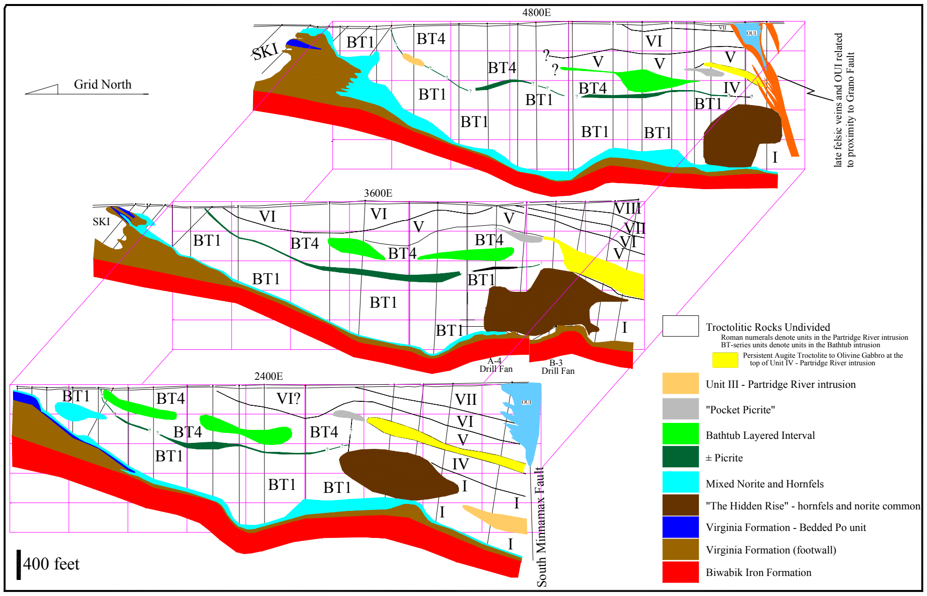
NRRI TR 2008/17

FINISH LOGGING OF DULUTH COMPLEX DRILL CORE (And a Reinterpretation of the Geology at the Mesaba (Babbitt) deposit)

By

Mark J. Severson
and
Steven A. Hauck



September, 2008
Technical Report
NRRI/TR-2008/17

Funded by the Minerals Coordinating Committee of the Minnesota Department of Natural Resources, Permanent University Trust Fund and the Natural Resources Research Institute

Project Nos. 1663-187-6574, 1896-783-1224, 1663-187-1600

Natural Resources Research Institute
University of Minnesota, Duluth
5013 Miller Trunk Highway
Duluth, MN 55811-1442

Cover Photo Caption
Block diagram of the major igneous units in the eastern end of the Mesaba deposit.

Recommended Citation
Severson, M.J. and S.A. Hauck, 2008, Finish Logging of Duluth Complex Drill Core (And a Reinterpretation of the Geology at the Mesaba (Babbitt) Deposit), University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/TR-2008/17, 68 p. + 94 plates.

Natural Resources Research Institute
University of Minnesota, Duluth
5013 Miller Trunk Highway
Duluth, MN 55811-1442
Telephone: 218-720-4272
Fax: 218-720-4329
e-mail: shauck@nrri.umn.edu

Web site: http://www.nrri.umn.edu/egg

ABSTRACT

This project was undertaken with the objective to finish logging all drill holes from the basal contact zone of the Duluth Complex. Logging of Duluth Complex holes by Natural Resources Research Institute (NRRI) personnel began in 1989, when Severson and Hauck (1990) defined the igneous stratigraphy for most of the Partridge River intrusion (PRI). During the ensuing years the NRRI logged a total of 955 holes and defined igneous stratigraphic sections for several more intrusions of the Duluth Complex. As of 2005, a remainder of over 220 holes had yet to be logged. At the end of this project, 295 holes, which include some recently-drilled holes, were logged with about 20 holes still to be logged from the far eastern end of the Mesaba deposit. Lithologic logs for most of the holes that have been logged since 1989 are now available on the NRRI Geology Group's website at www.nrri.umn.edu/egg/.

The vast majority of holes that were logged for this project were from the Mesaba (Babbitt) Cu-Ni±PGE deposit, and thus, this report deals mostly with that deposit. A result of logging a large number of holes at the Mesaba deposit indicates that most of the deposit does not exhibit a stratigraphic package that has been recognized within the nearby Partridge River intrusion. This suggests that most of the deposit is situated within another sub-intrusion, informally called the Bathtub intrusion (BTI). The BTI appears to have been fed by a vent in the Grano Fault area on the east side of the Mesaba deposit. Forty-two cross-sections from the Mesaba deposit, showing the geology in over 450 surface holes, are presented in this report. Another 26 cross-sections, showing the geology in 219 underground holes, are also presented for the Local Boy ore zone of the Mesaba deposit. All of these cross-sections are utilized to define the igneous stratigraphy of the BTI and adjacent PRI at the deposit.

All publically-available drill holes have now been logged from the Dunka Pit Cu-Ni deposit located in the South Kawishiwi intrusion (SKI). Nineteen cross-sections through the deposit are presented in this report. These cross-sections show the geology, potential Cu-Ni ore zones in the holes, and the down dip extent of potential mineable zones of the Biwabik Iron Formation at depth. Additional areas in the SKI where holes were logged for this project include the Maturi, Spruce Road, and Nokomis deposits. Cross-sections and hung stratigraphic sections are presented, and they show the geology intersected in these newly-logged holes relative to previously-logged holes.

Drill holes from two Oxide-bearing Ultramafic Intrusions (OUI) were also logged for this investigation. These logs include ten holes from the Longnose deposit and ten holes from the Water Hen deposit. Six cross-sections through the Longnose deposit are presented in this report.

In summary, the holes logged in this investigation have added greatly to our understanding of the geology of basal portions of the Duluth Complex. In some cases, the previously defined igneous stratigraphic sections for the various intrusions have held up remarkably well as additional holes are drilled and logged. Of course, there are always some exceptions to the rule. In other cases, e.g., the Mesaba deposit, as more holes were logged and/or drilled, the igneous stratigraphy had to be modified in order to explain differences in a group of holes that were situated in the BTI versus the nearby PRI. This change serves as an example that definition of igneous units, and modes of mineralization, in the Duluth Complex is an iterative process and has to be continuously refined as more data, in the form of new drill holes, are generated.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF APPENDICES

LIST OF PLATES

INTRODUCTION

BACKGROUND

Exploration for Cu-Ni deposits at the base of the Duluth Complex (Complex) began in 1948 and has continued intermittently ever since. During this 70 year time interval, over 25 exploration companies were/are actively involved in the drilling of at least 30 areas along the western edge of the Complex. At least ten Cu-Ni sulfide deposits, and several potential Fe-Ti-V oxide deposits (Fig. 1), were outlined by the drilling efforts (Miller et al., 2002a).

From 1988 through 2005, NRRI personnel logged 955 drill holes from the basal zone of the Duluth Complex. The major result of all these initial efforts was the establishment of igneous stratigraphic packages, which in turn were used to improve our understanding of the mineralization controls on the Cu-Ni deposits and the distribution of Platinum Group Elements (PGE). However, at the beginning of 2005, there were still over 220 drill holes (226,000 feet of core) that remained to be re-logged from portions of the Partridge River and South Kawishiwi intrusions (PRI and SKI, respectively). The main objective of this project was to complete a logging campaign of these remaining holes in the PRI and SKI.

To date, 224 holes have been relogged for this project totaling 198,979 feet of drill core. The bulk of these holes are from the Mesaba (Babbitt) deposit and are stored at the Minnesota Department of Natural Resources (MDNR) drill core library in Hibbing, MN. Also included were several holes that were recently drilled in the Maturi Extension/ Nokomis deposit by Duluth Metals Ltd. and several recently found drill cores from the Dunka Pit deposit (both are now stored at the MDNR library). In addition, 64 holes that were recently drilled by Teck Cominco American Inc. at their Mesaba (Babbitt) deposit were also logged; many of these holes were logged by Severson and permission was granted by Teck Cominco to use the geologic data in preparation of geologic cross-sections across the deposit. In total, all of the newly logged holes for this project (see Appendix A) were located in eight deposits within the PRI and SKI; including a few scattered holes in the Cloquet Lake and Tuscarora intrusions.

While this project made a significant dent in the total amount of holes logged along the western margin of the Duluth Complex, there are still about 20 holes that yet remain to be logged at the Mesaba deposit. Other holes not logged as part of this project include about 160 newly drilled holes at the Nokomis deposit and holes drilled after 1998 at the Birch Lake deposit; however, these holes are not publically available.

GEOLOGIC SETTING

The Duluth Complex (Fig. 1 - inset) is a large, composite, tholeiitic mafic intrusion that was emplaced into comagmatic flood basalts along a portion of the Midcontinent Rift System during the Mesoproterozoic (1.1 Ga, Keweenawan). The Duluth Complex and Beaver Bay Complex (younger than the Complex) both consist of numerous smaller intrusions that collectively comprise various Keweenawan-age rocks of the area. This report deals mainly with drilled basal portions of the Partridge River intrusion (PRI) and South Kawishiwi intrusion (SKI) and the recently-defined Bathtub intrusion (BTI). The detailed geology and mineral potential of the entire Duluth Complex and related rocks of northeastern Minnesota has recently been summarized in Miller et al. (2002), and the reader should refer to this publication, and to other NRRI publications, to become familiar with all aspects of the Complex. While this report briefly describes the geology for specific areas of the Complex, it is assumed that the reader is thoroughly familiar with all

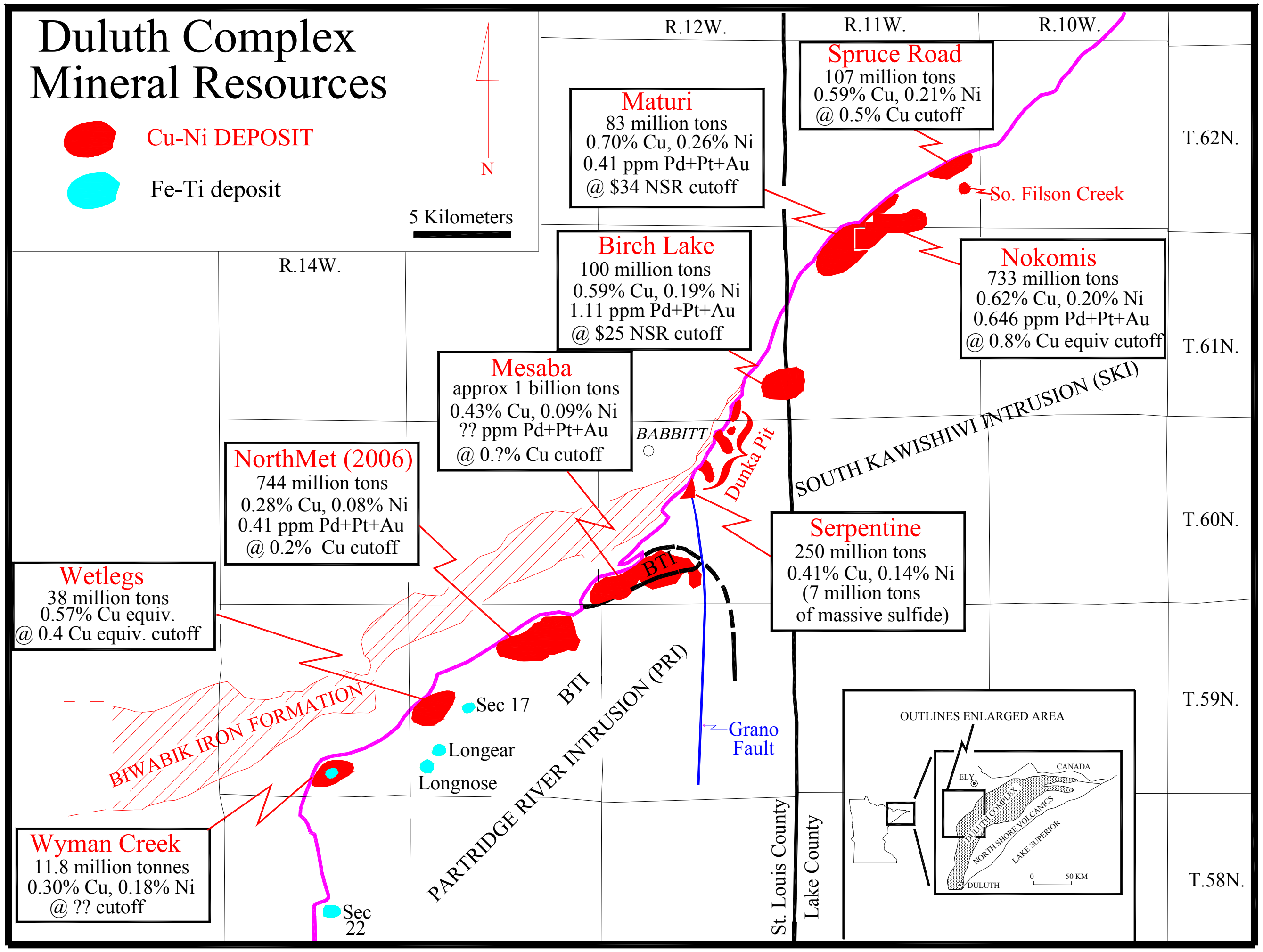


Figure 1. Location of Cu-Ni±PGE sulfide deposits, Fe-Ti±V oxide deposits (Oxide-bearing Ultramafic Intrusion - OUI), and other exploration areas along the western edge/base of the Duluth Complex. Note that the NorthMet deposit was previously referred to as the Dunka Road deposit, and the Mesaba deposit was referred to as the Babbitt deposit; the more recent names for these two deposits are used in this report. The reported indicated resources/reserves for each of the deposits were calculated by the exploration companies using different methods and different cutoffs and can be expected to be continually changed as more drilling takes place.

aspects of the Complex put forth in the following, at a minimum, publications:

- Miller, Green, Severson, Chandler, Hauck, Peterson, and Wahl, 2002, Geology and mineral potential of the Duluth Complex and related rocks of northeastern Minnesota: Minnesota Geological Survey Report of Investigations 58, 207 p.
- Hauck, Severson, Zanko, Barnes, Morton, Aliminas, Foord, and Dahlberg, 1997, An overview of the geology and oxide, sulfide, and platinum-group element mineralization along the western and northern contacts of the Duluth Complex: in GSA Special Paper 312, p. 137-185.
- Severson and Hauck, 1997, Igneous stratigraphy and mineralization in the basal portion of the Partridge River intrusion, Duluth Complex, Allen Quadrangle, Minnesota: University of Minnesota Duluth, Natural Resources Research Institute Technical Report NRRI/TR-97/19, 102 p.
- Severson, 1995, Geology of the southern portion of the Duluth Complex, northeastern Minnesota: University of Minnesota Duluth, Natural Resources Research Institute Technical Report NRRI/TR-95-26, 185 p.
- Severson, 1994, Igneous stratigraphy of the South Kawishiwi intrusion, Duluth Complex, northeastern Minnesota: University of Minnesota Duluth, Natural Resources Research Institute Technical Report NRRI/TR-93/34, 210 p.
- Severson and Hauck, 1990, Geology, geochemistry, and stratigraphy of the Partridge River intrusion: University of Minnesota Duluth, Natural Resources Research Institute Technical Report NRRI/GMIN-TR-89-11, 236 p.
- Other NRRI reports (see references at the back of this report) that discuss the geology and mineralization at the NorthMet (Dunka Road) deposit (Geerts, 1991, 1994), Mesaba (Babbitt) deposit (Severson, 1991; Severson and Barnes, 1991; Severson et. al, 1994a, 1994b; Patelke 1994; and Hauck and Severson, 2000); South Filson Creek deposit (Kuhns et al., 1990); and Serpentine deposit (Zanko et al., 1994).
- Detailed locations for all (up to 2003) of the publically available drill holes in the Duluth Complex (UTM coordinates, state plane coordinates, etc.), as well as detailed drill hole lithology, can be found in Patelke (2003). This report deals with only drill holes that were relogged for this project.

METHODOLOGY OF LOGGING DRILL CORE

The naming of gabbroic rock types in the Complex is largely based on the visual estimation of the percentages of minerals present in drill core and outcrop. For the rocks of this investigation, the major minerals present in the gabbroic rocks include: plagioclase, olivine, clinopyroxene (Cpx), orthopyroxene (Opx), and oxides and sulfides. Using visual estimates of these minerals, the rock type is assigned a name according to the classification scheme depicted in Figure 2. It is important to note that the visual estimates of one person may vary drastically from another person, or they may vary subtly for a single person from one day to another. Thus, the resultant rock type name may also vary accordingly. Attempts have been made to "smooth out" these visual estimation differences between more than one logger by using published percentage estimation charts (for example: charts for estimating percentage

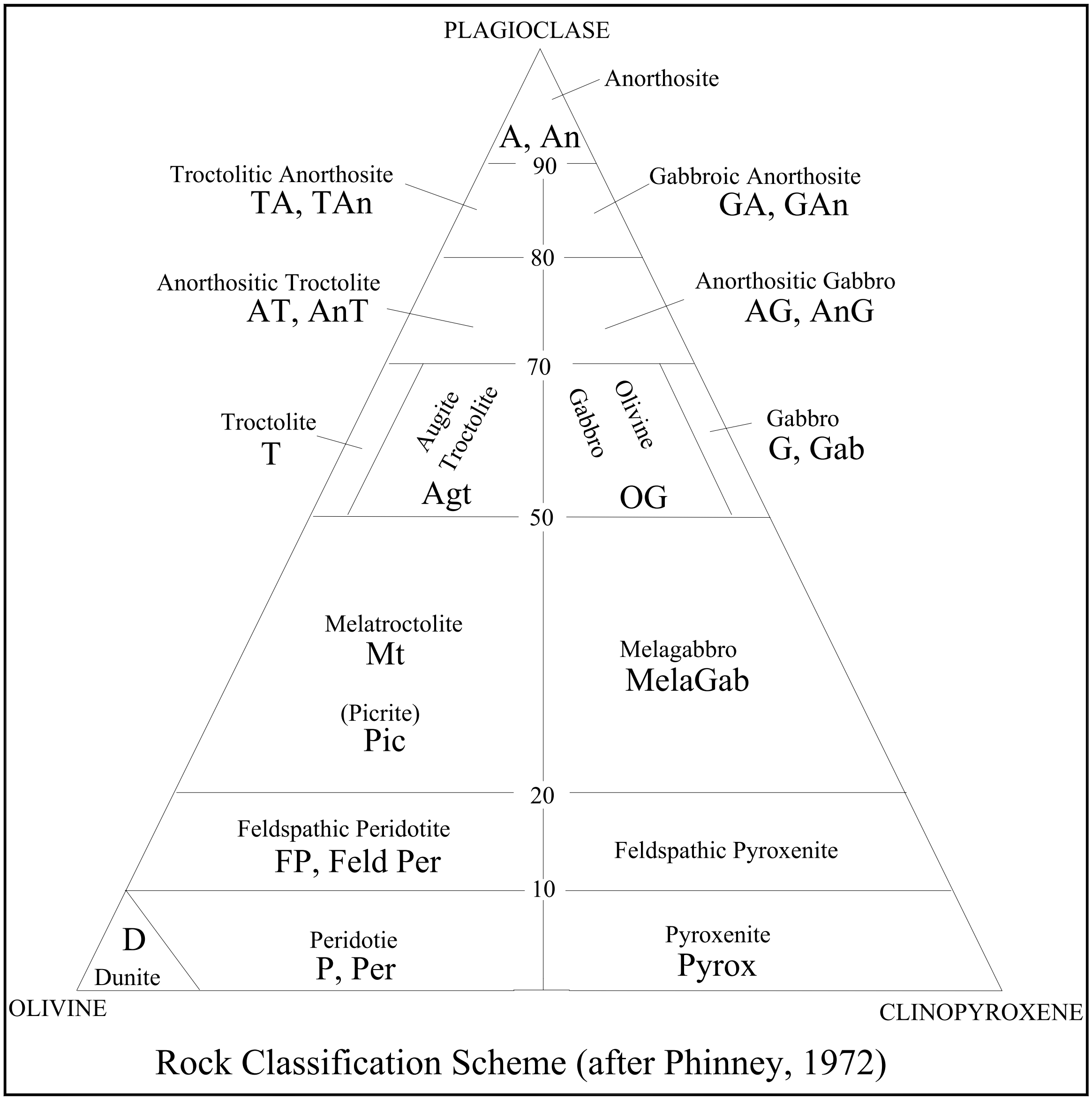


Figure 2. Rock classification scheme (after Phinney, 1972). Three letter abbreviations, e.g., Agt, AnT or TAn, were used in the logging campaigns after 2000.

in Compton, 1962, p. 332-333) and by communicating "what one sees" with another logger on a constant basis. However, in the end, estimates are just that – estimates –, and there will always be some variation in a given rock type name between loggers. Hopefully, the different loggers are somewhat close in their estimates, and there are only subtle shifts in rock type names across the fields as portrayed in Figure 2.

For the most part, the dominant rock types in the PRI, SKI, and BTI are troctolitic in nature, wherein plagioclase and olivine are the dominant cumulate phases with lesser, and variable, amounts of intercumulus Cpx, Opx, and oxides. Cumulus is defined only as the framework, or first generation, of touching and interpenetrating crystals that accumulated from a magma, and the term does not imply crystal settling (Irvine, 1982). Intercumulus, as defined by Irvine (1982), refers to "post-cumulus material" that occur as: 1) intercumulus space filling, e.g., oikocrystic and ophitic; 2) overgrowths on cumulus minerals; and 3) reaction replacements of cumulus minerals. Overall, the igneous rocks of the PRI, SKI, and BTI intrusions are medium- to coarse-grained orthocumulates (25-50% intercumulus material) and mesocumulates (7-25% intercumulus material), with minor adcumulus peridotite and dunite horizons. Noritic rocks are common near the basal contact, or in close proximity to sedimentary hornfels inclusions, due to silica contamination of the magma produced during assimilation of the country rocks. All of the troctolitic rocks can be further broken down into possessing a homogeneous or heterogeneous texture. Heterogeneous texture, or taxitic texture, is herein defined as zones where the grain size and modal percentages vary drastically and repeatedly over short distances.

DRILL HOLE LITHOLOGIC LOGS

The lithologic logs for each of the holes logged for this project have been scanned and electronic files of the logs (pdfs) can be downloaded from the Economic Geology Group's (EGG) website at www.nrri.umn.edu/egg/. In addition to these newly logged holes, all of the previous-logged 955 holes have also been scanned and are available on the EGG website.

CROSS-SECTIONS

Most of the holes that were relogged for this investigation were incorporated in geologic cross-sections that were previously prepared in AutoCad. Many of these cross-sections were constructed as much as 15 years ago, and, as the newly-logged holes of this investigation were added to them, the geology was changed accordingly. Several newly-constructed cross-sections were also prepared for this investigation. In total, cross-sections included with this report are as follows:

- 42 cross-sections for the Mesaba/Babbitt Cu-Ni±PGE deposit – these cross-sections supersede all of the cross-sections previously presented in Severson et al. (1994b);
- 26 cross-sections displaying the geology and inferred distribution of massive sulfide horizons of the Local Boy ore zone of the Mesaba (Babbitt) Cu-Ni±PGE deposit – these cross-sections supersede all of the cross-sections previously presented in Severson and Barnes (1991);
- 19 cross-sections for the Dunka Pit Cu-Ni±PGE deposit – these cross-sections supersede the Dunka Pit cross-sections presented in Severson (1994);
- 6 cross-sections for the Longnose Fe-Ti±V deposit (no previously-prepared cross-sections exist);
- one hung cross-section for the Maturi and Spruce Road Cu-Ni±PGE deposits and a cross-section for the Maturi deposit – these sections supersede sections previously presented in Severson (1994); and
- a hung stratigraphic cross-section for the Maturi Extension area and Nokomis Cu-Ni±PGE deposit – this section supersedes the hung section previously presented in Severson (1994) for what was then referred to as the Highway 1 Corridor (H1C) area.

