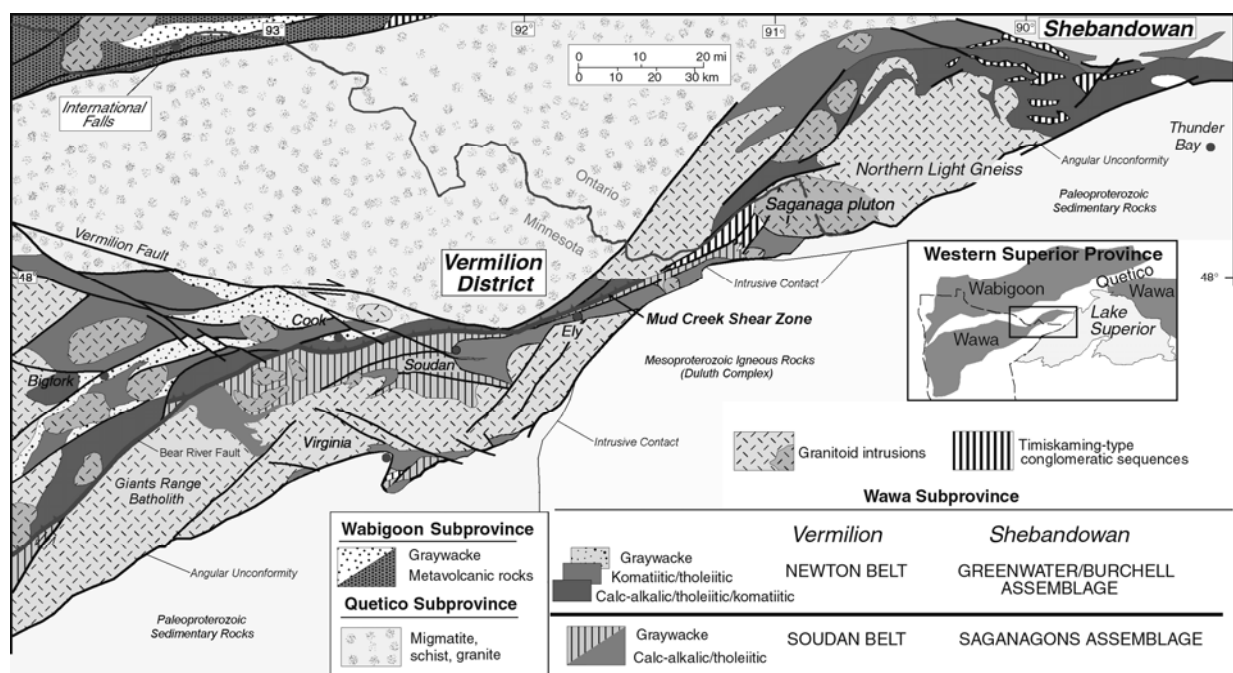


Figure 7-2. Simplified correlation map of Neoproterozoic assemblages across the U.S. - Canada border (modified from Peterson et al., 2001). Inset illustrates major subprovinces of the southwestern Superior Province.

Lithostratigraphic units in the western Vermilion district include: (1) the Lower member, Soudan Iron Formation member, and Upper member (Upper Ely) of the Ely Greenstone, the Lake Vermilion Formation (including the informally named Britt and Gafvert Lake sequences), and the Knife Lake Group of the Soudan belt; (2) the Bass Lake sequence (Peterson and Jirsa, 1999) and the Newton Lake Formation of the Newton belt; and, (3) syn- to post-tectonic granitoid intrusions of the Giants Range batholith, and a suite of post-tectonic alkalic stocks and plutons. Contacts between the different units are typically conformable, although considerable overlap in time and space is documented between volcanic and sedimentary sequences (Southwick, 1993). Rock types associated with the lithostratigraphic units in the area are presented in Table 7-1.

Table 7-1. Lithostratigraphic units within the western Vermilion district (from Peterson and Jirsa, 1999).

Intrusive Rocks	
Late Intrusions	Plutons and stocks of syenite, monzonite, diorite, and lamprophyre
Vermilion Granitic Complex	Granite, schist, amphibolite, and schist-rich migmatite
Giants Range Batholith	Granite, granodiorite, monzodiorite, and schist-rich migmatite
Supracrustal Rocks	
<i>Newton Belt</i>	
Newton Lake Formation	Tholeiitic and komatiitic basalt flows, intrusions, and clastic strata
Bass Lake Sequence	Tholeiitic basalt lava flows, iron-formation, and felsic porphyries
<i>Soudan Belt</i>	
Knife Lake Group	Graywacke, slate, conglomerate, & sheared equivalents
Lake Vermilion Formation	Graywacke, slate, dacitic tuff, and minor conglomerate
Gafvert Lake Sequence	Dacitic to trachyandesitic lava flows, tuffs, and intrusions
Britt Sequence	Tholeiitic basalt lava flows
Upper Ely Greenstone	Tholeiitic basalt lava flows and iron-formation
Soudan Iron Formation	Layered cherty iron-formation, epiclastic rocks, and tuff
Lower Ely Greenstone	Calc-alkalic & tholeiitic basalt-rhyolite lava flows, tuffs, epiclastic rocks and minor iron-formations

STRUCTURAL GEOLOGY

Periods of generally N-S directed compression resulted in three major regional deformation events in the Neoarchean terranes of northern Minnesota. The earliest deformation event (D_1) produced broad, locally recumbent folds within the Soudan belt and major fault zones throughout the region. In the Newton belt, D_1 was accommodated by thrust imbrication of large crustal blocks, resulting in mainly northward stratigraphic facing. Field relationships indicate that uplift, faulting, and the deposition of Timiskaming-type clastic sedimentary sequences in local fault-bounded basins occurred late in D_1 deformation (Jirsa, 2000). A large, map-scale structure related to D_1 deformation in the western Vermilion district is the Tower-Soudan Anticline, which is a west-plunging anticline within which the axis and plunge changes orientation along strike from nearly vertical in basalts to shallow NE plunging in the western sedimentary rocks. Axial-planar cleavage associated with this early fold typically is lacking, although Bauer (1985), Hooper and Ojakangas (1971), Hudleston (1976), and Jirsa et al. (1992) have described early cleavage (S_1) locally.

A second deformation event (D_2) associated with synchronous regional metamorphism resulted in foliation development and structures having largely dextral asymmetry. D_2 is constrained in the Vermilion district to the time period 2674 to 2685 Ma (Boerboom and Zartman, 1993), and between about 2680 and 2685 Ma in the Shebandowan (Corfu and Stott, 1998). Because D_2 deformation affected all of the supracrustal rocks in the area and is reasonably constrained by geochronology, the regional foliation (S_2) can be used in the field to temporally relate other structural, intrusive, and deformation events. The relationship between S_2 fabric and shear structures indicates that most shearing occurred relatively late in the D_2 event. Major shearing that produced the Mud Creek and related shear zones is attributed to the late stages of D_2 dextral transpression.

Structures related to the third deformation event (D_3) include abundant NE- and NW-trending faults that dissect the stratigraphic assemblages. Named structures related to D_3 include the NE-trending Waasa and

Camp Rivard faults east of the Soudan Mine area, and the WNW-trending, crustal-scale Vermilion and related faults that form the Wawa-Quetico Subprovince boundary.

ECONOMIC GEOLOGY

Since the mid-1860's, numerous mineral exploration programs have been conducted in the Vermilion district. Most of these exploration programs focused on identifying minable deposits of massive hematitic iron ores, such as those mined between 1883 and 1962 in the Soudan Iron Formation at the Soudan Mine. During the 1980s and early 1990s, subeconomic lode gold mineralization was discovered in close proximity to the east-west-trending Murray shear zone, which dissects the Lower Ely, and in close proximity to the Mud Creek shear zone, which separates the Soudan belt from the Newton belt to the north. Four VMS prospects occur within the Lower member of the Ely Greenstone, and occur in close proximity up-section from a semiconformable quartz-epidote alteration zone that extends for at least 19km along strike in the north limb of the Tower-Soudan Anticline (Peterson, 2001). These VMS prospects include the Skeleton Lake prospect (drilled by Exxon, 1972), the Eagles Nest prospect (drilled by Newmont, 1988), the Fivemile Lake prospect (drilled by Teck, 1994), and the Purvis Road prospect (drilled by Rendrag, 1999). Recent studies of these three types of mineral deposits in the Vermilion district link stratigraphy and structure, and thus help unravel the architecture of the greenstone belt. Brief descriptions of hematite, VMS, and lode gold mineralization in the field trip area are presented below.

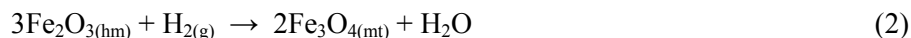
Origin of Massive Hematite from Algoma-Type Iron Formation

Most iron ores mined today comprise the iron oxide minerals magnetite, Fe_3O_4 (72% Fe); hematite, Fe_2O_3 (70% Fe); goethite, $\text{Fe}_2\text{O}_3(\text{s}) \cdot \text{H}_2\text{O}$, (63% Fe); and limonite, a mixture of hydrated iron oxides (up to 60% Fe). The world's most important iron ore resources occur in iron-rich sedimentary rocks (20% - 40% Fe) known as banded iron-formations (BIFs), which occur on all continents and are almost exclusively of Precambrian age. In many iron-mining districts, e.g., the Mesabi Range of northern Minnesota, the BIFs are mined as iron ore with the iron content concentrated into pellets (~65% Fe) in large on site facilities. In other districts, e.g., the historic Vermilion Range of the Soudan Mine area; Hamersley District, Western Australia, the BIFs are the source rocks for large, natural high-grade concentrations of iron that typically occur as bodies of massive hematite and/or hematite-goethite with >60% Fe.

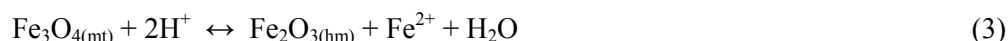
The origin of these important natural concentrations of iron minerals remains highly debated. The Fe atoms in hematite are all Fe^{3+} , whereas in magnetite they are comprised of two Fe^{3+} and one Fe^{2+} atoms. Therefore, the transformations of magnetite to hematite, or hematite to magnetite, in Fe-conservative systems is always a redox reaction, with the Fe^{2+} atoms in magnetite oxidized to Fe^{3+} atoms, or the Fe^{3+} atoms in hematite reduced to Fe^{2+} atoms, by reactions such as:



and



In the past, the study of the transformation of magnetite to hematite (1) and conversely hematite to magnetite (2) in natural systems has largely focused on these reactions, which require either an oxidizing or reducing agent and an occurrence under specific redox environments. Since virtually all of the known concentrations of high-grade iron ores are hematite-dominant, the exploration for such deposits has concentrated on supergene enrichment of magnetite-rich BIFs. In this model, magnetite-rich BIFs are uplifted and subjected to weathering under oxygenated conditions to form goethite-rich ores; and are subsequently buried and metamorphosed to hematite-rich ores (Morris, 1985). Problems with this model have recently been discussed by Ohmoto (2003) for the Tom Price Mine of the Hamersley district, and are applicable to the origin of the massive hematite ores of the Soudan Mine. Ohmoto (2003) has proposed an alternative mechanism for the transformation of magnetite-rich iron-formations to massive hematite ores by the acid-base reaction:



Similar to most acid-base reactions, reaction (3) would be most efficient at high temperatures, and such hydrothermal fluids are capable of leaching silica as well as Fe^{2+} from magnetite. In addition, the conversion of magnetite to hematite by reaction (3) produces a volume decrease of 32%, greatly increasing permeability of the rocks, which would facilitate further water-rock reactions and enhance conversion of banded chert-magnetite to massive hematite.

VMS-Associated Volcanic and Hydrothermal Alteration Processes, Lower Ely Greenstone

The Lower Ely Greenstone is composed of calc-alkalic and tholeiitic basalt and basalt-andesite, lava flows, tuffs, and lapilli tuffs with subordinate felsic lava flows, tuffs, epiclastic rocks, and iron formations (Schulz, 1980; Southwick et al., 1998; Jirsa et al., 2001; Hudak et al., 2002a, 2002b; Hoffman, 2007; Jansen et al., in press). The Lower Ely Greenstone has been subdivided into the older Fivemile Lake Sequence and the younger Central Basalt Sequence (Peterson and Patelke, 2003). The Central Basalt Sequence is correlative with the Armstrong Lake Basalts (Jirsa et al., 2001). The Fivemile Lake Sequence is characterized by abundant primary mafic and felsic volcanoclastic strata, highly amygdaloidal basalt and basalt-andesite pillow lavas and sheet flows, multiple selvege pillows, and epithermal-like zinc stringer mineralization that, taken together, indicate a shallow subaqueous depositional setting (Hudak et al., 2002a; Hudak et al., 2002b; Hudak et al., 2007; Hoffman, 2007). The overlying Central Basalt Sequence/Armstrong Lake Basalts comprise exceptionally well-preserved, generally sparsely amygdaloidal sheet flows and single selvege pillow lavas which are locally interstratified with subordinate banded iron formation and chert exhalite horizons, mafic tuff (interpreted primarily to be resedimented hyaloclastite), lithic wackes and polymict breccias that have been interpreted to have formed in a deep subaqueous setting (Peterson and Patelke, 2003; Peterson et al., 2005).

