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GEOLOGY AND MINERAL POTENTIAL OF THE DULUTH COMPLEX AND RELATED ROCKS OF NORTHEASTERN MINNESOTA

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Preface

James D. Miller, Jr.

Since the time of the first Minnesota state geological survey over 100 years ago, several generations of geologists have worked to unravel the geologic story of the intrusive igneous rocks of northeastern Minnesota, the Duluth Complex. Each progression in understanding resulted from a new input of data or new concepts about geological processes. Early studies recognized the general distribution of igneous rocks types. F.F. Grout's groundbreaking work in the Duluth area (Grout, 1918a-d) established many broad geologic attributes of the complex and developed fundamental concepts about how layered mafic intrusions form, many of which are still pertinent today. However, one of his principal ideas, that the Duluth Complex is a large, single, lopolithic intrusion (1918a), was proven to be an oversimplification by geologic mapping conducted throughout the complex between the 1950s and 1970s (Grout and others, 1959; Taylor, 1964; Green, and others, 1966; Bonnichsen, 1971, 1972; Davidson, 1972; Phinney, 1972; Green, 1982). These studies were spurred largely by efforts to establish a geological framework within which to understand the copper-nickel sulfide deposits that were first discovered in the early 1950s (see Chapter 2). This geologic mapping showed the Duluth Complex to consist of multiple intrusions and established the general sequence of intrusive events. In the early 1970s, acceptance of the plate-tectonic theory and recognition that the Duluth Complex was part of an intracontinental rift system created a new setting within which to evaluate the magmatic and tectonic history of the Duluth Complex (Weiblen and Morey, 1980).

The last regional compilation of the geology of the Duluth Complex was a 1:250,000-scale geologic map of the Two Harbors 1° x 2° sheet (Green, 1982). Since that time, many studies have been conducted on the Duluth Complex that have added new insights into its geology, structure, intrusive history, and mineralization. These studies have focused on five major objectives:

- Interpreting the geologic setting of the vast, poorly exposed, central part of the Duluth Complex using high-resolution aeromagnetic data acquired in the early 1980s (Chandler, 1990; Miller and Chandler, 1999).
- Unraveling the intrusive history of the complex and related volcanic and intrusive rocks with high-resolution U-Pb dating of gabbroic, anorthositic, and felsic rocks (Paces and Miller, 1993; Davis and Green, 1997; Sandland and others, 2001).
- Delineating the internal igneous stratigraphy of the various layered intrusions of the Duluth Complex with core logging, detailed mapping, and petrologic studies (Severson and Hauck, 1990; Miller and others, 1993a; Severson, 1994; Miller and Ripley, 1996; Severson and Miller, 1999).
- Mapping the hypabyssal components of the Beaver Bay Complex and distinguishing these from intrusions of the more deeply emplaced Duluth Complex (Miller and Chandler, 1997).
- Evaluating the potential for economic base- and precious-metal deposits in areas of known mineralization and in unexplored areas of the Duluth Complex (Hauck and others, 1997; Miller, 1999).

Along with the new insights into Duluth Complex geology generated by these studies, two other recent developments motivated the Minnesota Geological Survey to create a new regional geologic map of northeastern Minnesota. The first was the advance in compiling and producing geologic maps through the use of geographic information systems (GIS). The second was the revival in interest in the Duluth Complex as a mineral exploration target, especially for platinum group elements (PGEs). In 1999, on the recommendation of the Minnesota Minerals Coordinating Committee, the Minnesota Geological Survey, in collaboration with the Natural Resources Research Institute, began work on a new regional geologic map of northeastern Minnesota and a report that would summarize the geology and mineral potential of the Duluth Complex and related intrusions.

The present publication is the final technical report for this project. It accompanies a 1:200,000-scale geologic map of northeastern Minnesota (Geologic map of the Duluth Complex and related rocks, northeastern Minnesota; published as Minnesota Geological Survey Miscellaneous Map M-119, and herein cited as "M-119"). This map can be purchased from the Minnesota Geological Survey in paper form and is also available as a PDF file from the Minnesota Geological Survey web site (http://www.geo.umn.edu/mgs). In addition, an ArcView 3.2 version of the map and various related databases are compiled on the CD enclosed in the back pocket of this report (see Appendix for description and instructions for use).

OVERVIEW OF THE GEOLOGIC MAP

The geologic map of the Duluth Complex and related rocks, northeastern Minnesota (map M-119) is composed of two major components: a 1:200,000-scale geologic map that delineates over 270 mappable rock units; and a 1:500,000-scale geologic map that generalizes the rock units into 72 time–stratigraphic entities. Other figures and text on the map include: a map indexing the amount of outcrop exposure and drill hole coverage; a 1:500,000 gray-scale image of the first vertical derivative of aeromagnetic data, from which much of the geology over poorly exposed areas was interpreted; an index to 64 previously published and unpublished mapping projects that were incorporated into the present compilation; a correlation diagram for the 72 generalized time–stratigraphic units; brief descriptions of rock units; and a list of references cited in the map unit descriptions and the index to previous mapping.

The 1:200,000-scale geologic map is a mix of new interpretations and unaltered portrayals of previous mapping. Where the geologic interpretations were taken directly from previous mapping, the original map was scanned, registered to a NAD 83 base, and traced as polygons (geologic units) and lines (contacts and faults) in ArcView (version 3.2). As noted in the Appendix, the authorship of particular map units, contacts, and faults are given in the attribute tables (.dbf files) that are associated with the geologic unit and line coverages (ArcView .shp files) and can be found on the CD accompanying this report. In general, the geology of the northern part of the Duluth Complex and the main part of the Beaver Bay Complex was taken directly from previous mapping (Index to Mapping, Map M-119) with some local modifications and additions by Miller, Green, and Chandler. The geology of the northwestern part of the complex was reinterpreted by Severson and Miller from a number of overlapping studies. Green interpreted the geology of predominantly volcanic rocks along the North Shore and the volcanic/intrusive geology of eastern Cook County largely from his previously published and unpublished mapping, as well as from early maps by Grout and others (1959). The geology of the poorly exposed central part of the Duluth Complex and western Beaver Bay Complex was taken from a 1:100,000-scale map of this area (Miller and Chandler, 1999) and was largely interpreted from aeromagnetic data tied to scattered drill cores and outcrop. The geology of the poorly exposed southern part of the Duluth Complex and its volcanic/intrusive roof zone was newly interpreted by Miller and Severson based on reconnaissance mapping by Bonnichsen (1971), Green and others (1977), and Severson (1994). Miller and Green reinterpreted the geology of the Duluth area from an open-file map (Miller and others, 1993b) and recent unpublished field mapping. Finally, Peterson and Severson compiled and simplified the geology of the Archean and Paleoproterozoic footwall from various sources (Index to Mapping, M-119).

The brief map-unit descriptions present only the dominant lithologic attributes of the approximately 300 map units displayed on the 1:200,000-scale map. The color scheme for the units is designed to portray the dominant lithology, and thus, many units carry a common color. For example, 17 different troctolite cumulate units are the same shade of yellow. The descriptions of map units explain the basis by which the units are delineated, including geophysical interpretation, outcrop control, drill holes, and other criteria. Similar information is included in the GIS attribute data tables for all geologic units, contacts, and faults (see the CD and Appendix).

On the 1:500,000-scale generalized geologic map, lithostratigraphic units are combined into generalized time–stratigraphic units. The adjacent correlation diagram applies to these generalized units. For the Duluth and Beaver Bay Complexes, time–stratigraphic units generally correspond to discrete intrusions. However, no attempt was made to distinguish intrusions within rocks of the anorthositic series because of the structural complexity of these rocks. Isolated miscellaneous intrusions are grouped into undifferentiated felsic (generalized map unit `mgp` on map M-119) and mafic (generalized map unit `mdg` on M-119) units because of uncertain temporal relationships with other intrusive units. Because of uncertainties about how specific volcanic units correlate between the northeast and southwest limbs of the North Shore Volcanic Group, flow units are generalized into five volcanic sequences based on structural and stratigraphic position (see Chapters 1 and 5).

OVERVIEW OF REPORT

This report provides a general description of the Duluth Complex and related rocks as portrayed on map M-119, and assesses this geology in terms of the potential for non-ferrous mineral deposits. The report is divided into eight chapters. Chapter 1 formally defines the nomenclature and the stratigraphic and rock-type classifications used to describe the Mesoproterozoic (Keweenawan) rocks of northeastern Minnesota. Chapter 2 summarizes the history of geologic mapping and mineral exploration of the Duluth Complex. Chapter 3 describes the geophysical attributes of the Duluth Complex and related rocks and discusses how these data aid in interpreting the buried bedrock geology and the deeper geologic structure of northeastern Minnesota. Chapter 4 explains the geology and structure of the Archean and Paleoproterozoic rocks that form the footwall of the Duluth Complex. Chapter 5 describes the volcanic stratigraphy and structure of the comagmatic North Shore Volcanic Group, into which the Duluth Complex and related intrusions were emplaced. Chapter 6 details the geologic, structural, and stratigraphic relationships of the various intrusions of the Duluth Complex. Chapter 7 summarizes the geology of the Beaver Bay Complex and related hypabyssal intrusions. Chapter 8 describes types of mineralization that are known to occur or may potentially occur in the Duluth Complex and related Keweenawan rocks, and identifies new exploration target areas. The Appendix describes the types of digital image and data layers that are included on the CD (back pocket) and explains how to access those GIS layers within the ArcView program.

The authors hope that this report and its companion map will be valuable and enduring contributions to the geology of the Duluth Complex and the rocks related to it. We hope that it will spark interest in mineral exploration in previously overlooked regions of the Duluth Complex. But even if new deposits are not found, we hope that this map portrays the story of the Duluth Complex in a way that previous maps have not.

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REFERENCES

Bonnichsen, B., 1971, Outcrop map of southern part of Duluth Complex and associated Keweenawan rocks, St. Louis and Lake Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-11, scale 1:125,000.

———1972, Southern part of the Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 361-387.

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.

Davidson D.M., Jr., 1972, Eastern part of Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 354-360.

Davis, D.W., and Green, J.C., 1997, Geochronology of the North American Midcontinent rift in western Lake Superior and implications for its geodynamic evolution: Canadian Journal of Earth Sciences, v. 34, no. 4, p. 476-488.

Green, J.C., comp., 1982, Geologic map atlas of Minnesota, Two Harbors sheet: Minnesota Geological Survey, scale 1:250,000.

Green, J.C., Jirsa, M.A., and Moss, C.M., 1977, Environmental geology of the North Shore: Minnesota Geological Survey, 99 p.

Green, J.C., Phinney, W.C., and Weiblen, P.W., 1966, Gabbro Lake quadrangle, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-2, scale 1:31,680.

Grout, F.F., 1918a, Internal structures of igneous rocks; their significance and origin with special reference to the Duluth gabbro: Journal of Geology, v. 26, p. 439-458.

———1918b, The lopolith, an igneous form exemplified by the Duluth gabbro: American Journal of Science, series 4, v. 46, p. 516-522.

———1918c, Two-phase convection in igneous magmas: Journal of Geology, v. 26, p. 481-499.

———1918d, A type of igneous differentiation: Journal of Geology, v. 26, p. 626-658.

Grout, F.F., Sharp, R.P., and Schwartz, G.M., 1959, The geology of Cook County Minnesota: Minnesota Geological Survey Bulletin 39, 163 p., 16 pls.

Hauck, S.A., Barnes, S.J., Morton, P., Aliminas, H., 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.

Miller, J.D., Jr., 1999, Geochemical evaluation of platinum group element (PGE) mineralization in the Sonju Lake intrusion, Finland, Minnesota: Minnesota Geological Survey Information Circular 44, 32 p.

Miller, J.D., Jr., and Chandler, V.W., 1997, Geology, petrology, and tectonic significance of the Beaver Bay Complex, northeastern Minnesota, *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. 73-96.

———1999, Bedrock geologic map of the central Duluth Complex and western part of the Beaver Bay Complex, Lake and St. Louis Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-101, scale 1:100,000.

Miller, J.D., Jr., Green, J.C., Boerboom, T.J., and Chandler, V.W., 1993a, Geologic map of the Doyle Lake and Finland quadrangles, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-72, scale 1:24,000.

Miller, J.D., Jr., Green, J.C., and Chandler, V.W., 1993b, Preliminary geologic map of the Duluth area, St. Louis County, Minnesota: Minnesota Geological Survey Open-File Report 93-2, scale 1:48,000.

Miller, J.D., Jr., and Ripley, E.M., 1996, Layered intrusions of the Duluth Complex, Minnesota, USA, *in* Cawthorn, R.G., ed., Layered intrusions: Amsterdam, Elsevier Science, p. 257-301.

Paces, J.B., and Miller, J.D., Jr., 1993, Precise U-Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: Geochonological insights to physical, petrogenetic, paleomagnetic and tectonomagmatic processes associated with the 1.1 Ga Midcontinent rift system: Journal of Geophysical Research, v. 98, no. B8, p. 13997-14013.

Phinney, W.C., 1972, Northwestern part of Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 335-345.

Sandland, T.O., Wirth, K.R., Vervoort, J.D., Gehrels, G.E., Kennedy, B.C., and Harpp, K.S., 2001, Roles of fractional crystallization and assimilation in the production of Midcontinent rift granophyres: Madison, Wis., Institute on Lake Superior Geology, 47th Annual Meeting, Proceedings, v. 47, Program and Abstracts, pt. 1, p. 85-86.

Severson, M.J., 1994, Igneous stratigraphy of the South Kawishiwi intrusion, Duluth Complex, northeastern Minnesota: Natural Resources Research Institute Technical Report NRRI/TR-93/34, 210 p., 15 pls.

Severson, M.J., and Hauck, S.A., 1990, Geology, geochemistry, and stratigraphy of a portion of the Partridge River intrusion: Natural Resources Research Institute, Technical Report NRRI/GMIN-TR-89-11, 236 p., 4 pls.

Severson, M.J., and Miller, J.D., Jr., 1999, Bedrock geologic map of Allen quadrangle, Minnesota: Minnesota Geological Survey Miscellaneous Map M-91, scale 1:24,000.

Taylor, R.B., 1964, Geology of the Duluth Gabbro Complex near Duluth, Minnesota: Minnesota Geological Survey Bulletin 44, 63 p., 1 pl.

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

Chapter 1

TERMINOLOGY, NOMENCLATURE, AND CLASSIFICATION OF KEWEENAWAN IGNEOUS ROCKS OF NORTHEASTERN MINNESOTA

James D. Miller, Jr., John C. Green, and Mark J. Severson

There are several challenges to the comprehensive and consistent description of the rock types that comprise the Duluth Complex and related igneous rocks in northeastern Minnesota. These challenges include the lack of generally accepted descriptive terminology, rock type nomenclature and classification schemes, and stratigraphic designations for intrusive rocks. In this chapter, we define the terms, rock names, and classification schemes that have been adopted by the Minnesota Geological Survey for this project. The terminology and nomenclature defined below are used in the attribute tables associated with various digital data themes (such as outcrop, drill core, sample, and map units; also, see Appendix). We hope that this will serve to standardize the terminology, nomenclature, and classifications applied to all Keweenawan[1] igneous rocks in northeastern Minnesota and in the greater Lake Superior region.

DESCRIPTIVE TERMINOLOGY

The terminology to describe various field and petrographic attributes of rocks generally adheres to definitions recommended by the American Geological Institute's *Glossary of Geology* (Bates and Jackson, 1987) or those routinely used in petrologic literature (for example Irvine, 1982). We provide here the definitions of current terms that have been commonly used and misused in reference to intrusive igneous rocks of northeastern Minnesota. For descriptive terminology applied to volcanic rocks, see Chapter 5 and references therein.

Intrusive rock texture terminology

The overall texture of a mafic intrusive rock is typically defined by the textural relationship between clinopyroxene and plagioclase. This relationship is highlighted not only because these phases are nearly ubiquitous major minerals in mafic rocks, but also because the texture of clinopyroxene, in particular, implicates the degree of differentiation of the parent magma. The general terms are:

Ophitic—Multiple lath-shaped crystals of plagioclase totally enclosed in crystals of pyroxene.

Subophitic—Multiple lath-shaped crystals of plagioclase partially enclosed in crystals of pyroxene.

Intergranular—Generally equigranular euhedral to anhedral primary minerals (need not be augite and plagioclase), none enclosing the others.

In general, igneous rocks displaying ophitic texture crystallized from more primitive tholeiitic parent magmas, and rocks displaying an intergranular texture between augite and plagioclase crystallized from magmas that were more evolved.

In intrusive rocks with primary phases other than clinopyroxene that display overgrowth textures, the related terms that apply are:

Poikilitic—One phase completely envelops many other more granular phases (such as plagioclase-poikilitic).

Subpoikilitic—One phase partially envelops other more granular phases (such as olivine-subpoikilitic).

In rocks that have subophitic/subpoikilitic and ophitic/poikilitic textures, the enclosing mineral is called an *oikocryst* and the captured crystals are called *chadacrysts*. Other rock texture terms used in the digital database are as defined in the *Glossary of Geology* (Bates and Jackson, 1987).

Grain-size terminology

Terms for the absolute and relative grain sizes of intrusive igneous rocks are somewhat confusing because many of the minerals are non-granular (such as ophitic augite and poikilitic olivine) and non-equant (such as tabular plagioclase and platy

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[1] Morey and Green (1982) suggested that the term *Keweenawan* be used as the lithostratigraphic modifier for those rocks that are demonstrably part of the Midcontinent rift system.

ilmenite). As a rule, we recommend that grain size be determined from the primary mineral phases displaying a euhedral-granular to anhedral-granular habit. For rocks with plagioclase as the only granular phase, the width of the plagioclase laths should be used as the measure of grain size. Absolute grain-size designations may follow a generalized scale such as: *fine* (less than 1 millimeter), *medium* (1 to 5 millimeters), *coarse* (5 to 12 millimeters), and *very coarse/pegmatitic* (greater than 12 millimeters); or a more detailed scale, such as: *very fine* (less than 0.2 millimeter), *fine* (0.2 to 0.8 millimeter), *medium fine* (0.8 to 1.5 millimeters), *medium* (1.5 to 3 millimeters), *medium coarse* (3 to 7 millimeters), *coarse* (7 to 12 millimeters), *very coarse* (12 to 30 millimeters), and *pegmatitic* (greater than 30 millimeters). Where the generalized scale is used, the grain-size terms are prefaced with *generally* (such as generally medium-grained).

Terminology used to describe the relative range of grain sizes within non-poikilitic intrusive igneous rocks include:

Equigranular—Generally equal grain sizes for all granular phases.

Seriate—Gradational range in grain size of all granular phases.

Hiatal—Bimodal range in grain size of all granular phases.

Porphyritic—Bimodal range in grain size of one (or rarely two) primary phase type(s).

Modifiers based on contrast in grain size—*weakly, moderately, strongly*

Alternate terminology—*phase, -phyric* (such as plagioclase-phyric)

Such relative grain-size terms are not used when applied to rocks with abundant poikilitic/subpoikilitic phases. Oikocrysts are inherently larger than the more granular phases they enclose; the term *porphyritic* does not apply to ophitic texture.

Planar mineral alignment

One of the most common types of planar structures in intrusive igneous rocks is the alignment of elongate or tabular mineral phases. This feature goes by several different terms: *igneous lamination*, *fluxion structure*, or *foliation*; however, none of these terms is completely satisfactory. *Igneous lamination* is defined as the preferential alignment of tabular minerals (Bates and Jackson, 1987), but Irvine (1982) drew a distinction between *lamination* and *laminae*. *Laminae* refers to thin, sharply defined layers less than one-centimeter-thick. Therefore, when a rock is described as well laminated, it is not clear whether it is laminae or lamination that is being described. *Fluxion structure* is a term used by Grout (1918) to describe the parallelism of platy minerals in gabbroic rocks of the Duluth Complex. It has not been widely adopted, probably because of its genetic implications of an origin by flow. *Foliation* also is a term applied to intrusive igneous rocks displaying planar fabric. Although it is most commonly used to describe planar structures in deformed and metamorphosed rocks, the *Glossary of Geology* (Bates and Jackson, 1987) defined foliation as: "A general term for a planar arrangement of textural or structural features in any type of rock..." We have adopted the term *foliation* in this compilation.

The degree to which platy minerals are aligned parallel to a common plane (foliated, for example) is subdivided into five categories. The categories are linked to the estimated percentage of platy minerals that are aligned within 10° of a common plane. The levels are: *non-foliated* (less than 25 percent), *poorly foliated* (25 to 50 percent), *moderately foliated* (50 to 75 percent), *well foliated* (75 to 90 percent), and *very well foliated* (greater than 90 percent).

The term *non-foliated* is used when an intrusive rock contains platy minerals that show no preferred alignment. It is not used for a rock composed of equant grains, which would by definition have no potential to be aligned. *Decussate* is a term commonly misused as synonymous with non-foliated, but as defined in *Glossary of Geology* (Bates and Jackson, 1987), it should only be applied to rocks whose platy minerals show an orthogonal or crisscross alignment.

Layering

As one of the most notable features of mafic intrusions, layering and its genesis in igneous rocks have attracted much attention (for example Parsons, 1987; Naslund and McBirney, 1996; Irvine and others, 1998). Unfortunately, much of the terminology developed to describe various sorts of layering has strong genetic connotations. We have generally adopted a non-genetic terminology recommended by Irvine (1982) to describe layering. Because the layering described here refers to that observable in the field on an outcrop scale, cryptic layering is not considered here. The various elements of layering that can be noted and the terms to describe those elements are:

Type—*Modal, isomodal, graded modal, grain size, textural, phase, combination.*

Contrast (or demarcation)—*Strong, moderate, weak, subtle.*

Frequency—*Single layer, rhythmic, intermittent, irregular.*

Scale—*Centimeter, decimeter, meter, inconsistent, variable.*

Lateral continuity—*Continuous, discontinuous, lenticular, wispy.*

Other descriptors—*Wavy, cross-bedded, schlerien, colloform, trough, corrugated, deformed, slumped, and convoluted.*

ROCK NOMENCLATURE AND CLASSIFICATION SCHEMES

One of the challenges of compiling a regional map of the Duluth Complex from various studies involved the inconsistencies of rock nomenclature. One geologist's gabbro is another's oxide olivine gabbronorite. The problem is not so much varied levels of precision in classifying rock types; that is to be expected for varied levels of study (such as between detailed and reconnaissance investigations); rather, a more intractable problem occurs among studies of comparable detail that apply different rock-type definitions. For example, an oxide gabbro of the Sonju Lake intrusion is termed a two-pyroxene gabbro by Stevenson (1974) and a ferrogabbro by Miller and others (1993). Most recent studies of mafic rocks of the Duluth Complex have used a four-phase modal classification scheme similar to that proposed by Phinney (1972a). For felsic to intermediate rocks, some variant of the standard quartz-K-feldspar-plagioclase modal classification scheme (LeMaitre, 1989) has been used. More recently, for rocks that display obvious cumulate texture, cumulate rock classification schemes have been proposed (Foose and Cooper, 1978; Miller and Ripley, 1996). Both modal classifications and texture-based cumulate schemes are useful and should be retained with modifications. In this section, we critique some currently used classifications and propose modifications of these schemes for this and future work on Keweenawan intrusive rocks. See Chapter 5 and references therein for descriptions of classification schemes applied to volcanic rocks.

Previous modal classification schemes applied to mafic and ultramafic intrusive rocks

Although the names applied to mafic intrusive rock types in the Duluth Complex generally follow standard rock nomenclature, few studies have adopted the modal boundaries of the International Union of Geological Sciences (IUGS)-recommended classification scheme for mafic rocks (Streckeisen, 1976; LeMaitre, 1989), as shown in Figure 1.1a. Rather, most of the Duluth Complex studies over the past 40 years have used variations of a four-phase modal classification scheme similar to that developed by Davidson (1969) and Phinney (1972a). Davidson and Phinney's schemes differ only in the phase used for the fourth component along with plagioclase (Pl), olivine (Ol), and clinopyroxene (Cpx); Phinney used orthopyroxene (Opx; Fig. 1.1b) and Davidson used Fe-Ti oxide (Feox; Fig. 1.1c). Given that clinopyroxene and orthopyroxene are typically difficult to distinguish in hand samples and that orthopyroxene is much less common than clinopyroxene, the Davidson scheme is more practical. However, both classifications employ modal boundaries that ignore natural (both experimental and empirical) cotectic proportions of mineral phases expected to crystallize from basaltic magmas at low pressures (Fig. 1.1e). This is especially true in regard to the abundance of plagioclase. Another problem with both schemes involves the fact that neither of them identifies the modal fields of common rock types like olivine gabbro, augite troctolite, and gabbronorite. Severson and Hauck (1990) modified the Phinney scheme to identify modal boundaries for olivine gabbro and augite troctolite (Fig. 1.1d), but the unnatural boundaries defined by plagioclase abundance remained.

Proposed modal classification for mafic and ultramafic intrusive rocks

The modal classification scheme recommended for use with mafic and ultramafic intrusive rocks of the Duluth Complex and related intrusions is presented in Figure 1.2. It is a modification of schemes earlier proposed by Miller (1986, 1995) and Miller and Weiblen (1990) to alleviate problems in the schemes mentioned above. The major advantages of this scheme are:

1. It uses all five major essential mineral phases (Pl, Ol, Cpx, Opx, and Feox).
2. It defines modal boundaries that bracket natural modal populations.

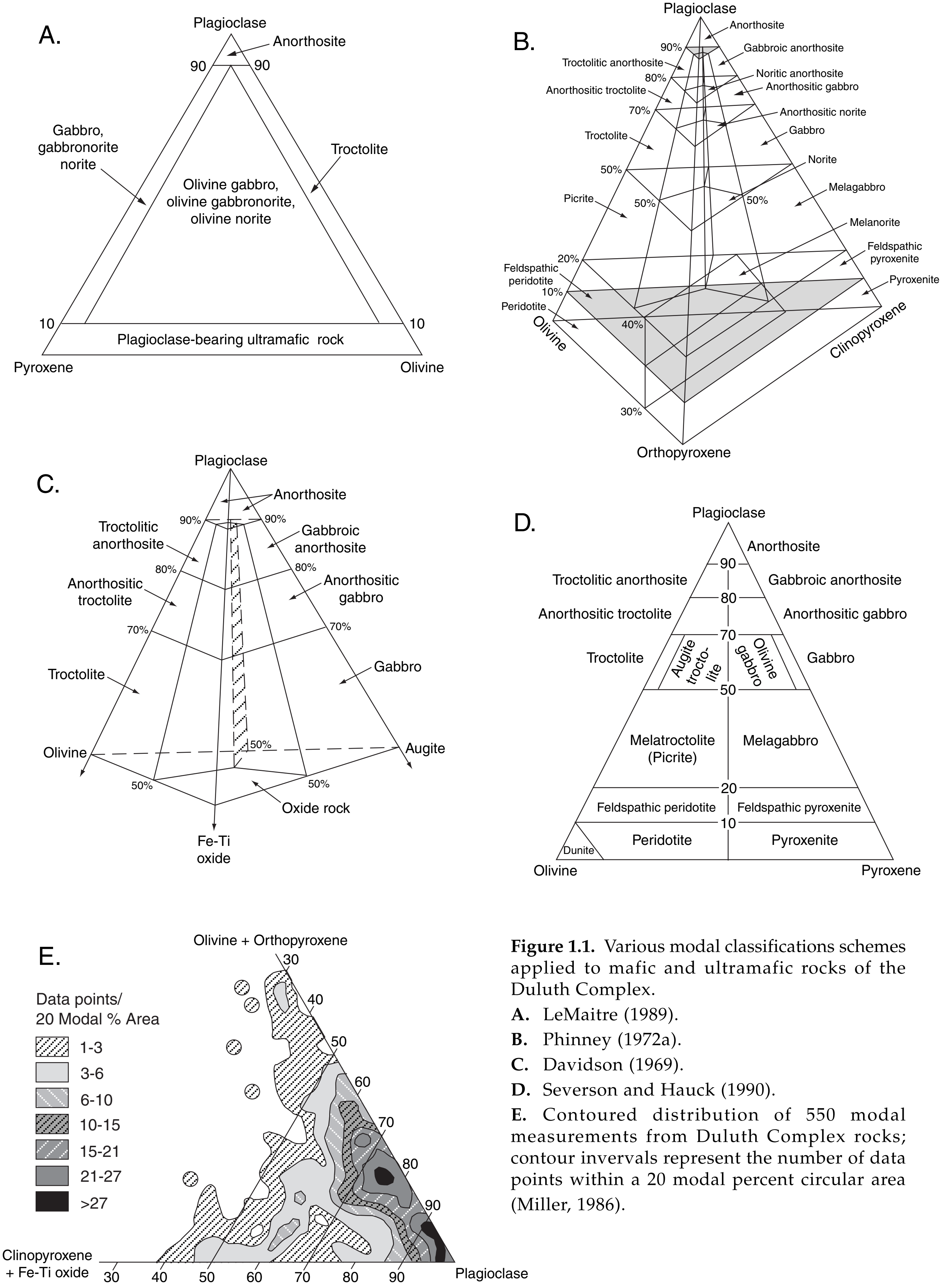

Figure 1.1. Various modal classifications schemes applied to mafic and ultramafic rocks of the Duluth Complex.

A. LeMaitre (1989).

B. Phinney (1972a).

C. Davidson (1969).

D. Severson and Hauck (1990).

E. Contoured distribution of 550 modal measurements from Duluth Complex rocks; contour invervals represent the number of data points within a 20 modal percent circular area (Miller, 1986).

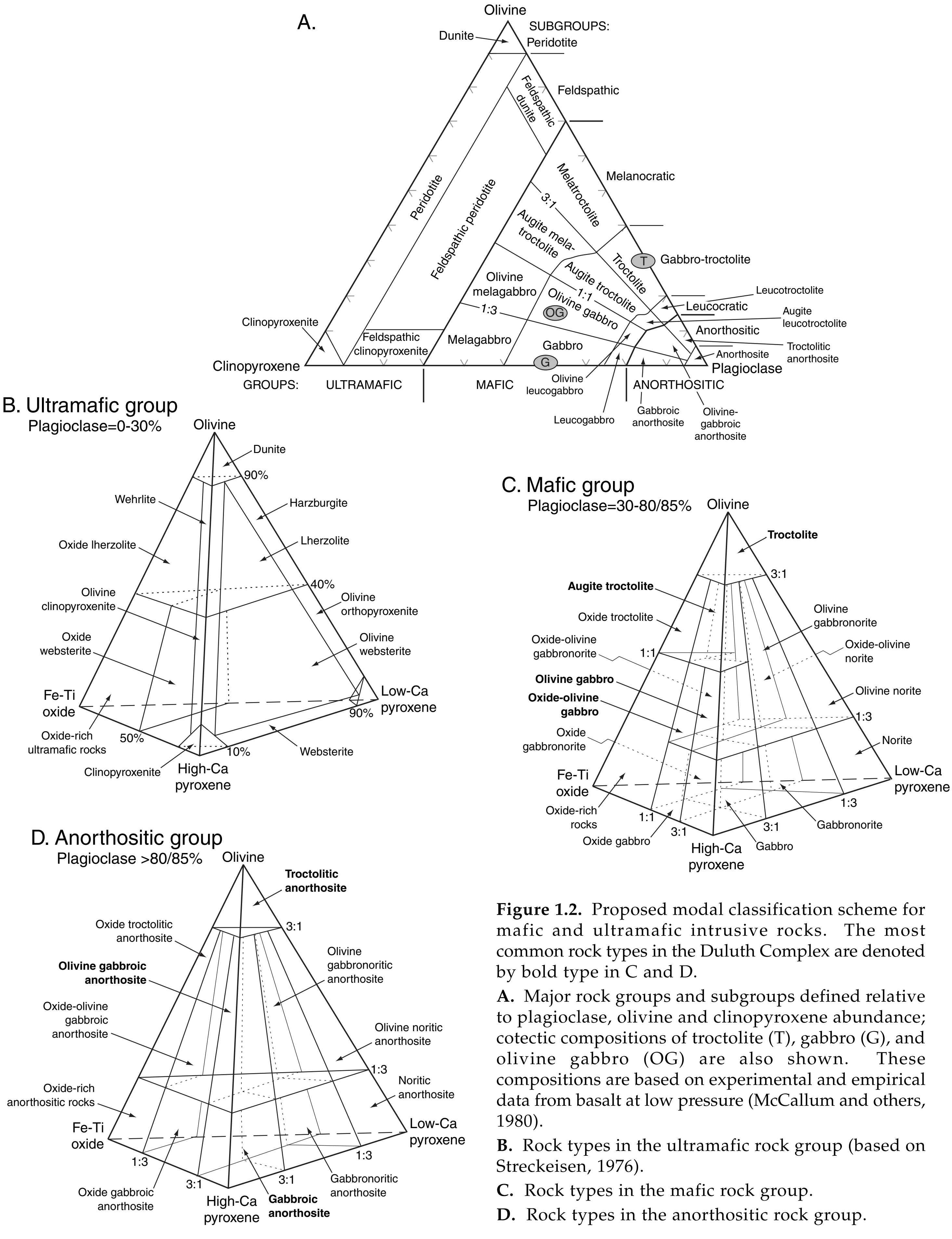

Figure 1.2. Proposed modal classification scheme for mafic and ultramafic intrusive rocks. The most common rock types in the Duluth Complex are denoted by bold type in C and D.

A. Major rock groups and subgroups defined relative to plagioclase, olivine and clinopyroxene abundance; cotectic compositions of troctolite (T), gabbro (G), and olivine gabbro (OG) are also shown. These compositions are based on experimental and empirical data from basalt at low pressure (McCallum and others, 1980).

B. Rock types in the ultramafic rock group (based on Streckeisen, 1976).

C. Rock types in the mafic rock group.

D. Rock types in the anorthositic rock group.

3. It uses simple mafic mineral ratios (3:1 or 1:1), which are easy to estimate in the field.

The first classification criterion for this scheme is based on the general abundance of plagioclase. This attribute defines three major rock groups and seven subgroups (Table 1.1). In Figure 1.2a, the modal positioning of the major rock groups and subgroups is shown relative to the three most common and petrologically important mineral phases in mafic and ultramafic rocks of the Duluth Complex—plagioclase, olivine, and clinopyroxene. The modal boundaries of plagioclase abundance that define the mafic rock subgroups in Table 1.1 are purposely variable. This acknowledges the fact that the cotectic proportion of plagioclase tends to be greater in olivine-rich troctolitic rocks compared to pyroxene-rich gabbroic rocks. A *cotectic* troctolite (Pl + Ol) should contain about 70 percent plagioclase, a gabbro (Pl + Cpx) about 60 percent plagioclase, and an olivine gabbro (Pl + Ol + Cpx) should contain about 57 percent plagioclase (points T, G, and OG in Fig. 1.2a).

Within each of the three major rock groups, individual rock names are based on the relative proportions of the four principal mafic mineral phases (Fig. 1.2): olivine, high-Ca pyroxene (augite, ferroaugite, ferrohedenbergite), low-Ca pyroxene (bronzite, hypersthene, pigeonite, inverted pigeonite), and Fe-Ti oxide (Ti-magnetite, ilmenite, Cr-Mg-Al spinel). The modal rock names for ultramafic rocks are plotted in Figure 1.2b. These modal boundaries retain the accepted IUGS recommendations (Streckeisen, 1976; LeMaitre, 1989). The rock names shown apply directly to rocks in the peridotite subgroup and form the root of names prefixed by *feldspathic* in rocks having 10 to 30 percent plagioclase (Table 1.1). Modal rock names for mafic rocks are plotted in Figure 1.2c. Here, too, the names apply directly to the gabbro-troctolite subgroup and the names form the roots of rock names in the melanocratic and leucocratic subgroups. In the melanocratic and leucocratic subgroups, the roots to the rock names are affixed with a prefix of *mela* (such as melatroctolite and olivine melagabbro) or *leuco* (such as leucogabbro and augite leucotroctolite). Figure 1.2d shows the modal classification of rocks associated directly with the anorthositic subgroup. Rocks with more than 95 percent plagioclase are a singular rock type—anorthosite. Although the number of possible rock types in this scheme is great, the majority of rocks in the Duluth Complex are of eight types: troctolite, augite troctolite, leucotroctolite, augite leucotroctolite, olivine gabbro, melatroctolite, olivine gabbroic anorthosite, and troctolitic anorthosite (Fig. 1.2c, d).

A modal rock name alone gives no indication of how various mafic intrusive rocks may have crystallized, and it can lead to ambiguity. For example, the implied mineral paragenesis of an olivine gabbro with ophitic augite is very different from a rock having the same modal composition, but with granular augite. Therefore, in addition to the modal rock name, rock type descriptions should include textural modifiers that note general rock texture, grain size, foliation development, and other noteworthy features. Moreover, modal rock names should include mineral modifiers (such as *apatitic* and *biotitic*) that recognize the presence of accessory mineral phases or that identify the presence of essential minerals that may not be sufficiently abundant to affect the modal rock name. In the latter case, it is important not to confuse a mineral modifier from a mineral name that is in the root of the rock name. Therefore, mineral modifiers should include the suffix *-bearing*

Table 1.1. Definitions of modal rock groups and subgroups for mafic and ultramafic rocks based on plagioclase abundance.

Group	Percent plagioclase	Subgroup	Percent plagioclase	Prefix
Ultramafic	<30	Peridotite	<10	
		Feldspathic	10–30	felspathic
Mafic	30–80/85	Melanocratic	30–50/55	mela-
		Gabbro-troctolite	50/55–75/80	
		Leucocratic	75/80–80/85	leuco-
Anorthositic	>80/85	Anorthositic	80/85–95	
		Anorthosite	>95	

(such as olivine-bearing gabbro as opposed to olivine gabbro). Similarly, if it is necessary to note that a gabbro-troctolite rock is on the plagioclase-rich or -poor side of its normal range, then the terms *melanocratic* and *leucocratic* should be used (such as leucocratic gabbro instead of leucogabbro, or melanocratic augite troctolite as opposed to augite melatroctolite).

Proposed cumulate classification code

In addition to a standard nomenclature based on modal mineralogy and texture, most studies of layered intrusions also employ a more interpretive cumulate nomenclature based on observations of mineral habit and mode (for example McCallum and others, 1980; Zientek and others, 1985). Most of the rocks comprising the intrusions of the Duluth Complex are cumulates as described by Irvine (1982, p. 131): "...an igneous rock characterized by a *cumulus framework* of touching mineral crystals or grains that were evidently formed and concentrated primarily through fractional crystallization. ... The fractionated crystals are called *cumulus crystals*. They typically are subhedral to euhedral, and generally they are cemented together by a texturally later generation of *postcumulus material* that appears to have crystallized from the *intercumulus liquid*..." Although cumulate classifications are used as an interpretive tool, they are based on the modal mineralogy and texture of the rock.

Foose and Cooper (1978) applied a cumulate classification code to rocks of the Duluth Complex that was similar to one developed for the Stillwater Complex (Zientek and others, 1985) and also focused only on cumulus mineralogy. However, because many intrusions of the Duluth Complex are composed of thick, unvaried sequences of plagioclase-olivine cumulates (POC, in Foose and Cooper's lexicon), that classification scheme has limited utility. Miller (1995) and Miller and Ripley (1996) proposed a cumulate classification code that recognized the importance of the intercumulus mineral assemblage in discriminating different cumulate rock types. The code is more informative than a simple modal classification because it provides an indication of the general habit and relative mode of all mineral phases. The three basic attributes of the code are:

1. It applies to rocks that show some igneous foliation or modal layering and therefore solidified under conditions in which mineral phases segregated from their parent magmas.
2. It lists abbreviations of all minerals composing greater than about 2 modal percent in decreasing order of abundance regardless of their cumulus status.
3. It denotes granular (cumulus) mineral phases with upper case letter abbreviations and interstitial (intercumulus) mineral phases with lower case abbreviations.

A slightly modified version of the cumulate code proposed by Miller (1995) and Miller and Ripley (1996) is given in Table 1.2. The table also gives examples of translations of the cumulate codes in conventional rock terminology using the textural terms and modal classification scheme described above (Fig. 1.2). It is clear from some translations that not all attributes of mode and texture can be captured in the cumulate code, but it remains a useful means of delineating cumulate rock types. This code is used in the map unit descriptions for the 1:200,000-scale map (M-119) and is used in the outcrop attribute table in GeMS.

Proposed modal classification for intermediate and felsic intrusive rocks

Intermediate to felsic rocks make up approximately 15 percent of the total area of Keweenawan intrusive rocks in northeastern Minnesota. Grout (1918) and Grout and others (1959) referred to these rocks as *red rock*. Subsequent studies have adopted the more geologically correct, but still general term of *granophyre*. Most studies that have described felsic and intermediate rocks in detail (for example Davidson, 1972; Nelson, 1991; Miller and others, 1993, 1994; Boerboom and Miller, 1994) have used the rock nomenclature and modal definitions of the standard quartz-alkali feldspar-plagioclase-feldspathoid (QAPF) felsic rock classification scheme (Streckeisen, 1976; LeMaitre, 1989). Because feldspathoid minerals are rare in the dominantly tholeiitic rocks of the Midcontinent rift (an exception being the alkaline rocks of the Coldwell Complex of Ontario), most rocks plot in the QAP half of the QAPF diagram (Fig. 1.3).

The IUGS recommends specific ranges of mafic mineral content for each QAP rock type (Streckeisen, 1976), which we adopt here. These are summarized in Figure 1.4. For compositions outside the specified ranges, the prefixes *leuco* and *mela* are used (such as quartz leucomonzonite). Additionally, Streckeisen (1976) recommended that the root name based on the QAP diagram should be prefaced with the dominant mafic phase(s),

Table 1.2. Proposed cumulate classification scheme.

Cumulus/Intercumulus Mineral Codes

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

* used with anorthositic group rocks

Cumulate code translation of some common rock types in the Duluth Complex

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

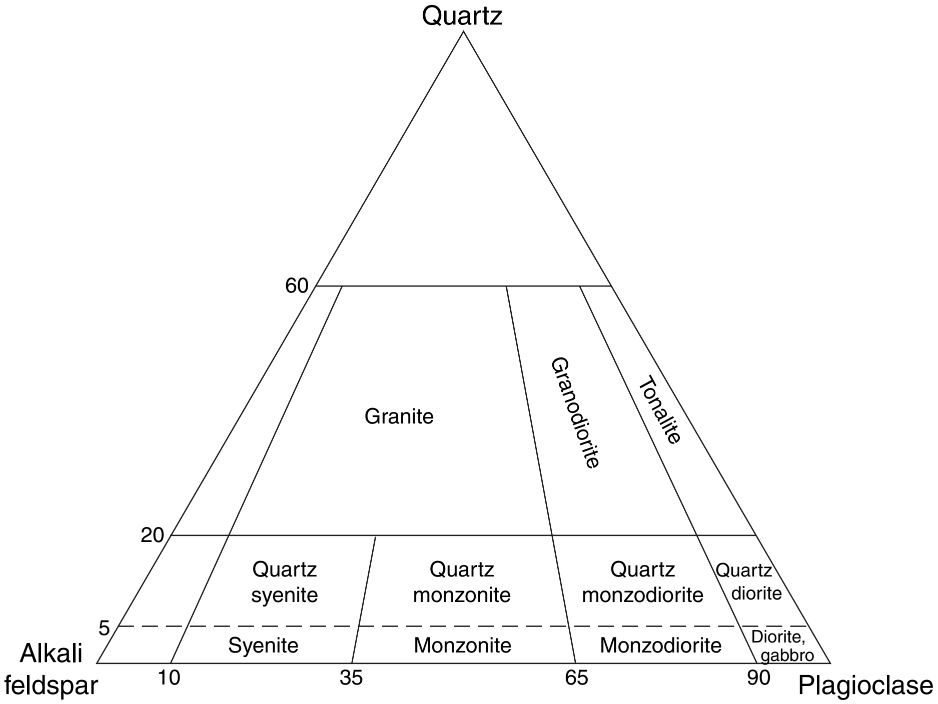

Figure 1.3. Classification of intermediate and felsic rocks based on the quartz-alkali feldspar-plagioclase (QAP) diagram (LeMaitre, 1989).

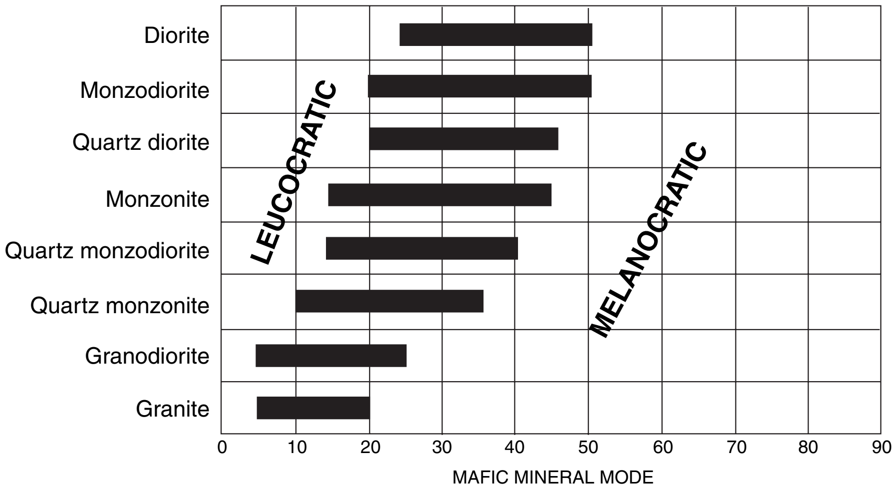

Figure 1.4. Expected range of mafic mineral abundance in intermediate and felsic rocks (modified from Streckeisen, 1976).

where known (such as pyroxene-oxide diorite and pyroxene-amphibole quartz monzodiorite). If mafic phases in intermediate rocks are difficult to identify or are altered, we suggest prefacing the modal root with *ferro* to acknowledge the presence of iron-rich phases (such as ferrodiorite and quartz ferromonzodiorite). Although the rock nomenclature and modal boundaries shown in Figures 1.3 and 1.4 are accepted and based on well documented natural modal boundaries, there are several practical problems with this scheme, especially when attempting to apply it in the field.

The first problem involves distinguishing intermediate (dioritic) from mafic (gabbroic) rocks. The generally accepted criterion for distinguishing diorite from gabbro is the change in plagioclase composition from less than An50 to more than An50. However, this measurement is impractical in field applications and problematic with petrographic study. Hyndman (1972) suggested additional criteria might include rock associations (diorite with more granitoid rocks, gabbro with more mafic rocks), mafic mineral assemblage (diorite = hornblende or biotite ± pyroxene; gabbro = pyroxene ± olivine ± hornblende), and plagioclase color (diorite—whitish or nearly whitish; gabbro—greenish gray to gray). These recommendations may work well in calc-alkaline granitic batholith complexes, but they have limited use in tholeiitic systems. Blatt and Tracy (1996) suggested describing diorite as rock that contains hornblende over pyroxene and that contains less than 35 modal percent high-temperature mafic minerals (olivine, pyroxene). A problem with the hornblende/pyroxene criterion is that many Keweenawan intermediate intrusive rocks with measured An values below 50 are dominated by clinopyroxene (ferroaugite and ferrohedenbergite) over hornblende (Miller and Chandler, 1997). This is true of many Keweenawan felsic rocks as well.

Based on field experience of mapping intermediate rocks in the Beaver Bay Complex and follow-up microprobe analyses of plagioclase composition, we recommend two simple criteria to distinguish intermediate from mafic rocks in the field and petrographically.

	Mafic mineral habit	Felsic mesostasis[2]
Intermediate	Prismatic, subprismatic	> 5 %
Mafic	Granular to poikilitic	< 5 %

A second problem with the present modal classification schemes involves determining the modes of felsic and intermediate rocks displaying a micrographic texture. In contrast to granitic-textured rocks common to mesozonal granitic batholiths and some Keweenawan felsic intrusions, most Keweenawan *red rock* intrusions display a micrographic texture. In these rocks, it is difficult

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[2] Miller and others (1993, 1994) defined felsic mesostasis as the fine-grained, typically pink matrix occurring between early formed minerals. As observed in thin section, it is composed of predominantly quartz and K-feldspar, usually micrographically intergrown, with minor Fe-silicates, Fe-Ti oxide and hydroxides, and accessory minerals (such as apatite, epidote, zircon, calcite, and sphene).

to determine the relative modes of alkali feldspar and quartz. Plagioclase is somewhat easier to distinguish because it commonly stands out against the pink color of micrographic alkali feldspar and quartz, especially if it has been altered white (kaolinitized or albitized). A CIPW normative calculation of whole-rock abundance would probably be a reasonable approximation of the mode, but because it requires chemical analysis, it would be impractical for a field-based study.

Based on the CIPW normative calculations of over 200 intermediate to felsic rock samples from various intrusions in northeastern Minnesota, it is clear that most Keweenawan rocks define a narrow field of QAP compositions (Fig. 1.5). This compositional field implies that Keweenawan intermediate to felsic rocks have compositions that cluster into four main rock groups: diorite-quartz diorite; monzodiorite-quartz monzodiorite; quartz monzonite or granodiorite; and granite. Whether normative compositions plot in the quartz monzodiorite field or the granodiorite field is dependent upon how the albite normative component is partitioned between plagioclase and alkali feldspar. If all albite is assigned to plagioclase, then the composition field crosses mostly through the granodiorite field (Fig. 1.5a). However, 25 microprobe analyses of alkali feldspar from intermediate rocks in the Duluth area (Miller, unpub. data) show an average albite component in alkali feldspar of approximately 25 percent. Using this partitioning percentage, the normative composition field crosses mostly through the quartz monzonite field (Fig. 1.5b). We suggest that this latter means of calculating QAP proportions be used because it is based on empirical data.

In lieu of a chemical analysis, we apply three field-based criteria for assigning intermediate to felsic rock names (Table 1.3). The criteria and their associated range of values are based on field and petrographic observations integrated with geochemical data from rocks from the Beaver Bay Complex (Miller, 1988; Miller and others, 1989, 1993, 1994; Boerboom and Miller, 1994). Essentially, the percentage of felsic mesostasis is the proportion of the pink component in the rock. The percentage of mafic phases (or color index) is as defined by the IUGS (Fig. 1.4). Rocks with greater than 5 normative percent quartz typically have visible free quartz in addition to that micrographically intergrown with alkali feldspar.

A third problem with the present modal classification schemes involves the confusion over the use of the terms *granophyre* and *granophyric*.

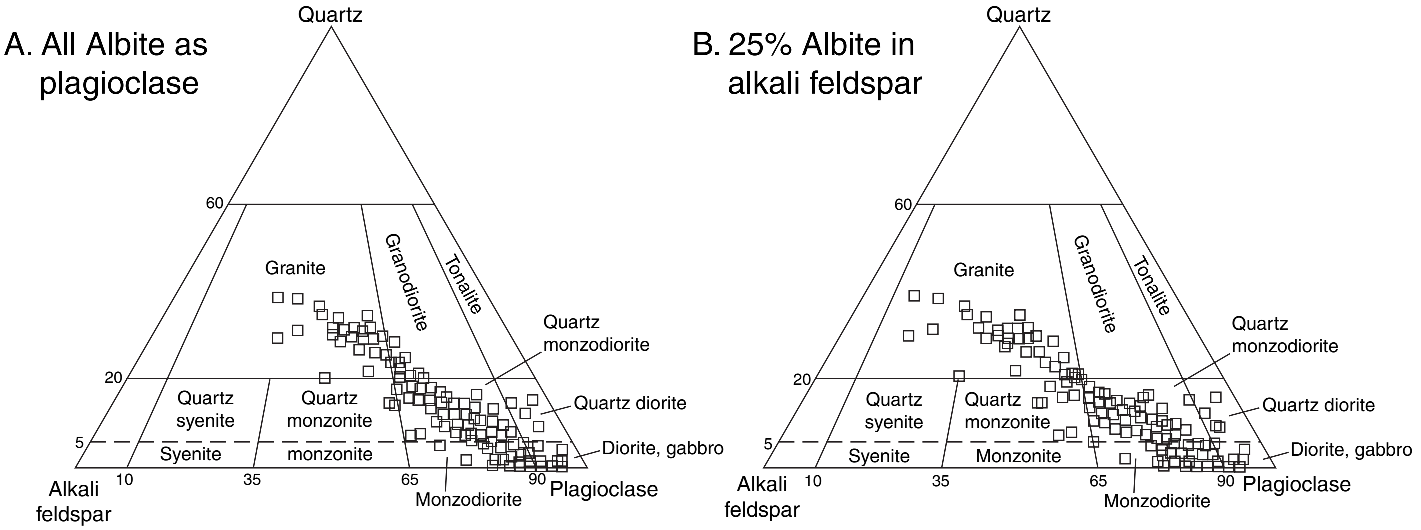

Figure 1.5. Quartz-alkali feldspar-plagioclase (QAP) components calculated from CIPW normative compositions of 210 intermediate to felsic rocks from Keweenawan intrusions (Green, 1979; Nelson, 1991; Miller, unpub. data).

A. Components calculated assuming that all normative albite is in the plagioclase component.

B. Components calculated assuming that 25 percent of the alkali feldspar component is composed of normative albite (for example A = 25 percent albite, 75 percent alkali feldspar).

Table 1.3. Field-based criteria for distinguishing intermediate and felsic Keweenawan intrusive rocks displaying micrographic textures.

Criteria	Diorite-quartz diorite	Monzodiorite-quartz monzodiorite	Quartz monzonite (granodiorite?)	Granite
percent felsic mesostasis	5-15	15-35	>35	>50
percent mafic phases	>25	>15	35-10	<20
visible quartz	No–diorite Yes–quartz diorite	No–monzodiorite Yes–quartz monzodiorite	Yes	Yes

Granophyre typically is used as a rock term that implies a granitic composition and a predominant micrographic texture. However, it also has been used to refer to small masses of micrographic alkali feldspar and quartz in the interstices of mafic to intermediate rocks. *Granophyric* has been used as both a compositional term (such as granophyric gabbro—gabbro that contains interstitial masses of micrographic alkali feldspar and quartz) and a textural term (such as granophyric granite—granite that displays a micrographic, rather than an intergranular texture). The *Glossary of Geology* (Bates and Jackson, 1987) noted a similar varied usage by defining granophyre as: “An irregular microscopic intergrowth of quartz and alkali feldspar. [And] ...as a fine-grained granitic rock having a micrographic texture.”

We use the term *granophyre* to loosely define a rock type that is a granite by mode or norm (Fig. 1.3) and predominantly displays micrographic texture. Other features common to granophyre as it occurs in northeastern Minnesota include a deep pink color (pinkish orange color when weathered); a leucocratic composition (less than 10 percent mafic phases); predominance of dry, high-temperature, Fe-rich mafic phases (ferrohedenbergite and fayalite) that typically display prismatic habit; miarolitic cavities; and weak plagioclase-porphyritic textures.

The micrographic feldspar and quartz commonly found in the interstitial or intercumulus areas of mafic to intermediate rocks are referred to as *felsic mesostasis*. However, it is commonly useful to refer informally to rocks containing this material as being granophyric. This term is not used, however, as a substitute for the compositional effect of felsic mesostasis on the total mode of the rock. In other words, a dioritic rock with a significant amount of felsic mesostasis is called a granophyric monzodiorite rather than a granophyric diorite. Similarly, for a gabbroic rock, the term *granophyric monzogabbro* rather than *granophyric gabbro* is used.

STRATIGRAPHIC CLASSIFICATION OF KEWEENAWAN ROCKS OF NORTHEASTERN MINNESOTA

In addition to ambiguous rock classification schemes applied to the Duluth Complex, another nomenclature challenge is the inconsistent stratigraphic designations of Keweenawan igneous rocks. We propose to subdivide the volcanic and sedimentary rocks of northeastern Minnesota into various lithostratigraphic units of group and formational status as shown in Table 1.4. Along these lines, we propose here to further subdivide the Keweenawan intrusive rocks of northeastern Minnesota into a variety of lithodemic units that more or less parallel lithostratigraphic nomenclature. This stratigraphic approach follows the recommendations of the North American Commission on Stratigraphic Nomenclature (NACSN, 1983) and the suggestions of Irvine (1982) for subdivisions within mafic layered intrusions.

Keweenawan intrusive rocks of northeastern Minnesota have been assigned to the Duluth and Beaver Bay Complexes for many years and they in turn have been further subdivided into various ranks of formal and informal lithodemic units. As defined by the NACSN (1983, p. 859): “A lithodemic unit is a defined body of predominantly intrusive, highly deformed, and/or highly metamorphosed rock, distinguished and delimited on the basis of rock characteristics. In contrast to lithostratigraphic units, a lithodemic unit generally does not conform to the Law of Superposition. Its contacts with other rock units may be sedimentary, extrusive, intrusive, tectonic or metamorphic.” The

Table 1.4. Stratigraphic classification of Keweenawan rocks of northeastern Minnesota.

Intrusive rock lithodemic units*	Examples	Volcanic/sedimentary lithostratigraphic units*	Examples
Supersuite	Midcontinent Rift Intrusive Supersuite	Supergroup	Keweenawan Supergroup
Complex	Duluth Complex	Group	North Shore Volcanic Group
	Beaver Bay Complex		
series	Early gabbroic series	sequence	Upper northeast sequence
	Felsic series		Lower northeast sequence
	Anorthositic series		Upper southwest sequence
	Layered series		Lower southwest sequence
	Cloquet Lake layered series?		Schroeder–Lutsen sequence
intrusion (lithodeme)	Partridge River intrusion	Formation	Lutsen basalts
	Silver Bay intrusions		Larsmont ophitic basalts
	Layered series at Duluth		Silver Bay porphyritic basalt
	Cloquet Lake layered series?		Baptism River lavas
	Lake One troctolite		Palisade Head rhyolite
	Blesner Lake diorite		Good Harbor Bay andesites
	Finland granophyre		Puckwunge Sandstone
	Scott Creek leucogabbro		Cut Face Creek sandstone
	Endion sill		
	Lichen Lake diabase		
zone/rock unit	troctolite zone–Layered series at Duluth	Member	Manitou trachybasalt flow–Schroeder basalts
	basal contact zone–South Kawishiwi intrusion		Indian Camp sandstone–Lutsen basalts
	augite troctolite cumulates–Partridge River intrusion		Silver Beaver rhyolite–Baptism River basalts
	interlayered troctolitic and anorthositic rocks–Tuscarora intrusion		
	ferromonzodiorite–Blesner Lake diorite		
subzone/macrocycle	Upper chill subzone–upper contact zone–Layered series at Duluth		
	gabbro subzone of second macrocycle–cyclic zone–Layered series at Duluth		
miscellaneous units	Freestanding layers, macrolayers, units, intervals, horizons, reefs, etc.		

*Lower case spelling denotes informal lithodemic and lithostratigraphic subdivisions.

highest formal rank within the lithodemic classification is *supersuite*, which is broadly correlative with *supergroup* in the lithostratigraphic nomenclature. Morey and Green (1982) defined all stratified sedimentary and volcanic rocks associated with the Midcontinent rift to be part of the Keweenawan Supergroup. We suggest all intrusive rocks associated with the rift be considered part of the Midcontinent Rift Intrusive Supersuite.

The next formal level below *supersuite* and *supergroup* are *suite* and *group*, respectively. The North Shore Volcanic Group is a lithostratigraphic designation referring to all Keweenawan volcanic and associated sedimentary rocks occurring in northeastern Minnesota (Goldich and others, 1961; Green, 1972; Chapter 5). Instead of *intrusive suite*, the term *complex* is an acceptable substitute according to the NACSN (1983) and has become well established in the literature. The two major complexes within the Midcontinent Rift Intrusive Supersuite in northeastern Minnesota are the Duluth Complex and the Beaver Bay Complex. As described in Chapter 6, the Duluth Complex includes all intrusive rocks emplaced into the base of the volcanic edifice of the North Shore Volcanic Group. The Beaver Bay Complex encompasses all intrusive rocks emplaced into a higher and central part of the North Shore Volcanic Group volcanic pile and is described in Chapter 7.

The next level of rank commonly used for Keweenawan intrusive rocks below complex is the informal designation of *series*. For the past 30 years, the Duluth Complex has been subdivided into four main series: *layered* (or *troctolitic*) *series*, *anorthositic series*, *felsic series*, and *early gabbroic series* (Davidson, 1972; Weiblen and Morey, 1980). As described in Chapter 6, each series corresponds to groups of rocks that are lithologically, structurally, and chronologically similar, and each represents unique modes of magma formation, emplacement, and crystallization. The Beaver Bay Complex has not been comparably subdivided. The NACSN (1983) advised against the use of the term *series*, which is a chronostratigraphic designator, and instead recommends the term *suite*. Irvine (1982) noted that *series* is a very commonly used term in layered intrusion nomenclature, though he recommended that it be used to identify structural divisions within an individual intrusion (such as marginal series, layered series, and border series). Because the term *series*, used in the lithostratigraphic sense, is entrenched in the literature of the Duluth Complex and has acquired structural and chronologic connotations, we recommend that it be retained.

No subdivision of the North Shore Volcanic Group has been proposed previously that would correspond to the series level for intrusive rocks. Moreover, the NACSN (1983) did not recognize a formal subdivision between *group* and *formation* for stratified rocks. We propose here that the North Shore Volcanic Group be subdivided into five informal sequences that are based on structural and stratigraphic position and magnetic polarity/geochronology. They are: 1. *Lower northeast sequence*; 2. *Upper northeast sequence*; 3. *Lower southwest sequence*; 4. *Upper southwest sequence*; and 5. *The Schroeder–Lutsen sequence*. These sequences are described in the explanation to map M-119 and in Chapter 5.

The most fundamental level of subdivision for intrusive rocks is *lithodeme*. The NACSN (1983, p. 860) defined a lithodeme as: "...a body of intrusive, pervasively deformed, or highly metamorphosed rock, generally non-tabular and lacking primary depositional structures, and characterized by lithic homogeneity." Lithodemes in igneous terranes are essentially intrusions, despite the fact that mafic layered intrusions are commonly tabular, often possess cumulate (depositional) structures, and tend to be compositionally zoned. The NACSN (1983) recommended that compound names be applied to lithodemes and be keyed to geographic location combined with a lithic term or a term that defines the shape of the intrusive body. We concur (Table 1.4), but use intrusion shape terms (such as *sill*, *dike*, and *intrusion*) only where the boundaries and the internal composition of the intrusive body are well defined by mapping, drilling, or geophysical expression. Unfortunately, several intrusion names have been inappropriately termed *layered series* (Table 1.4). The term *layered series at Duluth* is the name given by Taylor (1964) and seems appropriate to retain because it is the type locality of the Duluth Complex for both the layered series and the anorthositic series. Based on its geophysical attributes, the Cloquet Lake layered series may consist of several intrusions and thus may deserve series rank within the Beaver Bay Complex. However, because of its poor exposure, we rank the Cloquet Lake layered series on an intrusion level. We have renamed *Nathan's layered series* (Phinney, 1972b) in Cook County the *Poplar Lake intrusion*. This alleviates the use of the term *layered series*, and the use of a personal name in the geologic unit.

Because many intrusions were open to frequent magma recharge, we recognize that the distinction between major recharge events and discrete intrusions can be potentially difficult. In general, recharge events should result in features indicative of magma emplaced into another magma. Such features include gradational stratiform changes in rock type and cyclical cryptic variations. Because injected magmas may disrupt crystallized or semi-crystallized rock near feeder systems, crosscutting relationships must be evaluated in a regional context. In contrast, discrete intrusions should result in features indicative of a magma emplaced into solid or nearly solid rock, such as the development of sharp crosscutting contacts, inclusive relationships, and marginal contact zones that indicate relatively rapid cooling of the intruded magma.

The rank equivalent of lithodeme for stratified rocks is *formation*. Although volcanic packages within the North Shore Volcanic Group have been identified and informally named for some time (Green, 1972), the stratigraphic designation of these packages has not been defined. We recommend that these packages be defined as *volcanic formations*. The compound terms previously assigned to these packages correspond to NACSN (1983) recommendations. *Formational units* may be individual flows of distinctive lithology and significant thickness and lateral extent, or may be a group of flows that share a common lithologic character and/or are bounded by intrusions or unconformities. For most volcanic and sedimentary rock formations identified on map M-119, the dominant lithology is typically used in the name, and the plural is used if composed of multiple flows (such as the Lutsen basalts; also Table 1.4). For a volcanic package that is composed of a variety of lava types, the generic term *lavas* is used (such as the Lakeside lavas). The basic attributes of the sedimentary and volcanic formations are described on M-119 and are further discussed in Chapter 5.

The NACSN (1983) did not recognize any formal subdivisions of lithodemes, but further subdivisions are commonly employed in describing mafic layered intrusions. Irvine (1982) recommended the use of *zone* and *subzone* as first- and second-rank stratigraphic subdivisions of *series*, though we use the terms to subdivide *intrusions*. However, we apply the terms *zone* and *subzone* only to those intrusions that have a stratiform internal structure with well documented igneous stratigraphy. This type of subdivision has been applied to the layered series at Duluth (Miller and Ripley, 1996). Subdivisions within non-stratiform intrusions are typically based on lithologic differences, and thus map units are commonly based on the dominant lithology (such as the poikilitic olivine diabase unit of the Blesner Lake diorite; see M-119). Irvine (1982) also recommended the use of various unit terms that need not completely subdivide intrusions as *zone* and *subzone* do. Terms that might apply to these types of freestanding units include *layer*, *macrolayer*, *unit*, *interval*, *horizon*, and *reef*.

The subdivision of lithostratigraphic formations into "members" is occasionally used in the North Shore Volcanic Group to denote a unit that is distinctive from the rest of the formational unit. Sometimes this distinction is based on lithology (such as the Silver Beaver rhyolite member of the Baptism River basalts) or on physical attributes (such as the thick Terrace Point basalt member of the Lutsen basalts). In the Keweenawan sedimentary rock formations, no members have been distinguished.

REFERENCES

Bates, R.L., and Jackson, J.A., 1987, Glossary of geology (3rd ed.): American Geological Institute, 788 p.

Blatt, H., and Tracy, R.J., 1996, Petrology: Igneous, sedimentary and metamorphic: New York, W.H. Freeman, 529 p.

Boerboom, T.J., and Miller, J.D., Jr., 1994, Bedrock geologic map of the Silver Island Lake, Wilson Lake, and western Toohey Lake quadrangles, Cook and Lake Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-81, scale 1:24,000.

Davidson, D.M., Jr., 1969, Geologic map of the Kawishiwi Lake quadrangle, Lake and Cook Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-7, scale 1:24,000.

———1972, Eastern part of Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 354-360.

Foose, M.P., and Cooper, R.W., 1978, Preliminary geologic report on the Harris Lake area, northeastern Minnesota: U.S. Geological Survey Open-File Report 78-385, 24 p., 1 pl., scale 1:12,000.

Goldich, S.S., Nier, A.O., Baadsgaard, H., Hoffman, J.H., and Krueger, H.W., 1961, The Precambrian geology and geochronology of Minnesota: Minnesota Geological Survey Bulletin 41, 193 p., 5 pls.

Green, J.C., 1972, North Shore Volcanic Group, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 294-332.

———1979, Field trip guidebook for the Keweenawan (Upper Precambrian) North Shore Volcanic Group, Minnesota: Minnesota Geological Survey Guidebook Series 11, 22 p.

Grout, F.F., 1918, A type of igneous differentiation: Journal of Geology, v. 26, p. 626-658.

Grout, F.F., Sharp, R.P., and Schwartz, G.M., 1959, The geology of Cook County Minnesota: Minnesota Geological Survey Bulletin 39, 163 p., 16 pls.

Hyndman, D.W., 1972, Petrology of igneous and metamorphic rocks: New York, McGraw-Hill, 533 p.

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

Irvine, T.N., Andersen, J.C.O., and Brooks, C.K., 1998, Included blocks (and blocks within blocks) in the Skaergaard intrusion: Geologic relations and the origin of rhythmic modally graded layers: Geological Society of America Bulletin, v. 110, no. 11, p. 1398-1447.

LeMaitre, R.W., 1989, A classification of igneous rocks and glossary of terms: Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks: Oxford, Blackwell Scientific, 193 p.

McCallum, I.S., Raedeke, L.D., and Mathez, E.A., 1980, Investigations of the Stillwater Complex: Part 1. Stratigraphy and structure of the Banded zone: American Journal of Science, v. 280-A, p. 59-87.

Miller, J.D., Jr., 1986, The geology and petrology of anorthositic rocks in the Duluth Complex, Snowbank Lake quadrangle, northeastern Minnesota: Minneapolis, University of Minnesota, Ph.D. dissertation, 585 p.

———1988, Geologic map of the Silver Bay and Split Rock Point NE quadrangles, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-65, scale 1:24,000.

———1995, The Duluth Complex at Duluth, *in* Miller, J.D., Jr., ed., Field trip guidebook for the geology and ore deposits of the Midcontinent rift in the Lake Superior region: Minnesota Geological Survey Guidebook Series 20, p. 123-48.

Miller, J.D., Jr., Boerboom, T.J., and Jerde, E.A., 1994, Bedrock geologic map of the Cabin Lake and Cramer 7.5-minute quadrangles, Lake and Cook Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-82, scale 1:24,000.

Miller, J.D., Jr., and Chandler, V.W., 1997, Geology, petrology, and tectonic significance of the Beaver Bay Complex, northeastern Minnesota, *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. 73-96.

Miller, J.D., Jr., Green, J.C., and Boerboom, T.J., 1989, Geologic map of the Illgen City quadrangle, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-66, scale 1:24,000.

Miller, J.D., Jr., Green, J.C., Boerboom, T.J., and Chandler, V.W., 1993, Geologic map of the Doyle Lake and Finland quadrangles, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-72, scale 1:24,000.

Miller, J.D., Jr., and Ripley, E.M., 1996, Layered intrusions of the Duluth Complex, Minnesota, USA, *in* Cawthorn, R.G., ed., Layered intrusions: Amsterdam, Elsevier Science, p. 257-301.

Miller, J.D., Jr., and Weiblen, P.W., 1990, Anorthositic rocks of the Duluth Complex: Examples of rocks formed from plagioclase crystal mush: Journal of Petrology, v. 31, no. 2, p. 295-339.

Morey, G.B., and Green, J.C., 1982, Status of the Keweenawan as a stratigraphic unit in the Lake Superior region, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 15-26.

North American Commission on Stratigraphic Nomenclature, 1983, North American stratigraphic code: American Association of Petroleum Geologists Bulletin, v. 67, no. 5, p. 841-875.

Naslund, H.R., and McBirney, A.R., 1996, Mechanisms of formation of igneous layering, *in* Cawthorn, R.G., ed., Layered intrusions: Amsterdam, Elsevier Science, p. 1-43.

Nelson, N., 1991, A petrologic and geochemical study of granophyric granite in the roof of the Keweenawan Duluth Complex, Eagle Mountain, Cook County, Minnesota: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 151 p., 1 pl.

Parsons, I., ed., 1987, Origins of igneous layering: Boston, Reidel, 696 p.

Phinney, W.C., 1972a, 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.

———1972b, Northern prong, Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 346-353.

Severson, M.J., and Hauck, S.A., 1990, Geology, geochemistry, and stratigraphy of a portion of the Partridge River intrusion: Natural Resources Research Institute, Technical Report NRRI/GMIN-TR-89-11, 236 p., 4 pls.

Stevenson, R.J., 1974, A mafic layered intrusion of Keweenawan age near Finland, Lake County, Minnesota: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 160 p.

Streckeisen, A.L., 1976, Classification and nomenclature of igneous rocks: Earth-Science Reviews, v. 12, p. 1-35.

Taylor, R.B., 1964, Geology of the Duluth Gabbro Complex near Duluth, Minnesota: Minnesota Geological Survey Bulletin 44, 63 p., 1 pl.

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

Zientek, M.L., Czamanske, G.K., and Irvine, T.N., 1985, Stratigraphy and nomenclature for the Stillwater Complex, *in* Czamanske, G.K., and Zientek, M.L., eds., The Stillwater Complex, Montana: Geology and guide: Montana Bureau of Mines and Geology Special Publication 92, p. 21-23.

Chapter 2

HISTORY OF GEOLOGIC MAPPING AND MINERAL EXPLORATION IN THE DULUTH COMPLEX

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For the past 150 years, there has been continued interest in the Duluth Complex. During all phases of geologic mapping and mineral exploration in Minnesota, a substantial amount of study has been conducted on the Duluth Complex and related Keweenawan rocks. In this chapter, we provide a summary of mapping and exploration activities as a historical context for our current knowledge of the Duluth Complex, which is discussed in this report and portrayed on Miscellaneous Map M-119. The first half of this chapter describes the history of geologic mapping of the Duluth Complex. This history is tied closely to that of the Minnesota Geological Survey, which was established in 1872. The second half of the chapter describes the history of copper-nickel-platinum group element exploration in the Duluth Complex. This section documents the companies involved, the quantity of core drilled, and how exploration activity, which did not seriously begin until 1948, waxed and waned in response to public concerns and the market for copper, nickel, and more recently, platinum group elements.

GEOLOGIC MAPPING IN THE DULUTH COMPLEX

The history of geologic mapping in the Duluth Complex is divisible into four major periods of activity: 1. Early state and federal surveys (1852-1911), 2. Mapping by Grout and Schwartz (1911-1961), 3. Quadrangle-scale mapping (1961-1982), and 4. Aeromagnetic survey and recent mapping (1982-present). Each period of mapping had distinct motivations and emphases that reflected the various political, economic, and scientific realities of the time. The activities of each period also reflected the different philosophies of the directors of the Minnesota Geological Survey, which funded most of the mapping activities. The directors have been Newton H. Winchell (1872-1900), William H. Emmons (1911-1944), Frank F. Grout (1944-1946), George M. Schwartz (1946-1961), Paul K. Sims (1961-1973), Matt Walton (1973-1986), Priscilla C. Grew (1986-1993), and David L. Southwick (1993-2001). The benchmarks in geologic mapping of the Duluth Complex in the four different periods are summarized in Table 2.1 and are briefly discussed below.

Early state and federal surveys, 1852-1911

> "The numerous problems arising from the gabbro cannot all be considered as solved by the examinations the survey has given to them."
>
> N.H. Winchell, 1900, *Final Report v .5*, p. 56

This early period of geologic investigation is bracketed by two major federal studies: the Owen survey of 1852, and the Van Hise and Leith monograph of 1911. The Owen survey was the first comprehensive geologic survey of the state and laid the groundwork for the geological and natural history survey of Minnesota, which was conducted between 1872 and 1900. With the publication of the Van Hise and Leith monograph on the geology of the Lake Superior region, the basic geologic framework of the Keweenawan rocks was established and generally accepted. However, disagreements existed not only between U.S. Geological Survey and Geological and Natural History Survey of Minnesota geologists (for example Irving, 1883; Winchell, 1893; Van Hise and Leith, 1911), but also among geologists within the Natural History Survey (see Grant and N.H. Winchell's contributions to Winchell, 1899). Because igneous petrology was a relatively new science during this time, much of the disagreement about the origin and stratigraphic position of the Duluth Complex and related Keweenawan rocks stemmed largely from uncertainties about fundamental igneous processes, especially intrusive processes.

The Owen survey of 1852 was commissioned by the U.S. Department of the Treasury to evaluate the mineral wealth of the new states of Iowa (1846) and Wisconsin (1848), and the new territory of Minnesota (1849). Geologic investigation of northeastern Minnesota for the Owen survey was

Table 2.1. Chronology of geologic mapping in the Duluth Complex.