DONATED DRILL CORE

In 2006, Mark Severson was informed of the existence of several drill cores stored in a building at the Cliffs-Erie Site (old LTV taconite processing facility) by Richard Patelke of PolyMet Mining. In the course of asking permission to move these holes to the MDNR, Severson was also informed of the existence of more drill core that was stored in another nearby building. All of these holes have since been moved to the MDNR core facilities in Hibbing, MN. A listing of the holes can be found in Cliffs-Erie-donated-holes-2006.xls file that is included with this report (Appendix B). The holes were drilled at the Dunka Pit taconite mine by Newmont Mining Company (11 NM-series holes) and Erie Mining Company (58 8000-series holes) in the1960s and 1970s. The NM-series holes found at Cliffs-Erie were the iron-formation portions of holes that were given to Erie Mining Company for iron-formation assay purposes. These portions, coupled with the remainders of the same holes that were given to the MDNR, now make a complete record for all of the NM-series holes at the MDNR.

ACKNOWLEDGMENTS

This project was funded by the Minerals Diversification Plan of the Minnesota Legislature that is administered by the Minerals Coordinating Committee and the Permanent University Trust Fund. This investigation also drew on the observations of previous investigations funded by the Minerals Diversification Plan and by Minnesota Technology, Inc.

Special thanks are extended to the following corporations and individuals for providing access to private company records and drill core: Teck Cominco American Incorporated – Messrs. Al Samis, Timothy Jefferson, Paul MacRobbbie, Blake Borgeson, and Ms. Brigitte Dejou; Duluth Metals Incorporated – Messrs. Paul Albers, Kevin Boerst, Dave Oliver, and Rick Sandri; and Encampment Resources – Dr. Harold Noyes. Previous contributors to many NRRI projects are also gratefully thanked and include: E.K. Lehmann and Assoc. (now Franconia Minerals Corp.) - Messrs. Ernest Lehmann, John Beck, William Rowell, and Leon Gladen; American Shield Company – Mr. William Ulland; INCO Exploration and Technical Services - Messrs. Robert Bell and Andy Bite; PolyMet Mining Incorporated (formerly Fleck Resources Ltd.) – Messrs. Richard Patelke, Steven Geerts, John McGoran, Chris Mattson, Dr. Donald Gentry, and Ms. Leah Mach; United States Steel Corporation - Messrs. Dennis Hendricks and Cedric Iverson (deceased); Wallbridge Mining Company Limited - Messrs. Doug Hunter and Andy Bite; and Cliffs-Erie Ltd. – Bruce Gerlach.

Thanks are also extended to the MDNR for having the foresight to serve as a repository for exploration company records and for storing well over a million feet of drill core from the Complex – without the core, this project would not be possible. Mr. Tom Gardner (Rendrag Inc.), John Heine (NRRI), and Rick Ruhanen (MDNR) are kindly thanked for their assistance in moving forgotten core from the Cliffs-Erie site to the MDNR. Lastly, we are very grateful for the many discussions pertaining to the Duluth Complex that we had with Dr. Jim Miller and Dr. Penelope Morton of the University of Minnesota Duluth, Dr. Toumo Alapieti of the University of Oulu, Finland (deceased), and with our past and present compatriots at the NRRI – Messrs. Steven Geerts, Richard Patelke, Dean Peterson, and Larry Zanko.

IGNEOUS STRATIGRAPHY OF THE PARTRIDGE RIVER INTRUSION

INTRODUCTION

The Partridge River intrusion (PRI): 1) consists mainly of troctolitic cumulates; 2) contains at least three large sub-economic (low grade) Cu-Ni deposits; 3) dips gently to the southeast; and 4) 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). The basal 900 meters are known in great detail from studies of abundant drill core (Severson and Hauck, 1990, 1997; Severson, 1991, 1994; Severson et. al., 1994a, 1994b) and are subdivided into seven or more units that can be traced over a strike-length of 24 kilometers (15 miles).

The units of the Partridge River intrusion are recently described in Miller and Severson (2002) and are depicted in Figure 3. A short reiteration of earlier descriptions of the various units of the PRI is included in this report; however, it is important to point out a few pertinent features. First, Unit I at the base of the PRI is distinct in that it consists of a suite of heterogeneous-textured 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, which are collectively referred to as the Wetlegs Layered Interval (Fig. 3).

Unit III is a major marker bed throughout much of the PRI in that it is characterized by poikilitic leucotroctolite with distinctive olivine oikocyrsts. At the Mesaba/Babbitt deposit, Unit III is present as a thick unit only along the southern margin of the deposit, and as isolated small inclusions in the remainder of the deposit. The rapid pinch-out of Unit III to the north within the Mesaba/Babbitt deposit appears to be related to emplacement of a distinctly different sub-intrusion herein referred to as the Bathtub intrusion (BTI) (Figs. 1 and 3; see later discussion).

Overlying Unit III in the PRI are units IV through VIII. Unit IV varies from a troctolite to augite troctolite, 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 through 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.

NORTHMET DEPOSIT (DUNKA ROAD DEPOSIT)

The Dunka Road deposit (Fig. 1) was initially drilled by United States Steel Corporation (USSC) in the 1970s, with more recent drilling at the now renamed NorthMet deposit by PolyMet Mining Incorporated. Over 370 holes have now been drilled at the deposit, and the seven units of the PRI originally defined by Severson and Hauck (1990) have held up remarkably well. No new holes from the NorthMet Deposit were relogged for this investigation.

However, three holes located to the east and south of the deposit were relogged for this investigation. Hole BA-4, located southeast

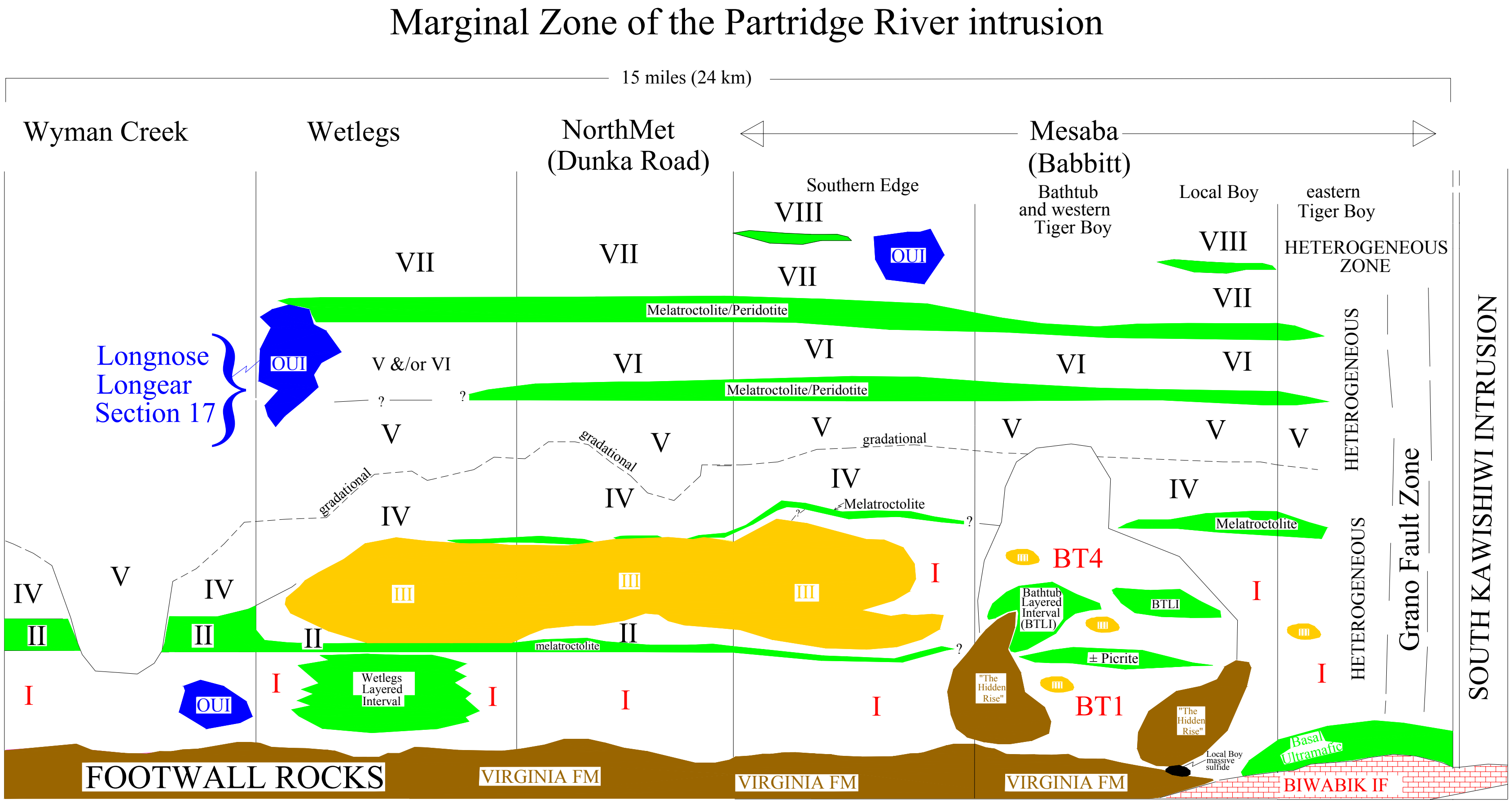


Figure 3. Generalized stratigraphy of the basal zone of the Partridge River intrusion (modified from Severson, 1994). Roman numerals (I through VIII) denote igneous units in the Partridge River intrusion; BT1 and BT4 denote igneous units in the Bathtub intrusion; and OUI denotes Oxide-bearing Ultramafic Intrusions. Stratigraphic relationships to the south of the Wyman Creek deposit are poorly understood and are not portrayed on this figure. Not all holes have been logged in the vicinity of the Grano Fault, and the igneous stratigraphy in the eastern end of the Tiger Boy ore zone of the Mesaba deposit is not fully defined.

of the deposit, intersected typical PRI type rocks including Units I through VII, possibly Unit VIII (similar to Units VI and VII), and abundant cross-cutting lenses of Oxide-bearing Ultramafic Intrusions (OUI), and granophyre (Fig. 4). Fiebor (1994) conducted a MS thesis on BA-4, but did not recognize any of the PRI units.

Holes BA-3 and BA-5, located south and south-southeast of the deposit respectively, were terminated well above the basal contact. Both drill holes intersect thick packages of troctolitic rock with multiple ultramafic layers and modally-bedded zones. However, since neither of the holes intersected footwall rocks nor Unit III at depth, it is not possible to correlate any of the units intersected in these holes with known PRI units.

WETLEGS AND WYMAN CREEK DEPOSITS

The Wetlegs deposit was initially drilled by Bear Creek Mining Co. (A4-series holes) and Exxon Corp. (W-series holes). The Wyman Creek deposit was drilled by USSC with some scattered drilling by Bear Creek and Exxon. No new holes were relogged in either area as part of this investigation, but detailed cross-sections of most of the holes from both deposits can be found in Severson and Hauck (1997).

SOUTHERN PORTION OF THE MESABA DEPOSIT (BABBITT DEPOSIT)

The Babbitt deposit (Fig. 1) was initially drilled by Bear Creek Mining Co. in the 1960s and early 1970s, with considerable drilling in the late 1970s by AMAX. The property, now renamed the Mesaba deposit, is currently being evaluated by Teck Cominco American Incorporated. 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 (Figs. 3 and 5, and Plates I and II). However, there are important changes to the stratigraphy in the southern portion of the Mesaba deposit that include:

- Units II and III exhibit abrupt northerly pinchouts and are missing from the stratigraphy in the Bathtub and Tiger Boy ore zones. This pinchout is due to the presence of the recently-recognized Bathtub intrusion that possesses an entirely different stratigraphic package (see discussions in the next chapter);
- Unit I exhibits an eastward-directed thickening at the expense of Unit III (Plate II). Thus, in some areas along the southern edge of the Mesaba deposit, Unit III is entirely enclosed within Unit I and some drill holes essentially encounter two tops of Unit I – one below a lense of Unit III and the other above the same lense of Unit III (see Figure 3 and Plate II);
- The Bathtub Layered interval (BTLI) consists of abundant ultramafic horizons interbedded with troctolitic rocks, and roughly occupies the same stratigraphic position as Unit III. The overall abundance of ultramafic layers, coupled with the lack of Unit III in the Bathtub area, suggests that this area is unique and probably formed as a smaller sub-intrusion located immediately to the north of the main magma chamber of the Partridge River intrusion. The feeder vent for the Bathtub intrusion (BTI) could have been located in close proximity to the Grano Fault on the far eastern portion of the Mesaba deposit;
- Massive sulfides with high Cu-Ni-PGE values are present at, and beneath, the basal contact of the PRI at the Local Boy ore zone – the Grano Fault of Severson (1994) may have served as a conduit for these massive sulfide occurrences.

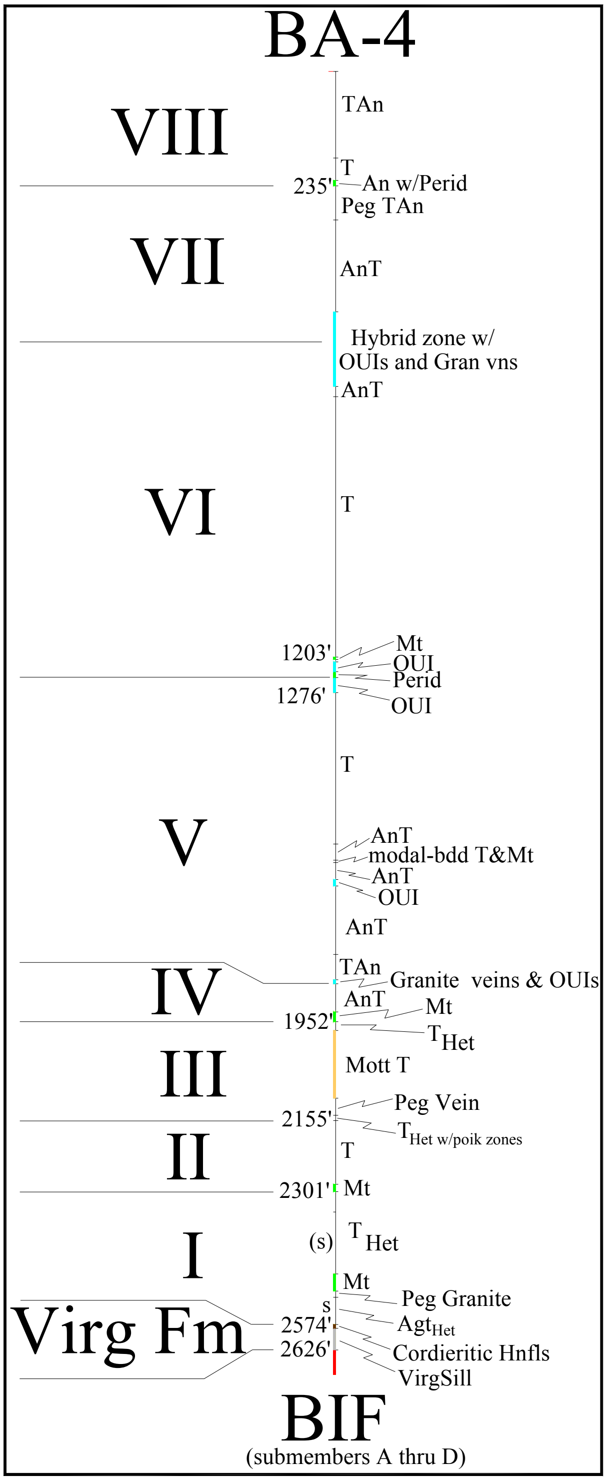


Figure 4. Distribution of PRI units (I through VIII) intersected in drill hole BA-4 located to the southeast of the NorthMet deposit. See Figure 2 for an explanation of the abbreviations used in this figure. The location of drill hole BA-4 is shown in Figure 5.

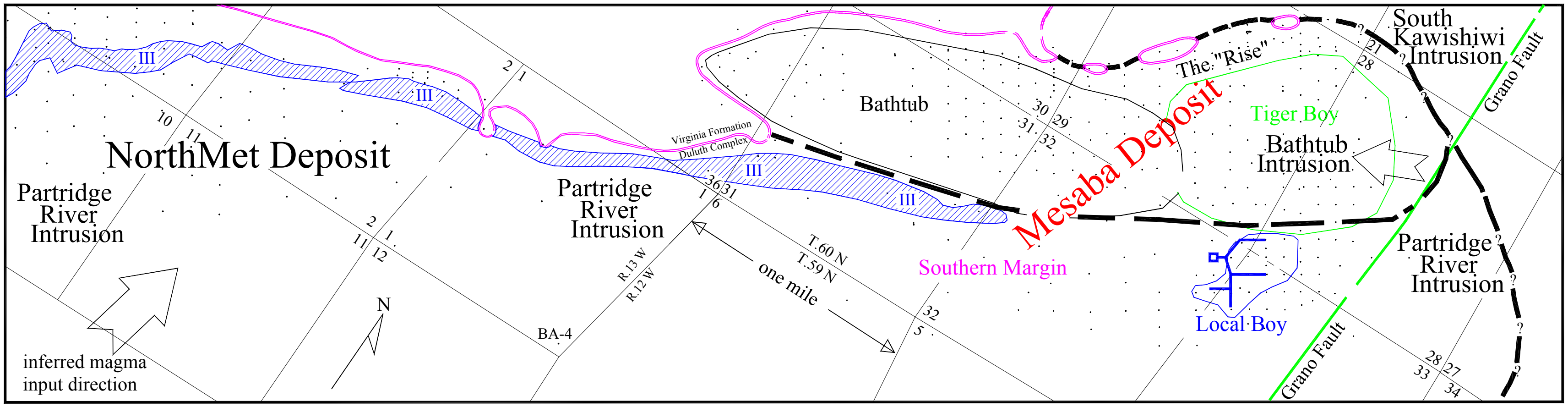


Figure 5. The Mesaba Cu-Ni deposit and generalized locations of the various ore zones (Southern Margin, Bathtub, Local Boy, and Tiger Boy) within the deposit, as well as, the inferred outline of the Bathtub intrusion. The position of the AMAX shaft and projected traces of four drifts are shown within the Local Boy ore zone. The relative positions of the NorthMet deposit, and the subcrop distribution of Unit III, are also portrayed. Large arrows depict the inferred direction of magma input for the PRI and BTI.

GEOLOGY OF THE MESABA DEPOSIT AND IGNEOUS STRATIGRPAHY OF THE BATHTUB INTRUSION

INTRODUCTION

The 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. Because the vast majority of holes that were relogged for this project were from the Mesaba deposit; a lengthy discussion pertaining to the geology of this deposit is included in this report. However, in order to more fully understand how recognition of the BTI originated, it is relevant to first discuss the chronological history of how the holes were relogged by personnel at the NRRI.

Severson (1991 – Plate II) made the first attempt at defining the igneous stratigraphy in the Mesaba deposit by first logging a line of holes across the southern edge of the deposit. He correctly recognized that PRI-type rocks were present, including the major marker unit – Unit III, and [incorrectly] concluded that the Mesaba deposit was thus hosted entirely by the PRI. A recreation of that stratigraphic line, along with additional recently-drilled Teck Cominco holes, is presented in Plate II of this report. Severson (1991 – Plate III) also logged a series of holes in the Bathtub portion of the deposit and recognized a significantly different stratigraphy consisting of multiple ultramafic layers in roughly the same stratigraphic position as Unit III. Hauck (1993) continued logging holes at Mesaba and also made similar conclusions: 1) Unit III was present only on the southern fringe of the deposit; and 2) ultramafic layers were exceedingly common in the Bathtub area – he informally designated these as the Bathtub Layered Series (BTLS) of the PRI [later renamed the Bathtub Layered interval (BTLI) of the PRI, Miller et al., 2002a]. The geology of many of the holes logged by Severson (1991) and Hauck (1993), along with additional recently-drilled Teck Cominco holes, in the Bathtub portion of the deposit is presented on Plate III of this report.

In 1994, the Mesaba deposit was controlled by Arimetco International, Inc. and employed NRRI geologists (Severson, Zanko, Patelke, and Heine) to quickly log as many holes as possible in order to determine where the top of sulfide mineralization took place in the holes. As long as the drill core was being scanned for this criterion, the geologists also made quick scan logs of the geology. This geology was eventually portrayed on a series of cross-sections across the deposit (Severson, et al., 1994b). Using these “minimal effort” logs, the authors still [incorrectly] concluded that all of the Mesaba deposit is contained within the PRI, but noted the dichotomy of the BTLI in the Bathtub portion of the deposit.

As a result of studying the PGE distribution in the Mesaba deposit, Severson and Hauck (2003) suggested that the rocks of the central portion of the Mesaba deposit could have formed as a smaller sub-intrusion located immediately north of the main magma chamber of the Partridge River intrusion. The feeder vent for this sub-intrusion, herein referred to as the Bathtub intrusion (BTI), was inferred to be located in close proximity to the Grano Fault. Discussions with Timothy Jefferson, of Teck Cominco American Inc., about the geology of the Mesaba deposit reinforced this concept and as a result, Jefferson called the intrusion the Bathtub intrusion as it is located mainly in the Bathtub ore zone of the deposit.

The concept that the Mesaba deposit is hosted by several intrusions, as well as the PRI, is not wholly new. Martineau (1989) first proposed that there are at least three intrusions present in the deposit that are roughly from north to south across the deposit: 1) Babbitt intrusion; 2) Dunka River intrusion, which also widens considerably to the northeast; and 3) Allen intrusion. According to Martineau (1989) each of these intrusions are progressively younger, and the first two are respectively cut off down dip to the south. However, the maps and cross-sections offered by Martineau (1989, 1991) are too crude and highly generalized for anyone to be able to accurately define the margins of his three intrusions, and thus, they are not recognized in this report. Interestingly, the cross-section of Martineau (1991, Fig. 1) does show an intrusive relationship between his Dunka River troctolite and Allen troctolite that is reminiscent of the intrusive relationship shown in Plate XXXV between the BTI and PRI, including an area similar to "The Hidden Rise" between the two. However, the cross-sections of Martineau (1989, Fig. 10) portray areas where his three cross-cutting intrusions occur in areas where the cross-sections of this report show a single intrusion with several subhorizontal ultramafic layers. Thusly, Martineau's three intrusion concept is **not** fully substantiated by this investigation. In other words, Martineau (1989, 1991) was roughly correct in some instances (1991), but way off the mark in other instances (1989).

COMMENTS REGARDING THE CROSS-SECTIONS OF THE MESABA DEPOSIT

The geology of the BTI, and adjacent PRI, at the Mesaba deposit is portrayed in 42 cross-sections of surface holes (scaled at 1 inch = 200 feet), and another 26 cross-sections for the underground holes (scaled at 1 inch = 50 feet) that accompany this report (Plates IV through XLIII and Plates XLV through LXX, respectively). These cross-sections form the basis of any discussion on the geology of the Mesaba deposit (see below). However, there are several criterions that must be kept in mind when reviewing the cross-sections, and the ensuing geologic discussions, that include:

1. Over 450 surface holes, and 219 underground holes, have been drilled at the Mesaba deposit – it would be virtually impossible for any single geologist to remember all of the generalities and nuances of the geology intersected in each of these holes. Therefore, much of the geology as shown in cross-sections becomes increasingly important;
2. Most of the holes, except for about 20 holes in the Grano Fault area, have been recently logged by at least nine different geologists over the past 18 years that include:
   - Mark Severson (NRRI) – 261 surface holes and 193 underground holes;
   - Steven Hauck (NRRI) – 84 surface holes;
   - Larry Zanko (NRRI) – 25 surface holes and 22 underground holes;
   - Richard Patelke (NRRI) – 25 surface holes and 1 underground hole;
   - John Heine (NRRI) – 2 surface holes;
   - Mike Takaichi (Teck Cominco) – 4 surface holes;
   - Tim Jefferson (Teck Cominco) – 6 surface holes;
   - Ashley Anderson (Teck Cominco) – 10 surface holes; and
   - Matt Reiderer (Teck Cominco) – 11 surface holes.