Major and trace element data (Hudak et al., 2007; Hoffman, 2007; Jansen, in press) indicate that the lithogeochemistry of volcanic rocks in the Lower Ely Greenstone is more complicated than previously thought (e.g. Southwick et al., 1998). In the Fivemile Lake Sequence, basalt and basalt-andesite flows and volcanoclastic rocks illustrate arc-like lithogeochemical characteristics, and rhyodacites and rhyolites have FI- and FII chemistries. In the Central Basalt Sequence, basalt and basalt-andesites with arc-like lithogeochemical signatures transition up-section into basalts with MORB-like trace element patterns and rhyodacites and rhyolites illustrate FI, FII, and FIII lithogeochemical characteristics. Hudak et al. (2007), Hoffman (2007) and Jansen et al. (in press) have proposed a tectonic model for the development of the Lower Ely which encompasses initial arc development followed by back-arc rifting and associated MORB-type and FIII-type volcanism immediately prior to the deposition of the overlying Soudan Iron Formation. This model appears to be most consistent with the observed stratigraphic, volcanological, and lithogeochemical characteristics of the Lower Ely, as well as studies of both ancient and modern back-arc basins which illustrate that the development of back-arc basins in oceanic volcanic arc settings are commonly associated with the presence of vigorous submarine hydrothermal activity which may produce Algoma-type iron formations and/or volcanogenic massive sulfide deposits (Franklin et al., 2005; Piercey et al., 2004).

Geological mapping by Peterson (2001) has indicated the presence of a regional semiconformable quartz-epidote alteration zone extending for at least 19 km along strike within the Lower Ely along the north limb of the Tower-Soudan anticline. This type of alteration is a common feature in many Archean VMS camps (e.g. Noranda (Gibson, 1989) and Snow Lake (Skirrow and Franklin, 1994)), and is attributed to silica- and calcium-dumping that occurs in the deep, sub-seafloor as downwelling hydrothermal fluids are heated to temperatures in excess of 350°C (Franklin, 1986; Franklin, 1993; Franklin et al., 2005). Semiconformable alteration zones associated with VMS systems are generally much larger in area than their associated mineralization, and therefore provide exploration geologists regional areas in which to concentrate more detailed, follow-up field mapping, geochemical studies, and geophysical surveys for identifying VMS targets.

The composition and distribution of hydrothermal alteration mineral assemblages in the Lower Ely is similar to that described in major lava-flow dominated VMS mining districts worldwide (e.g. the Noranda Camp, Quebec; Morton and Franklin, 1987; Franklin, 1996; Gibson et al., 1999; Hudak and Morton, 1999; Peterson, 2001; Hudak et al., 2002a,b). Results of recent studies in the Vermilion district (Hudak et al., 2002a; Hudak et al., 2002b; Hocker et al., 2003; Hudak et al., 2004; Hudak et al., 2006; Hoffman, 2007) indicate that not only are the compositions and geometries of the regional alteration mineral assemblages identical to those present in many lava flow dominated massive sulfide mining districts, but that detailed alteration mineral chemistries (Hocker et al., 2003) are also consistent with those associated with the VMS ore deposits in these mining camps. These two observations suggest that the processes that formed the alteration mineral assemblages in the Lower Ely were similar to those that formed equivalent alteration zones in well-established VMS mining camps.

A general genetic model for the formation of VMS deposits and associated hydrothermal alteration zone, as recently presented by Franklin et al. (1998), requires convective metalliferous hydrothermal fluid generation in the sub-seafloor environment via heating of down-welling seawater and leaching of metals from the enclosing volcanic and sedimentary strata (Fig. 7-3). The size of a convective hydrothermal system is a function of the abundance of heat in the upper two kilometers of the sub-seafloor crust (Franklin, 1996; Franklin et al., 1998). The intrusion of hypabyssal synvolcanic dikes and/or sills into the shallow sub-seafloor may vigorously enhance the dynamics of convective hydrothermal cells (Campbell et al., 1981). On reaching a critical reaction temperature of $\sim 350^{\circ}\text{C}$, sustained acid pH in the hydrothermal fluid (evolved fluid) is achieved, and metals are leached from the rocks into the evolved fluid via primary mineral breakdown by calcium metasomatism, silicification, and hydrolysis reactions (Seyfried et al., 1999). In basalt-dominated systems (such as that in the Lower Ely), leaching-related alteration of mafic "source" zones (lower semi-conformable alteration) forms a mineral assemblage composed of albite-epidote-zoisite/clinozoisite-actinolite-quartz. These zones are variably metal-depleted, and are characterized by patchy silicification and epidotization associated with areas metasomatically enriched in silica and calcium.

In lava flow-dominated stratigraphic sequences, regionally confined discordant "pipe-like", and more regionally extensive "semiconformable" alteration zones are present (Morton and Franklin, 1987). The "pipe-like" semi-conformable alteration zones are closely associated with zones of cross-stratal permeability (e.g. synvolcanic fault zones), and are characterized by well-defined vertically extensive alteration zones containing anomalous abundances of sericite, chlorite (both Fe- and Mg-rich varieties), actinolite/ferroactinolite, quartz, pyrite, and locally, chalcopyrite and/or pyrrhotite. Semiconformable alteration zones extend for several kilometers to tens of kilometers in the rocks stratigraphically beneath and adjacent to VMS mineralized horizons (Santaguida et al., 2002a; Santaguida et al., 2002b). In mafic-dominated volcanic environments, such alteration typically is associated with regional zones of spilitization (an alteration assemblage composed of albite + quartz + Mg-rich chlorite $\pm$ sericite), silicification (quartz $\pm$ albite), and epidote-quartz alteration (epidote + quartz $\pm$ actinolite $\pm$ carbonate) (Morton and Franklin, 1987; Gibson et al., 1999; Santaguida et al., 2002a, Santaguida et al., 2002b). Regional semiconformable alteration zones in felsic rocks in VMS producing camps such as Noranda (Quebec) or Sturgeon Lake (Ontario), typically comprise extensive zones of spilitization, silicification, and sericitization (sericite + quartz $\pm$ Mg-rich chlorite) (Morton and Franklin, 1987; Gibson et al., 1999).

Both discordant and semiconformable alteration zones have been discovered in the Vermilion district and have been described by Hudak and Morton (1999), Peterson (2001), Odette et al. (2001), and Hudak et al. (2002a). Semiconformable alteration zones in the Lower Ely are dominated by mineral assemblages containing various proportions of quartz, epidote, zoisite/clinozoisite, Fe-chlorite, Mg-chlorite, actinolite, ferroactinolite, sericite/pyrophyllite, and albite. Odette et al. (2001a, 2001b) and Hudak et al. (2002a) have shown via mass balance analysis that semiconformable quartz + epidote $\pm$ actinolite $\pm$ albite $\pm$ chlorite alteration mineral assemblages in the Fivemile Lake area are metasomatically enriched in calcium

and silica, and depleted in base metals (copper and zinc) by 50-90%. Pipe-like, northeast-trending disconformable alteration zones in the Lower Ely are largely composed of Fe-rich chlorite, sericite/pyrophyllite, actinolite and/or ferroactinolite. Pipe-like alteration zones that have been mapped up-section have, to date, not led to the discovery of economically significant VMS deposits, but have been instrumental in locating potential base metal sulfide-bearing stratigraphic horizons and localized chemical exhalites.

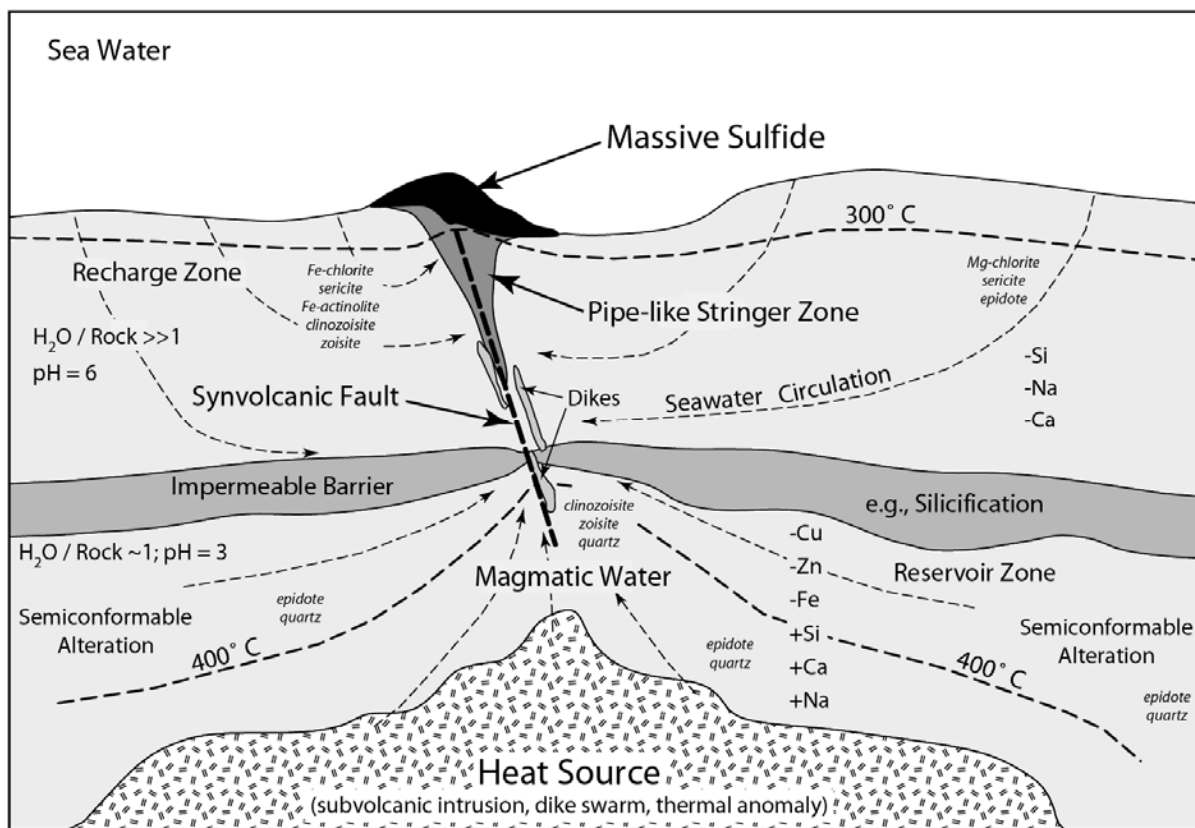


Figure 7-3. Simplified schematic model of a convective hydrothermal system associated with the formation of Noranda-type (Morton and Franklin, 1987) or lava-flow dominated-type (Gibson et al., 1999) VMS deposits (modified from Franklin, 1996).

Lode Gold Ore Deposit Model and Gold in the Vermilion District

The brief description of Archean lode-gold deposits that follows is presented as both a basic reference and also to highlight the important features of the model that will be seen during the field trip. Archean lode-gold deposits are one category of ore deposit classified as mesothermal lode-gold deposits (Hodgson, 1993). This deposit type has also been called orogenic gold (Groves et al., 2000), greenstone gold (Robert et al., 1991), Archean lode-gold, mesothermal gold-quartz veins, shear-hosted gold, low-sulfide gold-quartz veins (Berger, 1986b), lode-gold, Mother Lode veins (Bohlke and Kistler, 1986), and iron formation-hosted gold deposits (Berger, 1986a; McMillan, 1996; Rye and Rye, 1974; Fripp, 1976; Kerswill, 1993; Thorpe and Franklin, 1984; and Vielreicher et al., 1994).

Whatever the name, they are a widespread group of epigenetic ore deposits that have formed in similar settings throughout geologic time. In general, the deposits form during compressional or transpressional deformation at convergent plate margins in accretionary or collisional orogens (Fig.-7-4). They form over a large crustal-depth range (2 to 20 km) from deep-seated, low-salinity $\text{H}_2\text{O}-\text{CO}_2 \pm \text{CH}_4 \pm \text{N}_2$ ore fluids, with Au transported as reduced sulfur complexes. The ore fluids are generated during lower

crustal metamorphism from dehydration reactions. Regional structures provide the main control on distribution of lode gold deposits and mining camps. In many terranes, first-order faults or shear zones appear to have controlled regional fluid flow, with greatest ore-fluid fluxes in, and adjacent to, subsidiary faults, shear zones and/or large folds. Highly competent and/or chemically reactive rocks are the most common hosts to the larger deposits. Gold deposition occurs late during the evolutionary history of the host terranes, normally within D_3 or D_4 in a D_1 - D_4 deformation sequence. Absolute ages of mineralization support their late-kinematic timing, and, in general, suggest that deposits formed diachronously towards the end of the evolutionary history of hosting orogens.