Early State and Federal Surveys, 1852-1911

1852	*Report of a Geological Survey of Wisconsin, Iowa, and Minnesota,* by D.D. Owen is published; northeast Minnesota geology investigated by J.G. Norwood and C. Whittlesey.
1854	Treaty of 1854 with the Ojibwe; exploration begins in northeastern Minnesota.
1866	*Geology and Minerals—A Report of Exploration in the Mineral Regions of Minnesota During the Years 1848, 1859, and 1864*, by Whittlesey.
1866	*On the Metalliferous Regions Bordering on Lake Superior*, by H.H. Eames, first Minnesota State Geologist.
1871	*Geological Notes on Minnesota,* by J.H. Kloos, translated and republished in 1882 in the *Tenth Annual Report of the Geological and Natural History Survey of Minnesota.*
1872	Geological and Natural History Survey of Minnesota is created; N.H. Winchell appointed director and State Geologist.
1878	*Sixth Annual Report of the Geological and Natural History Survey of Minnesota;* first state reports on the crystalline rocks of the North Shore.
1880	*Eighth Annual Report of the Geological and Natural History Survey of Minnesota;* includes "The cupriferous series at Duluth," by N.H. Winchell.
1882	*Tenth Annual Report of the Geological and Natural History Survey of Minnesota;* includes "Preliminary List of Rocks" and "Typical Thin Sections of the Rocks of the Cupriferous Series in Minnesota," by N.H. Winchell, and "Geologic Notes on Minnesota," by Kloos.
1883	*The Copper-Bearing Rocks of Lake Superior*, by R.D. Irving, U.S. Geological Survey Monograph 5.
1887	*Fifteenth Annual Report of the Geological and Natural History Survey of Minnesota;* includes a report on the rocks of northeastern Minnesota by A. Winchell; also includes a generalized colored map of northeastern Minnesota by N.H. Winchell.
1887	*Preliminary Description of the Peridotytes, Gabbros, Diabases, and Andesytes of Minnesota,* by M.W. Wadsworth, Geological and Natural History Survey of Minnesota Bulletin 2.
1889	*Seventeenth Annual Report of the Geological and Natural History Survey of Minnesota;* includes "Report of Geological Observations Made in Northeastern Minnesota During the Summer of 1888," by U.S. Grant.
1891	*The Iron Ores of Minnesota,* by N.H. Winchell and H.V. Winchell, in Geological and Natural History Survey of Minnesota Bulletin 6; includes geologic map showing the gabbro belt classified as Norian and positioned between the Pewabic (Pokegama) Quartzyte and the Animikie slates.
1893	"The Basic Massive Rocks of the Lake Superior Region," by W.S. Bayley, in Journal of Geology, v. 1, also 1895, v. 3.
1893	"The Norian of the Northwest," by N.H. Winchell, included in Geological and Natural History Survey of Minnesota Bulletin 8; cites erroneous evidence for classifying gabbro within the Animikie.
1893	*The Anorthosytes of the Minnesota Coast of Lake Superior* and *The Laccolitic Sills of the North-West Coast of Lake Superior,* by A.C. Lawson, Geological and Natural History Survey of Minnesota Bulletin 8.
1898	"Geology of the Keweenawan Area in Northeastern Minnesota," by A.H. Elftman, American Geologist, v. 21 and v. 22.
1899	*The Geology of Minnesota, v. IV of the Final Report,* Geological and Natural History Survey of Minnesota; includes "The Geology of the Southern Portion of St. Louis County," "The Geology of the Northern Part of St. Louis County," and "The Geology of Lake County," by N.H. Winchell, and "The Geology of Cook County," by Grant.
1900	*The Geology of Minnesota, v. V of the Final Report,* Geological and Natural History Survey of Minnesota; includes "Structural Geology," by N.H. Winchell.
1903	*The Vermilion Iron-Bearing District of Minnesota,* by J.M. Clements, U.S. Geological Survey Monograph 45.
1911	*The Geology of the Lake Superior Region,* by C.R. Van Hise, and C.K. Leith, U.S. Geological Survey Monograph 52.

Mapping by Grout and Schwartz, 1911-1961

1911	W.H. Emmons appointed director of the reestablished Minnesota Geological Survey.
1914	F.F. Grout begins field studies of the Duluth gabbro.
1918	Publication of five papers generated from Grout's 1917 Ph.D. dissertation on the Duluth Complex (Grout, 1918a-e).

Table 2.1. continued

1919	G.M. Schwartz joins the University of Minnesota faculty and begins work with the Minnesota Geological Survey.
1932	*Geologic Map of Minnesota,* by Grout,1:500,000-scale.
1938	"Section Across Keweenawan Lavas at Duluth, Minnesota" by A.E. Sandberg, Geological Society of America Bulletin, v. 49.
1939	*The Geology of the Anorthosites of the Minnesota Coast of Lake Superior,* by Grout and Schwartz, Minnesota Geological Survey Bulletin 28, includes six geologic map plates.
1943	*Mineral Resources of Minnesota,* by Emmons and Grout, Minnesota Geological Survey Bulletin 30.
1944	"Tracing the Duluth Gabbro Contact with a Magnetometer," by Schwartz, Economic Geology, v. 39.
1944	Emmons retires from the Minnesota Geological Survey, Grout assumes position as interim director.
1946	Schwartz appointed director of the Minnesota Geological Survey.
1947	Aeromagnetic survey of northern Minnesota begins; 1-mile flight line spacing.
1949	*The Geology of the Duluth Metropolitan Area,* by Schwartz, Minnesota Geological Survey Bulletin 33; includes 19 geologic map plates.
1949-1950	*The Titaniferous Magnetites of Minnesota,* by Grout, Department of Iron Range Resources and Rehabilitation.
1951	*Precambrian Stratigraphy of Minnesota,* by Grout, J.W. Gruner, Schwartz, and G.A. Thiel, Geological Society of America Bulletin, v. 62.
1959	*The Geology of Cook County Minnesota,* by Grout, R.P. Sharp, and Schwartz, Minnesota Geological Survey Bulletin 39.
1961	*The Precambrian Geology and Geochronology of Minnesota,* by S.S. Goldich, A.O. Nier, H. Baadsgaard, J.H. Hoffman, and H.W. Krueger, Minnesota Geological Survey Bulletin 41.
1961	Schwartz retires, P.K. Sims appointed director of the Minnesota Geological Survey.

Quadrangle-Scale Mapping, 1961-1982

1964	*Geology of the Duluth Gabbro Complex Near Duluth, Minnesota,* by R.B. Taylor, Minnesota Geological Survey Bulletin 44; includes 1:24,000-scale, bedrock geologic map.
1965	*Our Land and Mineral Resources, a Long-Range Plan for Geologic Research in Minnesota,* by Sims, Minnesota Geological Survey.
1966	*Gabbro Lake Quadrangle, Lake County, Minnesota,* by J.C. Green, W.C. Phinney, and P.W. Weiblen, Minnesota Geological Survey Miscellaneous Map M-2, 1:31,680-scale.
1967	*Reconnaissance Geologic Map of Kangas Bay Quadrangle,* by Phinney, Minnesota Geological Survey Open-File Map, 1:24,000-scale.
1969	*Geologic Map of the Kawishiwi Lake Quadrangle, Lake and Cook Counties, Minnesota,* by D.M. Davidson, Minnesota Geological Survey Miscellaneous Map M-7, 1:24,000-scale.
1969	*Geologic Map of the Perent Lake Quadrangle, Lake County, Minnesota,* by Davidson, Minnesota Geological Survey Miscellaneous Map M-8, 1:24,000-scale.
1970	Reconnaissance geologic maps of the Babbitt, Babbitt NE, Babbitt SE, Babbitt SW, and Allen quadrangles, by B. Bonnichsen, Minnesota Geological Survey Open-File Maps, 1:24,000-scale.
1971	*Outcrop Map of Southern Part of Duluth Complex and Associated Keweenawan Rocks, St. Louis and Lake Counties, Minnesota,* by Bonnichsen, Minnesota Geological Survey Miscellaneous Map M-11, 1:125,000-scale.
1972	*Geology of Minnesota: A Centennial Volume,* by Sims and G.B. Morey, eds., Minnesota Geological Survey.
1973	Sims steps down as the Minnesota Geological Survey director; replaced by Matt Walton.
1974	Regional Copper-Nickel Study initiated, minor mapping by R.W. Beltrame and R.W. Cooper.
1977	*Reconnaissance Geologic Map of the Esko Quadrangle, St. Louis and Carlton Counties, Minnesota,* by J.A. Kilburg and Morey, Minnesota Geological Survey Miscellaneous Map M-25, 1:24,000-scale.
1977	Reconnaissance geologic maps of the Alice Lake, Beth Lake, Cherokee Lake, Eagle Mountain, Kelso Mountain, Lake Polly, Lima Mountain, and Pine Mountain quadrangles, by Davidson, Minnesota Geological Survey Miscellaneous Maps, 1:24,000-scale.
1977	*Reconnaissance Geologic Map of the Brule Lake Quadrangle, Cook County, Minnesota,* by Davidson and J.R. Burnell, Minnesota Geological Survey Miscellaneous Map M-29, 1:24,000-scale.

Table 2.1. continued

1977	*Geologic Map of Pigeon Point Quadrangle, Cook County, Minnesota,* by M.G. Mudrey, Minnesota Geological Survey Miscellaneous Map M-36, 1:24,000-scale.
1977	*Geologic Map of the South Lake Quadrangle, Cook County, Minnesota,* by Morey and H.D. Nathan, Minnesota Geological Survey Miscellaneous Map M-38, 1:24,000-scale.
1977	*Geologic Map of the Hungry Jack Lake Quadrangle, Cook County, Minnesota,* by E.A. Mathez, Nathan, and Morey, Minnesota Geological Survey Miscellaneous Map M-39, 1:24,000-scale.
1977	*Environmental Geology of the North Shore,* by Green, M.A. Jirsa, and C.M. Moss, Minnesota Geological Survey and the Minnesota State Planning Agency publication.
1977	*Bedrock Geology of the Hoyt Lakes–Kawishiwi Area, St. Louis and Lake Counties, Northeastern Minnesota,* by Morey and Cooper, Minnesota Geological Survey Open-File Map, 1:48,000-scale.
1978	*Geologic Map of the Gunflint Lake Quadrangle, Cook County, Minnesota,* by Morey and Nathan, Minnesota Geological Survey Miscellaneous Map M-42, 1:24,000-scale.
1981	*Geologic Map of the Long Island Lake Quadrangle, Cook County, Minnesota,* by Morey, Weiblen, J.J. Papike, and D.H. Anderson, Minnesota Geological Survey Miscellaneous Map M-46, 1:24,000-scale.
1982	*Geologic Map of Minnesota, Two Harbors Sheet,* by Green, Minnesota Geological Survey State Atlas, 1:250,000-scale.
	Aeromagnetic Survey and Recent Mapping, 1982-present
1983	*Aeromagnetic Map of Minnesota, Cook and Lake Counties* and *Aeromagnetic Map of Minnesota, St. Louis County,* by V.W. Chandler, Minnesota Geological Survey Aeromagnetic Maps A-1 and A-2, 1:250,000-scale.
1983	Natural Resources Research Institute established at the University of Minnesota Duluth.
1985	Beginning of USGS-sponsored Cooperative Geologic Mapping Program (COGEOMAP).
1986	Walton retires; P.C. Grew appointed as Minnesota Geological Survey director.
1987	Minnesota Minerals Coordinating Committee formed.
1988	*Geologic Map of the Silver Bay and Split Rock Point NE Quadrangles, Lake County, Minnesota,* by J.D. Miller, Jr., Minnesota Geological Survey Miscellaneous Map M-65, 1:24,000-scale.
1989	*Geologic Map of the Illgen City Quadrangle, Lake County, Minnesota,* by Miller, Green, and T.J. Boerboom, Minnesota Geological Survey Miscellaneous Map M-66, 1:24,000-scale.
1990	"Geologic Interpretation of Gravity and Magnetic Data Over the Central Part of the Duluth Complex, Northeastern Minnesota," by V.W. Chandler, Economic Geology, v. 85.
1990	*Geology, Geochemistry, and Stratigraphy of a Portion of the Partridge River Intrusion,* by M.J. Severson and S.A. Hauck, Natural Resources Research Institute Technical Report NRRI/GMIN-TR-89-11, includes 1:24,000-scale map.
1992	*Geologic Map of the North Shore of Lake Superior, Lake and Cook Counties, Minnesota: Part 1. Little Marais to Tofte,* by Green, Minnesota Geological Survey Miscellaneous Map M-71, 1:24,000-scale.
1993	*Preliminary Geologic Map of the Duluth Area, St. Louis County, Minnesota,* by Miller, Green, and Chandler, Minnesota Geological Survey Open-File Report 93-2, 1:48,000-scale.
1993	*Geologic Map of the Doyle Lake and Finland Quadrangles, Lake County, Minnesota,* by Miller, Green, Boerboom, and Chandler, Minnesota Geological Survey Miscellaneous Map M-72, 1:24,000-scale.
1993	D.L. Southwick appointed as interim Minnesota Geological Survey director, later (1994) fully appointed director.
1994	*Bedrock Geologic Map of the Cabin Lake and Cramer 7.5-Minute Quadrangles, Lake and Cook Counties, Minnesota,* by Miller, Boerboom, and E.A. Jerde, Minnesota Geological Survey Miscellaneous Map M-82, 1:24,000-scale.
1994	*Bedrock Geologic Map of the Silver Island Lake, Wilson Lake, and Western Toohey Lake Quadrangles, Cook and Lake Counties, Minnesota,* by Boerboom and Miller, Minnesota Geological Survey Miscellaneous Map M-81, 1:24,000-scale.
1994	*Igneous Stratigraphy of the South Kawishiwi Intrusion, Duluth Complex, Northeastern Minnesota,* by Severson, Natural Resources Research Institute Technical Report NRRI/TR-93/34.
1995	*Geology of the Southern Portion of the Duluth Complex,* by Severson, Natural Resources Research Institute Technical Report NRRI/TR-95/26; includes 1:63,000-scale geologic map.
1999	*Bedrock Geologic Map of Allen Quadrangle, Minnesota,* by Severson and Miller, Minnesota Geological Survey Miscellaneous Map M-91, 1:24,000-scale.

Table 2.1. continued

1999	*Bedrock Geologic Map of the Central Duluth Complex and Western Part of the Beaver Bay Complex, Lake and St. Louis Counties, Minnesota,* by Miller and Chandler, Minnesota Geological Survey Miscellaneous Map M-101, 1:100,000-scale.
2001	*Superimposed Magnetic on Gravity Anomaly Map of the Central Duluth Complex and Western Part of the Beaver Bay Complex, Lake and St. Louis Counties, Minnesota,* by Chandler, Minnesota Geological Survey Miscellaneous Map M-117, 1:100,000-scale.
2001	*Superimposed Magnetic on Gravity Anomaly Map of the Duluth Complex and Related Rocks, Northeastern Minnesota*, by Chandler, Minnesota Geological Survey Miscellaneous Map M-120, 1:200,000-scale.
2001	*Geologic Map of the Duluth Complex and Related Rocks, Northeastern Minnesota,* by Miller, Green, Severson, Chandler, and D.M. Peterson, Minnesota Geological Survey Miscellaneous Map M-119, 1:200,000-scale.

largely the responsibility of J.G. Norwood and C. Whittlesey. The Treaty of 1854 ceded land in northeastern Minnesota from the Ojibwe and opened the area to mineral exploration. Although significant independent mineral prospecting ensued, particularly for copper and iron ore similar to that found in upper Michigan a decade earlier, few official reports surfaced in the two decades following the Owen survey. Most notable among these was a follow-up report on the Owen survey by Whittlesey (1866), in which he focused on the mineral potential in Minnesota and was the first to recognize the Lake Superior syncline from similar geology on the north and south shores. In that same year, H. Eames, the first State Geologist, published a report on the mineralized areas of northern Minnesota (Eames, 1866). In 1871, J.H. Kloos published an obscure article in German on his geologic investigations of Minnesota including a description of gabbroic and basaltic rocks around Duluth (later translated and republished by Winchell [1882]).

Although Minnesota achieved statehood in 1858, a comprehensive state geological survey was not commissioned until 1872, when the Geological and Natural History Survey of Minnesota was created and N.H. Winchell was appointed director and State Geologist. Over the next 28 years, Winchell and his staff conducted field studies in all areas of Minnesota. These studies were summarized in twenty-four annual reports until 1898, and were ultimately compiled into five volumes of final reports, the last published in 1900. Geologic investigations of northeastern Minnesota were mostly conducted by N.H. Winchell, U.S. Grant (1885-1898), H.V. Winchell (1881, 1885-1898), and A.H. Elftman (1893-1897), as summarized by Schwartz (1964).

Winchell also recruited other geologists to temporarily assist in the survey. Among the geologists in this group was M.E. Wadsworth, a petrographer hired by Winchell in 1886 to examine specimens from the Duluth Complex collected during the 1879, 1880, and 1881 field seasons. The results of this study, which emphasized the alteration of the rocks, were published in the second bulletin of the Geological and Natural History Survey of Minnesota (Wadsworth, 1887). W.S. Bayley was hired for the 1890 field season and published several reports on the petrography of north shore basic rocks and the geology of Pigeon Point (Bayley, 1893a, b, 1895). A.C. Lawson, an associate professor at the University of California, was hired during the summer of 1891 to study the "…date and stratigraphic relations of the gabbro invasion" (Winchell, 1893, p. iii). This work resulted in the publication of two papers, one on the anorthosite occurrences of the Beaver Bay Complex and the other on the intrusions of the boundary area, which Lawson termed the Logan sills (Lawson, 1893a, b). Although Winchell's ideas on the formation and age of the Duluth gabbro were often debatable, his survey ultimately established the extent of the "gabbro belt" as arcing from Duluth north to the Kawishiwi area and east to the Gunflint Lake area. The fourth volume of the final report (Winchell, 1899) included 12 plates of geologic maps compiled by Winchell and Grant (four regional county maps and eight ~1:100,000-scale maps of specific areas along the basal contact of the Duluth Complex).

Even though the documentation of geologic phenomena related to the Duluth Complex by the Winchell survey was noteworthy, this accomplishment was somewhat overshadowed by his many misinterpretations[1], some of which were pointed out by his contemporaries (for example Irving, 1883; Clements, 1903). Beginning in the sixth annual report (Winchell, 1878), Winchell consistently implied the Duluth gabbro was eruptive by describing it as "the great gabbro flood," "the crowning overflow," "the great gabbro outflow," "a basic eruptive," and "the gabbro eruption" (for example Winchell, 1893). In the final report (Winchell, 1900), Winchell conceded the gabbro is intrusive into Animikian rocks, but still suggested that "the great gabbro flood" had a subaerial top. He believed the Beaver Bay Complex was "...due to the first (and the greatest) flow-movement from the gabbro mass toward the Lake Superior basin." And that the lack of "...distinct superficial phenomena can be attributed to the denudation of its accessible upper portions, and the same probably applies to explain the present condition of the surface of the gabbro area itself." (Winchell, 1900, p. 64 and 65). Moreover, Winchell concluded that the gabbro had a origin that was caused by "…the metamorphism and complete refusion of the Archean greenstones and their attendants" (Winchell, 1900, p. 980). Most of Winchell's contemporaries did not subscribe to this view, including his co-author (and son-in-law) U.S. Grant, who believed the gabbro was the source of metamorphism of the footwall rocks (Grant, 1899).

Winchell's notion of an eruptive origin to the gabbro and related diabase sills (Logan intrusions) in the Animikie rocks of the international border area led to even further debate about the age of the gabbro. Although he initially considered the gabbro the basal unit of the Keweenawan (or Cupriferous) Series (Winchell, 1878), his observation of "eruptive" diabase and gabbro interbedded with Animikie strata (Winchell, 1887) convinced him that the gabbro was Animikian in age. In a preface to Minnesota Geological Survey Bulletin 8, wherein Lawson gave evidence for the intrusive origin of the Logan intrusions (Lawson, 1893b), Winchell argued that the "eruptive gabbro" must be equivalent in age or older than most of the Animikie and assigned the rocks to the Norian series (Winchell, 1893). The existence of red rock (granophyre) above gabbro in many areas fit well into Winchell's theory. He interpreted the granophyre to be metamorphosed Animikie sedimentary rock deposited above the gabbro whose "...typical characters were destroyed in this region by the frequent outbursts of igneous eruption..." (Winchell, 1893, p. xiv). As further evidence of a pre-Keweenawan age for the gabbro, Winchell (1893) cited Lawson's other paper in this same bulletin in which he concluded that the anorthositic rocks of the Beaver Bay Complex were the exhumed surface of an older igneous terrane that is equivalent to the main Duluth gabbro and upon which Keweenawan lavas were erupted.

After Winchell began to view the Logan sills as intrusive (Winchell, 1899, 1900), he moved the gabbro back into the Keweenawan system, but made an erroneous distinction between a lower Cabotian Series (Duluth and Beaver Bay gabbros, red rock, and various intervals of trap rock) and an upper Manitou Series (Puckwunge Sandstone and volcanic suites now recognized as the Grand Portage lavas and the Schroeder–Lutsen sequence). This made for an unusual stratigraphy. Many of Winchell's mistaken views of Proterozoic stratigraphy grew not only from misinterpreting igneous rocks, but also from believing that all non-fossiliferous, undeformed sandstones were correlative with the lower Cambrian Potsdam Sandstone of the eastern United States. Winchell's ideas about the geologic history of the Keweenawan rocks at the close of his 28-year-long career with the survey are summarized in volume 5 of the final report of the Geological and Natural History Survey of Minnesota (Winchell, 1900).

One of the most important studies conducted on Keweenawan rocks during the Winchell era was the U.S. Geological Survey memoir by Irving (1883) on the copper-bearing rocks of Lake Superior. This study attempted to tie the various studies of Keweenawan geology together and took issue with some of Winchell's ideas regarding north shore volcanic geology. Winchell rebutted many of Irving's criticisms (for example Winchell, 1893),

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[1] A thorough discussion of the various interpretations of the gabbro during the Minnesota survey is beyond the scope of this report. To learn more about Winchell's changing theories about the origin and stratigraphic position of the gabbro and related Keweenawan rocks, see the various annual reports and volumes 4 and 5 of the final reports of the Geological and Natural History Survey of Minnesota.

but ultimately, Irving's ideas were accepted. Building on his own work on the Keweenawan section in Wisconsin, Irving (1883) argued for the volcanic nature of not only the basic volcanic rocks of the north shore, but also of the felsic rocks, which Winchell, among others, believed to be metamorphosed sediments. Irving's report included geologic maps of the north shore wherein he subdivided the Keweenawan strata into six subgroups that arc across northeastern Minnesota. He estimated that the stratigraphic section of intrusive, volcanic, and sedimentary rocks exposed along the north shore totaled up to 24,000 feet (7.3 kilometers) in thickness, later proven to be a remarkably accurate estimate. Lawson (1893a) disputed Irving's estimate because it did not fit with his interpretation that the anorthosites of the Beaver Bay area represented an exhumed pre-Keweenawan surface on which the "Cupriferous" lavas were erupted. According to Lawson: "There is something sadly astray with these estimates, and with the stratigraphy upon which they are based" (Lawson, 1893a, p. 21). Lawson failed to recognize that the anorthosite bodies are entirely inclusions suspended in intrusive diabase.

After the publication of volume 5 of the final report of the Geological and Natural History Survey of Minnesota in 1900, official geological investigations by the Minnesota Geological and Natural History Survey were discontinued until 1911 (Schwartz, 1964). It was during this hiatus that the U.S. Geological Survey conducted its studies of the Vermilion range, the Mesabi range (Leith, 1903), and the seminal study on the geology of the Lake Superior region (Van Hise and Leith, 1911). The study on the Vermilion district (Clements, 1903) included lengthy descriptions of the Duluth gabbro and the Logan sills in which their intrusive and comagmatic nature and their thermal effects on older country rock were documented. Clements also recognized many basic features of the gabbro including layering, gradations between normal and anorthositic gabbro, and the presence of fine-grained (hornfels) inclusions. The end of this early stage of geologic mapping of the Duluth Complex is marked by the publication of the Van Hise and Leith (1911) monograph that summarized the geology of the Lake Superior region.

Mapping by Grout and Schwartz, 1911-1961

> "Many of the problems [of the origin of Duluth Complex rocks] have only been revealed and remain to be worked out in detail. The extensive maps compiled by Professor Grout will furnish a basis for future geological work."
>
> G.M. Schwartz, 1959, *The Geology of Cook County* by Grout, Sharp, and Schwartz, p. v

Coincident with the release of the Van Hise and Leith monograph, the year 1911 marked the re-establishment of the Minnesota Geological Survey as a permanent subsidiary of the Department of Geology at the University of Minnesota, and the appointment of William H. Emmons as both chairman of the department and director of the Minnesota Geological Survey. Emmons quickly tapped into the skills of F.F. Grout, an assistant professor in the University of Minnesota's Geology Department, to conduct various field mapping projects and to supervise other projects for the Minnesota Geological Survey. Grout started his career-long work on the Duluth Complex in 1914 in the Duluth area. While working simultaneously on a study of the eastern Mesabi range, Grout included his field studies of various areas of the Duluth Complex in his Ph.D. dissertation in 1917. The results of this research were published in a series of five papers in 1918 (Grout, 1918 a-e). In one of these, Grout portrayed the Duluth Complex as a type example of a lopolith extending beneath Lake Superior to the south shore (Grout, 1918b). This view of the Duluth Complex as a singular enormous intrusion (Fig. 2.1) persisted in the literature for the next 50 years.

The focus of these papers and many other journal publications by Grout in the ensuing 40 years (Table 2.1) was to address the physical and chemical processes attending the emplacement, differentiation, and solidification of intrusive igneous rocks exemplified by the Duluth Complex. Grout was a contemporary of the petrologists N.L. Bowen, A. Johannsen, A. Harker, and A. Holmes, and was a major contributor to the scientific discourse on igneous petrology in the early part of the twentieth century. One of Grout's more provocative ideas was that liquid immiscibility may be an important process in the formation of felsic magmas (Grout, 1918e). A notable later paper by Grout on the Duluth Complex was published

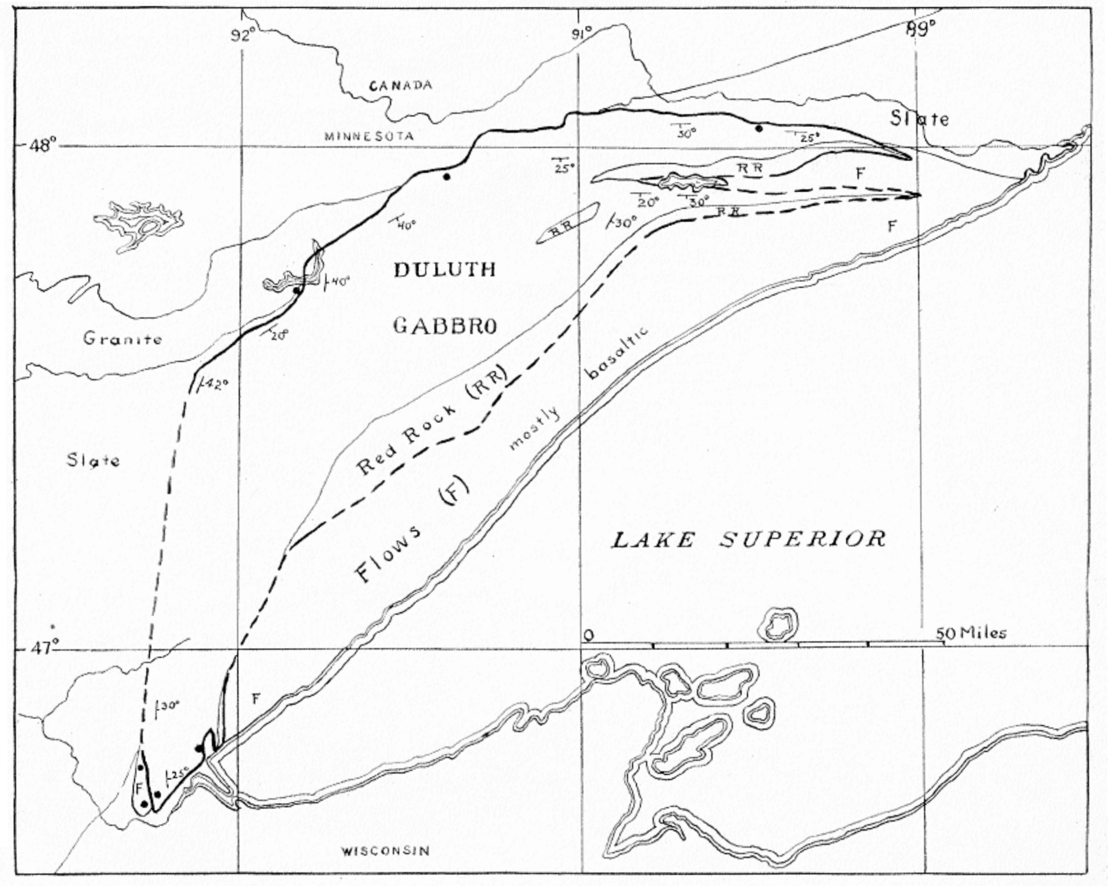

Figure 2.1. Generalized geologic map of the Duluth Complex (Grout, 1918a).

in the Geological Society of America Bulletin wherein he described the local abundance of mafic inclusions (mostly volcanic hornfels) and concluded that they caused only local contamination of the enclosing gabbro (Grout, 1930).

G.M. Schwartz joined the Geology Department of the University of Minnesota in 1919, and in 1922 he began his 37-year collaboration with Grout on mapping the Keweenawan geology of northeastern Minnesota. In 1932, Grout and Schwartz's work on the Keweenawan was incorporated into a 1:500,000-scale geologic map of Minnesota that portrayed the geology of the Duluth Complex as Grout mapped it in 1918 (Fig. 2.1), simply as gabbro and red rock. Although their field notebooks of investigations in various areas of northeastern Minnesota are filled with detailed mapping at a scale of 1:10,000 or larger, and although detailed outcrop descriptions can be found in their reports, Grout and Schwartz distinguished only a handful of general rock types and rarely drew geologic contacts on their published maps.

The first detailed mapping study of Keweenawan rocks by Grout and Schwartz was their report on the anorthosite occurrences along the north shore of Lake Superior (Grout and Schwartz, 1939). The five 1:31,500-scale (2 inches = 1 mile) township maps accompanying this report were the first of the generalized outcrop maps that became the standard form of geologic maps produced by Grout and Schwartz. Topographic base maps were not available at this time, and field work was done mostly along section lines. The geologic maps contained in the anorthosite report show generalized outcrop locations of six basic rock types (diabase, red rock, anorthosite, basalt, felsite, and conglomerate/sandstone) and show the attitudes of structural features. More detailed mapping of the anorthosite-bearing diabase and ferrogabbroic rocks of the Beaver Bay area was conducted later by Gehman (1957) as part of his doctoral dissertation. Other noteworthy dissertation-related mapping during the Grout and Schwartz era was that of Sandberg (1938) and Grogan (1940), who mapped different sections of the north shore northeast of Duluth.

During the 1940s, as Grout continued field studies in Cook County and assisted Emmons in compiling a summary of commercial mineral resources in Minnesota (Emmons and Grout, 1943), Schwartz embarked on several geophysical studies of the complex. In 1944, he conducted a ground magnetic survey to define the basal contact of the Duluth Complex north from Duluth (Schwartz, 1944). After becoming director of the Minnesota Geological Survey in 1946, he obtained funding from the U.S. Geological Survey to conduct aeromagnetic surveys of northern Minnesota beginning in 1947. These data, published in the form of 1:62,500-scale aeromagnetic maps, provided the first insights into the geology and sulfide and oxide mineralization of the poorly exposed southern and central Duluth Complex.

Schwartz began a study of the geology of the Duluth metropolitan area in 1937, but it was not published until 1949 (Schwartz, 1949). This report incorporated earlier mapping by Grout and recent mapping by Schwartz into fifteen generalized outcrop maps of townships wherein only outcrops of gabbro, red rock, basalt, and felsite were distinguished.

A year after Grout's retirement in 1948, a summary of his years of work on titaniferous magnetite occurrences in the Duluth Complex was published by the Iron Range Resources and Rehabilitation Commission (Grout, 1949-1950). In 1951, Grout, along with the major Precambrian geologists of Minnesota (J.W. Gruner, Schwartz, and G.A. Thiel), published a summary of the Precambrian stratigraphy of Minnesota that defined the stratigraphic nomenclature for the Keweenawan and other Precambrian rocks (Grout and others, 1951). A year after his death in 1958, Grout's geologic mapping in Cook County, which started in 1913, was summarized and published (Grout and others, 1959). A total of 29 generalized outcrop maps covering all Cook County townships were included in the report with the same rock type generalizations as portrayed in the Duluth area maps. For many areas in Cook County, these maps are the most recent geologic information available.

The Grout and Schwartz era of geologic mapping in the Duluth Complex ended with Schwartz's retirement as Minnesota Geological Survey director in 1961 and his replacement by P.K. Sims, a former geologist with the U.S. Geological Survey. The end of this period was marked by the publication of the summary of the Precambrian geology and geochronology of Minnesota by S.S. Goldich and others (1961).

Quadrangle-scale mapping, 1961-1982

> "Geologic mapping has lagged in Minnesota...The goal is to complete, in 10 years, geologic map atlases of the bedrock and surficial materials in the State at a scale of 4 miles to the inch (1:250,000); and to begin detailed mapping of specific areas that are critical to evaluation of resource potential and to urban development, using the standard 7 1/2- or 15-minute quadrangle topographic maps as bases."
>
> P.K. Sims, 1965, *Our Land and Mineral Resources, a Long-Range Plan for Geologic Research in Minnesota*, p. iii

The installment of P.K. Sims as Minnesota Geological Survey director in 1961 coincided with the tripling of the survey's budget, an expansion of its activities, and the ability to hire permanent staff (Schwartz, 1964). Sims laid out a long-range plan for the survey that first and foremost was to appraise the mineral resources of the state and "…to encourage development of new or potential resources by new industry" (Sims, 1965, p. iii). To accomplish this goal, Sims set out an ambitious plan of regional (1:250,000-scale) and detailed (1:63,500- or 1:24,000-scale) mapping in northern and northeastern Minnesota. For this work, he recruited faculty and graduate students mainly from the departments of geology at the Twin Cities and Duluth campuses of the University of Minnesota.

The first quadrangle-scale bedrock geologic map published by the Minnesota Geological Survey under Sims' direction was of the geology of the Duluth area by R. Taylor in 1964. Taylor conducted the mapping and petrologic study for his Ph.D. dissertation at the University of Minnesota, which he completed in 1955. Although guided in his work by Schwartz and Goldich, his advisor at the University of Minnesota, the 1:24,000-scale, full-color map reflected the U.S. Geological Survey influence Sims brought to the Minnesota Geological Survey. This map was the first to distinguish what were long recognized as the two main gabbro types comprising the Duluth Complex (Kloos, 1871). Taylor referred to them as the anorthositic gabbro (subsequently known as the anorthositic series) and the layered series.

Although he did not subdivide the layered series, Taylor (1964) recognized that its differentiated character was akin to the Skaergaard intrusion (Wager and Deer, 1939)—the standard against which all mafic layered intrusions are compared. Another noteworthy thesis-related mapping study conducted in the early 1960s was of the mafic and intermediate intrusive rocks around the Hovland area by N.W. Jones (1963).

The first geologic mapping program organized entirely under Sims was focused on the Gabbro Lake 15-minute quadrangle. This quadrangle straddles the base of the Duluth Complex where the initial copper-nickel discovery was made in 1948, and where exploration activities had peaked in the late 1950s, but were waning in the early 1960s (Watowich and others, 1981). Sims recruited W.C. Phinney of the University of Minnesota Twin Cities to map the gabbro part of the quadrangle, and J.C. Green of the University of Minnesota Duluth to map the Archean footwall rocks. Phinney in turn recruited P.W. Weiblen to map well foliated troctolites and gabbros around Bald Eagle Lake for his Ph.D. dissertation. The ensuing 1:31,680-scale map (Green and others, 1966) distinguished rocks belonging to the South Kawishiwi and Bald Eagle intrusions, and thereby demonstrated that the Duluth Complex consists of multiple intrusions, not the single lopolith portrayed by Grout.

Sims obtained increases in state and federal funding in order to accelerate geologic mapping. Between 1965 and 1971, Minnesota Geological Survey-supported geologists produced an array of reconnaissance and detailed maps of northeastern Minnesota. Phinney mapped the Forest Center 15-minute quadrangle and adjacent areas in the northwestern part of the Duluth Complex. D.M. Davidson (University of Minnesota Duluth) conducted semi-detailed reconnaissance mapping across a large area of the eastern Duluth Complex. B. Bonnichsen, who had completed his Ph.D. dissertation on the metamorphism of the Biwabik Iron Formation in 1968, undertook semi-detailed reconnaissance mapping in the Babbitt 15-minute quadrangle and in poorly exposed areas of the southern Duluth Complex. Weiblen mapped the Duluth Complex in the Long Island Lake and Gillis Lake quadrangles along the northern contact of the complex. Green began to work reconnaissance mapping of the volcanic and hypabyssal rocks along the north shore of Lake Superior. He was also given the task of compiling these and previous studies (mostly Grout and Schwartz's work) into a regional (1:250,000-scale) map of the Two Harbors sheet (Green, 1982a).

In addition to this work by Minnesota Geological Survey staff and University of Minnesota faculty, the Minnesota Geological Survey supported several masters theses and doctoral dissertations devoted to mapping in the Duluth Complex during the last half of the 1960s. Most notable among these was the detailed mapping and petrographic study by H.D. Nathan (1969) of early gabbroic series rocks in the Gunflint Lake, South Lake, and Hungry Jack Lake quadrangles along the northern contact of the Duluth Complex. E.A. Mathez (1971) mapped and studied the petrology of the Logan intrusions in the Hungry Jack Lake quadrangle. M.G. Mudrey (1973) mapped the Pigeon Point quadrangle at the very northeast corner of Minnesota and studied the petrology of the Pigeon Point sill. J.L. Renner (1969) studied the petrology of hornfels inclusions along the mineralized basal contact in the Dunka River area and showed their potential for sulfide and volatile contamination of the gabbro. J.A. Kilburg (1972) mapped and characterized the petrology of the volcanic rocks and diabase dikes of the Ely's Peak area, southwest of Duluth.

As shown in Table 2.1, only a few maps were actually published during this intense period of mapping (Davidson, 1969a, b; Bonnichsen, 1971). Some were released promptly as open-file maps (Phinney, 1967; Bonnichsen, 1970a-e), but many were not published until 1977 or later. Bonnichsen's open-file maps of the Babbitt, Babbitt NE, Babbitt SE, Babbitt SW, and Allen quadrangles were integrated into his regional (1:125,000) outcrop map of the southern Duluth Complex (Bonnichsen, 1971). With the exception of a partial open-file map of the Kangas Bay quadrangle (Phinney, 1967), Phinney's mapping of the northwestern part of the complex was never compiled or published. Nine reconnaissance geologic maps by Davidson (1977a-h) and Davidson and Burnell (1977) were published in black-and-white. Most of Green's mapping along the north shore was summarized in a report on the environmental geology of the north shore (Green and others, 1977) and the Two Harbors sheet (Green, 1982a). Some of Green's mapping was later published in a 1:24,000-scale strip map of the shoreline from Little Marais to Tofte (Green, 1992), and his mapping in the vicinity of the Beaver Bay Complex (for example Green, 1982b) was incorporated into more recent quadrangle maps (Miller, 1988; Miller and others, 1989, 1993a, 1994;

Boerboom and Miller, 1994). Most of Green's detailed outcrop mapping along the northeastern third of the shoreline has been digitally compiled in the CD accompanying this report and was the basis for the geologic interpretation of that part of shoreline portrayed on map M-119.

The delay in the production of geologic maps of areas studied in the late 1960s was due in part to combining Minnesota Geological Survey staff efforts and resources on the production of the treatise on Minnesota geology commemorating the centennial of the Minnesota Geological Survey (Sims and Morey, 1972). In this volume, Bonnichsen, Davidson, Green, Mathez, Morey, Mudrey, Phinney, and Weiblen contributed papers summarizing their recent mapping activities. These articles established, for the first time and in one place, the basic geologic framework of the North Shore Volcanic Group and related hypabyssal intrusions (Green, 1972), the southern Duluth Complex (Bonnichsen, 1972), the northwestern Duluth Complex (Phinney, 1972c), the northern extension of the Duluth Complex (Phinney, 1972b), the eastern Duluth Complex and Brule Lake gabbro (Davidson, 1972), and the Logan sills (Weiblen and others, 1972). The notion of the Duluth Complex as a singular intrusion was officially put to rest and its complex intrusive stratigraphy began to be deciphered. The main lithostratigraphic series (anorthositic, troctolitic [later, the layered series], felsic, and the layered series of Nathan [later the early gabbro series]) were established and other discrete intrusions were defined (the Partridge River, South Kawishiwi, Bald Eagle, and Tuscarora intrusions).

Budget cuts were another reason for the delay in the production of geologic maps. This ultimately prompted the departure of P.K. Sims as Minnesota Geological Survey director in 1973; Matt Walton replaced him. Walton, with a background in geological engineering, redirected the focus of the Minnesota Geological Survey toward environmental and land-use projects with an emphasis on applied research. By focusing on well-funded projects, Walton reestablished the financial health of the Minnesota Geological Survey, which would pay dividends in the next decade and beyond.

With interest in copper-nickel increasing again in the late 1960s through the 1970s, most of the research conducted on the Duluth Complex during the 1970s focused on mineral deposits. Between 1968 and 1981, at least nine graduate theses were devoted to evaluating the copper-nickel mineralization in exploration drill core that was either turned over to the state or provided directly by exploration companies. These included six M.S. theses (Johnson, 1968; Hardyman, 1969; Renner, 1969; Mogessie, 1976; Churchill, 1978; Molling, 1979) and three Ph.D. dissertations (Johnson, 1970; Mainwaring, 1975; Tyson, 1979). One of the major projects that focused on copper-nickel mineralization during the 1970s was the Regional Copper-Nickel Study commissioned by the state to evaluate the feasibility and environmental impacts of mining copper-nickel sulfide deposits. This study ran from 1974 to 1978.

Although many geologic maps within the Duluth Complex were published in 1977, little new mapping was done in the 1970s. A minor amount was conducted in 1974 and 1975 by R.J. Beltrame and R.W. Cooper in support of the Regional Copper-Nickel Study. Beltrame and Cooper's mapping was integrated with earlier mapping into a 1:48,000-scale open-file geologic map of the Hoyt Lakes–Kawishiwi area (Morey and Cooper, 1977). Other mapping projects in the 1970s included a detailed (1:12,000-scale) mapping study of the Harris Lake area in the South Kawishiwi intrusion by M.P. Foose and Cooper (1978). Also noteworthy was the detailed mapping and petrologic study of the Sonju Lake intrusion near Finland by R.J. Stevenson for his M.S. thesis (Stevenson, 1974), and a similar study of the Silver Cliff and Lafayette Bluff diabase intrusions north of Two Harbors by N.M. Pope (1976).

The end of the period of quadrangle-scale mapping is set at 1982 because this was when Green's 1:250,000-scale map of the Two Harbors $1^{\circ} \times 2^{\circ}$ sheet was published (Green, 1982a). This map, combined with the similarly scaled maps of the Hibbing sheet (Sims and others, 1970) and of east-central Minnesota (Morey and others, 1981a), regionally summarized all the detailed mapping of Keweenawan rocks during this period and were welcome improvements over the 1932 geologic map of Minnesota, which they replaced. Two of the largest units shown on the Two Harbors sheet are undivided Keweenawan rocks and undivided intrusive rocks of the Duluth Complex. The predominance of these map units reflects the lack of bedrock exposure within much of the Keweenawan terrane of northeastern Minnesota. At the same time that the Two Harbors map was being published, this problem of poor exposure was being addressed with the acquisition of high-resolution aeromagnetic data over northeastern Minnesota.

Aeromagnetic survey and recent mapping, 1982-present

> "Although the geophysical database is only a few years old, geologists using and thinking about the data already have come up with many new ideas and interpretations..."
>
> G.B. Morey, 1993, *A History of Geologic Mapping in Minnesota*, p. 25

The aeromagnetic surveys that began in 1947 and continued into the late 1960s were a critical aid in delineating the gross geologic features of buried bedrock in Minnesota (Sims, 1970). However, the one-mile flight line spacing was not sufficient to delineate features on the scale that would be helpful for mineral exploration or the interpretation of subtle geologic structures. In the late 1970s, Minnesota Geological Survey director Matt Walton convinced the State of Minnesota to support a high-resolution aeromagnetic survey of the entire state at a 0.25-mile flight line spacing and a mean ground clearance of 500 feet (152 meters). The first area surveyed was northeastern Minnesota (Chandler, 1983a, b).

The ability of the aeromagnetic data to reveal details about the covered portions of the Duluth Complex was evident immediately. Chandler (1990) integrated sparse outcrop and drill hole data with the new aeromagnetic data and a regional gravity survey, and developed a new geologic interpretation of the central Duluth Complex (Fig. 2.2). This interpretation laid the groundwork for a shallow drilling project in the central complex from 1989 to 1991, which in turn led to a revised geologic interpretation (Meints and others, 1993). A third iteration of geologic interpretation of the geophysical data was summarized in a 1:100,000-scale map of the central Duluth Complex (Miller and Chandler, 1999; Chandler, 2001a). This was the first Duluth Complex map to be produced digitally and, with minor modifications, formed the nucleus of map M-119.

With the exception of a few thesis-related mapping projects (Stevenson, 1974; Pope, 1976; Lehman, 1980; Motamedi, 1984; Ross, 1985; Miller, 1986; Jerde, 1991; Nelson, 1991; Patelke, 1996) and Foose and Cooper's (1978) mapping in the Harris Lake area, quadrangle-scale mapping had been largely dormant in the Duluth Complex since the time of Sims' departure from the Minnesota Geological Survey in 1973. This changed, however, in the mid-1980s with the initiation of the Cooperative Geologic Mapping Program (COGEOMAP) of the U.S. Geological Survey. Under this collaborative program, the Minnesota Geological Survey received annual funding between 1985 and 1992 to conduct quadrangle-scale mapping in the Beaver Bay Complex. The main purpose of the project was to delineate the various intrusive components of the Beaver Bay Complex, which had not been mapped since Grout and Schwartz's 1939 study and thesis work by Gehman (1957) and Stevenson (1974). Another objective was to determine the nature of the contact between the Beaver Bay and Duluth Complexes. The project resulted in the publication of five 1:24,000-scale geologic maps covering ten 7.5-minute quadrangles (Miller, 1988; Miller and others, 1989, 1993a, 1994; Boerboom and Miller, 1994) and a summary paper, which discussed the geology, petrology, and tectonic significance of the Beaver Bay Complex (Miller and Chandler, 1997).

Two other changes occurred at the state level in the 1980s that accelerated geologic research on the Duluth Complex. The first was the establishment of the Natural Resources Research Institute (NRRI) at the University of Minnesota Duluth in 1983. The NRRI was created to conduct research that would sustain and generate new industries based on natural resources in northern Minnesota. The main task of the minerals research group of the NRRI has been to reassess the geology, igneous stratigraphy, and copper-nickel-platinum group element mineralization along the heavily explored basal contact zone of the northwestern Duluth Complex (Fig. 2.3). The group has relogged over 950,000 feet (290 kilometers) of drill core, examined numerous thin and polished sections, and analyzed and assayed over 500 core samples. These studies have been released mainly as NRRI technical reports (for example Morton and Hauck, 1987; Severson and Hauck, 1990; Geerts, 1991; Severson, 1991, 1994, 1995; Severson and others, 1994; Hauck and others, 1997a), although a summary of much of this work was published in a Geological Society of America Special Paper (Hauck and others, 1997b).

The second positive change was the creation of the Minnesota Minerals Coordinating Committee in 1987. This committee allocates state funds through the Minnesota Department of Natural Resources for projects that promote mineral exploration and development. Its creation represented a reversal in the attitude of state government from one adversarial toward the mining industry in the mid-1970s, to the present approach of seeking to sustain and diversify the

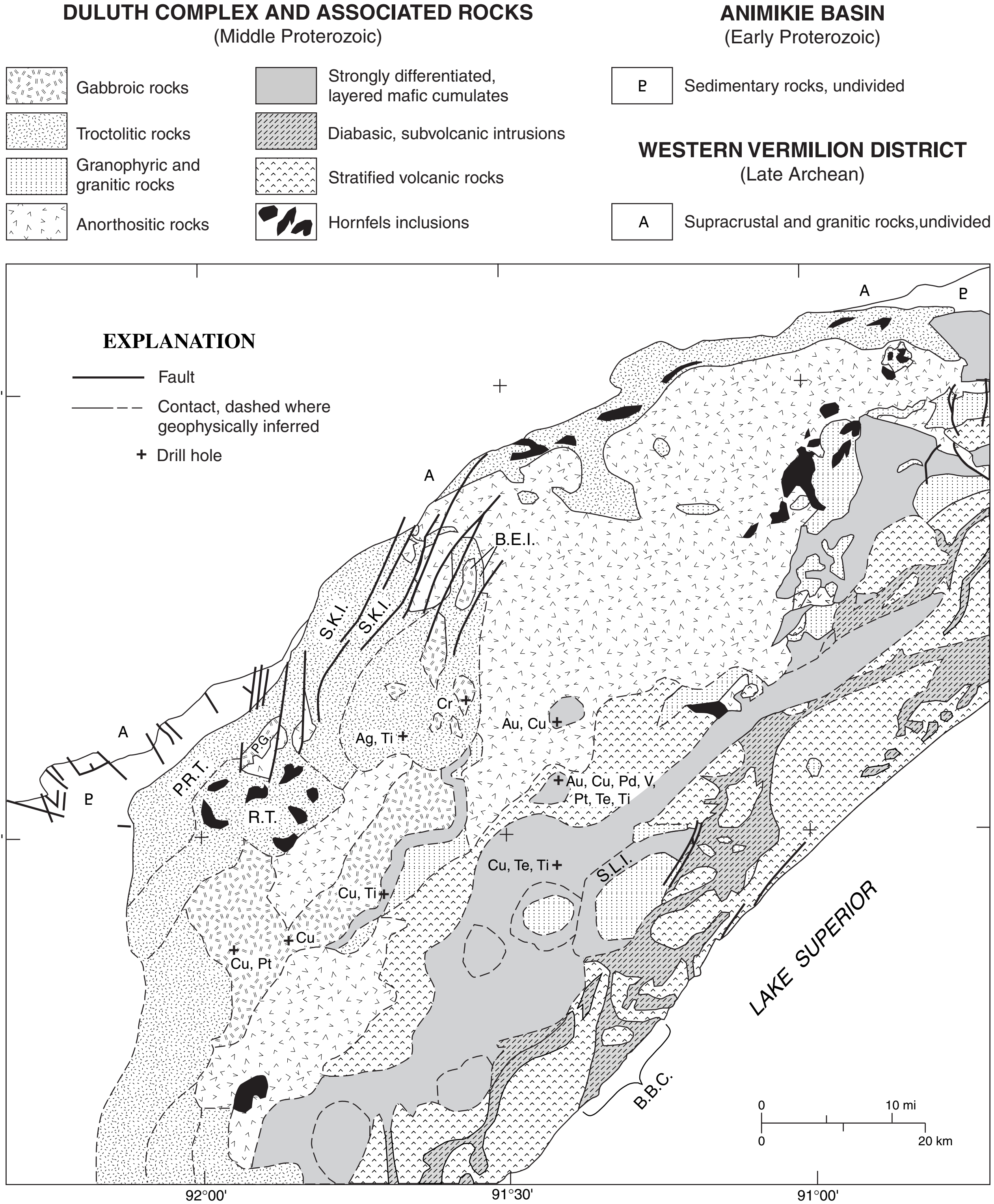

Figure 2.2. V.W. Chandler's geologic interpretation of the central Duluth Complex based on high-resolution aeromagnetic data integrated with gravity, outcrop, and drill core data (Chandler, 1990).

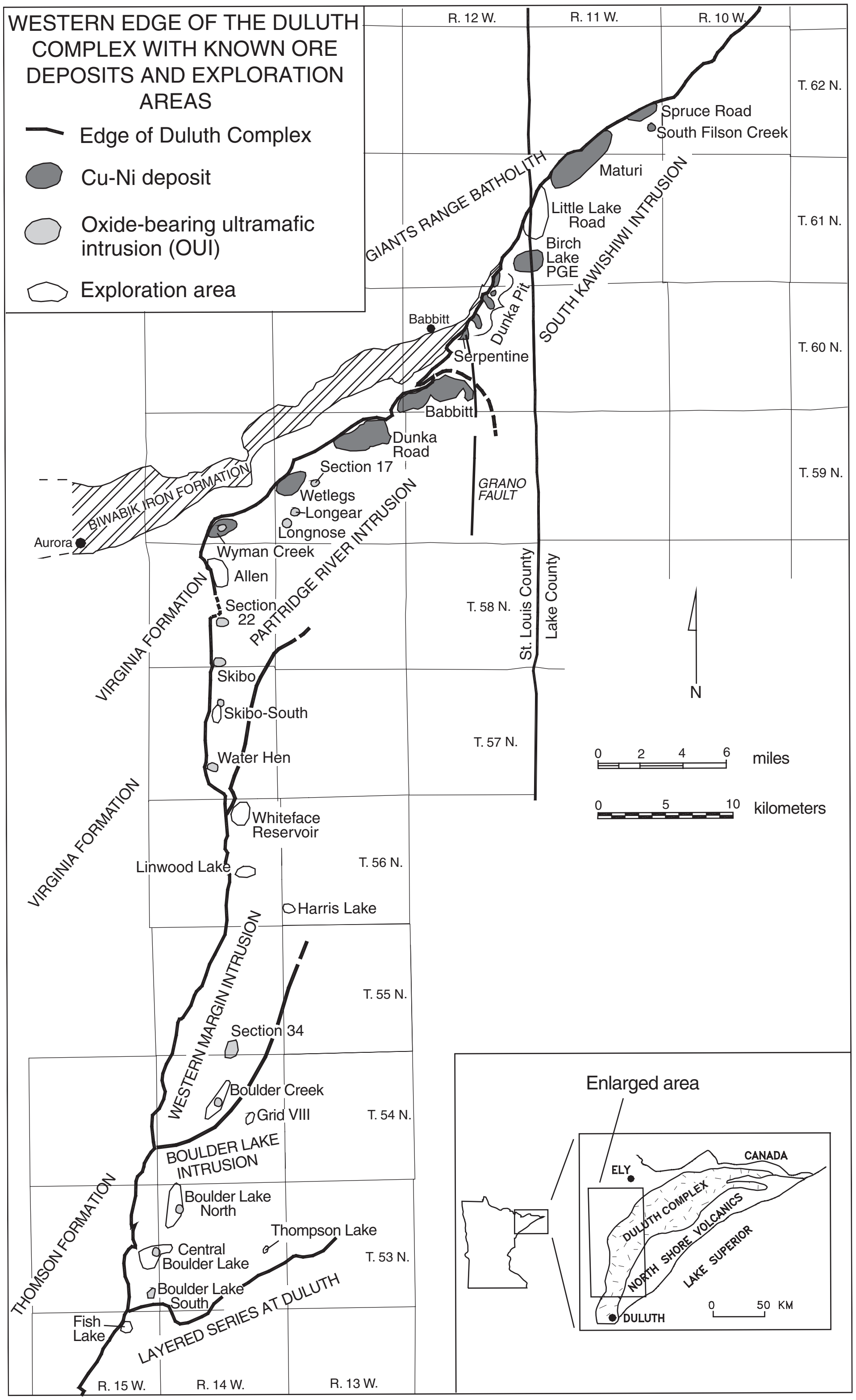

Figure 2.3. Location of copper-nickel sulfide deposits, Fe-Ti ± V deposits, and other exploration areas along the western base of the Duluth Complex (modified from Severson, in press).

minerals industry. The Minnesota Minerals Coordinating Committee has provided funding for the major projects conducted on the Duluth Complex for the past 14 years. In addition to supporting the shallow drilling and mapping project of the central Duluth Complex and most of the NRRI projects along the base of the Duluth Complex previously mentioned, Minerals Coordinating Committee funds also supported remapping of the Duluth Complex at Duluth (Miller and others, 1993b). This remapping of the type locality of the Duluth Complex studied earlier by Grout (1918a), Schwartz (1949), and Taylor (1964) is incorporated into map M-119. The Minerals Coordinating Committee also funded mapping in the Allen quadrangle in the northwestern part of the complex (Severson and Miller, 1999), which was the northwestern anchor of outcrop control for the central Duluth Complex map (Miller and Chandler, 1999). The Minerals Coordinating Committee recently supported studies on the potential for platinum group element reefs in the Duluth Complex and related intrusions (Miller, 1998, 1999). Finally, the Minerals Coordinating Committee funded the creation of this report and map M-119.

MINERAL EXPLORATION IN THE DULUTH COMPLEX

Exploration for copper-nickel sulfide deposits along the base of the Duluth Complex began in 1948 and has continued intermittently. During this period, over 1,700 holes totaling over 1.4 million feet (427 kilometers) of core have been drilled in the basal zone of the complex. At least ten copper-nickel deposits, portrayed on Figure 2.3, were defined by the drilling during that period. The term "deposit" is used loosely in this report to define areas where extensive exploratory drilling has intersected some copper-nickel mineralization; to date, these deposits are subeconomic. Known calculated resources for some of the deposits are shown in Table 2.2. Also shown in Figure 2.3 are the locations of exploration areas, defined as areas with minor drilling that intersected scattered zones of weak copper-nickel mineralization, and oxide-bearing ultramafic intrusions (OUIs) that are late intrusive, pod-like bodies that have Fe-Ti ± vanadium ± copper ± nickel potential.

At least 22 exploration companies have been involved in the drilling of 28 areas along the basal contact of the Duluth Complex (Fig. 2.3). Drilling activities between 1951 and 2000 by the various exploration companies at several different localities along the basal contact are summarized in Figure 2.4. Figures 2.5. 2.6, and 2.7 show the total amount of drilling by year, deposit, and company, respectively, that took place after the initial copper-nickel mineralization discovery in 1948. As can be seen in these figures, the vast majority of drilling was done at the Babbitt deposit; lesser but still substantial amounts of drilling were done at the Dunka Road, Spruce Road, and Maturi deposits (the total for the Dunka Pit area is inflated because about half of the drilling in the complex was conducted by the Erie Mining Company during drilling of the underlying iron-formation). The first phase of drilling occurred from 1954 to 1960 when the International Nickel Company (INCO) and Bear Creek Mining (a subsidiary of Kennecott Mining Company) conducted reconnaissance exploration and drilling at the Spruce Road, Maturi, and Babbitt deposits. The second phase of drilling took place from 1966 to 1981 after the leasing of state lands. Considerable footage was drilled by seven companies between 1967 and 1971 (Fig. 2.4) and the Babbitt deposit was extensively drilled by AMAX from 1974 to 1978.

Copper-nickel exploration activity

Outcrops that contain disseminated sulfide minerals were first noted at the base of the Duluth Complex by Grant (1899) and later by Nebel (1919); however, these occurrences were too sporadic and weakly mineralized to spark any exploration interest. More strongly mineralized rocks with copper stains were discovered in 1948 by local prospector F.S. Childers of Ely, Minnesota in an excavation into weathered gabbro rubble to obtain road aggregate (Watowich and others, 1981; Sims, 1991). The excavation was located along the basal contact in the vicinity of what is now referred to as the Spruce Road deposit (Fig. 2.3). Childers and partner R.V. Whiteside of Duluth concentrated their efforts along the basal contact of the complex in the vicinity of the Kawishiwi River and eventually drilled a 188-foot (57-meter) exploration hole in 1951. The hole, situated within what is now referred to as the Maturi deposit, intersected disseminated sulfides in gabbroic rock that averaged 0.36 percent copper and 0.13 percent nickel (Watowich and others, 1981).

In 1952, INCO and Bear Creek Mining began exploration programs that consisted of reconnaissance mapping, sampling, and geophysical surveys along the basal contact in an area that roughly extends from the Water Hen

Table 2.2. Calculated copper-nickel resources for various deposits along the western margin of the Duluth Complex. Compiled from Listerud and Meineke (1977); Kulas (1979); Watowich and others (1981); Anonymous (1994); Zanko and others, (1994); Peterson (1997); Clifford (1999); and Minnesota Department of Natural Resources open files.

(-) not available

Deposit (company)	Resources (in Mt)	Average Cu%	Average Ni%	Cu% cutoff	Cu/Ni ratio (x/1)
South Filson Creek (Hanna)	-	-	-	-	3.00
Spruce Road (INCO)	248	0.46	0.17	-	2.63
Maturi (INCO)	247 underground	0.50	0.19	-	2.40
Maturi Deep (Duval)	411	0.74	0.22	-	-
Dunka Pit (many)	272	0.25	-	-	-
Serpentine (Bear Cr., AMAX)	7	0.88	0.30	0.60	2.85
Babbitt/Minnamax (Bear Cr., AMAX)	364	0.84	0.19	0.60	4.11
Babbitt/Mesaba (Arimetco)	3300	0.46	0.12	0.38	-
Dunka Road (USS)	100 underground	0.77	0.24	-	3.43
Dunka Rd/NorthMet (PolyMet)	808	0.43	0.11	-	-
Wetlegs (Bear Creek, Exxon)	38	0.29	0.10	0.15	-
Wyman Creek (USS)	-	-	-	-	-
All deposits (Listerud and Meineke, 1977)	4400	0.66	0.20	0.50	3.30

deposit northeastward to the Spruce Road deposit (Fig. 2.3), and along the Gunflint Trail near the international border. During this same period, the Minnesota Geological Survey, in cooperation with the U.S. Bureau of Mines, began an examination of the Maturi–Spruce Road area that culminated in the drilling of three core holes in 1953. These holes were drilled to the immediate southwest of the Spruce Road deposit and provided low- to marginal-grade material for metallurgical tests (Grosh and others, 1955). Meanwhile, INCO acquired the Childers–Whiteside property and obtained prospecting permits for adjacent federal lands within the Superior National Forest. They began drilling operations during 1954 and 1955 at the Spruce Road and Maturi deposits; 40 holes were cored during this period. A potentially large tonnage of low-grade copper-nickel ore was indicated by this work. During 1956 and 1957, on the basis of geophysical surveys, INCO drilled 27 reconnaissance holes into other areas that included the Skibo, Wetlegs, and Dunka Pit deposits, in present-day terminology, and the Little Lake Road area (Fig. 2.3). Results from most of these areas were disappointing as the geophysical conductors were related to footwall sources (graphite ± pyrrhotite) or oxide-rich ultramafic intrusions rather than sulfide-rich zones in the Duluth Complex.

Drilling activities by Bear Creek Mining began three years after INCO started drilling (Fig. 2.4). In 1957, Bear Creek conducted a small drilling campaign to the immediate southwest of the Spruce Road deposit with marginal success.

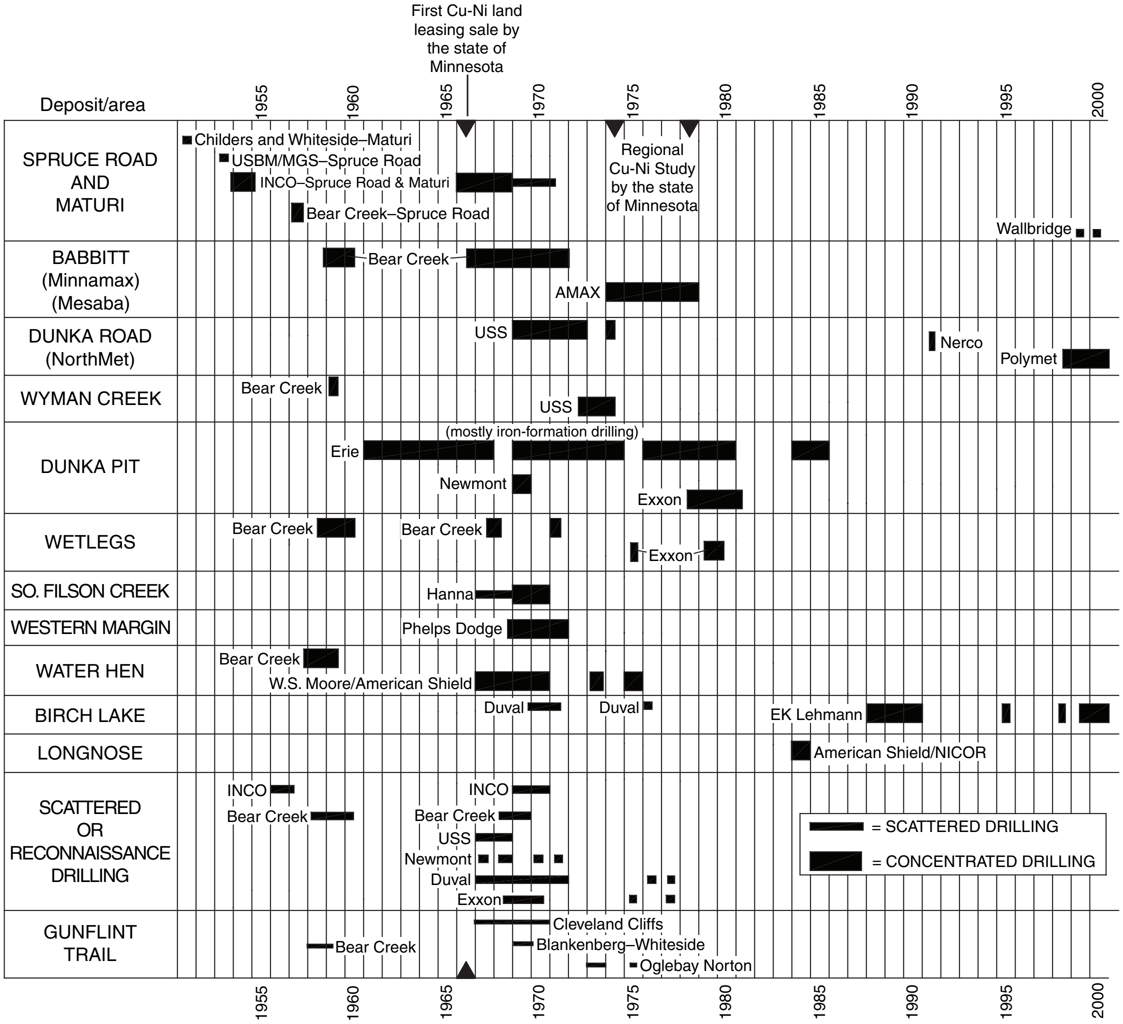

Figure 2.4. Chronology of drilling activities between 1950 and 2000 along the basal contact of the Duluth Complex.

Between 1957 and 1960, Bear Creek conducted an extensive drilling program that targeted scattered geophysical anomalies along the basal contact (Water Hen, Section 22, Allen, Wyman Creek, Longnose, Wetlegs, Babbitt, Dunka Pit, and Little Lake Road deposits [Fig. 2.3] and along the Gunflint Trail). Again, many of the geophysical anomalies were found to be related to either footwall or oxide ultramafic intrusion sources. The most interesting holes with regard to copper-nickel mineralization were located at the Babbitt deposit (referred to as the Babbitt #1 Grid), and in late 1958, Bear Creek began to concentrate most of their drilling effort on privately owned lands in this area. After 1960, all drilling activities by both Bear Creek and INCO were suspended for six years due to the low-grade nature of the ore, coupled with low metal prices, and the unavailability of state-owned mineral lands (Watowich and others, 1981).

Bear Creek Mining's drilling at the Dunka Pit area in 1959 and 1960 showed that the Biwabik Iron Formation extended for a considerable distance downdip beneath the Duluth Complex (Bonnichsen, 1968). Subsequently, Erie Mining Company acquired the property, conducted a drilling campaign, and defined a large tonnage of metamorphosed magnetic taconite that could be mined by open-pit methods. Drilling commenced in 1961 and continued until 1985 (Fig. 2.4); many of their holes were collared in the complex and intersected taconite ore at depth. Overburden stripping started in 1963, and the first taconite ore was shipped in 1965 (Bonnichsen, 1968). Weakly mineralized copper-nickel gabbroic material was stripped in portions of the pit and stockpiled. Over

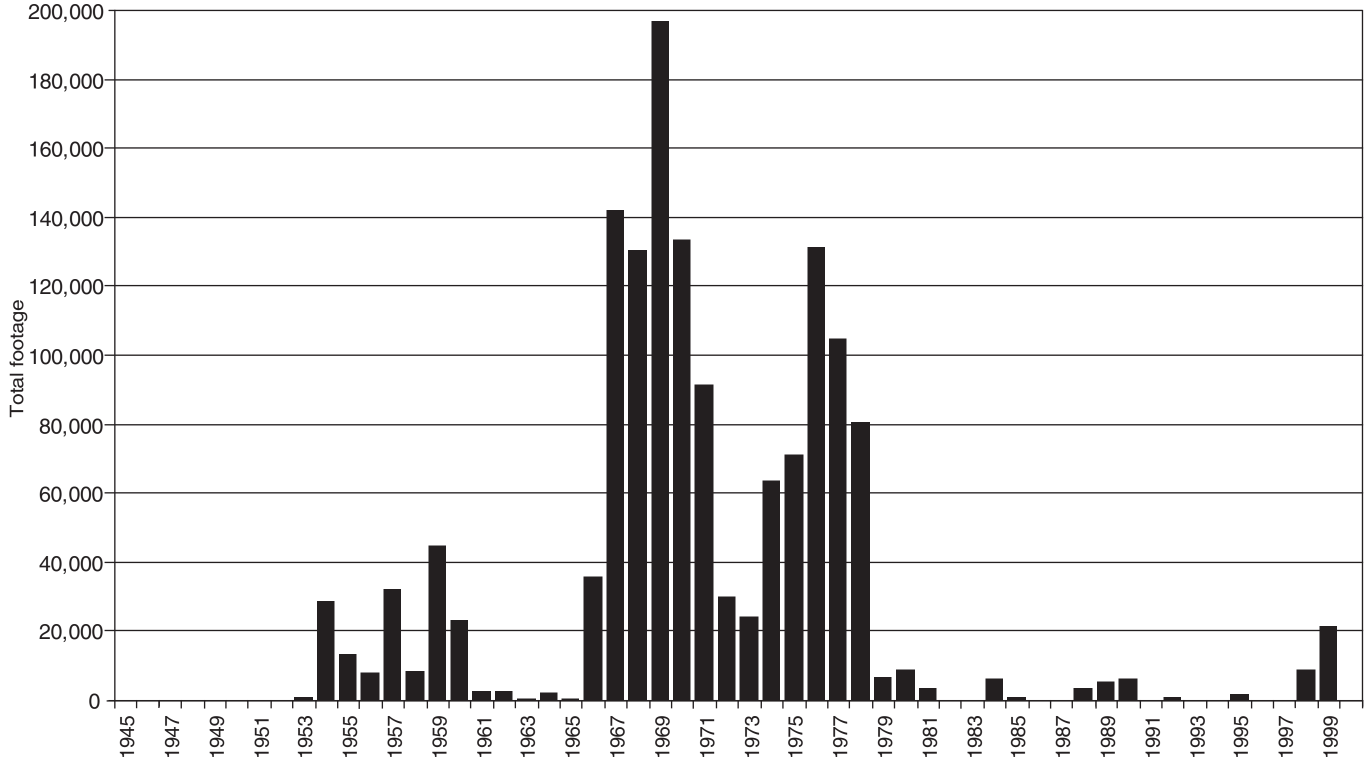

Figure 2.5. Histogram of annual exploration drilling footage from all companies along the basal contact of the Duluth Complex between 1948 and 2000.

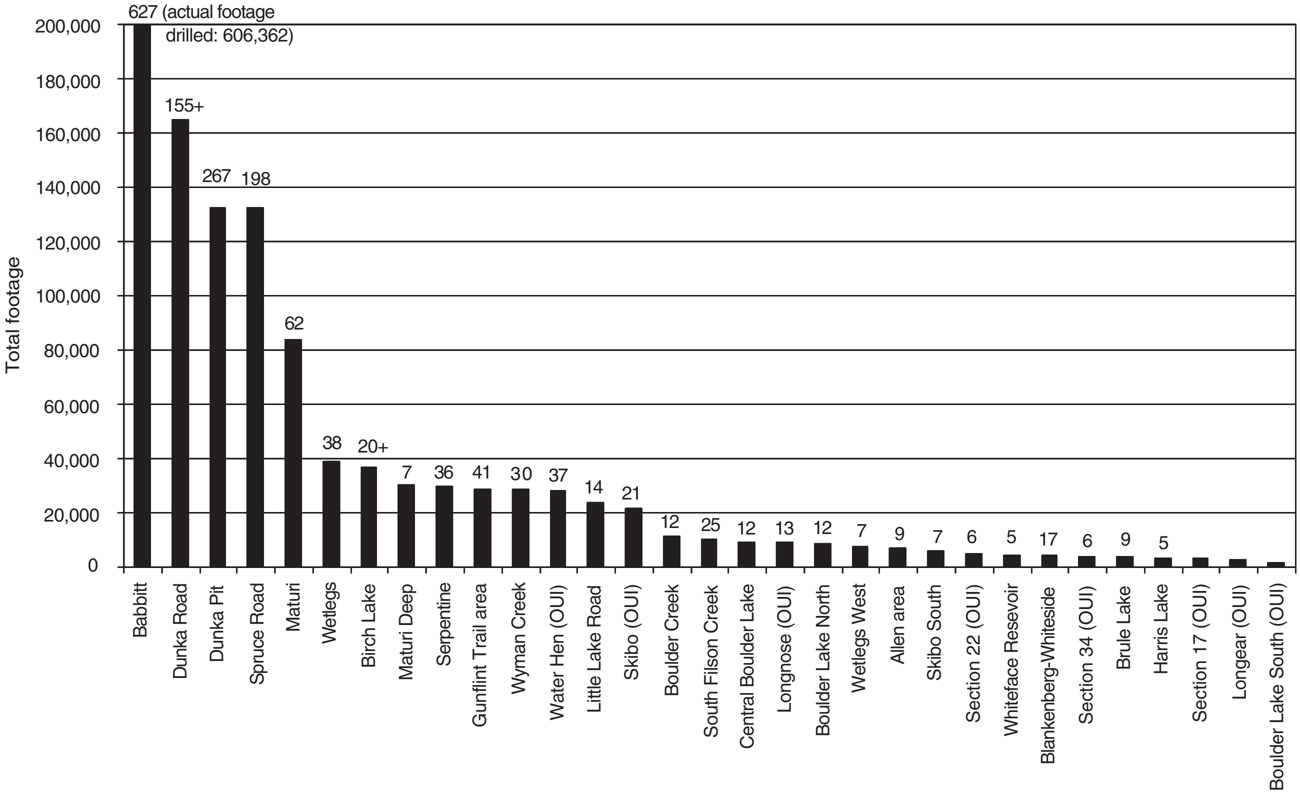

Figure 2.6. Histogram of total drilling footage collected from deposit/exploration areas along the basal contact of the Duluth Complex through the year 2000 (most locations shown on Fig. 2.3). Values above the columns designate the number of holes drilled.

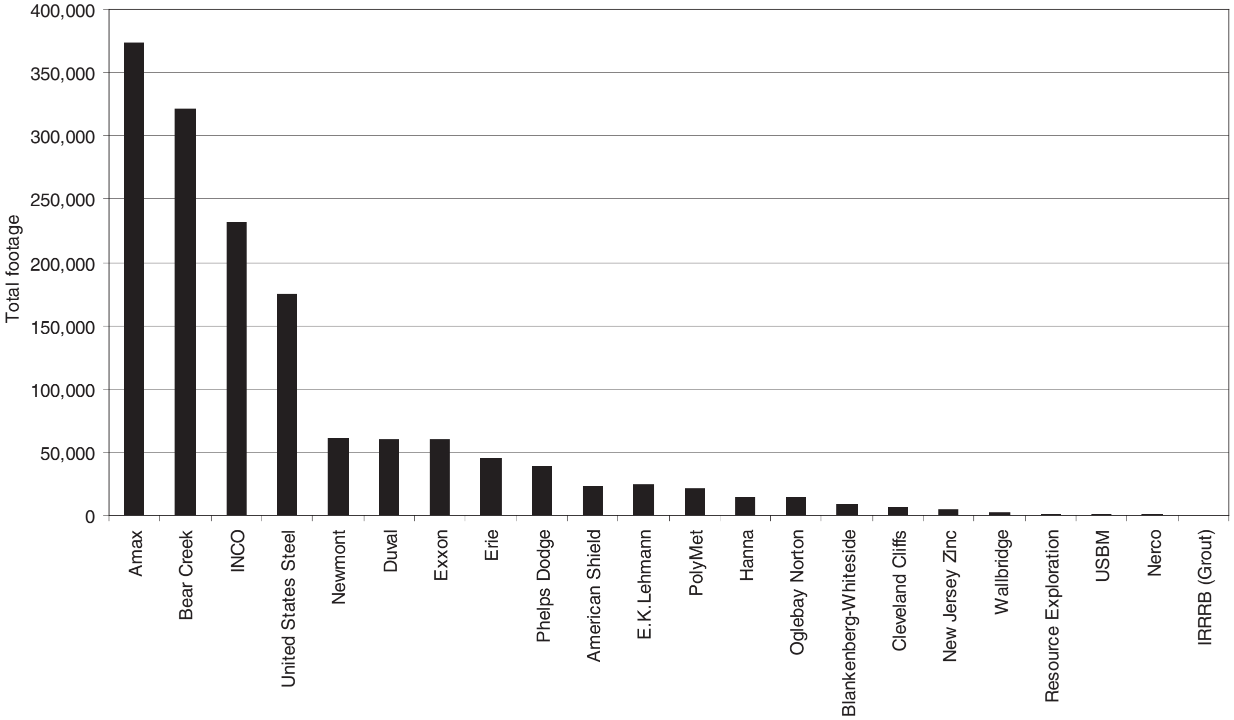

Figure 2.7. Histogram of total drilling footage acquired by various companies and public agencies along the basal contact of the Duluth Complex from 1948 to 2000.