3. All drill logs are not created equal as the holes have been logged in varying degrees of detail by various individuals at various times for various purposes – some of the first holes (circa 1991) were logged in sufficient detail, but were essentially "cutting teeth" holes in determining the igneous stratigraphy; whereas, others holes were "bare bones" scans of the holes whilst looking for where the top of sulfide mineralization began in the hole (circa 1994);
4. The naming of rock types, based on visual estimations of percentages of minerals present in the rocks, varies from one geologist to the next. For example, some geologists were more inclined to classify moderately olivine-enriched zones as a melatroctolite (called picrite early on in the logging days); whereas, other geologists were not so inclined and the same types of zones were classified as troctolite;
5. Sulfide content estimates vary from one geologist to the next – some of this reflects logging the core dry versus logging the core wet (sulfides are more readily visible in wet core, but rock type classifications are more easily made with dry core);
6. The first cross-sections (circa 1991-2000) were constructed on paper at 1 inch = 200 feet and digitized into AutoCad .dwg files; whereas, later relogged holes were entered directly into the same, or new, AutoCad files;
7. Some of the first cross-sections show drill hole drift down the hole; whereas, holes added during later periods do not show drill drift, and the cross-sections should only be used for correlation purposes;
8. Some of the holes in the cross-sections do not show all of the geology expressed in the lithologic drill logs due to too much detail in the log relative to space limitations when constructing the cross-sections;
9. The contact relationships between rock type changes (gradational, abrupt, or sharp contacts) are portrayed on the cross-sections for the earlier logged holes, but not for the later holes due to time constraints – however, the type of contact is often recorded on the lithologic drill logs;
10. Wherever measured, the inclination of modal bedding and ultramafic layering is shown on the left side of the drill hole trace in the cross-sections (the dips of bedding are always <u>assumed</u> to be to the south for display purposes). Unfortunately, these inclination features are not shown equally for all of the holes in the cross-sections because they were not always measured in the early days of logging the core (this is unfortunate as the modal bedding in the Bathtub Layered Interval (BTLI) is often steep). The inclination of the serpentinization foliation in the ultramafic layers is never portrayed on the cross-sections;
11. The inclination of bedding in the footwall Biwabik Iron Formation, especially in the C submember, is shown for most holes, but not all holes, in the cross-sections (as it too was not always recorded);
12. Some of the surface cross-sections in the Local Boy area also show the geology in the underground drill fans – more detailed versions of the geology in these same underground holes are shown in Plates XLV through LXIII;
13. The stratigraphy of the BTI and adjacent PRI are determined collectively by the igneous units intersected in groups of holes – there are always exceptions as defined by the units intersected in any single hole;

14. While constructing the cross-sections it was assumed that most of the igneous units occur as subhorizontal "sheets"; however, some subvertical igneous lenses are most likely present but would be impossible to correlate between widely-spaced drill holes;
15. There are numerable ultramafic layers in portions of the BTI. In some areas, this abundance makes it difficult to pick specific units (BTLI, "± Picrite," BT-sli, and BTI-uz units) out of the myriad of ultramafic layers.

There are several aspects of the geology at the Mesaba deposit that must be shown on each of the cross-sections presented in this report (Plates II through XLIII) because the deposit spatially overlaps into two intrusions. These aspects range from changes in rock type packages in the Partridge River intrusion versus the Bathtub intrusion, to changes in rock type in the footwall rocks. Many of these relationships are discussed in more detail below and, where appropriate, are simplified and schematically portrayed in several figures. However, the reader is also encouraged to look at the multitude of cross-sections included with this report to gain a more intrinsic feeling for the overall geology of the deposit.

FOOTWALL ROCKS

The drilled footwall rock types at the Mesaba deposit 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. The iron-formation is extensively exposed and drilled along the length of the Mesabi Range; whereas, the stratigraphy of the Virginia Formation is known only from drill hole descriptions. 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. The metamorphic variants of the footwall rocks are schematically portrayed in Figure 6.

Biwabik Iron Formation

The Biwabik Iron Formation (BIF) on the nearby Mesabi Range has typically been subdivided into four informal lithostratigraphic members (Wolff, 1919) that are, from the bottom up: Lower Cherty, Lower Slaty, Upper Cherty, and Upper Slaty. The cherty members are typically characterized by a granular (sand-sized) texture and thick-bedding (≥several inches); whereas, the slaty members are typically fine-grained (mud-sized) and thin-bedded (≤1 cm; note that slaty is a miner's term to denote bedding and does not indicate metamorphism or slaty cleavage). The cherty members are largely composed of chert and iron oxides, while the slaty members are composed of iron silicates and iron carbonates with local chert beds. Both cherty and slaty iron-formation types are interlayered at all scales; however, one rock type or the other predominates in each of the four informal members.

At the eastern end of the Mesabi Range, the Biwabik Iron Formation is further divided by the mining industry into at least 22 informal submembers (Gundersen and Schwartz, 1962). These submembers are schematically portrayed on Figure 7. Most of the drill holes at the Mesaba deposit intersect only the top 3 submembers (A, B, and C) of the iron-formation at the top of the Upper Slaty member.

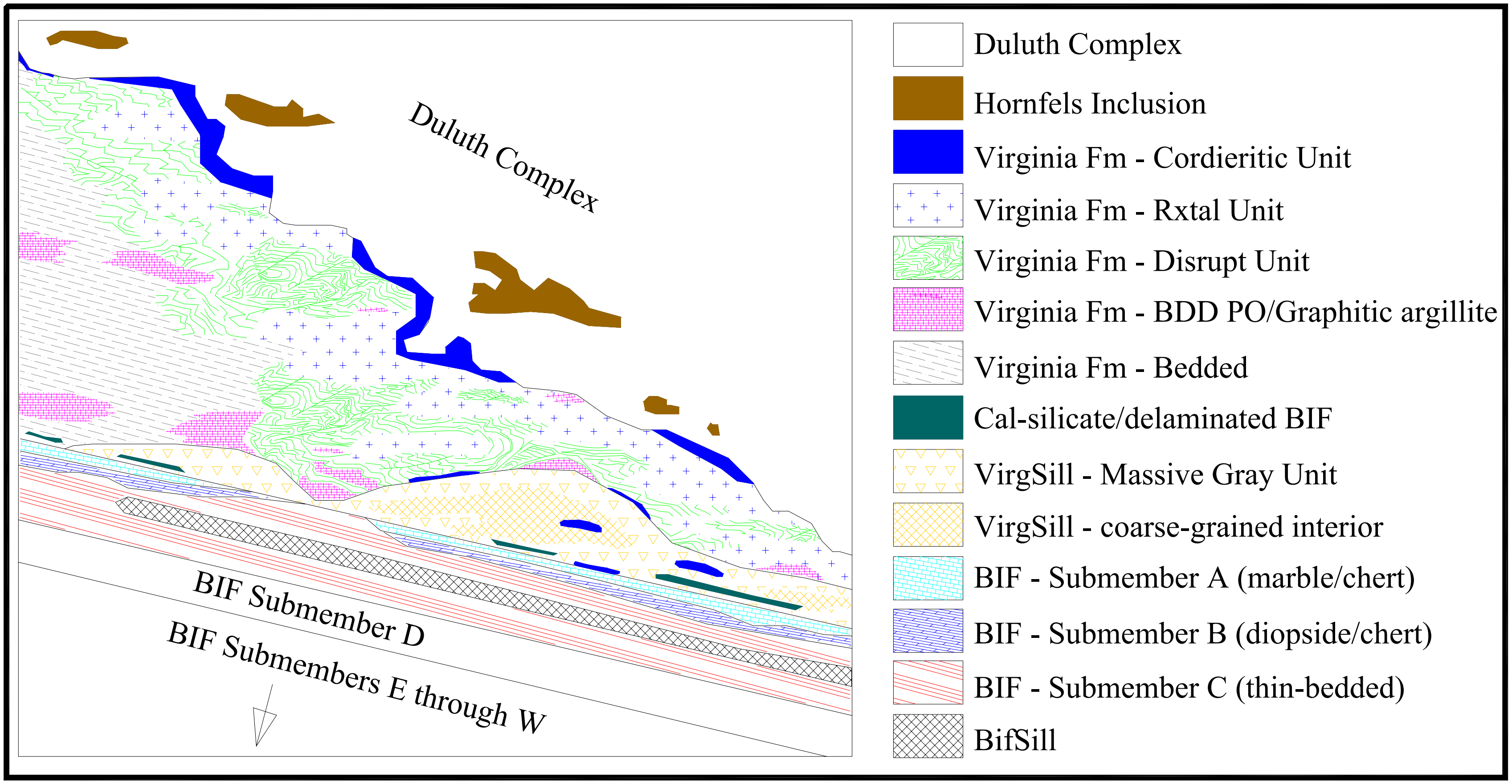


Figure 6. Schematic diagram showing the general relationships of the metamorphosed footwall rocks beneath the Duluth Complex at the Mesaba, NorthMet, Wetlegs, and Serpentine deposits.

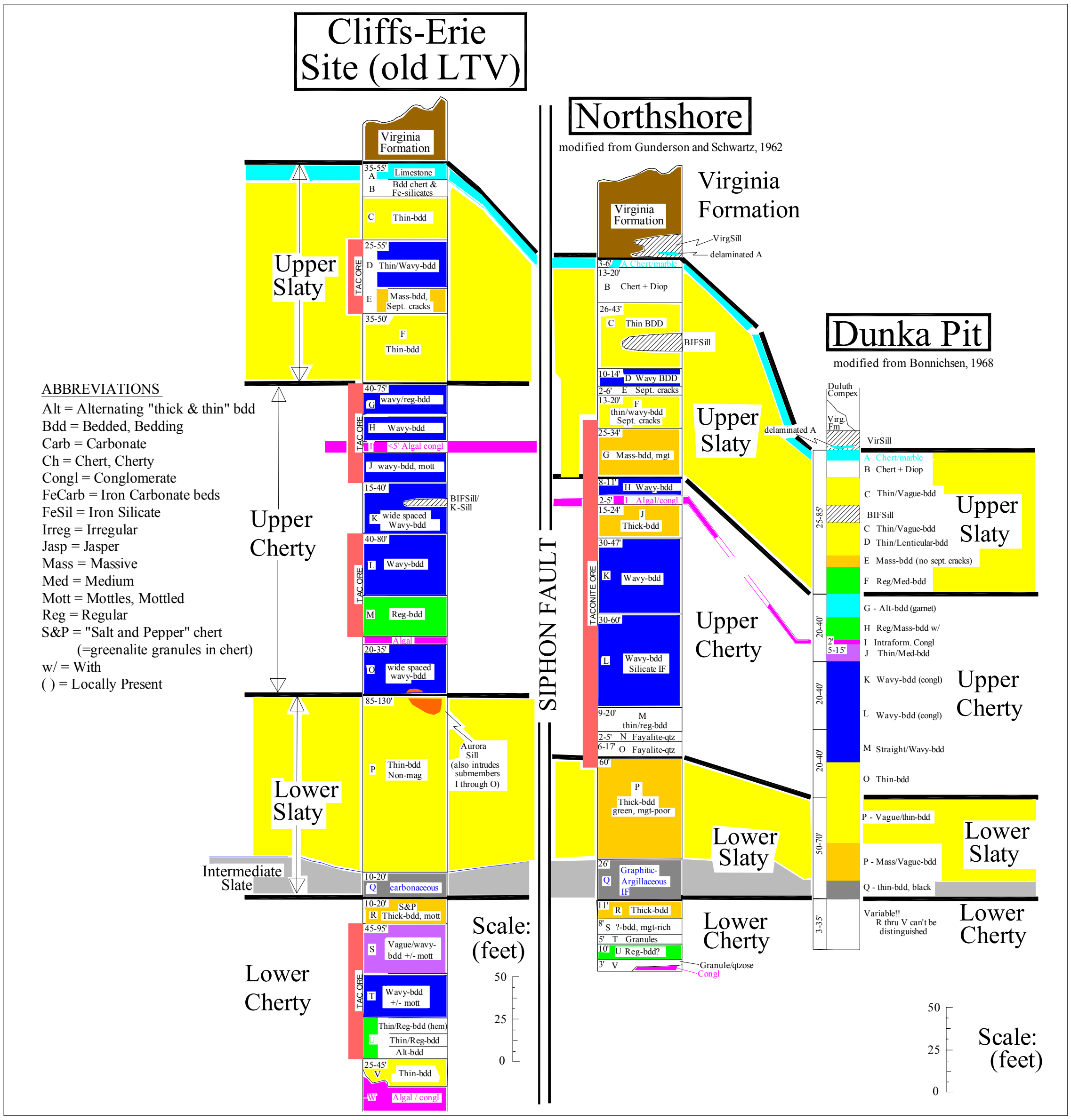


Figure 7. Stratigraphy of the Biwabik Iron Formation as used at three mines on the eastern end of the Mesabi Range. Both members and submembers of the iron-formation are displayed in this figure.

BIF Submember A – Chert and Marble

At the top of the Upper Slaty member is an interbedded chert and marble unit that is usually 3-6 feet thick. Both the chert and marble layers are white, fine- to medium-grained, and commonly alternate in 0.5-3.0 foot thick bands. In some areas, one of the two rock types may be dominant in the entire submember. In very localized areas, the chert and marble layers may be intimately interbedded with fine-grained argillaceous sediments. Near the base of submember A, the marble often contains thin, diopside-rich beds that increase in volume with depth into the underlying submember B. Rarely and very locally, the marble beds contain fine-grained magnetite. Andradite garnet is also locally present.

BIF Submember B – Chert and Diopside

The B submember of the BIF is typically 13-20 feet thick and consists of interbedded white chert beds and moderate-green, diopside-rich beds. Bedding planes between the two varieties are extremely irregular, forming bands that vary from 1 inch to over 1 foot thick. White marble beds may be locally present within the top few feet of submember B. Minerals present in lesser amounts include: hedenbergite, sphene, silicic feldspar, apatite, actinolite, cummingtonite, stilpnomelane, and chlorite (Gundersen and Schwartz, 1962). Pink, potassium feldspar-rich, granitic veins locally cross-cut the diopside beds; however, when the same vein crosses through adjacent chert beds, the vein pinches down dramatically. The basal contact with submember C varies from sharp to gradational.

BIF Submember C – Thin-bedded Taconite

This unit is the uppermost submember of the BIF that contains appreciable amounts of magnetite, though it is not processed for its iron content in the taconite mines. Submember C is characterized by thin-bedded (<2 mm), green, black, and gray beds of iron silicates, magnetite, and chert, respectively. Gundersen and Schwartz (1962) report that the green silicate beds consist chiefly of ferrohypersthene with lesser amounts of hedenbergite, fayalite, and cummingtonite; hisingerite veinlets are locally present. Average thickness is about 42 feet thick with a range of 36-47 feet thick (Gundersen and Schwartz, 1962).

BIFSill

Along the northern edge of the Mesaba deposit the C submember often contains a 2-18 foot-thick, fine- to medium-grained diabasic to granoblastic sill. Major constituents of the sill, in decreasing order, are plagioclase (45-65%), orthopyroxene (8-45%), and amphibole (brown hornblende; 1-18%), with lesser amounts of olivine, clinopyroxene (Cpx), inverted pigeonite, and biotite. Trace amounts of ilmenite (minute round “drops”), sulfides (dominantly pyrrhotite), and apatite are also found within the BIFSill. Commonly, the top and bottom few inches of the sill are chilled against submember C. In local areas, the central portion of the sill may contain plagioclase and hornblende phenocrysts up to four inches across.

The BIFSill exhibits a granoblastic texture indicative of metamorphism by the Duluth

Complex. Hauck et al. (1997) noted the geochemical similarity of the BIFSill to the Logan sills (1109 Ma) that intrude the Gunflint Iron Formation and Rove Formation. Because of this, Hauck et al. (1997) referred to the sill as a "Logan-type" sill but did not infer correlation, due to a lack of trace element and REE chemistry in Jones (1984) for detailed comparison purposes.

Virginia Formation

The Virginia Formation is a thick sequence of argillite, siltstone, and graywacke at the top of the Animikie Group. On the basis of lithotypes present in five drill holes, Lucente and Morey (1983) divided the Virginia Formation into two informal members – a lower argillaceous lithosome and an upper silty and sandy lithosome. The lower lithosome is approximately 600 feet thick and contains common intervals wherein black, thin-bedded, carbonaceous argillite is the dominant rock type; visible sulfides are locally present. These carbonaceous argillites indicate that deposition of the lower lithosome occurred by slow accumulation of black mud in deep water under anoxygenic conditions (Lucente and Morey, 1983). The distribution of carbonaceous argillite layers within the lower lithosome are staggered and overlapped at different horizons, indicating deposition in small, restricted basins, e.g. 3rd order basins, within the Animikie Basin. Fine-grained, sericite-rich tuffaceous beds are locally present within the lower lithosome. Also, chert and limestone beds may be present near the base of the Virginia Formation. The upper lithosome also consists dominantly of argillite, but it generally lacks carbonaceous argillite, and instead, contains abundant interbeds of siltstone and fine-grained graywacke that were deposited via turbidity currents in a prograding submarine fan complex (Lucente and Morey, 1983). All variety of Bouma sequences, A through D, are exhibited by the graywacke beds.

In close proximity to the Duluth Complex, the Virginia Formation is described as being a hornfels that, as defined by Turner (1968), is a non-foliated 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. The term is retained in this report. 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.

Furthermore, as the grade of metamorphism and associated deformation progressively increase towards the Complex several metamorphic textures are superimposed on the original sedimentary package. The effects of partial melting are profound, and portions of the hornfelsed Virginia Formation no longer even remotely resemble a sedimentary rock. This change is because melt pockets, first established at grain boundaries, eventually enlarged and coalesced to form interconnected melt networks, wherein the melt could move through and out of the rock depending on the driving force that squeezed it (Sawyer, 1999, p. 270). 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 6.

Cordieritic hornfels

Directly beneath the basal contact of the Duluth Complex, the adjacent Virginia Formation typically consists of massive/non-foliated, 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.

The cordieritic hornfels member is common to small hornfels inclusions within the Duluth Complex, on the periphery of large hornfels inclusions, and as an incomplete capping at the top of the footwall Virginia Formation. This capping, or rimming, is probably the result of enrichment in Mg and Al in the hornfels due to loss of granitic partial melts and H_2O, as described by Rao (1981), that produced a refractory restite that may have "protected" the footwall rocks and large hornfels inclusions from further assimilation by the Complex.

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 (Fig. 6). This rock type 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. Also, variably sized patches, or relicts, of the DISRUPT unit (see below) and the cordieritic unit are commonly found scattered throughout the recrystallized unit.

The RXTAL unit is properly classed as a diatexite. A diatexite is a rock in which partial melting is pervasive and the melt fraction in the rock exceeds the melt escape threshold (Sawyer, 1999). It appears that RXTAL unit generated at least 20-30% partial melts that enabled the rock to flow (Sawyer, pers. comm.) in response to heat and stresses applied during emplacement of the Duluth Complex. Duchesne (2004) locally found ≥26% partial melting in these rocks.

The RXTAL unit has been found in drill holes to be up to 150 feet thick and to extend down to depth of 700 feet beneath the Duluth Complex. Because of its ability to flow, the diatexite may have effectively "healed" early-formed fault zones, and thus, the diatexite may locally obscure their existence in the footwall rocks.

Disrupted unit (DISRUPT)

With increased distance from the Complex, the RXTAL unit progressively grades into the DISRUPT unit (Fig. 6) that 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 luecosome veins and patches containing quartz, K-spar (microperthite), plagioclase, and muscovite (Duchesne, 2004). Commonly present within the DISRUPT unit are variably-sized and gradational patches of the RXTAL unit, that increase in volume towards the basal contact. Further away from the basal contact, the DISRUPT unit grades progressively into the well-bedded argillaceous sequence that typifies the Virginia Formation.

The DISRUPT unit is properly classed as a metatexite. The partial melt fraction retained in metatexites is low (<20%) and the rocks "… are morphologically complex because the melt fraction is squeezed out of the deforming matrix and collects in whatever dilatant sites are present" (Sawyer, 1999, p. 269). The DISRUPT unit has been identified in drill holes to extend as far down as 500 feet beneath the Duluth Complex.

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 (Fig. 6). 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). The BDD PO unit is present in at least three horizons in the basal-most 640 feet of the Virginia Formation (Severson and Hauck, in prep.). According to Duchesne (2004), the BDD PO unit consists of varying mixtures of cordierite (with inclusions of Cr-spinel and Zn-V-rich rutile), magnesium biotite, K-spar, plagioclase, quartz, sillimanite, muscovite, graphite, and sulfides (5-15% pyrrhotite with local enrichments in chalcopyrite or sphalerite).

Partial melting of the graphitic argillite and BDD PO is evidenced by the common occurrence of white to pink "granitic" veins, wisps and patches. Bedding in both rock types is more than often highly contorted.

Calc-silicate hornfels

Commonly present within the RXTAL unit are discontinuous beds and disjointed pods (boudins?) of white- to light gray-colored calc-silicate hornfels. In drill core, the calc-silicate hornfels are generally < 2 feet thick, are often associated with thin-bedded, white siltstone or chert, and commonly exhibit outermost rounded contacts with the enclosing RXTAL unit; internal beds within the calc-silicate pods are often perpendicular to, and terminate against, these contacts. It is extremely difficult to tell in drill core if the calc-silicates represent boundinaged beds of original limey sediments or clusters of carbonate concretions. The distribution of the calc-silicates beds/pods is extremely variable in drill holes but they are especially common in some areas of the Mesaba deposit. This is especially true of the Local Boy area where calc-silicate "pods" are present in the footwall rocks, and in large hornfels rafts (where they are also associated with marble and diopside-rich beds; Severson and Barnes, 1991). The pods in the footwall at Local Boy have been mapped in the -1700-foot drift exposures of the Minnamax Shaft and have been described in detail by Kirstein (1979) and Matlack (1980). Kirstein (1979) notes that calc-silicate hornfels occur as pods that range from 4 inches to 8 feet in length and from 1 inch to 1 foot wide. The pods exhibit an overall boudin-like appearance with folded relict bedding that cannot be followed for more than 3-4 feet. Kirstein (1979) noted that the pods themselves show a wide variation in mineralogy consisting of: diopside (40-60% – generally concentrated at the rims and related to diffusion of Mg into the pods), wollastonite (0-50%), plagioclase/ anorthite (0-40% – most abundant in outer zones with diopside), grossular garnet (1-40%), idocrase, and sphene (0-3%), with localized minor amounts of calcite, poikiloblastic pyroxene, K-spar, cordierite, muscovite, fluorite, apophyllite, heulandite, laumontite, prehnite, and anhydrite. Sulfides can be present in trace amounts and include: pyrrhotite, chalcopyrite, galena, and sphalerite.

VirgSill

The VirgSill is generally present in the bottom 0.5-200 feet of the Virginia Formation (Fig. 6), and as local apophyses into the top of the Biwabik Iron Formation, e.g., in the vicinity of the Grano Fault at the Serpentine Cu-Ni deposit (Severson, 1994; Zanko et al., 1994). When present, the VirgSill ranges from a few inches thick to 197 feet thick. The thickest portions of the VirgSill are positioned over the Local Boy anticline, and the VirgSill is often absent in the Bathtub syncline indicating that structural controls in the footwall rocks were important during emplacement.