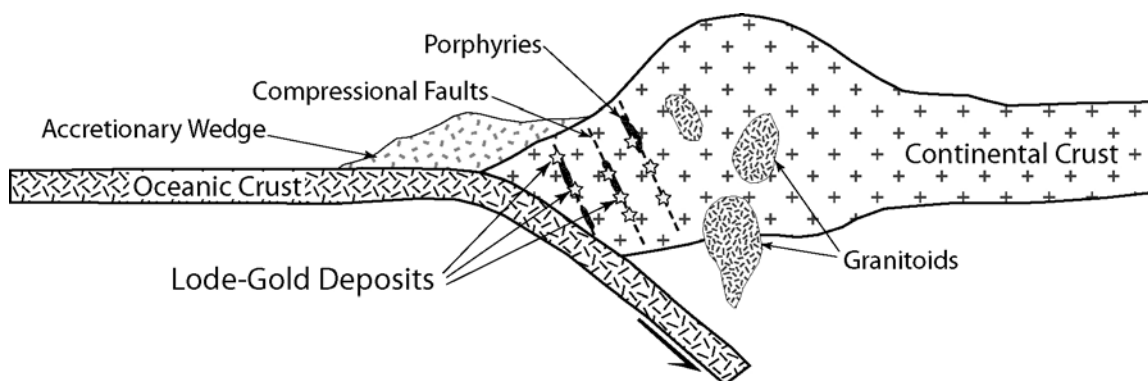


Figure 7-4. Generalized tectonic model for the formation of mesothermal gold deposits, after Groves et al., 2000.

The late timing of lode-gold deposits is critical to geology-based exploration methods, and hence mineral potential evaluations for these deposits. The late timing is critical because of the present structural geometry of: (1) the deposits, (2) the mining camps, and (3) the enclosing geologic terranes are essentially all similar to the structural geometry during gold mineralization. Therefore the interpretation of bedrock geological maps and cross-sections can be used to discern the physical conditions that existed at the time of ore deposition. Exploration for mesothermal lode-gold deposits should incorporate various aspects of the ore deposit model into criteria that can vector into the most favorable areas for hosting such mineralization. The most fundamental characteristic of this class of deposit is the spatial association of the deposits to regional structures. Zones of widespread carbonate alteration (adjacent to regional structures) should be identified and used to focus subsequent exploration. Within carbonate alteration zones, gold is typically only in areas containing quartz veins, silicification, and/or sericite alteration (with or without sulfides). Two general structural controls on the orientation of lode gold ore shoots include deflections and curvatures of shear zones, and where high strain zones intersect favorable geological elements (Poulsen and Robert, 1989).

A widespread area of gold mineralization occurs in numerous prospects east of Lake Vermilion, within the Vermilion greenstone belt of northeastern Minnesota. The mineralization occurs in rocks of the Neoproterozoic (~2.7 Ga) Bass Lake sequence (Peterson and Jirsa, 1999) of the Wawa subprovince of the Canadian Shield. This zone of abundant gold mineralization is bounded to the south by the Mud Creek shear zone and to the north by the Vermilion fault. The main access to these prospects is along the Mud Creek road (St. Louis County 38). A brief period of mineral exploration for lode-gold deposits in this immediate area of the Vermilion district occurred in the mid 1980s to early 1990s. These programs typically consisted of grid-based geologic mapping, bedrock sampling, ground geophysics, and the completion of soil geochemical surveys. Conversations with many of the people involved in gold exploration programs in the immediate field trip area (centered on Section 6, Township 62 North, Range 14 West), and compilation of all exploration data from the district as a whole (data from the terminated lease files of the Minnesota DNR), has led to the conclusion that interpretation of linear structural elements exposed in outcrops were not used in designing exploratory drilling plans. Therefore, many of the prospects discovered as a result of these exploration programs remain untested by drilling.

FIELD TRIP

All stop locations are given in Universal Transverse Mercator coordinates (UTM), Zone 15, using the North American Datum of 1983 (NAD83). Section subdivisions read from smallest to largest quarter; e.g., “NW, SE” should be read “NW quarter of the SE quarter.” The small map insets showing stop locations are taken from USGS 7.5-minute topographic quadrangles listed with each stop. The first day of the field trip will include stops located between the towns of Tower and Ely. A more detailed geological map with stop locations is given in Figure 7-5.

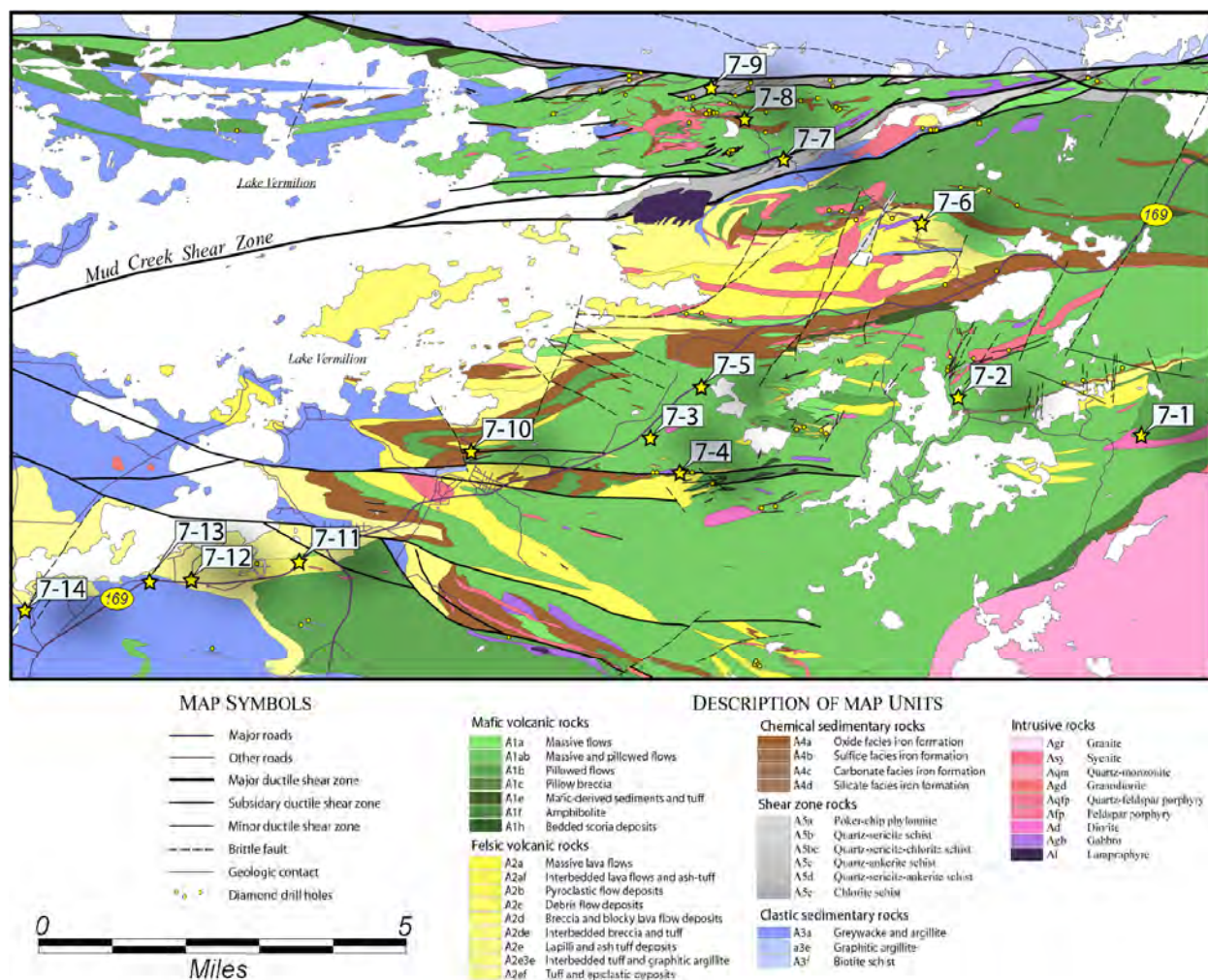
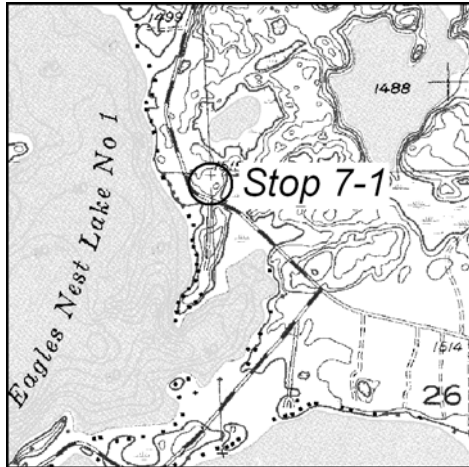


Figure 7-5. Simplified geological map of the field trip stops in the Vermilion district. Geology modified from Peterson, 2001.

FIELD TRIP STOPS

From Ely, our route into the Vermilion district will include driving west along Minnesota Highway 169 to the Bear Head Lake road (County road 128). Turn left (south) and continue approximately 1.6 miles to an outcrop on the east side of the roadway.



STOP 7-1.

Silicified Fivemile Lake sequence pillow lavas **/ Regional semi-conformable alteration**

Location: T.62N., R.14W., sec.22 SE, SE;
roadside outcrop along Highway 128 (Bear
Head Lake State Park road)

Eagles Nest 7.5-minute quadrangle

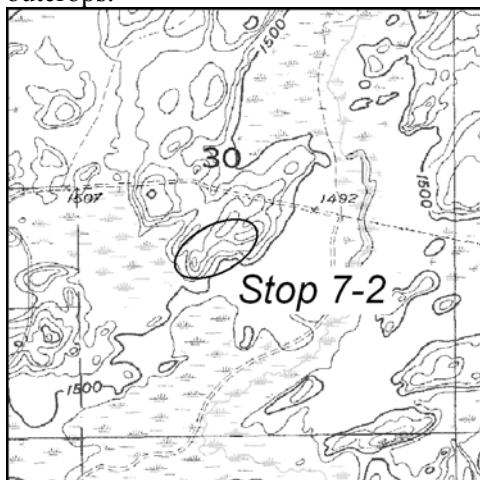
UTM: 567,810E/5,297,800N

DESCRIPTION:

At this location we can observe part of the regionally extensive quartz-epidote alteration zone. The outcrop contains relatively undeformed bun- and mattress-shaped pillows. Interpillow hyaloclastite zones are generally pale to dark green in color, and are chlorite and/or actinolite-rich. Minor red-brown staining locally occurs in these zones, and is indicative of the presence of trace amounts of pyrite and/or chalcopyrite. Pillow selvages commonly contain up to 10% round to oval, pipe-like quartz-epidote and/or actinolite chlorite amygdules. The cores of the pillows are typically pale green gray in color due to nearly wholesale replacement of the original igneous minerals by quartz and epidote. This quartz-epidote alteration is typical for much of the Lower Member of the Ely Greenstone (Lower Ely), and is one of the most important components of possible VMS exploration in the district (leaching of Cu & Zn) out of a large volume of rock due to hydrothermal alteration.

NEXT:

Continue on Highway 128 southeast for approximately 2.2 miles to the Purvis Forest Management Road. Turn left and continue about 0.4 mile to logging road on the right side (south). Follow logging road approximately 0.15 miles to a series of outcrops.



STOP 7-2

Xenolithic hornblende diorite, Purvis pluton

Location: T.62N., R.13W., sec.30 NE, SW.

Eagles Nest 7.5-minute quadrangle

UTM: 571,805E/5,296,855N

DESCRIPTION:

The Purvis pluton is an east-west trending, moderate-sized (~3km³), sill-like multiphase dioritic to tonalitic intrusion with a strike length of 5.7 km and a thickness that ranges from 100-1200 meters

(Peterson, 2001). This intrusion occurs in the lower stratigraphic section of the north limb of the Tower-Soudan anticline (Peterson and Jirsa, 1999; Jirsa et al., 2001). Recent work by Drexler and Hudak (in press) indicate that the intrusion has several phases, including 1) xenolithic hornblende diorite; 2) xenolithic hornblende tonalite; 3) xenolithic leucotonalite; 4) leucotonalite and trondhjemite; and 5) leucotonalite dikes.