4.5 million tons of low-grade material were estimated to have been stockpiled by 1981 (Watowich and others, 1981).

In 1966, INCO negotiated mining leases with the federal government and resumed exploration activities. That same year, the Minnesota Department of Conservation established regulations covering mining leases for copper and nickel on state lands (Sims, 1991). Leases were awarded to successful bidders by the Minnesota Department of Natural Resources in December of 1966. At least ten major mining companies either started or continued exploration and drilling programs at this time (Fig. 2.4). Seven of the companies started their exploration efforts by drilling scattered reconnaissance holes on geophysical targets. After a year or two, most of these companies began more concentrated drilling campaigns in specific areas. Table 2.3 lists the company or companies that conducted drilling campaigns in specific areas and/or deposits within the Duluth Complex. Benchmarks from the copper-nickel exploration between 1948 and the present are outlined in Table 2.4.

Between 1966 and 1978, over 1,330 holes were drilled at various locations along the base of the Duluth Complex. The vast majority of these holes were drilled within a band that extends from the Wyman Creek deposit to the Spruce Road deposit. INCO completed a major drilling effort at its Spruce Road and Maturi deposits, and sank a shaft at the Maturi deposit in 1966 and 1967. They decided that the mineralization at the Maturi deposit was too low-grade to support an underground mine and concentrated their efforts at the Spruce Road deposit. A surface bulk sample was collected at Spruce Road in 1974, and INCO announced their plans to establish an open-pit mine at the site. Bear Creek Mining concentrated most of their effort at the Babbitt and Serpentine deposits between 1967 and 1971. U.S. Steel Corporation started drilling at the Dunka Road deposit in 1969 and at the Wyman Creek deposit in 1973; drilling at both sites continued until 1974. Newmont conducted a modest drilling campaign at the Dunka Pit deposit from 1967 to 1969 and decided that the mineralization was too scattered to maintain continued interest. Also during this period, limited drilling campaigns were conducted by Duval Corporation, Exxon, and the M.A. Hanna Mining Company (South Filson Creek). At about the time that most of the drilling activity was

Table 2.3. Companies involved in various exploration areas along the basal contact of the Duluth Complex.

Deposit/exploration area	Company*
Spruce Road deposit	*INCO,* Bear Creek, and Wallbridge
South Filson Creek area	*Hanna* and Duval
Maturi deposit	*INCO* and Wallbridge with downdip holes by Hanna, Duval, and Newmont
Little Lake Road area	*INCO, Bear Creek,* Duval, and Lehmann
Birch Lake area	*Lehmann* and Duval
Dunka Pit deposit	*Bear Creek, Newmont, Erie Mining* (mostly iron-formation drilling), Exxon, Duval, and INCO
Serpentine deposit	*Bear Creek,* AMAX, Reserve Mining (mostly iron-formation drilling), and Resource Exploration
Babbitt/Minnamax/Mesaba deposit	*Bear Creek, AMAX,* INCO, and Exxon
Dunka Road /NorthMet deposit	*U.S. Steel, PolyMet,* and Nerco (two holes)
Section 17 OUI	*U.S. Steel* and INCO
Wetlegs deposit	*Bear Creek, Exxon,* and INCO
Longear OUI	American Shield/NICOR
Longnose OUI	*American Shield/NICOR,* and Bear Creek
Wyman Creek deposit	*U.S. Steel* and Bear Creek
Allen area	Bear Creek
Section 22 OUI	Exxon and New Jersey Zinc (one hole)
Skibo OUI	*INCO* and U.S. Steel (one hole)
Skibo South area	W.S. Moore and Phelps Dodge
Water Hen OUI	*Bear Creek, W.S. Moore*/American Shield, Phelps Dodge, New Jersey Zinc, Exxon, USBM
Whiteface Reservoir area	U.S. Steel
Linwood Lake area	U.S. Steel, W.S. Moore, and MN DNR
Harris Lake area	U.S. Steel and Phelps Dodge
Section 34 OUI	U.S. Steel
Boulder Creek area/OUI	Phelps Dodge
Grid VIII area	Phelps Dodge
Boulder Lake North area/OUI	*Phelps Dodge* and American Shield
Central Boulder Lake area/OUI	*Phelps Dodge*
Boulder Lake South OUI	*Phelps Dodge*
Gunflint Trail area	Bear Creek, Cleveland Cliffs/Amerada-Hess, Oglebay Norton, and Blankenberg-Whiteside
Brule Lake area	New Jersey Zinc

*Major explorers are in italics; details pertaining to joint venture activities are unknown.

winding down, AMAX reached an agreement with Bear Creek Mining to evaluate the mine potential of the Babbitt deposit. The deposit was renamed the Minnamax deposit. AMAX conducted an extensive exploration program at the deposit that consisted of drilling 228 surface drill holes (from 1974 to 1978), sinking a shaft with four drifts into massive sulfide mineralization near the basal contact at the Local Boy ore zone (from 1976 to 1977), and drilling 219 underground holes at Local Boy (from 1977 to 1978). After 1978, drilling activities decreased dramatically and only Exxon continued with small campaigns at the Dunka Pit and Wetlegs deposits until 1981.

While all of these activities were taking place, limited exploration also was going on along the basal contact to the south in a belt that extended from the Wyman Creek deposit to the Boulder Lake South area (Fig. 2.3). Scattered exploration holes (94) were drilled by Phelps Dodge Corporation, INCO, Bear Creek Mining, U.S. Steel, W.S. Moore Company, Exxon, American Shield Corporation,

Table 2.4. Chronology of copper-nickel-platinum group element exploration in Minnesota.

1948	Road excavation (Spruce Road) uncovers sulfide mineralization (copper stains).
1951	Childers and Whiteside (prospectors) drill one hole at Maturi deposit.
1952	International Nickel Company (INCO) starts mineral exploration.
1952	Bear Creek Mining (Kennecott) starts mineral exploration.
1953	Minnesota Geological Survey and U.S. Bureau of Mines drill 3 holes at Spruce Road (southwest of the Spruce Road deposit).
1954-1955	INCO leases site and drills on the Spruce Road and Maturi deposits.
1956-1957	INCO drills at four other sites (Little Lake Road, Dunka Pit, Wetlegs, and Skibo).
1957	Bear Creek starts reconnaissance drilling.
1958-1960	Bear Creek drilling on Babbitt deposit (B1 Grid).
1958-1960	Bear Creek drilling on their B2 Grid demonstrates that taconite ore is present beneath the Duluth Complex at Dunka Pit.
1961-1995	Erie Mining Company starts drilling and taconite mining operations at Dunka Pit; low-grade copper-nickel material is stockpiled.
1966	First State of Minnesota lease sales of state lands—at least 10 companies acquire leases. INCO is granted mining leases from the federal government at the Spruce Road and Maturi deposits.
1966-1967	INCO collects several bulk samples (1,043 tons) at the Spruce Road deposit and conducts drilling at the Spruce Road and Maturi deposits (some drilling in 1971).
1966-1969	Drilling in the Gunflint Trail area by Cleveland Cliffs and Amerada-Hess.
1967-1971	Bear Creek renews drilling at the Babbitt deposit, 105th hole intersects massive sulfide of the Local Boy ore zone.
1967-1968	INCO sinks shaft (1,090 feet [332 meters] deep) at the Maturi copper-nickel deposit and collects a 635-ton bulk sample
1969-1974	U.S. Steel (USS) begins drilling on the Dunka Road deposit.
1971	USS extracts a 300-ton bulk sample from a shallow test pit at the Dunka Road deposit; average grade is 0.61% copper, 0.18% nickel.
1973-1975	Oglebay-Norton conducts a drilling program along the Gunflint Trail in search of high-grade taconite in the Gunflint Iron Formation.
1974	INCO announces plan to mine and collects a 9,072-ton bulk sample. AMAX finalizes agreement with Kennecott to continue development of the Babbitt deposit.
1974-1978	AMAX drills on the Babbitt deposit (renamed the Minnamax Project).
1976	AMAX sinks 1,728-foot (527-meter) shaft (Minnamax shaft) to the Local Boy ore zone of the Babbitt copper-nickel deposit.
1974-1978	Regional Copper-Nickel Study by State of Minnesota—lease sales of state land suspended until 1982.
1977	AMAX underground drifting totals 3,760 feet (1,146 meters), 62,000 tons of rock removed, and bulk samples collected; underground diamond drilling begins (219 holes).
1977	Minnesota Department of Natural Resources (DNR) estimates that 4.4 billion tons of copper-nickel mineralized rock are present at the base of the Duluth Complex (Listerud and Meineke, 1977).
1978	AMAX collects a surface, low-grade bulk sample (520 tons).
1981	AMAX abandons their operations and the Minnamax shaft is closed.
1982	Lease sales of state land resumed.
1985-1986	High PGE values are documented in drill hole Du-15 from the Birch Lake area (MN DNR and MRRC cooperative effort). This discovery leads to intensive PGE sampling campaigns by both exploration companies and state agencies between 1987 and 1991.
1987	Last state lease for the Babbitt deposit terminated by Kennecott.
1988-present	E.K. Lehmann and Associates begin exploration on the Birch Lake PGE-copper-nickel deposit.
1988-1991	North Bay Exploration and Rhude-Fryberger, in cooperation with the Natural Resources Research Institute (NRRI), evaluate the PGE potential of the Local Boy ore zone at the Babbitt deposit.
1989	Fleck Resources acquires the Dunka Road deposit from USS and conducts PGE analyses on all previous USS drill sample intervals (pulps and reject material).
1990	Nerco Minerals Company drills two holes at the Dunka Road deposit to obtain material for hydrometallurgical tests.
1994-1996	Arimetco Incorporated evaluates the copper-nickel potential of the Babbitt deposit (renamed the Mesaba deposit). They collect two bulk samples in 1994 and 1995. Arimetco declares bankruptcy December, 1996.

Table 2.4. continued

1997	INCO revisits the Spruce Road and Maturi deposits to assess their potential for hosting high-grade copper-PGE footwall veins.
1998-present	PolyMet Mining Corporation (formerly Fleck Resources) starts drilling on the Dunka Road deposit (renamed the NorthMet deposit).
1999-present	INCO's U.S. subsidiary, American Copper and Nickel Company, joint ventures Spruce Road and Maturi deposits with Wallbridge Mining Company—Wallbridge drills two holes at the Spruce Road deposit and one hole at the Maturi deposit.
2000-present	PolyMet Mining Corporation and E.K. Lehmann and Associates (Beaver Bay Joint venture) continue to evaluate the PGE potential of their respective deposits. Cominco American Incorporated acquires both private and state leases for the Babbitt deposit (renamed the Mesaba deposit) and collects a 5,000-ton bulk sample for their hydrometallurgical process (CESL) in the spring of 2001.

and New Jersey Zinc between 1967 and 1975. Most of the drilling was concentrated on magnetic highs, and several oxide-rich bodies with Fe-Ti potential (OUIs of Severson, 1995) were discovered. Copper-nickel mineralization was intersected in both the oxide bodies and the troctolitic rocks, but it was generally too low-grade to be of importance.

Significantly lesser amounts of drilling for copper-nickel mineralization was also done in the Gunflint Trail area. Initially, the area to the immediate south of the Gunflint Trail was explored for titaniferous magnetite deposits associated with gabbroic rocks of Nathan's Layered Series (rocks now referred to as the Poplar Lake intrusion [Chapters 1 and 6]). Broderick (1917) and Grout (1949-1950) described these occurrences. Drilling for the magnetite bodies began sometime around 1900 and continued intermittently until 1947 when eleven holes were drilled by Grout (1949-1950) for the Department of Iron Range Resources and Rehabilitation (now referred to as the Iron Range Resources and Rehabilitation Board or IRRRB). Bear Creek Mining was the first company to actively explore for copper-nickel mineralization along the Gunflint Trail and drilled a few holes during 1958 and 1959, and in 1968. After the issuance of state mineral leases, Cleveland Cliffs Incorporated, in a joint venture with Amerada Hess, drilled ten holes from 1967 to 1970. Oglebay Norton was also active in the area, but they were primarily concerned with finding a taconite ore zone comparable to the metamorphosed taconite at Dunka Pit. They deepened two Cleveland Cliffs holes in addition to drilling six holes (from 1973 to 1975). A local prospector, R. Blankenberg, along with Whiteside, drilled several holes into the Duluth Complex (from 1969 to 1971); however, they were primarily interested in finding a silver vein system (arsenopyrite-rich massive sulfide veins) at the base of a Logan sill, and drilled 15 holes at Loon Lake between 1967 and 1971. One hole (LL-2) was also drilled to the south of the prospect within the Duluth Complex by the IRRRB in 1947.

New Jersey Zinc conducted an exploration program on the south shore of Brule Lake, which is located about eight miles (12 kilometers) to the south of the Gunflint Trail area. They sought copper-nickel mineralization at a basal contact zone of the Duluth Complex with the North Shore Volcanic Group, and drilled eight holes in 1967 and 1968.

Regional Copper-Nickel Study

The Regional Copper-Nickel Study that was conducted by the state between 1974 and 1978 had a significant impact on exploration activity in the Duluth Complex. Coincident with the study, the leasing of state lands was suspended between 1974 and 1981. The study, and moratorium on state leases, were responses to environmental concerns regarding the impact of sulfide mining. The factors and events that led to the study and moratorium were as follows. First, the mineralization that INCO outlined at the Spruce Road deposit is positioned very close to the environmentally sensitive Boundary Waters Canoe Area Wilderness (BWCAW). INCO requested approval from the U.S. Forest Service to establish an open-pit mine at Spruce Road in 1974. At the same time, Reserve Mining Company, an iron-mining company, was in litigation with the state and other federal agencies regarding Reserve's taconite tailing discharge into Lake Superior (Watowich and others, 1981). The tailings controversy heightened public concern about INCO's proposal to mine copper and nickel. The proposal drew strong opposition from environmental groups and some state legislators because of the proposed mine site's proximity to the BWCAW. Moreover, the U.S. Forest Service indicated that a thorough environmental impact study would be necessary before they could reach a decision on the mine application. Also in 1974, AMAX announced plans to sink a shaft at the Babbitt copper-nickel deposit, which further raised environmental concerns, and the necessary water disposal permits were denied. Eventually, the necessary permits were issued to AMAX in 1975 and they began sinking the shaft in 1976. By then, however, the Minnesota Legislature had instructed the Minnesota Environmental Quality Board to conduct the Regional Copper-Nickel Study in response to environmental concerns regarding the impact of sulfide mining. In the end, development of both the Spruce Road and Babbitt deposits was delayed pending results of the study. By the end of the study in 1978, copper and nickel markets had weakened and the development of both of these potential mines was indefinitely postponed (Lehmann, 1990). AMAX relinquished their land position at the Babbitt deposit and the Minnamax shaft was closed in 1981. Bear Creek Mining dropped all leased lands at the Babbitt deposit several years later. INCO continues to maintain their leases, but has not pursued any further developments.

The results of the Regional Copper-Nickel Study are summarized in five volumes. The study addressed such issues as: air and water quality, social and economic impacts, land and water use impacts, noise impacts, health impacts, and effects on wildlife and flora. Studies pertaining to the natural leaching characteristics of the ore and waste rock were started by the Minnesota Department of Natural Resources in 1976 and have continued to the present.

Platinum group element exploration activity

During the early phases of drilling (prior to about 1980), all of the exploration companies recognized that the copper-nickel deposits had some potential for hosting precious metals, especially platinum group elements (PGEs). However, PGEs were rarely analyzed for in the early exploration period because PGE assays were too expensive to acquire along with the copper-nickel assays, and the assays were often inaccurate and not replicable. Moreover, structural and lithologic controls on PGE mineralization were poorly understood. Based on limited PGE sampling, the companies assumed that the typical copper-nickel ore contained no more than a few hundred parts per billion combined platinum and palladium. In 1985, the Minnesota Department of Natural Resources and University of Minnesota (Minerals Resource Research Center [MRRC]) conducted a geochemical evaluation of chromium-bearing drill core (Duval drill hole Du-15) from the Birch Lake area. Significant values of about 9 parts per million combined platinum + palladium were discovered in portions of the hole (Sabelin and Iwasaki, 1985; 1986). A short time later, Morton and Hauck (1987) compiled all of the unpublished company PGE data for the Duluth Complex and reported the presence of significant PGE values, often associated with high copper contents, at the Dunka Road, Babbitt, and Water Hen deposits. These discoveries sparked renewed interest in the copper-nickel deposits of the Duluth Complex as potential polymetallic deposits. Additional drill holes were sampled and analyzed for PGEs throughout the Duluth Complex by both state agencies and private exploration companies. As a result, significant PGE values were discovered in many areas/deposits of the complex, and ongoing exploration and research are being conducted on the content and origin of PGE-bearing zones. PGE-bearing zones and potential mineralization models are described in Chapter 8.

At least four companies are currently evaluating the polymetallic potential of five areas along the basal contact. PolyMet Mining Corporation has acquired the Dunka Road deposit and renamed it the NorthMet deposit. PolyMet has recently drilled over 90 holes (from 1998 to 2001) and is conducting pre-feasibility studies. They plan on using a hydrometallurgical process to treat the copper-nickel-cobalt-PGE-gold sulfide ore. Cominco American Incorporated has acquired the Babbitt deposit and has renamed it the Mesaba deposit. They recently collected a 5,000-ton bulk sample and are evaluating the use of its proprietary Cominco Engineering Services Laboratory hydrometallurgical refining process. Cominco estimated the Mesaba deposit "...to contain resources of more than 700 million tonnes grading 0.46% copper and 0.12% nickel, equivalent to approximately 0.8% copper... In addition...the deposit contains important quantities of cobalt, platinum group and precious metals" (Godlewski, 2001). Recent drilling activities have also taken place at the Birch Lake PGE prospect in the vicinity of drill hole Du-15. E.K. Lehmann and Associates, the principal explorer in the Beaver Bay joint venture, acquired the property soon after the announcement of significant PGE values present in the bottom of Du-15. Between 1988 and 2000, Lehmann drilled 20 surface holes and 26 wedges to evaluate the PGE potential of the Birch Lake area at depths of 2,000 to 2,600 feet (610 to 792 meters) below the surface. In 1997, INCO began to renew their interest in the Maturi and Spruce Road deposits following the discovery of high-grade copper-PGE massive sulfide veins in the footwall rocks beneath the Sudbury Igneous Complex. INCO believed that rocks that are footwall to the Duluth Complex may also host similar high-grade veins. In 1999, INCO's U.S. subsidiary, American Copper and Nickel Company, joint-ventured their properties with Wallbridge Mining Company Limited. Wallbridge has recently drilled two holes at Spruce Road to evaluate the high-grade vein potential, and one hole at Maturi to evaluate the PGE potential associated with the disseminated copper-nickel mineralization. Falconbridge Limited recently acquired mineral leases in the vicinity of the Siphon fault and to the south of the Wyman Creek deposit (Fig. 2.3), and is in the early stages of initiating an exploration program.

In addition to the recent activity along the basal contact of the Duluth Complex, companies are showing interest in the possibilities of discovering PGE reef deposits at higher stratigraphic levels. Miller (1999) proposed that several intrusions within the Duluth and Beaver Bay Complexes appear to have petrologic attributes favorable for reef formation. These include the Sonju Lake intrusion, Cloquet Lake layered series, and Houghtaling Creek troctolite of the Beaver Bay Complex; and within the Duluth Complex they include the Greenwood Lake, Osier Lake, and Boulder Lake intrusions, and the layered series at Duluth. These bodies are portrayed on map M-119. Exploration companies that held mineral leases in the interior of the Duluth Complex and in the Beaver Bay Complex in 2001 include Falconbridge Limited, McVicar Minerals Limited, Polymet Mining Incorporated, and E.K. Lehmann and Associates.

REFERENCES

Anonymous, 1994, Arimetco improves reserve estimate at Masaba property: The Northern Miner, v. 80, no. 3, p. 3.

Bayley, W.S., 1893a, The eruptive and sedimentary rocks on Pigeon Point, Minnesota, and their contact phenomena: U.S. Geological Survey Bulletin 109, 121 p.

———1893b, The basic massive rocks of the Lake Superior region: III. The great gabbro mass of north-eastern Minnesota: Journal of Geology, v. 1, p. 688-716.

———1895, The basic massive rocks of the Lake Superior region: IV. The peripheral phases of the great gabbro mass in northeastern Minnesota: Journal of Geology, v. 3, p. 1-20.

Boerboom, T.J., and Miller, J.D., Jr., 1994, Bedrock geologic map of the Silver Island Lake, Wilson Lake, and western Toohey Lake quadrangles, Cook and Lake Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-81, scale 1:24,000.

Bonnichsen, B., 1968, General geology and petrology of the metamorphosed Biwabik Iron Formation, Dunka River area, Minnesota: Minneapolis, University of Minnesota, Ph.D. dissertation, 240 p., 1 pl.

———1970a, Reconnaissance geologic map of Allen quadrangle: Minnesota Geological Survey Open-File Map, scale 1:24,000.

———1970b, Reconnaissance geologic map of Babbitt NE quadrangle: Minnesota Geological Survey Open-File Map, scale 1:24,000.

———1970c, Reconnaissance geologic map of Babbitt quadrangle: Minnesota Geological Survey Open-File Map, scale 1:24,000.

———1970d, Reconnaissance geologic map of Babbitt SE quadrangle: Minnesota Geological Survey Open-File Map, scale 1:24,000.

———1970e, Reconnaissance geologic map of Babbitt SW quadrangle: Minnesota Geological Survey Open-File Map, scale 1:24,000.

———1971, Outcrop map of southern part of Duluth Complex and associated Keweenawan rocks, St. Louis and Lake Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-11, scale 1:125,000.

———1972, Southern part of the Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 361-387.

Broderick, T.M., 1917, The relation of the titaniferous magnetites of northeastern Minnesota to the Duluth Gabbro: Economic Geology, v. 12, p. 663-696.

Chandler, V.W., 1983a, Aeromagnetic map of Minnesota, Cook and Lake Counties: Minnesota Geological Survey Aeromagnetic Map A-1, 2 pls., scale 1:250,000.

———1983b, Aeromagnetic map of Minnesota, St. Louis County: Minnesota Geological Survey, Aeromagnetic Map A-2, 2 pls., scale 1:250,000.

———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.

———2001a, Superimposed magnetic on gravity anomaly map of the central Duluth Complex and western part of the Beaver Bay Complex, Lake and St. Louis Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-117, scale 1:100,000.

———2001b, Superimposed magnetic on gravity anomaly map of the Duluth Complex and related rocks, northeastern Minnesota: Minnesota Geological Survey Miscellaneous Map M-120, scale 1:200,000.

Churchill, R.K., 1978, A geochemical and petrological investigation of the Cu-Ni sulfide genesis in the Duluth Complex, Minnesota: Minneapolis, University of Minnesota, M.S. thesis, 101 p.

Clements, J.M., 1903, The Vermilion iron-bearing district of Minnesota: U.S. Geological Survey Monograph 45, 463 p.

Clifford, D., 1999, PolyMet's Progress: Mining Magazine, v. 181, no. 5, p. 303-309.

Davidson, D.M., Jr., 1969a, Geologic map of the Kawishiwi Lake quadrangle, Lake and Cook Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-7, scale 1:24,000.

———1969b, Geologic map of the Perent Lake quadrangle, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-8, scale 1:24,000.

———1972, Eastern part of Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 354-360.

———1977a, Reconnaissance geologic map of the Alice Lake quadrangle, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-33 scale 1:24,000.

———1977b, Reconnaissance geologic map of the Beth Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-26, scale 1:24,000.

———1977c, Reconnaissance geologic map of the Cherokee Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-30, scale 1:24,000.

———1977d, Reconnaissance geologic map of the Eagle Mountain quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-28, scale 1:24,000.

———1977e, Reconnaissance geologic map of the Kelso Mountain quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-27, scale 1:24,000.

———1977f, Reconnaissance geologic map of the Lake Polly quadrangle, Lake and Cook Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-34, scale 1:24,000.

———1977g, Reconnaissance geologic map of the Lima Mountain quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-32, scale 1:24,000.

———1977h, Reconnaissance geologic map of the Pine Mountain quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-31, scale 1:24,000.

Davidson, D.M., Jr., and Burnell, J.R., Jr., 1977, Reconnaissance geologic map of the Brule Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-29, scale 1:24,000.

Eames, H.H., 1866, On the metalliferous regions bordering on Lake Superior: St. Paul, Minn., Report of the State Geologist of Minnesota, 23 p.

Elftman, A.H., 1898a, Geology of the Keweenawan area in northeastern Minnesota. II: American Geologist, v. 21, p. 175-188.

———1898b, Geology of the Keweenawan area in northeastern Minnesota. III: American Geologist, v. 22, p. 130-149.

Emmons, W.H., and Grout, F.F., eds., 1943, Mineral resources of Minnesota: Minnesota Geological Survey Bulletin 30, 149 p.

Foose, M.P., and Cooper, R.W., 1978, Preliminary geologic report on the Harris Lake area, northeastern Minnesota: U.S. Geological Survey Open-File Report 78-385, 24 p., 1 pl., scale 1:12,000.

Geerts, S.D., 1991, Geology, stratigraphy, and mineralization of the Dunka Road Cu-Ni prospect, northeastern Minnesota: Natural Resources Research Institute, Technical Report NRRI/TR-91/14, 61 p.

Gehman, H.M., Jr., 1957, The petrology of the Beaver Bay Complex, Lake County, Minnesota: Minneapolis, University of Minnesota, Ph.D. dissertation, 92 p.

Godlewski, D., 2001, Cominco obtains rights to Mesaba copper-nickel deposit: Cominco American Incorporated, Cominco News Release 01-024-C (June 13, 2001), 1 p.

Goldich, S.S., Nier, A.O., Baadsgaard, H., Hoffman, J.H., and Krueger, H.W., 1961, The Precambrian geology and geochronology of Minnesota: Minnesota Geological Survey Bulletin 41, 193 p., 5 pls.

Grant, U.S., 1889, Report of geological observations made in northeastern Minnesota during the summer of 1888, *in* Winchell, N.H., 1889, Seventeenth annual report for 1888: Geological and Natural History Survey of Minnesota, p. 149-215.

———1899, The geology of the Gunflint Lake plate, *in* Winchell, N.H., ed., The geology of Minnesota: Geological and Natural History Survey of Minnesota, Final Report, v. 4, 481-490.

Green, J.C., 1972, North Shore Volcanic Group, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 294-332.

———comp., 1982a, Geologic map of Minnesota, Two Harbors sheet: Minnesota Geological Survey, scale 1:250,000.

———1982b, Geology of the Milepost 7 area, Lake County, Minnesota: Minnesota Geological Survey Report of Investigations 26, 12 p.

———1992, Geologic map of the North Shore of Lake Superior, Lake and Cook Counties, Minnesota: Part 1. Little Marais to Tofte: Minnesota Geological Survey Miscellaneous Map M-71, scale 1:24,000.

Green, J.C., Jirsa, M.A., and Moss, C.M., 1977, Environmental geology of the North Shore: Minnesota Geological Survey, 99 p.

Green, J.C., Phinney, W.C., and Weiblen, P.W., 1966, Gabbro Lake quadrangle, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-2, scale 1:31,680.

Grogan, R.M., 1940, Geology of a part of the Minnesota shore of Lake Superior northeast of Two Harbors, Minnesota: Minneapolis, University of Minnesota, Ph.D. dissertation, 145 p.

Grosh, W.A., Pennington, J.W., Wasson, P.A., and Cooke, S.R.B., 1955, Investigation of copper-nickel mineralization in the Kawishiwi River area, Lake County, Minnesota: U.S. Bureau of Mines Report of Investigations 5177, 18 p.

Grout, F.F., 1918a, Internal structures of igneous rocks; their significance and origin; with special reference to the Duluth Gabbro: Journal of Geology, v. 26, p. 439-458.

———1918b, The lopolith, an igneous form exemplified by the Duluth gabbro: American Journal of Science, series 4, v. 46, p. 516-522.

———1918c, The pegmatites of the Duluth Gabbro: Economic Geology, v. 13, p. 185-197.

———1918d, Two-phase convection in igneous magmas: Journal of Geology, v. 26, p. 481-499.

———1918e, A type of igneous differentiation: Journal of Geology, v. 26, p. 626-658.

———1930, Probable extent of abyssal assimilation: Geological Society of America Bulletin, v. 41, no. 4, p. 675-694.

———1932, Geologic map of the State of Minnesota: Minnesota Geological Survey, 2 pls., scale 1:500,000.

———1949-1950, The titaniferous magnetites of Minnesota: St. Paul, Minn., Office of the Commissioner of the Iron Range Resources and Rehabilitation, 117 p.

Grout, F.F., Gruner, J.W., Schwartz, G.M., and Thiel, G.A., 1951, Precambrian stratigraphy of Minnesota: Geological Society of America Bulletin, v. 62, no. 9, p. 1017-1078.

Grout, F.F., and Schwartz, G.M., 1939, The geology of the anorthosites of the Minnesota coast of Lake Superior: Minnesota Geological Survey Bulletin 28, 119 p., 6 pls.

Grout, F.F., Sharp, R.P., and Schwartz, G.M., 1959, The geology of Cook County Minnesota: Minnesota Geological Survey Bulletin 39, 163 p., 16 pls.

Hardyman, R.F., 1969, The petrography of a section of the basal Duluth Complex, St. Louis County, northeastern Minnesota: Minneapolis, University of Minnesota, M.S. thesis, 132 p.

Hauck, S.A., Severson, M.J., Ripley, E.M., Goldberg, S., Alapieti, T., 1997a, Geology and Cr-PGE mineralization of the Birch Lake area, South Kawishiwi intrusion, Duluth Complex: Natural Resources Research Institute, Technical Report NRRI/TR-97/13, 32 p.

Hauck, S.A., Severson, M.J., Zanko, L.M., Barnes, S.J., Morton, P., Aliminas, H.V., Foord, E.E., and Dahlberg, E.H., 1997b, 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.

Irving, R.D., 1883, The copper-bearing rocks of Lake Superior: U.S. Geological Survey Monograph 5, 464 p.

Jerde, E.A., 1991, Geochemistry and petrology of hypabyssal rocks associated with the Midcontinent rift, northeastern Minnesota: Los Angeles, University of California Los Angeles, Ph.D. dissertation, 305 p.

Johnson, R.G., 1968, Copper-nickel mineralization in the basal Duluth gabbro complex, northeastern Minnesota: A case study: Iowa City, University of Iowa, M.S. thesis, 91 p.

———1970, Economic geology of a portion of the basal Duluth Complex, northeastern Minnesota: Iowa City, University of Iowa, Ph.D. dissertation, 135 p.

Jones, N.W., 1963, The relationships between the Duluth gabbro and the dikes and sills in the vicinity of Hovland, Minnesota: Minneapolis, University of Minnesota, M.S. thesis, 90 p.

Kilburg, J.A., 1972, Petrology, structure, and correlation of the Upper Precambrian Ely's Peak basalts: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 97 p.

Kilburg, J.A., and Morey, G.B., 1977, Reconnaissance geologic map of the Esko quadrangle, St. Louis and Carlton Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-25, scale 1:24,000.

Kloos, J.H., 1882 (1871), Geological notes on Minnesota, *in* Winchell, N.H., Tenth annual report for 1881: Geological and Natural History Survey of Minnesota, p. 175-200.

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

Lawson, A.C., 1893a, The anorthosytes of the Minnesota coast of Lake Superior: Geological and Natural History Survey of Minnesota Bulletin 8, p. 1-23.

———1893b, The laccolitic sills of the north-west coast of Lake Superior: Geological and Natural History Survey of Minnesota Bulletin 8, p. 24-48.

Lehman, G.A., 1980, The bedrock geology of a portion of the Cramer 15′ quadrangle, Lake County, Minnesota: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 132 p.

Lehmann, E.K., 1990, Minnesota Department of Natural Resources, Minnesota Pollution Control Agency, and Project Environment Foundation, The report on the mining simulation project: Blandin Foundation, 90 p.

Leith, C.K., 1903, The Mesabi iron-bearing district of Minnesota: U.S. Geological Survey Monograph 43, 316 p.

Listerud, W.H., and Meineke, D.G., 1977, Mineral resources of a portion of the Duluth Complex and adjacent rocks in St. Louis and Lake Counties, northeastern Minnesota: Hibbing, Minn., Minnesota Department of Natural Resources, Division of Minerals Report 93, 74 p.

Mainwaring, P.R., 1975, The petrology of a sulfide-bearing layered intrusion at the base of the Duluth Complex, St. Louis County, Minnesota: Toronto, University of Toronto, Ph.D. dissertation, 251 p.

Mathez, E.A., 1971, Geology and petrology of the Logan intrusives of the Hungry Jack Lake quadrangle, Cook County, Minnesota: Tucson, University of Arizona, M.S. thesis, 111 p.

Mathez, E.A., Nathan, H.D., and Morey, G.B., 1977, Geologic map of the Hungry Jack Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-39, scale 1:24,000.

Meints, J.P., Jirsa, M.A., Chandler, V.W., and Miller, J.D., Jr., 1993, Scientific core drilling in parts of Itasca, St. Louis, and Lake Counties, northeastern Minnesota, 1989-1991: Summary of lithologic, geochemical, and geophysical results: Minnesota Geological Survey Information Circular 37, 159 p.

Miller, J.D., Jr., 1986, The geology and petrology of anorthositic rocks in the Duluth Complex, Snowbank Lake quadrangle, northeastern Minnesota: Minneapolis, University of Minnesota, Ph.D. dissertation, 585 p.

———1988, Geologic map of the Silver Bay and Split Rock Point NE quadrangles, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-65, scale 1:24,000.

———1998, Potential for reef-type PGE mineralization in the Duluth Complex: Evidence from the Layered Series at Duluth: The Minnesota Prospector, Special Issue, p. 8-12.

———1999, Geochemical evaluation of platinum group element (PGE) mineralization in the Sonju Lake intrusion, Finland, Minnesota: Minnesota Geological Survey Information Circular 44, 32 p.

Miller, J.D., Jr., Boerboom, T.J., and Jerde, E.A., 1994, Bedrock geologic map of the Cabin Lake and Cramer 7.5-minute quadrangles, Lake and Cook Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-82, scale 1:24,000.

Miller, J.D., Jr., and Chandler, V.W., 1997, Geology, petrology, and tectonic significance of the Beaver Bay Complex, northeastern Minnesota, *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. 73-96.

———1999, Bedrock geologic map of the central Duluth Complex and western part of the Beaver Bay Complex, Lake and St. Louis Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-101, scale 1:100,000.

Miller, J.D., Jr., Green, J.C., and Boerboom, T.J., 1989, Geologic map of the Illgen City quadrangle, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-66, scale 1:24,000.

Miller, J.D., Jr., Green, J.C., Boerboom, T.J., and Chandler, V.W., 1993a, Geologic map of the Doyle Lake and Finland quadrangles, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-72, scale 1:24,000.

Miller, J.D., Jr., Green, J.C., and Chandler, V.W., 1993b, Preliminary geologic map of the Duluth area, St. Louis County, Minnesota: Minnesota Geological Survey Open-File Report 93-2, scale 1:48,000.

Miller, J.D., Jr., Green, J.C., Severson, M.J., Chandler, V.W., and Peterson, D.M., 2001, Geologic map of the Duluth Complex and related rocks, northeastern Minnesota: Minnesota Geological Survey Miscellaneous Map M-119, scale 1:200,000.

Mogessie, A., 1976, Petrologic study of copper-nickel mineralization in the Tuscarora intrusion, Duluth Complex, northeastern Minnesota: Minneapolis, University of Minnesota, M.S. thesis, 137 p.

Molling, P.A., 1979, Petrology and mineralogy of a drill core (DDH 295) from the Partridge River troctolite of the Duluth Complex, Minnesota: Oxford, Ohio, Miami University, M.S. thesis, 150 p.

Morey, G.B., 1993, A history of geologic mapping in Minnesota: Minnesota Geological Survey, 26 p.

Morey, G.B., and Cooper, R.W., 1977, Bedrock geology of the Hoyt Lakes–Kawishiwi area, St. Louis and Lake Counties, northeastern Minnesota: Minnesota Geological Survey Open-File Report, scale 1:48,000.

Morey, G.B., and Nathan, H.D., 1977, Geologic map of the South Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-38, scale 1:24,000.

———1978, Geologic map of the Gunflint Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-42, scale 1:24,000.

Morey, G.B., Olsen, B.M., and Southwick, D.L., comps., 1981a, Geologic map of Minnesota, east-central Minnesota: Minnesota Geological Survey, scale 1:250,000.

Morey, G.B., Weiblen, P.W., Papike, J.J., and Anderson, D.H., 1981b, Geologic map of the Long Island Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-46, scale 1:24,000.

Morton, P., and Hauck, S.A., 1987, PGE, Au, and Ag contents of Cu-Ni sulfides found at the base of the Duluth Complex, northeastern Minnesota: Natural Resources Research Institute, Technical Report NRRI/GMIN-TR-87-04, 81 p.

Motamedi, S., 1984, The Keweenawan lavas in the city of Duluth: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 140 p.

Mudrey, M.G., Jr., 1973, Structure and petrology of the sill on Pigeon Point, Cook County, Minnesota: Minneapolis, University of Minnesota, Ph.D. dissertation, 310 p.

———1977, Geologic map of Pigeon Point quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-36, scale 1:24,000.

Mudrey, M.G., Jr., and Morey, G.B., 1972, Cook County fissure vein deposits, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 407-410.

Nathan, H.D., 1969, The geology of a part of the northeast segment of the Duluth Complex: Minneapolis, University of Minnesota, Ph.D. dissertation, 198 p.

Nebel, M.L., 1919, The basal phases of the Duluth Complex near Gabimichigami Lake, Minnesota and its contact effects: Economic Geology, v. 14, no. 5, p. 367-402.

Nelson, N., 1991, A petrologic and geochemical study of granophyric granite in the roof of the Keweenawan Duluth Complex, Eagle Mountain, Cook County, Minnesota: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 151 p., 1 pl.

Owen, D.D., 1852, Report of a geological survey of Wisconsin, Iowa, and Minnesota: Philadelphia, U.S. Department of the Treasury, 638 p.

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

Peterson, D.M., 1997, Ore deposit modeling of the footwall mineralization of the Duluth Complex: Hibbing, Minn., Minnesota Department of Natural Resources, Division of Lands and Minerals Project 317, 55 p., 46 pls.

Phinney, W.C., 1967, Reconnaissance geologic map of part of the Kangas Bay quadrangle: Minnesota Geological Survey Open-File Map, scale 1:24,000.

———1972a, 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.

———1972b, Northern prong, Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 346-353.

———1972c, Northwestern part of Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 335-345.

Pope, N.M., 1976, Petrology and structure of the Late Precambrian mafic sills east of Silver Creek, Lake County, Minnesota: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 157 p.

Renner, J.L., 1969, The petrology of the contact rocks of the Duluth Complex, Dunka River area, Minnesota: Minneapolis, University of Minnesota, M.S. thesis, 81 p.

Ross, B.A., 1985, A petrologic study of the Bardon Peak peridotite, Duluth Complex: Minneapolis, University of Minnesota, M.S. thesis, 140 p.

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): Minneapolis, Minn., Minerals Resources Research Center, University of Minnesota, 58 p.

———1986, Evaluation of platinum group metal occurrence in Duval 15 drill core from the Duluth Complex (Internal report): Minneapolis, Minn., Minerals Resources Research Center, University of Minnesota.

Sandberg, A.E., 1938, Section across Keweenawan lavas at Duluth, Minnesota: Geological Society of America Bulletin, v. 49, no. 5, p. 795-830.

Schwartz, G.M., 1944, Tracing the Duluth gabbro contact with a magnetometer: Economic Geology, v. 39, no. 3, p. 224-233.

———1949, The geology of the Duluth metropolitan area: Minnesota Geological Survey Bulletin 33, 136 p., 19 pls.

———1964, History of the Minnesota Geological Survey: Minnesota Geological Survey Special Publication SP-1, 39 p.

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

———1994, Igneous stratigraphy of the South Kawishiwi intrusion, Duluth Complex, northeastern Minnesota: Natural Resources Research Institute, Technical Report NRRI/TR-93/34, 210 p., 15 pls.

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

———in press, Geologic mapping and structural analysis of the Peter Mitchell Mine: Natural Resources Research Institute, Technical Report NRRI/TR-96/04.

Severson, M.J., and Hauck, S.A., 1990, Geology, geochemistry, and stratigraphy of a portion of the Partridge River intrusion: Natural Resources Research Institute, Technical Report NRRI/GMIN-TR-89-11, 236 p., 4 pls.

Severson, M.J., and Miller, J.D., Jr., 1999, Bedrock geologic map of Allen quadrangle, Minnesota: Minnesota Geological Survey Miscellaneous Map M-91, scale 1:24,000.

Severson, M.J., Patelke, R.L., Hauck, S.A., and Zanko, L.M., 1994, The Babbitt copper-nickel deposit, part B: Structural datums: Natural Resources Research Institute, Technical Report NRRI/TR-94/21b, 48 p., 6 pls.

Sims, P.K., 1965, Our land and mineral resources, a long-range plan for geologic research in Minnesota: Minnesota Geological Survey, 37 p.

———1970, Geologic map of Minnesota, bedrock geology: Minnesota Geological Survey Miscellaneous Map M-14, scale 1:1,000,000.

———1991, History of discovery of copper-nickel deposits in the Duluth Complex, northeastern Minnesota, *in* Hollister, V.F., ed., Porphyry copper, molybdenum, and gold deposits, volcanogenic deposits (massive sulfides), and deposits in layered rocks: Case histories of mineral discoveries: v. 3: Littleton, Colo., Society for Mining, Metallurgy and Exploration Inc., p. 197-199.

Sims, P.K., and Morey, G.B., eds., 1972, Geology of Minnesota: A centennial volume: Minnesota Geological Survey, 632 p., 2 pls.

Sims, P.K., Morey, G.B., Ojakangas, R.W., Viswanathan, S., comps., 1970, Geologic map of Minnesota, Hibbing sheet: Minnesota Geological Survey, scale 1:250,000.

Stevenson, R.J., 1974, A mafic layered intrusion of Keweenawan age near Finland, Lake County, Minnesota: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 160 p.

Taylor, R.B., 1964, Geology of the Duluth Gabbro Complex near Duluth, Minnesota: Minnesota Geological Survey Bulletin 44, 63 p., 1 pl.

Tyson, R.M., 1979, The mineralogy and petrology of the Partridge River troctolite in the Babbitt–Hoyt Lakes region of the Duluth Complex, northeastern Minnesota: Oxford, Ohio, Miami University, Ph.D. dissertation, 179 p.

Van Hise, C.R., and Leith, C.K., 1911, The geology of the Lake Superior region: U.S. Geological Survey Monograph 52, 641 p.

Wadsworth, M.W., 1887, Preliminary description of the peridotytes, gabbros, diabases, and andesytes of Minnesota: Geological and Natural History Survey of Minnesota Bulletin 2, 158 p.

Wager, L.R., and Deer, W.A., 1939, Geological investigations in East Greenland: Meddelelser om Groenland, v. 105, 335 p.

Watowich, S.N., Malcolm, J.B., and Parker, P.D., 1981, A review of the Duluth Gabbro Complex as a domestic source of critical and strategic metals: Society of Mining Engineers of AIME, preprint 81-351, 9 p.

Weiblen, P.W., Mathez, E.A., and Morey, G.B., 1972, Logan intrusions, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 394-406.

Whittlesey, C., 1866, Geology and minerals—A report of exploration in the mineral regions of Minnesota during the years 1848, 1859, and 1864: Cleveland, Ohio, Fairbanks, Benedict and Company, 54 p.

Winchell, N.H., 1878, Sixth annual report for 1877: Geological and Natural History Survey of Minnesota, 226 p.

———1880, Eighth annual report for 1879: Geological and Natural History Survey of Minnesota, 193 p.

———1882, Tenth annual report for 1881: Geological and Natural History Survey of Minnesota, 254 p.

———1887, Fifteenth annual report for 1886: Geological and Natural History Survey of Minnesota, 496 p.

———1893, The Norian of the northwest, *in* Lawson, A.C., The anorthosytes of the Minnesota coast of Lake Superior: Geological and Natural History Survey of Minnesota Bulletin 8, p. iii-xxxiv.

———1899, The geology of Minnesota: Geological and Natural History Survey of Minnesota, Final Report, v. 4, 629 p., 100 pls.

———1900, The geology of Minnesota: Geological and Natural History Survey of Minnesota, Final Report, v. 5, 1025 p., 6 pls.

Winchell, N.H., and Winchell, H.V., 1891, The iron ores of Minnesota: Geological and Natural History Survey of Minnesota Bulletin 6, 430 p., 1 pl.

Zanko, L.M., Severson, M.J., and Ripley, E.M., 1994, Geology and mineralization of the Serpentine copper-nickel deposit: Natural Resources Research Institute, Technical Report NRRI/TR-93-52, 90 p., 3 pls.

Chapter 3

GEOPHYSICAL CHARACTERISTICS OF THE DULUTH COMPLEX AND ASSOCIATED ROCKS

Val W. Chandler

INTRODUCTION

Geophysical methods are an integral part of most geologic investigations in the Duluth Complex. They provide a means to infer bedrock geology in areas covered by glacial deposits, and are almost the only way to investigate geologic structure at depth. Seismic, electrical, and electromagnetic methods have been used to investigate near-surface and deep-crustal geologic intricacies in the Duluth Complex. Paleomagnetic studies provide important time–stratigraphic information for both the rocks of the Duluth Complex and associated Keweenawan volcanic rocks. Gravity and magnetic methods have been essential to geologic mapping of the bedrock and to the production of Miscellaneous Map M-119. Both gravity and magnetic methods are sensitive to the lithologic variations within the complex, and high quality sets of data are easily accessible.

The first half of this chapter presents a summary of previous geophysical studies in the Duluth Complex region and their geologic significance. The second half describes the gravity and magnetic data sets that supported the compilation of geologic map M-119, and discusses the geologic significance of observed anomaly signatures. Many of the geographic and geologic features mentioned are located on the generalized geologic map in Figure 3.1. Detailed mapping can be found on M-119, available on the accompanying CD.

PREVIOUS GEOPHYSICAL INVESTIGATIONS

Gravity methods

Prior to the late 1960s, gravity data coverage of the Duluth Complex consisted of a few profiles and very coarse areal coverage (Thiel, 1956; Craddock and others, 1970). Using a gravity profile extending from Ely to Illgen City, Thiel (1956) estimated the dip of the basal contact to be about 17° eastward in the Babbitt area, and noted that stronger anomaly gradients along the base near Duluth implied somewhat steeper dips in that area. Thiel used a gravity profile extending along Minnesota Point to dispute a hypothesis that the Minnesota shoreline of Lake Superior marked a major fault between the North Shore Volcanic Group lavas and younger Keweenawan sandstones. White (1966) noted that the positive gravity signature associated with the Duluth Complex abruptly decreases near the Lake Superior shore, possibly indicating a pinching out of the complex along a basement ridge.

Modern gravity studies of the Duluth Complex began during the late 1960s when R.J. Ikola began acquiring gravity data for the Minnesota Geological Survey (Ikola, 1968, 1970; Chandler and Schaap, 1991). This surveying used spot elevations spaced approximately 0.8 to 1.6 kilometers apart along available roads, trails, and lakeshores. These gravity data have subsequently been used with magnetic anomaly data to supplement geologic mapping in the complex, either through direct use of the Bouguer anomaly data (Bonnichsen, 1972; Davidson, 1972; Sims, 1972) or through use of second derivative-enhanced data (Chandler, 1990; Miller and Chandler, 1999). Miller and others (1990) used gravity modeling to help argue that the granophyric rocks at the top of the Sonju Lake intrusion (Fig. 3.1) are too thick to simply be the upper differentiates of that intrusion. Gravity modeling has also been used to investigate the deep structure of the complex (Ferderer, 1982; Chandler and Ferderer, 1989; Allen, 1994; Chandler and Lively, 1998). Collectively, these studies indicate that the complex may be more than 10-kilometers-thick, and that the average dip of the basal contact varies from less than 30° along the northwestern margin, to 45° or more along much of the western margin. Chandler and Lively (1998) suggested that the low-to-moderate dips of the floor along the northwestern part of the complex might be accounted for by sagging, or by a series of small displacement, northeast-striking tensional faults forming a “step and riser” geometry along the floor of the complex (Weiblen and Morey, 1980; Chandler and Ferderer, 1989). In their model, the southeast-downwards displacement is truncated

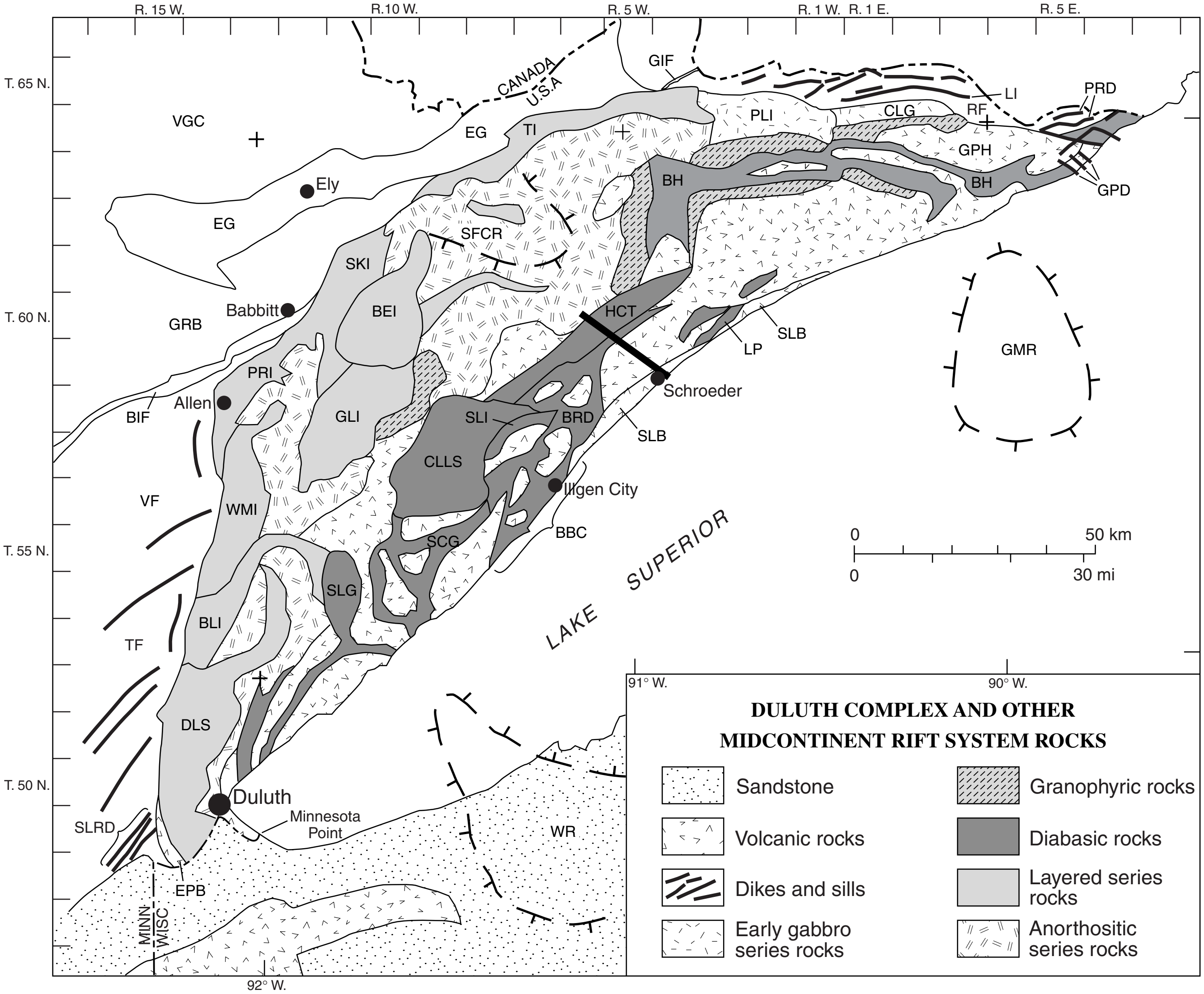

Figure 3.1. Generalized geologic map of the Duluth Complex and associated rocks. The outer boundary correlates with the edges of the data grids shown in Figures 3.3, 3.4, 3.5, and 3.6. The approximate position of the seismic profile in Figure 3.2 is shown by a heavy solid line. Geology generalized from Morey and others (1982) and Miller and others (2001). Abbreviations approximately locate features discussed in the text, and are defined as follows:

BEI—Bald Eagle intrusion
BIF—Biwabik Iron Formation (Paleoproterozoic)
BLI—Boulder Lake intrusion
BBC—Beaver Bay Complex
BH—Brule Lake and Hovland gabbros
BRD—Beaver River diabase
CLG—Crocodile Lake gabbro
CLLS—Cloquet Lake layered series
DLS—Layered series at Duluth
EG—Ely Greenstone (Archean)
EPB—Ely's Peak basalts
GIF—Gunflint Iron Formation
GLI—Greenwood Lake intrusion
GPH—Grand Portage basalts & Hovland lavas
GRB—Giants Range batholith (Archean)
GPD—Grand Portage dikes
HCT—Houghtaling Creek troctolite
LI—Logan intrusions
LP—Leveaux porphyritic diorite
PLI—Poplar Lake intrusion
PRD—Pigeon River diabase
PRI—Partridge River intrusion
RF—Rove Formation (Paleoproterozoic)
SCG—Silver Creek gabbro
SLRD—St. Louis River dikes
SLB—Schroeder–Lutsen basalts
SKI—South Kawishiwi intrusion
SLG—Sawmill Lake gabbro
SLI—Sonju Lake intrusion
TF—Thomson Formation (Paleoproterozoic)
TI—Tuscarora intrusion
VGC—Vermilion Granitic Complex (Archean)
VF—Virginia Formation (Paleoproterozoic)
WMI—Western Margin intrusion

Areas with heavy hatchures designate basement highs as follows:

GMR—Grand Marais ridge
SFCR—Schroeder–Forest Center ridge
WR—White's ridge

to the west by vertical, north–northwest-striking tear faults, thereby accounting for the generally steeper dips that are estimated for the western contact of the complex.

Gravity surveying has been conducted by several private companies searching for ore minerals at the base of the Duluth Complex, but few of these studies have become publicly available. In 1969, Humble Refining Company (Exxon Corporation) used a short gravity profile to help locate the basal contact in T. 58 N., R. 14 W., secs. 21 and 22 near Allen (Fig. 3.1; Minnesota Department of Natural Resources Exploration Archives [DNR]). In 1974, the New Jersey Zinc and American Shield Companies acquired detailed gravity grids (stations spaced every 100 feet [30 meters] along lines 400 feet [122 meters] apart) over the Longnose and Longear oxide-ultramafic intrusions in T. 59 N., R. 13 W., secs. 23 and 26, respectively (DNR). This surveying revealed that surprisingly strong anomalies, with amplitudes of 2 to 3 milligals, are associated with these small, but very dense intrusions.

Magnetic survey methods

Magnetic surveying predated all other geophysical methods in the Lake Superior region. During the search for iron ore in the late 19th and early 20th centuries, private surveys using compass and dip needle were conducted in many areas within and adjacent to the Duluth Complex. Broderick (1917, 1918) investigated the utility of dip needle and compass surveys for locating titaniferous magnetite deposits in the northern part of the Duluth Complex. Several of Broderick's surveys appeared in an assessment of the titaniferous magnetites of Minnesota by Grout (1949-1950). Schwartz (1943) used a Schmidt Balance magnetometer to trace the basal contact of the Duluth Complex in a glacial deposit-covered area between the Duluth and Allen areas (Fig. 3.1); he acquired 14 east–west profiles with readings taken every 161 meters for this study. Between the late 1940s and the late 1960s, the U.S. Geological Survey conducted aeromagnetic surveys that covered all of Minnesota. The Duluth Complex was surveyed using 1.61 kilometer-spaced lines that were flown 305 meters above the ground (Zietz and Kirby, 1970; Sims, 1972). The complicated, high-amplitude character of the observed anomalies, and the distorting effects of a commonly strong natural remanent magnetization (Jahren, 1965) impeded use of the aeromagnetic data for geologic mapping in the Duluth Complex at that time, although Bonnichsen (1971, 1972) qualitatively used some of the magnetic data for mapping in the southern part of the complex.

In 1979, the Minnesota Geological Survey began a statewide program of high-resolution aeromagnetic surveying with support from the Legislative Commission on Minnesota Resources (LCMR). Surveying over the Duluth Complex was conducted along north–south lines spaced 400 meters apart and flown 150 meters above the ground surface. East–west tie lines were flown 2 kilometers apart. The aeromagnetic data were gridded on a Lambert Projection at an interval of 213.36 meters using minimum curvature (Briggs, 1974). Additional information on the acquisition and compilation of these aeromagnetic data is given in Chandler (1991). In addition to their high resolution, the Minnesota Geological Survey data had advantages over the earlier U.S. Geological Survey data in that they were digitally based, allowing enhancement by a variety of computer-processing and graphic schemes.

The Minnesota Geological Survey aeromagnetic data have been used in a variety of geologic investigations of the Duluth Complex. Modeling of magnetic anomaly data has been a useful supplement to gravity modeling of the Duluth Complex (Ferderer, 1982; Chandler and Ferderer, 1989; Chandler and Lively, 1998). Derivative-enhanced grids of aeromagnetic and gravity data have been especially helpful in mapping the geology of the poorly exposed central part of the Duluth Complex (Chandler, 1990; Ferderer, 1991; Meints and others, 1993; Allan Spector and Associates, 1995; Miller and Chandler, 1997). Chandler and Ferderer (1989) used modeling and derivative-enhanced aeromagnetic data to investigate the relationship between footwall structure and copper-nickel sulfide mineralization along the northwestern margin of the complex. Several northwest-striking lineaments recognized in this study delineate minor faults in the footwall that may have provided structural controls for some of the copper-nickel mineralization.

Ground-based magnetic surveys have been used effectively to delineate some mineral prospects. For example, magnetic anomalies with amplitudes in excess of 10,000 nanoTeslas were detected in ground surveys by the New Jersey Zinc Company over the Longnose and Longear oxide-ultramafic intrusions (T. 59 N., R. 13 W., secs. 23 and 26; DNR).

Paleomagnetic methods

Paleomagnetic studies have been useful in establishing time–stratigraphic relationships for Keweenawan rocks in the western Lake Superior region (Halls and Pesonen, 1982). A reversed magnetization, with a declination/inclination of about 110°/-60°, characterizes the lower part of the North Shore Volcanic Group (Books, 1968; Palmer, 1970; Books and Green, 1972). Included among the reversed rock units are the Ely's Peak basalt, the Grand Portage basalts and the Hovland lavas (Fig. 3.1; see M-119). Early intrusive rocks that are associated with this reversed magnetization include most of the St. Louis River dikes (Carlton County dikes of Green and others, 1987), the Logan intrusions (Pesonen, 1979; Halls and Pesonen, 1982), the Grand Portage dikes (Green and others, 1987), and the layered mafic intrusions that form the base of the northeastern prong of the Duluth Complex (Beck, 1970), including the Poplar Lake intrusion and the Crocodile Lake gabbro (Fig. 3.1; see M-119). The upper part of the North Shore Volcanic Group (Palmer, 1970; Books, 1972), the Pigeon River dikes (Green and others, 1987), some St. Louis River dikes (Green and others, 1987), most of the Duluth Complex (Jahren, 1965; Beck, 1970), and all of the Beaver Bay Complex (Beck and Lindsley, 1969) possess a younger normal magnetization with a declination/inclination of about 290°/40°. The precise date of the reversed-to-normal transition is unknown, but it appears to have occurred during a time of relatively subdued magmatism between 1107 and 1099 Ma (see Chapter 5). A near-horizontal magnetization with a declination of about 290° is associated with the Fond du Lac sandstone (Watts, 1981), which overlies the North Shore Volcanic Group.

Seismic methods

Seismic refraction and reflection studies in western Lake Superior provide important information regarding the crustal structure beneath the region. Seismic refraction data from western Lake Superior (Anzoleaga, 1971; Halls and West, 1971; Luetgert and Meyer, 1982) estimate primary (P)-wave velocities of 5.0 to 5.6 and 6.0 to 6.5 kilometers per second for the North Shore Volcanic Group and the Duluth Complex, respectively. Deep crustal studies based on seismic refraction data indicate that the crust is about 40-kilometers-thick beneath the Duluth Complex, and that it thickens to over 50 kilometers beneath central Lake Superior (Smith and others, 1966; Halls, 1982). Seismic reflection studies associated with the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) produced conclusive evidence for basement ridges in western Lake Superior (Behrendt and others, 1988; Cannon and others, 1989; Allen, 1994; Allen and others, 1997). These ridges include White's ridge (White, 1966), located about 50 kilometers east of Duluth, and Grand Marais ridge, located about 100 kilometers further northeast (Fig. 3.1). These studies recognized sequences of volcanic rocks that range in thickness from more that 15 kilometers between the ridges, to near zero atop the highest part of the ridges. Interpretations of seismic reflection data by Thompson and others (1990) and Allen (1994) supported the possible correlation of the Schroeder–Lutsen basalts (Fig. 3.1)—the uppermost part of North Shore Volcanic Group—with the Portage Lake Volcanics of Michigan (Miller and Chandler, 1997; Chapter 5). Interpretation of seismic reflection data indicated that Keweenawan sandstones, which lap onto the North Shore Volcanic Group just off the Minnesota shore, thicken beneath Lake Superior along a slope of about 9° (Allen, 1994; Allen and others, 1997).

Compared to western Lake Superior, relatively few seismic surveys have been conducted over the Duluth Complex proper. In 1966, the New Jersey Zinc Company acquired 42 seismic refraction profiles along the western margin of the complex between townships 51 and 61 N. (DNR). This work, which was conducted to help target shallow bedrock areas favorable for airborne electromagnetic surveying, indicated that overburden thickness ranged from zero to over 61 meters (200 feet), and that bedrock velocities (primary-wave) averaged 6.1 kilometers per second (20,000 feet per second). A proprietary seismic reflection profile conducted by Geosource Incorporated between Ely and Schroeder revealed no recognizable reflections over Duluth Complex rocks, although a wedge-like group of highly disrupted, east-dipping reflections was evident for North Shore Volcanic Group rocks near Lake Superior (Fig. 3.2). This wedge appears to apex about 20 kilometers inland and increases to about 3 seconds reflection (two-way travel) time at the Lake Superior shore. Disregarding the effect of dip, a 3 second reflection time would equate to a thickness of 7.5 kilometers of volcanic rocks, using an assumed velocity of 5.0 kilometers per second. The disruptions in this reflective volcanic sequence are most likely caused by intrusions related to the Beaver Bay Complex, which are abundant in the

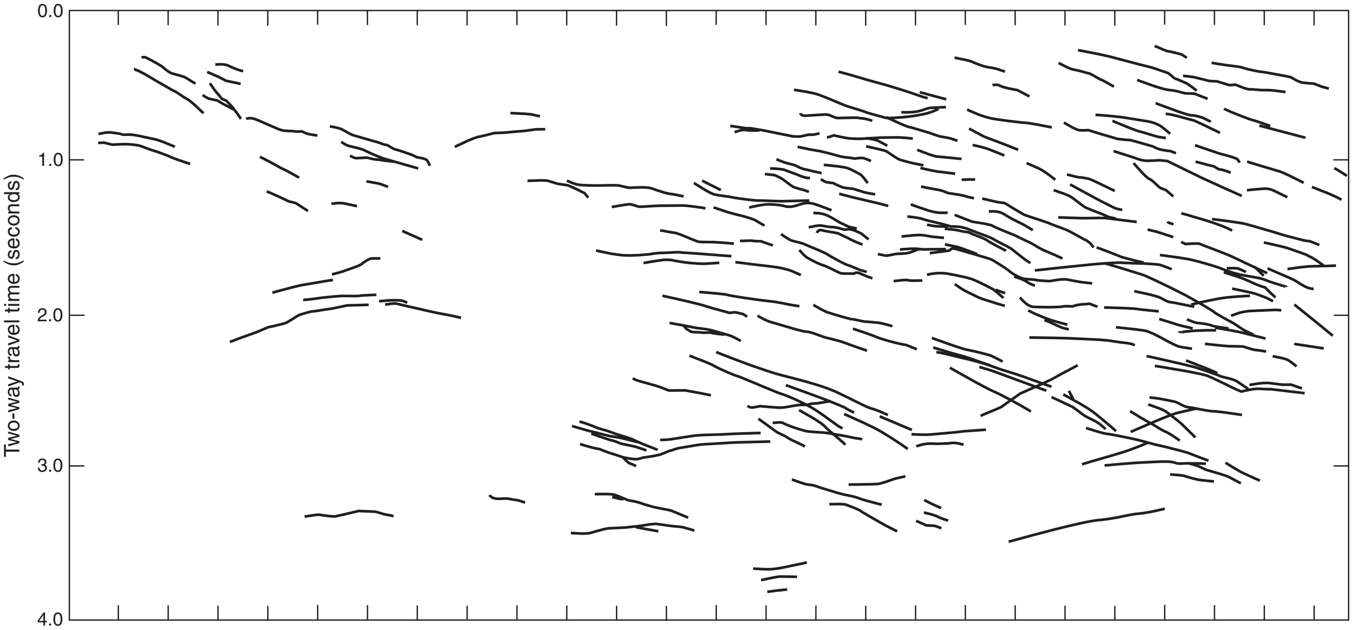

Figure 3.2. Form-line summary of reflections from the south end of Geosource Line 2. Approximate location of this segment is presented on Figure 3.1. Minor horizontal divisions are approximately 1 kilometer.

area (Miller and Chandler, 1997). In fact, the northern part of the seismic profile in Figure 3.2 crosses intrusions of Beaver River diabase and the Houghtaling Creek troctolite (Fig. 3.1).

Electrical and electromagnetic methods

Most of the electrical and electromagnetic studies of the Duluth Complex have been conducted by private companies, and were primarily focused on locating mineral deposits along the basal contact zone. Copper-nickel sulfide deposits, as well as small, oxide-ultramafic intrusions can produce detectable electromagnetic and induced polarization anomalies, provided they lie reasonably close to the surface. Unless otherwise stated, the studies that are described below are selected from exploration archives of the Minnesota Department of Natural Resources. Mineral deposit names and locations are those as defined by Severson (1995), and Hauck and others (1997); see Chapter 2, Figure 2.3 and Chapter 8.

Some of the mineral deposits along the basal contact of the Duluth Complex can be detected by airborne electromagnetic surveying. For example, an INPUT V (© Barringer Research Limited) survey, which was conducted in 1967 for the New Jersey Zinc Company, detected scattered, 2- to 6-channel anomalies in the vicinity of the Wyman Creek (T. 59 N., R. 14 W.) and Wetlegs (T. 59 N., R. 13 W.) sulfide deposits, although no strongly consistent relationships appear to exist. This survey also detected 4- to 6-channel anomalies over the Longnose and Longear oxide-ultramafic intrusions (T. 59 N., R. 13 W.); zones of massive iron oxides are the most likely conductors in these types of bodies, although graphite, which has been reported for similar intrusions elsewhere in the complex (Severson, 1995), may also contribute. The New Jersey Zinc Company survey, as well as other airborne electromagnetic surveys (for example, surveys for Bear Creek Mining Company in Tps. 60 and 61 N., R. 12 W. and Tps. 56 to 58 N., Rs. 13 to 15 W.), indicated strong conductors in the Animikie rocks along the footwall of the complex. These conductors probably consist chiefly of iron oxide-rich zones in the Biwabik Iron Formation and graphitic zones in the Virginia Formation.

Ground-based electromagnetic surveys in the Duluth Complex have been effective in delineating mineral deposits and in the subsequent targeting of exploration holes. For example, horizontal loop electromagnetic surveying by Bear Creek Mining Company over part of the Dunka Pit copper-nickel sulfide deposits (Tps. 60 and 61 N., R. 12 W.) yielded in-phase and out-of-phase anomalies stronger than –20 percent of primary field. Oxide-ultramafic intrusions can also produce in-phase and out-of-phase anomalies stronger than –20 percent of primary field, as evidenced by the New Jersey Zinc Company surveys over the Longnose (T. 59 N., R. 13 W.), Longear (T. 59 N., R. 13 W.), and Section 22 (T. 58 N., R. 14 W.) intrusions, and by an Exxon Corporation survey over the Water Hen intrusion (T. 57 N., R. 14 W.). Older electromagnetic surveys that are based on dip-angle/crossover methods have also been used to help locate exploration targets along the base of the complex; examples include a survey by the New Jersey Zinc Company over the eastern margin of the Dunka Road copper-nickel sulfide deposit (T. 59 N., R. 13 W.) and a survey for Amax Exploration Company south of the Water Hen intrusion (T. 57 N., R. 14 W.).

Mineralization along the base of the Duluth Complex is commonly associated with significant induced polarization signatures. Surveys by the New Jersey Zinc Company along the eastern edge of the Dunka Road copper-nickel sulfide deposit (T. 59 N., R. 13 W.) yielded induced polarization anomalies (time domain) that exceed 80 millivolt-seconds per volt, compared with background values of 10 to 30 millivolt-seconds per volt. Similar surveys by the New Jersey Zinc Company over the Spruce Road copper-nickel sulfide deposit (T. 62 N., R. 11 W.) yielded induced polarization anomalies in excess of 100 millivolt-seconds per volt, although these may actually reflect inclusions of iron-formation. A profile from this study that was adjacent to a test pit in the Spruce Road deposit does not show a discrete induced polarization anomaly, although somewhat high background levels of 50 millivolt-seconds per volt were reported. Many oxide-ultramafic intrusions are associated with induced polarization anomalies; for example, a survey over the Water Hen intrusion (T. 57 N., R. 14 W.) by Exxon Corporation yielded chargeability anomalies in excess of 70 millivolt-seconds per volt. Similarly, surveys by Cleveland Cliffs Incorporated in T. 58 N., R. 14 W. yielded induced polarization anomalies with maximum chargeabilities of 30 to 70 millivolt-seconds per volt, which may reflect extensions of the Skibo and Section 22 intrusions. In addition, the Cleveland Cliffs Incorporated data yielded induced polarization anomalies in excess of 100 millivolt-seconds per volt over the Virginia Formation to the west of the complex, which are probably due to disseminated sulfides or graphite. The Cleveland Cliffs Incorporated data also indicated that an induced polarization anomaly over the Virginia Formation near the center of section 29 corresponds to a 500-millivolt spontaneous potential anomaly. In map view, some of the induced polarization anomalies over the Virginia Formation in T. 58 N., R. 14 W. appear to form northeast-striking bands that could reflect bedrock structure.

The deep structure of the Duluth Complex was investigated in a magnetotelluric study by Adams (1990). A total of 19 stations were established to form two 40-kilometer-long profiles that intersected the basal contact of the complex near Babbitt (T. 60 N., R. 12 W.) and Allen (T. 58 N., R. 14 W.). Models generated to fit the observed magnetotelluric data yielded resistivities of 1 to 100 ohm-meters for Animikie rocks, 4,800 ohm-meters for Archean granitic rocks, and 30,000 ohm-meters for Duluth Complex rocks. Modeling of the magnetotelluric data, supplemented by gravity modeling, indicated abrupt steps in the floor of the Duluth Complex, favoring fault-controlled emplacement of the magmas. Adams suggested that reactivation of north–northeast-striking Archean faults may have accommodated this faulting. A maximum thickness of 11 kilometers was interpreted for the Duluth Complex, and the footwall of the complex was interpreted to consist chiefly of Archean granite with a resistivity of 4,800 ohm-meters. However, the footwall was interpreted to change 15 to 25 kilometers downdip to rocks with resistivities of only 25 to 360 ohm-meters, which Adams (1990) interpreted to represent metasedimentary rocks of either Archean or early Proterozoic age.

Heat-flow methods

Heat-flow values observed over Superior Province rocks in the Lake Superior region generally range between 37.6 and 62.7 mW/m^2 (41.8 mW/m^2 = 1 heat-flow unit or HFU), and are fairly typical of stable continental crust (Jessop and Lewis, 1978; Allis and Garland, 1979). According to Allis and Garland, the highest heat-flow values in the Superior Province tend to be associated with granitic rocks. Heat-flow data from Lake Superior indicate a trough of low heat-flow values along the entire north shore of the lake (Hart and others, 1994). Heat-flow values as low as 19.2 mW/m^2 lie off the Minnesota shore, although they rise to around 48.1 mW/m^2 at the tip and in the middle of western Lake Superior. Hart and others (1994) attributed the trough of low heat-flow values to a zone of pre-rift crust that has been highly extended and replaced almost entirely by mafic igneous rocks. Because no evidence of such a zone is evident from interpretations based on seismic reflection data (Cannon and others, 1989; Allen, 1994; Allen and others, 1997), Hart and others proposed that the zone is filled by non-reflective, mafic intrusions.

Radiometric methods

Most publicly available radiometric data in Minnesota are from the 1977 to 1981 airborne surveys of the National Uranium Evaluation (NURE) Program of the U.S. Department of Energy. Lively and Morey (1996) composited gamma-ray spectrometer data from individual NURE surveys into a set of 1:3,168,000-scale statewide maps representing concentrations of uranium, thorium, and potassium, and those are the data described here. In the area that includes the Duluth Complex, uranium ranges from 0.2 to 1.2 equivalent parts per million, radiogenic potassium ranges from 0.4 to 1.6 percent of total potassium, and thorium ranges from 0.5 to 5.0 parts per million. None of these values are significantly different from those observed over much of northeastern Minnesota, and they essentially reflect surficial deposits (Lively and Morey, 1996). However, a concentration of relatively higher levels roughly along the roof of the Duluth Complex implies that granophyric and other felsic bedrock may be contributing locally to these values.

DESCRIPTION OF DETAILED GRAVITY AND MAGNETIC GRIDS

Preparation of the gravity data

For this study, the Minnesota Geological Survey gravity data (described above) were merged with other recently acquired data from areas adjacent to the Duluth Complex. On-land gravity data in Canada were acquired at a spacing of 5 to 10 kilometers by the Geological Survey of Canada, and on-land gravity data in Wisconsin were acquired at a spacing of 0.8 to 1.6 kilometers by the Wisconsin Geological and Natural History Survey. Gravity data from Lake Superior were incorporated using the 6 by 6-kilometer gridded data from the Gravity Anomaly Map of North America (Committee for the Gravity Anomaly Map of North America, 1987). These data in turn were based on lake bottom stations that were spaced 5 to 10 kilometers apart (Wold and Berkson, 1977). Gravity data acquired by the Minnesota Geological Survey since the surveying by Ikola (1968, 1970) have also been incorporated. All gravity data were reduced according to the 1967 Geodetic Reference System (International Union of Geodesy and Geophysics, 1971), and the Bouguer correction assumed a sea-level datum and a density of 2.67 grams per cubic centimeter. Owing to the generally low relief of the area, no topographic corrections were applied.