Even though the sill was mapped almost 90 years ago to the south of the present-day Northshore taconite mine (Grout and Broderick, 1919), it was not identified in drill holes beneath the Duluth Complex until the 1990s (Severson, 1991). Identification of the VirgSill in drill core is hampered by the fine-grained granoblastic texture of the sill that makes it difficult to distinguish from the enclosing hornfelsed Virginia Formation rocks; both were metamorphosed by the Duluth Complex. Although no easy task, there are subtle characteristic features that help in the recognition of the VirgSill in drill core, especially the hard to identify MG unit, relative to the adjacent hornfelsed Virginia Formation that include:

- Massive, non-laminated texture with local moderately contorted flow bands;
- A slightly more brownish color due to the presence of hornblende;
- Generally biotite-poor relative to the Virginia Formation;
- Slightly coarser-grained (difficult to see in core unless it is split); and
- Sulfide-poor relative to the Virginia Formation.

The informal term of Cr-Sill was first used by Hauck et al. (1997) to highlight the relatively high chromium contents (typically 600-2,000 ppm) that are characteristic of the rock; however the term VirgSill, as first used by Severson (1994), is retained in this report. Later work (Severson et al., 1994a; Park et al., 1999) showed that the VirgSill could be further subdivided into two textural varieties.

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, Opx, and biotite, with local sulfides (pyrrhotite, chalcopyrite, and bornite).

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 1109 Ma); as is the BifSill. 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.

The VirgSill locally contains one or more inclusions of cordieritic hornfels that vary from six inches to 18 feet-thick. Also present in the sill are calc-silicate/chert inclusions that are fairly common near the base of the sill (up to four inclusions have been noted in some locales). The common occurrence of these calc-silicate/chert inclusions in a series of drill holes suggests that the inclusions actually occur as large, but vertically very thin, subhorizontal “curtains” of the A submember from the underlying Biwabik Iron Formation. Their morphology suggests that the calc-silicate “curtains” were delaminated from the Biwabik Iron Formation during emplacement of the VirgSill along bedding planes. In a few rare instances, the actual depositional contact between the Virginia and Biwabik formations can be seen in an individual inclusion at the base of the sill – this type of inclusion is characterized by cordieritic hornfels (Virginia Formation) overlying bedded calc-silicate/marble (Biwabik Iron Formation).

HANGING WALL ROCKS

Scattered occurrences of fine-grained basaltic rocks are sporadically present in drill holes, railroad cuts, and outcrops from the Hoyt Lakes area northeastward to the Spruce Road Deposit area. They are presumably correlative with the North Shore Volcanic Group (Keweenawan age; circa 1109-1098 Ma). These basalts are most often present as hanging wall inclusions within the Duluth Complex, but locally, the basalts are in direct contact with the Virginia Formation, e.g., Allen Quadrangle.

Typically, the basalt inclusions are fine-grained, granular textured, and consist of varying amounts of plagioclase, clinopyroxene, Opx, olivine, and inverted pigeonite, with rare to trace amounts of ilmenite, pyrrhotite, chalcopyrite, and apatite. For the most part, the basalt inclusions are located well above the basal contact of the Duluth Complex. In localized areas (Dunka Pit, Serpentine), the basalt inclusions are associated with, or contain internal beds of quartz-rich sandstone that are either correlative with the Nopeming or Puckwunge formations or with interflow sediments of the North Shore Group.

BSLT-Type Inclusions

Fine-grained, granular, pale olive-green colored rocks with plagioclase-filled ovoids/wisps are locally present in the upper portions of drill holes throughout the Mesaba deposit. In drill core, the rock generally exhibits a massive, relatively homogeneous texture with local internal zones that contain fine-grained, plagioclase-filled ovoids (vesicles?) that average about 5-10 mm in diameter. Contacts with the surrounding troctolitic rocks vary from sharp to gradational. The BSLT inclusions can locally be correlated between close-spaced drill holes, but their overall spatial distribution is as laterally discontinuous raft-like inclusions. In thin section, these rocks are characterized by a fine-grained, equigranular texture consisting of: 40-60% plagioclase, 25-50% augite, rare to 15% olivine, trace to 5% Opx, and minor ilmenite, pyrrhotite, chalcopyrite, and apatite.

CC-Type Inclusions

A fine-grained, granular rock of gabbroic composition with variable amounts of oxides was intersected in the top portions of several drill holes in the Local Boy area. Because the core strongly resembles rock outcrops exposed in the Colvin Creek area, described by Severson and Hauck (1990) and Patelke (1996), it is designated as "CC" on the accompanying cross-sections of this report. The rock exhibits a granular or granoblastic texture characterized by polygonal plagioclase that tend to meet at 120° triple point junctions. Variable amounts of Cpx and Opx occur as equant grains, slightly amoeboid grains, and minor oikocyrsts. Cpx is generally the more dominant pyroxene, but exceptions are present. Olivine is locally present and occurs as oikocyrsts. Hornblende is also locally present and occurs as reaction rims around oxides. Overall, the rock exhibits a massive appearance, but it may locally contain occasional plagioclase phenocrysts (up to 1.5 cm), ovoid plagioclase-filled wisps (vesicles?), and thin (< 1 cm) subparallel magnetite bands (beds?) displaying shallow dips of 10-30° (from horizontal).

The protolith of the CC-type inclusions was probably a magnetite-rich basalt, but there are variations that are somewhat perplexing, such as, modally bedded oxide horizons with adcumulus magnetite and green pleonaste. Severson (1991; Fig. 7) displayed the distribution of modally bedded magnetite horizons, in regards to CC-type inclusions, in the top of several holes in the Local Boy area.

PARTRIDGE RIVER INTRUSION AT THE MESABA DEPOSIT

As mentioned above, the southern edge of the Mesaba deposit is situated in the PRI; whereas, the central portion of the deposit is wholly situated in the BTI. These relationships are schematically portrayed in Figure 8, which is a “type-section” of most of the igneous units of both intrusions that are present in the Mesaba deposit. Figure 9 is also offered, in three parts, as a series of snap-shot cross-sections for a quick review of the geology present in the deposit progressing from the west end to the east end. The rocks of the PRI at the Mesaba deposit, as originally outlined in Severson et al. (1994a, 1994b) are discussed below, starting from the base and proceeding upwards.

Unit I

The lowest troctolitic unit of the PRI consists of intermixed troctolite and augite troctolite that locally grade to olivine gabbro. Most of the unit is sulfide-bearing. Augite troctolite is generally the dominant rock type in the bottom half of Unit I, but it is also locally common in the top half of the unit. Unique to Unit I are extreme variations in modal mineral percentage and average grain size; both change rapidly over zones from a few feet to tens of feet thick. Due to this heterogeneous texture, numerous internal contacts divide Unit I into several subunits that cannot be correlated from drill hole to drill hole. Thus, Unit I is a mixture of various troctolitic subunits that are probably related to continuous magma replenishment.

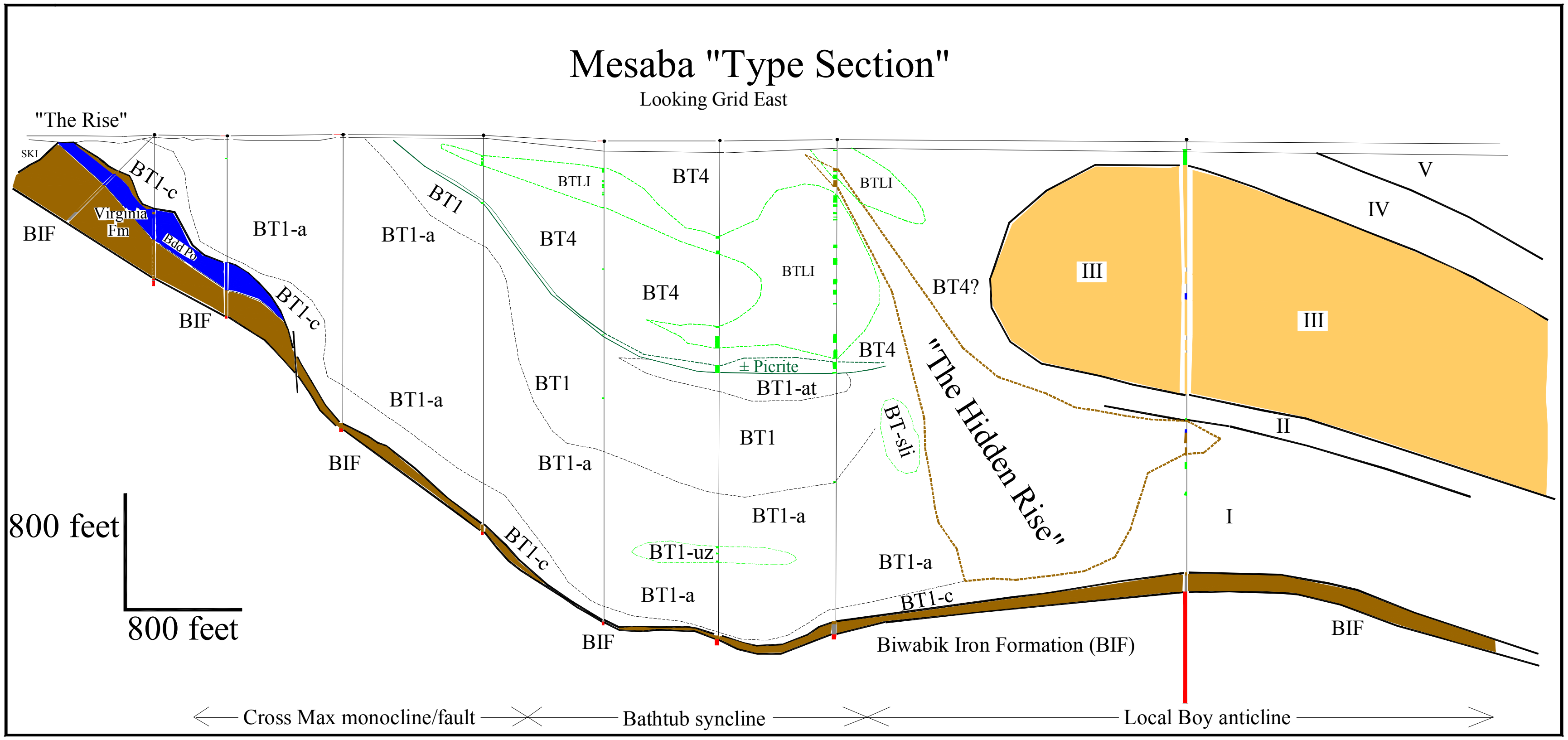


Figure 8. Schematic "type-section" cross-section, looking east, through the Mesaba deposit that crudely displays the spatial distribution of most of the igneous units in the Bathtub intrusion. Note that not all of the PRI units are shown on the right side of the figure. "The Hidden Rise," shown on the right side of this figure, is a hornfels-rich zone that is used to separate the PRI from the BTI.

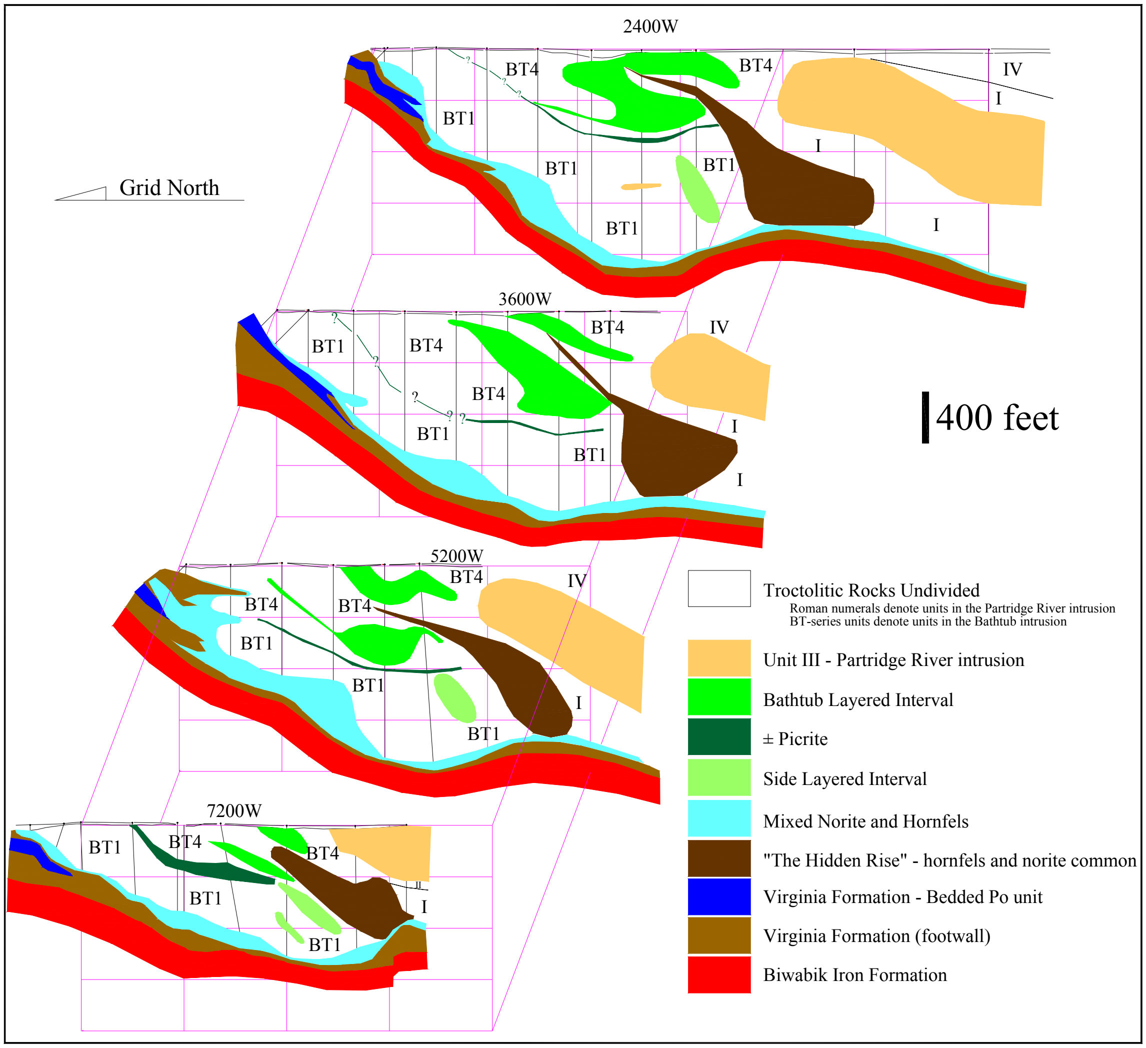


Figure 9a. Block diagram of the major igneous units in the western end of the Mesaba deposit. Roman numerals depict units in the Partridge River intrusion (PRI) and BT-series designators depict units in the Bathtub intrusion (BTI). Both intrusions are separated by “The Hidden Rise,” which is a zone with common sedimentary hornfels inclusions. Recognition of the separation between the PRI and BTI above “The Hidden Rise” is more tenuous.

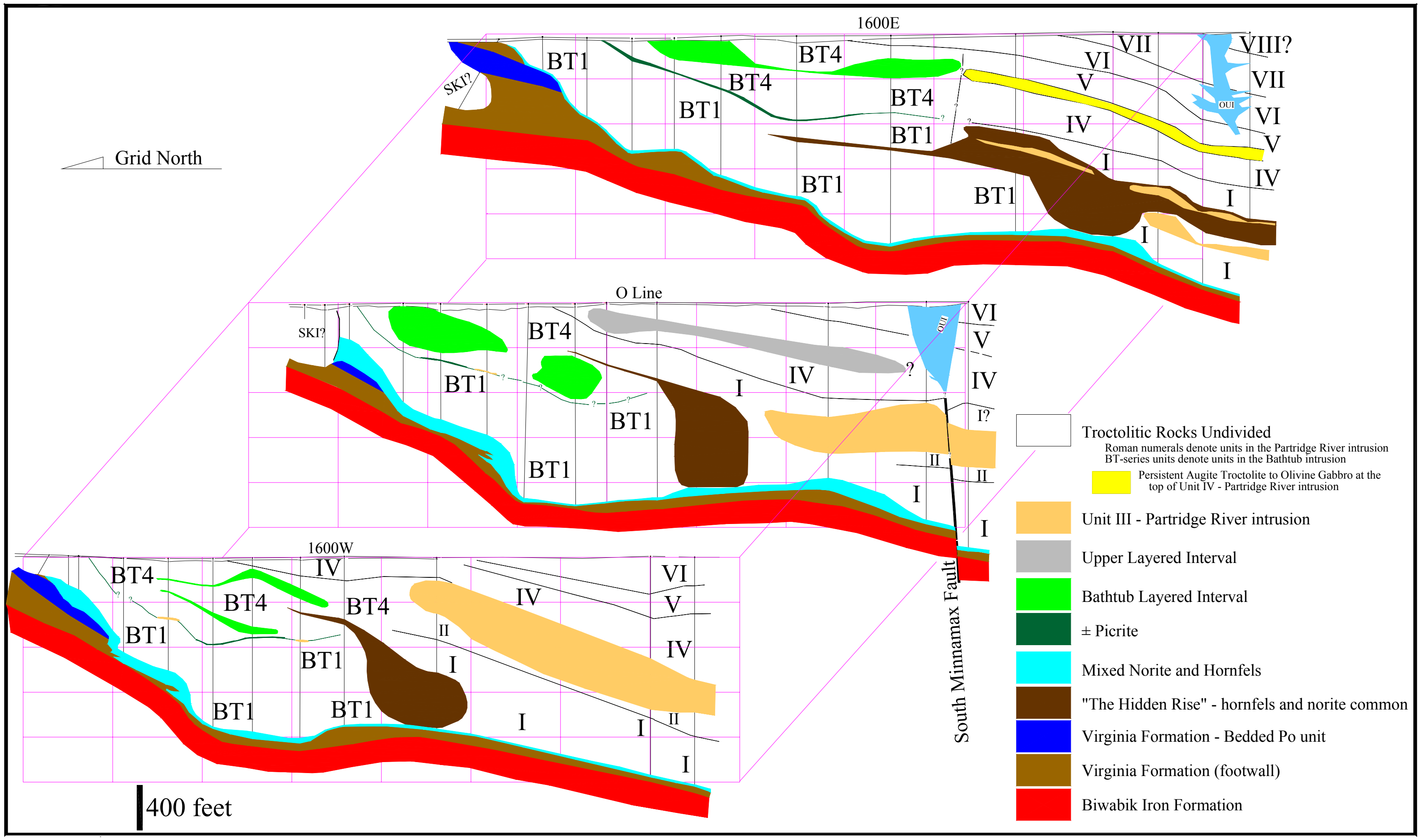


Figure 9b. Block diagram of the major igneous units in the central portion of the Mesaba deposit. Roman numerals depict units in the Partridge River intrusion (PRI) and BT-series designators depict units in the Bathtub intrusion (BTI). Both intrusions are separated by "The Hidden Rise," which is a zone with common sedimentary hornfels inclusions. Recognition of the separation between the PRI and BTI above "The Hidden Rise" is more tenuous.

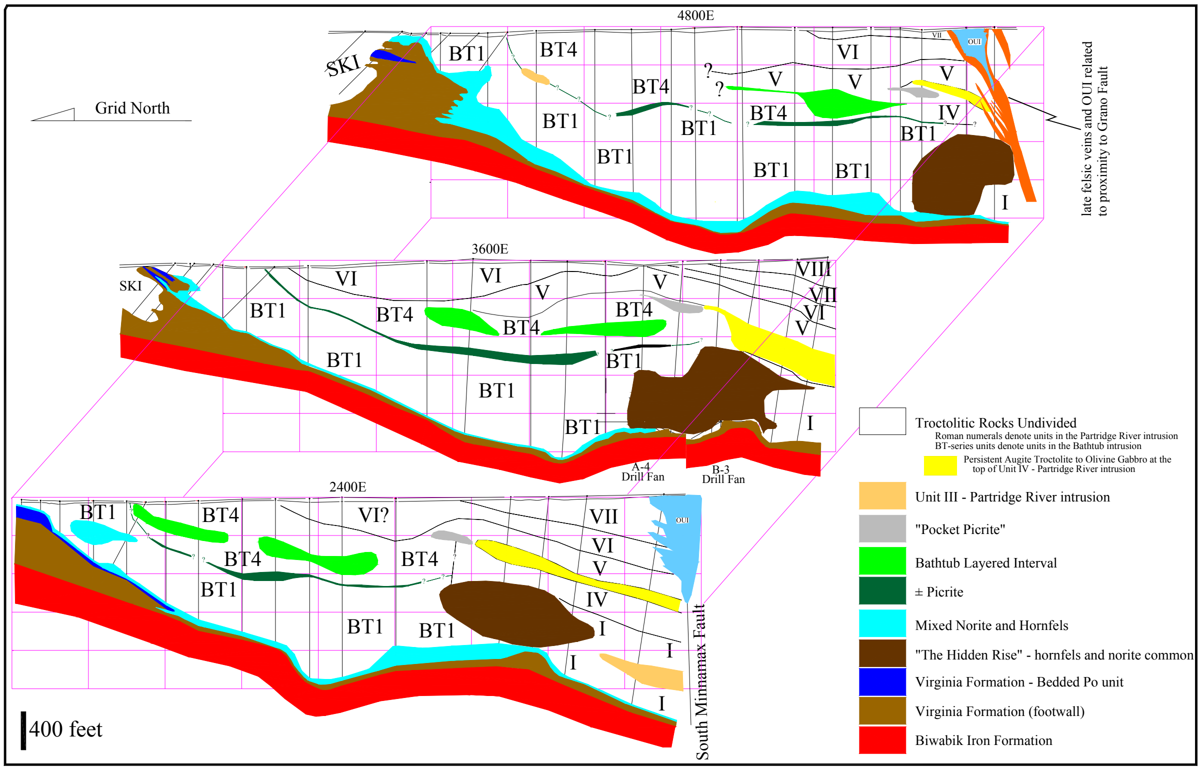


Figure 9c. Block diagram of the major igneous units in the eastern end of the Mesaba deposit. Roman numerals depict units in the Partridge River intrusion (PRI) and BT-series designators depict units in the Bathtub intrusion (BTI). Both intrusions are separated by "The Hidden Rise," which is a zone with common sedimentary hornfels inclusions. Recognition of the separation between the PRI and BTI above "The Hidden Rise" is more tenuous. Note that not all holes have been relogged in the extreme eastern end of the deposit, and this area is not portrayed in this figure.

Hornfels inclusions of Virginia Formation are most commonly present within Unit I. The inclusions vary from one inch to over 275 feet thick. Rock types are the same as those present in the footwall rocks beneath the basal contact. At the Mesaba deposit, the largest hornfels inclusions (up to 2,400 x 3,200 feet across) are present in the Local Boy area, where several raft-like inclusions are stacked above each other. The configuration of these inclusions suggests that Unit I was intruded along the bedding planes of the Virginia Formation in repeated pulses. Near the basal contact and surrounding hornfels inclusions, the intrusive rocks of Unit I have undergone sufficient silica contamination, and norite and gabbronorite are often the dominant rock type.

The thickness of Unit I is variable and ranges 300-600 feet thick (Plate II). The position of the top contact of Unit I is generally based on four criteria, of which, all or only one are present in a particular drill hole. These criteria include: 1) decrease in sulfide content upwards into sulfide-free rocks of Unit II; 2) presence of a semi-persistent coarse- to very coarse-grained (locally medium-grained or pegmatitic) anorthositic troctolite; 3) presence of a semi-persistent large hornfels inclusion of Virginia Formation (present only in the Local Boy area); and

4) appearance of a semi-persistent ultramafic horizon (base of Unit II or base of Unit IV). However, in some instances the top of Unit I is not as apparent, and the contact "pick" is based on where the known top is in surrounding drill holes.

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

Drill holes along the southern margin of the Mesaba deposit (Plate II) 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. Publically 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.