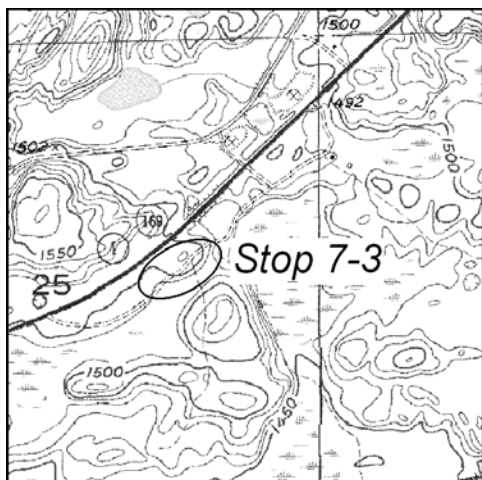
Detailed field mapping by Peterson (2001), Hovis (2001) and Drexler et al. (2004) suggest that the Purvis pluton is a synvolcanic intrusion based on the following characteristics: 1) it lacks a contact metamorphic aureole; 2) its uppermost contact is proximally associated with intense, semiconformable quartz + epidote alteration zones; 3) D₂ deformation fabrics occur in both the intrusion and the surrounding country rocks; and 4) early xenolithic diorite phases are cross-cut by thin, commonly D₂-deformed dikes of younger tonalite and trondhjemite phases. Galley (2002) and Galley (2003) have indicated that these characteristics are key features of synvolcanic intrusions temporally associated with the genesis of many Precambrian VMS deposits. Peterson (2001) has suggested that the Purvis pluton may have been the heat source that drove hydrothermal systems that produced the Eagles Nest and Purvis Road VMS prospects. This locale offers an opportunity to investigate the xenolithic hornblende diorite phase of the Purvis pluton. The outcrop adjacent to the road predominately contains four types of xenoliths: 1) dark green xenoliths of amygdaloidal (5-8%) basalt-andesite pillow lavas which locally have preserved selvages and interpillow hyaloclastite, and are locally contact metamorphosed along their margins; 2) pale green epidote + quartz-altered basalt-andesite lava xenoliths that are up to 15 cm in diameter; 3) rare coarse-grained gabbro/diorite xenoliths up to 3 cm in diameter; and 4) rare <1-2 cm diameter subangular chert xenoliths. Large iron-formation xenoliths up to several meters in diameter, and amphibolite xenoliths up to several centimeters in diameter, may be observed in xenolithic hornblende tonalite outcrops least of this location.

Iron-formation xenoliths present in outcrops east of here were likely derived from iron-formation horizons that occur immediately southwest of Purvis Lake. Basalt and altered basalt fragments also were derived from the surrounding Lower Ely. The presence of epidote-quartz altered mafic xenoliths suggests that this phase of the Purvis pluton stopped its way upward into an earlier-formed proximal zone of quartz-epidote alteration formed from high temperature seawater-rock interaction (e.g. Galley, 2003). Amphibolite xenoliths are believed to represent contact metamorphosed basalt fragments based on petrographic similarities (Drexler et al., 2004). Drexler et al. (2004) have shown that coarse-grained gabbro/diorite fragments likely represent xenoliths of the earliest phases of the pluton.

Studies of ancient VMS deposits has documented that the deposits commonly occur in depressions on the paleo-seafloor (3rd-order basins) while modern deposits on the seafloor are found on high-standing structures, such as ridges. These differences are probably more apparent than real, in that the modern deposits are generally confined to the axial graben, or depression, of what are otherwise are high-standing structures. In addition, both ancient and modern deposits occur in areas of anomalously high heat flow, generally linked to synvolcanic intrusions beneath the hydrothermal systems. The recent mapping in the Purvis Road area has shown the presence of all of the attributes of typical VMS-forming hydrothermal systems. These attributes include a synvolcanic intrusive heat source (the Purvis pluton), a paleotopographic high-standing structure, VMS-style alteration mineral assemblages, and the presence of Cu and Zn-rich massive sulfide (recent logging in this area has exposed numerous angular boulders of massive sulfide in the basal till).

NEXT:

Return to Highway 169, turn left (west) and travel approximately 4.4 miles to the junction with the Murray Forest management road. Turn left (south) and travel approximately 0.2 miles to south verging bend in the road. Get out and walk along the old logging road to the west.



Stop 7-3.
Shallow water volcanic rocks of the
Fivemile Lake sequence. Andesite,
Rhyolite, and Scoria

Location: T.62N., R.15W., sec.25 SW, NE

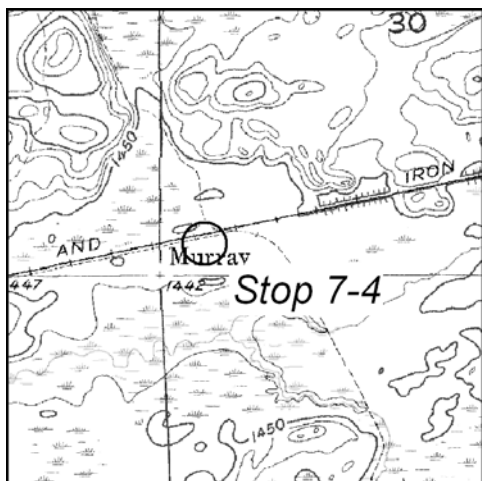
Soudan 7.5-minute quadrangle

UTM: 560,980E/5,297,025N

DESCRIPTION:

At this stop, we'll be examining a series of outcrops that display the varied geology of the shallow-water Fivemile Lake sequence (Peterson and Patelke, 2003). The short traverse will include outcrops of highly vesicular/amygdaloidal basaltic andesite, rhyolite lava flows and breccias, and a unit of andesitic scoria. Rocks of similar texture occur throughout the central core of the Lower Ely greenstone.

NEXT: Return to the bus and continue south along the Murray Forest Management road for approximately 0.6 miles to the junction of the old DM&IR rail line. Get out and walk west along the rail line for 50 meters to the outcrops on the north and south side of the rail line.



Stop 7-4.
Gold prospect along the Murray Shear Zone

Location: T.62N., R.14W., sec. 30, SW, SW

Soudan 7.5-minute quadrangle

UTM: 561,490E/5,296,205N

DESCRIPTION:

This is one of the few gold prospects in the lower member of the Ely Greenstone. South of the old rail line, intense shearing associated with the north edge of the Murray shear zone culminated with the formation of chlorite-ankerite-sericite schists. In the mid-1980s, Newmont Exploration discovered lode gold mineralization along the northern margin of the Murray shear zone. Gold mineralization in this area, named the Murray prospect by Newmont, is associated with quartz-carbonate-pyrite-galena-tetrahedrite veins in strongly sheared and carbonatized rocks. Newmont reported values up to 12.5 g/t gold during the course of their exploration.

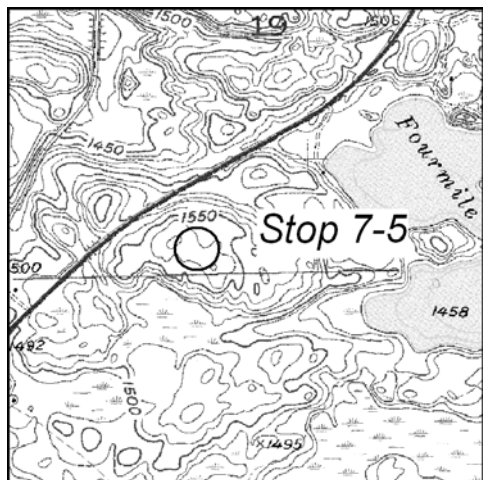
An estimate of the amount of displacement within the panel of rocks bounded by the Murray shear zone is given in Table 7-2 (Peterson and Patelke, 2003). These values were calculated geometrically by using the average plunge of measured lineations (71°) and two measured lines of possible correlative stratigraphy offset by the bounding shear zones. The calculated total displacement values (net slip) are quite large (up to 13.8 km, or 43,000 feet of net slip), but the displaced rocks would still fall within the range of depth generally associated with greenschist facies metamorphism.

Table 7-2. Calculated displacement along the Murray shear zone

Lineation Plunge	<i>Calculated Displacement (Kilometers)</i>		
	Strike Slip	Dip Slip	Net Slip
71°	4.5	13.1	13.8
71°	3.0	8.7	9.2

NEXT:

Return to Highway 169 via the Murray Forest Management Road. Turn right on Highway 169 and travel approximately 0.7 miles to the junction of a logging/gravel road on the south side of the highway. Walk up the road to the southwest to the very large outcrop on the top of the hill.



Stop 7-5.

Central Basalt Sequence Sheet Flows, Pillow Lavas, and Perlitic Hyaloclastite

Location: T.62N., R.14W., sec 19, SE, SW,

Soudan 7.5-minute quadrangle

UTM: 562,000E/5,297,800N

DESCRIPTION:

The Central Basalt sequence (Peterson and Patelke, 2003) comprises a steeply north-dipping (75°-vertical), north-facing sequence of sparsely amygdaloidal pillowed and massive lava flows of basalt andesite to basalt composition that are believed to be correlative with the tholeiitic Armstrong Lake volcanic sequence mapped in the Eagles Nest quadrangle (Jirsa et al., 2001). Hudak et al. (2007) and Jansen et al. (in press) have shown that the lowermost sections of the Central Basalt Sequence is composed of submarine basaltic andesite to basalt lava flows that have rare earth element lithogeochemical patterns similar to mafic rocks in oceanic volcanic arcs. However, locally, submarine basalt lava flows that occur within 50-200m stratigraphically below the contact between the Central Basalt Sequence and the overlying Soudan Member of the Ely Greenstone Formation illustrate MORB-like lithogeochemical patterns, and have suggested that this may document a change from an oceanic arc to back-arc environment immediately prior to the deposition of the Soudan Member. Relative to massive and pillowed basalt and andesite flows in the Fivemile Lake sequence, Central Basalt sequence lavas flows are notably less amygdaloidal, and lack multiple pillow rind structures. In addition, the Central

Basalt sequence lacks the thick sequences of scoriaceous basalt-andesite lapilli tuffs that are commonly interstratified with lava flows in the Fivemile Lake sequence. These characteristics of the Central Basalt sequence indicate eruption and deposition in a deeper submarine environment than the stratigraphically older Fivemile Lake sequence, and suggest overall increasing water depth during the temporal development of the Lower Ely. Deepening of the water column could be accommodated by extensional tectonics and normal faulting associated with the development of the proposed back-arc environment.

The outcrop comprises two east-southeast striking massive basalt flows, ranging from at least five to nine meters in thickness, that are separated by a ten meter thick flow unit comprising pillows and pillow lobes (Fig.7-6). All three lava flows at this vicinity illustrate tholeiitic, MORB-like lithogeochemistries (Hudak et al., 2007).

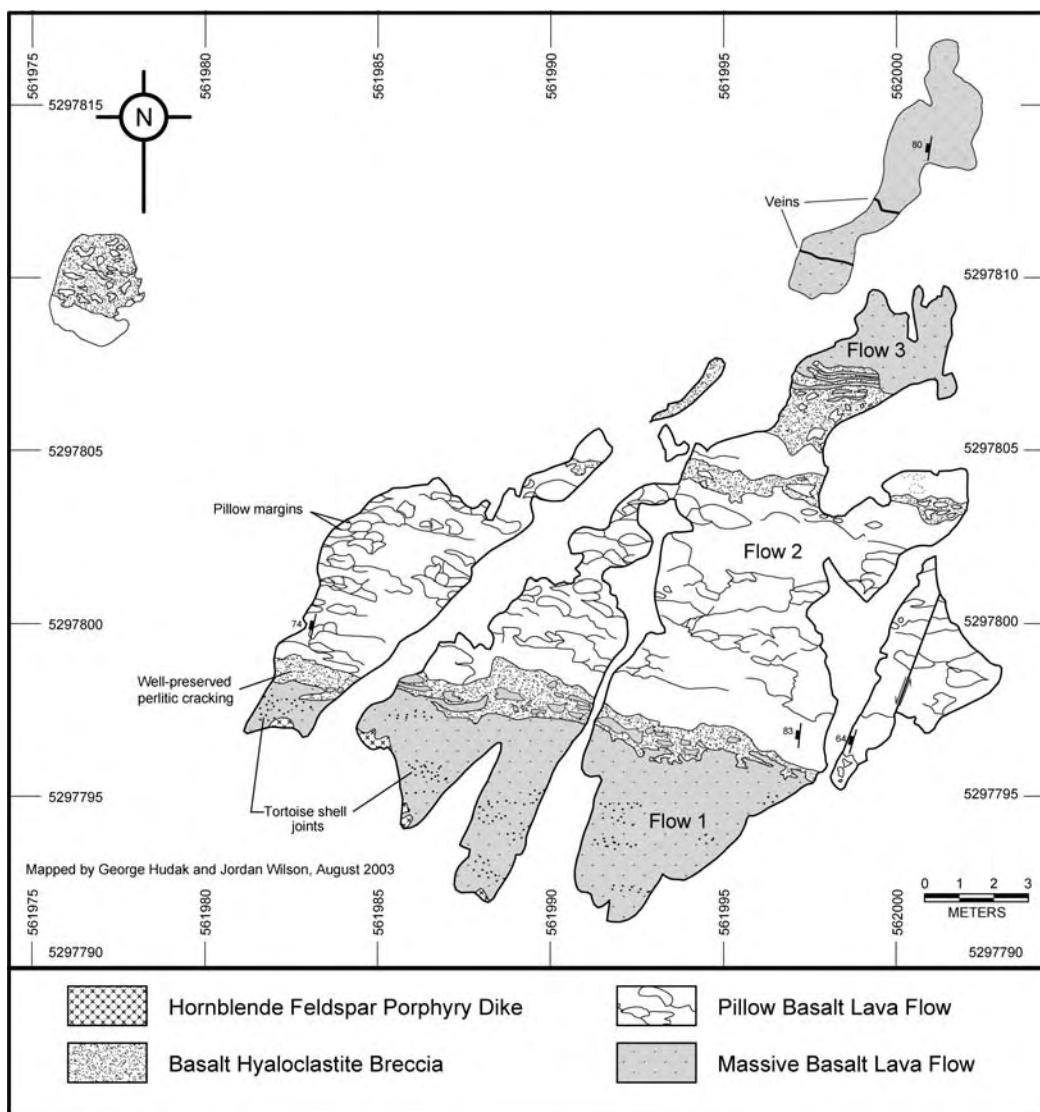


Figure 7-6. Detailed geological map of sheet flows, pillow lavas, *in-situ* hyaloclastite and associated “self-peperite”.