The merged gravity data were gridded to a Universal Transverse Mercator projection (zone 15) using minimum curvature with the following characteristics: grid interval = 400 meters, and number of rows/columns = 656/746. The gridded Bouguer gravity anomaly data are shown in Figure 3.3. In order to improve the gravity data for geologic mapping, the gridded data were transformed to the second vertical derivative of the gravity anomaly, which enhances the signatures of near-surface sources. To eliminate the minor effect of ledge topography and other noise, the derivative data were slightly smoothed by upward continuation to 2 kilometers above the surface. The processed data were re-gridded in order to register with the magnetic grid using a bi-cubic spline. The second derivative gravity data are shown in Figure 3.4. All gridding, derivative calculation, and continuation were conducted using potential field software of the U.S. Geological Survey (Phillips, 1997).

Principal-fact gravity data, and grids of the Bouguer and second derivative gravity data are available on the CD accompanying this report. Also included on this CD is Miscellaneous Map M-120 (Chandler, 2001), which presents the second derivative gravity data superimposed with first derivative magnetic data.

Preparation of the aeromagnetic data

The Minnesota Geological Survey aeromagnetic data were merged with data from Lake Superior, Canada, Wisconsin, and Michigan to form a large grid approximately centered over the Duluth Complex. Aeromagnetic data for Lake Superior and adjacent parts of Canada, Wisconsin, and Michigan were derived from a large data grid that was composited from various data sets by Teskey and others (1991) for the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE). The core of the GLIMPCE grid was data from Lake Superior that were acquired in 1987 by the Geological Survey of Canada, using north–south flight lines spaced 1,900 meters apart and 300 meters above the surface of Lake Superior (Teskey and others, 1991). Aeromagnetic data acquired in Wisconsin since the GLIMPCE compilation (Cannon and others, 1997; Daniels and others, 1998; Snyder, 1998) were also

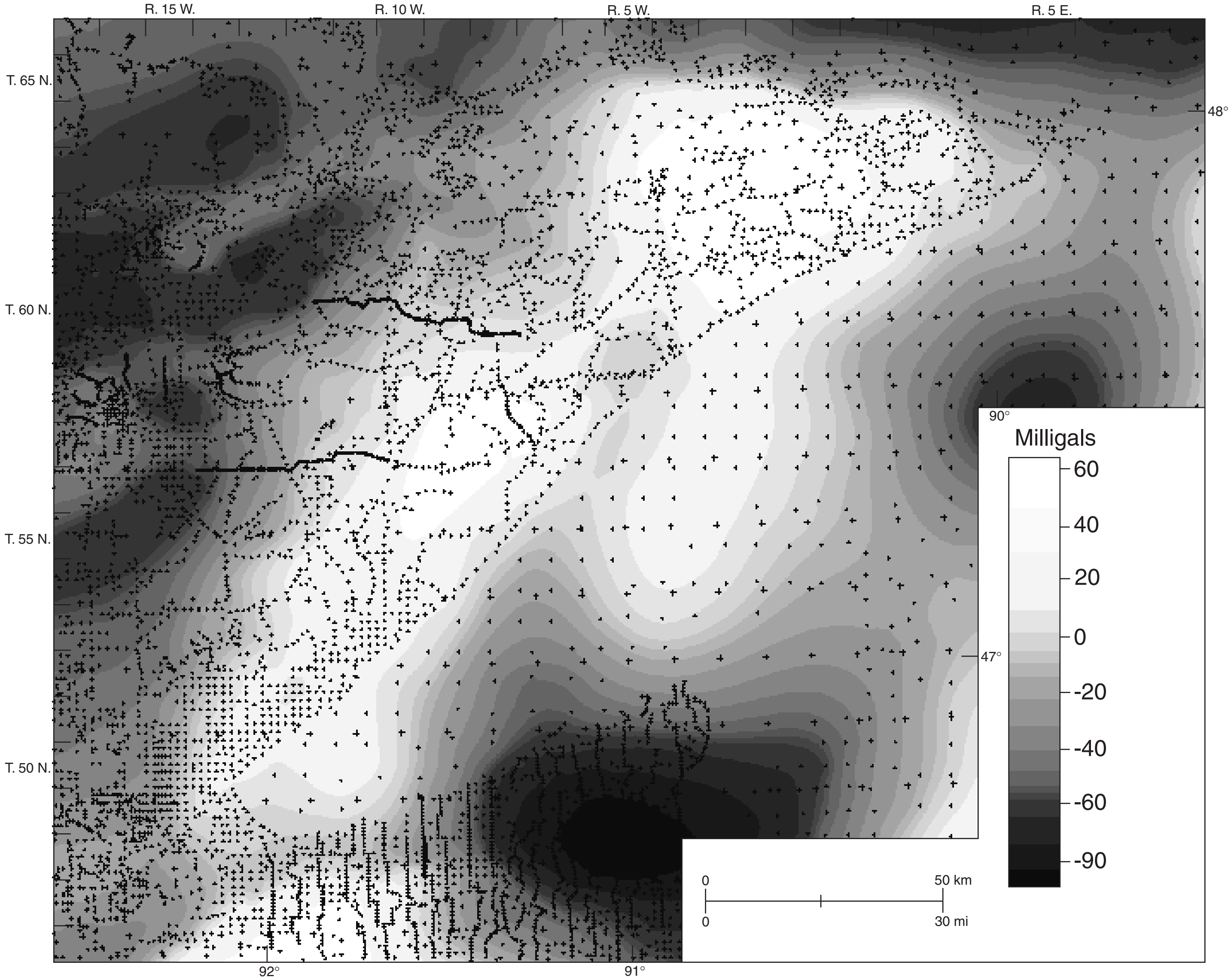

Figure 3.3. Bouguer gravity data, Duluth Complex region. Gravity stations indicated by small crosses, except in Lake Superior where small crosses indicate grid points from the Gravity Anomaly Map of North America (Committee for the Gravity Anomaly Map of North America, 1987). Larger crosses are 7.5 minute ticks.

incorporated into the present study. The GLIMPCE, Wisconsin, and Minnesota Geological Survey data grids were analytically continued to a common level of 150 meters above surface and re-projected into aligned Universal Transverse Mercator grids (zone 15) with a spacing of 213.36 meters. These re-projected grids were subsequently composited into a master grid that has 1,123 columns and 921 rows. Aeromagnetic data for this composited grid are shown in Figure 3.5. All of the grid manipulations were performed using potential field software of the U.S. Geological Survey (Phillips, 1997).

The merged aeromagnetic grid was processed to enhance its use for geologic mapping. Magnetic anomalies in the Duluth Complex tend to be skewed relative to their sources because of a strong natural remanent magnetization that is moderately inclined to the west (Chandler, 1990). This effect was mitigated by transforming the data to approximate vertical magnetic polarization (reduced to pole), assuming a source polarization

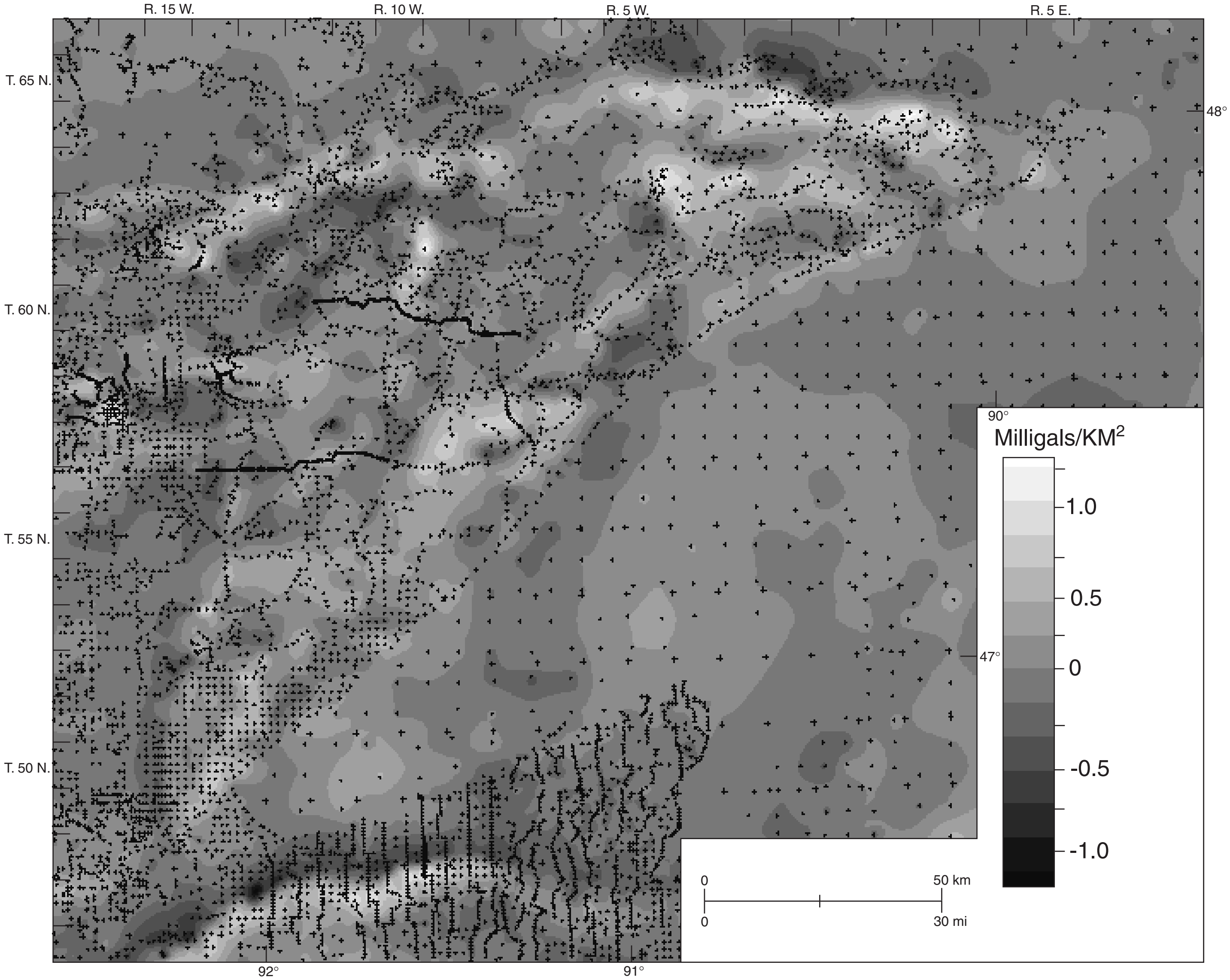

Figure 3.4. Second vertical derivative of gravity data, Duluth Complex region. Data slightly smoothed by upward-continuation to 2 kilometers above the surface. Gravity stations indicated by small crosses, except in Lake Superior where small crosses indicate grid points from the Gravity Anomaly Map of North America (Committee for the Gravity Anomaly Map of North America, 1987).

directed along a declination/inclination of 295°/50°, and an earth field with a declination/inclination of 2°/76°. The source polarization is based on a natural remanent magnetization that is directed along a declination/inclination of 290°/40°, and is three times stronger than the induced magnetization, all of which approximate the mid-range of values that were observed in previous studies of rock magnetization (Chandler, 1990). The earth's field declination/inclination were derived from the International Geomagnetic Reference Field (IGRF) model using the program GEOMAG (National Oceanic and Atmospheric Administration, 1995); the calculations assumed a latitude/longitude of 47.75° north/91° west, an elevation 1,500 feet above mean sea level, and a date of 1981.0. The reduced-to-pole magnetic data were further transformed to the first vertical derivative of the magnetic anomaly, which strongly emphasizes the signatures of sources at or near the

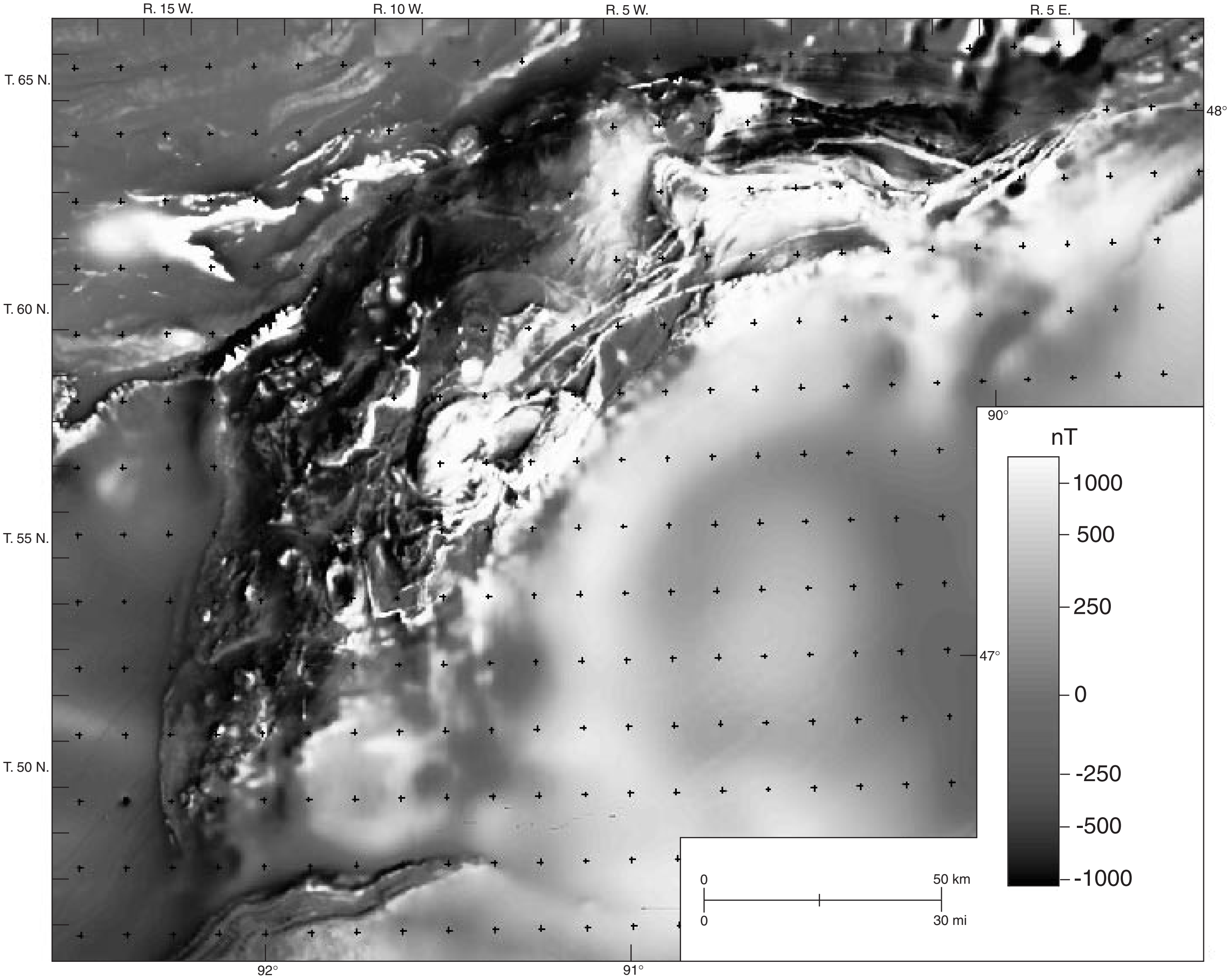

Figure 3.5. Total field aeromagnetic data, Duluth Complex region. Crosses are 7.5 minute ticks.

bedrock surface, and severely attenuates the signatures of deeply buried sources. The first vertical derivative data for the entire grid area are shown in Figure 3.6, and detailed subsets are shown in Figures 3.7 and 3.8. Reduction to pole and derivative calculations were performed using potential field software of the U.S. Geological Survey (Phillips, 1997).

Grids of the unfiltered aeromagnetic data and the derivation-enhanced reduced-to-pole magnetic data are included in the CD accompanying this report.

Density, magnetic susceptibility, and natural remanent magnetization data

Geologic interpretation of gravity and magnetic anomaly data in a given area is greatly enhanced by density, magnetic susceptibility, and natural remanent magnetization data for representative rock-types. Along with outcrop and drill-hole information, such rock-property data help to relate anomaly signatures to probable rock units, and provide important constraints for using anomaly data, both as a mapping tool and for modeling geology at depth. Unfortunately, studies presenting density, magnetic susceptibility, and

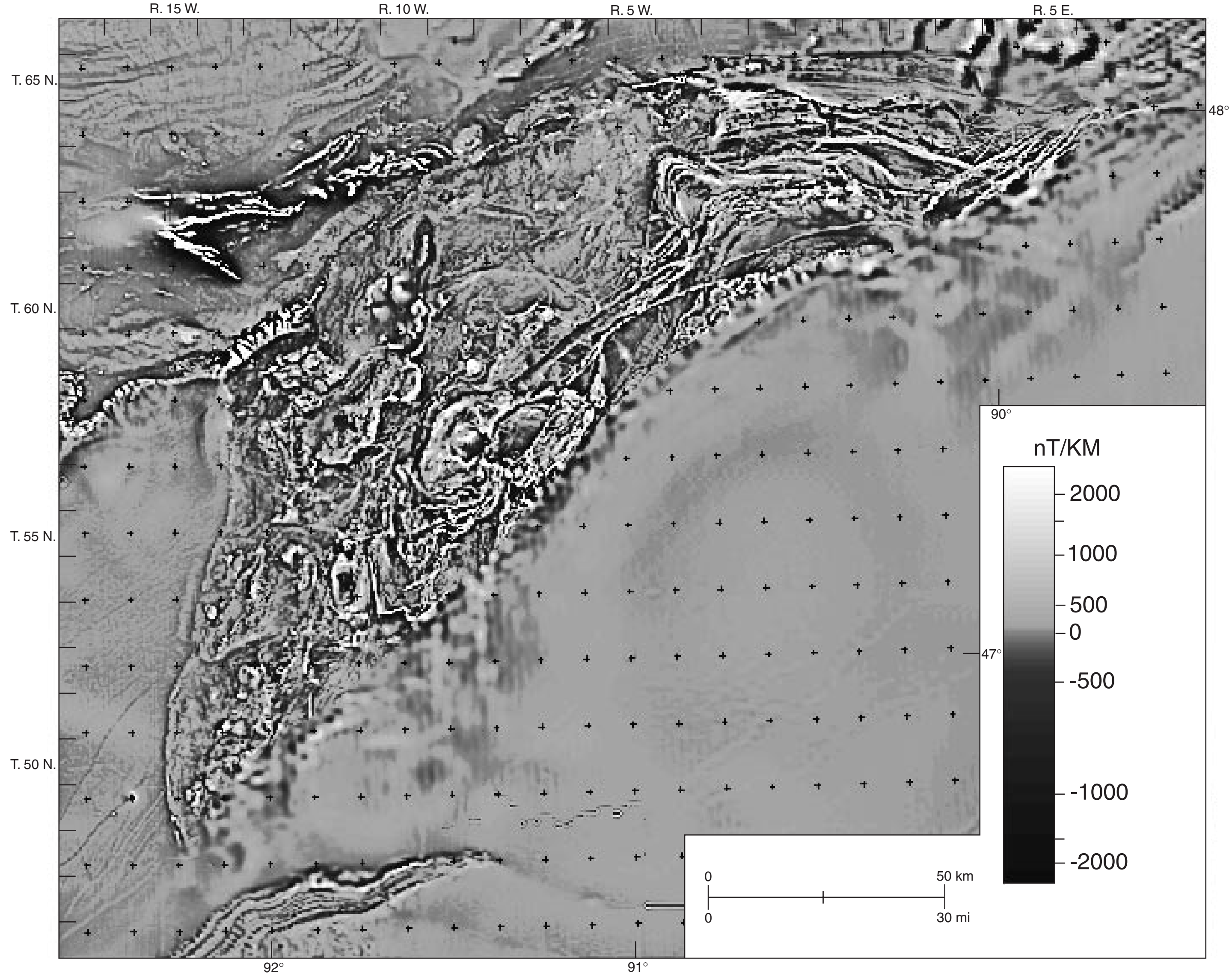

Figure 3.6. First vertical derivative of aeromagnetic data, Duluth Complex region. Data reduced to vertical polarization assuming a normally directed natural remanent magnetization that is normal for Keweenawan rocks. Minor reduction to pole errors may persist in the Duluth Complex and Keweenawan sequence, and significant reduction to pole errors may exist for Archean and Paleoproterozoic rocks outside the Duluth Complex. Crosses are 7.5-minute ticks. North–south linear high just north of 46°52′30″ N., 92°07′30″ W. is a compilation artifact.

natural remanent magnetization data for the Duluth Complex are relatively few (Beck, 1969; Chandler, 1990; Chandler, 1993), and tend to be somewhat limited in scope. Many of the above-cited paleomagnetic studies were chiefly concerned with the direction (and not intensity) of the natural remanent magnetization, and did not include data for density or magnetic susceptibility. Therefore, considerable effort was made during this project to compile a new, GIS-based database of density, magnetic susceptibility, and natural remanent magnetization values for the Duluth Complex and associated rocks.

Most of the density and magnetization data reported here (Tables 3.1, 3.2, and 3.3) were acquired during the last two decades by the Minnesota Geological Survey as part of an ongoing rock properties program. The U.S. Geological

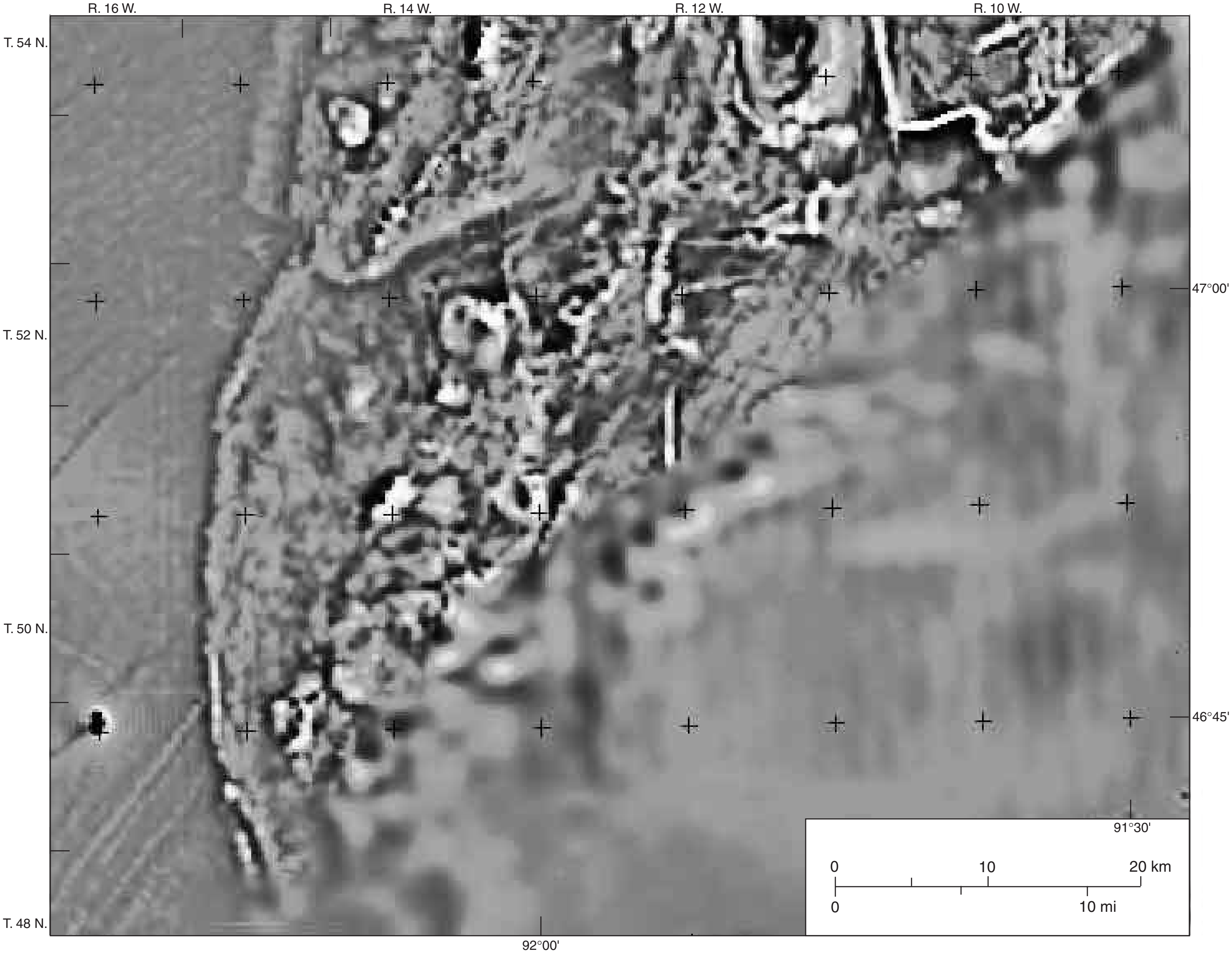

Figure 3.7. Detail of the first vertical derivative data for the southern part of the Duluth Complex. Gray-scale is the same as shown in Figure 3.6.

Survey acquired additional data in support of several earlier projects in northeastern Minnesota (Bath, 1962; Jahren, 1965; Sims, 1972). For both data sets preference was given to samples that included both density and magnetic susceptibility determinations. The combined database includes density and magnetic susceptibility data for 517 samples of Archean and Paleoproterozoic rocks (summarized in Table 3.1) and 362 samples of the Duluth Complex and associated Keweenawan rocks (summarized in Table 3.2). Also included are natural remanent magnetization data for 133 samples of the Duluth Complex and associated rocks (Table 3.3). No natural remanent magnetization data for Archean and Paleoproterozoic rocks are presently available, but previous studies by Symons (1966, 1967) and Sims (1972) indicated that natural remanent magnetization in these rocks tends to be weak, scattered, or sub-parallel to the present earth's field. Therefore, magnetic susceptibility should be a reasonable gauge of magnetization for Archean and Paleoproterozoic rocks. The full database from which Tables 3.1, 3.2, and 3.3 were

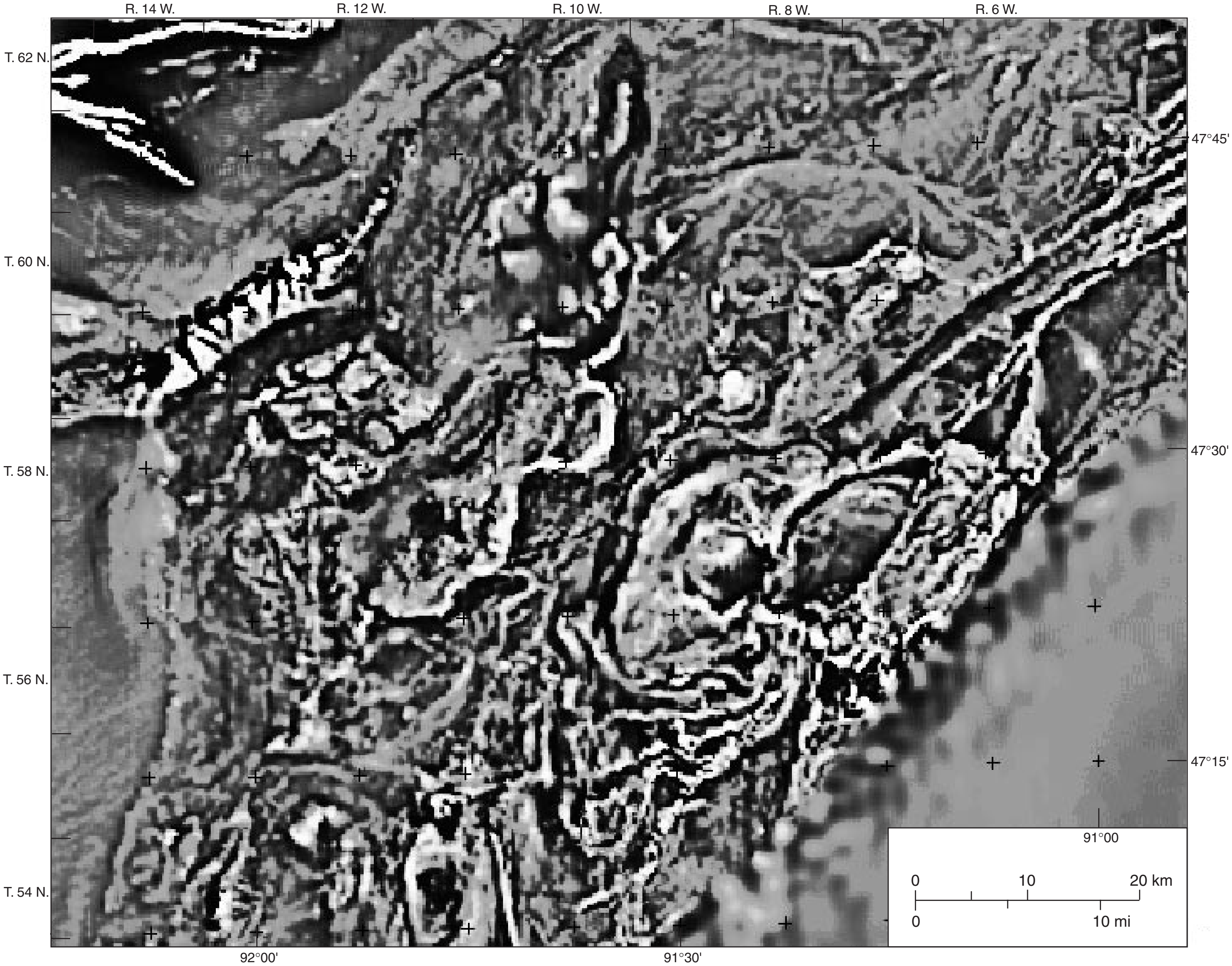

Figure 3.8. Detail of first vertical derivative data for the central part of the Duluth Complex. Grayscale is the same as shown in Figure 3.6.

derived is provided on the CD accompanying this report.

In the discussion to follow, terms used to describe density, magnetic susceptibility, and natural remanent magnetization values are defined as follows:

Density:
- *Low*: less than 2,700 kilograms/cubic meter
- *Moderate*: 2,700 to 2850 kilograms/cubic meter
- *High*: 2,851 to 3,000 kilograms/cubic meter
- *Very high*: greater than 3,000 kilograms/cubic meter

Magnetic susceptibility:
- *Low*: less than 0.0030 SI (Système Internationale)
- *Moderate*: 0.0030 to 0.0120 SI
- *High*: 0.0121 to 0.0630 SI
- *Very high*: greater than 0.0630 SI

Natural remanent magnetization:
- *Low*: less than 0.1430 SI
- *Moderate*: 0.1430 to 0.5730 SI
- *High*: 0.5731 to 3.0000 SI
- *Very high*: greater than 3.0000 SI

Table 3.1. Density and magnetic susceptibility (k) for Archean and Paleoproterozoic rocks surrounding the Duluth Complex. All units are SI. Animikie slate includes samples of the Rove, Thomson, and Virginia Formations, and Animikie iron-formation includes samples of the Biwabik and Gunflint Iron Formations.

Major association Rock-type	mean density	minimum density	max. density	mean k	median k	minimum k	maximum k	no. samples
Penokean orogen								
Animikie slate	2753	2650	2850	0.00063	0.00065	0.00013	0.00116	26
Animikie iron-formation	3147	2670	3920	0.43681	0.28338	0.00062	1.65742	21
Wawa subprovince								
Syenite	2644	2520	2860	0.01097	0.00050	0.00000	0.07957	10
Hypersthene gabbro	2948	2890	3020	0.00066	0.00038	0.00025	0.00128	5
Clinopyroxenite	2962	2610	3150	0.00408	0.00038	0.00000	0.03142	12
Granite	2613	2490	2860	0.00082	0.00013	0.00000	0.00804	33
Hornblende granite	2688	2590	2790	0.01318	0.00527	0.00041	0.03358	10
Monzonite–qtz. monzonite	2695	2390	3100	0.00520	0.00050	0.00000	0.04273	43
Granodiorite–tonalite	2650	2250	2880	0.00211	0.00013	0.00000	0.01508	25
Gneiss	2740	2650	2840	0.00223	0.00107	0.00075	0.00513	5
Dacitic–andesitic porphyry	2718	2500	3200	0.00094	0.00025	0.00000	0.00792	13
Biotite schist	2742	2490	3120	0.00154	0.00019	0.00000	0.01508	42
Conglomerate	2731	2340	3170	0.00080	0.00038	0.00000	0.00352	23
Graywacke and tuff	2780	2390	3120	0.00067	0.00038	0.00000	0.00352	43
Metaslate	2758	2580	3010	0.00133	0.00045	0.00000	0.01495	26
Iron-formation	2978	2620	3840	0.19599	0.02513	0.00033	1.11841	11
Felsic tuff	2726	2410	3070	0.00124	0.00038	0.00000	0.01081	51
Mafic tuff	2858	2430	3070	0.01018	0.00075	0.00000	0.04775	14
Basalt to andesite	2888	2320	3190	0.00538	0.00050	0.00000	0.12566	78
Metagabbro–metadiorite	2916	2580	3220	0.00913	0.00088	0.00000	0.06032	26
							Total	517

Description of unfiltered gravity and magnetic data

The unfiltered gravity (Fig. 3.3) and magnetic (Fig. 3.5) data display a variety of signatures, reflecting a wide range of geologic structures and associated density and magnetization contrasts. Terms describing the anomaly amplitudes are defined as follows:

Gravity anomaly amplitude:
- *Weak*: less than 5 milligals
- *Moderate*: 5 to 15 milligals
- *Strong*: greater than 15 milligals

Magnetic anomaly amplitude:
- *Weak*: less than 100 nanoTeslas
- *Moderate*: 100 to 500 nanoTeslas
- *Strong*: 501 to 5,000 nanoTeslas
- *Very strong*: greater than 5,000 nanoTeslas

Strong gravity and magnetic signatures west and northwest of the Duluth Complex reflect significant contrasts in density and magnetization among Archean and Paleoproterozoic rocks (Figs. 3.3 and 3.5). An elongate, strong gravity high, which strikes east–northeast across the northwestern part of the area (T. 62 N., R. 15 W. to T. 63 N., R. 10 W., Fig. 3.3), corresponds to the Archean Ely Greenstone (Fig. 3.1), which consists of high density rocks including basalt, andesite, mafic tuff, metagabbro sills, and iron-formation (Table 3.1). Most greenstone rocks typically have low magnetic susceptibilities and produce weak magnetic signatures, but associated iron-formations have very high magnetic susceptibilities and generate very strong (greater than 5,000 nanoTeslas), curvilinear magnetic highs (Table 3.1; Fig. 3.5). South of the Ely Greenstone (between T. 60 N., R. 16 W. and T. 62 N., R. 10 W.), a strong

Table 3.2. Density and magnetic susceptibility (k) for the Duluth Complex and Keweenawan rocks. All units are SI.

Rock-type	average density	min. density	max. density	average k	median k	minimum k	maximum k	no.
Fond du Lac sandstone	2373	2270	2530	0.00096	0.00032	0.00011	0.00437	6
Beaver River diabase	2897	2850	2960	0.00886	0.00687	0.00578	0.03679	3
Cloquet Lake layered series gabbro	2966	2860	3140	0.05831	0.04901	0.00503	0.11687	5
Silver Creek gabbro	2909	2800	2960	0.03761	0.03016	0.00324	0.08419	18
Sills in North Shore Volcanic Group								
Granophyric rocks	2697	2660	2730	0.06220	0.06283	0.04021	0.09048	6
Diabasic rocks	2867	2730	2990	0.04685	0.03951	0.00312	0.15039	39
North Shore Volcanic Group								
Felsic lavas	2597	2410	2750	0.01463	0.00200	0.00029	0.10059	10
Intermediate lavas	2810	2680	2960	0.07363	0.05955	0.03428	0.16336	8
Basaltic lavas	2837	2510	3020	0.02781	0.01307	0.00049	0.14285	27
Altered lavas	2886	2780	2980	0.05768	0.08093	0.00327	0.11003	5
Ely's Peak basalts	2930	2843	3076	0.00502	0.00129	0.00067	0.04147	20
Duluth Complex								
Bald Eagle intrusion (core gabbro)	3013	2970	3070	0.00219	0.00238	0.00109	0.00293	4
Bald Eagle intrusion (ring troctolite)	2951	2730	3150	0.00766	0.00613	0.00474	0.01773	8
Greenwood Lake intrusion gabbro	3138	3050	3210	0.04733	0.04618	0.03896	0.05799	4
Granitic and granophyric rocks	2629	2520	2830	0.01564	0.00710	0.00038	0.04511	10
Granodioritic rocks	2812	2660	2990	0.13121	0.10968	0.03403	0.29616	5
Anorthositic series gabbros	2838	2760	3130	0.02434	0.01957	0.00080	0.23228	32
Layered series troctolites	2940	2710	3240	0.00849	0.00606	0.00000	0.06786	128
St. Louis River dikes	2965	2780	3050	0.01515	0.01475	0.00087	0.02968	24
							Total	362

gravity low reflects the Giants Range batholith (Fig. 3.1), which includes masses of granite, monzonite, granodiorite, tonalite, and gneiss that are typically of low density (Table 3.1). Weak to moderate magnetic signatures characterize the parts of the batholith that consist of tonalite, gneiss, and granite (generally low magnetic susceptibilities from Table 3.1), whereas, those parts that are associated with moderate to strong magnetic signatures correlate with monzonites, granodiorites, and hornblende granites (moderate to high magnetic susceptibilities from Table 3.1). In the northwestern corner of the area (around T. 64 N., R. 17 W.), a subtly banded, weak to moderate magnetic signature and weak to moderate gravity lows (Figs. 3.2 and 3.5) reflect migmatized granitic and metasedimentary rocks of the Vermilion Granitic Complex (Fig. 3.1), where magnetic highs mark zones of granitic rocks and magnetic lows mark zones of biotite schist.

In the west-central part of the area, a narrow, sinuous belt of strong magnetic highs (between T. 58 N., R. 17 W. and T. 60 N., R. 12 W., Fig. 3.5) reflects the Paleoproterozoic Biwabik Iron Formation (Fig. 3.1), which typically has very high magnetic susceptibilities (Animikie iron-formation in Table 3.1). The magnetic highs associated with the Biwabik Iron Formation become very strong

Table 3.3. Natural remanent magnetization data for the Duluth Complex and Keweenawan rocks. An earth's field intensity of 59,856 nanoTeslas was used to calculate induced magnetization and was derived from program GEOMAG (National Oceanic and Atmospheric Administration, 1995), assuming a latitude/longitude of 47.75° N./91° W., an elevation 1,500 feet above mean sea level, and a date of 1981.0. All units are SI.

J = natural remanent magnetization polarization
dec. = declination of natural remanent magnetization
inc. = inclination of natural remanent magnetization (positive downwards)
I = induced polarization
Q = ratio of J to I

Rock unit	average J	median J	ave. dec.	med. dec.	ave, inc.	med. inc.	ave. I	median I	ave. Q	med. Q	no.
Beaver Bay Complex											
Ferrogabbro	3.311	3.742	302	301	48	47	2.275	2.334	1.46	1.60	5
Diabase	9.951	10.415	291	295	39	37	1.467	1.646	6.78	6.33	6
Silver Creek gabbro	14.886	12.698	288	283	35	39	1.875	1.437	7.94	8.84	16
Sills in the North Shore Volcanic Group, diabase	3.307	2.931	301	292	49	57	2.355	1.550	1.40	1.89	17
North Shore Volcanic Group, basalts	9.593	2.473	303	295	30	41	1.501	0.550	6.39	4.50	6
North Shore Volcanic Group, Ely's Peak basalts	2.679	0.738	302	290	27	67	0.730	0.796	3.67	0.93	5
Duluth Complex											
Anorthositic rocks	5.753	5.470	307	296	58	70	0.951	0.995	6.05	5.50	6
Troctolitic rocks	1.747	1.237	294	291	47	46	0.346	0.284	5.05	4.36	55
St. Louis River dikes											
Diabase, normal polarity	5.772	5.999	296	291	46	50	0.966	1.064	5.97	5.64	6
Diabase, reversed polarity	4.190	3.647	110	103	-64	-63	0.641	0.702	6.54	5.19	16

near the basal contact of the Duluth Complex, reflecting a strong natural remanent magnetization overprint of the iron-formation from Duluth Complex magmas (Bath, 1962). The area of weak magnetic signatures south of the Biwabik Iron Formation and west of the Duluth Complex (between T. 49 N., R. 17 W. and T. 58 N., R. 15 W., Fig. 3.5) reflects a thick sequence of essentially non-magnetic graywackes and slates (Virginia and Thomson Formations, Fig. 3.1) of the Animikie Group (Table 3.1). Two east-striking gravity highs and an intervening gravity low in the northern part of the Animikie basin (between T. 57 N., R. 17 W. and T. 57 N., R. 15 W., Fig. 3.3) most likely reflect Archean metavolcanic and granitic rocks, respectively, that underlie the Animikie rocks.

Strong gravity and magnetic signatures characterize the Duluth Complex (Figs. 3.3 and 3.5). The base of the Duluth Complex is associated with a sharp rise in gravity anomaly values (Fig. 3.3), reflecting the significantly higher densities of the troctolitic rocks at the base relative to those of most Archean and Paleoproterozoic rocks that form the footwall (Tables 3.1 and 3.2). The magnetic signature of the northern, northwestern, and western parts of the Duluth Complex is dominated by a strong, regional minimum (Fig. 3.5), implying that reversed magnetization may be present. However, reversed magnetization is known only for the volcanic rocks at the eastern and southern tips of the complex (Books, 1972; Books and Green, 1972; Davidson and others, 1976), and for two intrusions (Poplar Lake intrusion and Crocodile Lake gabbro) along the far northern margin of the Duluth Complex (Beck, 1970; Miller and others, 2001). Normal magnetization, directed along a declination/inclination of about 290°/40°, dominates the rest of the complex, and is commonly much stronger than induced magnetization (Jahren, 1965; Beck, 1970; Chandler, 1990; Table 3.3). Modeling of magnetic data (Ferderer, 1982; Chandler and Ferderer, 1989; Chandler and Lively, 1998) indicate that the large magnetic minimum along the western and northwestern margin of the complex is most likely a geometric effect of east and southeast-dipping sources having a normally directed magnetization that generally increases towards the interior of the complex. Strong, dot-like magnetic highs along the margin of the southern part of the Duluth Complex (Fig. 3.5) reflect either oxide-ultramafic intrusions or inclusions of hornfelsed volcanic rocks (see M-119).

Distinct gravity and magnetic anomalies correlate with individual intrusions in the interior of the Duluth Complex. A moderate gravity high associated with the Bald Eagle intrusion in the northwestern part of the complex (Tps. 61 and 62 N., R. 10 W., Figs. 3.1 and 3.3) is consistent with the higher density of the Bald Eagle rocks, relative to that of the surrounding anorthositic rocks (Table 3.2), and may, in part, reflect a subsurface feeder (Weiblen, 1965; Chandler, 1990). Two broad and strong gravity highs dominate the gravity signature of the complex (Fig. 3.3), and they correlate closely with strong, highly complex magnetic highs (compare Figs. 3.3 and 3.5). These two highly anomalous zones are interpreted to reflect dense, strongly magnetic intrusive centers within the volcanic roof of the complex; among other units, these centers include the Brule Lake–Hovland gabbros to the north and the Cloquet Lake layered series and Sonju Lake intrusion to the south (Tables 3.2 and 3.3; Fig. 3.1). Strong, linear-to-curvilinear magnetic highs extending between and beyond these two intrusive centers (Fig. 3.5) are interpreted to be dike-and-sill-like masses of mafic rocks, including the Pigeon River diabase, the Houghtaling Creek troctolite, the Beaver River diabase, the Leveaux porphyritic diorite, the Sawmill Lake gabbro, and the Silver Creek gabbro (Fig. 3.1; Miller and others, 2001). Compared to the intrusive rocks, relatively little magnetic signature can be ascribed to the low-dipping lavas of the North Shore Volcanic Group. Southeastwards from the Lake Superior shore, magnetic signatures become progressively more subdued, reflecting burial of anomaly sources by relatively younger Keweenawan sedimentary rocks. A buried intrusive center that may be similar to the one in the Cloquet Lake area is inferred from sub-circular gravity and magnetic highs about 20 kilometers east of Duluth (offshore from T. 51 N., R. 12 W., Figs. 3.3 and 3.5). Irregular magnetic highs appear to connect this inferred intrusive center with the Beaver River diabase and the Sawmill Lake–Silver Creek gabbros on shore (Figs. 3.1 and 3.3).

A negative gravity saddle that extends across the northwestern part of the Duluth Complex, and between the previously discussed gravity highs, (Fig. 3.3) may reflect relatively lower-density anorthositic rocks, which dominate this part of the complex (Fig. 3.1; Table 3.2). This gravity saddle could also reflect thinning of the Duluth Complex against a pre-Keweenawan basement high, the Schroeder–Forest Center Ridge (Fig. 3.1; Chandler, 1990; Allen, 1994; Miller and Chandler, 1997). This saddle aligns to the south with White's ridge in western Lake Superior (Fig. 3.1; White, 1966; Allen and others, 1997), and inclusions of pre-Keweenawan rocks are known in one intrusive unit in the saddle (Miller and Chandler, 1997; M-119).

Description of derivative gravity and magnetic data

The second derivative gravity data (Fig. 3.4) and the reduced-to-pole first vertical derivative magnetic data (Figs. 3.6, 3.7, and 3.8) display highly distinct anomaly patterns that are interpreted to outline mappable bedrock units. These data were used extensively in creating map M-119, especially in the poorly exposed central interior and western margin of the complex. Shaded relief presentations of total field magnetic anomaly data are used in Chapters 4, 6, and 7 to illustrate the magnetic signatures of geologic units, but derivative data were actually used in map compilation. Details beyond those shown on Figures 3.1 and 3.3 through 3.8 are available on M-119 and M-120 on the CD. Terms describing the derivative anomaly data are defined as follows:

Derivative gravity anomaly amplitude:
  Weak: less than 0.10 milligals/square kilometer
  Moderate: 0.10 to 0.0.5 milligals/square kilometer
  Strong: greater than 0.5 milligals/square kilometer

Derivative magnetic anomaly amplitude:
  Weak: less than 100 nanoTeslas/kilometer
  Moderate: 100 to 500 nanoTeslas/kilometer
  Strong: greater than 500 nanoTeslas/kilometer

Derivative magnetic anomaly character:
  Subdued: expression that is noticeably flat or weak
  Busy: many highs and lows packed closely together

Along the western margin of the complex, the first vertical derivative magnetic data (Figs. 3.4 and 3.6) indicate several small offsets in the basal contact that have been interpreted as minor faults (Figs. 3.7 and 3.8; M-119). A large cusp in the basal contact near 47° north occurs at the junction of the layered series at Duluth and the Boulder Lake intrusion (Tps. 52 and 53 N., R. 15 W., Figs. 3.1, 3.6, and 3.7). Narrow, northeast-striking magnetic anomalies beyond the western contact of the complex (Fig. 3.7) delineate a swarm of diabase dikes (the St. Louis River dikes) cutting the Animikie Thomson Formation (Fig. 3.1), and the predominantly negative sign of many of these anomalies indicate reversed magnetic polarity. Most dike anomalies are abruptly truncated by the Duluth Complex, but a few of the negative dike signatures fade out within a few kilometers of the complex (Fig. 3.7), possibly reflecting thermal resetting from Duluth Complex magmas. An intense magnetic low near the southern tip of the complex (T. 49 N., R. 16 W., Fig. 3.7) is interpreted to be a small plug of magnetically reversed gabbro. A belt of weak magnetic highs that lies immediately west of the Boulder Lake intrusion (T. 53 N., R. 15 W., Fig. 3.7) has been interpreted by Allan Spector and Associates (1995) to reflect a sill in the Animikie wallrock. Similarly, a belt of weak magnetic signature outbound from the southern extension of the Partridge River intrusion (T. 58 N., R. 14 W., Fig. 3.8) is interpreted as a sill-like body within Animikie rocks.

Reversely magnetized intrusions along the northern rim of the complex, including the Poplar Lake intrusion and the Crocodile Lake gabbro (Fig. 3.1; Beck, 1970; M-119), are characterized by a strong positive derivative gravity signature (Fig. 3.4) and a moderate-amplitude, banded derivative magnetic signature (Fig. 3.6). To the north, the area underlain by near-horizontal Animikie slate (Rove Formation; Fig. 3.1) and Logan intrusions (reversed magnetic polarity; Beck, 1970; Pesonen, 1979) is characterized by a strong negative derivative gravity signature and a distinctly banded derivative magnetic signature.

Rocks of the layered series along the base of the Duluth Complex are associated with moderate to strong highs in the derivative gravity data (Fig. 3.4) and weak, vaguely banded derivative magnetic anomalies (Figs. 3.6, 3.7, and 3.8). Among the units with these geophysical characteristics are the Tuscarora intrusion, the South Kawishiwi intrusion, the Partridge River intrusion, the Western Margin intrusion, the Boulder Lake intrusion, and the layered series at Duluth (Fig. 3.1). Based on apparent crosscutting relationships in the magnetic derivative data in Tps. 52 and 53 N., R. 15 W. (Fig. 3.7), Miller and others (2001) concluded that the layered series at Duluth cuts the Boulder Lake intrusion. In the upper part of the layered series at Duluth, the subdued magnetic signature grades to a busy magnetic pattern with moderate-amplitude highs, most likely reflecting oxide enrichment of relatively more evolved rocks, such as ferrogabbros, near the top of the sequence (Fig. 3.7). A corresponding increase in density in the upper part of the layered series at Duluth is implied by a strong high in the derivative gravity data (Fig. 3.4). By analogy, the positive gravity derivative signature and busy magnetic pattern associated with the Boulder Lake intrusion (Figs. 3.6 and 3.7) may indicate similarly evolved rocks.

Varied gravity and magnetic signatures correspond to troctolitic and gabbroic rocks in the interior of the Duluth Complex. The gabbroic rocks of the Greenwood Lake intrusion (Fig. 3.1) are associated with moderate highs in the derivative gravity data (Fig. 3.4) and a busy derivative magnetic signature (Figs. 3.6 and 3.8) that includes anomalies of moderate to strong amplitude. The sinuous, strong derivative magnetic high that bounds the Greenwood Lake intrusion to the east (Figs. 3.6 and 3.8) reflects highly differentiated, oxide-rich ferrogabbro in the uppermost part of the intrusion (Vadis and others, 1981). Miller and others (2001) interpreted the rocks of the Greenwood Lake intrusion to be cut by troctolitic rocks associated with an inferred southern extension of the Bald Eagle intrusion (Figs. 3.1, 3.6, and 3.8). The inferred southern extension of the Bald Eagle intrusion is characterized by subdued derivative magnetic signatures, except where inclusions of volcanic hornfels and oxide-rich gabbroic rocks produce isolated magnetic highs (see M-119; also Chandler, 2001). The well exposed northern prong of the Bald Eagle intrusion has a magnetic signature that consists of an elongate, ring-like low encompassing an axial high (Fig. 3.8), which reflects a troctolite ring and a gabbro core, respectively. As mentioned above, the gravity high that is associated with the northern prong of the Bald Eagle intrusion (Figs. 3.2, 3.3, and 3.4) may also reflect a steep-sided feeder, and the lack of a similar signature to the south may indicate thinning of the inferred southern extension into a spoon-like mass (Chandler, 1990).

Anorthositic rocks, which form a partially disrupted cap to the complex, are generally associated with moderate gravity lows and subdued magnetic signatures in the derivative data, although some notable exceptions occur (Figs. 3.1, 3.4, and 3.6). In the anorthositic rocks of the northwestern part of the complex, moderate gravity and magnetic highs commonly reflect small intrusions of relatively younger troctolitic and gabbroic rocks (see M-119; also Chandler, 2001). Some anorthositic rocks in the Duluth area correspond to moderate to strong gravity and magnetic highs. Some of these highs may reflect inclusions of volcanic hornfels, or they may reflect oxide-rich gabbros and troctolites that intrude and presumably underlie some of the anorthositic rocks. Granophyric rocks, which typically occur along the southeastern margin of the anorthositic rocks, are associated with moderate to strong lows in the derivative gravity data, and subdued derivative magnetic signatures.

The second derivative gravity data (Fig. 3.4) and the first vertical derivative magnetic data (Fig. 3.6) present additional details for the two large intrusive centers located in the Cloquet Lake and Brule Lake–Hovland areas (Fig. 3.1). At the Cloquet Lake center, crosscutting relationships, inferred from derivative magnetic anomaly patterns, imply an eastward migration of intrusive activity with time (Fig. 3.8); from oldest to youngest, this progression is the Cloquet Lake layered series, the Sonju Lake intrusion, and the Beaver River diabase (see M-119). The intrusions of the Cloquet Lake and the Brule Lake–Hovland centers appear to be joined along the Houghtaling Creek troctolite, although age relationships are not clear (Miller and Chandler, 1997). The continuation of intrusive rocks southwards from the Cloquet Lake layered series is indicated by strong highs in the derivative gravity and magnetic data, which extend to the Sawmill Lake–Silver Creek gabbros.

Many areas underlain by the North Shore Volcanic Group are associated with moderate to strong derivative gravity and magnetic signatures (Figs. 3.4 and 3.6) that display little correlation with the flows, and they most likely reflect intrusive rocks either within or below the flow sequences. Moderately to strongly negative gravity lows and subdued magnetic signatures along the Lake Superior shore may mark a few areas of relatively thick and undisturbed flow sequences; these areas include T. 51 N., Rs. 12 and 13 W. (Lakewood basalts, Sucker River basalts, Larsmount ophitic basalts), T. 54 N., Rs. 8 and 9 W. (Gooseberry River basalts), T. 58 N., R. 5 W. (Schroeder–Lutsen basalt and underlying flows), and Tps. 61 and 62 N., R. 3 W. to R. 1 E. (Kimball Creek rhyolite, Red Cliff basalts, Devil's Track rhyolite, Pincushion Mountain trachybasalt, Croftville basalts, Naniboujou basalts, and the Devil's Kettle porphyritic rhyolite; see M-119 for location of flow sequences). Of these sequences, the Sucker River basalts are distinguished by a subtle banding in the derivative magnetic data (Fig. 3.7). Assuming a dip of 15°, the average width of these bands equates to about 270 meters of flow section. Such a thickness is too great to reflect individual flows, and the banding must reflect some sort of cyclicity within the Sucker River sequence.

Southeastward into Lake Superior, the derivative gravity and magnetic signatures become noticeably more subdued, reflecting progressive burial of the above-described igneous rocks by Keweenawan sedimentary rocks (Figs. 3.4, 3.6, and 3.7). A derivative gravity low and zone of subdued derivative magnetic signature at the southwestern terminus of Lake Superior most likely reflect the southern extension of volcanic rocks that are exposed on shore between Duluth and Two Harbors. The intrusive center inferred beneath the Lake (off shore from T. 51 N., R. 12 W.) is characterized by a broad, sub-circular high in the derivative gravity data, which appears to connect to the derivative gravity highs associated with the Sawmill Lake–Silver Creek gabbros on shore (Fig. 3.4). A distinct low in the derivative gravity, which appears to extend from White's ridge (Fig. 3.1), extends along the lakeshore and crosses on shore in the vicinity of T. 58 N., R. 5 W., aligning with the inferred Schroeder–Forest Center ridge (Fig. 3.1).

CONCLUSIONS

Geophysical methods have greatly enhanced our knowledge of the geology of the Duluth Complex and associated rocks, but much more geophysical work remains to be done. The potential of the gravity and magnetic data grids compiled for this project is far from being fully realized, and the data should continue to be useful to future geologic mapping and mineral exploration in the area. Continued modeling of gravity and magnetic data should provide additional information about the subsurface structure of the complex. Paleomagnetic studies that take full advantage of the technological advances in paleomagnetism and geochronology that have been made over the last 30 years should also be a promising avenue of research. Renewed gravity surveying over the complex may also be timely, because many roads and trails developed during the last 30 years could be easily covered.

Seismic methods have been severely underused in the Duluth Complex and such work could address a variety of geologic complexities. For example, seismic refraction surveying to estimate the thickness of glacial deposits would yield information pertinent to both mineral exploration and ground water studies. The reconnaissance seismic refraction work by the New Jersey Zinc Company over 30 years ago (DNR) demonstrated the utility of such an approach. Seismic refraction and wide-angle reflection may also be useful in studying the deep structure of the complex. The investigation of deep structure magnetotelluric methods may also be a promising course of research; the single study done to date yielded promising results.

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REFERENCES

Adams, D.C., 1990, Footwall structure of the Duluth Complex in northeastern Minnesota, a geophysical investigation: Houghton, Mich., Michigan Technological University, M.S. thesis, 189 p.

Allan Spector and Associates, 1995, Report on aeromagnetic data interpretation, western Duluth Complex for the Minnesota Department of Natural Resources, Open-File Report: Hibbing, Minn., Minnesota Department of Natural Resources, Division of Minerals, 15 p.

Allen, D.J., 1994, An integrated geophysical investigation of the Midcontinent rift system, western Lake Superior, Minnesota, and Wisconsin: West Lafayette, Ind., Purdue University, Ph.D. dissertation, 267 p.

Allen, D.J., Hinze, W.J., Dickas, A.B., and Mudrey, M.G., Jr., 1997, Integrated geophysical modeling of the North American Midcontinent rift system: New interpretations for western Lake Superior, northwestern Wisconsin, and eastern Minnesota, *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. 47-72.

Allis, R.G., and Garland, G.D., 1979, Heat flow measurements under some lakes in the Superior Province of the Canadian Shield: Canadian Journal of Earth Sciences, v. 16, no. 10, p. 1951-1964.

Anzoleaga, R., 1971, Crustal structure in western Lake Superior from the integration of seismic and gravity data: Madison, Wis., University of Wisconsin, Ph.D. dissertation, 53 p.

Bath, G.D., 1962, Magnetic anomalies and magnetizations of the Biwabik Iron Formation, Mesabi area, Minnesota: Geophysics, v. 27, no. 5, p. 627-650.

Beck, M.E., 1969, Paleomagnetism and magnetic intensities of Keweenawan intrusive rocks from northeastern Minnesota: Riverside, Calif., University of California, Riverside, Ph.D. dissertation, 202 p.

———1970, Paleomagnetism of Keweenawan intrusive rocks, Minnesota: Journal of Geophysical Research, v. 75, no. 26, p. 4985-4996.

Beck, M.E., and Lindsley, N.C., 1969, Paleomagnetism of the Beaver Bay Complex, Minnesota: Journal of Geophysical Research, v. 74, no. 8, p. 2002-2013.

Behrendt, J.C., Green, A.G., Cannon, W.F., Hutchinson, D.R., Lee, M.W., Milkereit, B., Agena, W.F., and Spencer, C., 1988, Crustal structure of the Midcontinent rift system: Results from GLIMPCE deep seismic reflection profiles: Geology, v. 16, no. 1, p. 81-85.

Bonnichsen, B., 1971, Outcrop map of southern part of Duluth Complex and associated Keweenawan rocks, St. Louis and Lake Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-11, scale 1:125,000.

———1972, Southern part of the Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 361-387.

Books, K.G., 1968, Magnetization of the lowermost Keweenawan lava flows in the Lake Superior area: U.S. Geological Survey Professional Paper 600-D, p. D248-D254.

———1972, Paleomagnetism of some Lake Superior Keweenawan rocks: U.S. Geological Survey Professional Paper 760, 42 p.

Books, K.G., and Green, J.C., 1972, Further paleomagnetic data for Keweenawan rocks in the western Lake Superior area [abs.]: Geological Society of America, Minneapolis, Minn., Annual Meeting, Abstracts with Programs, v. 4, no. 7, p. 454.

Briggs, I.C., 1974, Machine contouring using minimum curvature: Geophysics, v. 39, no. 1, p. 39-48.

Broderick, T.M., 1917, The relation of the titaniferous magnetites of northeastern Minnesota to the Duluth Gabbro: Economic Geology, v. 12, p. 663-696.

———1918, Some features of magnetic surveys of the magnetite deposits of the Duluth Gabbro: Economic Geology, v. 13, p. 35-49.

Cannon, W.F., Daniels, D.L., and Snyder, S.L., 1997, New aeromagnetic map of the Midcontinent rift in northwestern Wisconsin and adjacent Minnesota: Geological Society of America, 1997 abstracts with Programs, v. 29, no. 4, p. 9.

Cannon, W.F., Green, A.G., Hutchinson, D.R., Lee, M.W., Milkereit, B., Behrendt, J.C., Halls, H.C., Green, J.C., Dickas, A.B., Morey, G.B., Sutcliffe, R.H., and Spencer, C., 1989, The North American Midcontinent rift beneath Lake Superior from GLIMPCE seismic reflection profiling: Tectonics, v. 8, no. 2, p. 305-332.

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.

———1991, Aeromagnetic anomaly map of Minnesota: Minnesota Geological Survey State Map S-17, scale 1:500,000.

———1993, Geophysical characteristics, *in* Sims, P.K., ed., The Lake Superior region and Trans-Hudson orogen, chap. 2 *of* Reed, J.C., Jr., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and VanSchmus, W.R., eds., The geology of North America, volume C-2, Precambrian: Conterminous U.S.: Geological Society of America, p. 81-88.

———2001, Superimposed magnetic on gravity anomaly map of the Duluth Complex and related rocks, northeastern Minnesota: Minnesota Geological Survey Miscellaneous Map M-120, scale 1:200,000.

Chandler, V.W., and Ferderer, R.J., 1989, Copper-nickel mineralization of the Duluth Complex, Minnesota—A gravity and magnetic perspective: Economic Geology, v. 84, no. 6, p. 1690-1696.

Chandler, V.W., and Lively, R.S., 1998, Gravity and magnetic modeling of the Duluth Complex in the Allen 7.5-minute quadrangle, St. Louis County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-90, scale 1:100,000.

Chandler, V.W., and Schaap, B.D., 1991, Bouguer gravity anomaly map of Minnesota: Minnesota Geological Survey State Map S -16, scale 1:500,000.

Committee for the Gravity Anomaly Map of North America, 1987, Gravity anomaly map of North America: Geological Society of America Map 2, 5 pls., scale 1:5,000,000.

Craddock, C., Mooney, H.M., and Kolehmainen, V., 1970, Simple Bouguer gravity map of Minnesota and northwestern Wisconsin: Minnesota Geological Survey Miscellaneous Map M-10, scale 1:1,000,000.

Daniels, D.L., Snyder, S.L., Nicholson, S.W., and Cannon, W.F., 1998, New aeromagnetic surveys in Wisconsin by the U.S. Geological Survey [abs.]: Institute on Lake Superior Geology, 44th Annual Meeting, Minneapolis, Minn., Proceedings, v. 44, Program and abstracts, pt. 1, p. 62-63.

Davidson D.M., Jr., 1972, Eastern part of Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 354-360.

Davidson, D.M., Jr., Halls, H.C., and Brunell, J.R., Jr., 1976, Paleomagnetism of the late Precambrian Brule Lake intrusions, Cook County, Minnesota [abs.]: Institute on Lake Superior Geology, 22nd Annual Meeting, St. Paul, Minn., p. 18.

Ferderer, R.J., 1982, Gravity and magnetic modeling of the southern half of the Duluth Complex, northeastern Minnesota: Bloomington, Ind., Indiana University, M.A. thesis, 99 p. (U of I?)

———1991, Aeromagnetic data interpretation for the McDougal Lakes area, Duluth Complex, Lake County, Minnesota, *in* Lawler, T.L., and Venske, E.A., Aeromagnetic interpretation pseudo-geologic maps, with evaluation, in Lake of the Woods and Lake Counties, Minnesota: Minnesota Department of Natural Resources, Division of Minerals report 290, Appendix 290-E, p. E1-E13.

Green, J.C., Bornhorst, T.J., Chandler, V.W., Mudrey, M.G., Jr., Myers, P.R., Pesonen, L.J., and Wilband, J.T., 1987, Keweenawan dykes of the Lake Superior region: Evidence for evolution of the Middle Proterozoic Midcontinent rift of North America, *in* Halls, H.C., and Fahrig, W.F., eds., Mafic dyke swarms: Geological Association of Canada Special Paper 34, p. 289-302.

Grout, F.F., 1949-1950, The titaniferous magnetites of Minnesota: St. Paul, Minn., Office of the Commissioner of the Iron Range Resources and Rehabilitation, 117 p.

Halls, H.C., 1982, Crustal thickness in the Lake Superior region, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 239-243.

Halls, H.C., and Pesonen, L.J., 1982, Paleomagnetism of Keweenawan rocks, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 173-201.

Halls, H.C., and West, G.F., 1971, A seismic refraction survey in Lake Superior: Canadian Journal of Earth Sciences, v. 8, no. 6, p. 610-630.

Hart, S.R., Steinhart, J.S., and Smith, T.J., 1994, Terrestrial heat flow in Lake Superior: Canadian Journal of Earth Sciences, v. 31, no. 4, p. 698-708.

Hauck, S.A., Severson, M.J., Zanko, L.M., Barnes, S.J., Morton, P., Alminas, 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.

Ikola, R.J., 1968, Simple Bouguer gravity map of southern part of Duluth Complex and adjacent areas, Minnesota: Minnesota Geological Survey Miscellaneous Map M-4, scale 1:125,000.

———1970, Simple Bouguer gravity map of Minnesota: Two Harbors Sheet: Minnesota Geological Survey Miscellaneous Map M-9, scale 1:250,000.

International Union of Geodesy and Geophysics, 1971, Geodetic reference system, 1967: International Association of Geodesy Special Publication 3, 115 p.

Jahren, C.E., 1965, Magnetization of Keweenawan rocks near Duluth, Minnesota: Geophysics, v. 30, no. 5, p. 858-874.

Jessop, A.M., and Lewis, T., 1978, Heat flow and heat generation in the Superior province of the Canadian Shield: Tectonophysics, v. 50, no. 1, p. 55-77.

Lively, R.S., and Morey, G.B., 1996, Aerial gamma-ray maps of Minnesota and adjacent areas of North Dakota and South Dakota: Minnesota Geological Survey Miscellaneous Map M-83, scale 1:3,168,000.

Luetgert, J.H., and Meyer, R.P., 1982, Structure of the western basin of Lake Superior from cross structure refraction profiles, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 245-256.

Meints, J.P., Jirsa, M.A., Chandler, V.W., and Miller, J.D., Jr., 1993, Scientific core drilling in parts of Itasca, St. Louis, and Lake Counties, northeastern Minnesota, 1989-1991: Summary of lithologic, geochemical, and geophysical results: Minnesota Geological Survey Information Circular 37, 159 p.

Miller, J.D., Jr., and Chandler, V.W., 1997, Geology, petrology and tectonic significance of the Beaver Bay Complex, northeastern Minnesota, *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. 73-96.

———1999, Bedrock geologic map of the central Duluth Complex and western part of the Beaver Bay Complex, Lake and St. Louis Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-101, scale 1:1,000,000.

Miller, J.D., Jr., Green, J.C., Severson, M.J., Chandler, V.W., and Peterson, D.M., 2001, Geologic map of the Duluth Complex and related rocks, northeastern Minnesota: Minnesota Geological Survey Miscellaneous Map M-119, scale 1:200,000.

Miller, J.D., Jr., Schaap, B.D., and Chandler, V.W., 1990, The Sonju Lake intrusion and associated Keweenawan rocks: Geochemical and geophysical evidence of petrogenetic relationships [abs.]: Institute on Lake Superior Geology, 36th Annual Meeting, Thunder Bay, Ontario, Proceedings, v. 36, Program and Abstracts, pt. 1, p. 66-67.

Morey, G.B., Sims, P.K., Cannon, W.F., Mudrey, M.G., Jr., and Southwick, D.L., 1982, Geologic map of the Lake Superior region, Minnesota, Wisconsin, and northern Michigan: Minnesota Geological Survey State Map S-13, scale 1:1,000,000.

National Oceanic and Atmospheric Administration, 1995, Geomagnetic field models and synthesis software, version 2.1: Boulder, Colo., The National Geophysical Data Center.

Palmer, H.C., 1970, Paleomagnetism and correlation of some middle Keweenawan rocks, Lake Superior: Canadian Journal of Earth Sciences, v. 7, no. 6, p. 1410-1436.

Pesonen, L.J., 1979, Paleomagnetism of late Precambrian Keweenawan igneous and baked contact rocks from the Thunder Bay District, northern Lake Superior: Geological Survey of Finland Bulletin, v. 51, p. 27-44.

Phillips, J.D., 1997, U.S. Geological Survey Potential-Field software package, version 2.2 for the PC: U.S. Geological Survey Open-File Report 97-725.

Schwartz, G.M., 1943, Report on magnetic work in St. Louis County in 1942: Report of investigations Number 1: St. Paul, Minn., Office of the Commissioner of the Iron Range Resources and Rehabilitation, 20 p., 7 pls.

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

Severson, M.J., and Miller, J.D., Jr., 1999, Bedrock geologic map of Allen quadrangle, Minnesota: Minnesota Geological Survey Miscellaneous Map M-91, scale 1:24,000.

Sims, P.K., 1972, Magnetic data and regional magnetic patterns, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 585-592.

Smith, T.J., Steinhart, J.S., and Aldrich, L.T., 1966, Crustal structure under Lake Superior, *in* Steinhart, J.S., and Smith, T.J., eds., The earth beneath the continents, a volume of geophysical studies in honor of Merle A. Tuve: American Geophysical Union Geophysical Monograph 10, p. 181-197.

Snyder, S.L., 1998, Aeromagnetic map of part of northwestern Wisconsin and adjacent areas: U.S. Geological Survey Open-File Report 98-228, scale 1:125,000, 2 pls.

Symons, D.T.A., 1966, A paleomagnetic study on the Gunflint, Mesabi, and Cuyuna iron ranges in the Lake Superior region: Economic Geology, v. 61, no. 8, p. 1336-1361.

———1967, Paleomagnetic evidence on the genesis of the hard hematite ore deposits of the Vermilion range, Minnesota: Canadian Journal of Earth Sciences, v. 4, no. 3, p. 449-460.

Teskey, D.J., Thomas, M.D., Gibb, R.A., Dods, S.D., Kucks, R.P., Chandler, V.W., Fadaie, K., and Phillips, J.D., 1991, High resolution aeromagnetic survey of Lake Superior: Eos, v. 72, no. 8, p. 81, 85-86.

Thiel, E., 1956, Correlation of gravity anomalies with the Keweenawan geology of Wisconsin and Minnesota: Geological Society of America Bulletin, v. 67, no. 8, p. 1079-1100.

Thompson, M.D., McGinnis, L.D., Ervin, C.P., and Mudrey, M.G., Jr., 1990, Evolution of an aborted late Precambrian continental margin beneath Lake Superior [abs.]: Eos, v. 71, no. 43, p. 1563.

Vadis, M.K., Gladen, L.W., and Meineke, D.G., 1981, Geological, geophysical and geochemical surveys of Lake, St. Louis and Cook Counties, Minnesota, for the 1980 drilling project: Minnesota Department of Natural Resources, Division of Minerals Report 201, 13 p.

Watts, D.R., 1981, Paleomagnetism of the Fond du Lac Formation and the Eileen and Middle River sections with implications for Keweenawan tectonics and the Grenville problem: Canadian Journal of Earth Sciences, v. 18, no. 5, p. 829-841.

Weiblen, P.W., 1965, A funnel-shaped, gabbro-troctolite intrusion in the Duluth Complex, Lake County, Minnesota: Minneapolis, University of Minnesota, Ph.D. dissertation, 161 p.

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

White, W.S., 1966, Tectonics of the Keweenawan basin, western Lake Superior region: U.S. Geological Survey Professional Paper 524-E, 23 p.

Wold, R.J., and Berkson, J.M., 1977, Bouguer gravity anomaly map of Lake Superior: U.S. Geological Survey Miscellaneous Field Studies Map MF-884, scale 1:500,000.

Zietz, I., and Kirby, J.R., 1970, Aeromagnetic map of Minnesota: U.S. Geological Survey Geophysical Investigations Map GP-725, scale 1:1,000,000.

Chapter 4

ARCHEAN AND PALEOPROTEROZOIC ROCKS THAT FORM THE FOOTWALL OF THE DULUTH COMPLEX

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Rocks adjacent to and below the Duluth Complex include Late Archean igneous, sedimentary, and metamorphic rocks of the Vermilion district, and Paleoproterozoic sedimentary rocks of the Animikie basin. Some of the structural, stratigraphic, and compositional attributes of these rocks have affected the orientation and mineralization styles in basal portions of the Duluth Complex. Archean rocks include three major lithostratigraphic groups of the Quetico and Wawa subprovinces of Superior Province (Card and Ciesielski, 1986). These are the Giants Range batholith, supracrustal rocks of the Vermilion district of the Wawa subprovince, and the Vermilion Granitic Complex of the Quetico subprovince. Paleoproterozoic rocks that are adjacent to the Duluth Complex include the Animikie Group, which unconformably overlies the Archean rocks.

The Archean rocks within and west of the M-119 map area have been investigated for more than a hundred years. J.M. Clements completed the first major publication in 1903 ("The Vermilion Iron-Bearing District of Minnesota"), and since that time, many geologists have mapped portions of the area and published numerous articles on its geology. Published maps include Green and Schulz (1982), Sims and Southwick (1985), and Peterson and Jirsa (1999; Chapter 2 contains a complete list of geologic mapping in the Duluth Complex area); and reports include several chapters in Green (1970), Morey and others (1970), Sims and Morey, (1972), and Jirsa and others, (1992).

Paleoproterozoic rocks that are adjacent to the Duluth Complex have also been investigated for more than a hundred years. The earliest studies were concerned primarily with geologic descriptions and mapping of the banded iron-formations that are common to the Lake Superior area. Many volumes pertaining to the Paleoproterozoic iron-formations of Minnesota (the Mesabi, Cuyuna, and Gunflint ranges or districts) have been published since 1900, but they are too numerous to mention individually in this report. Initially, all the iron-formations of the Lake Superior area were believed to have been deposited during a singular and unique temporal event—an idea that persisted into the 1980s (Morey, 1996). With the advent of recent tectonic interpretations, a model of time-transgressive iron-formation deposition evolved (Southwick and others, 1988; Morey and others, 1989; Morey and Southwick, 1995; Morey, 1996). According to this model, the rocks of the Animikie Group, including the Biwabik Iron Formation near the base of the sequence, were deposited in a migrating foredeep or foreland basin (the main bowl of the Animikie basin) that developed adjacent to a causative and older fold-and-thrust belt exposed to the south of the basin in central Minnesota.

ARCHEAN ROCKS

The Archean supracrustal rocks that lie adjacent to the Duluth Complex represent the western extension of the Wawa subprovince of the southern Superior Province of the Canadian Shield (Card and Ciesielski, 1986). This subprovince is composed of well-defined greenstone belts of metamorphosed komatiite, basalt, dacite, rhyolite, and sedimentary rocks, which are separated by belt-like domains of plutonic rocks (Williams and others, 1991). Based on stratigraphy and structure, the supracrustal rocks of the Minnesota section of the Wawa subprovince are divided into two distinct panels known as the Soudan and Newton belts (Jirsa and others, 1992; Southwick, 1993; Southwick and others, 1998). The belts are fault-bounded, and the relationships between stratigraphic units within each belt vary from conformable to faulted. The Soudan belt contains prominent folds and curvilinear structural trends, whereas, the Newton belt lacks large fold structures and consists of fault-bounded, homoclinal, dominantly north-facing stratigraphic sequences. The boundary between these contrasting structural panels can be traced geophysically across the width of Minnesota, and has been designated informally as the Leech Lake structural discontinuity (Jirsa and others, 1992).

In the map area, the Leech Lake structural discontinuity occurs along the Mud Creek shear zone (Hudleston and others, 1988), the Knife Lake fault, and small segments of the Vermilion and Wolf Lake faults (as defined by Sims and Southwick, 1985).

Structural geology of Archean rocks

Three periods of Archean deformation (D_1, D_2, and D_3) have affected the rocks within the map area. The first deformation (D_1) produced folding in the volcanic and sedimentary rocks of the Soudan belt (Hooper and Ojakangas, 1971; Hudleston, 1976; Hudleston and others 1987; Jirsa and others, 1992) and locally within the Quetico subprovince (Bauer, 1985). Large, map-scale structures related to D_1 deformation in the Soudan belt plunge to the west. These early folds typically lack axial-planar cleavage, although several authors (Hooper and Ojakangas, 1971; Hudleston, 1976; Bauer, 1985; Jirsa and others, 1992) have described locally developed, early cleavage (S_1). D_1 deformation in the Newton belt is less well-defined, and probably involved thrust stacking of competent volcanic units (Jirsa and others, 1992; Southwick and others, 1998).