Basal Ultramafic (BU) Unit

The Basal Ultramafic Unit (BU Unit) is a submember of Unit I defined by Severson (1994). It is located at the basal contact of the PRI in an area to the east of the Grano Fault, where the BIF is the footwall rock rather than the Virginia Formation. The BU Unit is characterized by an upper melatroctolite-peridotite zone that grades downward into a lower orthopyroxenite zone, which in turn, grades downward into partially melted BIF footwall rocks. The upper zone consists of alternating troctolitic and ultramafic horizons; oxide-bearing melatroctolite and peridotite are the dominant rock types. Massive oxide horizons, up to 19 feet thick, are common within the upper zone.

Unit II

Unit II is characterized by sulfide-poor, texturally-homogeneous, medium-grained troctolite that locally grades to augite troctolite and anorthositic troctolite. Minor hornfels inclusions and sulfide-bearing zones are present in some drill holes. Toward its base, Unit II grades into a persistent ultramafic horizon characterized by melatroctolite, peridotite, and/or olivine-rich (40%-50% olivine) troctolite. At its base, the ultramafic horizon is in sharp subhorizontal contact with the underlying Unit I. Unit II pinches out to the east along the southern margin of the Mesaba deposit, and it is not present in the Local Boy ore zone.

Unit III

Unit III is the most distinctive "marker bed" of the PRI at the Mesaba deposit. This unit is fine-grained (2-3 mm plagioclase laths) and is characterized by troctolitic anorthosite and anorthositic troctolite that locally grade to troctolite and augite troctolite. In all instances, the rock consistently grades to plagioclase-rich and olivine-rich patches that give the drill core an overall mottled texture. This mottled appearance is due to very coarse (up to 3.0 cm) olivine oikocrysts that are irregularly distributed throughout the rock. The mottled-texture and fine-grained nature make Unit III unique relative to all the other units of the PRI. Unit III is readily recognizable in drill core and easily correlated between drill holes. Unit III is present as a thick and continuous unit in most of the drill holes positioned along, and to the south of, the axis of the Local Boy anticline (Fig. 8). However, Unit III pinches out to east along the anticlinal axis, and it is only present as discontinuous lenses in the Local Boy ore zone. North of the anticline, Unit III is present as localized small inclusions within the BTI.

In some holes, Unit III contains internal zones wherein the olivine is cumulus rather than oikocrystic. These zones are present as both gradational zones and as cross-cutting zones, and they are indicated on the cross-sections of this report. However, for cross-section purposes, these internal zones are lumped with Unit III.

Unit IV

Unit IV is characterized by thick intervals of texturally-homogeneous troctolite and/or augite troctolite. In the Local Boy area, Unit IV grades upward into a persistent zone of augite-rich augite troctolite and olivine gabbro (yellow upper portion of Unit IV in Fig. 9c and Unit IV-a on the cross-sections of this report). This upper augite troctolite (Unit IV-a) was utilized as a major "marker bed" in the Local Boy area in that the western drill holes of Plate II have been hung on the top of this unit.

At its base, Unit IV has a semi-persistent ultramafic horizon that contains one or more melatroctolite and/or peridotite layers. In the south-central portion of the deposit, the same apparent base of Unit IV consists of multiple ultramafic layers spread over a thick interval (Fig. 9b and the cross-sections of Plates XXVI through XXIX). This interval is referred to as the Upper Layered Interval (ULI).

Unit IV generally exhibits a highly gradational upper contact with Unit V. In some areas, the contact between Units IV and V is difficult to determine, and some of the divisions shown on the cross-sections of this report are arbitrarily chosen.

In the eastern third of the Mesaba deposit is a very localized zone of ultramafic layers located near the top of Unit IV. This ultramafic zone is referred to as the “Pocket Picrite” (Fig. 9c and the cross-sections of Plates XXXIII though XXXVIII). The “Pocket Picrite," varies from a few feet to 25 feet thick and consists of alternating beds of melatroctolite, peridotite, dunite, olivine-rich troctolite, and troctolite.

Unit V

A texturally-homogeneous, medium- to coarse-grained, anorthositic troctolite characterizes Unit V. The bottom contact of Unit V is gradational into Unit IV, and the top contact is sharp against an ultramafic horizon that marks the base of overlying Unit VI.

Units VI, VII, and VIII

The uppermost units of the PRTI are remarkably similar, and thus, they are all described in this section. The units are characterized by texturally-homogeneous, medium- to coarse-grained, troctolite and/or anorthositic troctolite, with minor augite troctolite and troctolitic anorthosite. Each contains: 1) a basal ultramafic horizon(s); 2) modally bedded adcumulus magnetite horizons associated with ultramafic layers and/or CC-type inclusions (Severson, 1991); and 3) inclusions of Unit III. Due to these similarities, actual unit assignment to either Unit VI, VII, or VIII is difficult unless the drill hole penetrates a lower marker bed in the PRI, and the hole is hung and correlated accordingly. In portions of the eastern third of the Mesaba deposit, Units IV through VI overlie the units of the BTI (see later discussions on the timing of emplacement of the PRI versus the BTI).

BATHTUB INTRUSION AT THE MESABA DEPOSIT

The igneous stratigraphy of the newly named Bathtub intrusion (BTI) has until recently been treated as an anomaly relative to the known igneous stratigraphy of the nearby Partridge River intrusion (PRI). Severson et al. (1994b) presented numerous cross-sections across the Mesaba (Babbitt) deposit wherein they [incorrectly] subdivided the igneous stratigraphy of the entire deposit into the same seven units as defined in the PRI. However, in the Bathtub ore zone of the deposit, they noted the anomalous nature in the stratigraphy as defined by a lack of Units II and III and instead, the abundant presence of ultramafic layers at about the same stratigraphic level. In their correlations of units in the Bathtub ore zone, they incorrectly retained Units I and IV. These same incorrectly labeled units are now referred to as BT1 and BT4 for the lower two-most units of the BTI. Additional units of the BTI, as depicted in Figures 8 and 9 have also been singled out, and all are discussed below.

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;
- The BT1 Unit averages about 900 feet thick (with a range of 300-1,200 feet thick) and is thicker than Unit I at the nearby NorthMet deposit;
- The top of BT1 is not appreciably enriched in PGE; whereas, the top of Unit I in the nearby PRI (NorthMet deposit and southern portion of Mesaba deposit) does contain highly anomalous PGE values up to 2 ppm or more – this relationship was first noted by Severson and Hauck (2003); 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, in the cross-sections of this report, into several internal subunits based on the dominant presence of one rock type over other rock types. Contacts between these rock types vary from highly gradational to abrupt with locally measurable sharp contacts. The various subdivisions of the BT1 Unit are briefly discussed below.

<u>BT1</u>

The BT1 designator by itself (no suffix) on the cross-sections denotes areas where heterogeneous-textured troctolite is the dominant rock type, but near-equal amounts of augite troctolite and anorthositic troctolite may also be locally present.

BT1-a

This subunit of the BT1 on the cross-sections denotes areas where heterogeneous-textured **a**ugite troctolite grading to olivine gabbro is the dominant rock type. As in the above subdivision, near-equal amounts of troctolite and anorthositic troctolite may be locally present. 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 **c**ontamination 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 BTI.

BT1-uz

Wherever olivine-rich ultramafic rocks are common over appreciable intervals in the BT1 Unit this subunit is used to designate **u**ltramafic **z**ones. The morphology of the ultramafic rocks in these zones ranges from well-defined layers, with a well-defined serpentinization foliation, to zones where irregular ultramafic patches are presumably peppered throughout a troctolitic host rock. The latter example was not always logged in equal degree by various geologists, and as a result the true distribution of these “uz” zones within BT1 is not fully understood nor completely mapped out.

BT1-at

This subunit of the BT1 is used to denote areas where **a**northositic **t**roctolite 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 **S**ide **L**ayered **I**nterval (Figs. 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” (see Plates VIII through XI). 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 Figure 10.

“The Rise”

Along the extreme northern edge of the Mesaba deposit, the basal contact of the BTI rises steeply to the surface. However, in one area (generally east of grid line 800W and north of grid lines 400S to 400N on Plate I), the basal contact rises steeply toward the surface, and then drops off again in a northerly direction. This area (Fig. 5) has been referred to as "the Rise" (Severson et al., 1994a). Along "the Rise" are spatially discontinuous "islands" where the Virginia

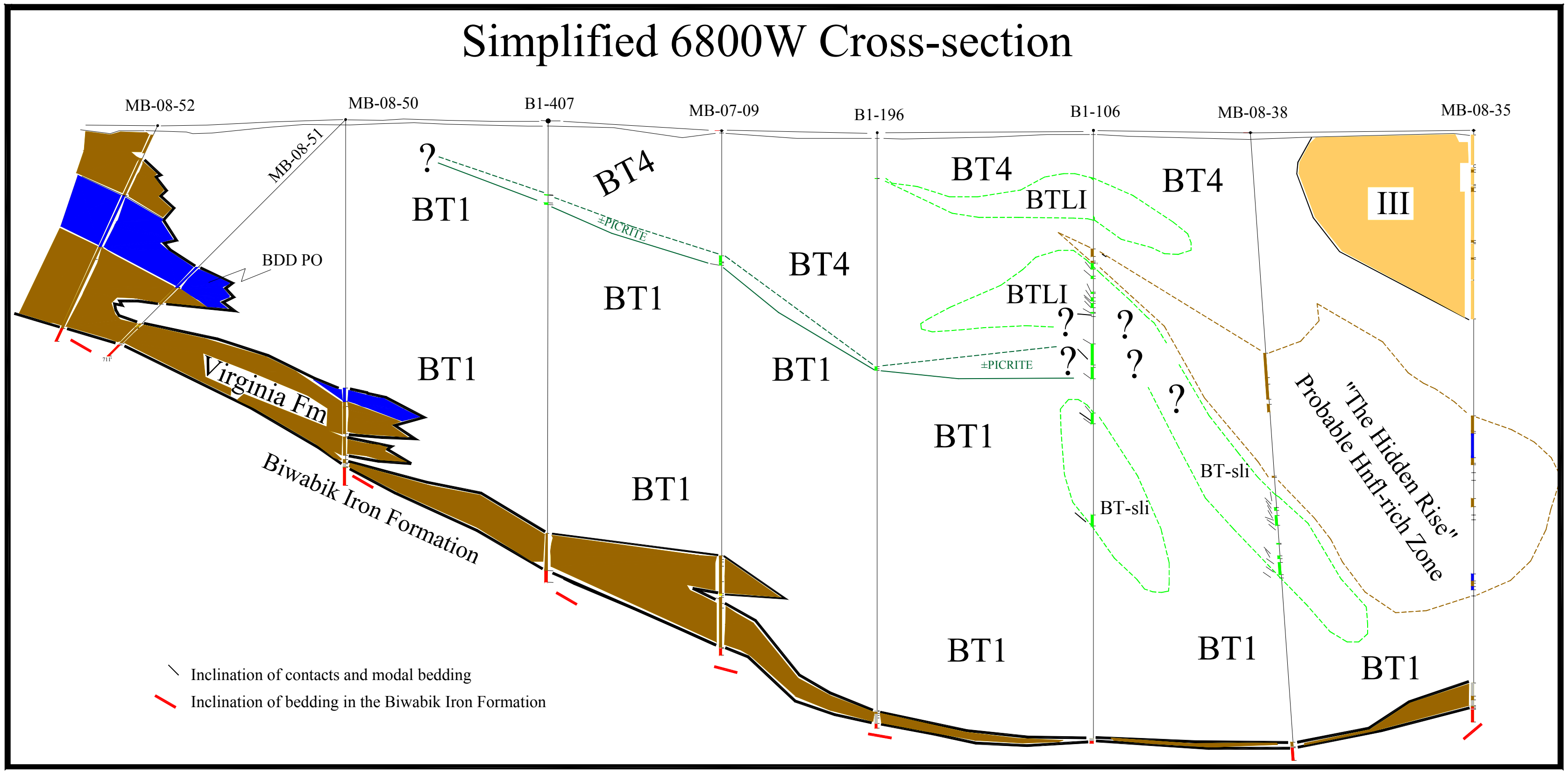


Figure 10. Simplified cross-section of the 6800W line at the Mesaba deposit. In this example, the correlation of the BTLI, "± Picrite," and BT-sli subunits between holes B1-106 and MB-08-38 is problematic. Note also that there are two BTLI subunits; of which the lowermost one merges with the "± Picrite" at depth in hole B1-106.

Formation actually subcrops beneath the glacial cover. In some locations, these Virginia Formation islands are undercut on the north by intrusive rocks of the [presumably] South Kawishiwi Intrusion. Severson et al. (1994a) suggests that the area of "the Rise" is one portion of the contact zone separating rocks of the Mesaba deposit (south of "the Rise") from rocks of the South Kawishiwi Intrusion (north of "the Rise"). Intrusive rocks north of "the Rise" are generally sulfide-poor relative to rocks that are positioned to the south of "the Rise."

“The Hidden Rise”

The “Hidden Rise” is a loosely-defined zone situated along the crest of the Local Boy anticline wherein scattered hornfels inclusions, and associated noritic rocks, are fairly common. The distribution of “The Hidden Rise” is displayed in Figure 9 and can be seen to occur throughout the Mesaba deposit. In this figure, the lowermost portion of this zone is anchored close to the basal contact of the Complex in the vicinity of the anticline and extends upwards in a northerly direction to well above the basal contact (up to 1,600 feet in some areas). Depending on how the borders for “The Hidden Rise” are drawn, this zone contains anywhere from 20-100% hornfels inclusions that range from a few inches to 130 feet thick. “The Hidden Rise” is unique in that it is a zone that contains common hornfels inclusions; whereas, hornfels inclusions are generally rare over much of the remainder of the Mesaba deposit (except for common hornfels located very near the basal contact and associated with the BT1-c subunit). When viewed collectively, the inclusions in “The Hidden Rise” define an east-west trending “ridge” that extends from one end of the deposit to the other, **and** coincidentally, 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 (probably during crystallization of Units I through III) and later served as a wall along the south edge of the BTI during formation of the BT1 and BT4 units. However, as the BTI units were intruded they probably assimilated much of “The Hidden Rise” thus producing the mixture of hornfels and intrusive rock that are currently preserved.

As mentioned above, “The Hidden Rise” can artistically be used to separate the BTI and PRI on the cross-sections. However, as this “ridge” does not extend upward all the way to the surface it, cannot be used to fully separate the upper BTI units, to the north of “The Hidden Rise,” from the upper PRI units to the south of “The Hidden Rise.” Attempts were made on the cross-sections to separate the upper PRI and BTI units without the use of this “ridge,” but this was a difficult endeavor and many question marks are utilized to appropriately denote these areas.

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 as been further subdivided, in the cross-sections of this report, into several internal subunits based on the dominant presence of one rock type over other rock types. The various subdivisions of the BT4 Unit are briefly discussed below.

BT4

The BT4 designator by itself (no suffix) on the cross-sections denotes areas where troctolite is the dominant rock type, but near-equal amounts of augite troctolite and anorthositic troctolite may also be locally present. The overall configuration of areas where troctolite is dominant are spatially highly irregular, and these areas do not always show good correlation, or predictability, from one cross-section to another cross-section.

BT4-a

This subunit of the BT4 on the cross-sections denotes areas where heterogeneous-textured **a**ugite troctolite is the dominant rock type. As in the above subunit, near-equal amounts of troctolite and anorthositic troctolite may be locally present. The BT4-a subunit exhibits somewhat better correlations from one cross-section to the next, but the overall spatial distribution of this rock type is typically irregular and non-predictable within the BT4 Unit. On many of the cross-sections, the BT4-a unit becomes progressively thicker to the north, and at some localities it is difficult to distinguish the BT1-a subunit from the BT4-a subunit (especially when the "± Picrite" is absent).

BT4-at

This subunit of the BT4 is used to denote areas where **a**northositic **t**roctolite is the dominant rock type. Thick zones of BT4-at are common to some cross-sections through the Mesaba deposit, and these zones show relatively good correlation and predictability with similar zones in adjacent cross-sections. The BT4-at Unit was originally correlated with Unit V of the PRI in Severson et al. (1994b).

"± 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 the horizon is variably present to the south in the contact zone between the PRI and BTI (Fig. 8). 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. This problematic relationship is portrayed in Figure 10. 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. In these instances, the "±

Picrite" is "carried over" from drill holes in adjacent areas where ultramafic horizons are not as plentiful, and the "± Picrite" is more easily defined by a single ultramafic horizon.

<u>Bathtub Layered Interval (BTLI)</u>

In the vicinity of the Bathtub syncline, ultramafic layers are extremely common within the BT4 Unit (Fig. 8). 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 (Fig. 9c). Conversely, in the western half of the deposit (Fig. 9a), the BTLI is confined to one or two, east-west trending, 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 also 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 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.”

Unfortunately, not all of the bedding and contact angles in the BTLI were routinely measured while logging core, especially during the 1994 relogging campaign. Wherever these measurements were taken are indicated on the cross-sections included with this report. (The dip direction of these BTLI beds are assumed to be southerly for display purposes.) However, the overall lack of measurements throughout the deposit makes it difficult to ascertain the spatial extent of steeply-inclined versus shallowly-inclined ultramafic beds, and prevents making any educated guesses as to the origin of the BTLI throughout the entirety of the Mesaba deposit.

Upper PRI Units and Timing of Emplacement

On many of the cross-sections, Units IV through VI of the PRI appear to extend northward and overlie the heterogeneous-textured BT4 Unit. This relationship, also depicted in Figure 9, 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 (Fig. 5). “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, e.g., Plate XI.
- Concurrent with or after the above activity, the BT1 Unit was intruded from a vent area located somewhere to the east (Fig. 5), 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 southwest. These upper units were emplaced over the BT4 Unit.

STRUCTURAL FEATURES AT THE MESABA DEPOSIT

Many of the structural features of the Mesaba deposit have been previously described in detail by Severson et al. (1994a, 1994b). However, as more holes were logged in this deposit some changes have been made, and a brief review of the structure is warranted.

Local Boy anticline and Bathtub syncline

The most prominent structural features at the Mesaba deposit are a pair of east-west-trending parallel folds, defined by contouring the top of the footwall Biwabik Iron Formation, that are referred to as the Local Boy anticline and Bathtub syncline. These folds have been previously described by Holst et al. (1986), Martineau (1989), Severson and Barnes (1991), and Severson et al. (1994a – Plate II). Both of these folds probably exerted strong controls on the style of emplacement of the BTI, and its basal contact mimics the form of the anticline and syncline. This relationship is readily seen by contouring the basal contact (Severson et al., 1994a – Plate

III), wherein a trough is positioned over the syncline, and a ridge is positioned over the anticline. Both of these structural features appear to diminish towards the west that roughly coincides with the western limit of the BTI.

Grano Fault

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 pyroxenitic lenses associated with the fault zone (Severson, 1994). These 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. 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 Babbitt 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.

The Grano Fault may have served as a feeder zone to the BTI, and to massive sulfides at the base of the PRI in the Local Boy ore zone. Severson and Hauck (2003) have speculated that magma that issued from the Grano Fault may have been initially enriched in PGE, 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.

South Minnamax Fault

The South Minnamax Fault, named by Hauck (1993) is an east-west trending fault along the extreme southern edge of the Mesaba deposit. Displacement of the fault, based on correlations and projections of units between only six drill holes, is generally 100-200 feet, but in one cross-section (Plate XVIII) a displacement of over 400 feet is indicated. Several OUI bodies occur at the surface along the trace of this fault (Plate I).

Cross Max Fault/Monocline

On the north limb of the Bathtub syncline, the Biwabik Iron Formation exhibits a steep rise towards the surface and then levels off again further north. This configuration defines a broad monocline on the north limb of the syncline. The area of this monocline-like feature coincides with steeper dips in the bedding of the iron-formation as seen in drill core. However, in some localized areas the steep bedding dips observed in core do not fully explain the apparent offset in the BIF, as projected between drill holes. In these instances the monocline appears to have been locally compounded by faulting. The Cross Max Fault (Plate I), named by Hauck (1993), is so indicated on some of the cross-sections where this monocline plus additional local faulting takes place. However, because these offsets, as related to faulting, are only sporadically present along the monocline, the overall existence of a single major fault is questionable.

North Minnamax Fault

North of the Cross Max Fault is another fault in the monocline that is referred to as the North Minnamax Fault (Plate I). The existence of this fault is also questionable as its apparent offset is sporadic and can not be traced very far in any direction.

Swamp Fault

The Swamp Fault (this study) is located at the far western end of the Mesaba deposit (Plate I). Intensely brecciated, slickensided, and gouge zones that are associated with this fault were intersected in several holes (Plates VII through XI). The placement of these holes that intersect the fault defines a northeast trend that coincides with a topographical lineament on the edge of a swamp (with a string of outcrops along the northwest edge of the swamp). However, while the existence of the fault is unquestionable, only minimal displacement of the footwall rocks on either side of the fault is indicated. Similar topographical lineaments, that are also inferred to be faults with minimal displacement, are located close to, and parallel to the Swamp Fault (Plate I).

Additional Faults

Numerous brecciated, slickensided, and fault gouge zones are intersected in many of the drill holes at the Mesaba deposit. This situation suggests that fault zones are common to the deposit. However, as many of these faults show minimal-to-no displacement in the footwall rocks they cannot be traced with certainty across the deposit. Thus, the trends of known fault intersections in these drill holes are unknown, and they are not shown on a map of the property (Plate I).

DEUTERIC ALTERATION OF ALL IGNEOUS UNITS AT THE MESABA DEPOSIT

Patches of deuteric alteration, characterized by uralitization, saussuritiztion, chloritization, and serpentinization are present in all the troctolitic units of the PRI and BTI. Uralitization is characterized by the replacement of interstitial Cpx by fine-grained mats consisting of radiating bundles of chlorite, hornblende, actinolite, sericite, ±tremolite, ±calcite that often interpenetrate with adjacent plagioclase crystals. Also associated with this type of alteration is variably saussuritized plagioclase, and moderately to strongly serpentinized and/or chloritized olivine. The dimensions of the uralitized zones in drill core vary from about one inch to tens of feet thick; in many instances, both uralitized and "fresh" rock alternate within these zones on a scale ranging from less than one inch to several feet thick. In some cases, the uralitization is related to hairline fractures (all are parallel and regularly spaced in some instances), and the alteration exhibits a diminished intensity away from the fractures (alteration halos down to 1 cm across have been noted in drill core). However, in many instances, large uralitized zones are not apparently related to fractures in drill core. Sulfide content does not usually show an increase in these zones. Attempts to correlate large uralitized zones between drill holes in the Mesaba deposit has not been conducted for this investigation.

Also present at Mesaba are saussuritized, serpentinized, and chloritized zones. Saussuritized zones are ubiquitous and vary from very strongly saussuritized thin pegmatites to saussuritized zones varying from less than one inch-thick to tens of feet thick. Within these zones, the saussuritization is variable and includes: 1) complete, or strong, saussuritization of all feldspars in the entire zone; 2) scattered patchy (measured in inches) saussuritization scattered throughout the zone; 3) spotted (1-2 cm) saussuritization throughout the zone; and 4) speckled (<2 mm) saussuritization throughout the zone. Serpentinization is usually confined to ultramafic layers and patches. Chloritization is variable and ranges from massive chlorite zones, wherein it is often difficult to tell the original rock type, to patchy-spotty-speckled distribution (as described above), to halos adjacent to joints and fractures.

Alteration of olivine to iddingsite, present as disseminated red spots that look like hematite, is also present in the tops of many drill holes. Typically, the iddingsite alteration occurs as halos adjacent to subhorizontal joints (some of the joints exhibit slickensides). Hauck (1993) noted these red spots in some of the earlier logged holes and tried to correlate them with what he referred to as the "Flat Fault." However, most of the iddingsite occurrences are associated with joints, or sets of subparallel joints, and not a consistent through-going fault zone.