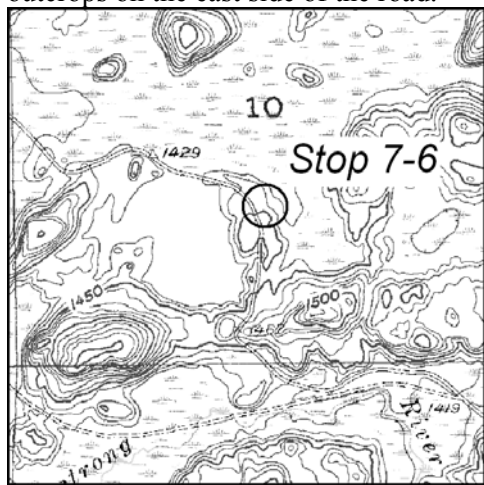
Flow 1, at the southern part of the outcrop, is composed of a pale- to dark green, faintly feldspar-phyric (~10% 0.5-1 mm laths), sparsely amygdaloidal, basalt sheet flow that locally exhibits tortoise-shell jointing formed in response to contraction during cooling. The uppermost 10-40 cm of the coherent part

of Flow 1 is generally silicified and epidotized. Petrographic observations indicate that this section of the flow also contains up to 70% <0.1 cm round spherulites. An irregular contact occurs between the coherent basalt flow and an overlying one- to two meter thick unit of dark green, exceptionally well-preserved perlitic in-situ hyaloclastite and associate self-peperite (c.f. Batiza and White, 2000). The hyaloclastite formed from non-explosive fracturing of the basalt glass developed on the flow top due to quenching by water, whereas the perlite formed following deposition by hydration of volcanic glass. An irregular contact occurs between the hyaloclastite and Flow 2, which is composed of north-facing mattress- to bun-shaped pillow lavas and pillow lobes with numerous “neck and knob” structures. Individual pillows have well developed perlitic hyaloclastite margins that range from 1-4 cm in width. Pillow buds indicate propagation from east to west, suggesting the volcanic vent was located east of this location. The coherent pillows and lobes are overlain by up to 2.5 meters of hyaloclastite breccia that contains 20-40% subround to subangular pale gray green basalt lapilli in a jigsaw puzzle-fit dark green perlitic hyaloclastite matrix.

The upper contact of Flow 2 and the overlying basalt sheet flow (Flow 3) is irregular, and is marked by thin (1-8 cm thick), sheet-like basalt fragments that are up to 1.6 meters in length. These fragments locally appear to be isoclinally folded about an east-west-trending fold hinge. Although the genesis of this structure is currently not well understood, it may be due to syneruptive deformation of either thin slabs of hot, basal flow margin crust from the overlying flow, or thin injections of basalt magma into the hyaloclastite from either the underlying pillows or the overlying sheet flow. Flow 3 comprises an at least ten-meter thick pale green-gray, slightly feldspar-phyric, sparsely amygdaloidal sheet flow. Steep, NNE-trending west dipping D₃ joints are well developed in this unit, as are lens-shaped psuedo-pillows that are up to 50 cm in diameter.

NEXT:

Return to Highway 169, turn right and travel approximately 3.1 miles to the junction of the Mud Creek road (County 38). Turn left (north) on 38 and travel approximately 1.5 miles to a series of low-lying outcrops on the east side of the road.



Stop 7-6.

Fragmental rocks of the Gafvert Lake sequence.

Location: T62N., R14W., sec. 10, NE,SW

Eagles Nest 7.5-minute quadrangle

UTM: 567,000E/5,301,490N

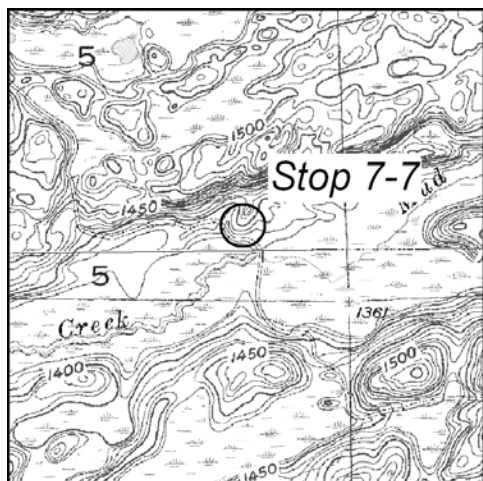
DESCRIPTION:

The informally named Gafvert Lake sequence (Peterson and Jirsa, 1999) is interpreted to represent an Archean stratovolcano of andesitic to dacitic composition that stratigraphically overlies rocks of the Ely Greenstone. The complex includes lava flows, fragmental rocks (tuff, lapilli tuff, tuff breccia, debris flow deposits) and porphyritic intrusions. The widespread nature of dacitic fragmental rocks of Gafvert affinity in the Vermilion district indicates that repeated episodes of explosive volcanism (Crater Lake type caldera formation) occurred in the area. Capping the central portion of the Gafvert Lake sequence are a number of thick massive pyrite horizons, that have metal signatures associated VMS, epithermal,

and biologic affinity (Peterson, 2001). We will examine a series of outcrops of fragmental dacitic deposits located on the east side of the Mud Creek road.

NEXT:

Continue northwest on 38 for approximately 2.1 miles to the boat landing parking area along Mud Creek. Walk approximately 100 meters north along road to the outcrop along the east side of the roadway.



STOP 7-7.

Mud Creek shear zone

Location: T.62N., R.14W., sec. 5, SE, SE;
Outcrop just northwest of Mud Creek near road.

Chad Lake 7.5-minute quadrangle.

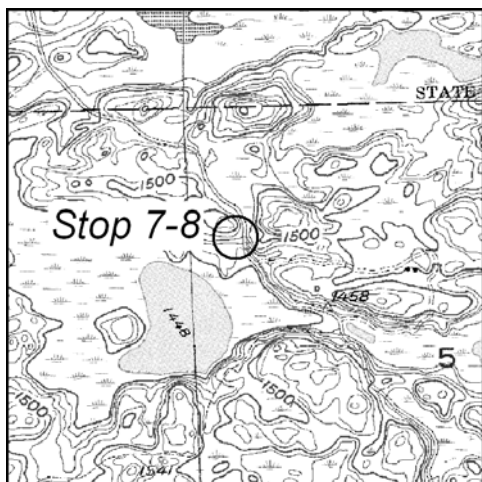
UTM: 564,230E/5,302,800N

DESCRIPTION:

The regional scale Mud Creek shear zone occupies the east-northeast trending valley of Mud Creek, which is clearly visible at this location. This shear zone separates rocks of the Newton Belt (here the Bass Lake sequence) to the north and rocks of the Soudan Belt (Gafvert Lake sequence and the Upper Ely Greenstone Formation) to the south. Development of this shear zone is a product of largely dextral transpressive deformation that has been partitioned into discrete zones, presumably late in D₂ deformation. It is generally believed that gold-bearing mineralization was introduced during these later deformation events, and the Mud Creek shear zone and environs continue to attract considerable attention as a gold target. The Mud Creek shear zone is analogous with major faults (Destor-Porcupine fault) and “breaks” (Cadillac-Larder Lake break) of major lode-gold mining districts in Canada. Historic gold assays taken from rocks of the shear zone itself are essentially devoid of gold, as is the case for most major structures within Archean lode-gold mining camps. This series of outcrops are located within the northern margin of the internal highly strained zone of the shear, and include outcrops of: (1) ankerite-sericite-quartz-green mica-pyrite schist with quartz and tourmaline knots, and (2) highly folded and compositionally banded phyllites with quartz veins. The protolith for these rocks are unknown, because of the intense deformation, but could be any of several rock types in the region, including quartzofeldspathic porphyry, metavolcanic rock, or graywacke.

NEXT:

Drive northwest along County 38 approximately 1.1 miles to widened portion of the road.



Stop 7-8.

Sheared quartz-feldspar porphyry, basal till, and detailed mapping interpretations

Location: T62N., R14W., sec. 5, SW, NW.

Chad Lake 7.5-minute quadrangle

UTM: 563,190E/5,303,615N.

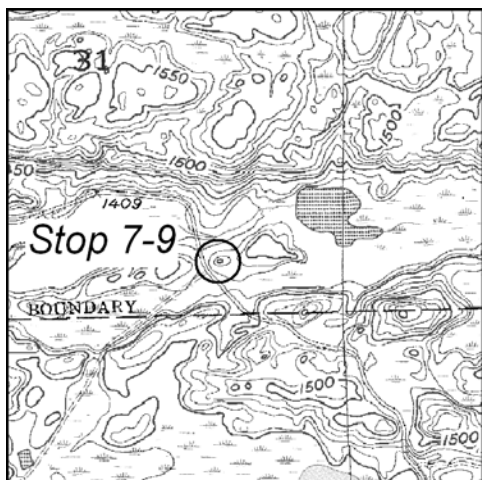
DESCRIPTION:

East of Lake Vermilion, the geology of the Bass Lake sequence is dominated by six basic rock types, which include: (1) Tholeiitic pillowed basalt flows interpreted to have formed in a deep-water setting based on volcanic textures; (2) Gabbro sills interpreted as synvolcanic in age due to their stratigraphic continuity and similar deformation as the enclosing pillowed basalts; (3) Felsic porphyries (feldspar porphyry and quartz-feldspar porphyry) interpreted to have intruded during late stages of D₂ deformation based on field relationships and geochronology (quartz-feldspar porphyry from the Pac Man Pond prospect returned a ²⁰⁷Pb/²⁰⁶Pb age of 2683.0 +/- 1.4 Ma (Peterson et al., 2001)); (4) Algoma-type iron-formation; (5) Thinly-bedded argillite and siltstone; and (6) Sheared rocks, which are dominated by chlorite-rich schist, phyllite, and phyllonite. In addition, localized areas of fragmental felsic volcanic rocks occur stratigraphically below distinct iron-formation horizons.

In the last twenty years, numerous gold prospects have been discovered in the eastern portion of the sequence. These prospects generally fall into one of three categories; (1) auriferous quartz-carbonate-pyrite veins and sulfidized zones in iron-formation; (2) auriferous quartz-sericite-ankerite-pyrite schists; and (3) felsic intrusive-hosted auriferous quartz veins and stockworks. All of the prospects are found within areas of moderate to strong iron-carbonate alteration, with the best mineralization commonly found within sericitic alteration zones. Numerous equigranular and porphyritic felsic intrusions occur within the areas of alteration and gold mineralization, and are a good guide for locating mineralized structures. The gold mineralization is generally related to deformation in subsidiary structures associated with movement along the D₂ Mud Creek shear zone. Widening of the roadbed of County 38 in 2003 exposed a number of new outcrops and cuts into the basal till in this area. Detailed geologic mapping of gold prospects north of the Mud Creek shear zone by Peterson and Patelke (2004a) included mapping these new exposures of the Bass Lake sequence. For this stop, we will traverse along County 38 and look at these new exposures.

NEXT:

Continue northwest along County 38 approximately 0.55 miles to a small yellowish outcrop on the east side of the road.



Stop 7-9.

The Kerr McGee gold prospect

Location: T63N., R14W., sec. 31, SE,SE

Chad Lake 7.5-minute quadrangle

UTM: 562,480E/5,304,610N

DESCRIPTION:

The Kerr McGee gold prospect is hosted within an extensive zone of highly strained rocks, interpreted to be a subsidiary structure associated with the Mud Creek shear zone. Moderate to high-grade gold mineralization at the Kerr McGee prospect occurs within multiple thin (0.2 – 2.0 meter) zones of quartz-sericite-ankerite-pyrite ± green mica ± tourmaline schist hosted by an extensive zone of essentially gold-barren chlorite-rich schist. Thin and probably boudined iron-formation horizons occur locally in the chlorite-rich schist, and locally are strongly mineralized in this area. Mineralized zones locally contain extensive foliation and shear parallel quartz, ankerite, and/or quartz-ankerite veins, and may widen in zones of silicification. The style of gold mineralization exposed in the Kerr McGee prospect is similar to both the Clear Cut (~½ mile west) and Railroad Zone (1½ miles east) prospects. In fact, the sericitic zone that hosts the mineralization may have continuity to both of these other prospects.

Three-dimensional visualization (Fig. 7-7) of the detailed lithological and structural mapping by Peterson and Patelke, (2004a) within the Kerr McGee prospect area reveals important information that can be used to design drilling plans that significantly increase the chance of intersecting gold mineralization exposed in outcrop at the surface. For example, drill hole RC-3, which is located 100 meters east of the main gold showing on the eastern side of this knob, was drilled due north (at a dip of 45°) and targeted to intersect the mineralization exposed in outcrop at the Kerr McGee showing. Chevron Resources drilled this hole in 1987, at the western boundary of their lease property (the Kerr McGee prospect was then held by Kerr McGee). Detailed structural mapping in these outcrops reveals that the rocks within the mineralized zone have moderate to strong elongation and intersection (foliation and shear planes) lineations trending 60° and dipping northeast at 72°. The best interpretation of the down-dip orientation of the mineralized zone is this lineation trend and plunge, and drill hole RC-3 never intersected the mineralized zone.