The second period of deformation (D_2) was regional in scale and associated with northwest-directed compression (Hudleston and others, 1988; Jirsa and others, 1992). Offset markers, asymmetrical structures, and rotation fabrics indicate that D_2 was transpressional, and the predominant kinematic sense was dextral (Hudleston, 1976; Schultz-Ela and Hudleston, 1991). Mesoscopic folds, metamorphic foliation (S_2), and lineations (L_2) were formed during D_2. Regional metamorphic grades that developed during D_2 range from low greenschist to medial amphibolite facies. The timing of D_2 deformation is bracketed between 2685 ± 4 Ma and 2674 ± 5 Ma (Boerboom and Zartman, 1993), a range consistent with the 2680 to 2685 Ma timing established by Corfu and Stott (1998) for much of the Wawa subprovince in Canada.

Structural features that developed after the main metamorphic event have been designated as D_3 structures (Jirsa and others, 1992). These structures are synchronous with or postdate a late intrusive suite of generally sub-alkalic to alkalic composition (Boerboom, 1994). D_3 deformation typically produced brittle, northeast- and northwest-trending faults that offset metamorphic zones developed during D_2. Major D_3 structures include the Vermilion, Burntside Lake, Waasa, Camp Rivard, and Wolf Lake faults. Other D_3 features include local crenulation folds and a weak, northeast-trending fabric in some of the late intrusions. Structural studies in the Quetico subprovince (Bauer, 1985) indicated that D_3 was a result of continued north–south compression during the late stages of D_2 deformation.

Lithostratigraphy of Archean rocks

Brief lithological descriptions of the Late Archean stratigraphic sequences and intrusive units within the area are given in Table 4.1. The stratigraphic units are separated based on their occurrence within the Newton and Soudan belts. Additionally, lithologic units within the Giants Range batholith, Vermilion Granitic Complex, and late intrusions are described. Many supracrustal units contain sill-like mafic intrusions and dikes, and stocks of felsic composition. The mafic intrusions are generally believed to be high-level magma bodies related to basaltic volcanism higher in the stratigraphy, and some of the felsic intrusions have a petrogenetic link to felsic units stratigraphically higher in the sequence.

Late intrusions

These intrusions generally fall into one of three compositional types: syenitic, monzodioritic, and granitic (Boerboom, 1994). Among these in the area mapped in M-119 are the syenodioritic Snowbank Lake (unit Aslg) and Kekekabic Lake (unit Agr) stocks.

Saganaga Tonalite

The 2689 ± 1 Ma (Corfu and Stott, 1998) Saganaga Tonalite (unit Ast, M-119) is a large (maximum dimensions of about 23 by 32 kilometers), composite intrusive body that occurs on the north-central edge of the map area. The intrusion consists dominantly of quartz-tonalite with a dioritic border phase. The intrusion is bounded by three distinct Archean terranes: 1. The northern edge is in fault contact with supracrustal rocks of the Newton belt; 2. The western and southern edges cut supracrustal rocks of the Soudan belt; and 3. The eastern edge (in Canada) intruded into rocks of the Northern Light Gneiss. In general, the intrusion probably represents the southwestern margin of the Northern Light Gneiss terrane.

Giants Range batholith

The Giants Range batholith (units Agm, Agre, and Agrp, M-119) trends east–northeast, is 8- to 40-kilometers-wide, and is approximately 241-

Table 4.1. Lithostratigraphic units within the Late Archean rocks of northeastern Minnesota.

Late Archean intrusive rocks	
Late intrusions	Plutons and stocks of syenite, monzonite, diorite, and lamprophyre
Saganaga Tonalite	Quartz-tonalite, diorite
Giants Range batholith	Granite, granodiorite, monzodiorite, schist-rich migmatite
Vermilion Granitic Complex	Granite, granodiorite, amphibolite, schist-rich migmatite
Late Archean supracrustal and hypabyssal intrusive rocks	
Newton belt	
Newton Lake Formation	Komatiitic and tholeiitic lava flows and intrusions, clastic strata
Soudan belt	
Knife Lake Group	Graywacke, slate, conglomerate, tuff, and sheared equivalents
Lake Vermilion Formation	Graywacke, slate, dacitic tuff, and minor conglomerate
Gafvert Lake sequence	Dacitic and andesitic flows, tuff-breccia, and tuff
Upper member Ely Greenstone	Tholeiitic basalt flows and iron-formation
Soudan Iron Formation member Ely Greenstone	Layered cherty iron-formation and tuff
Lower member Ely Greenstone	Calc-alkalic and tholeiitic flows and volcaniclastic strata

kilometers-long. The Giants Range batholith is a composite intrusion containing granite, monzonite, granodiorite, monzodiorite, and gneissic equivalents. Dikes and irregular pods of aplite and more rarely granite pegmatite cut the major intrusive units. Boerboom and Zartman (1993), Southwick (1993), and Boerboom (1994) have summarized intrusive relationships between rock units within the Giants Range batholith. The batholith intrudes supracrustal rocks of the Archean Wawa subprovince and forms part of the footwall to the Paleoproterozoic Animikie Group and the Mesoproterozoic Duluth Complex.

Most drill holes that penetrate through the Duluth Complex and into the Giants Range batholith encounter porphyritic quartz monzonite, although the rocks tend to be heterogeneous and include granite, monzonite, monzodiorite, quartz monzodiorite, granodiorite, and diorite, as well as syenite, quartz syenite, tonalite, hybrid rocks, and scattered hornfels inclusions of Archean supracrustal rocks. In many drill holes, the granitic rocks immediately below the basal contact of the Duluth Complex exhibit the effects of high-grade contact metamorphism, such as partial melting, metasomatism, and recrystallization. This is commonly expressed as a white, sericitized, diorite-like rock at the basal contact that consists mainly of plagioclase and orthopyroxene with little or no K-feldspar or quartz. This dioritic rock is locally present immediately below the Duluth Complex, and in those places it persists as far as 61 meters below the basal contact. With increasing depth beneath the Duluth Complex, these dioritic rocks commonly grade into pink granitic rock types having abundant K-feldspar and visible quartz. The same color/compositional change has been observed beneath the complex in drill holes from the Dunka Pit area (Bonnichsen, 1972).

Disseminated sulfides (principally chalcopyrite) occur sporadically in the uppermost 101 meters of Giants Range rocks below the basal contact of the Duluth Complex. In some cases, sulfide mineralization begins immediately below the basal contact; however, in other holes sulfide minerals are absent from the uppermost 30 meters but are present at depths of 61 to 91 meters below the basal contact. Veins and irregular pods of massive sulfide also occur within the uppermost 30 meters of the Giants Range batholith beneath the Duluth Complex. These typically are pyrrhotite-rich, but have much greater copper and nickel content than massive sulfides located within the overlying Duluth Complex. They appear to be related to fractional crystallization of an immiscible sulfide melt as it migrated into the footwall rocks during the emplacement of the Duluth Complex (Bonnichsen and others, 1980; Severson, 1994). Drill holes that intersect sulfide mineralization in the Giants Range batholith beneath the complex are spatially distributed along northeast-trending linear zones that probably reflect reactivated Archean fault zones (Severson, 1994).

Vermilion Granitic Complex

High-grade metasedimentary and felsic intrusive rocks of the Vermilion Granitic Complex occur within the northwestern part of the map area (unit `Avg`, M-119). These include biotite schist, schist-rich migmatite, and amphibolite, cut by intrusions of biotite granite and lesser amounts of granodiorite, tonalite, and diorite. The boundary between map unit `Avg` (M-119) and the supracrustal rocks of the Wawa subprovince is the Burntside Lake fault.

Ely Greenstone

The Ely Greenstone is a thick sequence of predominantly mafic volcanic rocks. It is divided into three members (Morey and others, 1970): the Lower and Upper members, composed of dominantly basaltic pillow lavas, and a medial member of iron-formation (the Soudan Iron Formation) and fragmental volcanic rocks. The Lower member (Lower Ely) consists mainly of pillowed and massive basalt and andesite flows of calc-alkalic and locally tholeiitic composition. Diabase and gabbro sills, isolated dacitic and rhyolitic lava flows and domes, and local fragmental units occur throughout the sequence. Pillows typically are irregularly shaped and well vesiculated, indicating moderate to shallow water depths of formation, and rare bedded scoria deposits may indicate local subaerial volcanism. Peterson (2001) has identified a major time-break in the volcanic stratigraphy of the Lower Ely in the northern limb of the Tower–Soudan anticline. The stratigraphic break marks a hiatus in basaltic-dominated volcanism, and a change to the deposition of oxide-facies iron-formation, felsic tuff and epiclastic felsic sediments, and local horizons of massive sulfide in the so-called middle series of the Lower Ely.

As presently mapped, the rocks of the Lower Ely below the medial hiatus (the informal lower series) appear to consist dominantly of large, shield-like sequences of pillowed and massive basalt and andesite flows, with rare zones of chert-magnetite iron-formation. Rocks of the Lower Ely above the medial hiatus (the upper series) are locally more diverse (Peterson, 2001), forming repeated basalt-andesite-dacite/rhyolite volcanic cycles of smaller scale (possibly isolated volcanic cones) than the shield-like lava flows of the lower series.

The medial unit of the Ely Greenstone, the Soudan Iron Formation (unit `Aif`, M-119), consists of laminated Algoma-type magnetite-chert iron-formation, interbedded with thin basalt flows and fragmental rocks of basaltic to dacitic composition. Thin dikes and sills of quartz-feldspar porphyry are common within the Soudan Iron Formation. In general, the basal contact of the Soudan Iron Formation member is gradational with the top part of the Lower Ely, with a general increase in iron-formation beds as the top of the Lower member is approached. The upper contact of the Soudan Iron Formation member is more diverse, in that the overlying stratigraphic units include volcanic and volcaniclastic sequences assigned formally to both the Upper member of the Ely Greenstone and the Lake Vermilion Formation, and the informally defined Gafvert Lake sequence (Peterson and Jirsa, 1999), which consists of dacitic and andesitic volcanic rocks derived from emergent stratovolcanos.

The Upper member of the Ely Greenstone (Upper Ely) consists dominantly of tholeiitic pillowed basalt that overlies the Soudan Iron Formation member along much of its strike length. The pillows typically are small (less than one meter), ovoid, and without vesicles, which indicates extrusion under deep water (Schulz, 1982). Numerous, thin, iron-formation horizons occur throughout the Upper Ely, along with synvolcanic mafic intrusions and carbonaceous fine-grained sediments. In addition, the Upper Ely interfingers with and overlies the Gafvert Lake sequence, and underlies and locally interfingers with the Lake Vermilion Formation on the south limb of the Tower–Soudan anticline (Schulz, 1980).

Schulz (1980) described the Upper Ely as a sequence of tholeiitic basalt lava flows associated with the development of a deep-water shield volcano. Geological studies (Morey and others, 1970; Schulz, 1980) have shown that tholeiitic Upper Ely basaltic volcanism was at least in part contemporaneous with calc-alkalic felsic volcanism of the Gafvert Lake sequence and epiclastic sedimentation of the Lake Vermilion Formation and the Knife Lake Group. A schematic block diagram of these geological relationships is presented in Figure 4.1.

Lake Vermilion Formation

Stratigraphically above, and interdigitated with the rocks assigned to the Ely Greenstone is a thick sequence of dacitic volcaniclastic rocks and turbiditic graywacke-slate. These epiclastic rocks

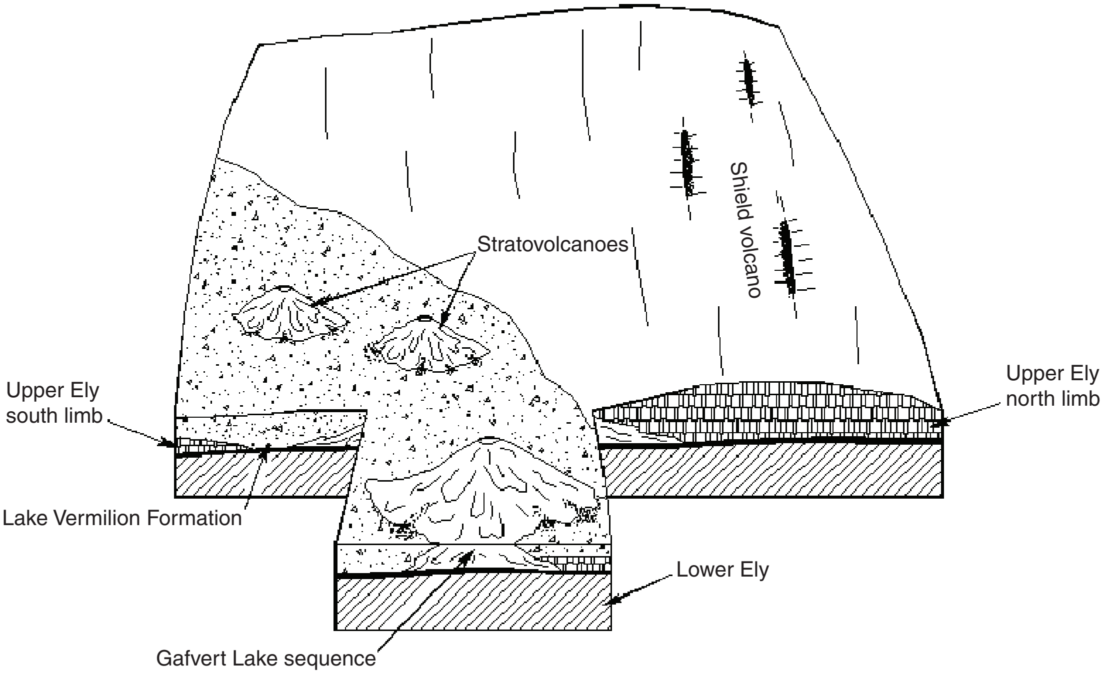


Figure 4.1. Schematic "snapshot" of the volcanic facies represented during the contemporaneous deposition of rocks of the Upper Member of the Ely Greenstone, Gafvert Lake sequence, and the Lake Vermilion Formation (modified from Peterson, 2001).

of dacitic provenance constitute the Lake Vermilion Formation (unit Alvf, M-119; Morey and others, 1970). The majority of the formation consists of lithic graywacke, which ranges from massive, unsorted, dacite rubble at one extreme, to micrograded, laminated, and reworked ash at the other (Ojakangas, 1972a). Tholeiitic basalt, iron-formation, and graphitic slate are locally interbedded with these sedimentary rocks. Coarse felsic detritus is more abundant in stratigraphically lower units, and higher parts of the section contain a greater amount of fine-grained, resedimented, felsic tuff and graywacke-argillite. Petrographic studies (Ojakangas, 1972a, b, 1985) have established that lithic clasts of dacite are the predominant framework components of the sandy or coarser strata of the formation. Other framework constituents include iron-formation, ferruginous chert, and various mafic volcanic rocks. Also represented are rare clasts of carbonaceous black slate, massive pyrite, and various granitoid rock types (Boerboom and Zartman, 1993). As a whole, the unit has the sedimentological attributes of a turbiditic slope-and-fan assemblage deposited in ring plains among evolved dacitic volcanic islands (Ojakangas, 1985), most likely represented locally by the Gafvert Lake sequence.

Knife Lake Group

As defined by Morey and others (1970), the rocks of the Knife Lake Group (unit Akga, M-119) overlie the Ely Greenstone and are overlain by rocks of the Newton Lake Formation. Exposures of rocks of the Knife Lake Group occur along the northern margin of map M-119. Gruner (1941), Green (1970), McLimans (1972), and Ojakangas (1972b) have presented detailed descriptions of the rocks of the Knife Lake Group in that area. Rock types include graywacke, slate, conglomerate (unit Akcg, M-119), tuffaceous sandstone (unit Akfv, M-119), basalt and andesite flows, and intrusions of gabbro and felsic porphyry. Major east–northeast-trending shear zones occur throughout the area and have produced well foliated phyllitic and phyllonitic rocks (unit Akph, M-119). Conglomerates with clasts eroded from the Saganaga Tonalite (2689 ± 1 Ma; Corfu and Stott, 1998) have been mapped as part of the Knife Lake Group (Hanson, 1972; McLimans, 1972). Green (1970) described foliated granitic clasts, unlike the Saganaga Tonalite, in conglomerates of the Knife Lake Group in the North Kawishiwi River area.

The presence of granitoid clasts in the conglomerates of the Knife Lake Group implies erosion of nearby granitoid source rocks, which generally are thought to post-date volcanism in the area. Because of these observations and the reinterpretation of the structural setting of the rocks of the whole Vermilion Greenstone belt (Jirsa and others, 1992), the stratigraphic position of the Knife Lake Group must be reexamined. One interpretation for some of the rocks of the Knife Lake Group is that they occupy Timiskaming-type extensional basins developed after 2689 Ma, and before about 2680 Ma, the date of D_2 deformation. Thus, parts of what is known as the Knife Lake Group may post-date both the Ely Greenstone and the Newton Lake Formation (Jirsa, 1998).

Newton Lake Formation

The Newton Lake Formation occurs in the northwestern corner of the map area. The formation is divided into two members (Morey and others, 1970): a mafic member west of Newton Lake, and a felsic to intermediate member to the east. The mafic member of the formation (unit Anmv, M-119) consists mainly of pillowed and massive basalt flows, iron-rich basaltic komatiite flows, and compositionally layered sills of mafic to ultramafic composition (Green and Schulz, 1977). The ultramafic intrusions occur as elongate, northeast-striking sills that grade from a basal zone of peridotite to pyroxenite, bronzite-gabbro, and gabbro (Schulz, 1974). Units of felsic volcaniclastic rocks, iron-formation, and siliceous marble are locally abundant, along with sheared equivalents of all of the rocks. The felsic member of the formation (unit Anfv, M-119) consists largely of dacitic flows, breccia, tuff-breccia, and tuff with minor amounts of graywacke and siliceous marble. Volcanic textures indicate that the felsic member formed in a shallow, subaqueous setting. These textures include high degrees of vesiculation of lava flows, scoriaceous breccias, bedded and graded tuffs, and coarse conglomeratic rocks (Schulz, 1980). Together, these indicate deposition as a shallow-water calc-alkalic pyroclastic cone or cones.

PALEOPROTEROZOIC ROCKS

The Paleoproterozoic rocks of Minnesota have been intensively explored for iron ore since about 1890. As a result, numerous iron-formations have been discovered and mined. These include the Biwabik Iron Formation (the Mesabi range and the Emily district, the latter of which was never mined), the Trommald Iron Formation (the Cuyuna North range), small operations on various iron-formations (the Cuyuna South range), and the Gunflint Iron Formation along the border with Canada, which was not mined in Minnesota. All of these iron-formations were at first considered to be time-synchronous, but recent interpretations have suggested otherwise. The rocks of the Mesabi, Emily, and Gunflint districts are considered to be in comparable stratigraphic positions and are assigned to the Animikie Group, deposited in the Animikie basin. However, rocks in the Cuyuna North and South districts are positioned to the south of the Animikie basin in a fold-and-thrust belt. Rocks of the fold-and-thrust belt (Southwick and others, 1988) are older than the Animikie basin and consist of several tectonically dismembered and juxtaposed structural panels, separated by geophysically-defined thrust faults that were tectonically stacked during the Penokean orogeny. Because the rocks of the fold-and-thrust belt are distant from the Duluth Complex, they are not described in this report. However, strata that were deposited within the Animikie basin, which lies north of the fold-and-thrust belt on the Mesabi and Gunflint ranges, are in contact with the Duluth Complex and are briefly described in this chapter. Rocks of the Animikie Group include (from bottom to top): the Pokegama Quartzite, the Biwabik Iron Formation, and the Virginia and Thomson Formations (slate-turbidite sequences). Each of these stratigraphic units was deposited more or less continuously in sedimentary environments that ranged from shallow water for the Pokegama Quartzite to deep water for the Virginia Formation. The Kakabeka Quartzite, Gunflint Iron Formation, and Rove Formation are the stratigraphic equivalents to the northeast along the Canadian border. Age dates for rocks beneath the Animikie Group (Beck, 1988; Hemming and others, 1990) and from an ash layer within the Gunflint Iron Formation (Fralick and Kissin, 1998) suggest that Animikie deposition began sometime between 2125 and 1930 Ma and continued beyond 1878 Ma.

Structural geology of Paleoproterozoic rocks in the Animikie basin

The overall structure of the Mesabi range is characterized by a gently-dipping homocline that strikes east–northeast and dips 5° to 15° to the southeast (Morey, 1972) with local sharp bends in strike such as the Virginia horn and siphon structure. Minor structures include small folds and faults. These minor structures, particularly the faults, were important factors in localizing the extent and distribution of the oxidized iron-ore bodies known as natural ores (Morey, 1972). Deformation of the Virginia and Thomson Formations increases from north to south within the Animikie basin. Slaty cleavage is weakly evident 16 to 24 kilometers south of the Mesabi range. Much further to the south, outcrops of the Thomson Formation exhibit upright, moderately tight, east-striking folds having well-developed and pervasive axial planar cleavage (Southwick and others, 1988). Within the fold-and-thrust belt, south of the main bowl of the Animikie basin, the increase in metamorphism and structural complexity is even more pronounced. Deformation of rocks in the Animikie basin and the fold-and-thrust belt took place during the Penokean orogeny between about 1900 and 1760 Ma, with the most intense activity centered around 1870 to 1850 Ma (Southwick and others, 1988).

Post-Penokean deformation of the Animikie Group that is related to emplacement of the Duluth Complex is readily evident on the extreme eastern end of the Mesabi range, where the rocks exhibit progressively steeper dips of 20° to 35° (locally as much as 45°). The intensity of metamorphism within the Biwabik Iron Formation increases to pyroxene hornfels-grade near the contact of the Duluth Complex (Bonnichsen, 1968; French, 1968). Small-scale detachment faults of apparently Keweenawan age in the Dunka Pit area are interpreted as the results of extensional stresses at the time of Duluth Complex emplacement (Holst and others, 1986). Studies of the basal contact at the Babbitt deposit (see Chapter 8) indicated that pre-complex structures in the footwall rocks controlled the morphology of the base of the Duluth Complex (such as the Local Boy anticline and Bathtub syncline) and the localization of massive sulfide mineralization at the Local Boy ore zone (Mancuso and Dolence, 1970; Watowich, 1978; Holst and others, 1986; Martineau, 1989; Severson and Barnes, 1991; Hauck and others, 1997). Severson and others (1996) also noted that the same structural features appear to have been reactivated numerous times during continued emplacement of the Duluth Complex and affected the distribution of specific units within the complex, such as the Bathtub layered interval.

Description of the Animikie Group and related rocks

Presented here are brief descriptions of the formations of the Animikie Group, starting at the base, and two pre-Duluth Complex sills that are probably Keweenawan in age, but are intricately associated with the Animikie footwall rocks. The relative distribution of the Animikie Group, the two sills, and the Duluth Complex are shown schematically in Figure 4.2.

Pokegama Quartzite

At the base of the Animikie Group are clastic rocks of the Pokegama Quartzite (unit Ppk, M-119) that have been divided into a lower *shaly* facies, deposited in a low-energy, tidal flat environment, and an upper *sandstone* facies, deposited in a subtidal, high-energy environment (Ojakangas, 1983). The Pokegama Quartzite was unconformably deposited on Archean rocks and ranges in thickness from zero to a few meters thick on the eastern end of the Mesabi range, to as much as 61-meters-thick at the western end of the range (White, 1954; Morey, 1979). It is only locally present beneath the Biwabik Iron Formation within the area of map M-119. Where present in drill holes (fewer than 20 holes intersected it), the Pokegama Quartzite consists of thick- to thin-bedded quartz arenite as thick as 8 meters.

Biwabik Iron Formation

The Biwabik Iron Formation (unit Pbi, M-119) has traditionally been subdivided into cherty iron-formation (granular and thick-bedded) and slaty iron-formation (thin-bedded). Both cherty and slaty iron-formation types are interlayered at all scales; however, one rock type or the other predominates in four informally defined lithostratigraphic members referred to as (from bottom to top): Lower Cherty, Lower Slaty, Upper Cherty, and Upper Slaty. The Biwabik Iron Formation is further subdivided into 22 informal submembers (Gundersen and Schwartz, 1962) that are used by the mining industry at the eastern end of the Mesabi range. These subdivisions are schematically portrayed in Figure 4.3. Adjacent to and beneath the Duluth Complex, the intensity of metamorphism within the Biwabik Iron Formation increases to pyroxene hornfels facies in the Dunka Pit and Peter Mitchell Mine (Bonnichsen, 1968; French, 1968). The Gunflint Iron Formation (unit Pgi, M-119) is similar to the Biwabik Iron Formation, but thin-bedded slaty intervals are much more dominant.

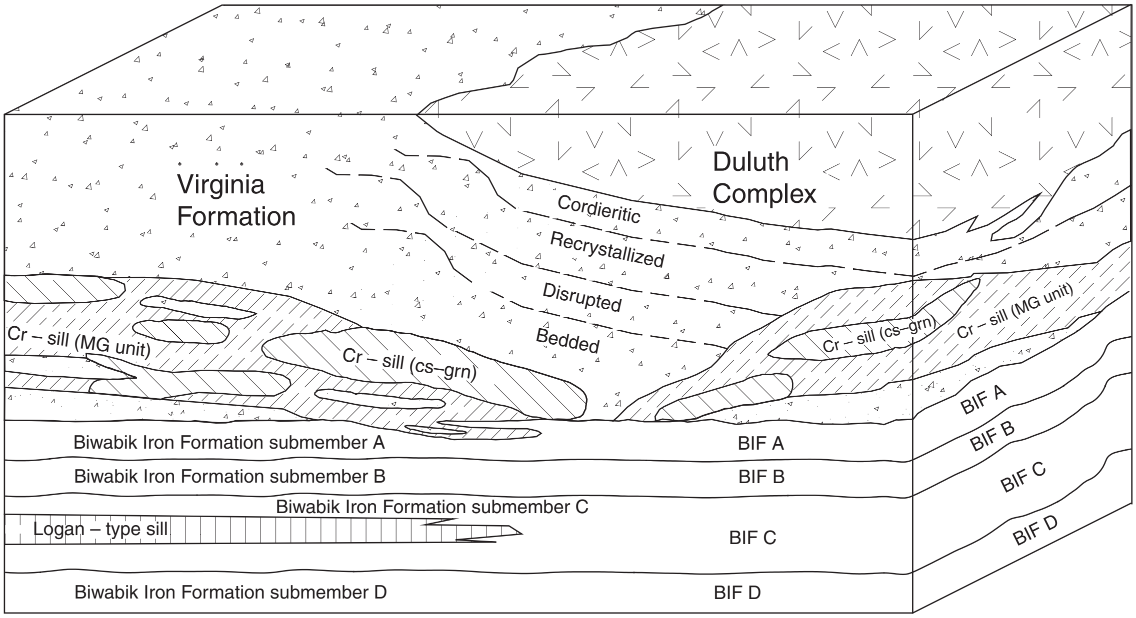


Figure 4.2. Schematic diagram showing the relationship between the Duluth Complex, Paleoproterozoic footwall rocks (Virginia Formation and Biwabik Iron Formation), and pre-complex sills (Cr-sill and Logan-type sill; modified from Severson and others, 1996). The Cr-sill is divided into a coarse-grained, green colored portion (cs-grn) and a massive, gray colored portion (MG unit).

Inclusions of Biwabik Iron Formation within the Duluth Complex exhibit many different textures due to the effects of partial melting and assimilation. These textures range from well-bedded, magnetite-rich iron-formation, in which there are crosscutting micro-veins of pyroxene-rich partial melt material, to massive oxide beds (restite) that are devoid of any bedding features. Intermediate to these vastly different textures, the metamorphosed iron-formation commonly consists of alternating, coarse-grained, orthopyroxene-rich bands; medium-grained, plagioclase-rich bands (possibly metasomatic replacements); and medium-grained, magnetite-rich bands. Alapieti (1991) described petrographic textures of massive oxide bands that could have formed by the sintering of pre-existing oxides in the iron-formation (atoll texture of Hulbert and Von Gruenewaldt, 1985). Where the Biwabik Iron Formation is in direct contact with the Duluth Complex, it exhibits elevated titanium (and commonly chromium) contents. This suggests that movement of titanium across the intrusive contact, from the Duluth Complex into the iron-formation, took place during emplacement of the complex (Muhich, 1993).

Virginia Formation

The Virginia Formation (unit Pvr, M-119), like its southern equivalent the Thomson Formation (unit Ptm, M-119) and its northern equivalent the Rove Formation (unit Prv, M-119), is a thick sequence of argillite, siltstone, and graywacke at the top of the Animikie Group. 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 carbonaceous and locally contains thin interbeds of chert and limestone. At the western end of the Mesabi range, the lower lithosome contains abundant intervals of carbonate-facies iron-formation, and the lower contact of the Virginia Formation with the Biwabik Iron Formation is gradational (Zanko and others, in press). Deposition of the lower lithosome occurred by slow accumulation of black mud (now carbonaceous argillite) in deep water under anoxygenic conditions, with localized deposition of iron-formation and limestone by orthochemical processes (Lucente and Morey, 1983). The upper lithosome consists dominantly of argillite, but it also contains abundant interbeds of siltstone and fine-grained graywacke that were deposited by

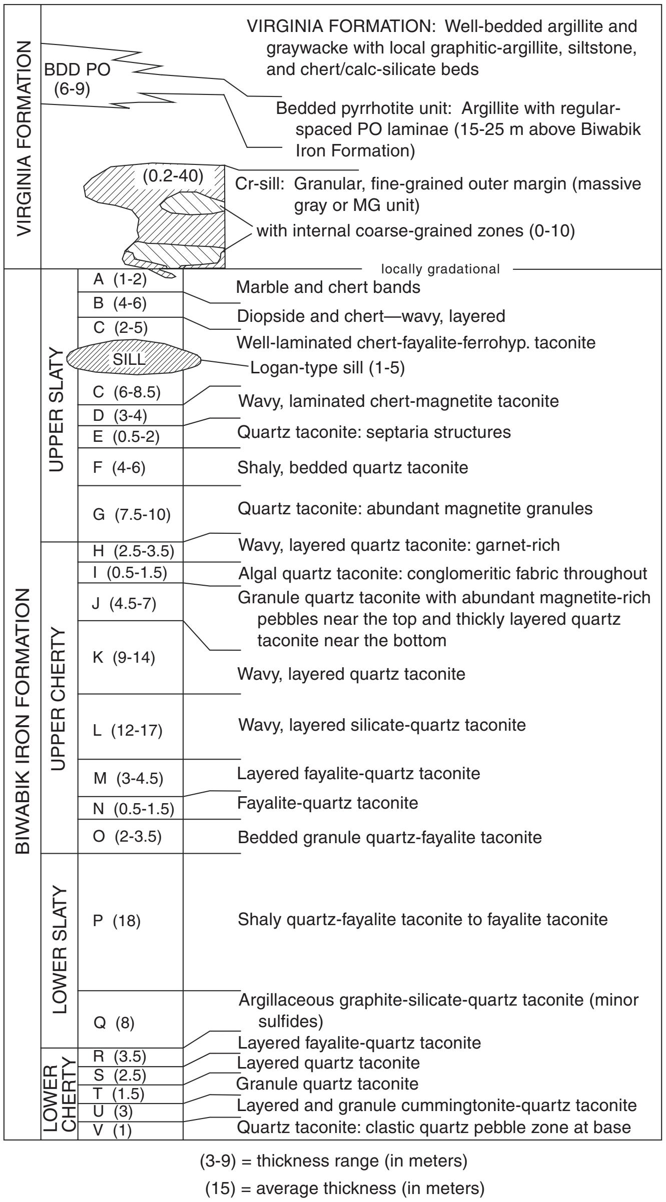


Figure 4.3. Stratigraphy of the Biwabik Iron Formation at the east end of the Mesabi range (modified from Gundersen and Schwartz, 1962; Severson, 1994).

turbidity currents in a prograding submarine fan complex (Lucente and Morey, 1983). The Rove Formation on the Gunflint range is remarkably similar to the Virginia Formation and has also been divided into a lower argillite member and an upper, thin-bedded graywacke member (Morey, 1969). Morey and Ojakangas (1970) have shown that the graywacke-argillite sequence of the Thomson Formation is similar to the top of the Rove Formation.

As noted above, the Virginia Formation is usually described as a thick sequence of well-bedded sedimentary rocks with argillite as the dominant rock type. However, in close proximity to the Duluth Complex, the grade of metamorphism and associated deformation progressively increase, and several metamorphic textures are superimposed on the original sedimentary package. Severson and others (1996) subdivided the Virginia Formation beneath and adjacent to the Duluth Complex into at least five informal members based largely on metamorphic attributes. These members, and pre-Duluth Complex sills, intruded into the footwall strata near the Duluth Complex and are briefly described below. Their distribution is shown schematically in Figure 4.2.

Cordieritic metasediments—Directly beneath the basal contact of the Duluth Complex, metasedimentary rocks of the Virginia Formation are generally cordierite-rich and display a bluish-gray color in drill core. Original bedding planes are preserved in some localities, but mostly the bedding planes have been obliterated by contact metamorphism.

Disrupted unit—Well-bedded argillite of the Virginia Formation is typically transformed into a highly deformed rock, or a metatexite (Sawyer, 1999) in close proximity to the Duluth Complex. Textures that characterize this rock 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 partial melt that are also chaotic and folded. The overall texture of the unit appears to be a result of a combination of partial melting and intense structural deformation related to emplacement of the Duluth Complex.

Recrystallized unit—The recrystallized unit is a higher-grade metamorphic equivalent of the disrupted unit, and properly classed as a diatexite (Sawyer, 1999). By contrast, rocks of the recrystallized unit were heated, generating 20 to 30 percent partial melts, which enabled the rock to flow (Sawyer, unpub. data) in response to stresses applied during emplacement of the Duluth Complex. All bedding planes are obliterated and what remains is a recrystallized rock that contains decussate medium-grained biotite. Within this recrystallized matrix are blocks/boudins of more structurally competent siltstone and calcsilicate hornfels (originally limey layers). Variably sized patches, or relicts, of the disrupted unit are commonly found scattered throughout the recrystallized unit.

Graphitic argillite and bedded pyrrhotite units—Carbonaceous argillite of the lower lithosome of the Virginia Formation is commonly preserved as graphitic argillite in close proximity to the Duluth Complex. This rock commonly contains as much as 5 percent disseminated pyrrhotite and variable amounts of staurolite and sillimanite. Wherever the unit contains regularly spaced laminae of pyrrhotite it is informally called the bedded-pyrrhotite unit. The bedded-pyrrhotite unit ranges from 6- to 30-meters-thick and is locally present in the basal 61 meters of the Virginia Formation. Wherever the bedded-pyrrhotite unit was intruded and assimilated by the Duluth Complex, it provided a local sulfur source for the pyrrhotite-dominated massive sulfide mineralization at the base of the Duluth Complex. Examples include massive sulfides at the Serpentine and Dunka Pit copper-nickel deposits (Severson, 1994; Zanko and others, 1994).

Cr-sill at the base of the Virginia Formation

Although probably Keweenawan in age, the Cr-sill is included in this section because of its close association with the footwall rocks at the Dunka Road, Babbitt, Serpentine, and Dunka Pit copper-nickel deposits. The sill is present in the bottom 0.15 to 40 meters of the Virginia Formation, and as apophyses into the top of the Biwabik Iron Formation near the Grano fault at the Serpentine deposit. Even though the sill was mapped 80 years ago (Grout and Broderick, 1919), it was not identified in drill core beneath the complex until the 1990s (Severson, 1991). Identification in drill core is hampered by the fine-grained granoblastic texture of the sill that makes it difficult to distinguish from hornfelsed Virginia Formation rocks. The informal term of Cr-sill was first used by Hauck and others (1997) to highlight the relatively high chromium contents (600 to 2,000 parts per million) that are characteristic of the rock. Later work (Severson and others, 1996; Park and others, 1999) showed that the sill could be further subdivided into two textural varieties.

One type is a fine-grained, massive, gray-colored unit (massive gray unit) that appears to be a border phase or chill zone (Park and others, 1999). The second type is a much coarser-grained, green-colored, olivine- and hornblende-bearing interior of the sill that is only locally present, but is easily identified in drill core (Fig. 4.2). Both the border and the coarser-grained interior of the Cr-sill contain variable amounts of plagioclase, olivine, clinopyroxene, orthopyroxene, hornblende, and biotite. The sill was metamorphosed by the Duluth Complex to a granoblastic texture, and thus is pre-complex in age. On this basis, it is inferred to be equivalent to the Logan sills.

Logan-type sill within the Biwabik Iron Formation

This sill also is described here because of its close association with the footwall rocks—in this case the Biwabik Iron Formation (Figs. 4.2 and 4.3). For the most part, the sill is contained within the C-submember of the Biwabik Iron Formation (Hauck and others, 1997) and is easily distinguished in drill core from the Babbitt deposit and to the north in the pit exposures of the Peter Mitchell and Dunka Pit taconite mines. The sill is 0.6- to 5-meters-thick, and pinches out to the west at the Peter Mitchell mine. The sill is again present to the west of the Siphon fault in the now idle pit exposures of the LTV taconite mine. There, the sill is 0.9- to 1.5-meters-thick, is contained within the K-submember of the Biwabik Iron Formation (Severson and Hauck, 1997), and can be traced approximately 4 kilometers to the west where it eventually pinches out. The sill is mineralogically similar to the Cr-sill, but contains much lower chromium contents (less than 600 parts per million). Hauck and others (1997) noted the geochemical similarity of the sill to the Logan sills (1109 Ma) that intrude the Gunflint Iron Formation and Rove Formation. Because of this, Hauck and others (1997) referred to the sill as a Logan-type sill but did not infer correlation.

RELATIONSHIPS OF FOOTWALL ROCKS TO THE DULUTH COMPLEX

Many geologic features of the footwall rocks influenced the orientation of the Duluth Complex basal contact and the copper-nickel-platinum group element mineralization within it.

Influence of footwall structures

The geometry of the footwall structures is in part mimicked by the form of the northwestern margin of the Duluth Complex (Fig. 4.4). These structures can be separated into three main types: 1. East–northeast-trending Archean shear zones

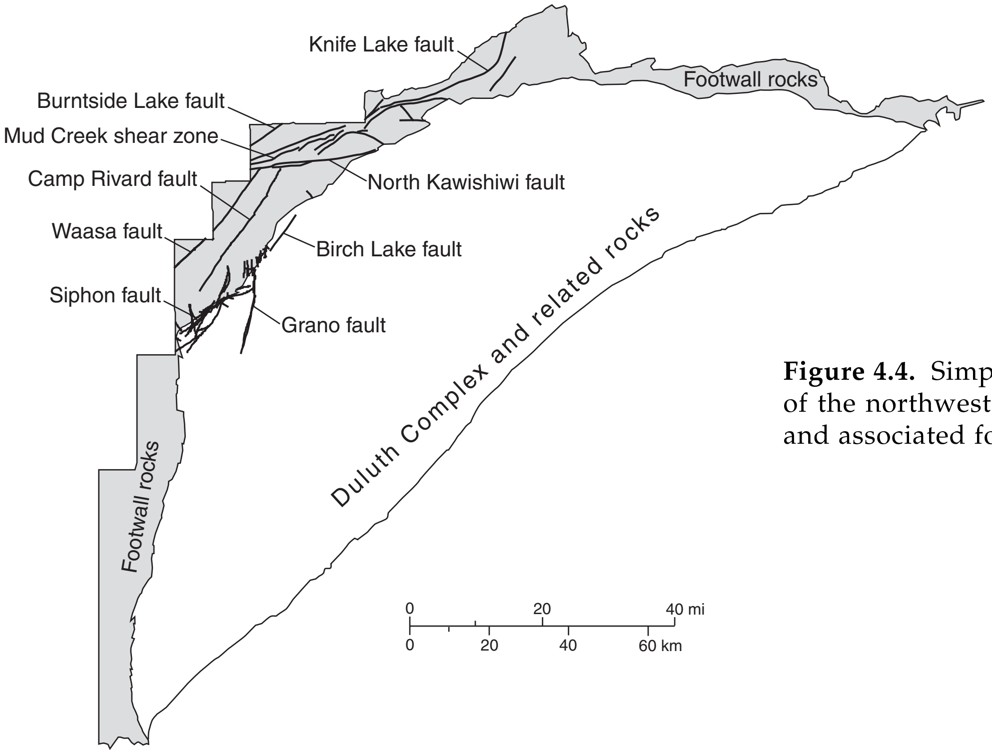


Figure 4.4. Simplified structural map of the northwestern Duluth Complex and associated footwall rocks.

(such as the Mud Creek shear zone and the Burntside Lake, Knife Lake, and North Kawishiwi faults); 2. Northeast-trending Archean faults (such as the Waasa and Camp Rivard faults); and 3. North-trending Paleoproterozoic faults (such as the Siphon fault). The geometric pattern of the footwall structures can be extrapolated within the Duluth Complex in many areas, and is interpreted to be the result of reactivation of preexisting structures during and/or after the emplacement of the Duluth Complex.

East–northeast-trending Archean shear zones appear to control portions of the basal contact of the Duluth Complex immediately north of the North Kawishiwi fault (Fig. 4.4). This relationship includes two northwest-trending embayments of the Duluth Complex, and also the general strike of the contact. Northeast-striking faults in the Duluth Complex (such as the Birch Lake fault and structures southeast of the Siphon fault) mimic the trend of Archean faults (Waasa and Camp Rivard faults), and may represent structures created by similar Archean faults reactivated beneath the Duluth Complex. North-trending faults mapped in the Biwabik Iron Formation include large growth faults such as the Siphon fault, and other minor structures. Faults of similar orientation are located within the Duluth Complex, and one (the Grano fault) appears to have affected localizing mineralization within the Local Boy ore zone of the Babbitt deposit. No detailed drilling along the extension of the Siphon fault in the Duluth Complex has been completed in order to test the importance of this structure for deposition of high-grade copper-nickel-platinum group element mineralization.

Influence of footwall rock-unit distribution

The importance of the regional distribution of footwall rock units on the Duluth Complex is typified by three features: 1. The northern and northwestern contact between the Duluth Complex and the footwall rocks follows the orientation of regional bedding within the Animikie Group; 2. The southwestern contact between the Duluth Complex and the Virginia/Thomson Formations is associated with Mesoproterozoic faulting; and 3. The north-central portion of the Duluth Complex is marked by an east–southeast-trending gravity low, which is interpreted to be the Late Archean Giants Range batholith beneath the Duluth Complex. In general, the Duluth Complex intruded along the unconformity between the Paleoproterozoic Animikie Group sedimentary rocks and volcanic rocks of the Mesoproterozoic

North Shore Volcanic Group. This generalized relationship can be seen in map view along the northwestern and northern margins of the Duluth Complex, although the complex actually intruded down-section through the Animikie Group to the northwest. Remnants of Animikie Group iron-formation are preserved as inclusions within the Duluth Complex in nearly their original stratigraphic orientation and location. The crosscutting relationship between the Duluth Complex and iron-formations of the Animikie Group is depicted in Figure 4.5. The contact between the Duluth Complex and the Thomson/ Virginia Formations in the southwestern portion of map M-119 is typically steep (Severson, 1995), and is interpreted to be largely associated with synmagmatic faulting during the development of the Midcontinent rift.

A large, east–southeast-trending gravity low cuts across the north-central Duluth Complex (Fig. 4.6). This gravity low is interpreted to be a ridge-like extension of the Late Archean Giants Range batholith beneath the Duluth Complex (Miller and Chandler, 1997; Chapter 3). The preservation of a ridge of granitic material in a mafic rift environment is perplexing. It may be due to relatively greater ductility of the granite during contact metamorphism from mafic melts of the Duluth Complex, in contrast to the adjacent regions of Archean mafic volcanic rocks (such as the extension of the Ely Greenstone), which may have behaved in a brittle manner. Whatever the origin of the gravity low, it appears to have exerted some control on the shapes of individual intrusions within the overlying Duluth Complex (such as the Greenwood Lake, Wilder Lake, and Bald Eagle intrusions; Fig. 4.6). Portions of each of these intrusions are either aligned along or curve towards the gravity low. The curvilinear nature of these intrusions may represent magma ascension that was controlled by the ridge of granitic material.

Footwall contamination and sulfur sources

The interaction of footwall strata with the lower parts of many intrusions within the Duluth Complex (such as the Partridge River and South Kawishiwi intrusions) created zones of distinct rock types and textures within the basal parts of the Duluth Complex. The interaction between the footwall rocks and the basal Duluth Complex can include footwall assimilation, dehydration of footwall strata and volatile fluxing into the Duluth Complex, chilling and repeated magma injection, and metasomatism. Multiple combinations of these phenomena in the basal portions of the

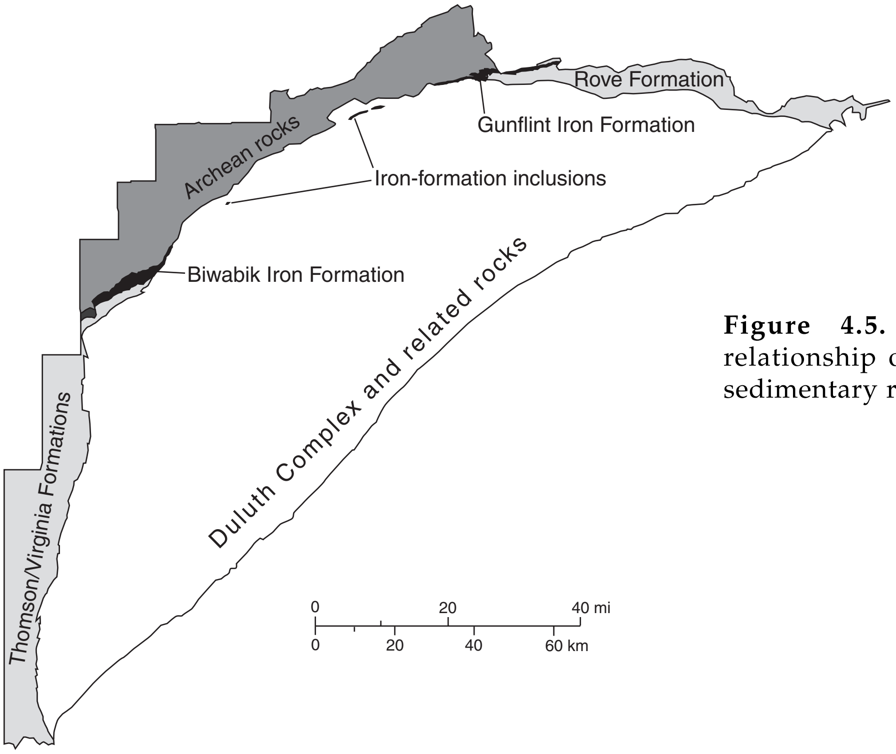


Figure 4.5. Regional crosscutting relationship of the Duluth Complex and sedimentary rocks of the Animikie Group.

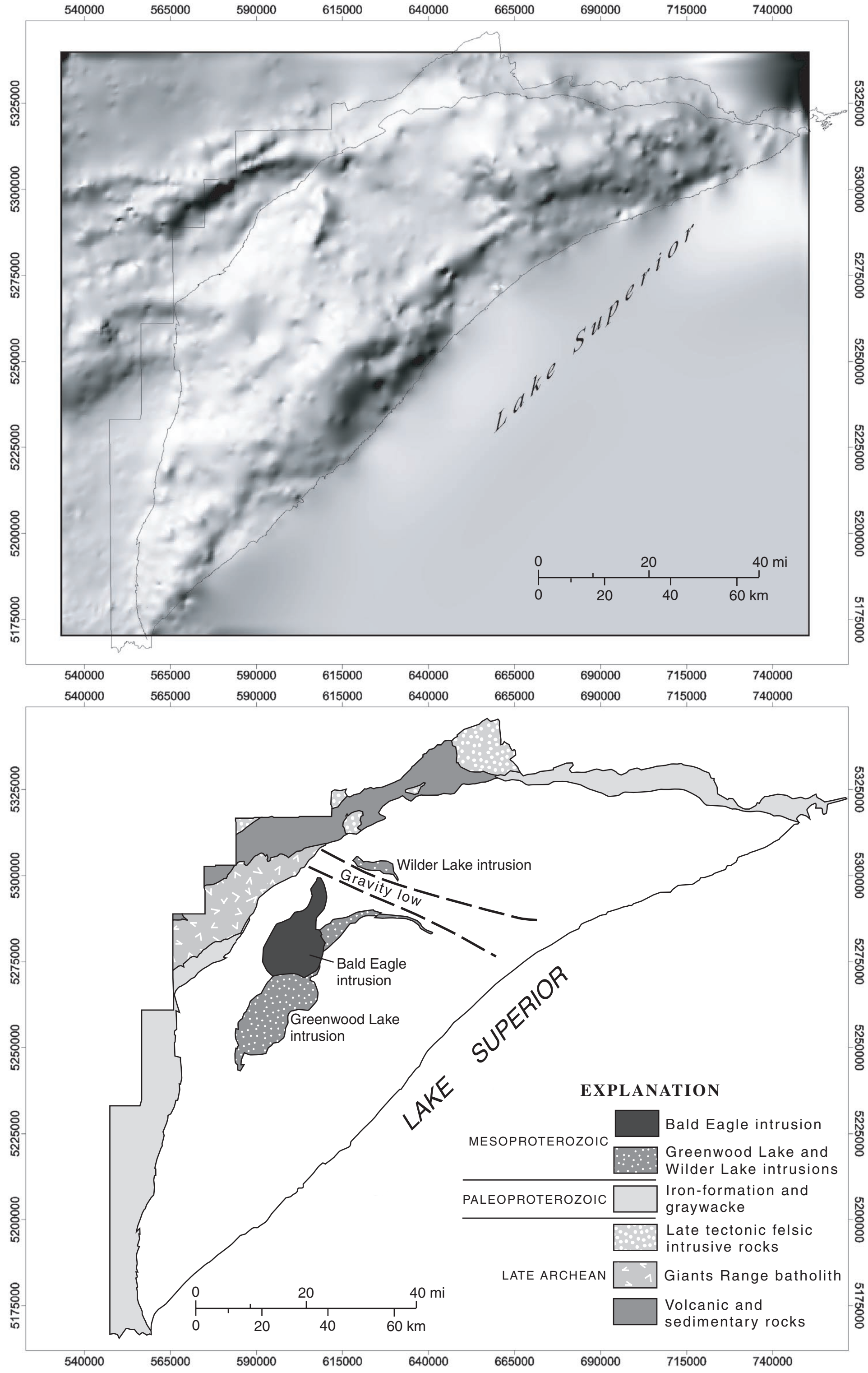


Figure 4.6. Shaded relief Bouguer gravity anomaly map and simplified interpretation. UTM coordinates (zone 15, NAD 83) are given.

Duluth Complex created footwall inclusions, zones of noritic rocks, and the distinctive heterogeneous troctolitic rocks that typify these basal contaminated zones. Local sources of sulfur, especially from within the Paleoproterozoic rocks, had an integral role in the generation of copper-nickel mineralization along the base of the Partridge River and South Kawishiwi intrusions. Sulfur isotope data confirms that the bulk of the sulfur at the Babbitt deposit (Ripley, 1986; Ripley and Alawi, 1986; Ripley and Al-Jassar, 1987; Andrews and Ripley, 1989; Taib and Ripley, 1993), the Dunka Road deposit (Ripley, 1981), and the Water Hen oxide-rich ultramafic intrusion (Mainwaring and Naldrett, 1977) is of sedimentary origin and was derived from the Virginia Formation. However, the isotopic heterogeneity at the Local Boy ore zone of the Babbitt deposit indicates that the addition of sulfur through an in situ process alone is considered inadequate (Ripley, 1986). Ripley (1986) further proposed that the copper necessary to produce the massive sulfide was scavenged from a secondary or auxiliary magma chamber at depth.

Additional sulfur sources that have not been previously considered could include the following: 1. Mineralized shear and fault zones within Late Archean supracrustal rocks; 2. VMS-style mineralization within Late Archean volcanic rocks; 3. Large mineralized inclusions within the Giants Range batholith; and 4. Bedded syngenetic Fe-sulfide in the Rove Formation and Gunflint Iron Formation. Moreover, the ridge of the Giants Range batholith beneath the Duluth Complex may contain some of these local sulfur sources, which could lead to local contamination and possible copper-nickel mineralization along the base of intrusions in contact with the footwall ridge.

SUMMARY

Many features of the Late Archean and Paleoproterozoic rocks beneath and adjacent to the Mesoproterozoic Duluth Complex influenced both the regional setting and localized copper-nickel-platinum group element mineralization of the Duluth Complex. The south to southeast dip of the Paleoproterozoic sedimentary rocks is similar to the orientation of intrusive units of the Duluth Complex. Preserved Logan-type and Cr-rich sills mapped in taconite pits and intersected in drill holes indicate a direct correlation between early Duluth Complex sills and bedding in the footwall Paleoproterozoic sedimentary rocks. Towards the center of the Duluth Complex, similar early sills may have enhanced assimilation of Paleoproterozoic footwall units into magmas of the Duluth Complex. The assimilation of large amounts of Paleoproterozoic strata (some of which is sulfide-bearing) into basal intrusions of the Duluth Complex led to the incorporation of large amounts of sulfur into magmas of the Duluth Complex. The sulfur-enriched basal troctolitic magmas (such as the Partridge River and South Kawishiwi intrusions) host the vast majority of the copper-nickel-platinum group element deposits of the Duluth Complex.

In contrast, the footwall Late Archean strata are typically oriented near vertical, essentially perpendicular to the orientation of the units of the Duluth Complex. The interplay between the Late Archean rocks and the Duluth Complex is largely structural. Reactivation of favorably orientated Late Archean structures during development of the Midcontinent rift appears to control the regional distribution of intrusive units of the Duluth Complex. Moreover, the large east–southeast-trending gravity low (interpreted to be a ridge-like extension of the Late Archean Giants Range batholith) affected the regional distribution of intrusive units within the Duluth Complex. Assimilation of sulfide-bearing Late Archean rocks added sulfur to basal troctolitic magmas of the Duluth Complex, although it may have been less important to the copper-nickel-platinum group element mineralization than sulfur from the footwall Paleoproterozoic rocks.

REFERENCES

Alapieti, T.T., 1991, Duval-15: Preliminary report on the microscopic study of drill hole Duval-15: Minnesota Department of Natural Resources, Division of Minerals Report 291, 56 p.

Andrews, M.S., and Ripley, E.M., 1989, Mass transfer and sulfur fixation in the contact aureole of the Duluth Complex, Dunka Road Cu-Ni deposit, Minnesota: Canadian Mineralogist, v. 27, no. 2, p. 293-310.

Bauer, R.L., 1985, Correlation of early recumbent and younger upright folding across the boundary between an Archean gneiss belt and greenstone terrane, northeastern Minnesota: Geology, v. 13, no. 9, p. 657-660.

Beck, J.W., 1988, Implications for Early Proterozoic tectonics and the origin of continental flood basalts, based on combined trace element and neodymium/strontium isotopic studies of mafic igneous rocks of the Penokean Lake Superior belt, Minnesota, Wisconsin and Michigan: Minneapolis, University of Minnesota, Ph.D. dissertation, 262 p.

Boerboom, T.J., 1994, Alkalic plutons of northeastern Minnesota, *in* Southwick, D.L., ed., Short contributions to the geology of Minnesota: Minnesota Geological Survey Report of Investigations 43, p. 20-38.

Boerboom, T.J., and Zartman, R.E., 1993, Geology, geochemistry, and geochronology of the central Giants Range batholith, northeastern Minnesota: Canadian Journal of Earth Sciences, v. 30, no. 12, p. 2510-2522.

Bonnichsen, B., 1968, General geology and petrology of the metamorphosed Biwabik Iron Formation, Dunka River area, Minnesota: Minneapolis, University of Minnesota, Ph.D. dissertation, 240 p., 1 pl.

———1972, Southern part of the Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 361-387.

Bonnichsen, B., Fukui, L.M., and Chang, L.Y., 1980, Geologic setting, mineralogy, and geochemistry of magmatic sulfide deposits, Duluth Complex, U.S.A.: Proceedings, 5th quadrennial International Association on the Genesis of Ore Deposits Symposium, Stuttgart, Germany, p. 545-565.

Card, K.D., and Ciesielski, A., 1986, DNAG subdivisions of the Superior Province of the Canadian Shield: Geoscience Canada, v. 13, no. 1, p. 5-13.

Clements, J.M., 1903, The vermilion iron-bearing district of Minnesota: U.S. Geological Survey Monograph 45, 463 p.

Corfu, F., and Stott, G.M., 1998, Shebandowan greenstone belt, western Superior Province: U-Pb ages, tectonic implications, and correlations: Geological Society of America Bulletin, v. 110, no. 11, p. 1467-1484.

Fralick, P.W., and Kissin, S.A., 1998, The age and provenance of the Gunflint lapilli tuff [abs.]: Institute on Lake Superior Geology, 44th Annual Meeting, Minneapolis, Minn., Proceedings, v. 44, Program and Abstracts, pt. 1, p. 66-67.

French, B.M., 1968, Progressive contact metamorphism of the Biwabik Iron-formation, Mesabi range, Minnesota: Minnesota Geological Survey Bulletin 45, 103 p.

Green, J.C., 1970, Lower Precambrian rocks of the Gabbro Lake quadrangle, northeastern Minnesota: Minnesota Geological Survey Special Publication SP-13, 96 p., 4 pls.

Green, J.C., and Schulz, K.J., 1977, Iron-rich basaltic komatiites in the early Precambrian Vermilion District, Minnesota: Canadian Journal of Earth Sciences, v. 14, no. 10, p. 2181-2192.

———1982, Geologic map of the Ely quadrangle, St. Louis and Lake Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-50, scale 1:24,000.

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

Gruner, J.W., 1941, Structural geology of the Knife Lake area of northeastern Minnesota: Geological Society of America Bulletin, v. 52, no. 10, p. 1577-1642.

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.

Hanson, G.N., 1972, Saganaga batholith, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 102-107.

Hauck, S.A., Severson, M.J., Zanko, L.M., Barnes, S.J., Morton, P., Alminas, 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.

Hemming, S., McLennan, S.M., Hanson, G.N., and Krogstad, K.M., 1990, Pb isotope systematics in quartz [abs.]: Eos, v. 71, no. 17, p. 654-655.

Holst, T.B., Mullenmeister, E.E., Chandler, V.W., Green, J.C., and Weiblen, P.W., 1986, Relationship of structural geology of the Duluth Complex to economic mineralization: Minnesota Department of Natural Resources, Division of Minerals Report 241-2, [variously paged], 8 pls.

Hooper, P.R., and Ojakangas, R.W., 1971, Multiple deformation in Archean rocks of the Vermilion district, northeastern Minnesota: Canadian Journal of Earth Sciences, v. 8, no. 4, p. 423-434.

Hudleston, P.J., 1976, Early deformational history of Archean rocks in the Vermilion district, northeastern Minnesota: Canadian Journal of Earth Sciences, v. 13, no. 4, p. 579-592.

Hudleston, P.J., Bauer, R.L., Southwick, D.L., Schultz-Ela, D.D., and Bidwell, M.E., 1987, Structural geology of the boundary between Archean terranes of low-grade and high-grade rocks, northern Minnesota, *in* Balaban, N.H., ed., Field trip guidebook for selected areas in Precambrian geology of northeastern Minnesota: Minnesota Geological Survey Guidebook Series 17, p. 1-42.

Hudleston, P.J., Schultz-Ela, D.D., and Southwick, D.L., 1988, Transpression in an Archean greenstone belt, northern Minnesota: Canadian Journal of Earth Sciences, v. 25, no. 7, p. 1060-1068.

Hulbert, L.J., and Von Gruenewaldt, G., 1985, Textural and compositional features of chromite in the Lower and Critical Zones of the Bushveld Complex south of Potgietersrus: Economic Geology, v. 80, no. 4, p. 872-895.

Jirsa, M.A., 1998, Timiskaming-type pull-apart basin sequences in the western Superior Province of Minnesota [abs.]: Geological Society of America, Annual Meeting, Toronto, Abstracts with Programs, v. 30, p. 291.

Jirsa, M.A., Southwick, D.L., and Boerboom, T.J., 1992, Structural evolution of Archean rocks in the western Wawa subprovince, Minnesota: Refolding of precleavage nappes during D2 transpression: Canadian Journal of Earth Sciences, v. 29, no. 10, p. 2146-2155.

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.

Mainwaring, P.R., and Naldrett, A.J., 1977, Country rock assimilation and the genesis of Cu-Ni sulfides in the Water Hen intrusion, Duluth Complex, Minnesota: Economic Geology, v. 72, no. 7, p. 1269-1284.

Mancuso, J.D., and Dolence, J.D., 1970, Structure of the Duluth gabbro complex in the Babbitt area, Minnesota [abs.]: Institute on Lake Superior Geology, 16th Annual Meeting, Thunder Bay, Ontario, Proceedings, v. 16, Program and Abstracts, pt. 1, 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: London, Institution of Mining and Metallurgy, p. 117-137.

McLimans, R.K., 1972, Granite-bearing conglomerates in the Knife Lake Group, Vermilion district, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 91-97.

Miller, J.D., Jr., and Chandler, V.W., 1997, Geology, petrology, and tectonic significance of the Beaver Bay Complex, northeastern Minnesota, *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. 73-96.

Morey, G.B., 1969, The geology of the Middle Precambrian Rove Formation in northeastern Minnesota: Minnesota Geological Survey Special Publication 7, 62 p.

———1972, Gunflint range, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 218-225.

———1979, Stratigraphic and tectonic history of east-central Minnesota, *in* Balaban, N.H., ed., Field trip guidebook for stratigraphy, structure and mineral resources of east-central Minnesota: Minnesota Geological Survey Guidebook Series 9, p. 13-28.

———1996, Continental margin assemblage, *in* Sims, P.K., and Carter, L.M.H., eds., Archean and Proterozoic geology of the Lake Superior region, U.S.A., 1993: U.S. Geological Survey Professional Paper 1556, p. 30-44.

Morey, G.B., Green, J.C., Ojakangas, R.W., and Sims, P.K., 1970, Stratigraphy of the Lower Precambrian rocks in the Vermilion district, northeastern Minnesota: Minnesota Geological Survey Report of Investigations 14, 33 p.

Morey, G.B., and Ojakangas, R.W., 1970, Sedimentology of the Middle Precambrian Thomson Formation, east-central Minnesota: Minnesota Geological Survey Report of Investigations 13, 32 p.

Morey, G.B., and Southwick, D.L., 1995, Allostratigraphic relationships of Early Proterozoic iron-formations in the Lake Superior region: Economic Geology, v. 90, no. 7, p. 1983-1993.

Morey, G.B., Southwick, D.L., and Ojakangas, R.W., 1989, The Penokean orogen in east-central and northern Minnesota *in* Hanshaw, P.M., ed., Field trips for the 28th IGC: 28th International Geological Congress, Field trip guidebook T-145, p. 43-59.

Muhich, T.G., 1993, Movement of titanium across the Duluth Complex–Biwabik Iron Formation contact at Dunka Pit, Mesabi Iron Range, northeastern Minnesota: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 154 p.

Ojakangas, R.W., 1972a, Archean volcanogenic graywackes of the Vermilion district, northeastern Minnesota: Geological Society of America Bulletin, v. 83, no. 2, p. 429-441.

———1972b, Graywackes and related rocks of the Knife Lake Group and Lake Vermilion Formation, Vermilion district, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 82-90.

———1983, Tidal deposits in the early Proterozoic basin of the Lake Superior region—The Palms and the Pokegama Formations: Evidence for subtidal-shelf deposition of Superior-type banded iron-formation, *in* Medaris, L.G., Jr., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 49-66.

———1985, Review of Archean clastic sedimentation, Canadian Shield: Major felsic volcanic contributions to turbidite and alluvial fan-fluvial facies associations, *in* Ayres, L.D., Thurston, P.C., Card, K.D., and Weber, W., eds., Evolution of Archean supracrustal sequences: Geological Association of Canada Special Paper 28, p. 23-47.

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.

Peterson, D.M., 2001, Development of Archean lode-gold and massive sulfide deposit exploration models using geographic information system applications: Targeting mineral exploration in northeastern Minnesota from analysis of analog Canadian mining camps: Minneapolis, University of Minnesota, Ph.D. dissertation, 503 p., 12 pls., 1 cd.

Peterson, D.M., and Jirsa, M.A., comps., 1999, Bedrock geologic map and mineral exploration data, western Vermilion district, St. Louis and Lake Counties, northeastern Minnesota: Minnesota Geological Survey Miscellaneous Map M-98, scale 1:48,000.

Ripley, E.M., 1981, Sulfur isotopic studies of the Dunka Road Cu-Ni deposit, Duluth Complex, Minnesota: Economic Geology, v. 76, no. 3, p. 610-620.

———1986, Origin and concentration mechanisms of copper and nickel in Duluth Complex sulfide zones—a dilemma: Economic Geology, v. 81, no. 4, p. 974-978.

Ripley, E.M., and Alawi, J.A., 1986, Sulfide mineralogy and chemical evolution of the Babbitt Cu-Ni deposit, Duluth Complex, Minnesota: Canadian Mineralogist, v. 24, pt. 2, p. 347-368.

Ripley, E.M., and Al-Jassar, T.J., 1987, Sulfur and oxygen isotope studies of melt-country rock interaction, Babbitt Cu-Ni deposit, Duluth Complex, Minnesota: Economic Geology, v. 82, no. 1, p. 87-107.

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

Schulz, K.J., 1974, Differentiated mafic-ultramafic sills in the Archean Vermilion District, northeastern Minnesota: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 212 p.

———1980, The magmatic evolution of the Vermilion greenstone belt, NE Minnesota: Precambrian Research, v. 11, p. 215-245.

———1982, Magnesian basalts from the Archean terrains of Minnesota, *in* Arndt, N.T., and Nisbet, E.G., eds., Komatiites: London, Allen and Unwin, p. 171-186.

Schultz-Ela, D.D., and Hudleston, P.J., 1991, Strain in an Archean greenstone belt of Minnesota: Tectonophysics, v. 190, p. 233-268.

Severson, M.J., 1991, Geology, mineralization, and geostatistics of the Minnamax/Babbitt Cu-Ni deposit (Local Boy area), Minnesota, part 1:

Geology: Natural Resources Research Institute, Technical Report, NRRI/TR-91/13a, 96 p.

———1994, Igneous stratigraphy of the South Kawishiwi intrusion, Duluth Complex, northeastern Minnesota: Natural Resources Research Institute, Technical Report NRRI/TR-93/34, 210 p., 15 pls.

———1995, Geology of the southern portion of the Duluth Complex: 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: Natural Resources Research Institute, Technical Report NRRI/TR-91/13b, 216 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: Natural Resources Research Institute, Technical Report NRRI/TR-97/19, 102 p., 4 pls.

Severson, M.J., Patelke, R.L., Hauck, S.A., and Zanko, L.M., 1996, The Babbitt copper-nickel deposit, part C: Igneous geology, footwall lithologies, and cross-sections: Natural Resources Research Institute, Technical Report NRRI/TR-94/21c, 79 p.

Sims, P.K., and Morey, G.B., eds., 1972, Geology of Minnesota: A centennial volume: Minnesota Geological Survey, 632 p., 2 pls.

Sims, P.K., and Southwick, D.L., 1985, Geologic map of Archean rocks, western Vermilion district, northern Minnesota: U.S. Geological Survey Miscellaneous Investigations Map I-1527, scale 1:48,000.

Southwick, D.L., comp., 1993, Geologic map of Archean bedrock, Soudan–Bigfork area, northern Minnesota: Minnesota Geological Survey Miscellaneous Map M-79, scale 1:100,000.

Southwick, D.L., Boerboom, T.J., and Jirsa, M.A., 1998, Geologic setting and descriptive geochemistry of Archean supracrustal and hypabyssal rocks, Soudan–Bigfork area, northern Minnesota: Implications for metallic mineral exploration: Minnesota Geological Survey Report of Investigations 51, 69 p.

Southwick, D.L., Morey, G.B., and McSwiggen, P.L., 1988, Geologic map (scale 1:250,000) of the Penokean orogen, central and eastern Minnesota, and accompanying text: Minnesota Geological Survey Report of Investigations 37, 25 p., 1 pl.

Taib, N.I., and Ripley, E.M., 1993, Distribution and genesis of Cu-Ni sulfides in a multiple intrusive sequence, Babbitt area, Duluth Complex, MN [abs.]: Geological Society of America Annual Meeting, Boston, Mass., Abstracts with Programs, v. 25, no. 6, p. A400-A401.

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., comp., Productivity in Lake Superior Mining District, Proceedings, 39th Annual Minnesota Mining Symposium: University of Minnesota, Minneapolis, Minn., p. 19.1-19.11.

White, D.A., 1954, Stratigraphy and structure of the Mesabi range, Minnesota: Minnesota Geological Survey Bulletin 38, 92 p., 4 pls.

Williams, H.R., Stott, G.M., Heather, K.B., Muir, T.L., and Sage, R.P., 1991, Wawa subprovince, *in* Thurston, P.C., Williams, H.R., Sutcliffe, R.H., and Stott, G.M., eds., Geology of Ontario: Ontario Geological Survey Special Volume 4, pt. 1, p. 485-542.

Zanko, L.M., Severson, M.J., Oreskovich, J.A., Heine, J.J., and Hauck, S.A., in press, Oxidized taconite geological resources for a portion of the western Mesabi Range (west half of the Arcturus mine to the east half of the Canisteo mine), Itasca County, Minnesota—A GIS-based resource analysis for land-use planning: Natural Resources Research Institute, Technical Report NRRI/TR-2001/40.

Zanko, L.M., Severson, M.J., and Ripley, E.M., 1994, Geology and mineralization of the Serpentine copper-nickel deposit: Natural Resources Research Institute, Technical Report NRRI/TR-93/52, 90 p., 3 pls.

Chapter 5

VOLCANIC AND SEDIMENTARY ROCKS OF THE KEWEENAWAN SUPERGROUP IN NORTHEASTERN MINNESOTA

John C. Green

The Duluth Complex and related intrusions of the Midcontinent Rift Intrusive Supersuite (Chapter 1, Table 1.4) were largely emplaced into a comagmatic edifice of volcanic and minor sedimentary rocks that now extend along Minnesota's north shore of Lake Superior and are referred to as the North Shore Volcanic Group (Goldich and others, 1961). Although previous publications have subdivided the North Shore Volcanic Group into informal volcanic suites and distinctive flows (Green, 1972, 1982), the 1:200,000-scale map accompanying this report (M-119) represents the first time that the North Shore Volcanic Group has been subdivided into formational entities on a geologic map. A brief description of the North Shore Volcanic Group and associated sedimentary formations of the Keweenawan Supergroup is given here to supplement the information provided on the geologic map about these formational units.

NORTH SHORE VOLCANIC GROUP

Rock classification, recognition, and textures

As a coherent tholeiitic compositional suite, the volcanic rocks of the North Shore Volcanic Group can be described using only a few rock names (Fig. 5.1). The most primitive rocks are olivine tholeiites, which form an iron-enrichment trend with further evolution. They display ophitic textures and pahoehoe surfaces nearly everywhere. Most olivine tholeiites are aphyric, but those that are porphyritic contain dominantly plagioclase phenocrysts, less commonly olivine. Transitional basalts contain somewhat higher alkalies and other incompatible elements than the olivine tholeiites, but generally not enough to classify them as alkalic. Their texture is typically intergranular and fine- to medium-grained. Porphyritic varieties generally contain small phenocrysts of plagioclase, olivine, clinopyroxene, and magnetite. The reversed-polarity Hovland lavas, however, are characterized by transitional basalts (grading to basaltic andesites) that contain abundant, large, tabular, plagioclase phenocrysts. Transitional basalt flow surfaces are generally smooth (pahoehoe), although a few show breccia tops.

The basaltic andesites and andesites (greater than 52 percent SiO_2) are tholeiitic, rather than calc-alkaline; they show iron enrichment and contain only anhydrous ferromagnesian minerals. These rocks are typically fine-grained and intergranular to felty or pilotaxitic, and many contain small phenocrysts of plagioclase, olivine, clinopyroxene, and magnetite. The andesites generally weather to a red-brown color, and have flow-brecciated (aa) tops but not bases. Many flows that contain 50 to 55 percent silica show millimeter-scale oxidation lamination (Green, 1989) parallel to the base. A few highly iron-enriched flows, separable only by chemical analysis, can be called ferroandesites.

Carmichael (1964) first used the name "icelandite" for rocks intermediate in character between andesites and rhyolites in the Tertiary lavas of eastern Iceland. They might be considered the tholeiitic equivalent of calc-alkaline dacite in orogenic suites. Other examples of these rocks have been described from the Galapagos (McBirney and Williams, 1969) and the Miocene of Nevada–Oregon (Wallace and others, 1980). Very large flows of similar composition in the Etendeka volcanics of Namibia have been referred to as quartz latites by Milner and others (1992). Icelandites in the North Shore Volcanic Group (Green and Fitz, 1993) are characterized chemically by SiO_2 contents ranging from 60 to 68 percent, high FeO* (averaging 7 percent), $K_2O + Na_2O$ values between 6.5 and 9 percent, a potassium/sodium atomic ratio of about 0.9, and an Mg number [Mg/(Mg + Fe) atomic] averaging 0.14. Petrographically, North Shore Volcanic Group icelandites grade continuously from the andesites to somewhat paler colors (brown or tan), but have a similar phenocryst assemblage. Quartz and alkali feldspar are common in the groundmass but never occur as phenocrysts. Flowtop features (crusty to coarsely brecciated) indicate that the icelandites were erupted as lavas.

The rhyolites have higher silica and total alkali contents, and lower FeO than the icelandites. They

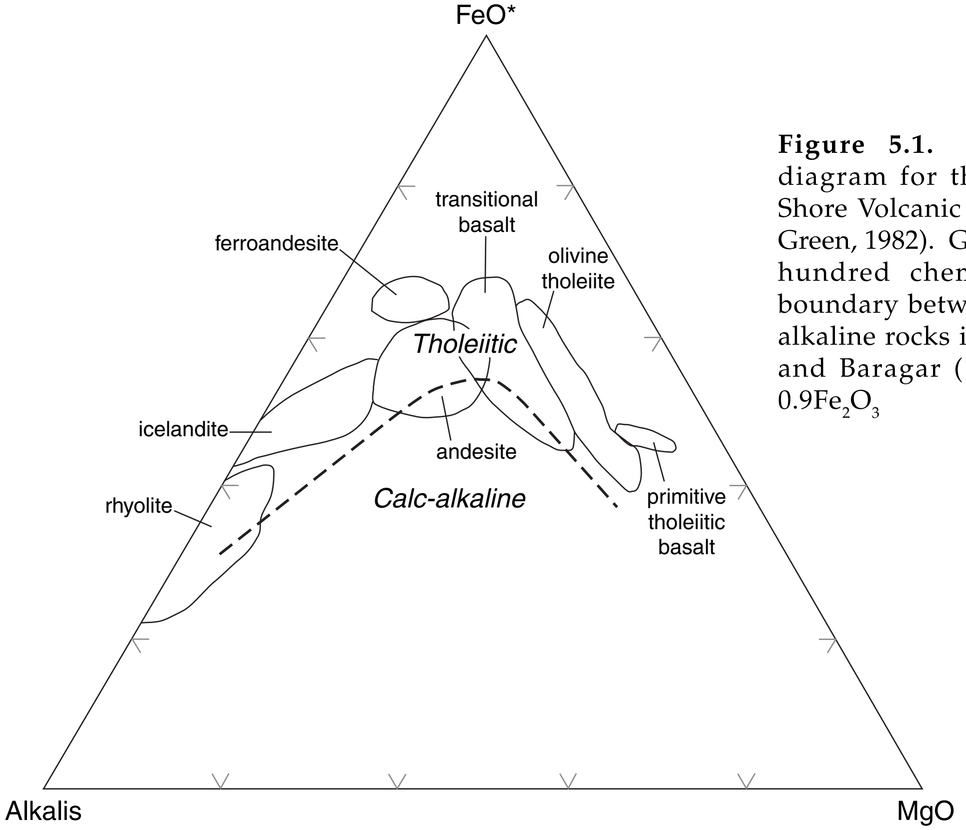


Figure 5.1. AFM compositional diagram for the lavas of the North Shore Volcanic Group (modified from Green, 1982). Generalized from several hundred chemical analyses. The boundary between tholeiitic and calc-alkaline rocks is modified from Irvine and Baragar (1971). FeO* = FeO + $0.9Fe_2O_3$

are generally light gray, pink, or red. Several are very thick, extensive, and voluminous (up to several hundred cubic kilometers; Green and Fitz, 1993). Although most rhyolites are porphyritic (phenocrysts of quartz, alkali feldspar ± plagioclase, and altered fayalite ± ferroaugite), some lack quartz and alkali feldspar phenocrysts, and rare flows are aphyric. Groundmass textures are fine-grained holocrystalline, typically with a meshwork of platy quartz paramorphs after primary tridymite, which may show a flow structure. A "snowflake" texture is common, in which poikilitic quartz patches (coalesced ex-tridymite grains) enclose small, dusty alkali-feldspar grains. In quartz-phyric flows, these poikilitic quartz patches are in optical continuity with adjacent quartz phenocrysts (Green, 1990). Outcrop-scale flow structure, including folding, is common near flow tops and bases. In some flows, distinct fiamme, deformed to varying degrees, are recognizable. These imply an explosive eruption that produced a pyroclastic flow, which welded and remobilized to produce a rheoignimbrite.