While many of the above alteration assemblages are recorded in the lithologic logs for many of the drill holes, the actual location of these zones has **not** been indicated in the included cross-sections. Likewise, the overall configuration of how these zones connect between holes has not been presented on the cross-sections.

CHLORINE DROPS AS COATINGS ON THE DRILL CORE AT THE MESABA DEPOSIT

Slimy, rust-colored, fluid drops that form via a deliquescent process are locally present on the drill core surfaces of several drill holes within the Mesaba deposit. These drops are also reported from other holes scattered throughout the PRI and SKI (Dahlberg et al., 1988; Severson and Hauck, 1990; Severson, 1991, Severson, 1994; Severson, 1995; Dahlberg and Saini-Eidukat, 1991; and Hauck et al., 1997). Dahlberg and Saini-Eidukat (1991) report that the drops appear on freshly cut drill core surfaces within four months of exposure to air. Personal observations of recently-drilled Teck Cominco core indicate that during the summer months the drops begin to form within hours after the core was washed with water (before logging the core). In these instances, the first indications of chlorine drops are the formation of brown rust spots, salt crystals lining cracks and vugs, and the core's persistence to retain a wet appearance long after it had been washed and sat out on the core logging tables. In some instances the core was heated by close proximity to halogen lamps, in attempts to dry it out, and water was observed to continuously "ooze" out of cracks in the core as it began to dry.

Analysis of the brown fluid drops indicates high chlorine content values up to 3,000 ppm (Dahlberg, 1987; Dahlberg et al., 1988; Dahlberg and Saini-Eidukat, 1991). Saini-Eidukat et al. (1994) have found that the chlorine in the drill core is actually tied up in a newly-discovered mineral referred to as hibbingite. The rusty liquid Cl-drops that coat the core are actually a break down product of akaganéite (Saini-Eidukat et al., 1994). The chlorine drops noted in this, and previous studies, are mostly associated with variably serpentinized ultramafic rocks (both layers and OUIs), but they can also occur in: vuggy zones, sulfide-bearing zones, massive oxide zones, and even in the BIF submember C that contains olivine. Slimy drops, and more commonly dried-up encrustations, are also present on the basal massive sulfide drill core from the Local Boy ore zone area (Severson and Barnes, 1991). Hauck et al. (1997) also present a detailed description of other forms of chlorine-rich precipitations (green, blue and black) that coat the drill core surfaces. The overall distribution of Cl precipitates that are present in drill holes is indicated on the cross-sections accompanying this report.

The presence of hibbingite in the drill core is indicative of late magmatic movement of chlorine through the crystal pile of the various intrusions and laterally into the footwall rocks. However, the mechanism that produced the initial high Cl content within the rocks is unknown. Dahlberg and Saini-Eidukat (1991) suggest that the rocks of the Duluth Complex were subjected to invasion by Cl-bearing solutions during or after serpentinization. These Cl-bearing solutions may have moved upwards along fault zones and then laterally into the adjacent rocks. Alternatively, intrusion-wide, upward-moving, chlorine-rich fronts may have lead to formation of hibbingite as has been speculated by Severson (1994). Hauck et al. (1997) suggest the chlorine-rich fluids were formed during collapse of the Midcontinent Rift System that expelled Cl-rich evaporite-fluids.

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 (Fig. 5). 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; Figs. 11 through 14). Underground fan drilling (217 holes) was completed in 1978 to further define the massive sulfide distribution. The massive sulfides of the Local Boy ore zone have been described in detail in several reports (Severson and Barnes, 1991; Hauck and Severson, 2000) and more recently in Miller et al. (2002a). The conclusions of Miller et al. (2002a) were made after a second phase of relogging the underground holes at Local Boy was completed in 1994 by Severson and Zanko (unpublished data). This second phase was initiated when Arimetco Inc. controlled the property, and NRRI geologists were contracted to finish logging the underground holes and make more up-to-date cross-sections. Before the project was completed, Arimetco Inc. declared bankruptcy, and the resultant cross-sections were never released in an NRRI report. The cross-sections that were originally prepared for Arimetico Inc. are herein included with this report (Plates XLX through LXX), as well as a brief review of the massive sulfide mineralization at Local Boy.

It is important to note that the surface cross-sections prepared for this report suggest that the Local Boy ore zone is situated on the edge of the Partridge River intrusion. Local Boy is also associated with “The Hidden Rise.”

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.,

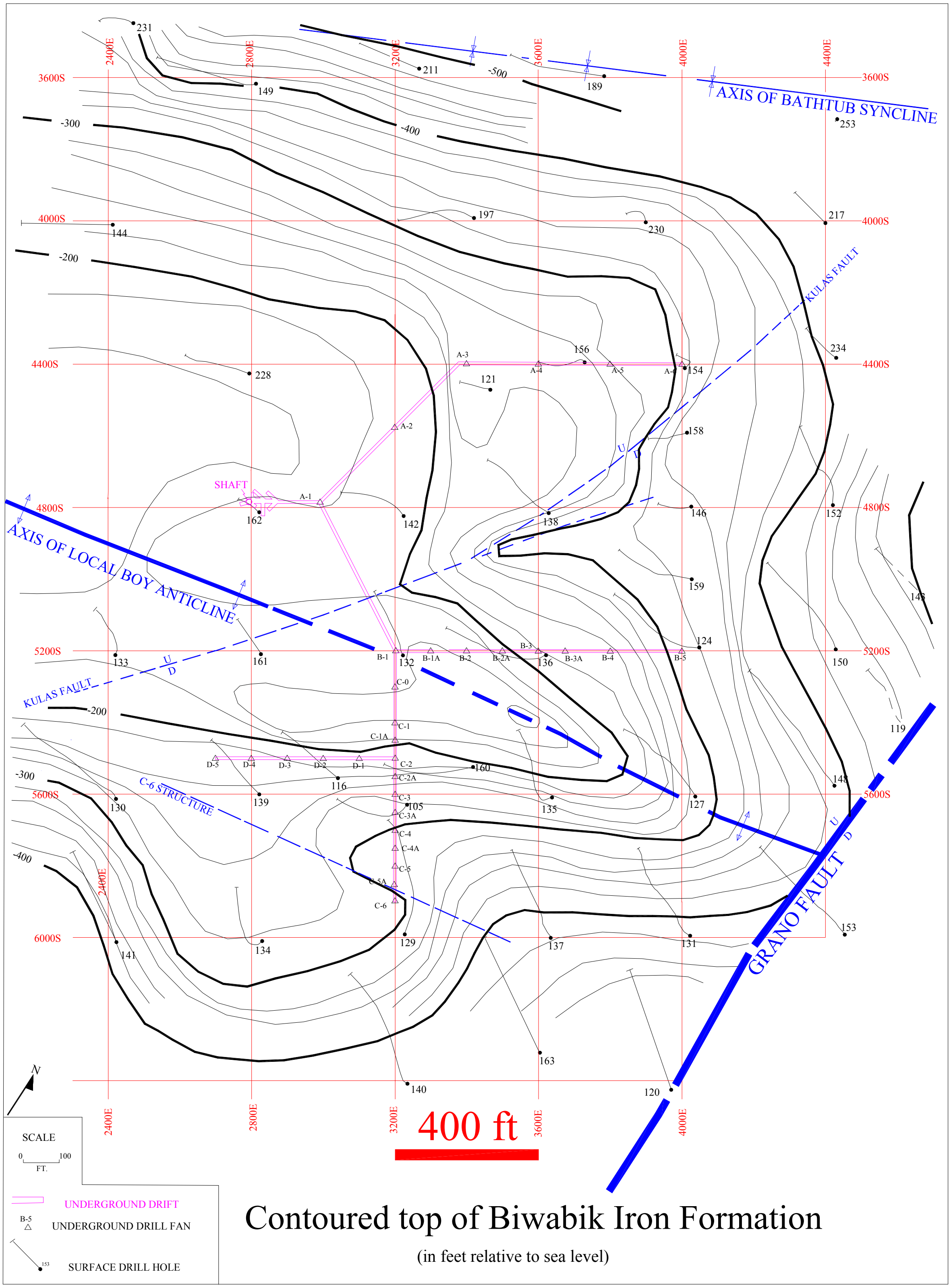
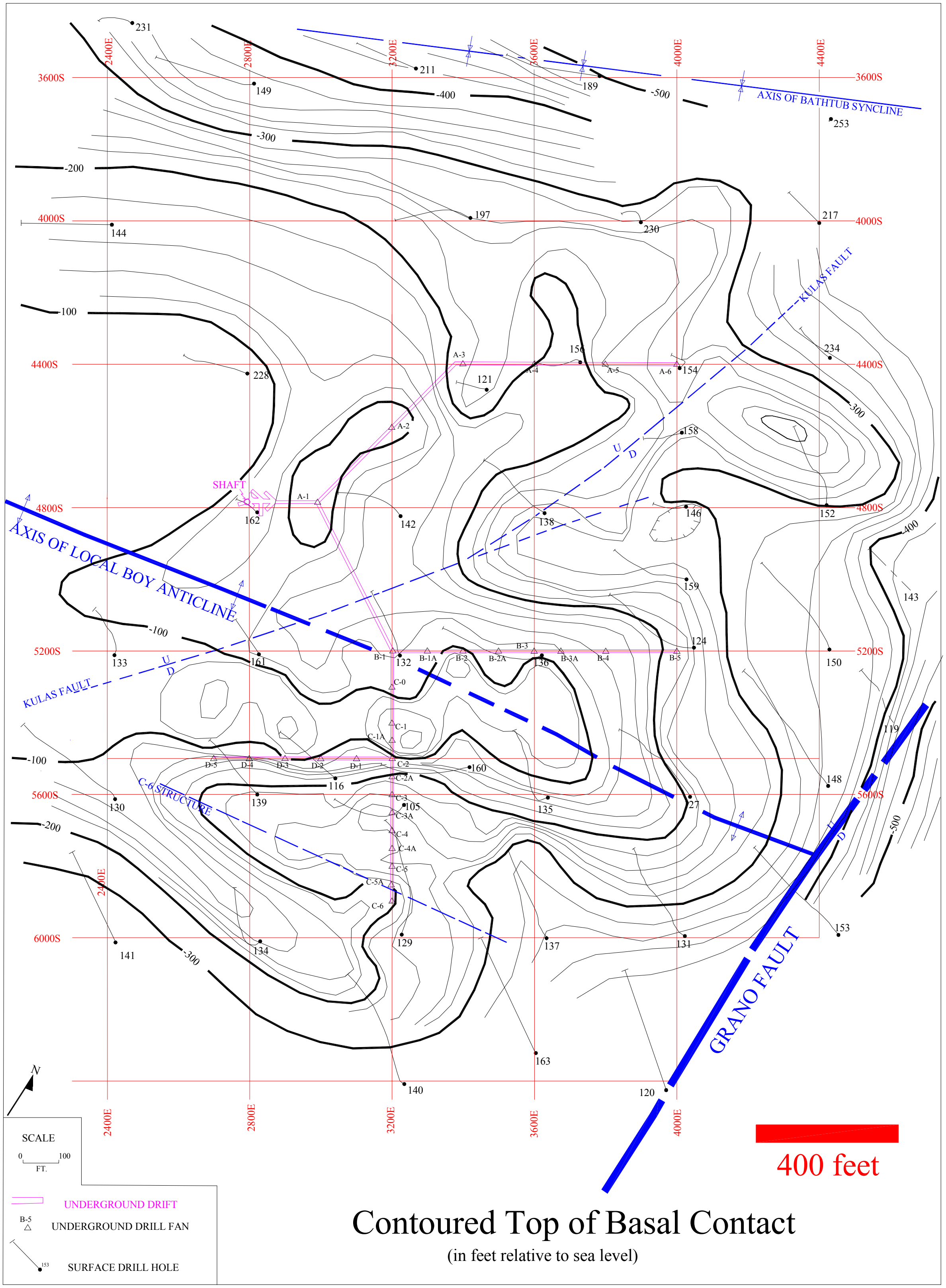


Figure 11. Contoured top of the Biwabik Iron Formation at Local Boy.



Contoured Top of Basal Contact

(in feet relative to sea level)

Figure 12. Contoured top of the basal contact between the Virginia Formation (footwall) and the Partridge River intrusion at Local Boy.

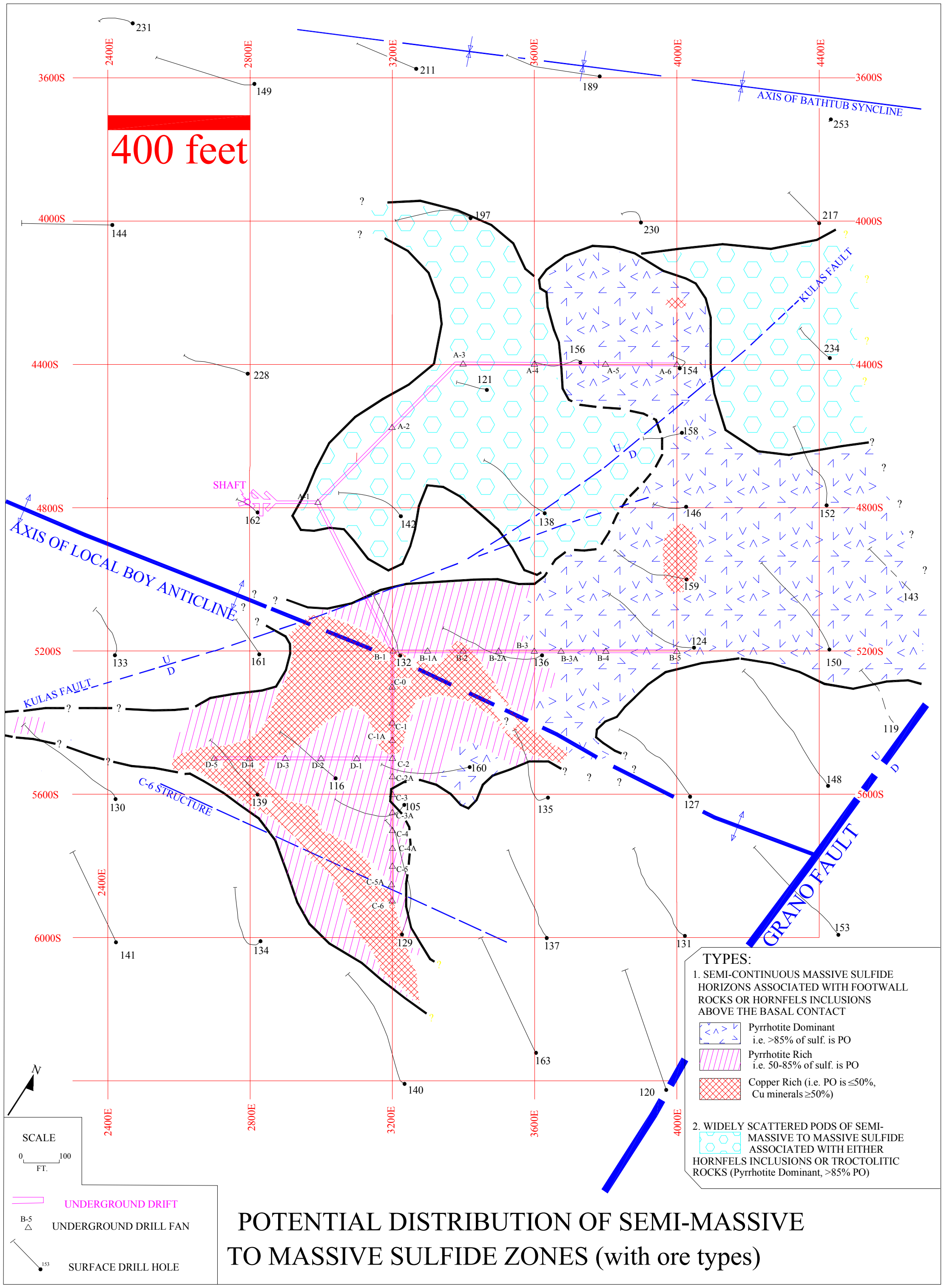


Figure 13. Potential distribution of semi-massive to massive sulfide types (Cu-poor versus Cu-rich) at the Local Boy ore zone.

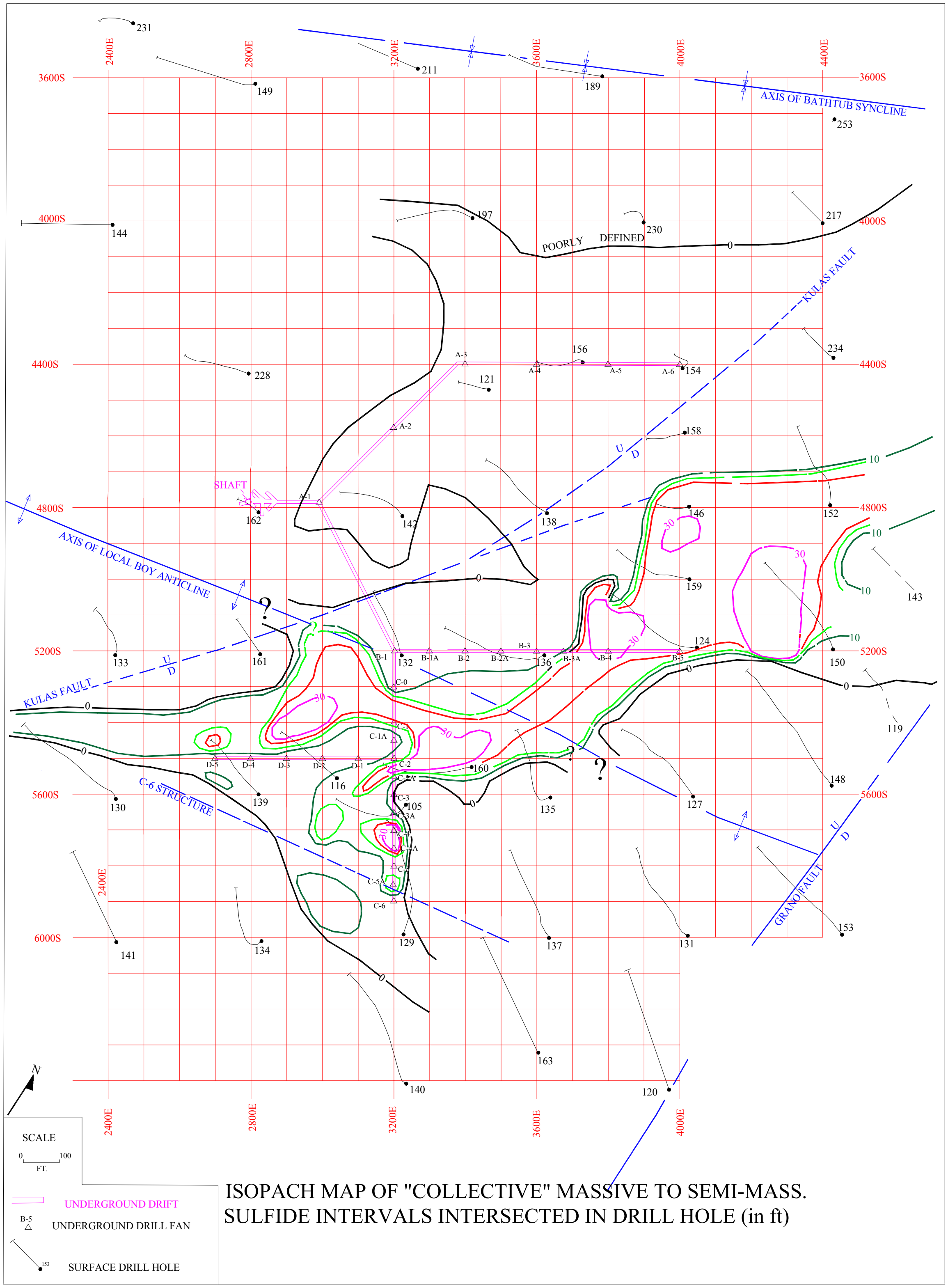


Figure 14. Isopach map of the cumulative thickness of the massive sulfide zones at the Local Boy ore zone. Note that the massive sulfides are not present as a continuous blanket, but rather, as one or more stacked disjointed/separated multiple horizons near the basal contact.

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 situation 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 11. Similar anticline geometries are also present for the basal contact as shown in Figure 12. All the data indicate that an EW-trending anticline is the major structural feature present within the footwall rocks of the Local Boy area.

The spacing of the contours in Figure 11 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 Figures 10 and 11. This fault was initially mapped by Jim Kulas in the underground drifts at Local Boy. In preparing the cross-sections included in this report, Severson and Zanko (1994, unpublished data) noted a fault offset of 10-20 feet in some of the cross-sections. Upon comparison to the Kulas map, they noted a good coincidence of his mapped fault with the overall trend of offsets in their cross-sections 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 Lower Proterozoic 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 situation 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 similar mechanism is proposed for the Norilsk-Talnakh deposits in Russia. This vein-like setting scenario is further substantiated by:

- In core, the sulfides exhibit textures with the footwall rocks that are indicative of structural preparation and sulfide flooding. These textures, progressing from simple to more complex (Severson and Barnes, 1991), include:
    - Hornfels with widely scattered chalcopyrite-filled hairline fractures that cut all the silicate grains;
    - Hornfels with <10% sulfides - sulfides are interstitial to the granoblastic texture;

  - Hornfels with 10-30% interstitial sulfides that look as though they were "flooded" into microbrecciated zones that coalesced into sulfide blebs (up to 2-3 cm). The sulfide blebs are connected to each other by curvilinear sulfide-filled hairline fractures that cut across silicate grains;
  - Hornfels with 10-40% sulfides present in blebs, ptygmatic lenses, and bifurcating lenses;
  - Semi-massive sulfides (30-70% sulfides) that contain internal patches of granoblastic silicate grains;
  - Massive sulfide (>70% sulfides) that locally contain isolated granoblastic silicate grains and widely scattered granoblastic patches;
  - Massive sulfide zones that contain <10% medium- to coarse-grained, subhedral to euhedral Opx, plagioclase, biotite, and occasionally olivine grains surrounded by the massive sulfide; and
  - Late massive sulfide veins, of varying dimensions and orientations that cut across all of the above sulfide textures (these are particularly hard to recognize in drill core unless sharp contacts with the other sulfide types are present). Late veins are also present within the troctolite-hosted disseminated ore, but these are uncommon overall. Matlack (1980) reports in the underground workings the veins are in sharp contact with the host lithologies and some of the veins cut the inclusions, but do not extend into the adjacent troctolitic rocks. He also reports that the veins are up to 3 feet thick.

- The massive sulfides are spatially situated along the axis of the Local Boy anticline indicating structural control was important to their formation; and
- There is no systematic increase in sulfide content with depth in the overlying troctolitic rocks as would be expected if the massive sulfides formed via a gravitational settling mechanism.

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 13 is an attempt to show, in a planar view, where the 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 13 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.

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 (Fig.

14), 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 in the vicinity of the Grano Fault; and 3) the Biwabik Iron Formation rarely contains sulfides – except in the vicinity of the Grano Fault.

Sulfide minerals at Local Boy include pyrrhotite, pentlandite, chalcopyrite, talnakhite, cubanite, maucherite (nickel arsenide), sphalerite, bornite, and late mackinawite, chalcocite, covellite, godlesvskite, and native silver. A more description of these minerals, along with microprobe compositions, microphotographs, and possible paragenetic sequence, are presented in Severson and Barnes (1991) and McSwiggen (1999).

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. This condition also suggests that as the immiscible sulfide melt fractionally crystallized in an east-to-west direction it progressively became enriched in PGE towards the west.

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 they 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.