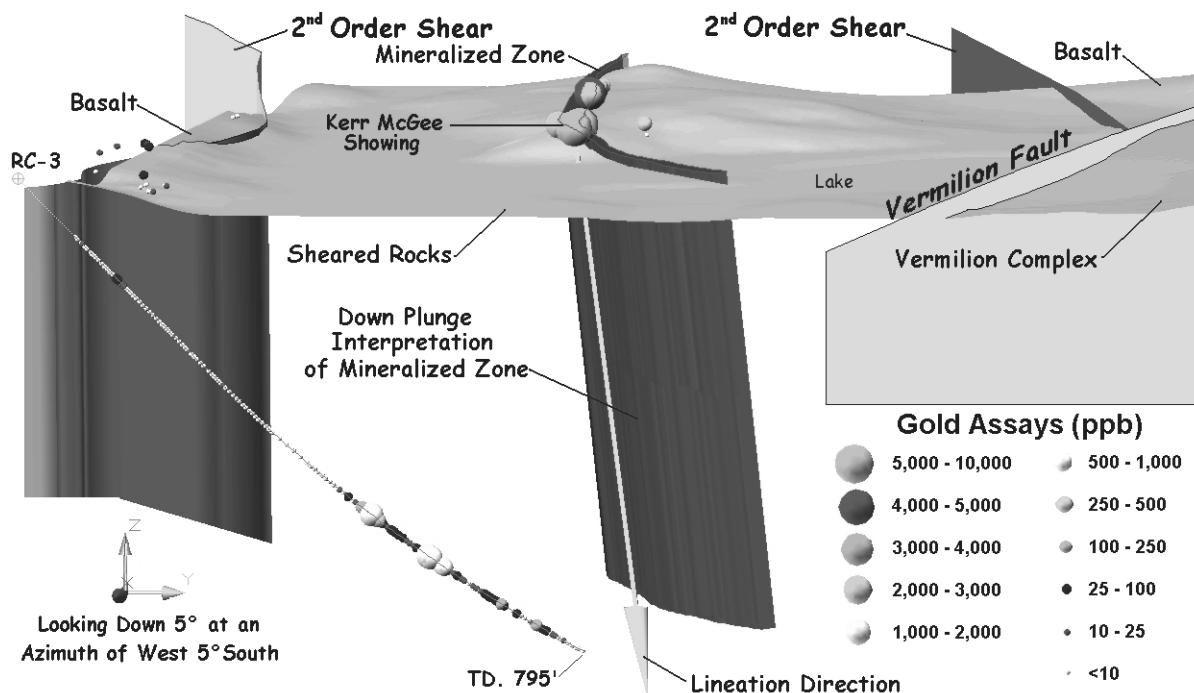
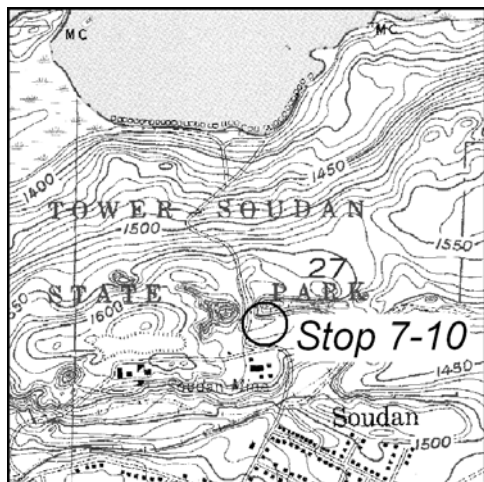


Figure 7-7. Three-dimensional view of the relationship between structural boundaries, the mineralized zone exposed on the surface at the Kerr McGee prospect, and drill hole RC-3. Upward extension to the surface of the two anomalous zones (> 1,000 ppb gold) intersected in hole RC-3 would place these zones in the black spruce and cedar swamp located south-southeast of the prospect.

NEXT:

Return to Highway 169 via County 38. Turn right (west) and travel approximately 7.3 miles to the junction of Jasper road in the town of Soudan. Turn right on Jasper road and follow road to the T-junction (~0.5 miles). Turn right, go up the hill, disembark at mine buildings and walk about 150 feet north and up-hill to outcrop on the right.



STOP 7-10.

Archean Soudan iron-formation member of Ely Greenstone

No hammering please!

Location: T.62N., R.15W., sec. 27, NE, NE;
Soudan Mine State Park.

Soudan 7.5-minute quadrangle

UTM: 557,120E/5,296,660N

DESCRIPTION:

This classic exposure of the Soudan iron-formation member of the Ely Greenstone lies on the north limb of the Tower-Soudan anticline, and at the stratigraphic top of the volcanic sequences known collectively as the Lower member of the Ely Greenstone. The outcrop displays two generations of tight folding in

delicate laminae of chert (creamy white), chert-hematite jasper (red), and magnetite-chert (black to silver-colored). The second generation of folds (F_2) is tectonic in origin, having subvertical axial surfaces that trend east, and steeply plunging axes. Most display Z-asymmetry. The earlier folds (F_{0-1}) appear to have been sharply refolded to produce complex interference patterns. Lundy (1985) studied folding at this locality and concluded that some of the apparent interference structures are the product of early-formed sheath folds that did not involve refolding by D_2 . The F_1 structures are predominantly intrafolial, and exhibit a great variety of style and orientation; implying they formed by layer-parallel, soft-sediment slumping (Fig. 7-8). Lundy's mapping of this outcrop is an interesting demonstration of unraveling details at a single outcrop that led to recognition that D_1 deformation was not systematic here, but likely soft sediment. Furthermore, it is a microcosm of regional-scale deformation



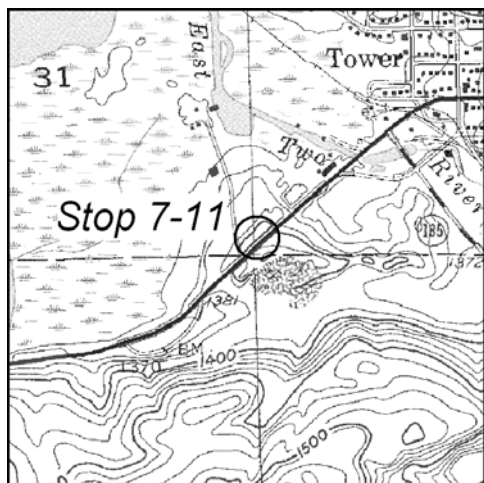
Figure 7-8. Outcrop map showing bedding trajectories and several generations of folds and faults (from Lundy, 1985). F_1 folds are nonsystematic and include nappe and sheath fold geometries.

It is interesting to observe the rhythmic microlaminae (1 mm or so thick) in various cherty beds exposed here and speculate about the paleoenvironment—that is, whether these represent daily heating/cooling, tidal, climatic, annual, or some other repetitive influence in the depositional environment. What is known about units of iron-formation in the Ely Greenstone, of which there are many, is that deposition occurred during periods of relative volcanic and tectonic quiescence by the slow subaqueous “rain” of chemical precipitates.

The deep excavations in this area are the early workings of the Soudan iron mine, the first in Minnesota. The mine produced about 16 mt of high-grade hematite ore (60-63 percent iron content) from 1884 until 1962, when the land was deeded to the State of Minnesota and converted to a park. Most of the production came from underground workings that began here in 1900, and which now can be visited on guided tours. The mine also houses an underground physics research facility at 2340 feet below the surface. A massive expansion of that facility is under consideration to create a national underground laboratory at considerably greater depths (Peterson and Patelke, 2003).

NEXT:

Return to Highway 169 and turn right. Follow 169 through the town of Tower to the large outcrops immediately west of town (approximately 3.1 miles).



STOP 7-11

Archean fragmental volcanic rocks

Location: T.62N., R.15W., sec. 32, SW, SW;
Highway 169 road cut, west edge village of
Tower.

Tower 7.5-minute quadrangle.

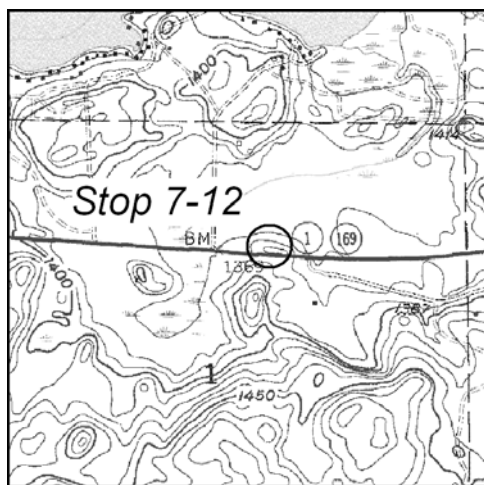
UTM: 553,380E/5,294,430N

DESCRIPTION:

This outcrop consists of fragmental, variably reworked volcanic conglomerate and tuffaceous rocks of the Gafvert Lake sequence of the Lake Vermilion Formation. The rock is composed of about 85-95 percent dacitic detritus, 3-5 percent gray clasts of graywacke, slate, and basaltic andesite, and a small percentage of magnetic and sulfidic fragments. Fragments range in size from a few millimeters to 20 cm. The generally poorly developed sorting and bedding, together with varied clast composition, implies a debris-flow origin. Compare these rocks with those of Stop 7-6.

NEXT:

Continue west on Highway 169 approximately 1.5 miles to road cut.



STOP 7-12. Archean dacitic tuff/ Paleoproterozoic or Mesoproterozoic diabase dike

Location: T.61N., R.16W., sec. 1, SW, NE;
Highway 169 road cut.

Tower 7.5-minute quadrangle.

UTM: 551,160E/5,293,960N

DESCRIPTION:

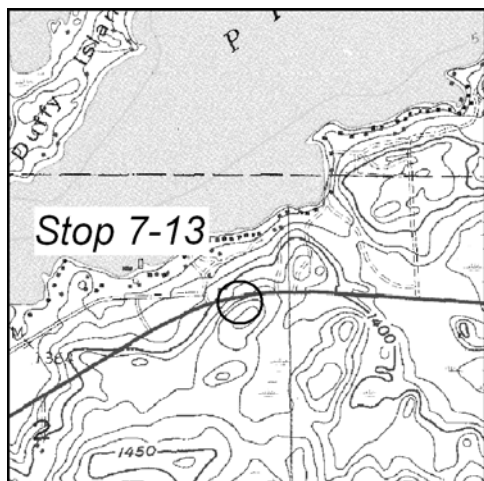
These road cuts expose outcrops of white, dacitic tuffaceous sedimentary rock, a component of the Lake Vermilion Formation. Regionally, the formation consists of all compositional gradations between what

appears to be first-cycle tuff, tuffaceous greywacke, and mixed-source greywacke, interbedded on all scales. In a general way, the tuffaceous component increases in proportion to the east toward the Tower-Soudan anticline. The presumed source of the dacitic volcanic detritus exposed in this area is stratovolcanos of Gafvert Lake affinity, which overlie the composite volcanic shield complex of the Ely Greenstone. Ring plains and irregular basins composed of detritus shed from the high-standing volcanic complex are now represented by the Lake Vermilion Formation.

The northeast-trending, steeply dipping, seven-meter wide diabase dike that cuts tuffaceous rocks has been the source of considerable debate. Its petrographic (olivine-bearing) and geochemical (silica undersaturated) composition is similar to Mesoproterozoic dikes (Schmitz, 1994); yet it lies nearly along strike with, though east of, dikes of the Paleoproterozoic Kenora-Kabetogama dike swarm.

NEXT:

Continue west on Highway 169 approximately 0.7 mile to Stop 7-13.



STOP 7-13.

Multiply folded Archean greywacke

Location: T.61N., R.16W., sec. 2, NE, NE; south side of Highway 169 just east of CR 526.

Tower 7.5-minute quadrangle.

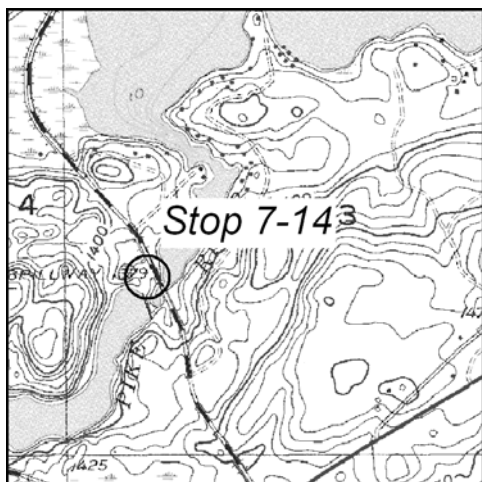
UTM: 550,050E/5,294,000N

DESCRIPTION:

This outcrop at the road and several smaller ones in the bush nearby show the superposition of two generations of folds in thin-bedded, well-graded greywacke of the Lake Vermilion Formation. The second-generation folds (F_2) are associated with a regional axial plane cleavage in which sedimentary clasts are flattened. The earlier F_1 folds have no associated cleavage and tend to be erratic in form, trend, and distribution. Folds display “eye” and “mushroom” shapes that locally are interpreted to be sheath folds (Hudleston and others, 1987). These characteristics are consistent with deformation of poorly lithified sediment. The superposition of deformation events is manifest in the transection of F_1 folds by cleavage related to D_2 . In this area and to the west, one can find anticlinal synclines and synclinal anticlines, indicating stratigraphic inversion prior to D_2 folding.