Lithostratigraphy and structure

As stated above, the Midcontinent rift volcanic rocks and interbedded redbeds in northeastern Minnesota comprise the North Shore Volcanic Group (Goldich and others, 1961; Green, 1972, 1977, 1982; Basaltic Volcanism Study Project, 1981). In general, these rocks form an arcuate stack that is slightly tilted toward the southeast and forms the roof rocks into and under which the Duluth Complex and associated hypabyssal intrusions were emplaced. At the southwest end of the North Shore Volcanic Group near Duluth, the volcanic rocks strike north with a 10° to 20° easterly dip; at the northeast end at Grand Portage, the flows strike east–west with a 10° southerly dip (see M-119). Thus, traveling northeast along the Lake Superior shore from Duluth, and southwest from Grand Portage, one encounters successively higher flows in the volcanic stratigraphy until the Tofte–Lutsen area in southern Cook County, where the highest exposed flows crop out. Exposure is generally excellent along the eroding lakeshore, and along the lower, high-gradient stretches of tributary streams, providing good control on the stratigraphy. A stack of volcanic rocks approximately 9.7-kilometers-thick has been measured in the "southwest limb" (southwest of Tofte; Fig. 5.2), and another stack of volcanic rocks about 7.2-kilometers-thick has been measured in the "northeast limb" (Lutsen to Grand Portage). This implies nearly continuous subsidence during the rifting process.

The difference in stratigraphic thickness between the two limbs reflects major complications in the central area, which appears not to have subsided at the same rate as in the limbs, and into which many of the subvolcanic intrusions were emplaced. Except for the capping Schroeder–Lutsen basalt sequence, no stratigraphic unit can be traced from one limb to the other; each limb has its own stratigraphic column (Tables 5.1 and 5.2).

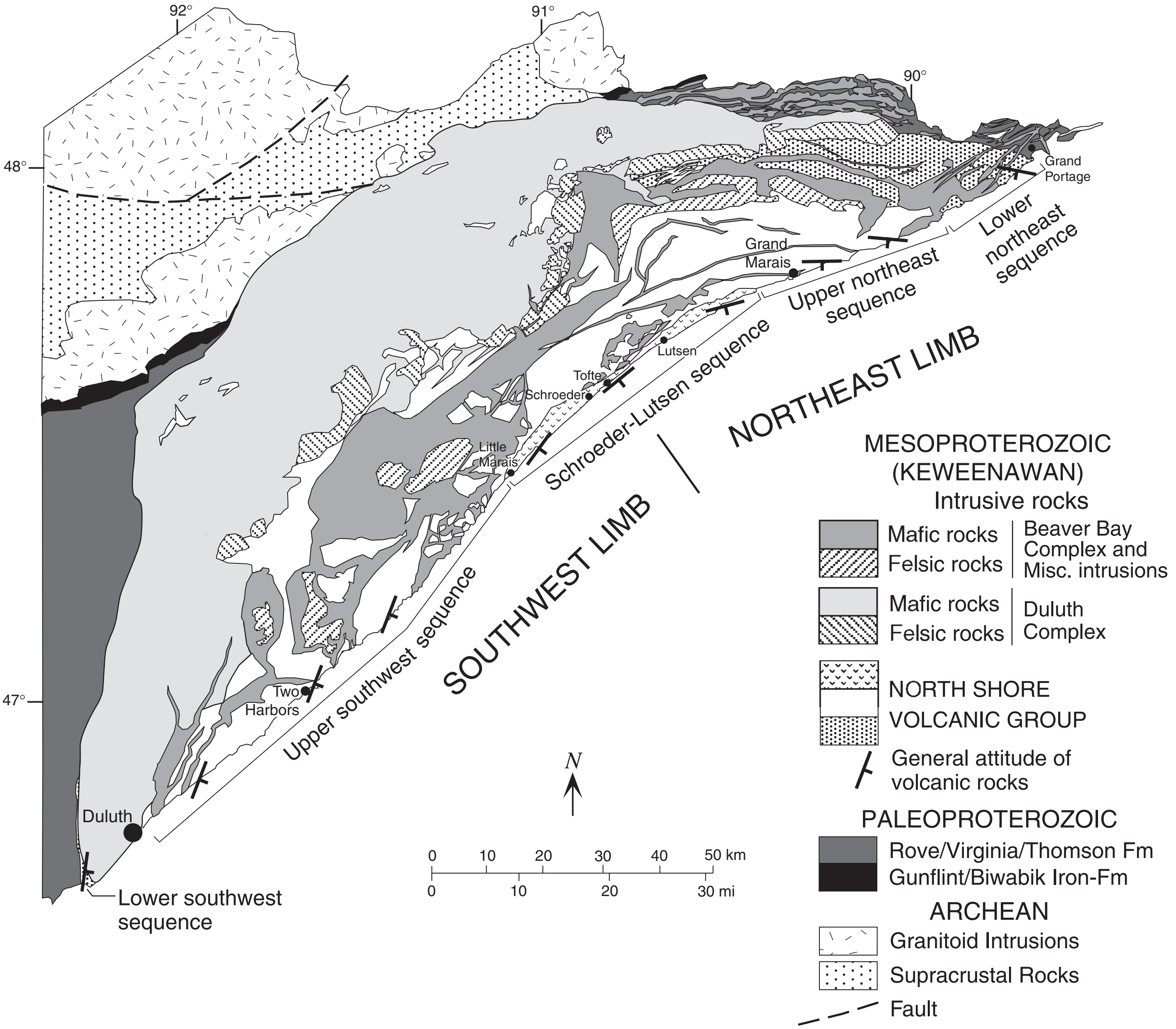


Figure 5.2. Generalized geologic map showing the basic structure and distribution of volcanic sequences of the North Shore Volcanic Group. Regional dips of volcanic rocks are typically less than 25°.

To aid in the correlation of intrusive and extrusive rock units throughout the Midcontinent rift system, their paleomagnetic polarity has been used. Nearly all of the igneous and sedimentary rocks associated with the Midcontinent rift were formed either during an earlier, reversed-polarity interval or a succeeding normal-polarity interval. Thus, in each limb of the North Shore Volcanic Group, the lower stratigraphic units show reversed polarity, and the upper sequences show normal polarity. This polarity reversal forms the basis for distinguishing upper and lower sequences in the northeast and southwest limbs (Tables 5.1 and 5.2). U-Pb zircon dates demonstrate that the reversed-polarity magmatism occurred mainly in the time interval from 1108 to 1107 Ma; whereas, around the Lake Superior basin, normal-polarity magmatism occurred mainly in the interval from 1099 to 1094 Ma (for example Davis and Paces, 1990; Paces and Miller, 1993; Davis and Green, 1997). These two pulses were separated by a magmatically inactive time (at least in the upper crust), which appears to be expressed as a slight unconformity in the volcanic sequence on the north shore (Tables 5.1 and 5.2). However, because intrusions subsequently penetrated along this horizon in the North Shore Volcanic Group, this unconformity has not been recognized in outcrop.

One other significant gap in the stratigraphic continuity of the North Shore Volcanic Group occurs near the stratigraphic top, where the Schroeder–Lutsen sequence overlies the upper units of the northeast and southwest sequences (Tables 5.1 and 5.2). In the northeast limb, southwest of Grand Marais (Fig. 5.2), the basal flow of the Schroeder–Lutsen sequence (Terrace Point basalt member) overlies a thick sandstone and siltstone unit (Cut Face Creek sandstone), which in turn conformably overlies the Good Harbor Bay andesites of the upper northeast sequence (Table 5.2). However, in the southwest limb, the basal Schroeder–Lutsen sequence flow overlies a thinner sandstone and conglomerate unit (the Little Marais conglomerate) that in turn rests in sharp angular unconformity atop structurally disturbed flows of the Bell Harbor Bay lavas near Little Marais (Table 5.1). Furthermore, the gently dipping Schroeder basalts have not been penetrated by the abundant hypabyssal intrusions of the Beaver Bay Complex that complicate the underlying volcanic sequence in this mid-shore area (Green, 1992; Miller and others, 1993). Attempts to date the Schroeder–Lutsen sequence have been unsuccessful to this point.

Finally, a 150-meter-thick sequence of basalt, andesite, and rhyolite flows, isolated by faults from the adjacent Schroeder–Lutsen sequence, underlies the south flank of Carlton Peak near Tofte (Green, 1996). These lavas, well exposed below the Carlton Peak quarry, are probably also faulted against the older volcanic rocks to the northwest. Dated at 1094.3 ± 2.0 Ma (D. Davis, unpub. data, 2001), this package contains the youngest volcanic rocks yet dated on the Midcontinent rift in Minnesota. It is comparable in age and stratigraphic position to a rhyolite in the Porcupine Volcanics across the rift in Michigan (Zartman and others, 1997; Green and others, 2001), and to the upper part of the Portage Lake Volcanics (Davis and Paces, 1990). Because these lavas at Carlton quarry are intruded by anorthosite-bearing diabase at Carlton Peak, this date in turn sets a minimum age for that large intrusive complex.

As explained in Chapter 1, the five lithostratigraphic sequences comprising the two limbs of the North Shore Volcanic Group are further subdivided into informal formational units (Tables 5.1 and 5.2). Some formational units are individual flows of distinctive lithology and/or substantial thickness and lateral extent. Most are suites of lava flows that have distinct lithologic characteristics or that are separated by intrusions. Some lava formations contain distinct flows or sedimentary rock units within an otherwise homogeneous package of lavas. Such units are given informal member rank (such as the Silver Beaver rhyolite member of the Baptism River lavas, Manitou transitional basalt member of the Schroeder basalts, and Indian Camp sandstone member of the Lutsen basalts).

Physical volcanology

The volcanic rocks of the Midcontinent rift, including the North Shore Volcanic Group, represent one of the world's oldest and best-preserved examples of plateau lavas. However, they are not typical in that they contain a greater thickness of flows and, in the North Shore Volcanic Group, a higher proportion of evolved compositions. They are similar physically and chemically to the Tertiary lavas that make up eastern Iceland (Sigvaldason, 1974; Walker, 1974; Green, 1977; Wood, 1978), and they formed similarly over a plume at another major rift. The rocks also resemble the late Tertiary and Quaternary volcanic rocks of the southern Snake River Plain, Idaho and southeastern Oregon, because of their interbedded basalts and large

Table 5.1. Generalized stratigraphy of the southwest limb of the North Shore Volcanic Group showing U/Pb ages (Davis and Green, 1997; Green and others, 2001). Breaks in stratigraphy due to intrusions or unconformities are noted in italics.

Approximate thickness (meters)		Formational units	Lithologic character	U/Pb ages (Ma)
9735	Total section			
	150	Carlton Quarry lavas (*fault bounded*)	basalt, andesite, and rhyolite flows	1094.3±2.0
945	Schroeder–Lutsen sequence (normal polarity)			
	900	Schroeder basalts	ophitic olivine tholeiite basalt flows; includes Manitou transitional basalt and Pork Bay breccia	
	<45	Little Marais conglomerate	polymict volcanic conglomerate and sandstone	
		angular unconformity		
8275	Upper southwest sequence (normal polarity)			
	565	Bell Harbor lavas	mostly quartz tholeiite basalt and basaltic andesite flows	
	100	Palisade Head rhyolite	gray-pink, porphyritic rhyolite flow	1096.6±1.7
		Beaver Bay Complex		~1096
	700	Baptism River lavas	mixed lavas, mostly basalt; includes 165-meter-thick Silver Beaver rhyolite	
	20	Silver Bay porphyritic basalt	ophitic basalt flow with abundant large plagioclase phenocrysts	
	730	Gooseberry River basalts	mixed basalt flows, mostly ophitic	
		Lafayette Bluff, Silver Creek diabase intrusions		
	315	Two Harbors basalts	mixed aphyric basalt flows; quartz tholeiite flows at base	
	550	Larsmont basalts	ophitic olivine tholeiite flows	
		Stony Point–Knife Island diabase sheet		
	1500	Sucker River basalts	mixed basalt flows, mostly ophitic	
	1350	Lakewood lavas	mostly basalt flows; rhyolite, icelandite, and ferroandesite at base	
		Lester River diabase sill		
	1285	Lakeside lavas	mixed basalt, andesite, icelandite, and rhyolite flows	1098.4±1.9
		Endion diabase sill		
	1160	Leif Erickson Park lavas	mixed basalts, andesites	
		Duluth Complex		~1099
370	Lower southwest sequence (reversed polarity)			
	370	Ely's Peak basalts	porphyritic, diabasic, and ophitic basalts; basal flow pillowed	
BASE				
	>8	Nopeming Sandstone	white to tan quartzite and conglomerate	
		angular unconformity		
		Thomson Formation (Paleoproterozoic)		

Table 5.2. Generalized stratigraphy of the northeast limb of the North Shore Volcanic Group showing U/Pb ages (Davis and Green, 1997). Breaks in stratigraphy due to intrusions or unconformities are noted in italics.

Approximate thickness (meters)		Formational units	Lithologic character	U/Pb ages (Ma)
7259	Total section			
455	Schroeder–Lutsen sequence (normal polarity)			
	435	Lutsen basalts	olivine tholeiite basalts, mostly ophitic; includes Indian Camp sandstone and Terrace Point basalt members	
	20	Cut Face Creek sandstone	red, laminated, ripple-marked sandstone	
		disconformity (inferred)		
3768	Upper northeast sequence (normal polarity)			
	131	Good Harbor Bay andesites	brown, porphyritic basaltic andesite flows	
	122	Breakwater basalt	brown, columnar-jointed basalt flow	
	348	Grand Marais felsites	pink to gray porphyritic rhyolite and felsite	
	335	Croftville basalts	intergranular basalt and andesite flows	
	250	Devil Track rhyolite	aphyric, intergranular rhyolite flow	
	70	Maple Hill rhyolite	porphyritic rhyolite flow	
	274	Red Cliff basalts	ophitic olivine tholeiite flows, some plagioclase-phyric	
	366	Kimball Creek rhyolite	porphyritic rhyolite flow	
	539	Marr Island lavas	mixed basalt, tholeiitic andesite, and icelandite flows	
	198	Naniboujou basalts	intergranular basalt flows	
	235	Devil's Kettle rhyolite	porphyritic ash-flow tuff	1097.7±1.7
	900	Brule River lavas	interbedded basalt and rhyolite flows	1100.2±2.2
		Brule Lake–Hovland gabbro		
3036	Lower northeast sequence (reversed polarity)			
	1932	Hovland lavas	mostly plagioclase-phyric basalt flows; some rhyolite and andesite	1107.7±1.9
		Brule Lake/Hovland gabbro (Reservation River diabase)		
	67	Red Rock rhyolite	red/tan, porphyritic rhyolite	1107.9±1.8
	92	Deronda Bay andesite	tan/brown, porphyritic andesite	
	945	Grand Portage lavas	basalt lava flows, pillowed at base	
BASE				
	60	Puckwunge Sandstone	tan/white, cross-bedded quartz sandstone	
		slight angular unconformity		
		Rove Formation (Paleoproterozoic)		

rhyolites (for example Bonnichsen and Kauffman, 1987; Link and Hackett, 1988; Reidel and Hooper, 1989; Manley, 1996).

The basalts range in character from typical flood flows as voluminous as tens of cubic kilometers to more modest, "plains-type" flows (Greeley, 1982) and thin flow units less than a meter thick. At Duluth in the southwest limb, and Grand Portage in the northeast limb, the lowest flows in the volcanic sequences are pillowed, and thus inferred to have erupted subaqueously; however, nearly all of the other flows were erupted subaerially. The flows show different physical characteristics, closely tied to their chemical compositions and viscosities (Green, 1979, 1989; Green and Fitz, 1993). Olivine tholeiites, which dominate the North Shore Volcanic Group, all have pahoehoe surfaces, with or without ropy structures. Other physical characteristics of the various rock types were previously discussed in the "Rock classification, recognition, and textures" section of this chapter.

All of the flows ranging in composition from basalts to icelandites were erupted as lavas. The rhyolites are notable in their abundance relative to other plateau-lava sequences, their size (up to several hundred cubic kilometers), and extent (Green and Fitz, 1993). Several rhyolites show textural evidence of rheomorphic flow after eruption as ash-flow tuffs, though some were lavas. One of the largest, the Devil Track rhyolite in Cook County, which is as thick as 250 meters and can be traced for 40 kilometers along strike, has ambiguous features that make its mode of eruption difficult to discern; it may be a lava flow. Nearly all the icelandites and rhyolites show evidence of an unusually high temperature of eruption, such as magmatically crystallized groundmass tridymite. The evidently low viscosity of these large rhyolites is attributed to their high temperature, high iron and fluorine contents, and low oxidation state (Green and Fitz, 1993).

Geochemistry and chemostratigraphy

The North Shore Volcanic Group constitutes a subalkalic, tholeiitic suite that ranges continuously from rather primitive olivine tholeiite to rhyolite, and shows a strong iron-enrichment trend (Fig. 5.1; also Basaltic Volcanism Study Project, 1981; Green, 1982; Brannon, 1984). However, relative abundances are strongly bimodal; basalts are greatly predominant, but rhyolites make up 10 to 25 percent of the section. The basalts show trace element and isotopic evidence of derivation mostly from a mantle plume (Nicholson and others, 1997), whereas most of the rhyolites include major contributions from partial melting of the Archean basement (Vervoort and Green, 1997). The most common basalt type, ophitic olivine tholeiite, is generally aluminum-rich (16 to 18 percent Al_2O_3); the most primitive flows have Mg numbers of about 0.65 to 0.68.

The basal few flows in both limbs of the North Shore Volcanic Group have a unique geochemical and petrographic character. Typically they contain augite phenocrysts, are aluminum-poor, and are rich in both compatible (chromium and nickel) and incompatible elements (titanium, phosphorus, and lanthanum) with steep chondrite-normalized lanthanum/ytterbium ratios. This suggests derivation by relatively small-fraction melting of the initial plume head (Nicholson and others, 1991, 1997; Green, 1995).

In general, there is little stratigraphic regularity of compositional change within the North Shore Volcanic Group, with the following exceptions. In the middle of the upper southwest sequence, there is a marked upward progression toward more primitive compositions through a 3.4-kilometer section from rhyolite east of the Lester River into a thick group of primitive olivine tholeiites in the Knife River–Two Harbors area (Brannon, 1984). This includes the Lakewood lavas, the Sucker River basalts, and the Larsmont basalts. In contrast, in the lower northeast sequence, the approximately 1-kilometer-thick basal Grand Portage lavas progress upsection from basalt to increasingly evolved compositions, ending with Red Rock rhyolite (Green, 1995). As mentioned above, the Schroeder–Lutsen sequence, the youngest in the North Shore Volcanic Group, is composed almost entirely of olivine tholeiites.

All of the North Shore Volcanic Group has been affected to some degree by hydrothermal/burial metamorphism. The more permeable (fractured, vesicular) tops and bases of the flows have undergone considerable mineralogical change (deposition of amygdule minerals, alteration of primary minerals), but in many cases the massive flow interiors are remarkably little-altered. Where alteration has approached equilibrium, mineral assemblages range from lower greenschist facies at the base of the North Shore Volcanic Group to zeolite facies at the top (Schmidt, 1993; Schmidt and Robinson, 1997).

Interflow sedimentary rocks

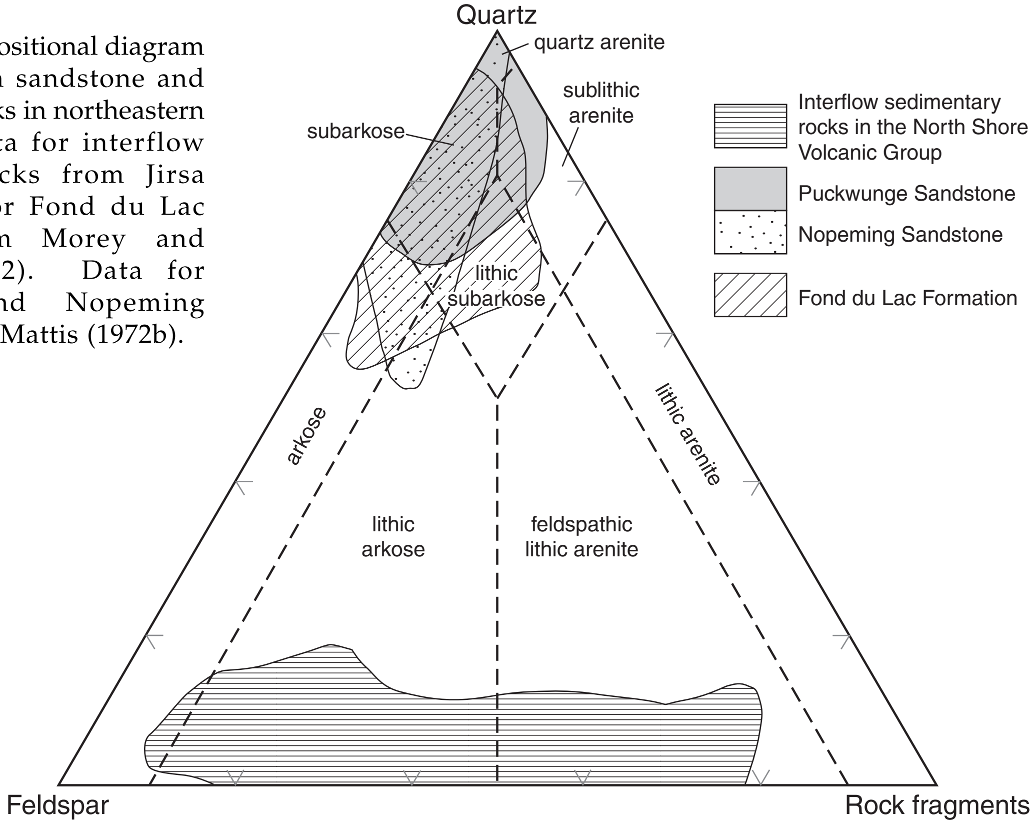
Clastic redbed strata occur at many horizons within the North Shore Volcanic Group (Jirsa, 1984). They are lenticular and range in thickness from a few centimeters to about 100 meters. As these rocks are relatively soft and erodable compared to the adjacent volcanic flows, they are mostly covered and are exposed only along actively eroding sites such as streambeds and the lakeshore. They are predominantly red to brown, well sorted sandstone, with minor conglomerate, siltstone, and shale. Conglomerate beds are most abundant in the midshore area from Little Marais to Lutsen.

Compositionally, these redbeds are mainly immature lithic arkose and feldspathic lithic arenite (Fig. 5.3). The angular to subrounded clasts are mainly plagioclase, mafic to felsic volcanic rock fragments, clinopyroxene, and Fe-Ti oxides; devitrified or replaced volcanic ash particles and shards are present in a few beds. Quartz is uncommon to absent. The framework grains have been variably cemented with hematite, calcite, prehnite, and a variety of zeolites, depending on the local hydrothermal/burial/contact metamorphic conditions. In some places hydrothermal minerals have replaced many or most of the clasts.

A few of these redbed units have thicknesses in excess of 25 meters. These include a cross-bedded sandstone in Leif Erickson Park in Duluth (35 meters), which disconformably overlies an eroded basalt flow; the Little Marais conglomerate (and sandstone) exposed in the Manitou River area near Little Marais (as thick as 45 meters); the Indian Camp sandstone (68 meters) northeast of Lutsen; and the Cut Face Creek sandstone southwest of Grand Marais (100 meters), which can be traced for at least 4 kilometers along strike. Of these, the Little Marais and Cut Face Creek units occur at the base of the Schroeder–Lutsen basalt sequence. The sandstone in these units is typically planar- or cross-bedded, and some beds are ripple-marked or mud-cracked. The rocks are inferred to be dominantly fluvial, deposited by moderate-gradient, east- to southwest-flowing streams from sources nearly entirely within the subsiding Midcontinent rift basin (Jirsa, 1984).

Many flowtop breccias of andesite and basalt with aa structure contain laminated red sandstone

Figure 5.3. Compositional diagram for Keweenawan sandstone and conglomerate rocks in northeastern Minnesota. Data for interflow sedimentary rocks from Jirsa (1984). Data for Fond du Lac Sandstone from Morey and Ojakangas (1982). Data for Puckwunge and Nopeming Sandstones from Mattis (1972b).



as a matrix because sand filtered down from the flow surface. Similarly, red, laminated sandstone and siltstone form clastic dikes or crevice-fillings a few centimeters wide in the upper parts of some lava flows.

KEWEENAWAN SEDIMENTARY ROCKS NOT ASSOCIATED WITH THE NORTH SHORE VOLCANIC GROUP

Puckwunge Sandstone

The Puckwunge Sandstone (Mattis, 1972a, b) comprises mineralogically and texturally mature, light-colored, well-indurated quartz arenites that disconformably underlie the basal, reversed-polarity North Shore Volcanic Group lavas (Grand Portage lavas, Table 5.2) in northeastern Minnesota. The Puckwunge Sandstone is exposed discontinuously from Lucille and Grand Portage Islands westward for approximately 40 kilometers. Dipping about 10° to the south, it overlies the Paleoproterozoic (Animikie) Rove Formation with a slight angular unconformity (Ojakangas and Morey, 1982). It has a maximum exposed thickness of 60 meters, and locally contains a basal conglomerate with well-rounded pebbles of vein quartz, quartzite, chert, jasper, iron-formation, slate, and argillite (Fig. 5.3).

Nopeming Sandstone

The Nopeming Sandstone (Mattis, 1972a, b; Ojakangas and Morey, 1982) conformably underlies the basal Midcontinent rift lavas southwest of Duluth. Like the Puckwunge Sandstone, the Nopeming Sandstone is composed of pale, mature, well-indurated quartz arenite and quartz conglomerate (Fig. 5.3). It is exposed intermittently over a north–south strike length of about 0.8 kilometer and dips gently to the east. The Nopeming Sandstone has a maximum exposed thickness of about 7.5 meters, although its base is not exposed and its true thickness may be somewhat greater. The sandstone was unconsolidated when the basal lava flow was erupted; the basal flow is pillowed, and the pillow bases deformed the underlying quartzose, silty sediment. The quartzite overlies slate and graywacke of the Paleoproterozoic Thomson Formation along a profound angular unconformity (Kilburg and Morey, 1977).

Fond du Lac Formation

The Fond du Lac Formation unconformably overlies the Paleoproterozoic Thomson Formation, the Ely's Peak basalts, and the Duluth Complex at the southern end of the map area (Morey, 1967, 1972; Morey and Ojakangas, 1982). Although only approximately 245 meters of strata are exposed, the formation may be as thick as 2.1 kilometers, according to seismic evidence.

The Fond du Lac Formation is composed principally of red to brown sandstone and siltstone with local volcanic conglomerate, mudstone, and shale. A basal quartz-pebble conglomerate is exposed in the bed of Little River. The sandstone is mostly poorly sorted arkose that contains clasts of quartz, chert, microcline, and micas; these characteristics imply a source outside the Midcontinent rift, though minor volcanic components are locally present (Fig. 5.3). Matrix material includes clays, hematite, and calcite cement.

This formation is considered to be correlative with the Orienta Sandstone of the Bayfield Group of Wisconsin and the Jacobsville Sandstone of Michigan, and to be fluvially deposited during and after post-rifting uplift of the central horst of the Midcontinent rift. Depositional structures indicate eastward transport.

REFERENCES

Basaltic Volcanism Study Project, 1981, Pre-Tertiary continental flood basalts, *in* Basaltic volcanism on the terrestrial planets: New York, Pergamon Press, p. 30-77.

Bonnichsen, B., and Kauffman, D.F., 1987, Physical features of rhyolite lava flows in the Snake River Plain volcanic province, southwestern Idaho, *in* Fink, J.H., ed., The emplacement of silicic domes and lava flows: Geological Society of America Special Paper 212, p. 119-145.

Brannon, J.C., 1984, Geochemistry of successive lava flows of the Keweenawan North Shore Volcanic Group: St. Louis, Mo., Washington University, Ph.D. dissertation, 312 p.

Carmichael, I.S.E., 1964, The petrology of Thingmuli, a Tertiary volcano in eastern Iceland: Journal of Petrology, v. 5, no. 3, p. 435-460.

Davis, D.W., and Green, J.C., 1997, Geochronology of the North American Midcontinent rift in western Lake Superior and implications for its geodynamic evolution: Canadian Journal of Earth Sciences, v. 34, no. 4, p. 476-488.

Davis, D.W., and Paces, J.B., 1990, Time resolution of geologic events on the Keweenaw Peninsula and implications for development of the Midcontinent rift system: Earth and Planetary Science Letters, v. 97, p. 54-64.

Goldich, S.S., Nier, A.O., Baadsgaard, H., Hoffman, J.H., and Krueger, H.W., 1961, The Precambrian geology and geochronology of Minnesota: Minnesota Geological Survey Bulletin 41, 193 p., 5 pls.

Greeley, R., 1982, The Snake River Plain, Idaho: Representative of a new category of volcanism: Journal of Geophysical Research, v. 87, no. B4, p. 2705-2712.

Green, J.C., 1972, North Shore Volcanic Group, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 294-332.

———1977, Keweenawan plateau volcanism in the Lake Superior region, *in* Baragar, W.R.A., Coleman, L.C., and Hall, J.M., eds., Volcanic regimes in Canada: The proceedings of a symposium: Geological Association of Canada Special Paper 16, p. 407-422.

———1979, Field trip guidebook for the Keweenawan (Upper Precambrian) North Shore Volcanic Group, Minnesota: Minnesota Geological Survey Guidebook Series no. 11, 22 p.

———1982, Geology of Keweenawan extrusive rocks, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 47-55.

———1989, Physical volcanology of mid-Proterozoic plateau lavas: The Keweenawan North Shore Volcanic Group, Minnesota: Geological Society of America Bulletin, v. 101, no. 4, p. 486-500.

———1990, Primary tridymite crystallization and inferences from tridymite and quartz textures in high-T Keweenawan rhyolites and granophyres, Minnesota [abs.]: Geological Society of America, Annual Meeting, Abstracts with Programs, v. 22, p. A289-A290.

———1992, Geologic map of the North Shore of Lake Superior, Lake and Cook Counties, Minnesota: Part 1. Little Marais to Tofte: Minnesota Geological Survey Miscellaneous Map M-71, scale 1:24,000.

———1995, Chemostratigraphy at the fringe of the Midcontinent rift system: The northeast limb of the North Shore Volcanic Group, Minnesota [abs.], *in* International Geological Correlation Program, Proceedings: International geological correlation program project 336 field conference and symposium on the petrology and metallogeny of volcanic and intrusive rocks of the Midcontinent rift system, Duluth, Minnesota: Duluth, Minn., University of Minnesota Duluth Continuing Education Extension, p. 55-56.

———1996, Geology on display: Geology and scenery of Minnesota's north shore state parks: St. Paul, Minn., Minnesota Department of Natural Resources, 70 p.

Green, J.C., Davis, D.W., and Schmitz, M.D., 2001, Three new zircon dates for the Midcontinent rift, north shore, Minnesota: More data, more questions [abs.]: Institute on Lake Superior Geology, 47th Annual Meeting, Madison, Wis., Proceedings, v. 47, Program and Abstracts, pt. 1, p. 29.

Green, J.C., and Fitz, T.J., III, 1993, Extensive felsic lavas and rheoignimbrites in the Keweenawan Midcontinent rift plateau volcanics, Minnesota: Petrographic and field recognition: Journal of Volcanology and Geothermal Research, v. 54, p. 177-196.

Irvine, T.N., and Baragar, W.R.A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Journal of Earth Sciences, v. 8, no. 5, p. 523-548.

Jirsa, M.A., 1984, Interflow sedimentary rocks in the Keweenawan North Shore Volcanic Group, northeastern Minnesota: Minnesota Geological Survey Report of Investigations 30, 20 p.

Kilburg, J.A., and Morey, G.B., 1977, Esko quadrangle, St. Louis and Carlton Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-25, scale 1:24,000.

Link, P.K., and Hackett, W.R., eds., 1988, Guidebook to the geology of central and southern Idaho: Idaho Geological Survey Bulletin 27, 319 p.

Manley, C.R., 1996, Physical volcanology of a voluminous rhyolite lava flow: The Badlands lava, Owyhee Plateau, southwestern Idaho: Journal of Volcanology and Geothermal Research, v. 71, no. 2-4, p. 129-154.

Mattis, A.F., 1972a, Puckwunge Formation of northeastern Minnesota, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 412-415.

———1972b, The petrology and sedimentation of the basal Keweenawan Sandstones of the north and south shores of Lake Superior: Minneapolis, University of Minnesota, M.S. thesis, 123 p.

McBirney, A.R., and Williams, H., 1969, Geology and petrology of the Galapagos Islands: Geological Society of America Memoir 118, 197 p.

Miller, J.D., Jr., Green, J.C., Boerboom, T.J., and Chandler, V.W., 1993, Geologic map of the Doyle Lake and Finland quadrangles, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-72, scale 1:24,000.

Milner, S.C., Duncan, A.R., and Ewart, A., 1992, Quartz latite rheoignimbrite flows of the Etendeka Formation, north-western Namibia: Bulletin of Volcanology, v. 54, no. 3, p. 200-219.

Morey, G.B., 1967, Stratigraphy and petrology of the type Fond du Lac Formation, Duluth, Minnesota: Minnesota Geological Survey Report of Investigations 7, 35 p.

———1972, Petrology of Keweenawan sandstones in the subsurface of southeastern Minnesota, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 436-449.

Morey, G.B., and Ojakangas, R.W., 1982, Keweenawan sedimentary rocks of eastern Minnesota and northwestern Wisconsin, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 135-146.

Nicholson, S.W., Shirey, S.B., and Green, J.C., 1991, Regional Nd and Pb isotopic variations among the earliest Midcontinent rift basalts in western Lake Superior [abs.], *in* Geological Association of Canada/Mineralogical Association of Canada Joint Annual Meeting, Toronto, Program with Abstracts, v. 16, p. 90.

Nicholson, S.W., Shirey, S.B., Schulz, K.J., and Green, J.C., 1997, Rift-wide correlation of 1.1 Ga Midcontinent rift system basalts: Implications for multiple mantle sources during rift development, *in* Bornhorst, T.J., ed., Petrology and metallogeny of intraplate mafic and ultramafic magmatism: Canadian Journal of Earth Sciences, v. 34, no. 4, p. 504-520.

Ojakangas, R.W., and Morey, G.B., 1982, Keweenawan pre-volcanic quartz sandstones and related rocks of the Lake Superior region, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 85-96.

Paces, J.B., and Miller, J.D., Jr., 1993, Precise U-Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: Geochronological insights to physical, petrogenetic, paleomagnetic, and tectonomagmatic processes associated with the 1.1 Ga Midcontinent rift system: Journal of Geophysical Research, v. 98, no. B8, p. 13997-14013.

Reidel, S.R., and Hooper, P.R., 1989, Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, 386 p.

Schmidt, S.T., 1993, Regional and local patterns of low-grade metamorphism in the North Shore Volcanic Group, Minnesota, USA: Journal of Metamorphic Geology, v. 11, no. 3, p. 401-414.

Schmidt, S.T., and Robinson, D., 1997, Metamorphic grade and porosity and permeability controls on mafic phyllosilicate distributions in a regional zeolite to greenschist facies transition of the North Shore Volcanic Group, Minnesota: Geological Society of America Bulletin, v. 109, no. 6, p. 683-697.

Sigvaldason, G.E., 1974, Basalts from the centre of the assumed Icelandic mantle plume: Journal of Petrology, v. 15, no. 3, p. 497-524.

Vervoort, J.D., and Green, J.C., 1997, Origin of evolved magmas in the Midcontinent rift system, northeast Minnesota: Nd-isotope evidence for melting of Archean crust: Canadian Journal of Earth Sciences, v. 34, no. 4, p. 521-535.

Walker, G.P.L., 1974, The structure of eastern Iceland, *in* Kristjansson, L., ed., Geodynamics of Iceland and the north Atlantic area: Dordrecht, Holland, D. Reidel Publishing Company, p. 177-188.

Wallace, A.B., Drexter, J.W., Grant, N.K., and Noble, D.C., 1980, Icelandite and aenigmatite-bearing pantellerite from the McDermitt caldera complex, Nevada–Oregon: Geology, v. 8, no. 8, p. 380-384.

Wood, D.A., 1978, Major and trace element variations in the Tertiary lavas of eastern Iceland and their significance with respect to the Iceland geochemical anomaly: Journal of Petrology, v. 19, no. 3, p. 393-436.

Zartman, R.E., Nicholson, S.W., Cannon, W.F., and Morey, G.B., 1997, U-Th-Pb zircon ages of some Keweenawan Supergroup rocks from the south shore of Lake Superior, *in* Bornhorst, T.J., ed., Petrology and metallogeny of intraplate mafic and ultramafic magmatism: Canadian Journal of Earth Sciences, v. 34, no. 4, p. 549-561.

Chapter 6

GEOLOGY OF THE DULUTH COMPLEX

James D. Miller, Jr. and Mark J. Severson

The Duluth Complex and associated Keweenawan intrusions in northeastern Minnesota constitute one of the largest mafic intrusive complexes in the world, second only to the Bushveld Complex of South Africa. These rocks cover an arcuate area of over 5,000 square kilometers (Fig. 6.1) and give rise to two strong gravity anomalies (+50 and +70 milligals) that imply intrusive roots more than 13-kilometers-deep (Allen and others, 1997). Since the publication of the 1:250,000-scale geologic map of the Two Harbors sheet (Green, 1982), many new insights have been gained about the geology, petrology, structure, and intrusive history of this magmatic system. The new geologic map of northeastern Minnesota (M-119, Miller and others, 2001) and this report summarize these new insights.

The geologic picture of the Duluth Complex portrayed on map M-119 includes both new mapping and information that dates back to Grout and Schwartz's outcrop maps of Cook County (Grout and others, 1959). Recent detailed mapping in the complex has included remapping the type locality of the Duluth Complex at Duluth (Miller and others, 1993b), reconnaissance mapping in the southern Duluth Complex (Severson, 1995), and mapping and core logging along the northwestern margin of the complex (Miller, 1986; Severson and Hauck, 1990; Severson, 1994; Severson and Miller, 1999). U-Pb dating of zircons from mafic and felsic intrusions (Paces and Miller, 1993; Green and others, 2001; Sandland and others, 2001) has aided interpretation of the intrusive history of the Duluth Complex. In addition, many petrologic studies (Chalokwu and Grant, 1990; Miller and Weiblen, 1990; Chalokwu and others, 1993; Lee and Ripley, 1996; Miller and Ripley, 1996) have led to a better understanding of the crystallization histories of the various intrusions of the complex. But the most significant new insights into the geology of the Duluth Complex comes from interpretations of high-resolution aeromagnetic data gathered over much of the glacially masked central and southern areas (see Chapter 3). This database, which was acquired as the Two Harbors geologic map was being published in 1982, forms the primary basis for the identification of several newly recognized Duluth Complex intrusions (the Greenwood Lake, Osier Lake, Western Margin, and Boulder Lake intrusions). Moreover, the geologic descriptions of these and other poorly exposed Duluth Complex intrusions rely heavily on interpretations of their aeromagnetic characteristics.

In this chapter we provide brief summaries of the various intrusive components that make up the Duluth Complex. These summaries focus on defining the areal extent of the intrusions, their relationship to surrounding rocks, their internal structure and igneous stratigraphy, and an interpretation of their crystallization histories.

TECTONOMAGMATIC SETTING

The intrusive rocks and comagmatic flood basalts underlying most of northeastern Minnesota were emplaced during the development of the Mesoproterozoic (Keweenawan) Midcontinent rift about 1.1 billion years ago. The Midcontinent rift can be traced by its geophysical signature from its exposure in the Lake Superior region along a 2,000-kilometer-long, segmented, arcuate path from Kansas to lower Michigan. Geologic mapping and, more critically, geophysical modeling of aeromagnetic, gravity, and seismic data show the rift to be composed of a deep (30 kilometers) asymmetric basin infilled with a lower sequence of volcanic rocks, locally as much as 20-kilometers-thick, and an upper sequence of fluvial sedimentary rocks (Cannon and others, 1989; Allen and others, 1997). Conceptually, the evolution of the Duluth Complex and related igneous rocks is interpreted in terms of the interactions between a deep mantle plume and mature continental lithosphere (Nicholson and Shirey, 1990; Shirey and others, 1994). Geochronologic studies indicate that the magmatic activity occurred in four distinct stages within the span of about 23 million years (Davis and Paces, 1990; Paces and Miller, 1993; Davis and Green, 1997; Zartman and others, 1997). Field observations and petrologic evidence relate each of these stages, termed the *early*, *latent*, *main*, and *late magmatic stages* (Miller and Vervoort, 1996), to thermal and dynamic changes within the plume and plume-impacted lithosphere.

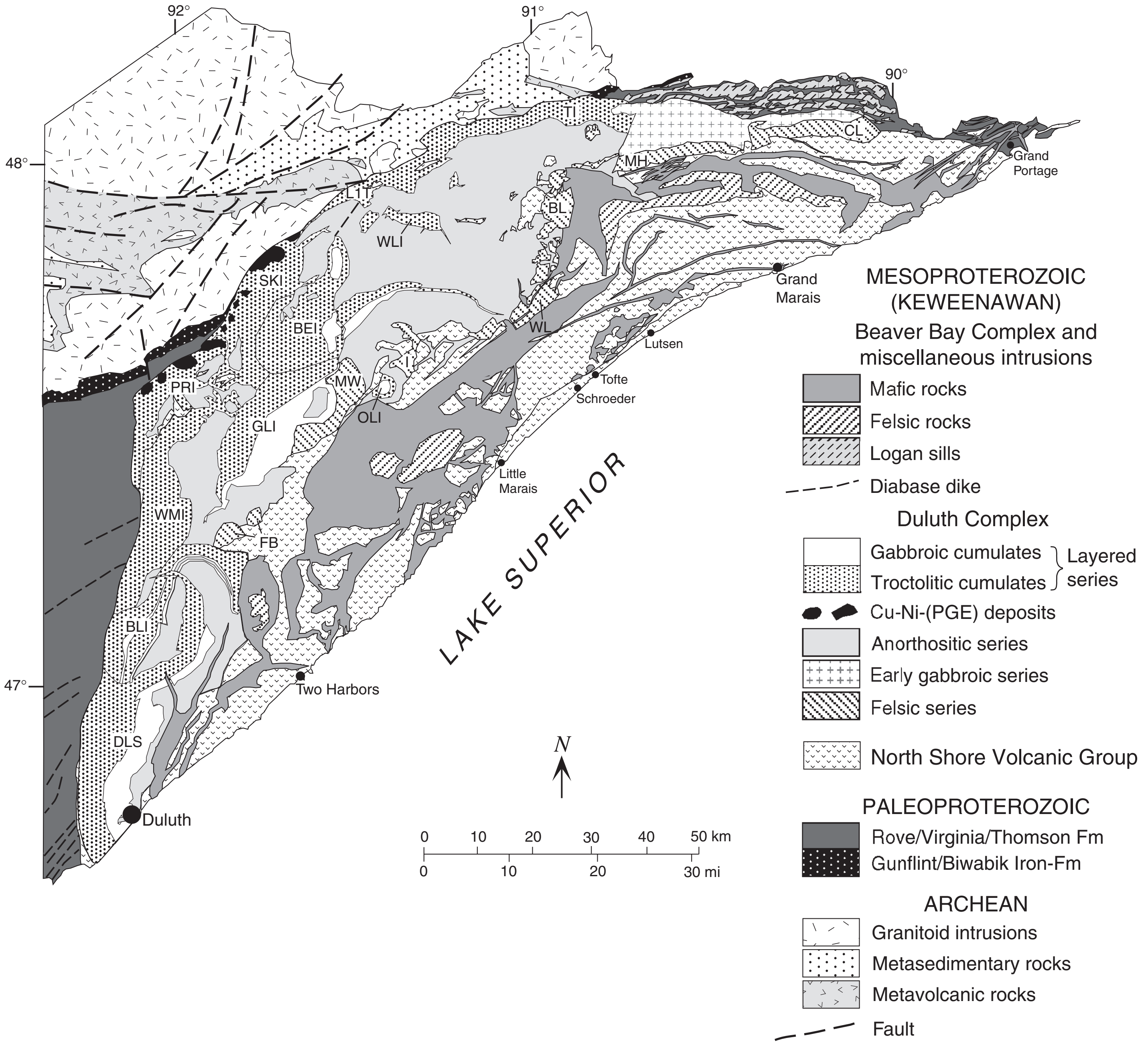


Figure 6.1. Generalized geology of northeastern Minnesota highlighting individual intrusions of the Duluth Complex. Layered series intrusions are:

BEI—Bald Eagle intrusion
GLI—Greenwood Lake intrusion
PRI—Partridge River intrusion
WMI—Western Margin intrusion
BLI—Boulder Lake intrusion
L1T—Lake One troctolite
SKI—South Kawishiwi intrusion
WLI—Wilder Lake intrusion
DLS—Layered series at Duluth
OLI—Osier Lake intrusion
TI—Tuscarora intrusion

Felsic Series intrusions:

BL—Beth Lake granophyre (and Wine Lake monzodiorite)
FB—Fairbanks/Brimson granophyres
MW—Mt. Weber granophyre
I—Isabella granophyre
WL—Whitefish Lake granophyre
CL—Cucumber Lake granophyre
MH—Misquah Hills granophyre

The *early magmatic stage* (1109 to 1107 Ma) occurred during a time of reversed magnetic polarity and was characterized by the rapid and voluminous eruption of initially primitive magmas derived directly from the plume. This quickly gave way to more evolved and crustally contaminated mafic magmas as well as felsic melts. This stage is thought to represent the impact of the mantle plume head with the initially cool and brittle lithosphere, the rapid heating of the lithosphere by mantle-derived melts, and the eventual contamination of those melts by their staging in the lower crust. This mafic underplating likely resulted in felsic melts being formed by partial melting of the lower crust.

The *latent magmatic stage* (1107 to 1102 Ma) was a period during which volcanic activity was largely dormant, except for possibly rhyolitic volcanism. This stage is thought to represent a period of continued mantle plume upwelling and melting, extensive crustal underplating, and lower crustal melting. Crustal anatexis created a rheological and density barrier to the passage of mafic magmas to the upper crust. The lack of significant downwarping during this volcanic hiatus suggests that the upper crust and lower crust became decoupled and that crustal dilation was occurring only in the lower crust.

The *main magmatic stage* (1102 to 1094 Ma) was a period of normal magnetic polarity conditions during which volcanic activity was renewed. This stage was characterized by moderate rates of eruption of uncontaminated (except for rhyolite) but diverse magma compositions. It is thought to represent the onset of upper crustal separation, the evacuation of lower crustal magma chambers, and continued mantle plume melting.

The *late magmatic stage* (1094 to 1086 Ma) was a period of waning volcanic activity but continued subsidence of the rift basin. This led to the development of evolved composite volcanoes and the interbedding of lava flows and basin sediments. This period probably represents the loss of the plume heat source by plate drift (Davis and Green, 1997) and the thermal collapse of the rift basin.

U-Pb ages indicate that various intrusions of the Duluth Complex were emplaced during the early and main magmatic stages of the Midcontinent rift (Paces and Miller, 1993; Vervoort, unpub. data, 2001). Early stage intrusions include the large granophyre bodies occurring in the roof zone of the Duluth Complex (the Cucumber Lake, Misquah Hills, and Whitefish Lake granophyres; see M-119) and the gabbroic intrusions occurring at the northeastern end of the Duluth Complex (the Crocodile Lake and Poplar Lake intrusions; see M-119). Gradational relationships between the roof zones of these gabbros and the overlying granophyre bodies imply that the felsic rocks preceded emplacement of the gabbros. The overall evolved nature of these mafic and felsic intrusions implies that they were emplaced late in the early magmatic stage, probably contemporaneous with the eruption of the evolved and contaminated Hovland lavas (M-119). A precise age of 1106.9 ± 0.8 Ma for the basal gabbro of the Poplar Lake intrusion (formerly Nathan's layered series) is consistent with this interpretation. The large volume of anorthositic rocks and the eleven discrete mafic layered intrusions that make up the remainder of the Duluth Complex were emplaced during the main magmatic stage. Despite field relationships that typically imply that anorthositic rocks were emplaced before troctolitic to gabbroic cumulates of the various mafic intrusions, five U-Pb zircon ages of these rocks taken from the northwestern and southern parts of the Duluth Complex are basically indistinguishable, clustering around 1099 Ma (Paces and Miller, 1993; Green and Davis, 2001).

GENERAL DEFINITION OF THE DULUTH COMPLEX

Over the years, many misperceptions and uncertainties have existed about what defines the Duluth Complex. Although Keweenawan intrusive igneous rocks compose more than 60 percent of the bedrock geology of northeastern Minnesota (Fig. 6.1), only about half of that percentage constitutes the Duluth Complex, as defined here. Some of these misperceptions have grown from publications that portrayed the Duluth Complex as comprising all Keweenawan intrusive rocks in northeastern Minnesota (for example Weiblen, 1982; Chalokwu and Grant, 1990). Although this generalizing was typically done to simplify the geologic picture, it has perpetrated the idea that the Duluth Complex is larger and more homogeneous than it is. Uncertainties about the limits of the Duluth Complex, evident in the Two Harbors map, for example (Green, 1982), have been due either to insufficient exposures or inadequate mapping. We attempt to clarify this uncertainty on map M-119 with the incorporation of new mapping in the roof zone of the Duluth Complex, recent geochronologic data, and interpretations of the high-resolution aeromagnetic data.

Some past uncertainty about the Duluth Complex came from the lack of detailed mapping in the transition between the deep-seated intrusions of the Duluth Complex and the more hypabyssal bodies emplaced higher in the volcanic pile. Much of this uncertainty was resolved with the mapping conducted by Boerboom and Miller (1994) and Miller and others (1994). This mapping showed that the upper part of the Duluth Complex is characterized by a mixed assemblage of granophyre, gabbroic anorthosite cumulates, and strongly recrystallized mafic hornfels. Beaver Bay Complex intrusions (Chapter 7), on the other hand, more commonly are hypabyssal, non-cumulate rocks that are largely enclosed within volcanic rocks. Although some notable cumulate rock units occur in the Beaver Bay Complex (the Sonju Lake and Silver Bay intrusions, Houghtaling Creek troctolite, and phases of the Cloquet Lake layered series; see M-119), these are the exceptions.

Bedrock mapping of the contact between the Beaver Bay Complex and central Duluth Complex has assisted in the projections of the unexposed roof zone of the Duluth Complex to the south (Fig. 6.1) using aeromagnetic data. Semi-continuous septa of recrystallized volcanic rocks lying above anorthositic and felsic rocks can be inferred southward from areas of exposure (Boerboom and Miller, 1994) by their elevated aeromagnetic anomaly pattern and by rare outcrop and drill core (Miller and Chandler, 1999; Chandler, 2001; M-119).

One of the most significant changes to what had been considered to be the Duluth Complex occurs along its northeastern extent. Rocks formerly regarded as part of the eastern Duluth Complex (Davidson, 1972; Green, 1982), namely the Brule Lake–Hovland gabbro and related felsic intrusions (the Eagle Mountain and Pine Mountain granophyre bodies), are now classified as miscellaneous intrusions (M-119). These rocks are clearly situated above the main mass of anorthositic and felsic rocks that mark the roof zone of the central Duluth Complex. Moreover, recent U-Pb ages (Sandland and others, 2001; J. Vervoort, unpub. data, 2001) show that granophyre bodies occurring within and along the roof zone of the complex (Mt. Weber, Whitefish Lake, Misquah Hills, and Cucumber Lake granophyres; see M-119) have distinctly older ages (1109 to 1106 Ma) than the Eagle Mountain and Pine Mountain granophyres (1098 ± 4 and 1095 ± 4 Ma, respectively; J. Vervoort, unpub. data, 2001). Additionally, the higher-level granophyres are roughly contemporaneous with felsic and mafic phases of the Beaver Bay Complex (Finland granophyre—1092 ± 7 Ma, J. Vervoort, unpub. data, 2001; Sonju Lake intrusion—1096.1 ± 0.8 Ma, Silver Bay intrusions—1095.8 ± 1.2 Ma, Paces and Miller, 1993). More detailed mapping of these well exposed, higher level rocks will be needed before it is clear whether they should be grouped with the Beaver Bay Complex or whether they constitute an intrusive complex distinct from either the Duluth or Beaver Bay suites.

As reinterpreted, the Duluth Complex is physically defined as a more or less continuous mass of mafic to felsic plutonic rocks that extends in an arcuate fashion from Duluth nearly to Grand Portage. It is bounded by a footwall of predominantly Paleoproterozoic and Archean rocks, a hanging wall of largely mafic volcanic rocks and hypabyssal intrusions, and internally, it contains only scattered bodies of strongly granoblastic mafic volcanic and sedimentary hornfels. Defining the Duluth Complex more genetically, it is composed of multiple discrete intrusions of mafic to felsic tholeiitic magmas that were episodically emplaced into the base of a comagmatic volcanic edifice between 1108 and 1098 Ma.

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

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

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

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

Layered series—A suite of stratiform troctolitic to ferrogabbroic cumulates that comprises at least 11 variably differentiated mafic layered intrusions and occurs mostly along the base of the Duluth Complex. These intrusions were emplaced during main stage magmatism, but generally after the anorthositic series (~1099 Ma).

This chapter describes the four main rock series and emphasizes the various intrusions of the layered series, especially those lying outside the Boundary Waters Canoe Area Wilderness. These bodies host all of the known mineralization presently identified in the complex and have the best potential for hosting undiscovered mineralization (see Chapter 8).

FELSIC SERIES

Known for decades as the "red rock" of the Duluth Complex (Winchell, 1899; Grout and others, 1959), the felsic and less abundant intermediate rocks that form a semi-continuous mass of granophyre bodies in the eastern and central roof zone of the Duluth Complex are collectively referred to as the felsic series (Fig. 6.1). The major individual intrusions that comprise the felsic series are (from east to west): the Cucumber Lake granophyre, the Misquah Hills granophyre, the Wine Lake monzodiorite, the Beth Lake granophyre, the Whitefish Lake granophyre, the Isabella granophyre, the Mt. Weber granophyre, and the Fairbanks/Brimson granophyres. Except for the Isabella granophyre and the Fairbanks/ Brimson granophyres, these bodies are generally well exposed and form regional topographic highs. The Cucumber Lake granophyre was mapped in reconnaissance by Babcock (1959) and Grout and others (1959). Extensive reconnaissance mapping by Davidson (1977a-e) and Davidson and Burnell (1977) established the extent of the Misquah Hills granophyre and the intermingled Wine Lake monzodiorite and Beth Lake granophyre. The Whitefish Lake granophyre was mapped in detail by Boerboom and Miller (1994), although the relationship between it and the Beth Lake granophyre remains unclear. Bonnichsen (1971) and Venske (unpub. data) mapped the poorly exposed Mt. Weber granophyre in reconnaissance. The Isabella granophyre is unexposed and inferred from two drill cores and a subdued aeromagnetic anomaly expression. The Fairbanks/Brimson granophyre bodies are completely inferred from aeromagnetic data. As mentioned above, the younger Pine Mountain and Eagle Mountain granophyre bodies (M-119), previously assigned to the felsic series by Davidson (1972), are not considered part of the Duluth Complex.

The granophyre bodies of the felsic series exhibit three general types of contact relationships with surrounding rocks. Where granophyre is in contact with mafic volcanic rocks, the contacts are sharp, the granophyre has a leucogranite composition and may be chilled, and the volcanic rock is typically recrystallized to a granoblastic texture (Davidson, 1972; Boerboom and Miller, 1994). Where granophyre is in contact with early gabbroic series rocks (the Poplar Lake intrusion and Crocodile Lake gabbro), contact relationships are very gradational over tens of meters or more and the contact zone is marked by an interval of various intermediate rock types. Where the granophyre is in contact with gabbroic anorthositic rocks of the anorthositic series, contact relations vary from broadly to narrowly gradational depending on proximity to the Duluth Complex roof zone. Although Davidson (1972) noted broadly gradational contacts in two small granophyre bodies occurring far into the extensive area of anorthositic series rocks in the Perent Lake (Davidson, 1969b) and Long Island Lake (Morey and others, 1981) quadrangles, he also noted the presence of fine-grained norite and gabbro, which may be volcanic hornfels. Closer to the roof zone, the contact between felsic series and anorthositic series rocks is more abrupt and shows the anorthositic series to be younger. For example, in the Wilson Lake quadrangle (Boerboom and Miller, 1994) this contact is characterized by the gabbroic anorthosite becoming medium fine-grained and well-foliated parallel to a meter-wide contact zone of heterogeneously blended granophyre and fine-grained mafic rock.

Except for the intermediate rocks that occur in gradational contact zones with early gabbro intrusions, most of the felsic series granophyre bodies are remarkably homogeneous, composed of a reddish, micrographic leucogranite and typically containing less than 5 percent mafic phases. The one notable exception to this is the Wine Lake monzodiorite (Wine Lake intrusion of Grout and others, 1959 and Davidson, 1977d), which occurs in the roof zone of the complex where the upper contact curves from northerly to easterly in the Kelso Mountain quadrangle (Fig. 6.1). Davidson (1977d) noted that the intermediate rocks appear to underlie the granitic rocks in the area and thus may be older. Whether these intermediate rocks represent a distinct intrusion or perhaps a thicker, shallow-dipping contact zone between granitic rocks (Beth Lake granophyre) and anorthositic series rocks will require more detailed mapping.

Emplacement and origin of felsic series magmas

Early magmatic stage ages (~1108 Ma) and contact relationships with other units of the Duluth Complex noted above imply that the felsic series intrusions may be the earliest Duluth Complex intrusions. The consistently gradational relationship between felsic series and early gabbro series rocks implies that the granophyres were emplaced before the gabbroic intrusions. If the felsic rocks were younger than the early gabbro series intrusions, sharp intrusive contacts should have developed between the two rock types. In fact, it is likely that the granophyre bodies caused the gabbroic magmas to intrude beneath them by acting as density and rheological barriers. Anorthositic series rocks display a chilled intrusive contact with felsic series granophyre. Such a chill is logical given the long period of time (~8 million years) between their intrusions. Where the granophyre bodies became enveloped by anorthositic series magma, their more gradational contact relationships can be explained by prolonged heating and local melting of the granophyre by the anorthositic series magmas.

The origin of these granophyre bodies has received little attention until recently. Sm-Nd data from the felsic series granophyres (Fig. 6.2) show them to have near mantle ε_{Nd} values (-1 to -5; Vervoort and Green, 1997; Sandland and others, 2001). This implies possible origins by: 1. Extreme crystallization differentiation of Keweenawan magmas; 2. Partial melting of Keweenawan rocks; 3. Partial melting of high Sm/Nd ratio Archean rocks (such as greenstone) in the lower crust; or 4. Partial melting of Paleoproterozoic rocks in the lower crust.

The enormous volume of granophyres makes their formation by extreme differentiation, either in situ or in some deeper crustal setting, unlikely. The early gabbros are volumetrically inadequate to have generated the large volume of felsic melt that produced the Misquah Hills and Cucumber Lake granophyres. Moreover, the igneous stratigraphy of the Poplar Lake intrusion does not show the progression of cumulate rock types expected to lead to such extreme differentiation (Nathan, 1969). Additionally, the granophyres of the central Duluth Complex have no associated early gabbro bodies. The creation of large volumes of extremely felsic melts by differentiation in a deeper staging chamber also seems unlikely as it requires the complete closure of large magma chambers at a time when enormous volumes of

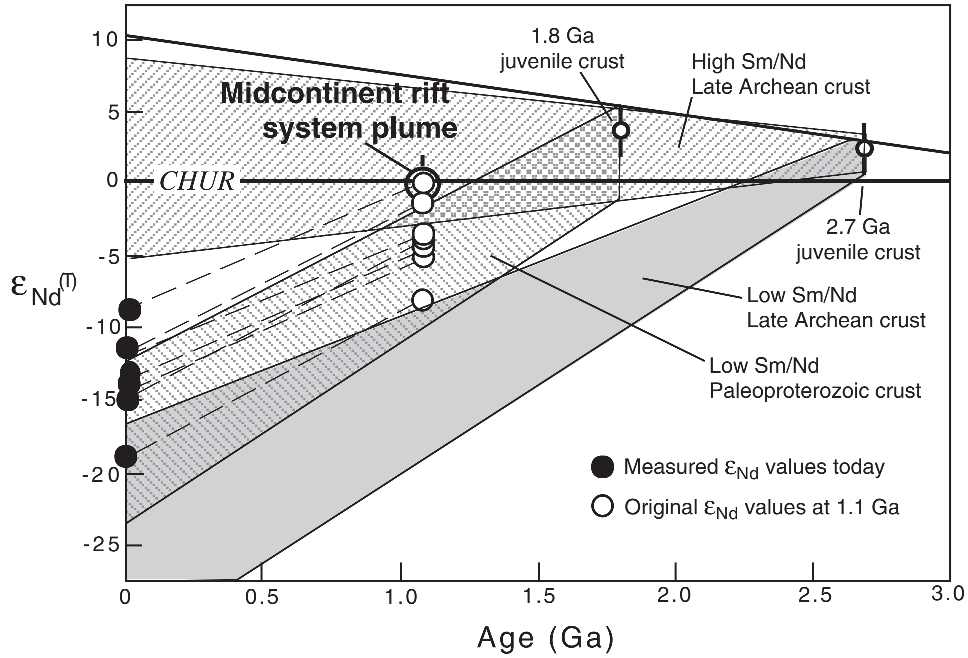


Figure 6.2. ε_{Nd} compositions of felsic series granophyres and evolutionary trends of possible source materials. Modified from Vervoort and Green (1997). CHUR = chondritic uniform reservoir.

mafic melt were being generated from the plume head during the early magmatic stage of the Midcontinent rift.

An origin by partial melting of the lower crust is a more plausible explanation, but the nature and age of the source material must be defined. Given the early age of the granophyres in the evolution of the Midcontinent rift, it is unlikely that a sufficient volume of Keweenawan intrusive rocks or sufficiently buried volcanic rocks could have remelted to generate such magma. If the source materials were Archean rocks, their very low ε_{Nd} values would require that the source materials be exclusively Archean mafic rocks with high Sm/Nd ratios (Fig. 6.2). It is unlikely that such rocks would be selectively melted from the Archean crust. A third possible source is Paleoproterozoic rocks; however, because of their low Sm/Nd ratio and position in the uppermost crust, it is unlikely that melting of Animikie sedimentary rocks produced the felsic series melts. Alternatively, Miller and Vervoort (1996) speculated that the Paleoproterozoic source may have been amphibolitized mafic material that formed with igneous activity related to the Kenora–Kabetogama dike swarm at 2.1 Ga, or to volcanic activity evident in rocks of the Marquette Range Supergroup (2.2 to 1.85 Ga) in east-central Minnesota (Morey, 1996).

EARLY GABBRO SERIES

In a detailed field-mapping study conducted on the Duluth Complex, Nathan (1969) documented the presence of an early intrusive suite of interlayered oxide-rich gabbro, olivine gabbro, troctolite, and anorthosite in the Gunflint Trail area of northeastern Minnesota. Nathan recognized that this suite (which came to be called the layered series of Nathan [Weiblen and Morey, 1980] but is now termed the Poplar Lake intrusion) was crosscut by gabbroic anorthosite and leucotroctolitic rocks to the west that are now classified as part of the anorthositic series and the Tuscarora intrusion of the layered series, respectively. Rocks of the Poplar Lake intrusion have reversed magnetic polarity (Beck, 1970) and thus are generally correlative with lower lavas of the North Shore Volcanic Group and Logan intrusions. This general correlation was substantiated by a precise U-Pb zircon age of 1106.9 ± 0.6 Ma for the lower part of the Poplar Lake intrusion (Paces and Miller, 1993). The poorly mapped gabbroic rocks east of the Poplar Lake intrusion are distinguished as the Crocodile Lake intrusion, although they may prove to be a continuation of the Poplar Lake body.

As defined by Nathan (1969), the Poplar Lake intrusion is composed of at least 27 sheetlike units of mafic cumulates and intermediate to felsic rocks. These have been simplified into six major units on the geologic map (M-119). A basal contact zone is composed of varitextured, nonfoliated, biotitic and sulfide-bearing olivine gabbro, augite troctolite, and gabbronorite (unit plcz, M-119). Immediately above the contact zone are predominantly oxide-olivine gabbro to oxide troctolite cumulates (unit plfg, M-119), including some intervals very rich in Fe-Ti oxide (unit plox, M-119). These ferrogabbroic cumulates give way up-section to predominantly gabbroic cumulates (unit plgb, M-119) with multiple intervals of troctolitic cumulates (unit pltc, M-119) and several intervals of anorthositic cumulates (unit plas, M-119). As mentioned above, the contact between the gabbroic cumulates and the overlying Misquah Hills granophyre is marked by a narrow interval of intermediate rocks (unit fmhm, M-119; Nathan, 1969; Davidson, 1977b, c, e; Davidson and Burnell, 1977).

Nathan (1969) interpreted the interbedding and local crosscutting of various cumulate rock types as indicative of multiple, discrete, sheetlike intrusions of varied magma types that experience little in situ differentiation. Although his petrographic descriptions were very detailed, Nathan collected little microprobe data and no whole rock geochemistry to confirm his interpretations. A new geologic and geochemical study of the Poplar Lake intrusion (Jerde and others, 2001) should reveal more information on its mode of formation.

What little is known about the igneous stratigraphy of the Crocodile Lake intrusion comes from investigations by Babcock (1959), wherein he examined the petrography of rocks collected across four traverses of the intrusion and the overlying Cucumber Lake granophyre. He found locally foliated, olivine-poor gabbro in the lower section that became irregularly more granophyric up-section and ultimately blended into overlying granophyre. Babcock interpreted this gradational relationship as the result of fractional crystallization and differentiation of a single magma. More detailed study of this intrusion is needed.

ANORTHOSITIC SERIES

The anorthositic series of the Duluth Complex is a structurally complex suite of medium- to coarse-grained, variably foliated, plagioclase-rich cumulates that occurs over the entire breadth of the complex from the western edge of the Poplar Lake intrusion to the southern terminus of the Duluth Complex at Duluth (Fig. 6.1). The upper contact of the anorthositic series against volcanic or granophyric rocks is typically sharp and somewhat chilled. The lower contact is commonly formed against layered series rock, although in the Ojibway Lake quadrangle, anorthositic series rocks are in direct contact with Archean granite (Green and others, 1966). Some layered series intrusions are completely enveloped by anorthositic series rocks (such as the Wilder Lake, Greenwood Lake, and Osier Lake intrusions). Over the entire exposure area of the anorthositic series, its lithologic character, internal structure, and contact relationships with adjacent rocks remain fundamentally constant. The series seems to have been emplaced more or less synchronously over its entire extent, as two samples from very different parts of the complex (one from the north-central part, the other from the Duluth area) have nearly identical U-Pb ages of 1099.1 ± 0.6 Ma and 1099.3 ± 0.6 Ma (Paces and Miller, 1993).

The typical rock type of the anorthositic series is an altered, coarse-grained, moderately foliated, ophitic olivine leucogabbro composed of about 80 percent plagioclase. With the exception of some occurrences of granular olivine in subcotectic abundance, subhedral to euhedral plagioclase is the only cumulus phase in these rocks. Lithologic variability on a small (outcrop) scale is a ubiquitous feature of the anorthositic series (Miller and Weiblen, 1990). The rocks vary in plagioclase mode (from 70 to 99 percent); in mafic mineral proportions; in olivine texture from granular to poikilitic (oikocrysts up to 15 centimeters across); in grain size from medium to very coarse; and in abundance of felsic mesostasis from 0 to 20 percent. Moreover, moderate to nearly complete hydrothermal alteration of olivine, pyroxene and, to a lesser degree, plagioclase is evident in most rocks of the anorthositic series. Despite variations in texture and modal mineralogy, and the complex zoning of individual crystals, the average plagioclase composition remains constant at An_{65-62} (Miller and Weiblen, 1990; Saini-Eidukat, 1991). This constancy in An content contrasts with the variability in the mg# of mafic silicates, and defines a distinct trend of An-Fo variation compared to layered series rocks, which more closely resemble normal gabbroic differentiation trends (Fig. 6.3). In general, mineralogic and chemical variations indicative of in situ differentiation due to fractional crystallization are lacking in anorthositic series rocks (Miller and Weiblen, 1990).

Characteristic rocks other than olivine gabbroic anorthosite and leucogabbro are associated with the anorthositic series in different areas of the complex. In the Allen and Babbitt SW quadrangles, there is a coarse-grained, ophitic to intergranular, olivine-oxide gabbro, which Bonnichsen (1974) referred to as the Powerline gabbro. Although this gabbro cuts anorthositic rocks, it occurs with anorthositic rocks and volcanic hornfels as large inclusions within troctolitic rocks of the Partridge River intrusion (Severson and Miller, 1999). This mixed assemblage of olivine oxide gabbro, gabbroic anorthosite, and mafic hornfels gives rise to a very complex aeromagnetic signature, which has been used to infer similar rocks in poorly exposed parts of the complex (unit asmx, M-119).

Another distinctive rock type of the anorthositic series is a poikilitic olivine gabbroic anorthosite, which contains olivine oikocrysts up to 10 centimeters in diameter. This rock type occurs throughout the anorthositic series, but is usually mixed with other anorthositic lithologies. Where it exclusively occurs over large areas in the northwestern part of the complex, it is distinguished as map unit aspa (M-119). Another unique anorthositic rock type is a poikilitic noritic anorthosite that occurs in an oval-shaped area near the northwestern contact of the complex (unit asna, M-119) and cuts other anorthositic rocks (Phinney, 1972). The Katydid Lake gabbroic anorthosite and the Scott Creek leucogabbro are mappable examples of porphyritic rock types (units akga and aslg, respectively, M-119; also see Boerboom and Miller, 1994; Miller and others, 1994) that are characteristic of the upper contact zone of the anorthositic series. The roof zone of the anorthositic series at Duluth is marked by a medium-grained, variably porphyritic, ophitic olivine gabbro (unit aspg, M-119).

Although they are rarely layered, anorthositic series rocks typically have discernible plagioclase foliation. The attitude of this foliation is extremely variable on an outcrop-to-outcrop scale (Fig. 6.4). Furthermore, contrasting rock types are in contact across sharp (but unchilled) to gradational boundaries. Discrete inclusions of one type of

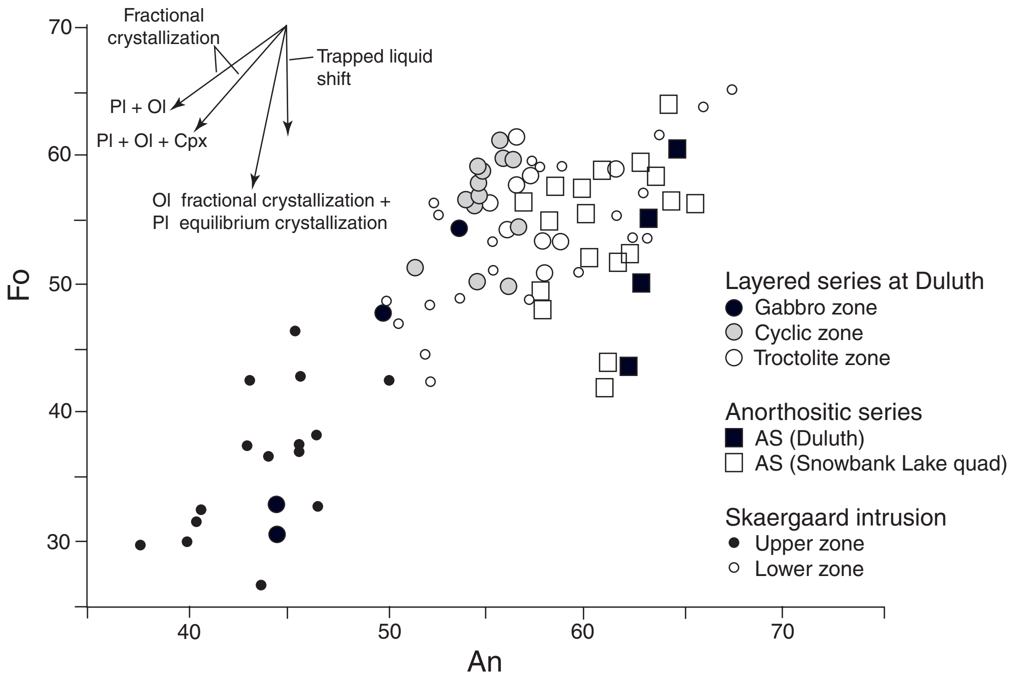


Figure 6.3. Covariation of Fo in olivine and An in plagioclase in the layered series at Duluth, anorthositic series, and Skaergaard intrusion rocks. Arrows indicate the compositional effects of igneous processes that may give rise to the trends observed. Layered series and anorthositic series data from Duluth are based on the average of multiple microprobe analyses (Miller and others, 1993b, unpub. data). Anorthositic series data from the Snowbank Lake quadrangle in the northwestern part of the Duluth Complex are from Miller (1986); Skaergaard data are from McBirney (1989).

Figure 6.4. Schematic diagram summarizing the structural relationships between anorthositic series rocks commonly seen on an outcrop scale in the Snowbank Lake quadrangle (modified from Miller, 1986). Relationships: 1. Gradual to abrupt stratiform change in lithology; 2. Crosscutting foliation indicating an intrusive relationship; 3. Inclusions with enclosing rock showing concordant foliation; 4. Variation in foliation orientation in the absence of lithologic change; 5. Irregular distribution of intercumulus mafic phases independent of foliation orientation.

anorthositic rock (typically a more leucocratic type) in another are common (Taylor, 1964; Miller and Weiblen, 1990). In the Snowbank Lake quadrangle, at least three intrusive episodes of anorthositic series rock formation can be distinguished (Miller 1986; Miller and Weiblen, 1990). Each successive episode produced less leucocratic compositions. Because of these outcrop-scale structural complexities, it is difficult to divide the anorthositic series into lithologic subunits. Although anorthositic series rocks commonly contain many auto-inclusions (Fig. 6.4), they contain relatively few inclusions of non-anorthositic rocks. In the northwestern part of the Duluth Complex, anorthositic and gabbroic rocks occur together with mafic hornfels bodies as inclusions in layered series rocks, but within this mixed assemblage, the hornfels rarely occur as isolated blocks within the anorthositic rocks (Miller, 1986; Severson and Miller, 1999).

Origin of anorthositic series rocks

Nearly every previous geologist studying this area has interpreted the rocks of the anorthositic series as a product of the multiple emplacement and static crystallization of plagioclase crystal mushes. Grout (1918a) attributed the erratic orientation of plagioclase alignment, which he termed “fluxion structure,” to crystal suspension in a convecting, viscous magma. Taylor (1964) described the anorthositic rocks at Duluth as having the appearance of an “igneous breccia.” He interpreted the concordant alignment of plagioclase in one anorthositic rock type around an inclusion of another as evidence that the former was intruded as a crystal mush. Davidson (1969a, 1972) and Phinney (1969, 1972) noted similar features in the northern and northwestern parts of the complex and also attributed them to crystal mush flow. Miller and Weiblen (1990) cited field, petrographic, and mineral chemical evidence to support the theory that the anorthositic series was formed from multiple intrusions of variably differentiated basaltic magma physically enriched in intratelluric plagioclase of a near constant composition. The apparent lack of compositional characteristics of anorthositic series rocks that would indicate in situ differentiation is probably related to the highly viscous nature of these crystal mushes. The compositional variability that is evident in these rocks and their hyperfeldspathic nature is probably related to differentiation and the physical enrichment of plagioclase in deeper staging chambers. Under higher pressures of the lower crust, plagioclase should be buoyant in basaltic magmas (Kushiro, 1980).