IGNEOUS STRATIGRPAHY OF THE SOUTH KAWISHIWI INTRUSION

INTRODUCTION

The South Kawishiwi intrusion (SKI) consists mainly of troctolitic cumulates, dips gently to the southeast, and contains at least six Cu-Ni±PGE deposits. 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). Footwall rocks include the 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 (Severson, 1994; Zanko et al., 1994) and is subdivided into 17 different units (Fig. 15) that are present over a strike-length of 31 kilometers (19 miles). 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 during the following discussions 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). Sm-Nd (Hauck et al., 1997) and Re-Os data (Shafer et al., 2003; Ripley et al., 2008) support this conclusion;
- 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 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 (see discussion below), are the inferred reason for high PGE values at the Nokomis deposit.

Note: As intensive drilling is currently taking place at the Birch Lake, Nokomis, and South

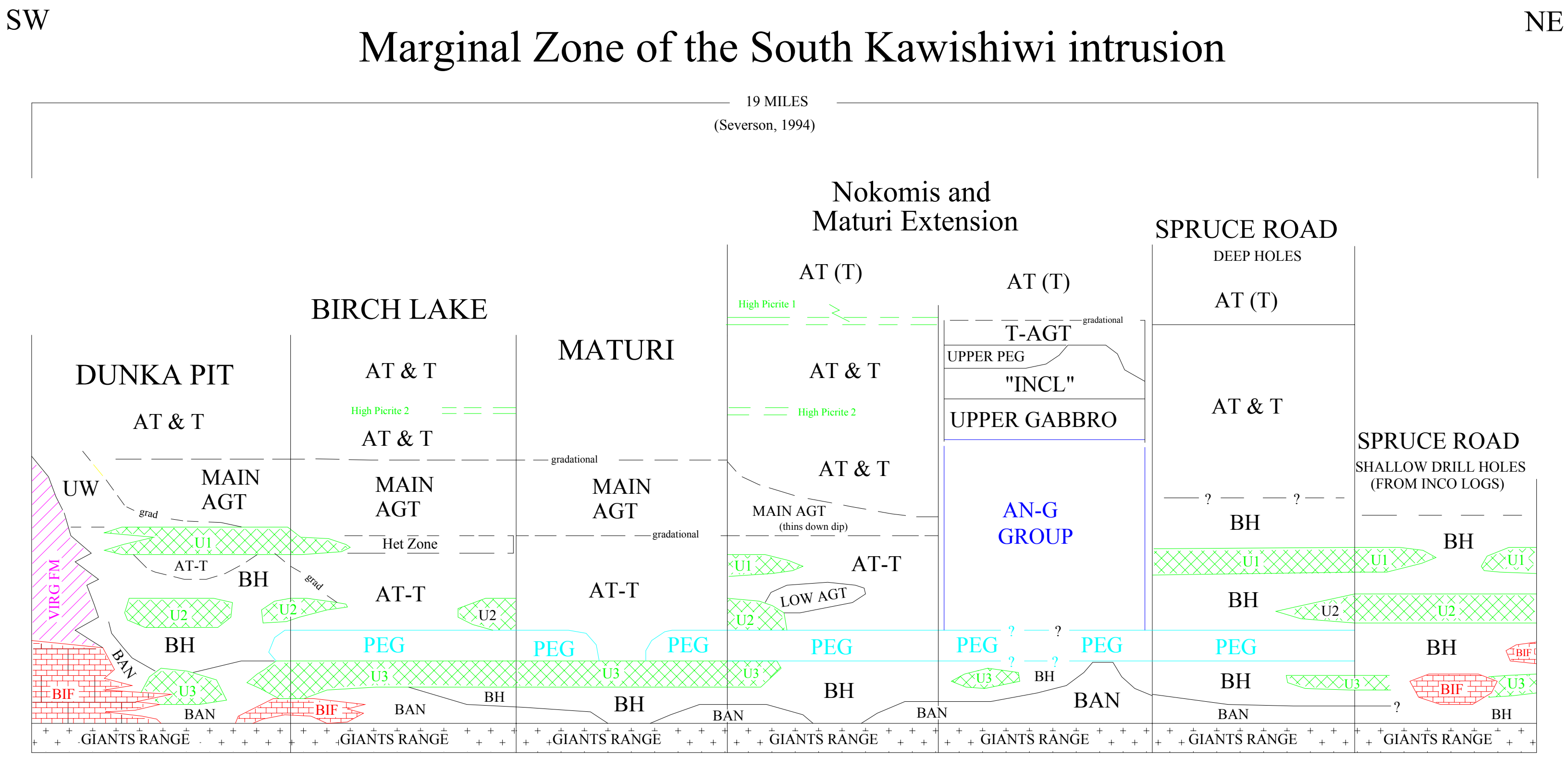


Figure 15. Generalized stratigraphy of the basal zone of the South Kawishiwi intrusion (modified from Severson, 1994; and included in Miller and Severson, 2002). The lowermost igneous units are: BAN = Basal Augite Troctolite and Norite; BH = Basal Heterogeneous; U3 = Ultramafic 3; PEG = Pegmatitic unit of Foose (1984); U2 = Ultramafic 2; U1 = Ultramafic 2; AT-T = Anorthositic Troctolite to Troctolite; UW = Updip Wedge; Main AGT = Main Augite Troctolite.

Filson Creek deposits, many of the above statements can be expected to be modified as more data becomes publically-available.

BIRCH LAKE DEPOSIT

A few widely-spaced holes were drilled in the Birch Lake area (Fig. 1) 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 Cr_2O_3 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 have since been drilled at Birch Lake. No new holes from the Birch Lake deposit were relogged for this investigation. The rocks and potential mineralization style were first described in detail by Severson (1994) and summarized more recently by Severson and Hauck (2003).

DUNKA PIT DEPOSIT

Exploration for Cu-Ni deposits and drilling at the Dunka Pit deposit (Fig. 1) began around 1957. Over the course of the next 14 years, five base metal mining companies completed various drilling campaigns in the area, but the Cu-Ni grades were generally low and further exploration activities were curtailed. During this same period, it was revealed that the Duluth Complex overlay metamorphosed Biwabik Iron Formation, and the Dunka Pit taconite mine was eventually opened by the Erie Mining Company.

Several new holes were relogged from the Dunka Pit deposit as part of this investigation. These holes, and previously-logged holes, were used to generate 18 cross-sections (Plates LXXII through XC) through the deposit. These cross-sections are included with this report and show the geology, zones with blocked out Cu grades, and the potential extent of yet-to-be-mined Biwabik Iron Formation (via underground methods?). Note that the Cu grades shown on the cross-sections are for consecutive zones with >0.20 Cu (note that the grade shown in the blocks are for the average Cu grade **not** the weighted average Cu grade).

The cross-sections presented in this report are attempts to show the geology intersected in the majority of holes that were drilled through the Complex and are still preserved and have been relogged. The following is a listing of holes that were relogged, but are not yet shown on any cross-section: NM-19, NM-22, NM-23, NM-24, NM-39, NM-45, NM-50, NM-51, NM-61, NM-62, NM-63, and NM-64.

SERPENTINE DEPOSIT

The Serpentine deposit (Fig. 1) was initially discovered by Bear Creek Mining Company in 1958 as part of a follow-up drilling campaign of an airborne electromagnetic conductor (Kulas, 1979). The name "Serpentine" was chosen for the deposit due to the presence of a sinuous massive sulfide located at the basal contact of the Complex. AMAX calculated that the deposit contains 250 million tons of reserves at a 0.20% cut-off, with a higher-grade reserve of over 7 million tons, at a 0.60% cut-off, with a grade of 0.88% Cu and 0.30% Ni (Kulas, 1979; Zanko et al., 1994).

The presence of pyrrhotite-rich massive to semi-massive sulfide at the basal contact at

Serpentine makes this an unusual deposit (Zanko et al., 1994). There, the massive sulfide has been classed as "footwall controlled" (Severson, 1994) in that a sulfide-rich member of the Virginia Formation, the BDD PO unit, provided a local sulfur source. The massive sulfide zone is also located close to the Grano Fault (Severson, 1994; Zanko et al., 1994), which caused intense fracturing of the footwall rocks that could then be assimilated by the intruding magma to provide sulfur.

Only one hole, BF-3, was relogged from the Serpentine deposit for this investigation (scanned log available at the NRRI-Economic Geology Group's website). The collar location for this hole was unknown until March 2008, after a lengthy search of the available data. The hole was located on the Babbitt B-1 grid (Mesaba/Babbitt deposit) at 9250E and 3650N (584,248E, 5,281,160N UTM-NAD27). The location of hole BF-3 relative to the other holes at Serpentine is shown in Figure 16.

MATURI DEPOSIT

The very first exploration drill hole in search of Cu-Ni deposits in the Duluth Complex was cored in the Maturi deposit (Fig. 1) by Fred S. Childers and Roger V. Whiteside in 1951. Eventually, International Nickel Company (INCO) picked up the property, and INCO outlined a sizeable, but low-grade, Cu-Ni deposit. A shaft was sunk on the property in 1966-67 to collect material from the basal contact zone for metallurgical tests. INCO took their bulk sample from pyrrhotite-rich material, which is more prevalent near the basal contact, and decided that the grade was too low to support an underground mine. INCO then concentrated their efforts at the nearby Spruce Road deposit. In addition to INCO, another four companies conducted drilling campaigns in the Maturi deposit area (including the Little Lake Road area - Fig. 1). A few holes from the Maturi deposit were relogged about five years ago. These relogged holes have been added to a previous stratigraphic section and a cross-section that were originally presented in Severson (1994). The new holes are shown in Plates XCI and XCII of this report.

NOKOMIS DEPOSIT

The geology of the Highway 1 Corridor area (H1C area), much of which is now contained within the newly-defined Nokomis deposit (Fig. 1), was first described by Severson (1994) for an area straddling Highway 1, where six extremely deep drill holes intersected an exotic package of intrusive rocks. Severson (1994) theorized that the holes penetrated an Anorthositic Series inclusion of formidable size (3,500 feet thick) that overlies the PEG, U3, and BH units at great depth (Fig. 15). Peterson (2001) suggested that high PGE contents within the BH Unit (beneath the inclusion) formed as a result of confined turbulent magma flow, and thus an increased R-factor, beneath a "pillar" of anorthosite. Peterson (2001) further hypothesized that a macrodike that served as a feeder to the Bald Eagle intrusion (Weiblen and Morey, 1980; Chandler, 1990) may have also served as a feeder to the South Kawishiwi intrusion in the H1C area (Severson et al., 2002).

Permission was granted to log the first seven holes (out of over 150 newly drilled holes as of this writing) from the Nokomis deposit. The geology of these holes is presented the hung stratigraphic section of Plate XCIII.

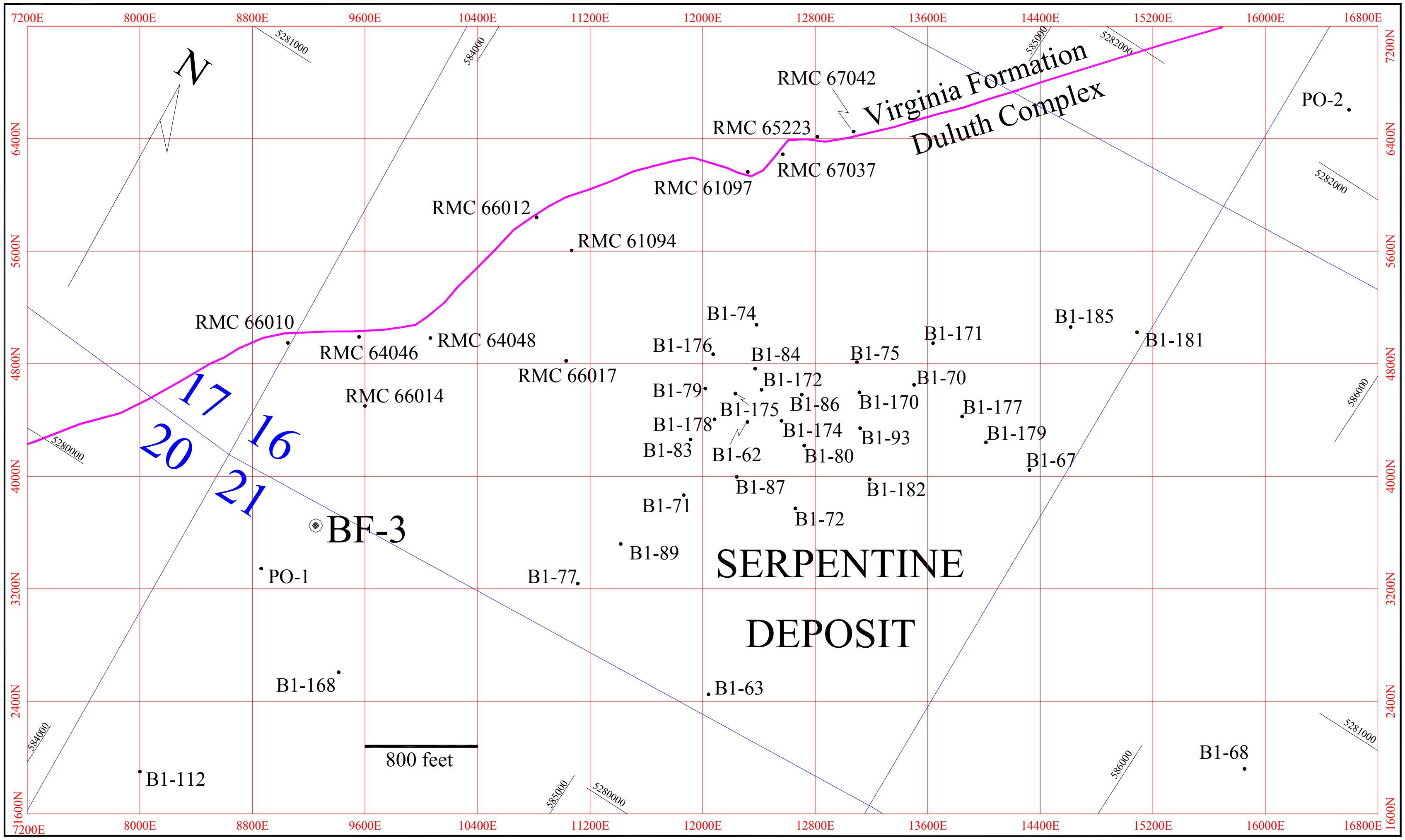


Figure 16. Location of newly-discovered drill hole BF-3 in the Serpentine deposit area (T.60N., R.12W.). Babbitt B-1 grid system shown in red; UTM coordinate system (NAD27) shown in black.

SPRUCE ROAD DEPOSIT

It was at the Spruce Road deposit that the first good indications of Cu-Ni mineralization were uncovered while constructing a forest access road in 1948 (Severson et al., 2002). From 1954 to 1971, INCO drilled the deposit out at 200-foot centers, and in 1974, applied for a mining permit on Federal lands. This application, and other coincidental actions, drew strong opposition from environmental groups, and a Regional Environmental Impact Study was imposed during 1974-1978 (Miller et al., 2002b). By the end of the study, INCO was no longer interested in pursuing a mining endeavor; however, they continued to maintain their leases in both the Spruce Road and Maturi deposits. In 1997, INCO's subsidiary, American Copper and Nickel Company, joint ventured both of the deposits with Wallbridge Mining Company Limited, and began to conduct exploration campaigns for high-grade footwall vein mineralization (Miller et al., 2002b). Wallbridge drilled two holes (WM-1 and WM-2) at Spruce Road. Both of these holes are presented in the hung stratigraphic section of a Plate XCI.

SOUTH FILSON CREEK DEPOSIT

The majority of drilling at the South Filson Creek deposit (Fig. 1) was conducted by Hanna Mining Company in the late 1960s. There, the Cu-Ni mineralization is hosted by troctolitic rocks (AT & T Unit of Severson, 1994), both in outcrop and in the tops of several drill holes that are situated well above the basal contact. In 1987, encouraging high PGE values (>1.0 ppm) were reported in these "cloud" zone sulfides by the Steve Hauck of the NRRI. A subsequent study of the PGE mineralization (Kuhns et al., 1990) indicated the PGE were related to a magmatic event that produced the "cloud" zone, followed by a late-stage hydrothermal event that concentrated and deposited the PGE in extremely fine, discontinuous, microscopic, sulfide veinlets. The veinlets are inferred to be associated with a NE-trending fault zone along the south branch of the Filson Creek (Kuhns et al., 1990).

All of the K-series holes at South Filson Creek were relogged for this investigation, as well as, six additional holes drilled by Encampment Resources in 2004. However, no cross-sections displaying the geology in these holes were completed for this investigation.

Encampment Resources has been drilling on this, and on adjacent properties, since early spring of 2008.

OXIDE ULTRAMAFIC INTRUSIONS (OUI)

Introduction

Several late-stage pegmatitic plugs and vertical bodies of Oxide-bearing Ultramafic Intrusions (OUI) intrude the troctolitic rocks of the Partridge River intrusion. The acronym OUI was first used by Severson and Hauck (1990) to designate cross-cutting bodies of dunite, peridotite, melatroctolite, clinopyroxenite, and orthopyroxenite that had a high percentage of oxides. At least thirteen OUI, as separate intrusive plugs, have been intersected in drill holes along the basal contact zone of the Duluth Complex (Fig. 17). In general, the OUI are spatially arranged along linear trends, suggesting that structural control was important to their genesis (Severson and Hauck, 1990; Severson, 1995). Drill holes from OUI plugs that were relogged as part of this investigation include ten holes from the Longnose deposit and six holes from the Water Hen deposit.

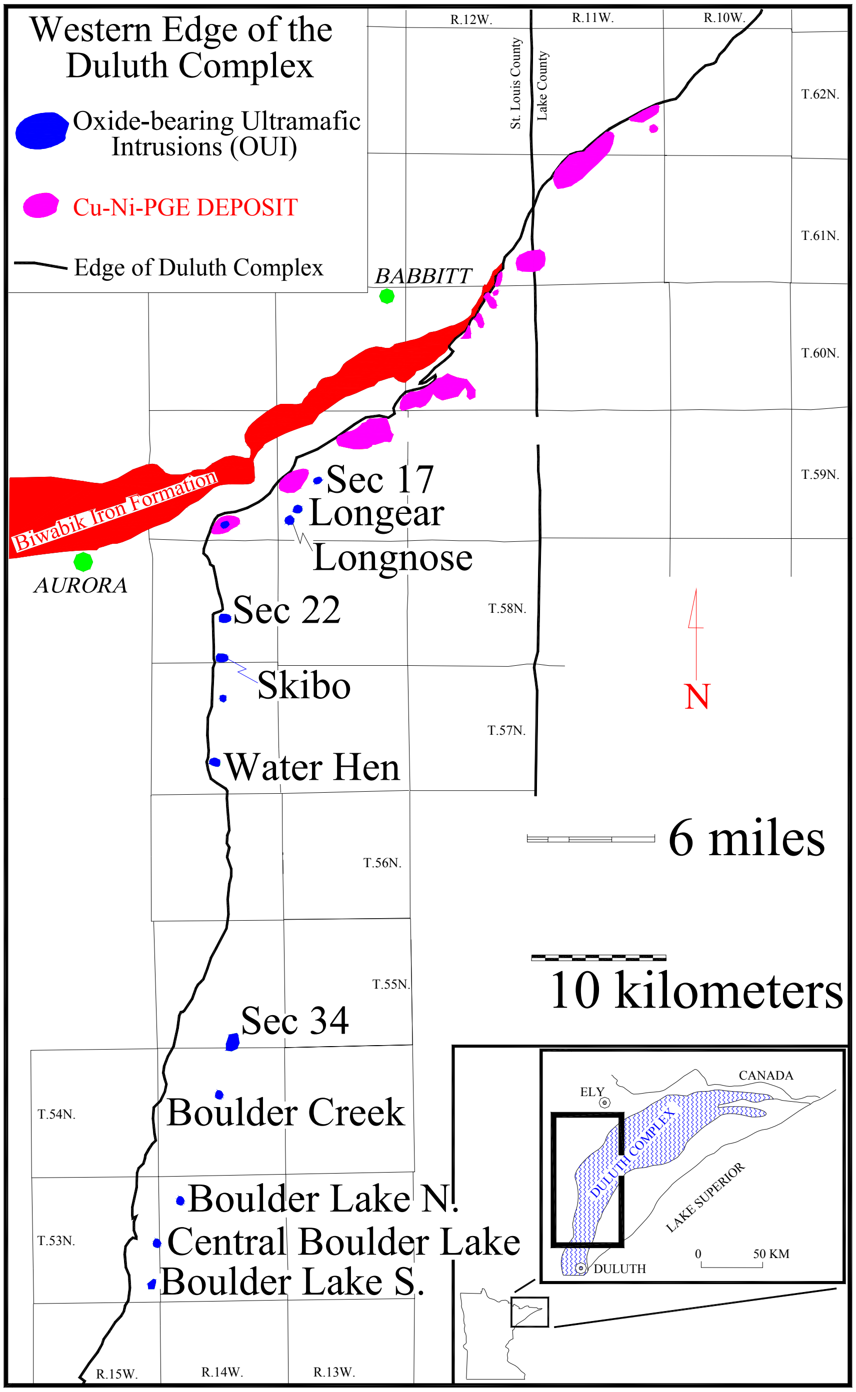


Figure 17. Location of Fe-Ti±V oxide deposits (Oxide-bearing Ultramafic Intrusion – OUI) along the western edge/base of the Duluth Complex.

LONGNOSE DEPOSIT

The Longnose deposit was initially drilled by Bear Creek Mining Co. in 1958 on the basis of a coincident magnetic high and electromagnetic anomaly. Drill hole A1-1 was one of the first holes to ever encounter an OUI in the Complex (INCO drilled several holes into an OUI plug at the Skibo deposit first). Hole A1-1 intersected oxide-rich peridotite and pyroxenite at 14-335 feet, which was the cause of the geophysical anomalies. This same area was again drilled by Exxon Corp. in 1969 (hole BA-6), and it also intersected the OUI at 15-81 feet. American Shield Corp., of Duluth, MN, drilled hole LN-1 in 1975 to test the OUI for Fe-Ti potential. The remainder of the holes (LN-2 through LN-10) were drilled in 1984 in a joint venture agreement between American Shield Corp. and Northern Illinois Corp. (Nicor).

All of the LN-series holes were relogged for this investigation. A drill hole location map and six cross-section through the deposit are portrayed in Plate XCIV of this report.

WATER HEN DEPOSIT

From 1957 through 1975, 37 holes have been drilled in the Water Hen deposit (Fig. 1) by various companies and joint venture endeavors. Most of these holes intersect an OUI body that intrudes troctolitic rocks of the Partridge River intrusion. The detailed geology of the area, and several cross-sections through the deposit, are most recently summarized in Severson (1995). Ten holes in the Water Hen area were logged as part of this investigation – no new cross-sections have been generated. Prime Merichem Resources currently hold this property.

CONCLUSIONS

This project is the culmination of 17 years of logging almost all of the publically available drill holes from the basal zone of the Duluth Complex. Drill holes have now been logged, and igneous stratigraphic sections have been defined for the Partridge River, South Kawishiwi, Western Margin, and Boulder Lake intrusions, and they have been presented in numerous publications by the Natural Resources Research Institute. Publically available holes from the basal contact that have yet to be logged include 20 holes from the eastern end of the Mesaba deposit, 11 underground holes from the Local Boy ore zone, and various holes that were drilled in the vicinity of the Gunflint and Fernberg trails in Minnesota.

Over the years, the stratigraphy for most of the Cu-Ni±PGE deposits in the South Kawishiwi intrusion has held up remarkably well during recent drilling. A similar situation exists for the defined stratigraphy in the Partridge River intrusion, especially at the NorthMet Cu-Ni±PGE deposit. The only area where the stratigraphy had to be modified, as a result of the work of this project, was the Mesaba Cu-Ni±PGE deposit. At this locality, it appears that the majority of the deposit is hosted by the newly-defined Bathtub intrusion (BTI). Two major units comprise the BTI, referred to as BT1 and BT4, and each is comprised of several subunits that are described in detail in this report. The BTI appears to be a short lived magma chamber as it was eventually overridden by the upper units of the Partridge River intrusion from the south.