NEXT:

Continue approximately 1.7 miles to the west to the junction of 77. Turn right on 77 and follow for approximately 0.6 miles to the outcrop on the left side of the road on the north side of the Pike River Dam.



STOP 7-14.

Archean greywacke at Pike River Dam

Location: T.61N., R.16W., sec. 3, NW, SW;
west side of County Road 77, on N side of river.

[Note that Fortune Bay Casino—the overnight
hotel—lies to the north off of CR 77].

Tower 7.5-minute quadrangle.

UTM: 547,300E/5,293,340N

DESCRIPTION

One of the truly classic outcrops of greywacke of the Lake Vermilion Formation is beautifully exposed at this stop. Prior to about the 1950s, no depositional mechanism could satisfactorily explain the coincidence in graywacke of; 1) coarse sand derived from a source many kilometers distant and having an altered clayey matrix; 2) interbedded black slate; and 3) the lack of evidence for reworking in shallow water (indicative of deposition below wave base). This was changed when the concept of turbidity currents was introduced to the geological profession by Kuenen and Migliorini (1950). Despite widespread publication on turbidites in more modern geologic settings through the 1950s and 1960s, the facies model was not refined and applied to Archean and Proterozoic strata in the Lake Superior region until somewhat later (Morey, 1965; Ojakangas, 1966).

The geology of field trip stops in the Virginia Horn area is presented in Figure 7-9.

NEXT:

Return to Highway 169 and turn west. Travel south on Highway 169 approximately 28 miles to the junction with Highway 53; follow 53 south approximately 0.7 miles to the Laurentian Divide wayside rest Stop.

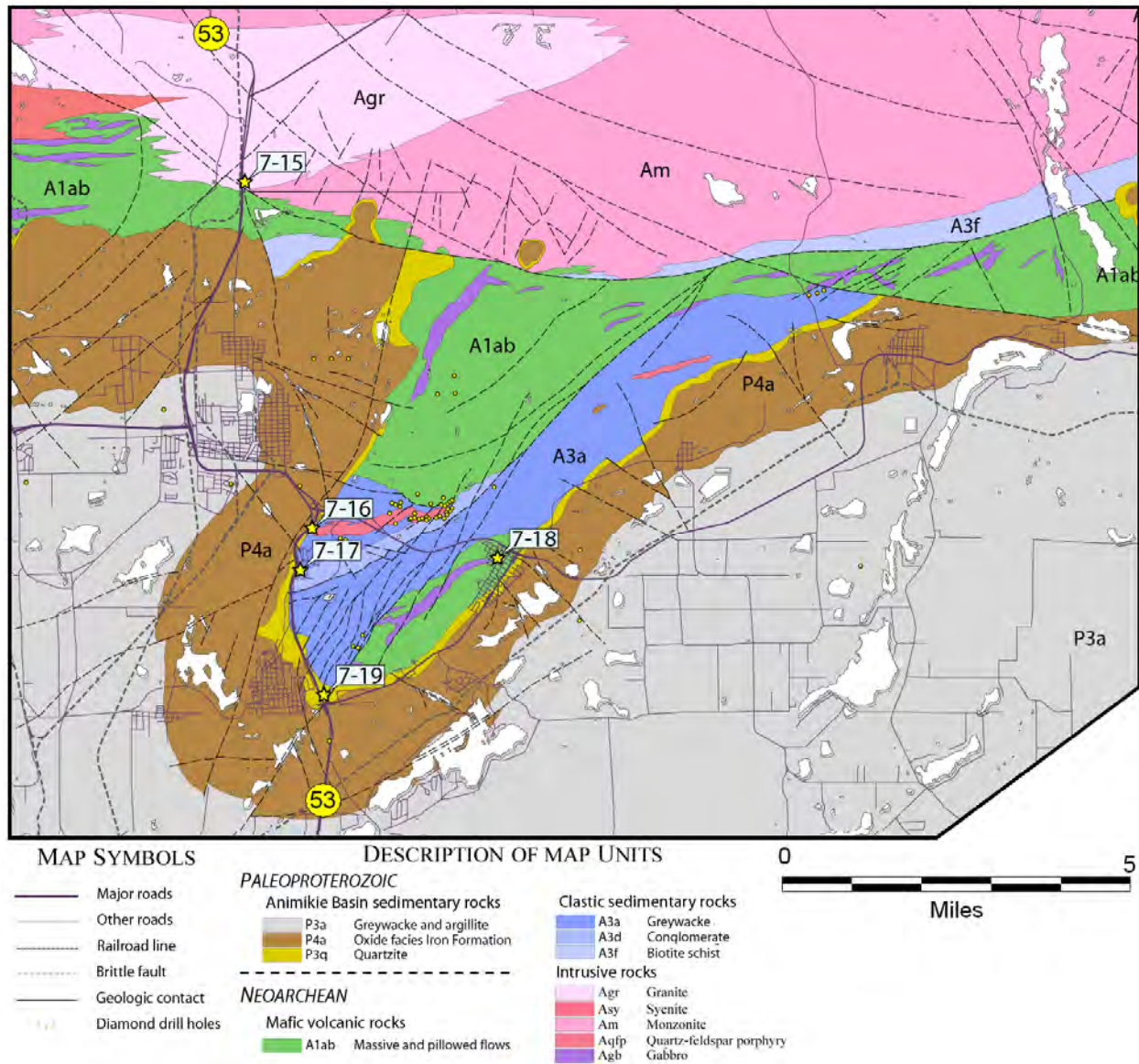
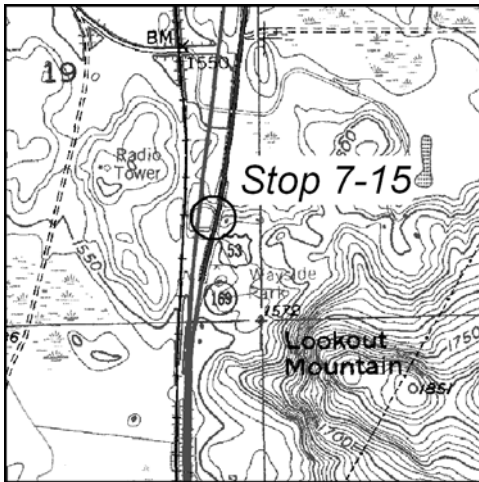


Figure 7-9. Generalized geologic map of the Virginia horn area (modified from Jirsa and others, 1998) showing details of field trip stops 9-15 to 9-19.



STOP 7-15.

Archean Giants Range batholith at "Confusion Hill," Laurentian Divide

Location: T.59N., R.17W., sec.19 SE, SE;
wayside off Highway 53.

Virginia 7.5-minute quadrangle.

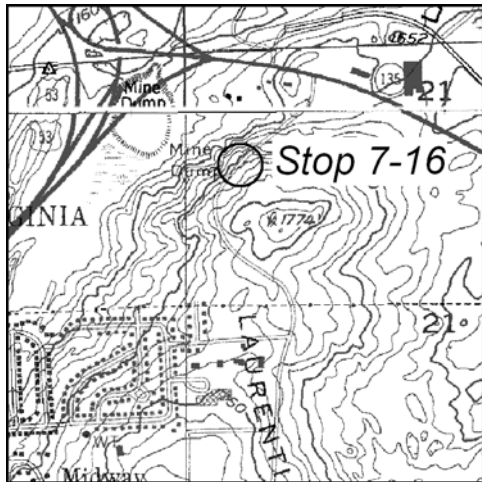
UTM: 534,337E/5,269,458N

DESCRIPTION:

Exposed near this wayside and in road cuts on both sides of the highway is an array of variably layered intrusions having both tonalitic (white) and dioritic (black) compositions. A cursory look shows intrusive relationships that conclusively demonstrate that diorite was emplaced into tonalite at one locality, and at another, tonalite was emplaced into diorite. In detail, all compositions intermediate between the two end members are also present locally. Although the dioritic component is abundant here, the bulk of the mapped unit is tonalitic. Emplacement of this unit, now known as the Lookout Mountain tonalite, probably involved some degree of magma mingling. Dikes of tonalite that cut the adjacent high-grade supracrustal rocks of the Minntac sequence contain metamorphic fabrics, yet little evidence of metamorphic origin can be seen in the interior of the body, implying it is syntectonic with respect to D₂ deformation. U-Pb zircon dates (Boerboom and Zartman, 1993) of two components of the batholith exposed to the north bracket the age of D₂ deformation between about 2674 and 2682 Ma. Exposures at Confusion Hill are a small part of the Giants Range batholith, which forms the core bedrock of the Laurentian (drainage) divide. The batholith is a 40-mile wide belt of intrusions that can be traced on geophysical maps and outcrop east to the Mesoproterozoic Duluth Complex, and west beyond the western border of Minnesota. It separates Archean supracrustal sequences in the Virginia horn from those of the Tower-Soudan area—making stratigraphic correlation between the two districts speculative.

NEXT:

Follow Highway 53 south through the town of Virginia. Take the exit for Highway 135 (east) approximately 0.5 miles to Bourgin Road. Turn right (south) on Bourgin Road and continue about 0.4 mile to large cut on left (east) side of road.



STOP 7-16.

Archean graywacke and slate, intruded by quartzofeldspathic porphyry.

Location: T.58N., R.17W., sec.21 SW, SW;
road cuts on east side of the Bourgin Road.

Eveleth 7.5-minute quadrangle.

UTM: 536,311E/5,260,659N

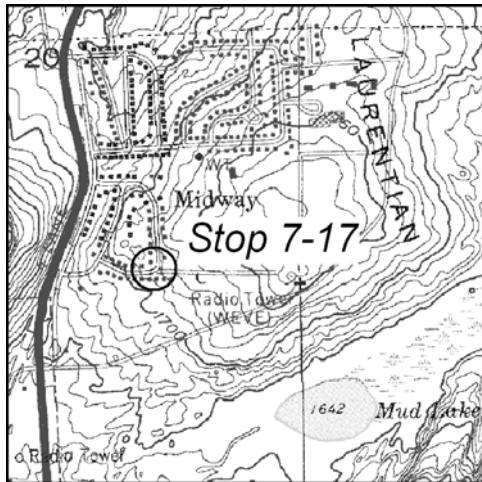
DESCRIPTION:

Outcrops along this side of the road expose quartzofeldspathic porphyry (QFP) intruded into variably deformed graywacke, siltstone, and slate of the Mud Lake sequence. The sedimentary rocks here are moderately deformed, but much of that deformation is inferred to predate the main cleavage-forming event D_2 , and some may be soft-sediment in origin. The QFP is large and continuous to the east, but at this locality it appears to be segmented into a zone of multiple dikes. Both graywacke and QFP are intensely altered to some combination of iron-carbonate minerals (ankerite, ferroan dolomite) and sericite. Regionally, this style of alteration is common, though not always associated with QFP intrusions—presumably because the QFP remained more structurally rigid than the enclosing sedimentary rocks during the shear-related deformation event that accompanied alteration late in D_2 . Most gold mineralization in the area is closely allied to this alteration, yet this outcrop is surprisingly barren.

One of the earliest gold discoveries in Minnesota was made by J.W. Gruner (in Grout, 1937) in a railroad cut not far from stop 7-16. The cut exposes graywacke intruded by quartzofeldspathic porphyry, having visible gold associated with small quartz veins. Despite several episodes of mineral exploration in this area (most notably by Newmont Exploration in the 1980s) no economic gold deposits have been discovered.

NEXT:

Follow Bourgin road to the south and west to a frontage road on the east side of Hwy 53. Turn north (right) on the frontage road and travel about 0.2 miles to first road to right, turn up-hill and continue to #7 Mesabi Lane.



STOP 7-17.
Archean conglomerate

Private driveway!

Location: T.58N., R.17W., sec.20 SW, SE, No. 7
 Mesabi Lane; village of Midway.

Eveleth 7.5-minute quadrangle.

UTM: 535.713E/5.259.459N

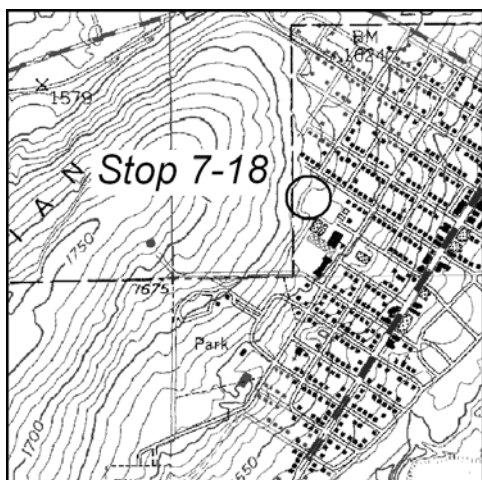
DESCRIPTION:

Archean conglomerate and lithic sandstone that form the driveway here are part of the northeast-trending Midway sequence, containing these strata types locally interbedded with subaerially deposited, calc-alkalic (trachyandesitic) volcanic rocks. The sequence is inferred to have formed after earliest deformation (D_1) of the enclosing graywacke and basaltic rocks of the Mud Lake sequence, but before the cleavage-forming D_2 deformation that affected both sequences. The conglomerate contains clasts of basalt, graywacke, porphyritic trachyandesite, and quartzofeldspathic porphyry (QFP). This provenance indicates that the older Archean rocks of the Mud Lake sequence were intruded by QFP, deformed, and uplifted, to provide detritus to what was probably a successor or “pull-apart” basin developed along a major structure now occupied by the Pike River fault zone.