Most previous studies of the Duluth Complex interpreted the anorthositic series as having formed significantly earlier than layered series rocks, and by magmatic processes unrelated to the younger stratiform intrusions. In most areas of the complex, inclusions of anorthositic series rocks abound within layered series intrusions, and in some areas these anorthositic series inclusions occur along with blocks of volcanic hornfels. Although anorthositic rocks occur as layers within some layered series troctolite (such as units skta and tuta of the South Kawishiwi and Tuscarora intrusions, respectively, M-119), inclusions of troctolite have not been reported within anorthositic series rocks. These observations and a well-documented chilled margin of the layered series against the anorthositic series at Duluth (Taylor, 1964) seemed to imply that anorthositic rocks were cold and considerably older than the layered series (Miller and Weiblen, 1990). However, this interpretation had to be revised when precise U-Pb dates showed the anorthositic series and layered series had essentially the same age of 1099 Ma (Paces and Miller, 1993). Miller and Ripley (1996) later noted that composition of the chilled margin at Duluth was too evolved to be parental to the layered series. Instead of representing thermal quenching, they suggested that the chilled margin probably represents quenching of an evolved, hydrous magma due to decompression attending magma venting from the chamber.

The common age of the anorthositic series and the layered series, and local observations of interlayered troctolitic and anorthositic rock types suggest that the two series may be genetically as well as temporally linked. One way that they may be linked is for the layered series and the anorthositic series to have formed from the same batch of moderately plagioclase-enriched magma. Upon emplacement, intratelluric plagioclase may have segregated to the roof zone by flotation, and the underlying magma evolved by fractional crystallization from the floor up. This model seems to best explain the Tuscarora intrusion along the northern contact of the Duluth Complex (M-119). As described in detail below, troctolitic rocks at the basal contact (tuta and tutr, M-119) grade upward into a zone of interlayered troctolitic and anorthositic cumulates (tuat, M-119) and then into typical anorthositic series rocks (Morey and others, 1981).

Another possible link between the anorthositic and layered series is for both series magmas to have been tapped from the same deep crustal chamber that was initially highly charged with suspended plagioclase. Whereas early extractions from this deep staging chamber had high crystal loads, such crystal suspensions were progressively flushed out, resulting in successively less crystal-rich magmas. This model seems best able to explain the lithologic and structural attributes and contact relationships of the Duluth Complex at Duluth and along the northwestern contact area. Additionally, because the 1099-Ma age of the Duluth Complex approximately marks the transition from the latent stage to the main magmatic stage of Midcontinent rift evolution, this model fits well with the latent stage being a period of extensive underplating of the crust.

LAYERED SERIES

The layered series is a suite of stratiform, troctolitic to ferrogabbroic cumulates that consists of at least eleven discrete mafic layered intrusions dispersed throughout the Duluth Complex (Fig. 6.1). All were emplaced during the main stage of Midcontinent rift magmatism, although only the layered series at Duluth has been precisely dated at about 1099 Ma (Paces and Miller, 1993; Green and others, 2001)[1]. Rocks of the layered series were previously referred to as the troctolitic series (Bonnichsen, 1972; Weiblen, 1982) and the troctolite-olivine gabbro series (Davidson, 1972). We adopt the *layered series* designation first used by Taylor (1964) for the stratiform mafic rocks because it is less restrictive. The level of exposure of layered series intrusions varies from very good for those along the northern and northwestern margin of the Duluth Complex (the Tuscarora, Lake One, Wilder Lake, South Kawishiwi, and Partridge River intrusions) to very poor for those in the central and southern part (the Greenwood Lake, Osier Lake, Western Margin, and Boulder Lake intrusions). The layered series at Duluth and the Bald Eagle intrusion vary from well exposed to poorly exposed over their areal extents. For those intrusions that are poorly exposed, our conclusions about internal structure and igneous stratigraphy are interpreted from aeromagnetic data integrated with sparse outcrop and drill core data.

Most layered series intrusions are thick (3 to 7 kilometers), sheetlike bodies in which foliation and layering dip gradually southeastward toward the axis of the Midcontinent rift. The exceptions are the Bald Eagle intrusion, which is largely funnel-shaped, the Osier Lake intrusion, which has a plug-like shape, and the Wilder Lake gabbro, which is sheetlike, but dips to the north. Many intrusions were emplaced between a cap of anorthositic series rocks and a floor of pre-Keweenawan rocks (the Tuscarora, Lake One, South Kawishiwi, Partridge River, Western Margin, and Boulder Lake intrusions and the layered series at Duluth). The Bald Eagle and Greenwood Lake intrusions were emplaced between earlier-formed layered series intrusions and the anorthositic series, and the Wilder Lake and Osier Lake intrusions were emplaced entirely within the anorthositic series. Crosscutting relationships of aeromagnetic patterns associated with the various intrusions (Figs. 6.5 and 6.6) suggest that emplacement occurred by sequential northwest to southeast

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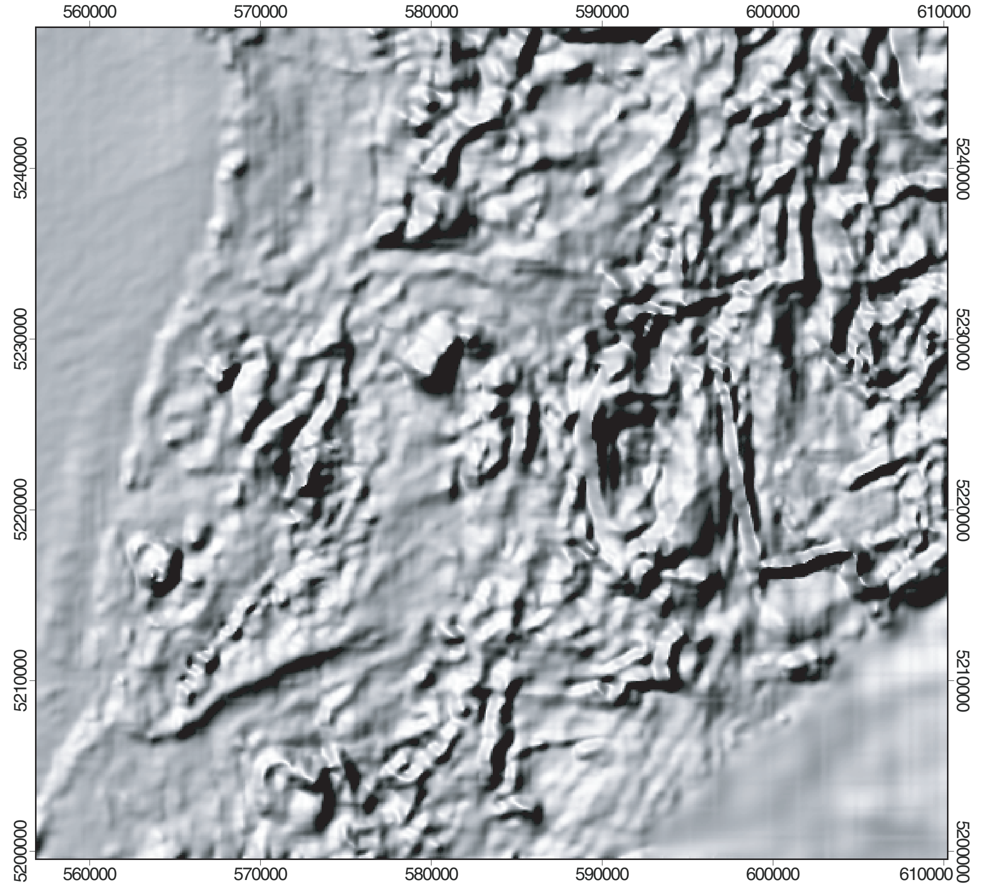
[1] Paces and Miller (1993) also dated a gabbro sample (PG-2, 1098.6 ± 0.5 Ma) thought to be associated with the Partridge River intrusion, but subsequent mapping showed this rock (the Powerline gabbro of Bonnichsen, 1974) to be more closely associated with the anorthositic series.

Figure 6.5. Shaded-relief map of total magnetic field data over the south-central Duluth Complex and generalized geologic map (from M-119) at the same scale. Solid lines denote inter-intrusion contacts; dashed lines denote intra-intrusion contacts. See M-119 for subunits of intrusions. UTM coordinates (NAD 83 datum) border the area. Layered series intrusions:

BLI—Boulder Lake intrusion
DLS—Layered series at Duluth
WMI—Southern part of Western Margin intrusion

Also shown:

AS—Anorthositic series rocks
CLLS—Cloquet Lake layered series
FB—Fairbanks/Brimson granophyre bodies
SC—Silver Creek gabbro/granophyre
SL—Sawmill Lake gabbro/granophyre
T/V—Thomson/Virginia Formations
V—Volcanic rocks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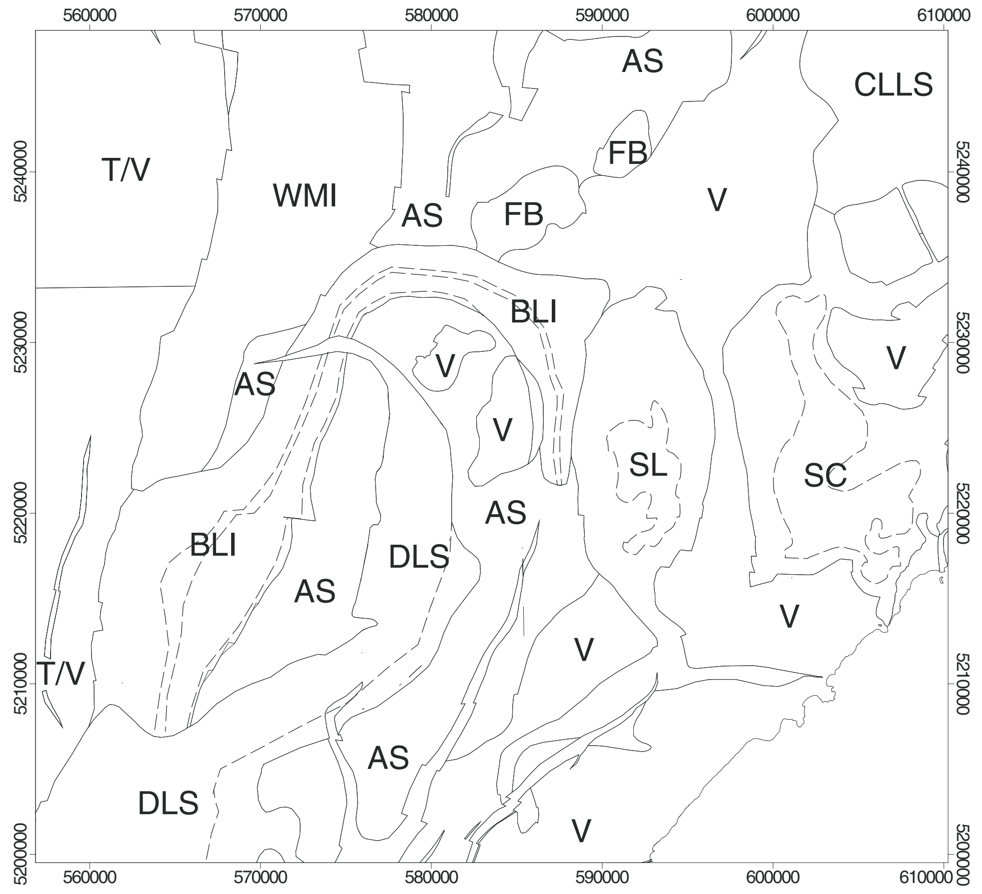
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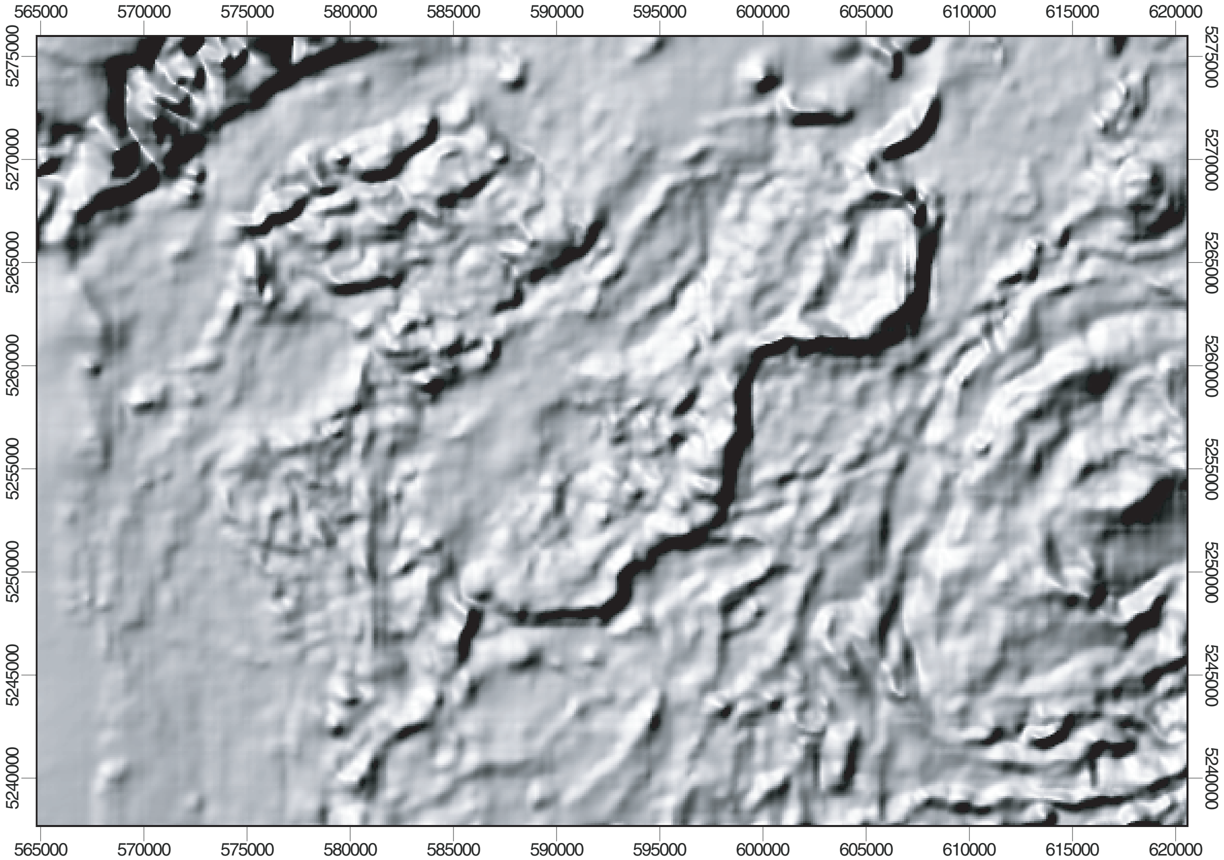
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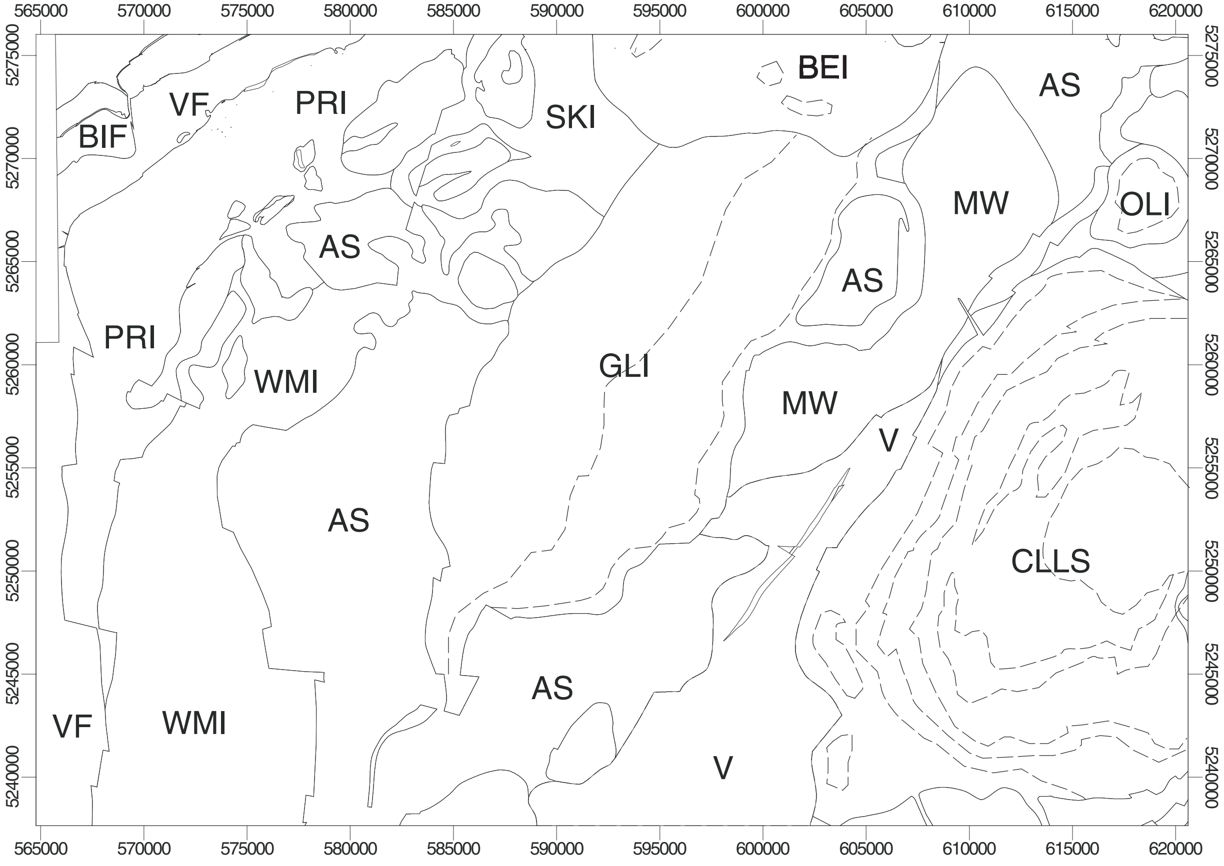
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overplating of older intrusions by younger ones. More precise age dating is needed to confirm this interpretation.

Intrusions of the layered series range from poorly differentiated troctolitic bodies such as the Partridge River and South Kawishiwi intrusions, to well-differentiated systems such as the layered series at Duluth and the Greenwood Lake intrusion (Miller and Ripley, 1996). The igneous stratigraphies of layered series intrusions demonstrate a general sequence of cumulus mineral crystallization that is typical of tholeiitic intrusions (Wager and Brown, 1968):

Olivine ± Cr-spinel →
Plagioclase + Olivine →
Plagioclase + Clinopyroxene + Fe-Ti Oxide ± Olivine ± Pigeonite →
Plagioclase + Clinopyroxene + Fe-Ti Oxide + Apatite ± Olivine

However, noteworthy differences exist among the intrusions in the relative order and timing of cumulus arrivals, primarily those of augite (Cpx) and Fe-Ti oxide (Ox). The observed variations in cumulus phase and cryptic layering largely reflect differences in the openness of the systems to recharge, eruption, and country rock assimilation, but also may have been influenced by differences in parent magma composition, the efficiency of fractional crystallization, and the conditions of crystallization (such as P_{total}, fO_2, PH_2O).

In the discussion below, we focus on the geologic setting and igneous stratigraphy of the various layered series intrusions. For more detailed petrologic discussions of the genesis and crystallization histories of the layered series magmas, see Chalokwu and Grant (1990), Chalokwu and others (1993), and Miller and Ripley (1996).

Layered series at Duluth

The well-exposed gabbroic rocks that form the escarpment above the city of Duluth have long been recognized as the type section of the Duluth Complex. Early surveys recognized the presence of two distinct rock types in the Duluth area (Winchell, 1899), but Grout was the first to interpret the layered gabbros as a product of convection and magma differentiation (Grout, 1918a-c). Taylor (1964) produced the first detailed (1:24,000-scale) geologic map of the complex in the Duluth area and defined the main distinctions between the layered and anorthositic series. Moreover, based on field, petrographic, and limited geochemical data, Taylor recognized basic similarities between the layered series at Duluth and the Skaergaard intrusion, which Wager and Deer (1939) had established as the definitive example of fractional crystallization of a tholeiitic magma. More recently, detailed mapping in the Duluth area by Miller and Green has delineated much more about the structure and cumulate stratigraphy of the layered series (Miller and others, 1993b; Miller and Ripley, 1996).

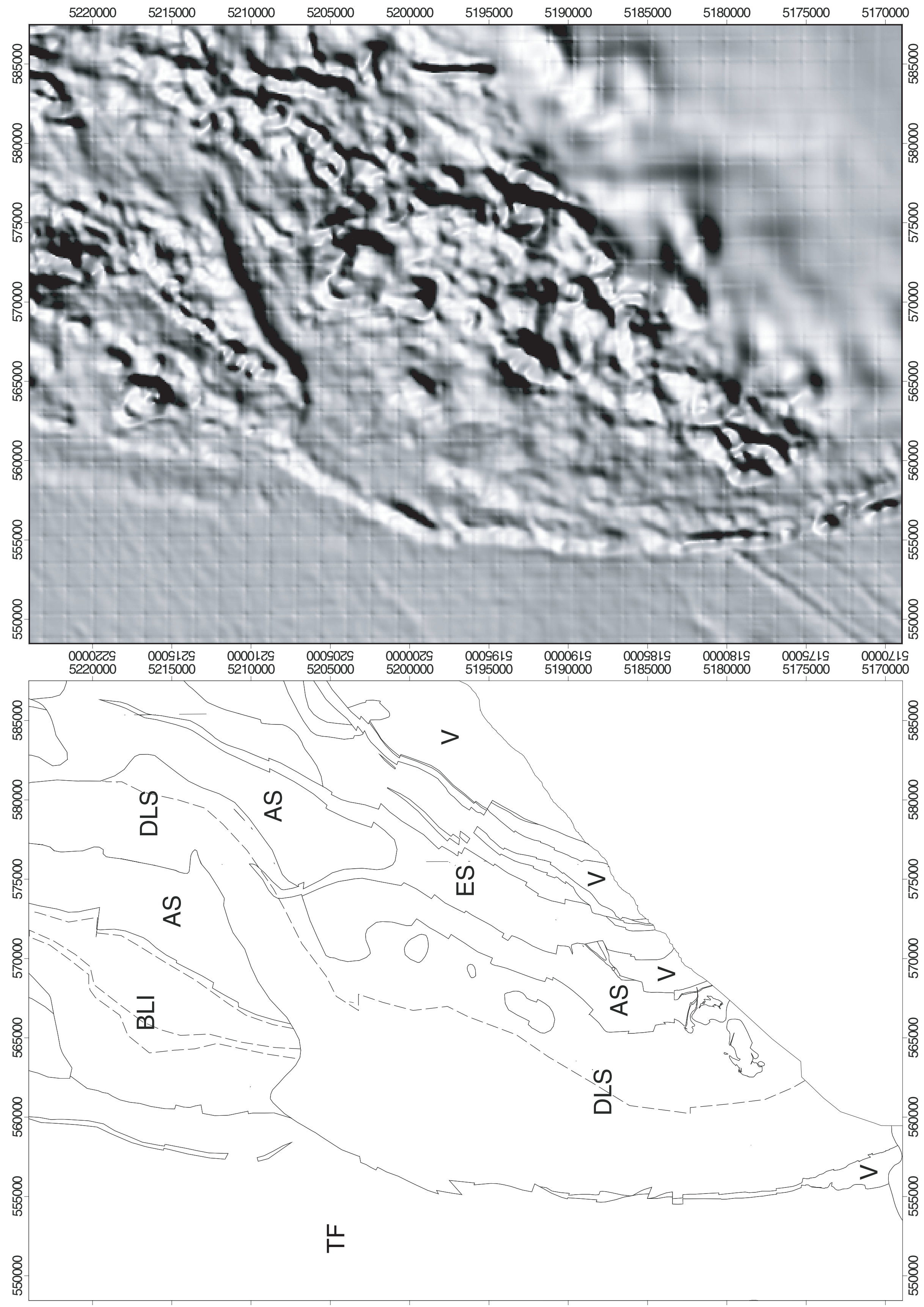
The layered series at Duluth is a well-differentiated, 3- to 4.5-kilometer-thick, east-dipping, sheetlike mafic layered intrusion; the southernmost intrusion of the Duluth Complex. Exposure is very good along the 600-foot (183-meter) escarpment above Lake Superior and the St. Louis River estuary, but is intermittent inland. Aeromagnetic data show that the layered series at Duluth has a north–south strike length of about 60 kilometers and eventually pinches out into the Boulder Lake intrusion (Figs. 6.1, 6.5, and 6.7). The hanging wall of the layered series at Duluth consists of olivine gabbroic and troctolitic anorthosite of the anorthositic series, which according to U-Pb dating was emplaced just prior

Figure 6.6. Shaded-relief map of total magnetic field data over the central Duluth Complex and generalized geologic map (from M-119) at the same scale. Solid lines denote inter-intrusion contacts; dashed lines denote intra-intrusion contacts. See M-119 for subunits of intrusions. UTM coordinates (NAD 83 datum) border the area. Layered series intrusions:

BEI—Southern Bald Eagle intrusion
PRI—Partridge River intrusion
GLI—Greenwood Lake intrusion
SLI—Southern South Kawishiwi intrusion
OLI—Osier Lake intrusion
WMI—Northern part of Western Margin intrusion

Also shown:

AS—Anorthositic series rocks
MW—Mt. Weber granophyre
BIF—Biwabik Iron Formation
V—Volcanic rocks
CLLS—Cloquet Lake layered series
VF—Virginia Formation



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to the intrusion of the layered series at Duluth at 1099 Ma (Paces and Miller, 1993). The footwall of the layered series at Duluth at its southern end is composed of reversed polarity lavas of the Ely's Peak basalts. Layering and foliation in the layered series at Duluth, which dip 20° to 40° to the east, and modeling of aeromagnetic and gravity data, indicate that the basal contact is not conformable with shallow-dipping (~15°) Keweenawan basalt flows in the footwall, but instead dips at a greater than 35° angle (Miller and others, 1993b). Aeromagnetic data further imply that the basalt is cut out by the layered series at Duluth to the north, where the footwall becomes graywacke and slates of the Thomson Formation.

The layered series at Duluth is divided into five major zones based on dominant rock type (Fig. 6.8; M-119). The basal contact zone (unit dlsb, M-119) is composed of coarse-grained, taxitic olivine gabbro and augite troctolite. The lowermost cumulate sequence is the troctolite zone (unit dlst, M-119). It is 1- to 2-kilometers-thick, consists mostly of homogeneous foliated troctolitic (PO) cumulates, and locally displays modal and textural layering, especially in its lower third. The cyclic zone forms the medial section of the layered series at Duluth (unit dlsc, M-119) and is characterized by cyclical variations in cumulus mineralogy between troctolitic and gabbroic (PCFO) cumulates (Fig. 6.9). The persistent occurrence of gabbroic cumulates defines the gabbro zone (unit dlsg, M-119). Gabbroic cumulates, in turn, grade upward into unlaminated (noncumulate) apatitic quartz ferromonzodiorite, which composes most of the upper contact zone (unit dlsu, M-119). This quartz ferromonzodiorite complexly mixes with a fine-grained biotitic ilmenite ferrodiorite, which ultimately forms a "chilled" contact with anorthositic series rocks. A body of melanogranophyre (unit dlsm, M-119) that irregularly cuts through the anorthositic series probably represents the uppermost differentiate of the layered series at Duluth. This igneous stratigraphy is complimented by cryptic layering of cumulus mineral compositions (Fig. 6.8), and together these imply the layered series at Duluth generally formed by bottom-up fractional crystallization of a moderately evolved, olivine tholeiitic parent magma.

Although the layered series at Duluth is overall a well-differentiated intrusion, the repeated progression from troctolitic to gabbroic cumulates in the cyclic zone indicates that it did not fractionally crystallize as a closed system. The cyclic zone consists of at least five macrocycles (each 50- to 200-meters-thick) within which troctolitic cumulates grade upward to gabbroic cumulates (Fig. 6.9). Macrocycle boundaries are marked by the abrupt regression in the cumulus mineralogy from gabbroic back to troctolitic cumulates. The gabbroic parts of the macrocycles commonly contain inclusions of anorthositic series rocks and the very uppermost parts of the macrocycles locally have discontinuous layers of fine-grained gabbroic adcumulate (microgabbro). This cyclicity in phase layering does not correspond to a complementary cryptic variation in mineral chemistry (Miller and Ripley, 1996). Based on these characteristics, Miller and Ripley (1996) suggested that the macrocyclic phase layering is predominantly related to devolatilization and decompression that attended magma venting events from a shallow chamber (less than 5-kilometers-deep), with magma recharge possibly having a secondary effect.

Boulder Lake intrusion

At least five exploration areas were drilled (29 holes with 22,161 feet [6.75 kilometers] of core) in the Boulder Lake area between 1968 and 1971, and are described in detail by Severson (1995). This drill core has been integrated with aeromagnetic data to infer the existence of a southeast-dipping, sheetlike intrusion we term the Boulder Lake

Figure 6.7. Shaded-relief map of total magnetic field data over the southern Duluth Complex and generalized geologic map (from M-119) at the same scale. Solid lines denote inter-intrusion contacts; dashed lines denote intra-intrusion contacts. See M-119 for subunits of intrusions. UTM coordinates (NAD 83 datum) border the area. Layered series intrusions:

DLS—Layered series at Duluth   BLI—Southern part of the Boulder Lake intrusion

Also shown:

AS—Anorthositic series rock   ES— Endion diabase sill   V—Volcanic rocks   TF—Thomson Formation

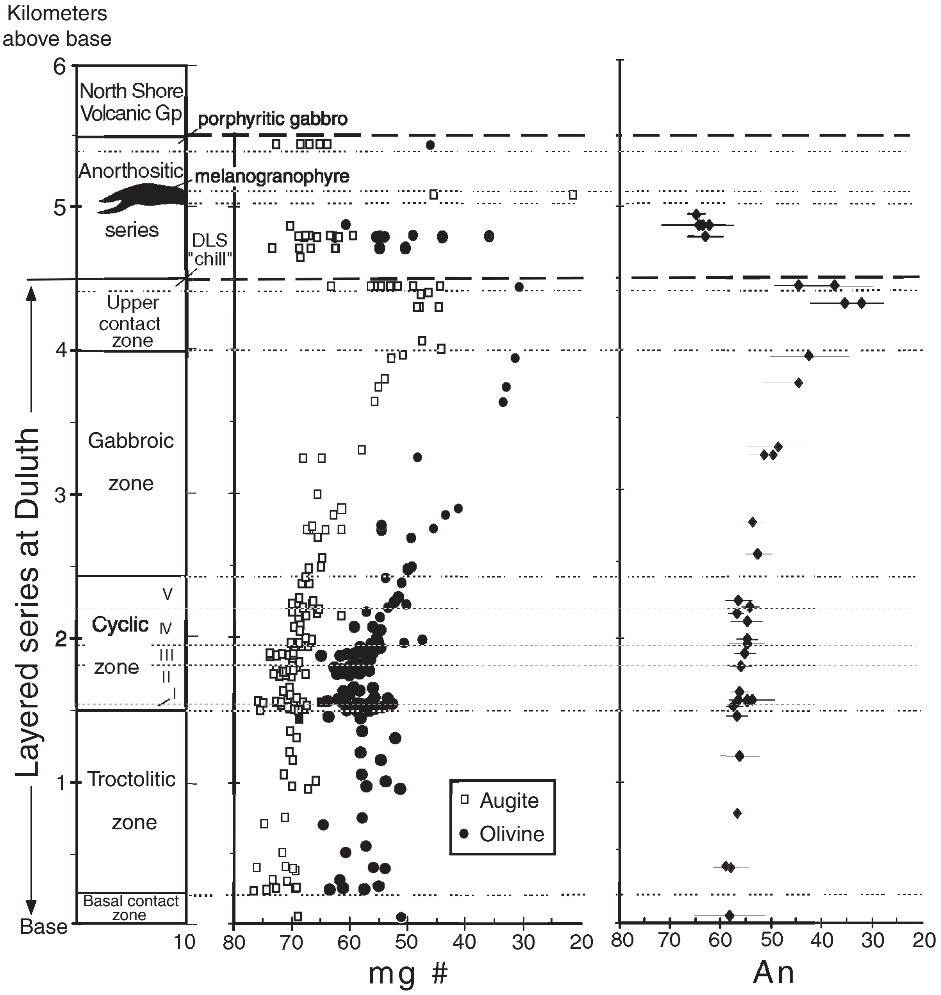

Figure 6.8. Igneous stratigraphy and cryptic variation of olivine, pyroxene, and plagioclase composition through the layered series at Duluth. Mg values of olivine and pyroxene and An content of plagioclase are based on multiple microprobe analyses (error bars indicate one standard deviation).

intrusion[2] (Fig. 6.1). The intrusion is interpreted to be composed of two macrocycles of troctolite to oxide-rich gabbro. A subdued aeromagnetic signature characterizes the outer (lower) troctolitic parts of each cycle and a narrow magnetic high corresponds to gabbroic intervals (Fig. 6.5). Drilling on the magnetic highs intersected well-foliated and modally bedded, oxide-bearing gabbro cumulates (Severson, 1995). Much of the drilling into the Boulder Lake intrusion focused on circular highs related to transgressive oxide-ultramafic bodies (OUIs, see Chapter 8). The uppermost gabbro interval appears to be in contact with anorthositic series rocks. Scattered outcrop of anorthositic and gabbroic rocks and a large area of mafic volcanic hornfels (near Bear Lake; Severson, 1995) imply a mixed anorthositic series assemblage (unit asmx, M-119), which is consistent with the busy aeromagnetic signature over this area (Fig. 6.5).

The outline and contact relationships of the Boulder Lake intrusion to adjacent rock types is based entirely on interpretation of aeromagnetic

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[2] In a geologic map of the central Duluth Complex, Miller and Chandler (1999) referred to this body as the Pequaywan Lake intrusion, but it was later realized that anorthositic series rocks underlie the Pequaywan Lake area.

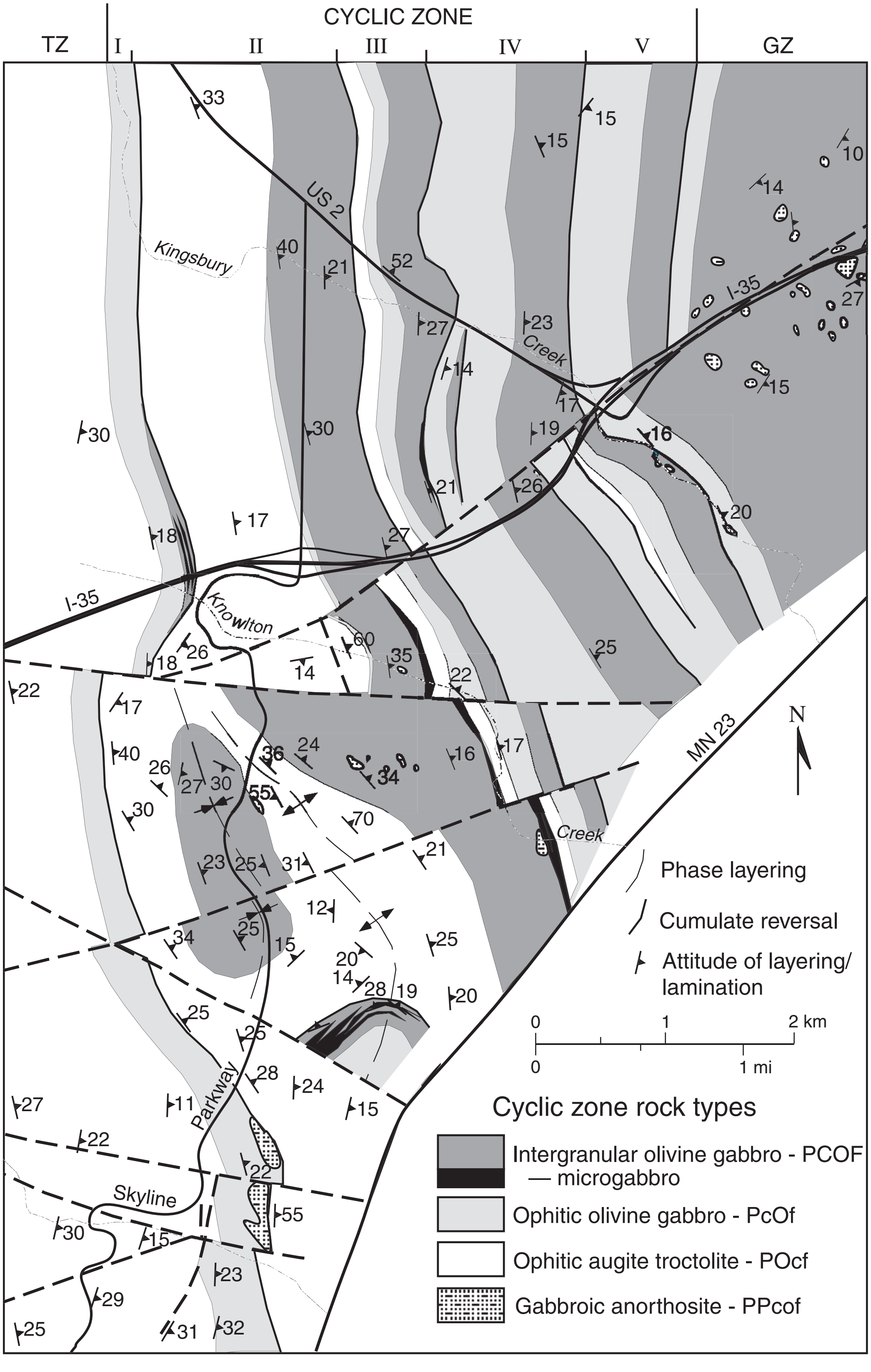


Figure 6.9. Geology of the layered series at Duluth cyclic zone in the vicinity of Interstate 35, U.S. Highway 2, and Skyline Parkway.

data (Fig. 6.5). A pronounced aeromagnetic "ledge" marks the basal contact of the intrusion against argillaceous sedimentary rocks in the vicinity of Boulder Lake. From there, the contact extends north for 15 kilometers and then arcs to the east–northeast and appears to cut across the aeromagnetic grain of the Western Margin intrusion and into the busy aeromagnetic signal of the anorthositic series. The easternmost extension of the lower contact appears to abut the Sawmill Lake gabbro, another intrusive unit interpreted largely from aeromagnetic data.

The southern margin of the Boulder Lake intrusion is sharply truncated by troctolitic rocks of the layered series at Duluth. A strong magnetic high is developed where the layered series at Duluth cuts across gabbroic intervals in the Boulder Lake intrusion and overlying anorthositic series rocks. This may be a metamorphic effect enhancing the magnetite content of these oxide-bearing rocks. A similar thermal effect is inferred where the northernmost projection of the layered series at Duluth appears to cut back across the Boulder Lake intrusion (M-119). The intrusion of the layered series at Duluth would explain why the two linear magnetic anomalies associated with two gabbro intervals merge into one large anomaly southwest of American Lake (T. 55 N., R. 13 W., sec. 29).

Western Margin intrusion

With only a handful of outcrops in the 50-kilometer distance between the Allen–Babbitt area and the Boulder Lake area, the geology of the western margin of the Duluth Complex has remained unknown. In the first attempt to interpret high-resolution aeromagnetic data over the central Duluth Complex, Chandler (1990) recognized that the internal structure of the southern Partridge River intrusion is overrun by another anomaly emanating from the basal contact (Fig. 6.6). He speculated in his geologic interpretation that one or two troctolitic intrusions might compose the western margin of the Duluth Complex (see Chapter 2, Fig. 2.2). After reevaluating the aeromagnetic data and reviewing available drill core and outcrop along the western margin, Miller and Chandler (1999) concluded that a single, large, troctolitic intrusion forms the western margin of the complex, and named it the Western Margin intrusion.

Knowledge of this body comes from its aeromagnetic signature, 37 drill cores (23,365 feet [7.1 kilometers] of core) and very rare outcrop. The intrusion is 5 to 10 kilometers in width and has a strike length of over 40 kilometers (Fig. 6.1). Like other predominantly troctolitic bodies, the Western Margin intrusion has a subdued aeromagnetic pattern and a subtle striping that probably reflects some stratiform variability in rock type. An aeromagnetic "ledge" characterizes the basal contact. Drilling and some outcrop in the Linwood Lake area (Severson, 1995) show the basal contact is against strongly recrystallized graywacke and slate of the Virginia Formation. The basal contact and the internal striping of aeromagnetic anomalies are offset in several places by inferred east–northeast-and west–northwest-trending faults (M-119).

To the north, the Western Margin intrusion cuts across the subdued anomaly pattern of the Partridge River intrusion and also projects into an area inferred to consist of mixed anorthositic, gabbroic, and hornfels rocks (unit asmx, M-119; also Fig. 6.6). In the southeast corner of the Allen quadrangle, an augite-poor troctolite cuts anorthositic and gabbroic rocks that form the roof zone of the Partridge River intrusion (Severson and Miller, 1999). The aeromagnetic signature of this troctolite is similar to that of the basal zone of the Western Margin intrusion. The Boulder Lake intrusion apparently cuts the Western Margin intrusion on the south (Fig. 6.5). The south-trending internal anomaly pattern of the Western Margin intrusion is truncated by a thin cuspate magnetic high interpreted to be caused by contact metamorphism of the Boulder Lake body.

The hanging wall of the Western Margin intrusion is inferred to consist of mixed anorthositic, gabbroic, and hornfelsic rocks (unit asmx, M-119) based on a heterogeneous magnetic signature, a few drill cores, and rare outcrop. This aeromagnetic pattern contrasts sharply with the subdued pattern and subtle striping that characterizes the intrusion. A drill core taken near Otto Lake (OL-1) near the inferred upper contact of the Western Margin body shows a heterogeneous mix of troctolitic rocks and anorthositic inclusions.

The igneous stratigraphy of the Western Margin intrusion is poorly known, but appears to consist mainly of troctolitic cumulates. Exploration drilling (Chapter 2, Fig. 2.3), which targeted aeromagnetic anomalies associated with oxide ultramafic rocks (OUIs) and basal sulfide mineralization (Severson, 1995), also tended to encounter troctolite with minor occurrences of anorthositic and melanocratic rocks. Thick intersections of pyrrhotite-rich sulfide mineralization were encountered in troctolitic rocks in the Whiteface Reservoir area at the northern end of the intrusion. Toward the midsection of the intrusion, a thick, subhorizontal package of serpentinized melatroctolite and peridotite with internal troctolitic to anorthositic layers was intersected in the Harris Lake exploration area. A large, oxide-bearing, ultramafic plug (OUI) that intrudes anorthositic rocks was drilled in the Section 34 exploration area near the southern part of the intrusion. Igneous units intersected at the Boulder Creek exploration area at the south end of the intrusion include heterogeneous troctolitic rocks, well-foliated troctolite and olivine gabbro cumulates, and a disjointed stratabound OUI. The Boulder Creek area is the only place where cumulus augite-bearing gabbro was observed. The predominance of troctolitic cumulates and the occurrence of melanocratic intervals high up in the sequence such as at Harris Lake imply a very open magmatic system. This attribute, along with minor basal sulfide mineralization and its structural position relative to the Partridge River intrusion, all suggest that the Western Margin intrusion may correlate with the South Kawishiwi intrusion in time and style of emplacement.

Partridge River intrusion

The Partridge River intrusion (Bonnichsen, 1974) has been studied in detail because it hosts at least four sub-economic copper-nickel deposits and at least seven potential Fe-Ti deposits. The Partridge River intrusion consists mainly of troctolitic cumulates that are exposed in an arc-shaped area that extends from the Water Hen Fe-Ti deposit area (T. 57 N., R. 14 W., sec. 27) to the Babbitt copper-nickel deposit (T. 60 N., R. 12 W., secs. 31-33; Fig. 6.1). Miller and Ripley (1996) estimated that the Partridge River intrusion is 2.5-kilometers-thick. Its footwall includes the Paleoproterozoic Virginia Formation (slate and graywacke), and to a lesser extent, the Biwabik Iron Formation. The top of the Partridge River intrusion is in complex contact with anorthositic rocks (unit asau, M-119), gabbroic rocks (unit asgb, M-119), mafic volcanic hornfels (magnetic and non-magnetic varieties; units nsmb and nsbh, M-119), and in one location, an unusual, fine-grained and cross-bedded sedimentary hornfels (Colvin Creek hornfels of Bonnichsen, 1972; Patelke, 1996; unit nssh, M-119). This assemblage of anorthositic, gabbroic, and hornfelsic rocks are also present as large inclusions within the interior of the Partridge River intrusion (Severson and Miller, 1999) and are thought to represent earlier roof zone septa that were overplated by later emplacement of Partridge River intrusion magmas.

The basal 900 meters of the Partridge River intrusion are known in great detail from the abundance of exploration drill core. This marginal zone, consisting of varied troctolitic and gabbroic rock types, is subdivided into seven stratigraphic units (Severson and Hauck, 1990, 1997; Geerts, 1991; Severson, 1991, 1994) that can be correlated over a strike length of 24 kilometers (Fig. 6.10). All of these igneous units generally exhibit shallow dips (10° to 20°) to the southeast. The stratigraphy shown in Figure 6.10 is based on the relogging of almost 700 drill holes, or 672,000 feet (205 kilometers) of drill core. The units of the Partridge River marginal zone are briefly described below starting at the base of the Partridge River intrusion. For locations of ore deposit areas mentioned below, see Figure 2.3 in Chapter 2.

Unit I (unit prcz, M-119)—Unit I is the dominant sulfide-bearing member of the Partridge River intrusion. It consists of a heterogeneous mixture of ophitic troctolitic to gabbroic rocks that contain abundant inclusions of hornfelsic sedimentary footwall rocks and minor thin, discontinuous layers of melatroctolite and peridotite. Noritic rocks are common at the basal contact and peripheral to sedimentary hornfels inclusions, probably due to contamination of the magma. An ultramafic interval, consisting of an oxide-bearing peridotite overlying an oxide-bearing pyroxenite, is present at the base of Unit I in areas where the Partridge River intrusion is in direct contact with the Biwabik Iron Formation (the extreme southeastern portion of the Babbitt deposit).

Unit II (unit prmt, M-119)—This unit exhibits considerable variation from one copper-nickel deposit to the next. At the Dunka Road and Babbitt deposits, Unit II consists of homogeneous troctolitic rocks, with minor sulfide mineralization, and a fairly persistent basal ultramafic layer that separates Unit II from Unit I. The upper contact with Unit III is gradational at the Dunka Road deposit. At the Wetlegs deposit, Unit II is either a single ultramafic layer immediately beneath Unit III, and/or the Wetlegs layered interval (Fig. 6.10), which consists of repeated, thin cyclic units that internally grade upward from ultramafic

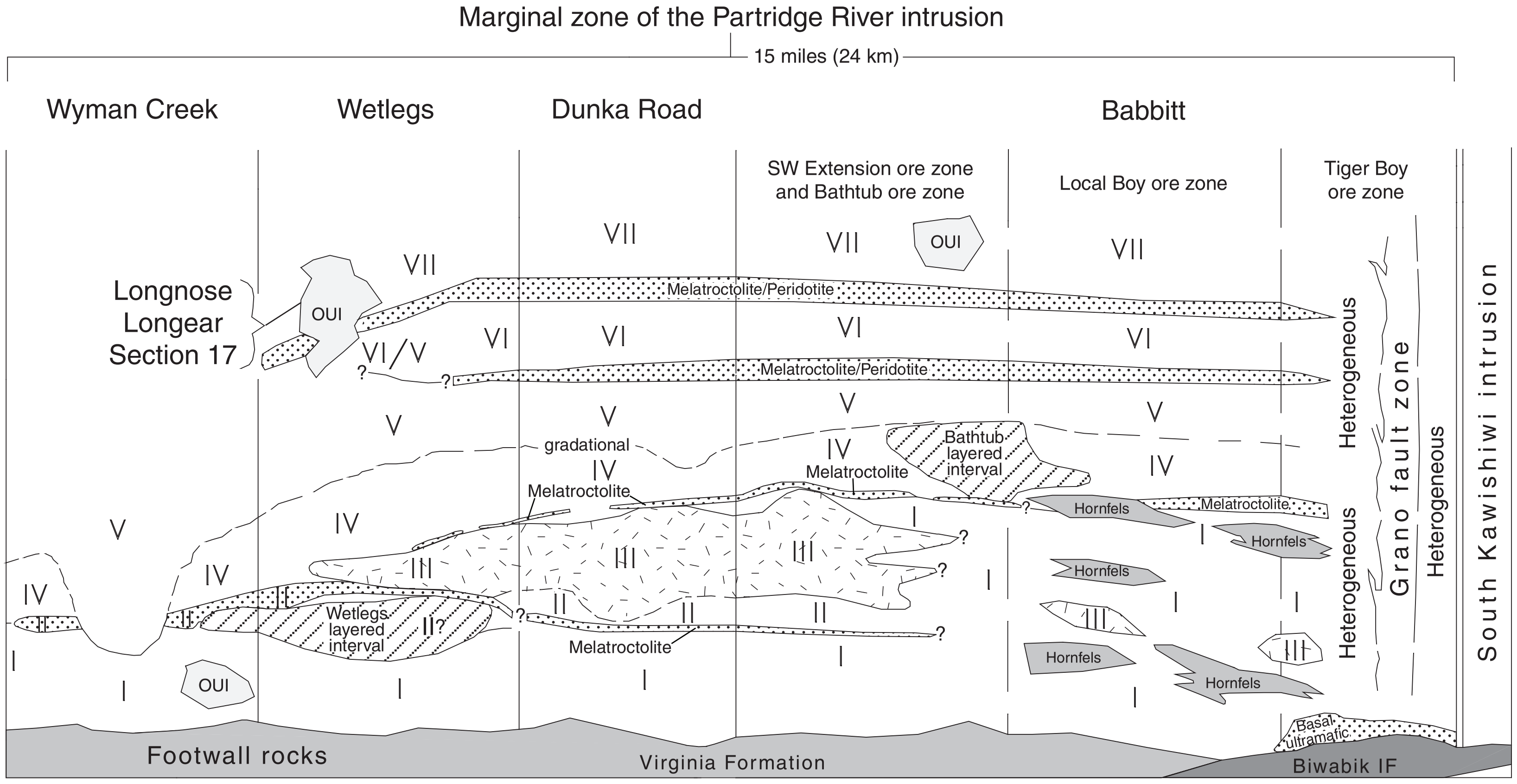


Figure 6.10. Generalized stratigraphy of the marginal zone of the Partridge River intrusion (modified from Severson, 1994). Stratigraphic relationships for the area between the Wyman Creek deposit and the Water Hen deposit are poorly understood and are not portrayed on this figure.

rock to troctolite. Still farther to the west at the Wyman Creek deposit, Unit II consists of a single ultramafic horizon that separates sulfide-bearing and heterogeneous troctolitic rocks of Unit I from homogeneous troctolitic rocks of Unit IV.

Unit III (unit prpt, M-119)—This unit consists of poikilitic leucotroctolite that commonly grades into poikilitic/ophitic augite troctolite. Because of its fine-grained texture and distinctive olivine oikocrysts that impart a mottled appearance, Unit III is a useful marker horizon, although it is absent from the Wyman Creek deposit and portions of the Babbitt deposit. Hornfelsed basalt inclusions, or roof rocks, are commonly associated with Unit III at the Dunka Road deposit. This relationship, and the highly gradational contact of Unit III with Unit II, suggest that Unit III may have formed as a roof cumulate during crystallization of Unit II.

Unit IV (unit prat, M-119)—Homogeneous ophitic augite troctolite that contains a local basal unit of ultramafic rock. Unit IV typically exhibits a highly gradational upper contact with Unit V. A cyclic sequence of alternating troctolitic and ultramafic layers, termed the Bathtub layered interval (Fig. 6.10), is present in the Bathtub ore zone of the Babbitt deposit.

Unit V (unit prct, M-119)—Unit V consists of homogeneous, coarse-grained leucotroctolite. At the Wyman Creek deposit, drill hole relationships suggest that Unit V cuts downward into the lower units (Fig. 6.10).

Units VI and VII (unit prtr, M-119)—Each of these units consist of homogeneous leucotroctolite that locally grades into ophitic augite troctolite; both also contain a fairly persistent ultramafic base. Several other similar units (Unit VIII and up) are present above these two units, but they are not defined by drilling.

Oxide ultramafic intrusions (OUI)—Several late-stage pegmatitic plugs and vertical lenses of oxide-bearing ultramafic intrusions intrude the troctolitic rocks of the Partridge River intrusion. Severson and Hauck (1990) first used the acronym OUI to designate crosscutting pegmatitic bodies of peridotite, melatroctolite, melagabbro, and clinopyroxenite that contain a high percentage of coarse-grained oxides (15 to 100 percent). Known OUI bodies in the Partridge River intrusion with Fe-Ti potential occur at: Section 17, Longnose, Longear, Wyman Creek, Section 22, Skibo, Skibo-South, and Water Hen (see Chapter 2, Fig. 2.3). In all instances, the OUI are spatially arranged along linear trends, suggesting that structural control was important to their genesis. In addition, the Longnose–Longear–Section 17 group of OUIs is positioned over a window in the basal contact where the Biwabik Iron Formation is the footwall rock. This relationship suggests a genetic link between assimilation of iron-formation at the basal contact and formation of OUI along a coincident fault zone.

Attributes of the more heterogeneous units (I and II) near the base of the Partridge River intrusion are interpreted to indicate rapid magma replenishment in a progressively developing magma chamber, and magmatic contamination from assimilated footwall rocks. The more homogeneous upper units (IV through VII), each floored by a persistent ultramafic layer, were probably emplaced later in a well-developed magma chamber. The ultramafic layers in the upper units, and abundant ultramafic layers of the Wetlegs and Bathtub layered intervals, probably represent the inception of episodic magma injection that crystallized more primitive ultramafic layers before mixing with the resident magma.

The contact zone between the Partridge River intrusion and South Kawishiwi intrusion is poorly exposed and poorly drilled (Fig. 6.1). All of the units of the Partridge River intrusion marginal zone, including the upper units, become unrecognizable in the contact zone with the South Kawishiwi intrusion, and correlation of igneous units in one drill hole to another is difficult. Severson (1994) reasoned that the heterogeneous contact zone of the Partridge River intrusion (unit prhz, M-119) originally formed at the contact with pre-Keweenawan footwall rocks, and that later emplacement of the South Kawishiwi intrusion effectively removed the footwall portion and positioned South Kawishiwi intrusion intrusive rocks up against Partridge River intrusion intrusive rocks. Complicating the picture of the contact zone is the coincident Grano fault zone (Fig. 6.10; also Chapter 2, Fig. 2.3), which appears to have been repeatedly reactivated during and after emplacement of the Partridge River and South Kawishiwi intrusions. The Grano fault may have also served as a feeder channel to the massive sulfides of the Local Boy ore zone at the Babbitt deposit (see Chapter 8).

More petrologic studies have been conducted on the Partridge River intrusion than any other intrusion in the Duluth Complex. These studies pertain to drill holes in the Babbitt deposit (Grant and Molling, 1981; Tyson and Chang, 1984; Ripley and Alawi, 1986; Chalokwu and Grant, 1987, 1990; Martineau, 1989; Grant and Chalokwu, 1992; Chalokwu and others, 1993), and one study pertains to the Dunka Road deposit (Rao and Ripley, 1983). Most of the studies investigate a stratigraphic section intersected in one or a few drill holes that represents only a small fraction of the Partridge River intrusion magmatic system. Divergent progenetic interpretations have resulted from these studies and have been summarized by Miller and Ripley (1996).

South Kawishiwi intrusion

The South Kawishiwi intrusion, as defined by Green and others (1966), hosts at least five subeconomic copper-nickel deposits and a potential platinum group element-copper-nickel deposit (Chapter 2, Fig. 2.3). The South Kawishiwi intrusion is dominantly composed of troctolitic cumulates that are exposed in an 8- by 32-kilometer arcuate band (Fig. 6.1; M-119). Footwall rocks include the Virginia Formation in the Serpentine and Dunka Pit deposits, the Biwabik Iron Formation in the Dunka Pit and Birch Lake deposits, and the Archean Giants Range batholith in the Dunka Pit deposit north to the Spruce Road deposit. The presence of Biwabik Iron Formation as inclusions 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, leaving the Giants Range batholith as the dominant footwall rock type. Also present as inclusions in the Dunka Pit and Serpentine deposits are mafic volcanic hornfels (probably North Shore Volcanic Group) and quartz sandstone hornfels (probably equivalents to the Puckwunge and Nopeming Sandstones). Anorthositic rocks (unit asau, M-119) abut the South Kawishiwi intrusion on the northeast and enclose a possible South Kawishiwi intrusion feeder dike (units sktr and skgp, M-119) that extends farther northeast. To the east, the South Kawishiwi intrusion is inferred to be in semi-conformable contact with the Bald Eagle intrusion (Fig. 6.11). However, based on their relative crosscutting relationships to the Greenwood Lake intrusion, it is clear that the Bald Eagle intrusion is younger than the South Kawishiwi intrusion (Chandler, 1990; Meints and others, 1993).

The South Kawishiwi intrusion consists of five major map units (Green and others, 1966; Phinney, 1967; Bonnichsen, 1971; Morey and Cooper, 1977; Foose and Cooper, 1978). These are, from the base upward:

1. A basal contact zone that is a heterogeneous mix of sulfide-bearing troctolitic, gabbroic, and noritic rocks with abundant hornfels inclusions (unit skcz, M-119);
2. A thick unit of subophitic to ophitic augite troctolite (unit skat, M-119) that contains an internal ophitic olivine gabbro unit (unit skog, M-119);
3. A discontinuous and localized layer of poikilitic leucotroctolite (unit skpt, M-119);
4. A thick, homogeneous sequence of ophitic troctolite (unit sktr, M-119);
5. An uppermost, thick sequence of homogeneous troctolite (unit skta, M-119) that contains numerous lensoidal layers and inclusions of anorthositic rocks.

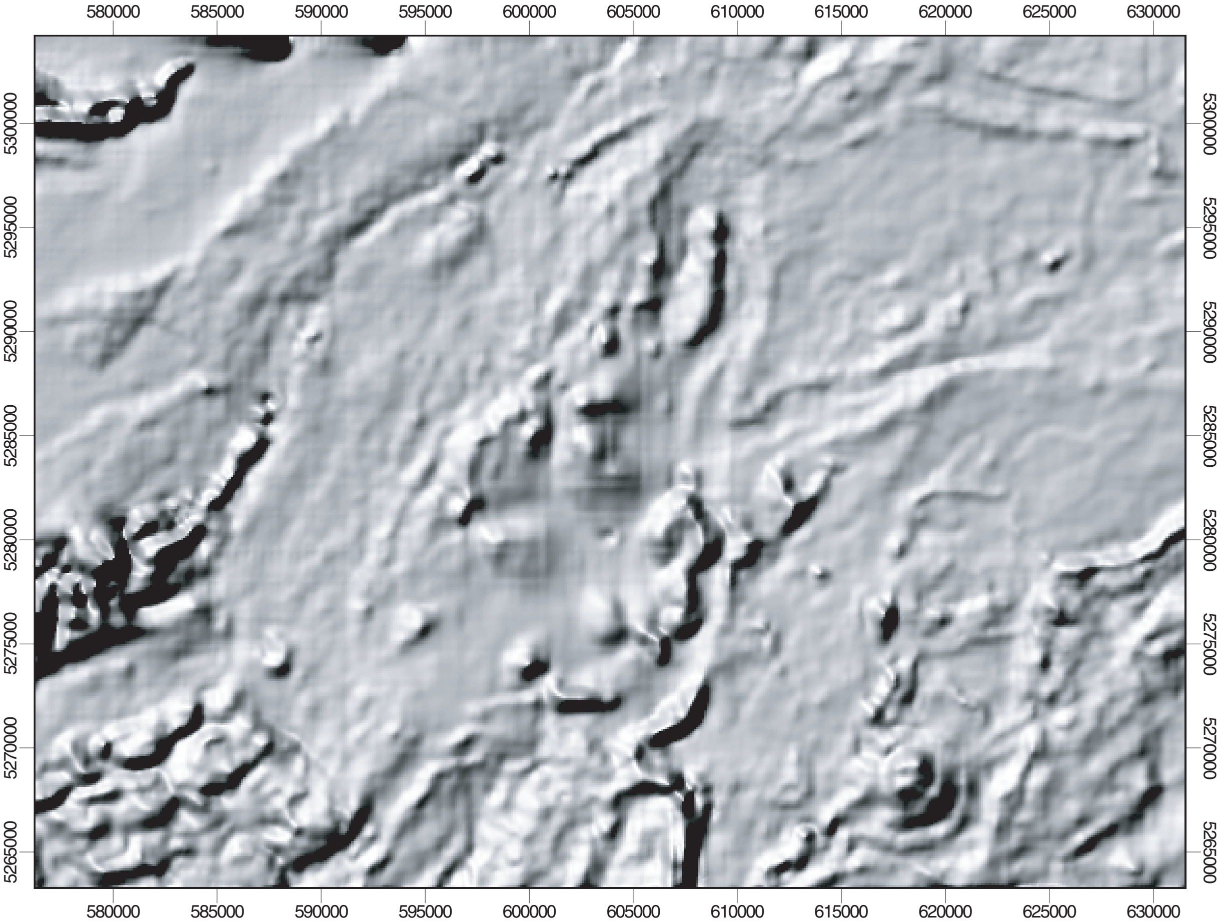
Severson (1994) and Zanko and others (1994) further subdivided the marginal zone of the South

Figure 6.11. Shaded-relief map of total magnetic field data over the northwestern Duluth Complex and generalized geologic map (from M-119) at the same scale. Solid lines denote inter-intrusion contacts; dashed lines denote intra-intrusion contacts. See M-119 for subunits of intrusions. UTM coordinates (NAD 83 datum) border the area. Layered series intrusions:

BEI—Bald Eagle intrusion
GLI—Northern part of the Greenwood Lake intrusion and its eastern extension
OLI—Osier Lake intrusion
PRI—Northeastern part of the Partridge River intrusion
SKI—South Kawishiwi intrusion
WLI—Wilder Lake intrusion

Also shown:

AS—Anorthositic series rocks
BIF—Biwabik Iron Formation
GRG—Giants Range Granite
HT—Houghtaling Creek troctolite
IG—Isabella granophyre
MW—Mt. Weber granophyre
V— Volcanic rocks
VF—Virginia Formation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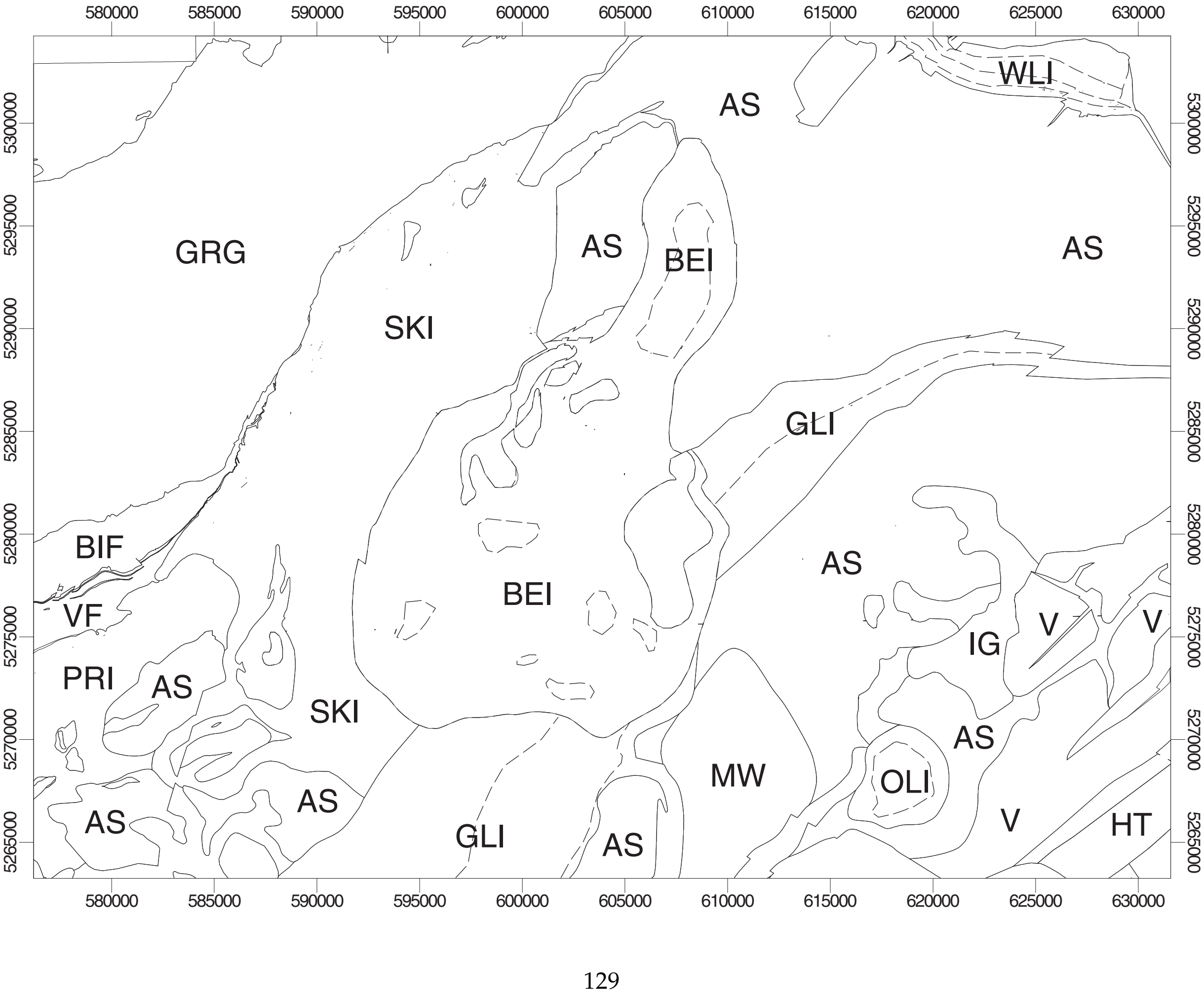
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Kawishiwi intrusion (including units skcz, skat, skog, and sktr, M-119) into 17 different lithostratigraphic units (Fig. 6.12) that are present in over 180 drill holes over a strike length of 31 kilometers. Sulfide mineralization is confined to the BH, BAN, UW, and U3 units, and to a lesser extent the U1 and U2 units. Major marker horizons that are correlated in drill holes include three horizons with abundant cyclic ultramafic layers (U1, U2, and U3 units) and a pegmatite-bearing unit (PEG unit) that was initially recognized by Foose (1984). A large, anorthositic inclusion (less than 1-kilometer-thick) is intersected in six deep drill holes in the State Highway One corridor area (AN-G unit, Fig. 6.12).

The lowest units of the marginal zone (Fig. 6.12) are the most varied with respect to textures, rock type, and sulfide content. They are unevenly distributed along the strike length of the South Kawishiwi intrusion in a "compartmentalized" fashion, suggesting a complicated intrusive history. The lowest units were emplaced early into several restricted magma chambers via repeated and close-spaced magmatic pulses. The U1, U2, and U3 units (Fig. 6.12) represent periods of rapid and continuous magma injection that crystallized more primitive ultramafic layers before mixing with the resident magma. The U3 unit is unique among the lower units in that it contains several massive oxide pods (titanomagnetite-rich) along its entire length. A spatial correspondence between the U3 unit and footwall iron-formation suggests that most of the massive oxide pods are iron-rich "restite" produced by the magmatic digestion of iron-formation. The U3 unit also contains the majority of the high platinum group element values that have been sampled within the South Kawishiwi intrusion. The upper units of the South Kawishiwi intrusion are continuous throughout the intrusion. Their continuity and monotonous troctolitic composition suggest that they crystallized in a more quiescent and open magmatic system characterized by widely spaced magmatic pulses.

Lake One troctolite

Following reconnaissance-scale mapping by Phinney (1972, unpub. data), Miller (1986) identified a multiply emplaced suite of troctolitic cumulates centered on Lake One. Full characterization of this intrusion will require additional mapping to the east, therefore we designate this body as the Lake One troctolite.

The footwall of the Lake One troctolite consists of Archean granite, greenstone, and metasedimentary rocks. However, scattered inclusions of iron formation and bedded, cordierite-bearing sedimentary hornfels, presumably of Paleoproterozoic age, occur within a kilometer of the basal contact. Their occurrence and the more common occurrence of basaltic hornfels implies that some thickness of the Biwabik Iron Formation and Virginia Formation were sandwiched between basal Keweenawan volcanic rocks and Archean basement rocks, and that these subhorizontally layered rocks were effectively delaminated by troctolitic intrusions.

The hanging wall of the Lake One troctolite is composed of various rock types of the anorthositic series. The contact between the troctolitic rocks and the anorthositic series is very irregular in shape and character. Green and others (1966) did not distinguish troctolitic from anorthositic rocks in the northeast part of the Gabbro Lake 15-minute quadrangle (Ojibway Lake 7.5-minute quadrangle), but based on the southeast dipping structure and hornfels occurrences, the contact can be inferred to extend from Pagami Lake to the southwestern corner of Lake One. In the Snowbank Lake quadrangle, the contact curves southeast to Rock Island Lake and the western shore of Lake Three, and then irregularly back to the north through Lake Two. From Lake Two, it curves to the east and more or less parallels the basal contact. Despite the irregular shape of the contact, the troctolitic rocks consistently strike to the northeast (roughly parallel to the basal contact) and dip to the southeast, except in the Rock Island Lake area where the dip locally reverses to the north to define a synform/antiform pair. Where the contact between the Lake One troctolite and the anorthositic series is structurally disconformable, the change in lithology is abrupt, but the two rocks are rarely observed in contact. This suggests possible fault contacts, especially in places where the troctolite strikes at right angles to the inferred contact. However, in a few places where the contact can be approximated to within several meters, troctolitic rocks are somewhat finer grained, nonfoliated, and host scattered anorthosite inclusions, thus implying a normal intrusive relationship. In the southern Lake Two area, however, contacts are locally marked by zones of troctolite with abundant anorthosite inclusions (unit l1mx, M-119); and in another area of Lake Two, the foliation in the troctolite is semi-

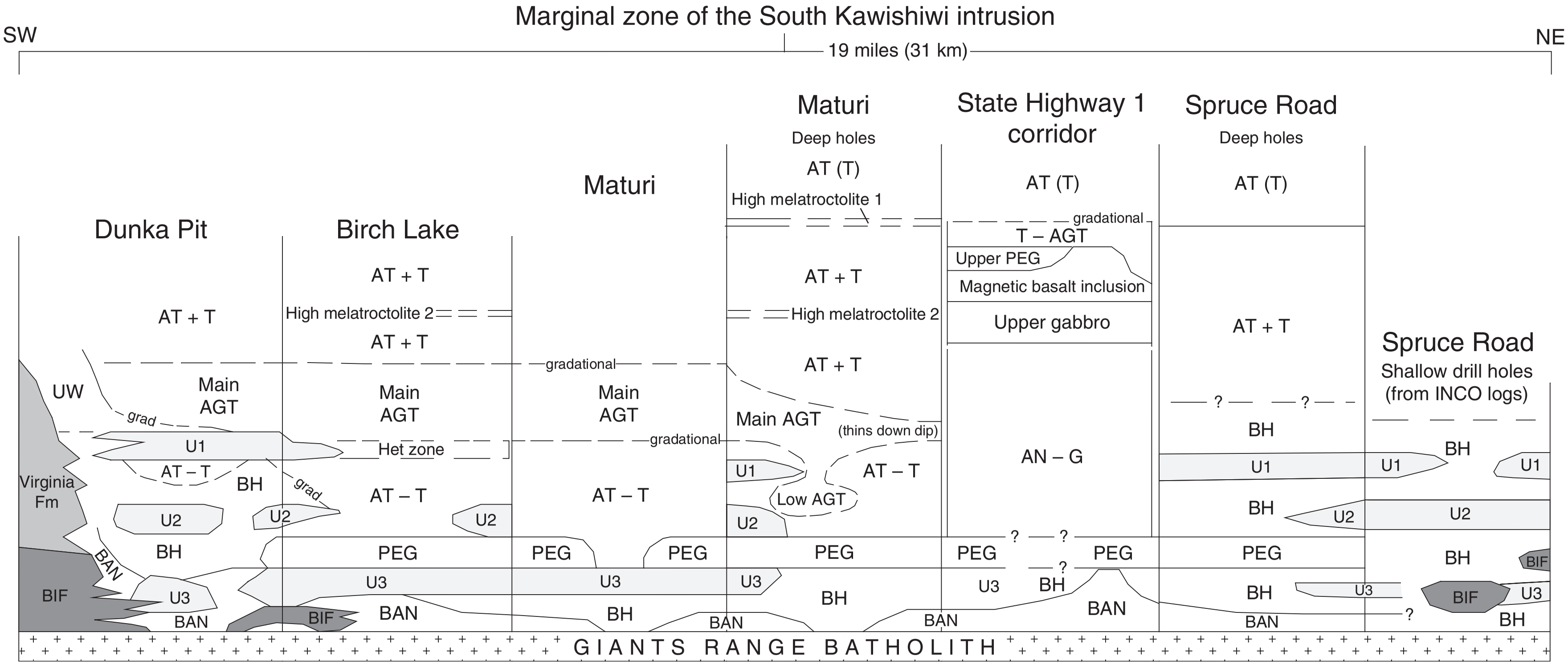


Figure 6.12. Generalized stratigraphy for the marginal zone of the South Kawishiwi intrusion (modified from Severson, 1994).

conformable to a steep contact and a more gradational contact relationship is inferred.