Recognition of a new intrusion in the majority of the Mesaba deposit could have ramifications on the perceived distribution of Cu-Ni ore zones and on the identification of PGE enriched zones. Previous sampling campaigns at Mesaba were structured to look for stratabound PGE-enriched horizons associated with ultramafic horizons at the top of the basal unit. This concept worked well in the Partridge River intrusion, e.g., the top of Unit I at the NorthMet deposit, Wetlegs deposit, and on the southern edge of the Mesaba deposit (Severson and Hauck, 2003), but failed to show significant PGE enrichment in roughly the same stratigraphic position in the nearby BTI/Bathtub ore zone. The proposed existence of another intrusion helps to explain why this concept failed at Mesaba. However, other concepts regarding sulfide mineralization and PGE enrichment at Mesaba need to be taken into account. For example, the more common presence of massive sulfide horizons near the basal contact of the BTI suggest that sulfide settling was a more important mineralizing mechanism than in the other intrusions. In addition, thick zones of coarse-grained disseminated sulfides are fairly common in the bottom of the BT1 Unit, and a sulfide-settling mechanism can again be invoked. Furthermore, Severson and Hauck (2003) noted that PGE in scattered samples within the BTI exhibited an overall increase in content in a west-to-east direction toward the Grano Fault – the inferred vent area for the BTI. Hopefully, with continued drilling and sampling at the Mesaba deposit a clearer picture of the overall Cu-Ni±PGE distribution will emerge.

A clearer picture for the geology for the Dunka Pit deposit is also presented in this report with the inclusion of numerous newly made cross-sections. Hopefully, these cross-sections can be used to more fully understand the Cu-Ni potential, and the underground taconite potential in this area. PGE analyses at Dunka Pit are sparse, and the PGI distribution is as yet largely unknown.

And lastly, several new cross-sections have been made of the recently logged holes at the Longnose Fe-Ti±V deposit. As titanium becomes a more sought after commodity in the future, these OUI bodies of the Duluth Complex will become increasingly more important as a potential titanium source.

REFERENCES

Chandler, V.W., 1990, Geologic interpretation of gravity and magnetic data over the central part of the Duluth Complex, northeastern Minnesota: Economic Geology, v. 85, no. 4, p. 816-829.

Compton, R.R., 1962, Manual of Field Geology: New York, John Wiley and Sons, Inc., 378 p.

Dahlberg, E.H., 1987, Drill core evaluation for platinum group mineral potential of the basal zone of the Duluth Complex: Minnesota Department of Natural Resources, Division of Lands and Minerals, Report 255, 60 p.

Dahlberg, E.H., Saini-Eidukat B., Peterson, D., Seyfried, W.E., and Weiblen, P.W., 1988, Evidence for precipitation from chlorine brines in drill core from the Duluth Complex (abs.): 34th Annual Institute of Lake Superior Geology, Marquette, Michigan (handout).

Dahlberg, E.H., and Saini-Eidukat, B., 1991, A chlorine-bearing phase of drill core of serpentinized troctolitic rocks of the Duluth Complex, Minnesota: Canadian Mineralogist, v. 29, p. 239-244.

Duchesne, L., 2004, Partial melting in microstructures associated with the contact aureole of the Duluth Igneous Complex: Unpublished M.S. thesis [in French], University of Quebec at Chicoutimi, 217 p.

Fiebor, B., 1994, Petrochemistry and platinum-group element concentrations of drill core BA-4 through the Partridge River intrusion, Duluth Complex, Minnesota: Unpublished M.S. thesis, Auburn University, Auburn, Alabama, 202 p.

Foose, M.P., 1984, Logs and correlation of drill holes within the South Kawishiwi intrusion, Duluth Complex, northeastern Minnesota: United States Geological Survey, Open-file Report 84-14 p. .

Geerts, S.D., 1991, Geology, stratigraphy, and mineralization of the Dunka Road Cu-Ni prospect, northeastern Minnesota: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/TR-91/14, 63 p.

Geerts, S. D., 1994, Petrography and geochemistry of a platinum group element-bearing horizon in the Dunka Road prospect, (Keweenawan) Duluth Complex, northeastern Minnesota: University of Minnesota Duluth, Unpublished M.S. thesis, 100 p.

Grout, F.F. and Broderick, T.M., 1919, The magnetite deposits of the eastern Mesabi range, Minnesota: Minnesota Geological Survey Bulletin 17, 58 p.

Gundersen, J.N. and Schwartz, G.M., 1962, The geology of the metamorphosed Biwabik Iron-formation, eastern Mesabi district, Minnesota: Minnesota Geological Survey Bulletin 43, 139 p.

Hauck, S.A., 1993, Geology and mineralization of the Bathtub Cu-Ni area, Minnamax Cu-Ni deposit: University of Minnesota Duluth, Natural Resources Research Institute, Unpublished draft report, NRRI/TR-93/48, 59 p.

Hauck, S.A., and Severson, M.J., 2000, Platinum-group element-gold-silver-copper-nickel-cobalt assays primarily from the Local Boy ore zone, Babbitt deposit, Duluth Complex, northeastern Minnesota: An update: University of Minnesota Duluth, Natural Resources Research Institute, Report of Investigations NRRI/RI-2000/01, 48 p.

Hauck, S.A., Severson, M.S., Zanko, L.M., Barnes, S.-J., Morton, P., Aliminas, H.V., Foord, E.E., and Dahlberg, E.H., 1997, An overview of the geology and oxide, sulfide, and platinum-group element mineralization along the western and northern contacts of the Duluth Complex *in* Ojakangas, R.W., Dickas, A.B., and Green, J.C., eds., Middle Proterozoic to Cambrian rifting, central North America: Geological Society of America Special Paper 312, p. 137-185.

Holst, T.B., Mullenmeister, E.E., Chandler, V.W., Green, J.C., and Weiblen, P.W., 1986, Relationship of structural geology to the Duluth Complex to economic mineralization: Minnesota Department of Natural Resources, Division of Minerals Report 241-2, p. .

Irvine, T.N., 1982, Terminology for layered intrusives: Journal of Petrology, v. 23, no. 2, p. 127-162.

Jones, N.W., 1984, Petrology of some Logan diabase sills, Cook County, Minnesota: Minnesota Geological Survey Report of Investigations 29, 40 p.

Kirstein, M. H., 1979, Contact metamorphism of the Virginia Formation in the Minnamax deposit, St. Louis County, Minnesota: University of Minnesota Duluth, Unpublished M.S. thesis, 60 p.

Kuhns, M.J., Hauck, S.A., and Barnes, R.J., 1990, Origin and occurrence of platinum group elements, gold and silver in the South Filson Creek Copper-nickel mineral deposit, Lake County, Minnesota: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/GMIN-TR-89-15, 60 p.

Kulas, J.E., 1979, Serpentine reserve - Minnamax project: Unpublished AMAX company report on file at the Minnesota Department of Natural Resources, Minerals Division, Hibbing, MN, 5 p.

Lucente, M.E., and Morey, G.B., 1983, Stratigraphy and Sedimentology of the Lower Proterozoic Virginia Formation, northern Minnesota: Minnesota Geological Survey Report of Investigations 28, 28 p.

Mancuso, J.D., and Dolence, J.D., 1970, Structure of the Duluth Gabbro Complex in the Babbitt area, Minnesota (abs.): 16th Annual Institute on Lake Superior Geology, Thunder Bay, Ontario, v. 16, p. 27.

Martineau, M.P., 1989, Empirically derived controls on Cu-Ni mineralization: A comparison between fertile and barren gabbros in the Duluth Complex, Minnesota, U.S.A. *in* Prendergast, M.D., and Jones, M.J., eds., Magmatic Sulphides - The Zimbabwe Volume: Institute of Mining and Metallurgy, London, p. 117-137.

Martineau, M.P., 1991, Platinum-group element geochemistry of the Cu-Ni mineralization in the basal zone of the Babbitt deposit, Duluth Complex, Minnesota – A discussion: Economic Geology, v. 86, no. 6, p. 1355-1358.

Matlack, W.F., 1980, Geology and sulfide mineralization of the Duluth Complex-Virginia Formation contact, Minnamax deposit, St. Louis County, Minnesota: University of Minnesota Duluth, Unpublished M.S. thesis, 90 p.

McSwiggen, P.L., 1999, Platinum-palladium group minerals, gold, silver, and cobalt in the Minnamax copper-nickel sulfide deposit, Duluth Complex, northeastern Minnesota: Minnesota Geological Survey Report of Investigations 54, 27 p.

Miller, J.D., Jr. and Severson, M.J., 2002, Geology of the Duluth Complex *in* Miller, J.D., Jr., Green, J.C., Severson, M.J., Chandler, V.W., Hauck, S.A., Peterson, D.M., and Wahl, T.E., 2002a, Geology and mineral potential of the Duluth Complex and related rocks of northeastern Minnesota: Minnesota Geological Survey Report of Investigations RI-58, p. 106-143.

Miller, J.D., Jr., Green, J.C., Severson, M.J., Chandler, V.W., Hauck, S.A., Peterson, D.M., and Wahl, T.E., 2002a, Geology and mineral potential of the Duluth Complex and related rocks of northeastern Minnesota: Minnesota Geological Survey Report of Investigations RI-58, 207 p.

Miller, J.D., Jr., Severson, M.J., and Hauck, S.A., 2002b, History of geologic mapping and mineral exploration in the Duluth Complex *in* Miller, J.D., Jr., Green, J.C., Severson, M.J., Chandler, V.W., Hauck, S.A., Peterson, D.M., and Wahl, T.E., 2002a, Geology and mineral potential of the Duluth Complex and related rocks of northeastern Minnesota: Minnesota Geological Survey Report of Investigations RI-58, p. 21-51.

Muhich, T.G., 1993, Movement of Ti across the Duluth Complex-Biwabik Iron-formation contact at Dunka Pit, Mesabi Iron Range, northeastern Minnesota: University of Minnesota Duluth, Unpublished M.S. thesis, 154 p.

Park, Y.R., Ripley, E.M., Severson, M.J., and Hauck, S.A., 1999, Stable isotopic studies of mafic sills and Proterozoic metasedimentary rocks located beneath the Duluth Complex, Minnesota: Geochimica et Cosmochimica Acta, v. 63, no. 5, p. 657-674.

Patelke, R.L., 1994, The Babbitt copper-nickel deposit, Part A: Digital drill hole data files for the Babbitt and Serpentine deposits: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/TR-94/21a, 48 p.

Patelke, R.L., 1996, The Colvin Creek body, a metavolcanic and metasedimentary mafic inclusion in the Keweenawan Duluth Complex, northeastern Minnesota: University of Minnesota Duluth, Unpublished M.S. thesis, 232 p.

Patelke, R.L., 2003, Exploration drill hole lithology, geologic unit, copper-nickel assay, and location database for the Keweenawan Duluth Complex, northeastern Minnesota: Universityi of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/TR-2003/21, 96p.

Peterson, D.M., 2001, Development of a conceptual model of Cu-Ni-PGE mineralization in a portion of the South Kawishiwi intrusion, Duluth Complex, Minnesota (abs.): Society of Economic Geologists, Second Annual PGE Workshop, Sudbury, Ontario.

Phinney, W.C., 1972, Duluth Complex, History and nomenclature *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A Centennial Volume: Minnesota Geological Survey, p. 333-334.

Rao, B.V., 1981, Petrogenesis of sulfides in the Dunka Road copper-nickel deposit, Duluth Complex, Minnesota, with special references to the role of contamination by country rock: Unpublished Ph.D. Dissertation, Indiana University, Bloomington, Indiana, 372 p.

Ripley, E.M., Shafer, P., Li, C., and Hauck, S.A., 2008, Re-Os and O isotopic variations in magnetite from the contact zone of the Duluth Complex and the Biwabik Iron Formation, northeastern Minnesota: Chemical Geology, v. 249, p. 213-226.

Sabelin, T., and Iwasaki, I., 1985, Metallurgical evaluation of chromium-bearing drill core samples from the Duluth Complex (Contract report of Minnesota Department of Natural Resources, Division of Minerals): University of Minnesota, Minneapolis, Minerals Resources Research Center, 58 p.

Sabelin, T., and Iwasaki, I., 1986, Evaluation of platinum group metal occurrence in Duval 15 drill core from the Duluth Complex: University of Minnesota, Minneapolis, Minerals Resources Research Center, Internal report, 23 p.

Saini-Eidukat, B., Kucha, H.K., and Keppler, H., 1994, Hibbingite, γ-$Fe_2(OH)_3Cl$, a new mineral from the Duluth Complex, Minnesota, with implications for oxidation of Fe-bearing compounds and transport of metals: American Mineralogist, v. 79, p. 555-561.

Sawyer, E.W., 1999, Criteria for the recognition of partial melting: Physical Chemistry Earth, vol. 24, no. 3, p. 269-279.

Severson, M.J., 1991, Geology, mineralization and geostatistics of the Minnamax/Babbitt Cu-Ni deposit (Local Boy area), Minnesota, Part I: Geology: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/TR-91/13a, 96 p.

Severson, M.J., 1994, Igneous stratigraphy of the South Kawishiwi intrusion: Duluth Complex, northeastern Minnesota: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/TR-93/34, 210 p.

Severson, M.J., 1995, Geology of the southern portion of the Duluth Complex: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/TR-95/26, 185 p.

Severson, M.J., and Barnes, R.J., 1991, Geology, mineralization and geostatistics of the Minnamax/Babbitt Cu-Ni deposit (Local Boy area), Minnesota, Part II: Mineralization and geostatistics: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/TR-91/13b, 216 p.

Severson, M.J., and Hauck, S.A., 1990, Geology, geochemistry, and stratigraphy of a portion of the Partridge River intrusion: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/GMIN-TR-99-11, 236 p.

Severson, M.J., and Hauck, S.A., 1997, Igneous stratigraphy and mineralization in the basal portion of the Partridge River intrusion, Duluth Complex, Allen quadrangle, Minnesota: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/TR-97/19, 102 p.

Severson, M.J., and Hauck, S.A., 2003, Platinum Group Elements (PGEs) and Platinum Group Minerals (PGMs) in the Duluth Complex: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/TR-2003/37, 296 p.

Severson, M.J., and Hauck, S.A., in prep., Chemical and mineralogical classification of potential waste rocks in the eastern Mesabi Range and beneath the Duluth Complex: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report.

Severson, M.J., Miller, J.D., Jr., Peterson, D.M., Green, J.C., and Hauck, S.A., 2002, Mineral potential of the Duluth Complex and related intrusions *in* Miller, J.D., Jr., Green, J.C., Severson, M.J., Chandler, V.W., Hauck, S.A., Peterson, D.M., and Wahl, T.E., 2002, Geology and mineral potential of the Duluth Complex and related rocks of northeastern Minnesota: Minnesota Geological Survey Report of Investigations RI-58, p. 164-200.

Severson, M.J., Patelke, R.L., Hauck, S.A., and Zanko, L.M., 1994a, The Babbitt copper-nickel deposit, Part B: Structural datums: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/TR-94/21b, 48 p.

Severson, M.J., Patelke, R.L., Hauck, S.A., and Zanko, L.M., 1994b, The Babbitt copper-nickel deposit, Part C: Igneous geology, footwall lithologies, and cross-sections: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/TR-94/21c, 79 p.

Shafer, P., Hauck, S.A., and Severson, M.J., 2003, Re-Os systematics of Cr-PGE mineralized zones in the Partridge River and South Kawishiwi intrusions and the Layered Series at Duluth, Duluth Complex, northeastern Minnesota:

University of Minnesota Duluth, Natural Resources Research Institute, Report of Investigation NRRI/RI-2003/19, 28 p.

Turner, F.J., 1968, Metamorphic Petrology – mineralogical and field aspects: McGraw-Hill Book Company, New York, 403 p.

Watowich, S.N., 1978, A preliminary geological view of the Minnamax copper-nickel deposit in the Duluth Gabbro at the Minnamax project: *in* Graven, L.K., compiler, Productivity in Lake Superior Mining, 39th Proceedings Annual Mining Symposium, University of Minnesota, Minneapolis, p. 19.1-19.11.

Weiblen, P.W., and Morey, G.B., 1980, A summary of the stratigraphy, petrology, and structure of the Duluth Complex, Minnesota: American Journal of Science, v. 280-A, p. 88-133.

Wolff, J.F., 1919, Recent geologic developments on the Mesabi range, Minnesota: American Institute of Mining and Metallurgical Engineers Transactions, v. 56, p. 142-169.

Zanko, L.M., Severson, M.J., and Ripley, E.M., 1994, Geology and mineralization of the Serpentine copper-nickel deposit: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/TR-93/52, 90 p.

APPENDIX A:

Listing of Drill Holes Logged in 2006-2007

Dunka Pit

NM-12	829 ft.
NM-13	657 ft.
NM-14	285 ft.
NM-15	745 ft.
NM-16	754 ft.
NM-18	548 ft.
NM-19	614 ft.
NM-20	568 ft.
NM-24	658 ft.
NM-27	640 ft.
NM-28	513 ft.
NM-29	400 ft.
NM-31	163 ft.
NM-32	298 ft.
NM-44	400 ft.
NM-45	280 ft.
NM-46	400 ft.
NM-47	387 ft.
NM-50	466 ft.
NM-51	401 ft.
NM-60	543 ft.
NM-64	213 ft.
8004	272 ft.
8005	203 ft.
8010	411 ft.
8011	291 ft.
8012	149 ft.
8014	340 ft.
8016	272 ft.
8020	318 ft.
8021	260 ft.
8032	425 ft.
8035	332 ft.
8040	401 ft.
8042	271 ft.
8043	39 ft.
8045	151 ft.
8051	350 ft.
8070	191 ft.
8395	100 ft.
8423B	194 ft.
8424	30 ft.
B2-6	323 ft.
B2-8	405 ft.
B2-14	482 ft.
BF-1	199 ft.
BF-2	852 ft.
BF-3	700 ft.
Total	20,103 ft./50 holes

South Filson Creek

K-5	307 ft.
K-6	300 ft.
K-9	300 ft.
K-10	100 ft.
K-11	362 ft.
K-12	214 ft.
K-13	100 ft.
K-14	100 ft.
K-15	100 ft.
K-16	265 ft.
K-17	189 ft.
K-18	200 ft.
K-19	200 ft.
K-20	250 ft.
K-21	150 ft.
K-22	200 ft.
K-23	200 ft.
K-24	100 ft.
K-25	166 ft.
K-26	186 ft.
K-27	200 ft.
K-28	100 ft.
K-29	494 ft.
SFC-01	668 ft.
SFC-02	539 ft.
SFC-03	538 ft.
SFC-04	717 ft.
SFC-05	358 ft.
SFC-06	206 ft.
Total	7,809 ft./29 holes

Water Hen

CN-4	695 ft.
CN-5	589 ft.
SL-4	673 ft.
SL-5	670 ft.
SL-15	721 ft.
SL-21	606 ft.
SL-22	124 ft.
SL-23	131 ft.
SL-24	262 ft.
SL-25	429 ft.
Total	4,900 ft./10 holes

Longnose

LN-1	634 ft.
LN-2	570 ft.
LN-3	502 ft.
LN-4	612 ft.
LN-5	602 ft.
LN-6	595 ft.
LN-7	602 ft.
LN-8	402 ft.
LN-9	400 ft.
LN-10	330 ft.
Total	5,249 ft./10 holes

Mesaba/Babbitt

B1-3	932 ft.
B1-4	1018 ft.
B1-5	795 ft.
B1-7	1004 ft.
B1-9	460 ft.
B1-10	692 ft.
B1-14	566 ft.
B1-17	576 ft.
B1-18	686 ft.
B1-23	977 ft.
B1-24	1590 ft.
B1-25	512 ft.
B1-26	434 ft.
B1-27	1187 ft.
B1-28	1234 ft.
B1-29	1703 ft.
B1-36	929 ft.
B1-37	600 ft.
B1-40	1226 ft.
B1-42	1649 ft.
B1-59	794 ft.
B1-61	2088 ft.
B1-69	2024 ft.
B1-78	1675 ft.
B1-78A	871 ft.
B1-94	1625 ft.
B1-97	1675 ft.
B1-98	1317 ft.
B1-104	2181 ft.
B1-107	232 ft.
B1-111	573 ft.
B1-114	1163 ft.
B1-118	1834 ft.
B1-118A	333 ft.
B1-143	2082 ft.
B1-144	900 ft.
B1-149	2055 ft.
B1-151	1945 ft.
B1-155	2086 ft.
B1-173	2028 ft.
B1-184	1780 ft.
B1-184A	685 ft.
B1-184B	315 ft.
B1-188	611 ft.
B1-191	1066 ft.
B1-195	1415 ft.
B1-196	1266 ft.
B1-197	1920 ft.
B1-198	691 ft.
B1-200	317 ft.
B1-202	1516 ft.
B1-209	1965 ft.
B1-217	2028 ft.
B1-218	1645 ft.
B1-222	2062 ft.
B1-223	2065 ft.
B1-224	1479 ft.
B1-234	1994 ft.
B1-237	1598 ft.
B1-239	2025 ft.
B1-241	1963 ft.
B1-244	1108 ft.

B1-248	1933 ft.
B1-249/249A	1159 ft.
B1-253	1955 ft.
B1-254	370 ft.
B1-262	670 ft.
B1-267	1225 ft.
B1-268	2100 ft.
B1-274	425 ft.
B1-275	543 ft.
B1-292	1127 ft.
B1-310	517 ft.
B1-319	1375 ft.
B1-322	795 ft.
B1-323	825 ft.
B1-325	1212 ft.
B1-326	593 ft.
B1-328	425 ft.
B1-329	747 ft.
B1-333	805 ft.
B1-336	20 ft.
B1-337	697 ft.
B1-339	403 ft.
B1-341	843 ft.
B1-342	965 ft.
B1-346	510 ft.
B1-349	331 ft.
B1-366	626 ft.
B1-367	1661 ft.
B1-372	1013 ft.
B1-375	365 ft.
B1-377	348 ft.
B1-378	965 ft.
B1-379	1100 ft.
B1-381	1113 ft.
B1-382	945 ft.
B1-383	1194 ft.
B1-385	1485 ft.
B1-394	1795 ft.
B1-396	1294 ft.
B1-397	1347 ft.
B1-400	1018 ft.
B1-403	595 ft.
B1-408	1305 ft.
B1-413	525 ft.
B1-421	1935 ft.
B1-426	62 ft.

66305	236 ft.
66315	1001 ft.
Total	124,263 ft./110 holes

Maturi Extension/Nokomis deposit

MEX-1	3975 ft.
MEX-2	2547 ft.
MEX-3	4084 ft.
MEX-4	3177 ft.
MEX-5	3477 ft.
MEX-6	2396 ft.
MEX-7	2964 ft.
MEX-17	2736 ft.
Total	25,356 ft./8 holes

Spruce Road

WM-2	2,300 ft.

Cloquet Lake intrusion

STP-1	474 ft.
STP-2	480 ft.
STP-3	300 ft.
Total	1,254 ft./3 holes

Tuscarora intrusion

ON-1	510 ft.

Dunka Road South

BA-3	3,588 ft.
BA-4	3,647 ft.

GRAND TOTAL OF HOLES LOGGED AND FOOTAGE

224 holes/198,979 ft.

Mark Severson – 198 holes/167,047 ft.
Steve Hauck – 26 holes/31,932 ft.

APPENDIX B:

Listing of core holes from the Dunka Pit area that were recently found and transferred to the Minnesota Department of Natural Resources Drill Core Library in Hibbing, MN.

(Cliffs-Erie-donated-holes-2006.xls on CD in back pocket of this report)

APPENDIX C:

ArcGis data files for maps showing the distribution of drill holes logged in the Partridge River and South Kawishiwi intrusions for this investigation.

(materials on CD in back pocket of this report)