Midway sequence conglomerate has previously been interpreted as a basal sediment (Sutton, 1963), and as a proximal turbidite fan deposit (Levy, 1991), positionally transitional with graywacke and slate of the Mud Lake sequence. Subsequent work (Jirsa, 2000) indicates that the conglomerate is part of a Timiskaming-type clastic and volcanic sequence that unconformably overlies the older volcanic strata. Deposition of the Midway sequence required uplift, subaerial erosion, continental volcanism, and deposition in isolated basins along a major structural break.

NEXT:

Return to Highway 135. Turn right and follow 135 approximately 2.4 miles to a residential street on the northwest side of the town of Gilbert. Turn right and go 5 blocks and park by the Gilbert Junior High School.



STOP 7-18.

Archean pillowed and massive greenstone

Location: T.58N., R.17W., sec.23 NW, SE, SW;
north edge of athletic fields, Gilbert Junior High School.

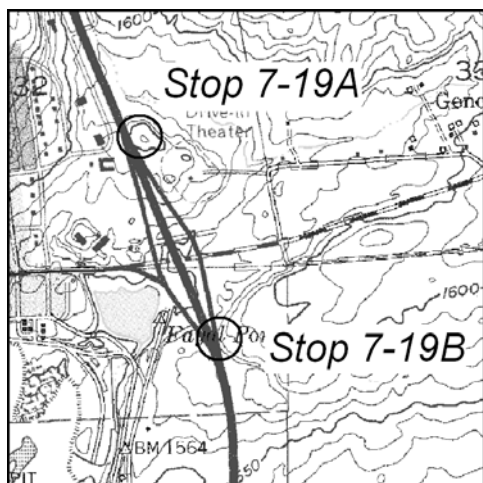
Gilbert 7.5-minute quadrangle

DESCRIPTION:

Outcrop of pillowed and massive basalt is part of the Archean Mud Lake sequence, metamorphosed to low greenschist-grade. Pillow shapes indicate stratigraphic facing is to the northwest, which places this outcrop on the south side of a major D₁ structure known as the Mud Lake syncline. Note also the presence locally of fractures filled with reddish jasper, presumably deposited in depressions on the rock surface by overstepping of Paleoproterozoic seas during deposition of the Biwabik Iron Formation.

NEXT:

Follow residential roads to Highway 37 in the center of Gilbert. Turn right and travel on 37 approximately 3.3 miles to the on/off ramps onto Highway 53.



STOP 7-19.

Paleoproterozoic Pokegama Quartzite (A) and Biwabik Iron Formation (B)

Location: T.58N., R.17W., sec.32 SE, SE, and adjacent, junction of Highways 37 and 53.

Eveleth 7.5-minute quadrangle.

UTM: scattered outcrops extend from
535,956E/5,256,913N on the north (stop 9-19A), to
536,263E/5,256,200N on the south (stop 9-19B).

DESCRIPTION 7-19A:

Unconformably overlying the Neoarchean rocks of the Virginia Horn area is the Animikie Group sediments of Paleoproterozoic age. Coarse grain size and massive beds as thick as 1.5 m characterize this outcrop of the sandy, upper member of the Pokegama Quartzite. Thin beds of shale and siltstone separate the massive beds. Ojakangas (1993) interpreted the deposition of this facies as within high-energy, lower tidal or subtidal environment.

DESCRIPTION 7-19B:

This exposure of gently southeast-dipping strata is part of the Lower Cherty member of the Biwabik Iron Formation. It overlies and is generally in transition with the Pokegama Quartzite at stop 5-5A. Notice that both formations have sandy textures and cross-bedding, implying a moderately high-energy depositional environment. The most significant difference between these two units is the abrupt change in sediment source from the extrabasinal quartz grains in the Pokegama, to recycled, chemically precipitated chert in the Biwabik. Measurements of cross-bedding in the iron-formation are bimodal, implying deposition in a tidally influenced marine environment (Ojakangas, 1993).

OPTIONAL FIELD TRIP LOCATIONS

Highlighting Neoproterozoic bedrock in the Vermilion District: 3 driving/hiking traverses within striking distance of Ely

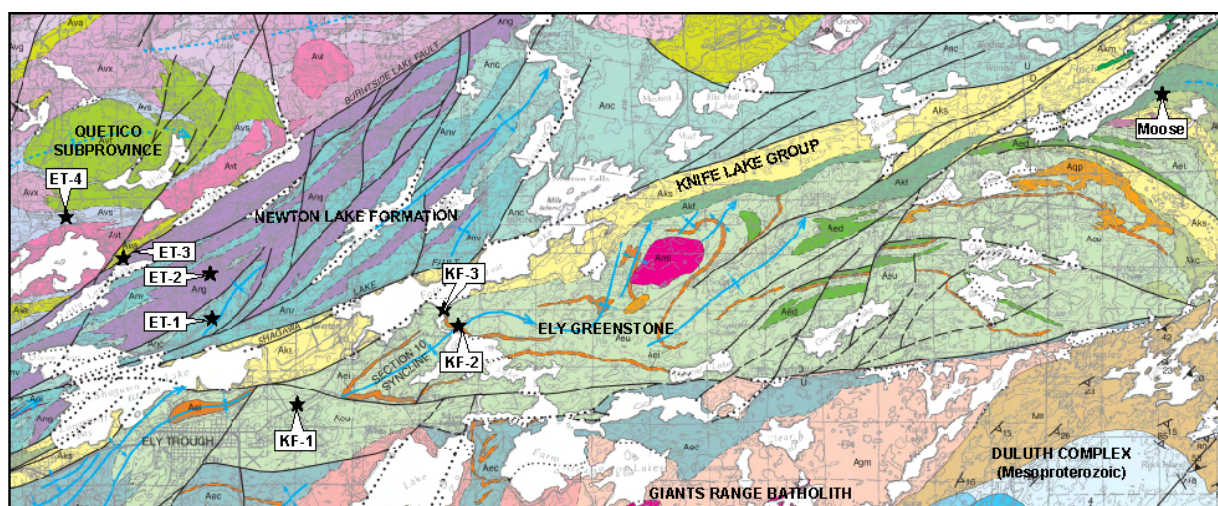


Figure 7-10. Geologic map of the Ely to Moose Lake area (clipped and modified from Jirsa and Miller, 2004)

KAWISHIWI FALLS TRAVERSE (approximate round trip from Ely = 1-2 hours)

Metabasalt and iron-formation of the Neoproterozoic Ely Greenstone.

Stop KF-1—Pillowed metabasalt; UTM: 588,370E/5,307,100N (NAD 83)

Directions: Drive east of Ely (set odometer at junction hwy 1 with hwy 169 or County road 18-Fernberg Trail) and drive east for about 1.3 miles. Outcrop on north (left) side of road is classic example of pillowed metabasalt; note radiating chlorite amygdules and concentric jointing in pillows. Stratigraphic younging is to the north.

Stop KF-2—Iron-formation lens; UTM: 592,785E/5,309,288N (NAD 83)

Directions: Continue east on hwy 169 (also County road 18) to crossing of Kawishiwi River at about 4.5 miles from starting mileage; park near bridge and walk farther east to first outcrop on south (right) side of road. Outcrop consists of gray, magnetite-hematite-chert iron-formation with minor pyrite.

Stop KF-3—Kawishiwi Falls, metabasalt; UTM: 592,440E/5,309,755N (NAD 83)

Directions: Cross bridge over Kawishiwi River; continue 0.3 mile farther east to driveway north of trail that leads to the falls parking lot. Follow walking trail northwest of parking lot for about 0.35 miles to falls.

ECHO TRAIL TRAVERSE (approximate round trip from Ely = 1-2 hours)

Neoproterozoic Newton Lake Formation and the Wawa/Quetico subprovince boundary.

This traverse visits newly created roadside outcrops along the Echo Trail north of Ely. The Newton Lake Formation is a package of presumably thrust-stacked tholeiitic to komatiitic lava flows, mafic to ultramafic sills, and thin felsic tuff. It differs from the Ely Greenstone in the abundance of ultramafic rocks and general lack of iron-formation. Judging from geochronologic work in the adjacent Shebandowan Greenstone Belt in Ontario (Corfu and Stott, 1998), the two formations are approximately coeval at ca. 2720 Ma. Metasedimentary rocks of the Quetico subprovince to the north represent graywacke deposited as foreland-basin fill during D₁ orogenesis and eventual accretion of the Wawa subprovince to the evolving craton at ca. 2699-2696 Ma.

Directions to start of Echo Trail: Drive east of Ely along hwy 169 to County Road 88 about 0.9 mile east of junction of highways 1 and 169. Turn north (left) on 88 and follow it around the east end of Shagawa Lake for 2.2 miles to Echo Trail (County Road 116) turn-off on the right (north). Set odometer here and drive northward on Echo Trail to stops.

Stop ET-1—Spherulitic pillowed basalt of the Newton Lake Formation;

UTM: 585,745E/5,309,470N; 0.5 miles north of CR #88 on west (left) side of Echo Trail.

Steeply dipping pillowed basalt, with stratigraphic younging to the south. Metamorphic grade is low greenschist. Note local presence of large vacuoles in pillows showing “drain-back” features.

Stop ET-2—Metadiabase and felsic tuff of Newton Lake Formation

UTM: 585,748E/5,310,655N; 1.25 miles north of 88 on west (left) side of Echo Trail.

Roadcut exposes about 100 foot-thick unit of cherty-looking to granular felsic tuff displaying delicate pristine bedding features. This unit may be a block “floating” in metadiabase. Small outcrop on east side of road shows metadiabase cut by coarse grained hornblende-pyroxene-biotite lamprophyre containing inclusions of metadiabase.

Stop ET-3—View of Burntside fault (a drive-by).

UTM: 583,254E/5,311,035N; 3.25 miles north of 88 at junction with Somero Road (Tnsp #4651).

Prominent NE-striking linear depression separates steep rock walls of low greenschist grade Newton Lake Formation of the Wawa subprovince on the south, from higher metamorphic grade rocks of the Quetico subprovince on the north.

Stop ET-4—Quetico subprovince metasedimentary and intrusive rocks.

UTM: 581,590E/5,312,295N; 4.0 miles north of 88 on east (right) side of Echo Trail about 0.1 mile north of junction with Passi Road (CR #803).

Note that relict graded bedding and other sedimentary features are preserved locally, despite amphibolite grade metamorphism and local migmatization.

MOOSE LAKE TRAVERSE (approximate round trip from Ely 2-4 hours)

Neoproterozoic Knife Lake Group

Directions: Drive about 16 miles east of Ely on hwy 169-Fernberg Road to left turn at Moose Lake Road (CR #183); go 2.5 miles northeast along Moose Lake Road to parking area on the right for the *Secret-Blackstone Lakes trail area*. Hike eastward along a series of trails that cross outcrops, and veer off the trails onto some of the larger exposures.

The Knife Lake Group contains the youngest supracrustal strata in the Vermilion district, exposed as thin layers on and tectonic wedges within older volcanic units (Ely and Newton Lake). Two major sequences are recognized; an older package of alkalic hornblende-phyric volcanic, volcanoclastic, and derived sedimentary rocks; and a younger sequence of polymictic conglomeratic strata known locally as the Ogishkemuncie conglomerate. It appears that parts of both sequences are exposed along the multitude of

trails. Though both sequences are fragmental at this location; the Ogishkemuncie can be distinguished by the presence of clasts of red and black iron-formation, black and white chert, vein quartz, and quartz-phyric granitoid derived from the Saganaga Tonalite exposed about 20 miles to the northeast. Lithology and sedimentary structures indicate alluvial fan, fluvial, and fluvial-lacustrine deposition; though some apparently deeper water turbiditic sediments occur locally.

Moose Lake, just to the west, is one of a linear chain of lakes that parallels faults associated with the Shagawa Lake-Knife Lake trend. This fault system appears to have been long-lived, and may initially have controlled development of a successor basin into which at least some of the Knife Lake strata were deposited. These supracrustal rocks can be correlated on the basis of lithologic and relative temporal setting with the Shebandowan Assemblage in adjacent Ontario (Corfu and Stott, 1998). There, the alkalic volcanic rocks and Saganaga Tonalite were dated at about 2689 Ma, and the younger conglomerate units (like the Ogishkemuncie) have dates in the range of 2684-2682 Ma. The latter evolved during regional transpressive deformation (D_2) at about 2685-2680 Ma.

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