A stratiform sequence of troctolitic cumulates over 1.5-kilometers-thick is exposed between the basal contact and the axis of the synformal structure in the vicinity of Rock Island Lake. Figure 6.13 shows the modal variations across this stratigraphic section. The generalized map units shown in M-119 are also noted. Except for a heterolithic basal contact zone (unit `l1cz`, M-119) and an overlying zone of medium- to coarse-grained ophitic olivine gabbro to augite troctolite (unit `l1og`, M-119), the Lake One troctolite is composed of homogeneous to intermittently layered, medium-grained, well-foliated, ophitic melatroctolite, troctolite, and augite troctolite. However, subtle variations in the distribution of modal layering and the abundance of ophitic augite define three macrocyles (Fig. 6.13). The basal cycle grades from the lower medium- to coarse-grained olivine gabbro to augite troctolite cumulates (PcOf, POcf), to intermittently layered, medium-grained, ophitic troctolite (PO), and further to intermittently layered augite troctolite (POcf) that becomes medium coarse-grained near the top. The second cycle starts abruptly with a narrow interval of medium-grained troctolite that contains augite troctolite inclusions; this grades abruptly to rhythmically layered troctolite and melatroctolite (PO/OP). This troctolite gives way to medium-grained, coarsely ophitic augite troctolite (POcf) that contains augite oikocrysts up to 15-centimeters-wide. Another abrupt change in mode and texture marks the base of the third macrocycle. The basal zone of this uppermost cycle is composed of homogeneous, well-laminated granular oxide-bearing troctolite (POF). This rock grades into a medium-grained ophitic augite-

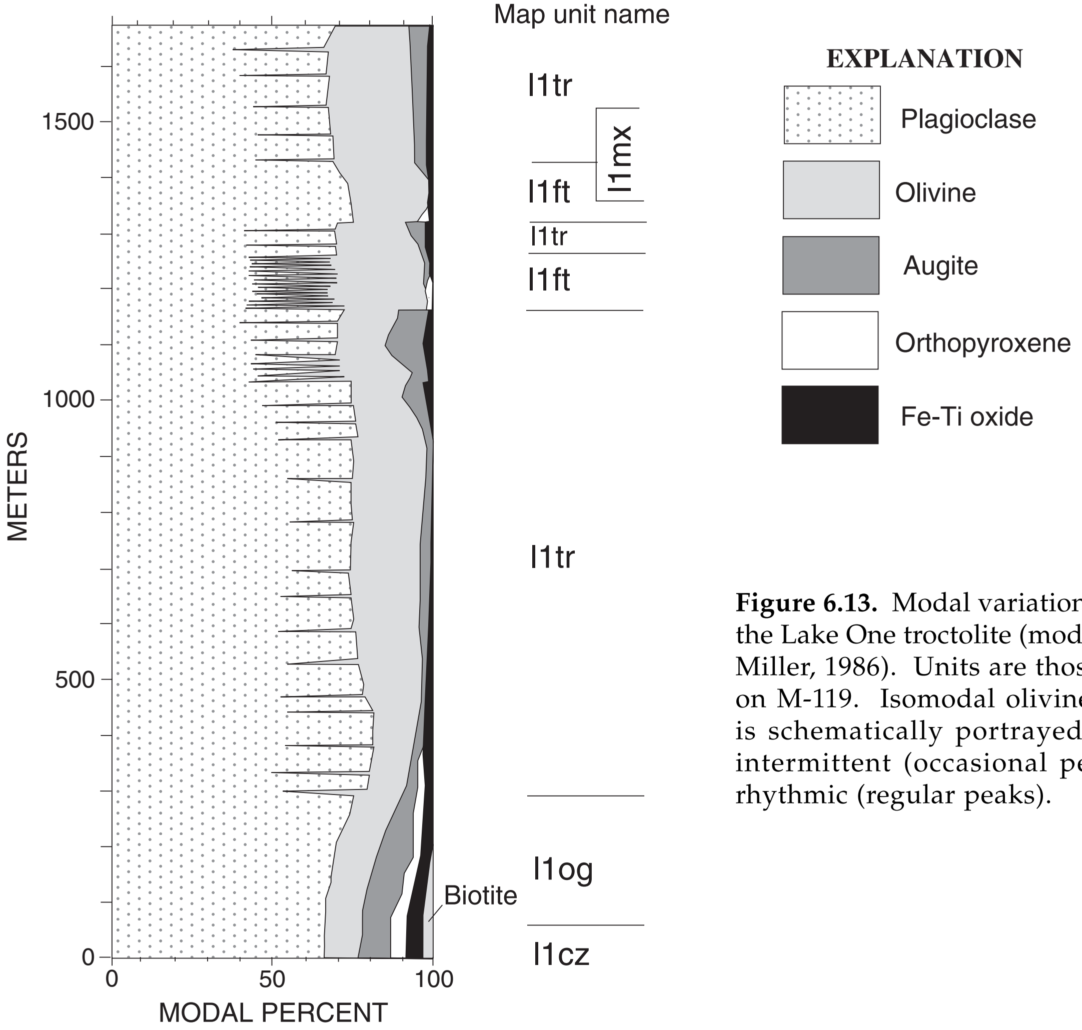


Figure 6.13. Modal variations through the Lake One troctolite (modified from Miller, 1986). Units are those defined on M-119. Isomodal olivine layering is schematically portrayed as being intermittent (occasional peaks) and rhythmic (regular peaks).

bearing troctolite, the uppermost unit of the Lake One troctolite preserved in the synformal axis north of Rock Island Lake. The oxide troctolites that reappear on the south limb of this synformal structure display a strong modal layering not observed on the north limb. These cyclical changes in mode and texture and limited data on mineral compositions (Miller, 1986) suggest that a least three major episodes of magma emplacement were responsible for the formation of the Lake One troctolite.

Tuscarora intrusion

Troctolitic and interlayered anorthositic rocks that cut the Poplar Lake intrusion of the early gabbro series and locally underlie it have been termed the Tuscarora intrusion by Weiblen and others (1972) and Morey and others (1981). Although its western limit is unknown, a sufficient strike length of these stratiform rocks (greater than 20 kilometers) has been mapped to warrant retention of the "intrusion" label. The Tuscarora is distinct among layered series intrusions because of its abundance of anorthositic as well as troctolitic cumulates.

The Tuscarora intrusion has been mapped in the Gunflint Lake quadrangle (Morey and Nathan, 1978), the Long Island Lake quadrangle (Morey and others, 1981), and the Gillis Lake quadrangle (Weiblen and Beitsch, unpub. data). The eastern contact of the Tuscarora intrusion irregularly cuts across the layered gabbros of the Poplar Lake intrusion in the western Gunflint Lake quadrangle (Nathan, 1969; Morey and Nathan, 1978). Nathan (1969) mapped a late intrusive sheet of anorthositic rocks emplaced into the basal zone of the Poplar Lake intrusion that may be related to the Tuscarora intrusion. The western extent of the Tuscarora intrusion is unknown, but reconnaissance mapping by Phinney in the Ogishkemuncie Lake and Kekekabic Lake quadrangles and a continuity in the aeromagnetic signature suggest that it may extend for at least 30 kilometers. In the Fraser Lake area of the Kekekabic Lake quadrangle, Phinney (1972) noted a chilled contact of one troctolitic rock against another. It is unclear if this is a major contact between two layered series intrusions (such as the Tuscarora and the Lake One). Because of this uncertainty, however, the basal zone of troctolitic rocks between the Lake One area and the Gillis Lake quadrangle are mapped as undifferentiated troctolite (unit trct, M-119). Where it has been mapped, the basal contact of the Tuscarora intrusion is predominantly against the Paleoproterozoic Rove Formation and Gunflint Iron Formation, and the early Keweenawan Logan sills within them (Morey and others, 1981). In the Gillis Lake quadrangle, the Tuscarora intrusion cuts through the Paleoproterozoic section and comes into contact with Archean metasedimentary and metavolcanic rocks.

Morey and others (1981) recognized three main units of the Tuscarora intrusion in the Long Island Lake quadrangle. A basal zone is composed of fine- to medium-grained, ophitic olivine gabbro to augite troctolite that is locally enriched in sulfide (unit tuta, M-119). Above this thin interval is a unit of medium- to fine-grained, well-foliated troctolite (unit tutr, M-119), the lower part of which is generally finer-grained. These troctolites are in turn overlain by a 100-meter-thick sequence of interlayered anorthositic gabbro (leucogabbro) and troctolite (unit tuat, M-119). Morey and others (1981) noted, "These two rock types are interlayered on a scale of several centimeters to several meters. Contacts between layers are sharp. The general dip of the layering is near horizontal..." The authors interpreted this unit as transitional between the troctolite unit and the anorthositic rocks exposed in the southern part of the quadrangle. The anorthositic rocks were described as, "Medium-grained anorthositic gabbro. Contains 75 to 80% cumulus plagioclase (An_{55-60}) and varying proportions of augite, olivine, and iron oxides in a poikilitic texture." Morey and others (1981) interpreted these anorthositic rocks to be the upper unit of the Tuscarora intrusion (their unit tag); however, in generalized maps of the complex (for example Davidson, 1972; Weiblen and Morey, 1980), these anorthositic rocks were grouped with the anorthositic series. Map M-119 also portrays these anorthositic rocks as part of the anorthositic series. The interlayered nature of the transition between troctolitic and anorthositic cumulates in the Tuscarora intrusion suggests more clearly than elsewhere in the Duluth Complex that the layered series and anorthositic series rocks may be linked petrogenetically, as implied by their similar ages (Paces and Miller, 1993).

Scattered throughout the Tuscarora intrusion are mafic volcanic hornfels bodies of varied size (the largest is about 2.5-kilometers-wide). Hornfels bodies are abundant in the troctolitic rocks of the northern Duluth Complex, composing up to 15 percent of the zone according to estimates by Grout (1930). Most bodies, like the ones in the Tuscarora intrusion, are recrystallized mafic volcanic rocks of the North Shore Volcanic Group. They have gabbroic mineral assemblages and locally display relict volcanic structures (such as meta-amygdules). Some inclusions along the northern troctolite zone were evidently derived from Paleoproterozoic sedimentary rocks; one notable footwall inclusion is an 8-kilometer-long band of recrystallized iron-formation (unit Pif, M-119). The abundance and lateral continuity of this and other inclusions along particular horizons in the troctolitic cumulates suggest that the Tuscarora and related troctolitic rocks to the west were emplaced as multiple, semi-conformable sheetlike intrusions into the base of the volcanic pile and into the shallow-dipping Paleoproterozoic sedimentary rocks immediately beneath them.

Wilder Lake intrusion

Reconnaissance mapping in the northwestern part of the Duluth Complex (Phinney, 1972, unpub. data; Miller, 1986) has revealed a mafic layered intrusion, termed the Wilder Lake intrusion, that is distinct in its structural setting, cumulate stratigraphy, and cryptic layering from other layered series intrusions of the complex. This mapping and a distinctively striped aeromagnetic pattern (Fig. 6.11) indicate that the Wilder Lake intrusion extends at least 10 kilometers from North Wilder Lake east-southeast to Arrow Lake.

The Wilder Lake intrusion differs from other layered series intrusions because it dips to the northeast rather than the southeast. Also, instead of being sandwiched between pre-Keweenawan basement rocks and a cap of anorthositic series rocks, the Wilder Lake intrusion is completely enveloped by plagioclase cumulates of the anorthositic series (Fig. 6.1). The northeasterly dip of the intrusion may reflect the control of an underlying southeast-trending structural ridge of Archean rocks, which has been postulated by Miller and Chandler (1997) to be an extension of the Giants Range batholith. The reversed direction of dip, higher level of emplacement, and chilled lower margin suggest that the Wilder Lake intrusion is younger than the layered series intrusions along the base of the Duluth Complex.

Another distinctive characteristic of the Wilder Lake intrusion is its cumulate stratigraphy (Fig. 6.14): Fe-Ti oxide arrives as a cumulus phase before augite. A fine- to medium-grained, non-foliated to poorly foliated, subophitic olivine gabbro forms a 25- to 100-meter-thick basal contact zone (unit wlog, M-119). Above this is a 100-meter-thick interval of intermittently layered ophitic augite troctolite cumulates (POc; unit wllt, M-119) that grades upward to a homogeneous augite-poor troctolite cumulate (PO; unit wltr, M-119). The adcumulate troctolite grades over a few meters into a well-foliated ilmenite troctolite (POF) that is about 50-meters-thick and contains about 8 percent modal ilmenite. The abrupt cumulus arrival of augite marks the most differentiated unit, a 25-meter-thick interval of well-foliated, olivine oxide gabbro (PCOF). The POF and PCOF cumulates are combined as the wlfg unit on the geologic map (M-119). The PCOF cumulate abruptly gives way to well laminated and locally modally layered, augite-poor troctolite (unit wllt, M-119) that persists upward through the rest of the section and into a structurally complex, anorthositic inclusion-rich roof zone (unit wlrz, M-119). Gabbroic anorthosite inclusions are observed in all units exposed around North Wilder Lake, but are particularly abundant in the roof zone.

In addition to the cumulus arrival of ilmenite before augite, a distinctive and anomalous feature of the Wilder Lake intrusion is the reversed cryptic variation of mg# in both olivine and augite upwards through the cumulate sequence (Fig. 6.14). The result is that the most primitive olivine and augite compositions occur in the most mineralogically evolved cumulates. Olivine in the PCFO cumulate has an Fo content almost 15 percent greater than olivine from the basal contact zone. The mg# of augite in the oxide troctolite cumulate (POF) is almost 10 mole percent greater than augite at the upper and lower contacts. Interestingly, where augite is cumulus (PCFO unit), it is more iron-rich than in adjacent units where it is intercumulus and in minor abundance. Miller and Ripley (1996) suggested that this may indicate less trapped liquid in the cumulates and consequently less of a trapped-liquid shift.

Bald Eagle intrusion

Another layered series intrusion that displays a distinctive cumulate stratigraphy is the Bald Eagle intrusion (Weiblen, 1965; Weiblen and Morey, 1980). It occurs inboard of the northwestern margin of the Duluth Complex (Fig. 6.1) and was emplaced partially within rocks of the anorthositic series and partially within the South Kawishiwi and Greenwood Lake intrusions. Steep foliation and layering (Weiblen, 1965; Green and others, 1966) and a subtle gravity anomaly over the area imply that the northern part of this intrusion has a funnel shape that necks down to a steep feeder. Aeromagnetic data imply that the Bald Eagle

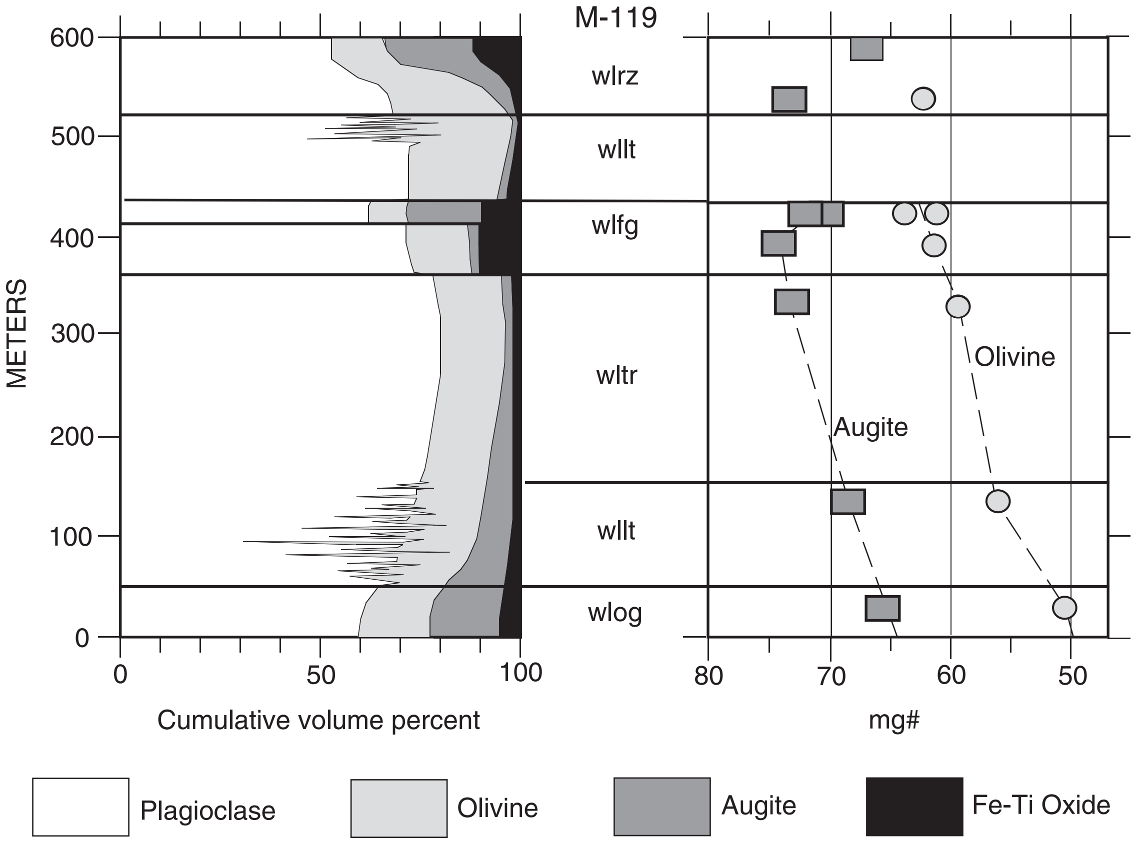


Figure 6.14. Modal and cryptic variation of mg# (MgO/[MgO+FeO]) in olivine and augite in the Wilder Lake intrusion (modified from Miller, 1986 and Miller and Ripley, 1996). Units are those defined on M-119.

intrusion extends considerably south of the area of exposure (Fig. 6.11) and flattens out to a shallow-dipping sheet.

As mapped by Weiblen (1965) in the northern area of exposure, the Bald Eagle intrusion consists of an outer zone of troctolitic adcumulates (unit betr, M-119) and an inner core of olivine gabbro adcumulates (unit begb, M-119). The rocks are well-foliated and locally display a downdip lineation. Isomodal layering of olivine and plagioclase abundance is common in the troctolite unit, especially where it is steeply dipping. Graded layering is rare. Interstitial Fe-Ti oxide composes less than 1 percent of either rock type and chromium spinel occurs exclusively in the troctolite. The transition from PO to PCO cumulates occurs over a 100-meter-wide zone within which interstitial pyroxene increases in abundance, leucocratic compositions become common, and olivine gabbroic and troctolitic rock types become interlayered. Weiblen (1965) noted general cryptic differences in mafic silicates between these two cumulate rock types, but not in plagioclase. Microprobe analyses show that olivine in the troctolite zone varies between Fo_{77} and $Fo_{70,}$ and in the gabbro core between Fo_{69} to Fo_{62}. However, a systematic study of the cryptic variation through the intrusion was not conducted.

In contrast to other layered series intrusions where the cumulus arrival of Fe-Ti oxide is close to that of augite (such as the layered series at Duluth and Wilder Lake intrusion), oxide never appears in the Bald Eagle intrusion despite about half the intrusion being composed of PCO cumulates. Because of its upright funnel shape and the depth of erosion, whatever upper differentiates may have existed in the intrusion have not been preserved. Despite an incomplete cumulate sequence, it is nevertheless remarkable that about 50 percent of the approximately 2.5 kilometers of stratigraphic section is composed of PCO cumulates. The cause of the extended delay in the onset of oxide crystallization is unclear. The absence of a chilled margin and the thoroughly adcumulate nature of the intrusion make it difficult to speculate if this delay is due to a unique parent magma composition. Weiblen and Morey (1980) interpreted the limited cryptic variation, the steep dip of lamination and layering, and adcumulate nature of the Bald Eagle intrusion as indicative of its being an open conduit to higher intrusions and perhaps volcanic flows. If correct, the delay in oxide crystallization may reflect open-system conditions throughout the crystallization of the Bald Eagle intrusion.

Aeromagnetic data over the poorly exposed southern part of the Bald Eagle intrusion are characterized by a very subdued oval-shaped anomaly area locally punctuated with magnetic highs (Fig. 6.11). The subdued areas are interpreted to be composed of the same troctolite cumulates exposed to the north that have widened and flattened out into a spoon-shaped basin. The magnetic highs vary in shape and area and have an apparent variety of sources. Drilling indicates that some of the southernmost anomalies are volcanic hornfels bodies (unit nsmb, M-119), whereas some anomalies in the north are anorthositic to gabbroic rocks of the anorthositic series (unit asmx, M-119). One drill hole (NE-2) into the large, hook-shaped anomaly in the eastern part of the Bald Eagle intrusion encountered an olivine-oxide gabbro (PCFO) cumulate (Sellner and others, 1985). This rock resembles the upper gabbroic zone of the Greenwood Lake intrusion (unit glgb, M-119) more than the oxide-free gabbro core of the Bald Eagle intrusion. The possibility of this anomaly representing a large xenolith of Greenwood Lake gabbro is consistent with the interpretation of crosscutting aeromagnetic patterns along the southern margin of the Bald Eagle intrusion. Here the northeast-trending internal structure of the Greenwood Lake intrusion is clearly truncated by the east–west pattern of the Bald Eagle intrusion (Fig. 6.11). Aeromagnetic anomaly data also imply that the northeastern continuation of the Greenwood Lake intrusion emerges from the eastern margin of the Bald Eagle intrusion.

Field and geophysical data suggest that emplacement of the Bald Eagle and South Kawishiwi intrusions may be closely linked (Morey and Weiblen, 1980). At the northern margin of the Bald Eagle intrusion, a macrodike of well-foliated troctolite arcs northwest to southwest and merges with the middle of the South Kawishiwi intrusion. Green and others (1966) mapped the macrodike as part of the South Kawishiwi intrusion, but its composition is very similar to the troctolitic phase of the Bald Eagle intrusion. Peterson (2001) proposed a model for the mineralization of the South Kawishiwi intrusion whereby the initial emplacement of the intrusion was formed by sulfide-contaminated magmas that emerged from the macrodike and flowed south between a footwall of Archean granite and a hanging wall of anorthositic series rocks (see Chapter 8, Figs 8.6 and 8.7). In the Babbitt NE and Slate Lake West quadrangles, field mapping (Green and others, 1966; Foose and Cooper, 1978) showed the Bald Eagle and the South Kawishiwi intrusions to be in direct contact. The South Kawishiwi intrusion is characterized by augite-poor troctolite with abundant lenticular to irregular-shaped bodies of troctolitic to olivine gabbroic anorthosite (unit skta, M-119). Troctolites of the Bald Eagle intrusion are recognized by being well foliated and free of anorthositic rocks (unit betr, M-119). However, the internal structures of both units are conformable and parallel aeromagnetic anomaly patterns extending south from the area of exposure suggest that this contact continues to be conformable.

These observations and interpretations suggest that the Bald Eagle and South Kawishiwi intrusions were emplaced by successive overplating of magmas from a common feeder that largely underlies the northern Bald Eagle intrusion and extends along the trace of the macrodike. Figure 6.15 shows a possible model to relate the emplacement of the lower mineralized and upper unmineralized parts of the South Kawishiwi intrusion and the higher overplating of the Bald Eagle intrusion. The model further speculates that the Bald Eagle intrusion had a more complete differentiation sequence that has been eroded away and that this magma system may have fed surface eruptions. If correct, the aeromagnetic interpretation that the Greenwood Lake intrusion crosscut the South Kawishiwi intrusion and was cut by the Bald Eagle intrusion further implies that considerable time elapsed between the intrusion of the upper South Kawishiwi and the Bald Eagle intrusions. Growth of the volcanic pile during this hiatus could explain why the Bald Eagle intrusion was emplaced at a considerably higher structural position, well into the anorthositic series (Fig. 6.15).

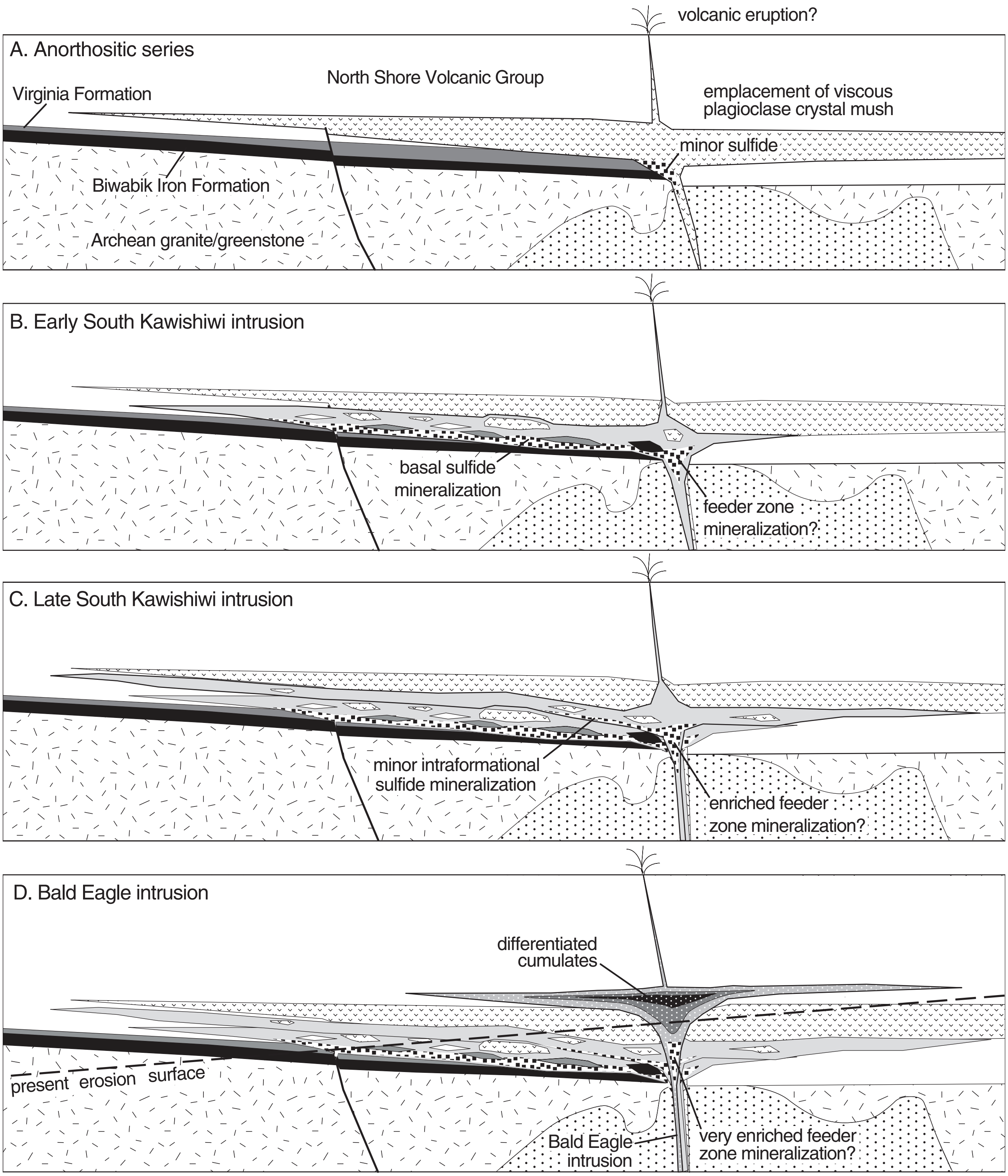


Figure 6.15. Interpretive model for the emplacement and mineralization of the South Kawishiwi and Bald Eagle intrusions via a common feeder system.

A. Emplacement of plagioclase crystal mushes to create anorthositic series rocks.

B. Emplacement of the lower part of the South Kawishiwi intrusion beneath the anorthositic series; the marginal zone becomes sulfide mineralized due to contamination by Paleoproterozoic footwall rocks.

C. Emplacement of the unmineralized upper part of the South Kawishiwi intrusion.

D. Emplacement and in situ differentiation of the Bald Eagle intrusion; the complete differentiation sequence is not preserved at the present erosion level.

Greenwood Lake intrusion

The Greenwood Lake intrusion is one of the largest and most differentiated intrusions in the Duluth Complex. Being almost completely unexposed, its existence was recognized only recently as a result of drilling and a reinterpretation of aeromagnetic data (Meints and others, 1993; Miller and Chandler, 1999). The only exposure of the Greenwood Lake intrusion are scattered outcrops of olivine oxide gabbro cumulates exposed along the LTV Mining railroad grade on either side of Lake County Highway 2. Bonnichsen (1972) first described these gabbros, but did not speculate as to what intrusive system they may belong. Weiblen and Morey (1980) interpreted these gabbro exposures to be upper differentiates of the Bald Eagle intrusion.

The identification of the Greenwood Lake intrusion occurred soon after the acquisition of high-resolution aeromagnetic data in 1981. One of the more distinctive aeromagnetic anomalies over the Duluth Complex is a 30-kilometer-long, sinuous, strong magnetic high that cuts northeasterly across Greenwood Lake (Fig. 6.6) and is referred to as the Snake anomaly (Vadis and others, 1981). The Snake anomaly straddles outcrops of granophyre forming Mt. Weber to the east and the gabbro exposures along the LTV railroad grade to the west. The anomaly was drilled in 1981 by U.S. Steel near Lake County Highway 2 (DDH 27015) and by the Minnesota Department of Natural Resources (DNR) about 7 kilometers to the southwest (DDH S-1). The DNR drill hole encountered 30 feet (9 meters) of medium-grained, olivine-bearing oxide gabbro cumulates that contain about 10 percent oxide, but are locally layered with oxide-rich bands (up to 30 percent) and sulfide (pyrrhotite and chalcopyrite up to 4 percent; Vadis and others, 1981). Drill hole SE-2 was drilled by the DNR in 1986 near the southern terminus of the Snake anomaly. This 554-foot (169-meter) drill core intersected medium- to fine-grained oxide gabbro and oxide troctolite that contains abundant inclusions of anorthositic rocks.

The first attempt to interpret the geology of the Greenwood Lake area from the new aeromagnetic data and the drill holes into the Snake anomaly was by Chandler (1990). He recognized that the east-dipping gabbro exposures were part of a busy aeromagnetic pattern that projected beneath the entire length of the Snake anomaly (Fig. 6.6). Chandler interpreted the ferrogabbros of the Snake anomaly to be extreme differentiates of the underlying gabbro cumulates. He also recognized that this gabbro/ferrogabbro terrane was not part of the Bald Eagle intrusion, but rather was truncated by the subdued anomaly pattern of the troctolitic rocks forming the southern part of the Bald Eagle intrusion (Figs. 6.6 and 6.11). Lacking outcrop or drill core and drawing analogies to subdued anomaly patterns over the large area of anorthositic rocks in the north-central complex, Chandler attributed the similarly subdued aeromagnetic anomaly northwest of (beneath) the gabbro terrane to anorthositic series rocks (Chapter 2, Fig. 2.2).

In 1991, the Minnesota Geological Survey conducted a shallow drilling project that revealed that the subdued northwestern anomaly was actually related to troctolitic cumulates, not anorthositic series rocks. A total of four 10-foot (3-meter) drill cores were acquired west of (down section of) the Snake anomaly in what would come to be regarded as the Greenwood Lake intrusion (Meints and others, 1993). Two holes (CDC-40 and CDC-54) were drilled into oxide olivine gabbro cumulates and confirmed Chandler's (1990) interpretation that the gabbroic cumulates exposed in the railroad cuts to the north extend to the south beneath the Snake anomaly. A drill hole near the inferred contact with the Bald Eagle intrusion (CDC-48) yielded a puzzling rock—varitextured ophitic olivine gabbro with poikilitic olivine. The most informative drill hole, however, was CDC-52, which was drilled into the subdued aeromagnetic anomaly previously interpreted as anorthositic rocks. This hole yielded a medium-grained, moderately foliated ophitic troctolite. With this discovery, a complete differentiation sequence was identified beneath the Snake anomaly and the body was termed the Greenwood Lake intrusion in a subsequent map of the central Duluth Complex (Miller and Chandler, 1999).

Foliation in outcrop and in drill core from the Greenwood Lake intrusion dips from 10° to 30° east–southeast. Estimating an average dip of 15°, the total stratigraphic thickness of the Greenwood Lake intrusion is over 7 kilometers, making it one of the thickest layered series intrusions. Based on the transition from a subdued to busy aeromagnetic pattern, troctolitic and gabbroic cumulates appear to compose subequal thicknesses. Based exclusively on the magnetic data, the southern part of the intrusion appears to narrow down abruptly to a width of 2 kilometers or less. This suggests that the southern limit of the intrusion may be controlled by a syn-magmatic or post-solidification fault. As mentioned above, the Greenwood Lake intrusion is truncated by the Bald Eagle intrusion on the north. However, a similar anomaly pattern to that associated with the main body of the Greenwood Lake intrusion can be traced east of the Bald Eagle intrusion. The anomaly arcs to the southeast, narrows in width, and appears to merge with the Wilson Lake ferrogabbro of the northern Beaver Bay Complex (Figs. 6.6 and 6.11). A genetic link is possible given that the Greenwood Lake intrusion appears to be one of the youngest in the Duluth Complex and the Wilson Lake ferrogabbro is one of the earliest intrusions in the Beaver Bay Complex.

Osier Lake intrusion

Just west of Osier Lake and near the inferred upper contact of the central Duluth Complex is a subcircular aeromagnetic anomaly that is about 5 kilometers across and is composed of an outer magnetic low and a central magnetic high (Figs. 6.6 and 6.11). Two drill holes into the anomaly indicate the presence of a concentrically zoned, well-differentiated mafic stock termed the Osier Lake intrusion (Miller and Chandler, 1999).

In 1985, the Minnesota Department of Natural Resources drilled a 954-foot (291-meter) drill hole (NR-1) into the central magnetic high (Sellner and others, 1985). Beyond a 224-foot-thick (68-meter) cover of glacial overburden, the entire drill core consists of well-foliated, commonly layered, medium-grained oxide gabbro to olivine oxide gabbro (PCF ± O cumulate). The average rock contains 50 to 60 percent foliated plagioclase, 30 percent granular augite, 7 to 15 percent Fe-Ti oxide, 0 to 3 percent olivine, and traces of chalcopyrite. The Minnesota Geological Survey drilled a 303-foot (92-meter) drill hole (CDC-14b) in 1991 into the outer magnetic low (Meints and others, 1993). Beneath a thick glacial overburden of 275 feet (84 meters) and 20 feet (6 meters) of regolith, a 5-foot (1.5-meter) core of bedrock was recovered. The rock is a deeply weathered, coarse-grained, moderately foliated, ophitic oxide-rich augite melatroctolite.

An outer ring of troctolitic cumulates and an inner core of olivine oxide gabbro cumulates is consistent with the Osier Lake intrusion being a well differentiated stock. The internal structure of the intrusion is difficult to determine because NR-1 was drilled at an angle of 52° to the northeast (roughly at a right angle to the outer contact of the intrusion). Layering and foliation are at a 70° to 80° angle to the core axis. Foliation is poorly developed and difficult to see in the weathered melatroctolite (CDC-14b).

Because it is isolated within anorthositic series rocks, the age of the Osier Lake intrusion relative to other layered series intrusions is unknown. Its high structural position suggests that it may be one of the youngest intrusions. Also, its circular form may indicate that it is a deeply eroded feeder to a larger sheetlike intrusion.

REFERENCES

Allen, D.J., Hinze, W.J., Dickas, A.B., and Mudrey, M.G., Jr., 1997, Integrated geophysical modeling of the North American Midcontinent rift system: New interpretations for western Lake Superior, northwestern Wisconsin, and eastern Minnesota, *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. 47-72.

Babcock, R.C., Jr., 1959, Petrogeny of the granophyre and intermediate rock in the Duluth Gabbro of northern Cook County, Minnesota: Madison, Wis., University of Wisconsin, M.S. thesis, 47 p.

Beck, M.E., 1970, Paleomagnetism of Keweenawan intrusive rocks, Minnesota: Journal of Geophysical Research, v. 75, no. 26, p. 4985-4996.

Boerboom, T.J., and Miller, J.D., Jr., 1994, Bedrock geologic map of the Silver Island Lake, Wilson Lake, and western Toohey Lake quadrangles, Cook and Lake Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-81, scale 1:24,000.

Bonnichsen, B., 1971, Outcrop map of southern part of Duluth Complex and associated Keweenawan rocks, St. Louis and Lake Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-11, scale 1:125,000.

———1972, Southern part of the Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 361-387.

———1974, Geology of the Ely–Hoyt Lakes district, northeastern Minnesota: Minnesota Geological Survey Open-File Report, 29 p.

Cannon, W.F., Green, A.G., Hutchinson, D.R., Lee, M.W., Milkereit, B., Behrendt, J.C., Halls, H.C., Green, J.C., Dickas, A.B., Morey, G.B., Sutcliffe, R.H., and Spencer, C., 1989, The North American Midcontinent rift beneath Lake Superior from GLIMPCE seismic reflection profiling: Tectonics, v. 8, no. 2, p. 305-332.

Chalokwu, C.I., and Grant, N.K., 1987, Reequilibration of olivine with trapped liquid in the Duluth Complex, Minnesota: Geology, v. 15, no. 1, p. 71-74.

———1990, Petrology of the Partridge River intrusion, Duluth Complex, Minnesota: 1. Relationships between mineral compositions, density and trapped liquid abundance: Journal of Petrology, v. 31, no. 2, p. 265-293.

Chalokwu, C.I., Grant, N.K., Ariskin, A.A., and Barmina, G.S., 1993, Simulation of primary phase relations and mineral compositions in the Partridge River intrusion, Duluth Complex, Minnesota: Implications for the parent magma composition: Contributions to Mineralogy and Petrology, v. 114, no. 4, p. 539-549.

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.

———2001, Superimposed magnetic on gravity anomaly map of the central Duluth Complex and western part of the Beaver Bay Complex, Lake and St. Louis Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-117, scale 1:100,000.

Davidson, D.M., Jr., 1969a, Geologic map of the Kawishiwi Lake quadrangle, Lake and Cook Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-7, scale 1:24,000.

———1969b, Geologic map of the Perent Lake quadrangle, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-8, scale 1:24,000.

———1972, Eastern part of Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 354-360.

———1977a, Reconnaissance geologic map of the Beth Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-26, scale 1:24,000.

———1977b, Reconnaissance geologic map of the Cherokee Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-30, scale 1:24,000.

———1977c, Reconnaissance geologic map of the Eagle Mountain quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-28, scale 1:24,000.

———1977d, Reconnaissance geologic map of the Kelso Mountain quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-27, scale 1:24,000.

———1977e, Reconnaissance geologic map of the Lima Mountain quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-32, scale 1:24,000.

Davidson, D.M., Jr., and Burnell, J.R., Jr., 1977, Reconnaissance geologic map of the Brule Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-29, scale 1:24,000.

Davis, D.W., and Green, J.C., 1997, Geochronology of the North American Midcontinent rift in western Lake Superior and implications for its geodynamic evolution: Canadian Journal of Earth Sciences, v. 34, no. 4, p. 476-488.

Davis, D.W., and Paces, J.B., 1990, Time resolution of geologic events on the Keweenaw Peninsula and implications for development of the Midcontinent rift system: Earth and Planetary Science Letters, v. 97, p. 54-64.

Foose, M.P., 1984, Logs and correlation of drill holes within the South Kawishiwi intrusion, Duluth Complex, northeastern Minnesota: U.S. Geological Survey Open-File Report 84-14, variously paged, 1 pl.

Foose, M.P., and Cooper, R.W., 1978, Preliminary geologic report on the Harris Lake area, northeastern Minnesota: U.S. Geological Survey Open-File Report 78-385, 24 p., 1 pl., scale 1:12,000.

Geerts, S.D., 1991, Geology, stratigraphy, and mineralization of the Dunka Road Cu-Ni prospect, northeastern Minnesota: Natural Resources Research Institute, Technical Report NRRI/TR-91/14, 61 p.

Grant, N.K., and Chalokwu, C.I., 1992, Petrology of the Partridge River intrusion, Duluth Complex, Minnesota: II. Geochemistry and strontium isotope systematics in drill core DDH-221: Journal of Petrology, v. 33, no. 5, p. 1007-1038.

Grant, N.K., and Molling, P.A., 1981, A strontium isotope and trace element profile through the

Partridge River troctolite, Duluth Complex, Minnesota: Contributions to Mineralogy and Petrology, v. 77, no. 3, p. 296-305.

Green, J.C., comp., 1982, Geologic map of Minnesota, Two Harbors sheet: Minnesota Geological Survey, scale 1:250,000.

Green, J.C., Davis, D.W., and Schmitz, M.D., 2001, Three new zircon dates for the Midcontinent rift, North Shore, Minnesota: More data, more questions [abs.]: Institute on Lake Superior Geology, 47th Annual Meeting, Madison, Wis., Proceedings, v. 47, Program and Abstracts, pt. 1, p. 29.

Green, J.C., Phinney, W.C., and Weiblen, P.W., 1966, Gabbro Lake quadrangle, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-2, scale 1:31,680.

Grout, F.F., 1918a, Internal structures of igneous rocks; their significance and origin; with special reference to the Duluth Gabbro: Journal of Geology, v. 26, p. 439-458.

———1918b, Two-phase convection in igneous magmas: Journal of Geology, v. 26, p. 481-499.

———1918c, A type of igneous differentiation: Journal of Geology, v. 26, p. 626-658.

———1930, Probable extent of abyssal assimilation: Geological Society of America Bulletin, v. 41, no. 4, p. 675-694.

Grout, F.F., Sharp, R.P., and Schwartz, G.M., 1959, The geology of Cook County Minnesota: Minnesota Geological Survey Bulletin 39, 163 p., 16 pls.

Jerde, E.A., Salvato, D.J., Thole, J., and Wirth, K.R., 2001, The early gabbroic series of the Midcontinent rift system: Continued assessment of magmatic origins: Institute on Lake Superior Geology, 47th Annual Meeting, Madison, Wis., Proceedings, v. 47, Program and Abstracts, pt. 1, p. 36-37.

Kushiro, I., 1980, Viscosity, density, and structure of silicate melts at high pressures, and their petrological applications, *in* Hargraves, R.B., ed., Physics of magmatic processes: Princeton University Press, p. 93-120.

Lee, I., and Ripley, E.M., 1996, Mineralogic and oxygen isotopic studies of open system magmatic processes in the South Kawishiwi intrusion, Spruce Road area, Duluth Complex, Minnesota: Journal of Petrology, v. 37, no. 6, p. 1437-1461.

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: London, Institute of Mining and Metallurgy, p. 117-137.

McBirney, A.E., 1989, The Skaergaard layered series: I. Structure and average compositions: Journal of Petrology, v. 30, no. 2, p. 363-397.

Meints, J.P., Jirsa, M.A., Chandler, V.W., and Miller, J.D., Jr., 1993, Scientific core drilling in parts of Itasca, St. Louis, and Lake Counties, northeastern Minnesota—1989-1991: Summary of lithologic, geochemical, and geophysical results: Minnesota Geological Survey Information Circular 37, 159 p.

Miller, J.D., Jr., 1986, The geology and petrology of anorthositic rocks in the Duluth Complex, Snowbank Lake quadrangle, northeastern Minnesota: Minneapolis, University of Minnesota, Ph.D. dissertation, 585 p.

Miller, J.D., Jr., Boerboom, T.J., and Jerde, E.A., 1994, Bedrock geologic map of the Cabin Lake and Cramer 7.5-minute quadrangles, Lake and Cook Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-82, scale 1:24,000.

Miller, J.D., Jr., and Chandler, V.W., 1997, Geology, petrology, and tectonic significance of the Beaver Bay Complex, northeastern Minnesota, *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. 73-96.

———1999, Bedrock geologic map of the central Duluth Complex and western part of the Beaver Bay Complex, Lake and St. Louis Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-101, scale 1:100,000.

Miller, J.D., Jr., Green, J.C., and Chandler, V.W., 1993b, Preliminary geologic map of the Duluth area, St. Louis County, Minnesota: Minnesota Geological Survey Open-File Report 93-2, 1 pl., scale 1:48,000.

Miller, J.D., Jr., Green, J.C., Severson, M.J., Chandler, V.W., and Peterson, D.M., 2001, Geologic map of the Duluth Complex and related rocks, northeastern Minnesota: Minnesota Geological Survey Miscellaneous Map M-119, scale 1:200,000.

Miller, J.D., Jr., and Ripley, E.M., 1996, Layered intrusions of the Duluth Complex, Minnesota, USA, *in* Cawthorn, R.G., ed., Layered intrusions: Amsterdam, Elsevier Science, p. 257-301.

Miller, J.D., Jr., and Vervoort, J.D., 1996, The latent magmatic stage of the Midcontinent rift: a period of magmatic underplating and melting of the lower crust: Institute on Lake Superior Geology, 42nd Annual Meeting, Cable, Wis., Proceedings, v. 42, Program and Abstracts, pt. 1, p. 33-35.

Miller, J.D., Jr., and Weiblen, P.W., 1990, Anorthositic rocks of the Duluth Complex: Examples of rocks formed from plagioclase crystal mush: Journal of Petrology, v. 31, no. 2, p. 295-339.

Morey, G.B., 1996, Continental margin assemblage, *in* Sims, P.K., and Carter, L.M.H., eds., Archean and Proterozoic geology of the Lake Superior region, U.S.A., 1993: U.S. Geological Survey Professional Paper 1556, p. 30-43.

Morey, G.B., and Cooper, R.W., 1977, Bedrock geology of the Hoyt Lakes–Kawishiwi area, St. Louis and Lake Counties, northeastern Minnesota: Minnesota Geological Survey Open-File Report, scale 1:48,000.

Morey, G.B., and Nathan, H.D., 1978, Geologic map of the Gunflint Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-42, scale 1:24,000.

Morey, G.B., Weiblen, P.W., Papike, J.J., and Anderson, D.H., 1981, Geologic map of the Long Island Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-46, scale 1:24,000.

Nathan, H.D., 1969, The geology of a part of the northeast segment of the Duluth Complex: Minneapolis, University of Minnesota, Ph.D. dissertation, 198 p.

Nicholson, S.W., and Shirey, S.B., 1990, Midcontinent rift volcanism in the Lake Superior region: Sr, Nd, and Pb isotopic evidence for a mantle plume origin: Journal of Geophysical Research, v. 95, no. 7, p. 10851-10868.

Paces, J.B., and Miller, J.D., Jr., 1993, Precise U-Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: Geochronological insights to physical, petrogenetic, paleomagnetic and tectonomagmatic processes associated with the 1.1 Ga Midcontinent rift system: Journal of Geophysical Research, v. 98, no. B8, p. 13997-14013.

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

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: Society of Economic Geologists, Second Annual PGE Workshop, Sudbury, Ontario.

Phinney, W.C., 1967, Reconnaissance geologic map of part of the Kangas Bay quadrangle: Minnesota Geological Survey Open-File Map, scale 1:24,000.

———1969, The Duluth Complex in the Gabbro Lake quadrangle, Minnesota: Minnesota Geological Survey Report of Investigations 9, 20 p.

———1972, Northwestern part of Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 335-345.

Rao, B.V., and Ripley, E.M., 1983, Petrochemical studies of the Dunka Road Cu-Ni deposit, Duluth Complex, Minnesota: Economic Geology, v. 78, no. 6, p. 1222-1238.

Ripley, E.M., and Alawi, J.A., 1986, Sulfide mineralogy and chemical evolution of the Babbitt Cu-Ni deposit, Duluth Complex, Minnesota: Canadian Mineralogist, v. 24, pt. 2, p. 347-368.

Saini-Eidukat, B., 1991, Platinum group elements in anorthositic rocks of the Duluth Complex, Minnesota: Petrogenetic and economic implications: Minneapolis, University of Minnesota, Ph.D. dissertation, 146 p.

Sandland, T.O., Wirth, K.R., Vervoort, J.D., Gehrels, G.E., Kennedy, B.C., and Harpp, K.S., 2001, Roles of fractional crystallization and assimilation in the production of Midcontinent rift granophyres: Institute on Lake Superior Geology, 47th Annual Meeting, Madison, Wis., Proceedings, v. 47, Program and Abstracts, pt. 1, p. 85-86.

Sellner, J.M., Lawler, T.L., Dahlberg, E.H., Frey, B.A., and McKenna, M.P., 1985, 1984-1985 geodrilling report: Minnesota Department of

Natural Resources, Division of Minerals Report 242, 75 p.

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

———1994, Igneous stratigraphy of the South Kawishiwi intrusion, Duluth Complex, northeastern Minnesota: Natural Resources Research Institute, Technical Report NRRI/TR-93/34, 210 p., 15 pls.

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

Severson, M.J., and Hauck, S.A., 1990, Geology, geochemistry, and stratigraphy of a portion of the Partridge River intrusion: Natural Resources Research Institute, Technical Report NRRI/GMIN-TR-89-11, 236 p., 4 pls.

———1997, Igneous stratigraphy and mineralization in the basal portion of the Partridge River intrusion, Duluth Complex, Allen quadrangle, Minnesota: Natural Resources Research Institute, Technical Report NRRI/TR-97/19, 102 p., 4 pls.

Severson, M.J., and Miller, J.D., Jr., 1999, Bedrock geologic map of Allen quadrangle, Minnesota: Minnesota Geological Survey Miscellaneous Map M-91, scale 1:24,000.

Shirey, S.B., Klewin, K.W., Berg, J.H., and Carlson, R.W., 1994, Temporal changes in the sources of flood basalts: Isotopic and trace element evidence from the 1100 Ma old Keweenawan Mamainse Point Formation, Ontario, Canada: Geochimica et Cosmochimica Acta, v. 58, no. 20, p. 4475-4490.

Taylor, R.B., 1964, Geology of the Duluth Gabbro Complex near Duluth, Minnesota: Minnesota Geological Survey Bulletin 44, 63 p., 1 pl.

Tyson, R.M., and Chang, L.L.Y., 1984, The petrology and sulfide mineralization of the Partridge River troctolite, Duluth Complex, Minnesota: Canadian Mineralogist, v. 22, pt. 1, p. 23-38.

Vadis, M.K., Gladen, L.W., and Meineke, D.G., 1981, Geological, geophysical, and geochemical surveys of Lake, St. Louis and Cook Counties, Minnesota, for the 1980 Drilling Project: Minnesota Department of Natural Resources, Division of Minerals Report 201, 13 p.

Vervoort, J.D., and Green, J.C., 1997, Origin of evolved magmas in the Midcontinent rift system, northeast Minnesota: Nd-isotope evidence for melting of Archean crust: Canadian Journal of Earth Sciences, v. 34, no. 4, p. 521-535.

Wager, L.R., and Deer, W.A., 1939, Geological investigations in East Greenland: Meddelelser om Groenland, v. 105, 335 p.

Wager, L.R., and Brown, G.M., 1968, Layered igneous rocks: San Francisco, W.H. Freeman, 588 p.

Weiblen, P.W., 1965, A funnel-shaped, gabbro-troctolite intrusion in the Duluth Complex, Lake County, Minnesota: Minneapolis, University of Minnesota, Ph.D. dissertation, 161 p.

———1982, Keweenawan intrusive igneous rocks, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 57-82.

Weiblen, P.W., Davidson, D.M., Jr., Morey, G.B., and Mudrey, M.G., Jr., 1972, Geology of Cook County, *in* Field trip guidebook for Precambrian geology of northeastern Cook County, Minnesota: Minnesota Geological Survey Guidebook Series, no. 6, p. 1-61.

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

Winchell, N.H., 1899, The geology of Minnesota: Geological and Natural History Survey of Minnesota, Final Report, v. 4, 629 p., 100 pls.

Zanko, L.M., Severson, M.J., and Ripley, E.M., 1994, Geology and mineralization of the Serpentine copper-nickel deposit: Natural Resources Research Institute, Technical Report NRRI/TR-93/52, 90 p., 3 pls.

Zartman, R.E., Nicholson, S.W., Cannon, W.F., and Morey, G.B., 1997, U-Th-Pb zircon ages of some Keweenawan Supergroup rocks from the south shore of Lake Superior, *in* Bornhorst, T.J., ed., Petrology and metallogeny of intraplate mafic and ultramafic magmatism: Canadian Journal of Earth Sciences, v. 34, no. 4, p. 549-561.

Chapter 7

GEOLOGY OF THE BEAVER BAY COMPLEX AND RELATED HYPABYSSAL INTRUSIONS

James D. Miller, Jr. and John C. Green

Hypabyssal mafic, intermediate, and felsic intrusions that occur within the medial and upper parts of the volcanic edifice of the North Shore Volcanic Group are grouped separately from the deeper-seated intrusions of the Duluth Complex. The largest concentration of these subvolcanic intrusions occurs in the central part of the North Shore Volcanic Group and comprises the Beaver Bay Complex (Fig. 7.1). Isolated intrusions outside the Beaver Bay Complex are designated as miscellaneous intrusions on map M-119. In this chapter, these miscellaneous intrusions are grouped as those that intrude the northeast volcanic sequence and those that intrude the southwest sequence. Reconnaissance mapping (Grout and others, 1959; Jones, 1963; Davidson, 1972, 1977a-h; Davidson and Burnell, 1977) shows that the extensive area of gabbroic rocks mapped as the Brule Lake–Hovland gabbro (M-119) is composed of many individual intrusions. Detailed mapping may show that this group of mafic intrusions and the felsic bodies overlying them (the Eagle Mountain and Pine Mountain granophyres) form a coherent intrusive complex comparable to the Beaver Bay Complex.

In addition to their higher level of emplacement in the volcanic pile, the hypabyssal intrusions are distinct from Duluth Complex intrusions in several other ways. Most occur as thin (less than 2-kilometers-thick) sheets and dikes that are more commonly enclosed by volcanic rocks than by other intrusions. Although locally layered, most hypabyssal intrusions do not display igneous foliation or other cumulate textures and lack obvious signs of in situ differentiation. Those hypabyssal intrusions that do display cumulate textures and cryptic layering indicative of magma differentiation are: 1. Especially thick (greater than 2 kilometers; such as the Cloquet Lake layered series, Brule Lake–Hovland gabbro, and Houghtaling Creek troctolite); 2. Situated beneath an insulating cap of granophyre (such as the Sonju Lake intrusion, Brule Lake–Hovland gabbro, and Cloquet Lake layered series); and/or 3. Late composite intrusions (such as the Silver Bay intrusions, Brule Lake–Hovland ferrogabbro, and late phases of the Beaver River diabase).

Limited radiometric dating suggests that most hypabyssal intrusions are generally younger than the Duluth Complex. U-Pb ages of Duluth Complex intrusions range from 1109 to 1099 Ma (Paces and Miller, 1993; Davis and Green, 1997; Vervoort, unpub. data, 2001). With the exception of the Logan intrusions, dated hypabyssal intrusions are generally younger than 1099 Ma (Table 7.1). However, field relationships imply that the youngest Duluth Complex and the oldest Beaver Bay Complex intrusions have not been dated. Moreover, some units within the Beaver Bay Complex appear to be crosscut by Duluth Complex intrusions (the Shoepack Lake diorite is cut by Whitefish Lake granophyre) and others appear to be comagmatic with Duluth Complex intrusions (the Cabin Creek porphyritic diorite = the anorthositic series; the Wilson Lake ferrogabbro = the Greenwood Lake intrusion). More geochronologic studies are necessary to determine the amount of overlap in emplacement ages between the Duluth Complex and hypabyssal intrusions.

BEAVER BAY COMPLEX

The intrusive igneous rocks that form pronounced highlands in the area around the town of Beaver Bay were named the Beaver Bay Group by Irving (1883) and the Beaver Bay Diabase by Winchell (1899). The large blocks of nearly pure anorthosite that occur as xenoliths in some of the diabase intrusions have been the subject of numerous studies (Lawson, 1893; Elftman, 1898; Grout and Schwartz, 1939; Morrison and others, 1983). Grout and Schwartz (1939) applied the term "Beaver Bay Complex" to intrusive rocks that extend some 20 kilometers inland from exposures on Lake Superior's shoreline between Split Rock Point and Little Marais (Fig. 7.1). Although various "facies" of intermediate to mafic intrusive rock were recognized by Grout and Schwartz, all were classified as diabase. Only anorthosite inclusions and granophyre bodies (red rock) were distinguished from diabase as mapped units of the Beaver Bay Complex. Although obscured by thick glacial overburden, the boundary between the Beaver Bay Complex “diabase” and deeper-seated Duluth Complex “gabbros” was believed to be transitional. The multiple-intrusive nature of the Beaver Bay Complex was first documented by Gehman (1957) with his detailed mapping and petrologic study of the area between Split Rock Point and Beaver Bay, but more recent studies (Miller, 1988; Shank, 1989) have revised his

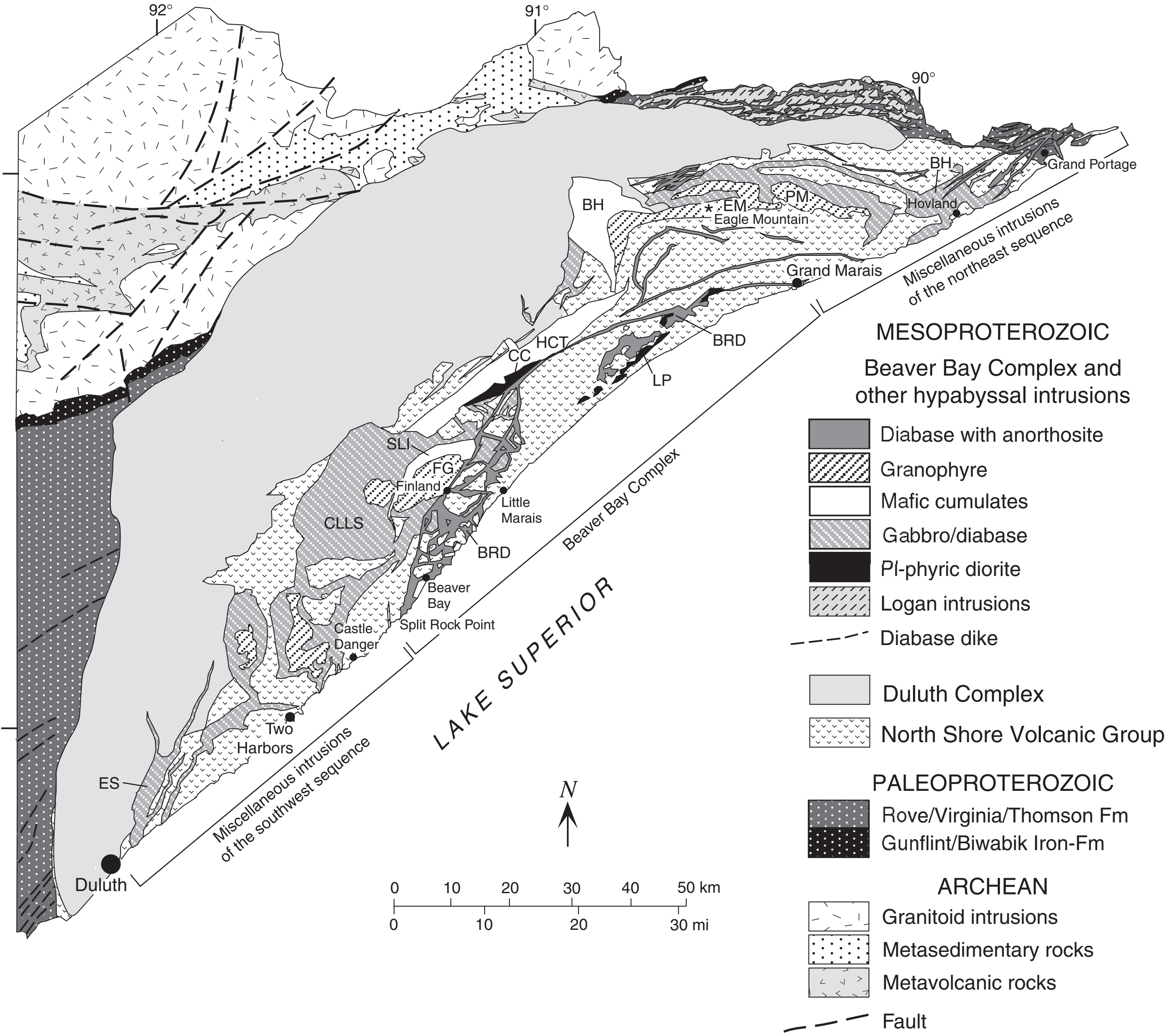


Figure 7.1. Geology of northeastern Minnesota showing the location and general lithologies of the Beaver Bay Complex and other hypabyssal intrusions. Major labeled intrusions are:

BH—Brule Lake–Hovland gabbro
BRD—Beaver River diabase
CLLS—Cloquet Lake layered series
CC—Cabin Creek porphyritic diorite
EM—Eagle Mountain granophyre
ES—Endion sill
FG—Finland granophyre
HCT—Houghtaling Creek troctolite
LP—Leveaux porphyritic diorite
PM—Pine Mountain granophyre
SLI—Sonju Lake intrusion

Table 7.1. U-Pb ages of hypabyssal intrusions.

Intrusion	U-Pb age	±Error	Reference
Logan intrusions	1108.8	+4/-2	Davis and Sutcliffe, 1985
Eagle Mountain granophyre	1098.5	3.6	J. Vervoort, unpub. data, 2001
Pine Mountain granophyre	1095.3	3.7	J. Vervoort, unpub. data, 2001
Finland granophyre	1097.8	4.4	J. Vervoort, unpub. data, 2001
Sonju Lake intrusion	1096.1	0.8	Paces and Miller, 1993
Silver Bay intrusions	1095.8	1.2	Paces and Miller, 1993

interpretations. Stevenson (1974) delineated several more intrusive units of the Beaver Bay Complex, including the well-differentiated Sonju Lake intrusion in the area north of Finland. Another detailed mapping study of a small part of the Beaver Bay Complex came out of site preparation for the Milepost 7 tailings basin, which was constructed for the taconite milling operation near Silver Bay (Green, 1982). With the exception of these few areas, however, the detailed geology and petrology of the Beaver Bay Complex was poorly understood until recently.

In 1993, the Minnesota Geological Survey completed an eight-year program to map the bedrock geology of the Beaver Bay Complex at 1:24,000-scale and to characterize its transition into the Duluth Complex. The project was funded in part through the U.S. Geological Survey's COGEOMAP program. All or parts of eleven 7.5-minute quadrangles covering over 900 square kilometers were mapped. Five geologic maps were produced from the project (Miller, 1988; Miller and others, 1989, 1993, 1994; Boerboom and Miller, 1994). This mapping showed the Beaver Bay Complex to be composed of at least thirteen major intrusive units. A summary of the fundamental geologic, petrologic, and structural characteristics of these intrusions was given by Miller and Chandler (1997). They also discussed the role of the Beaver Bay Complex in the tectono-magmatic evolution of the Midcontinent rift. In this section, we summarize the basic attributes of the Beaver Bay Complex intrusions that demonstrate various styles of emplacement, a broad range of parental magma compositions, and distinct crystallization histories.

Geologic definition of the Beaver Bay Complex

The Beaver Bay Complex covers an area of more than 600 square kilometers and straddles the general boundary between the southwest and northeast limbs of the North Shore Volcanic Group (see Chapter 5). As defined by Miller and Chandler (1997), the Beaver Bay Complex includes all intrusions along the Lake Superior shoreline from Split Rock Point north to Grand Marais, and inland as far as 20 kilometers (Fig. 7.1). The exposed northwestern boundary of the Beaver Bay Complex is the northeast-trending macrodike of the Houghtaling Creek troctolite and its associated flanking intrusions (the Wilson Lake ferrogabbro and Dam Five gabbronorite; M-119). The predominant rock types to the northwest of the Houghtaling Creek troctolite are a mix of gabbroic anorthosite, granophyre, and volcanic hornfels typical of the roof zone of the Duluth Complex (Chapter 6). The distinctive aeromagnetic signature of the Houghtaling Creek troctolite can be traced to the southwest where it merges with the concentric anomaly patterns of the poorly exposed Cloquet Lake layered series (Fig. 7.2), which defines the western extent of the Beaver Bay Complex. To the northeast, the Houghtaling Creek macrodike is interpreted to pinch out and intersect miscellaneous intrusions that trend in a more northerly direction (the Sawbill Lake gabbro, Brule Lake–Hovland olivine gabbro, and Lichen Lake and Lake Clara diabases; Fig. 7.3). South of the Houghtaling Creek troctolite and subparallel to it is the main Beaver River diabase dike, which can be traced east past Lutsen. Miller and Chandler (1997) described the geology of the Beaver Bay Complex in terms of its three main areas of exposure (southern, northern, and eastern). Here the individual intrusions of the Beaver Bay Complex are described in their relative order of emplacement.

Description of intrusions

The earliest intrusive phase of the Beaver Bay Complex is a strongly contaminated, inclusion-laden mafic rock that occurs in the northern Beaver

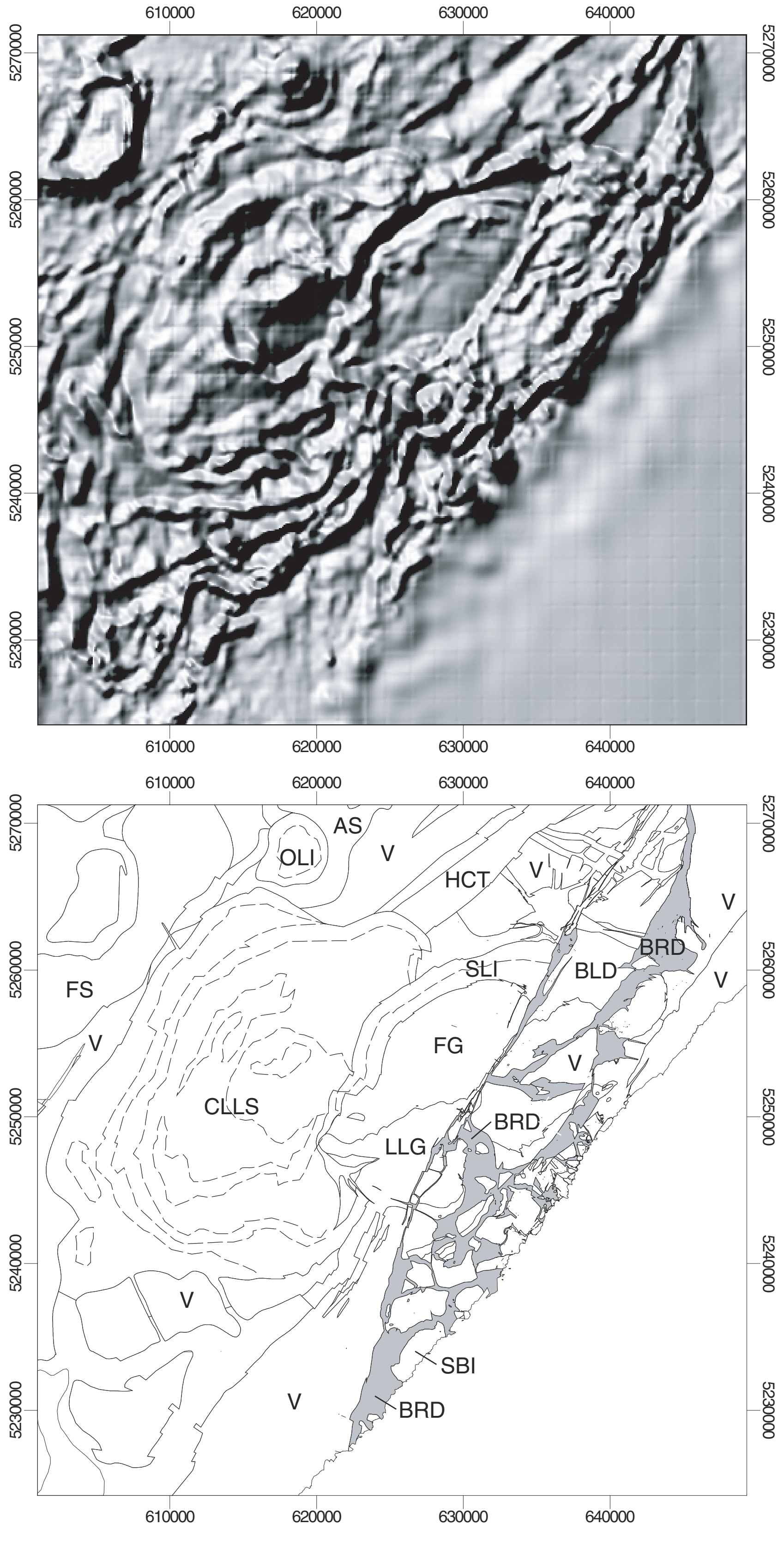
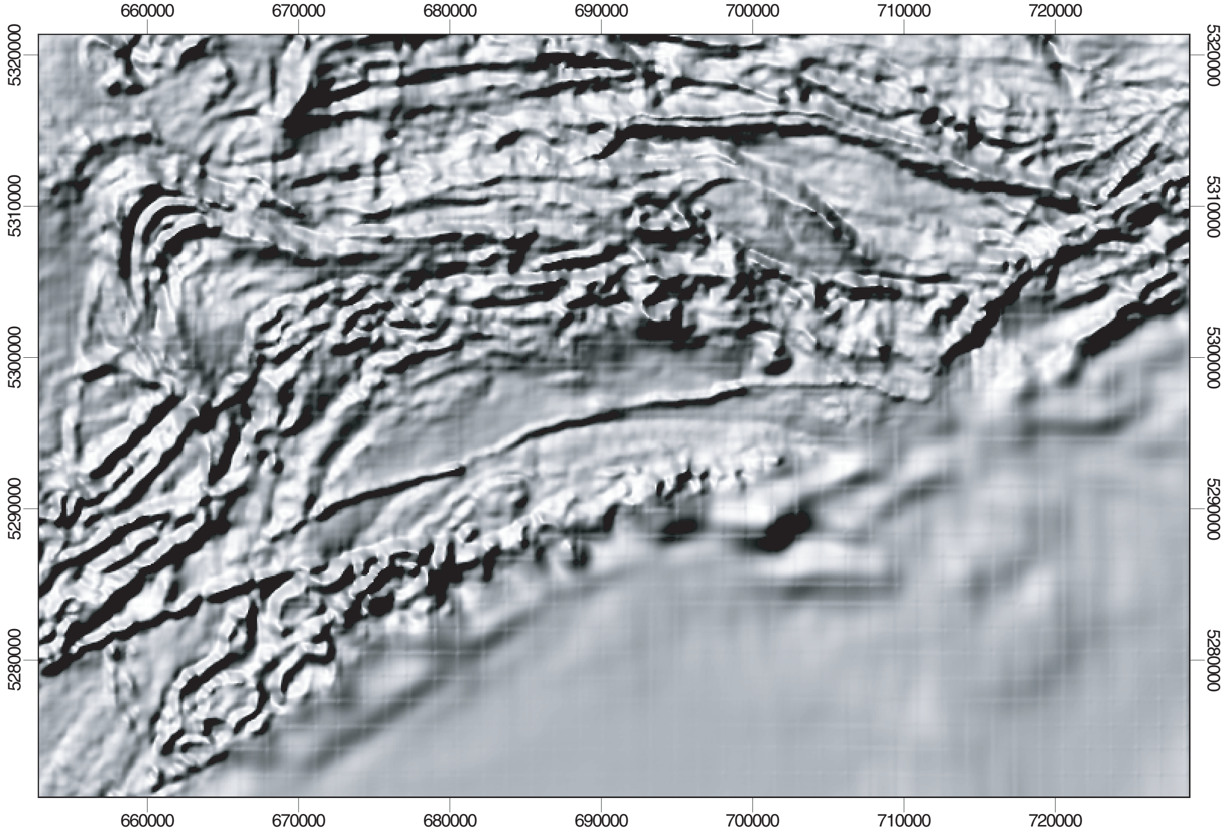


Figure 7.2. Shaded-relief image of total magnetic field data over the southern Beaver Bay Complex and generalized geologic map (from M-119) at the same scale. Solid lines denote inter-intrusion contacts; dashed lines denote intra-intrusion contacts. See M-119 for subunits of intrusions. Number labels are NAD 83-based UTM grid coordinates. North Shore Volcanic Group is denoted V. Labeled intrusions of the Beaver Bay Complex are:

BLD—Blesner Lake diorite
BRD—Beaver River diabase (shaded)
CLLS—Cloquet Lake layered series
FG—Finland granophyre
HCT—Houghtaling Creek troctolite
LLG—Lax Lake gabbro
SBI—Silver Bay intrusions
SLI—Sonju Lake intrusion

Duluth Complex units:

AS—Anorthositic series
FS—Felsic series
OLI—Osier Lake intrusion



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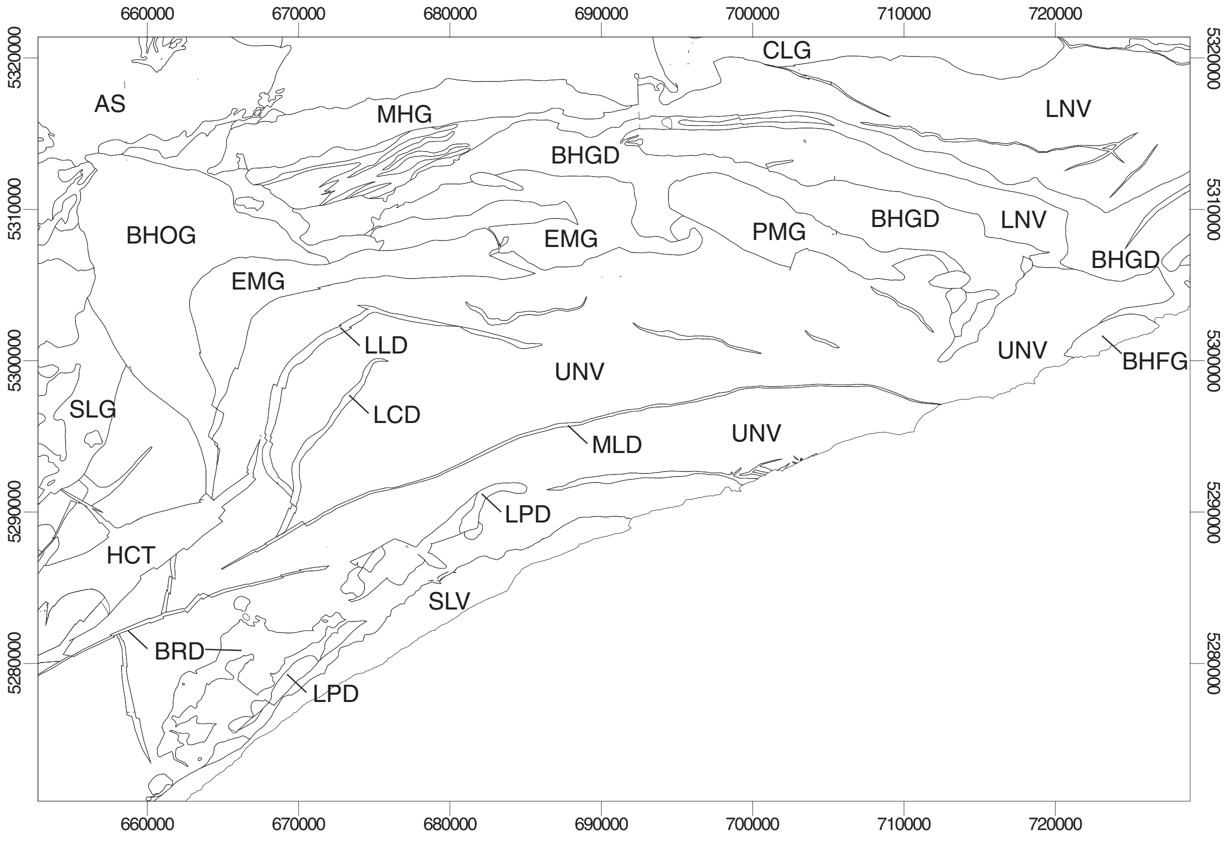

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Bay Complex and is termed the *Shoepack Lake diorite* (unit slid, M-119; Boerboom and Miller, 1994; Miller and others, 1994). Although contact relationships with other Beaver Bay Complex rocks are obscure, this rock type is clearly intruded by both granophyre (the Whitefish Lake granophyre, U-Pb age 1109.6 ± 4.0 Ma, Vervoort, unpub. data, 2001) and gabbroic anorthosite rocks of the Duluth Complex. This implies that the Shoepack Lake diorite may be one of the earliest Keweenawan intrusions in northeastern Minnesota. The rock is characterized by angular inclusions of varied type, shape, and size in a black, dense aphanitic matrix. Felsic volcanic rocks are the most common inclusion type, although mafic volcanic and gabbroic rocks are locally present. The occurrence of granitic gneiss, biotite schist, and amphibolite inclusions, presumably of Archean age (Boerboom, 1994), corresponds with a northwest-trending saddle in the Bouguer gravity (Chapter 3, Fig. 3.3) that is thought to represent a crustal ridge of basement rocks (Miller and Chandler, 1997).

The next youngest intrusive phase is represented by sheetlike intrusions of plagioclase-phyric ferrodiorite that occur in two areas of the Beaver Bay Complex. In the northern Beaver Bay Complex, this rock type is mapped as the *Cabin Creek porphyritic diorite* (unit ccpd, M-119; Boerboom and Miller, 1994; Miller and others, 1994), and in the eastern Beaver Bay Complex, as the *Leveaux porphyritic diorite* (unit lvpd, M-119; Green, 1992). The rock contains subequant to tabular phenocrysts of labradoritic plagioclase as large as 4 centimeters (typically 1 to 2 centimeters) and rare cognate inclusions of anorthosite in a fine-grained, ferrodiorite to quartz ferromonzonite matrix. Plagioclase phenocrysts typically compose 30 to 40 percent of the rock, although some phases are aphyric and others contain as much as 50 percent phenocrysts. In the Leveaux porphyry, the lower part of the approximately 100-meter-thick sheeted body is aphyric and the upper part contains 40 percent phenocrysts on average. The composition and texture of plagioclase phenocrysts (An_{60} average) and the ferrodioritic composition of the matrix are consistent with these intrusions representing hypabyssal equivalents of anorthositic series rock of the Duluth Complex. Miller and Weiblen (1990) suggested that the parental magmas to the anorthositic series were plagioclase crystal mushes—basaltic to dioritic magmas charged with variable concentrations of intratelluric plagioclase.

The next youngest phase of intrusion in the Beaver Bay Complex is somewhat uncertain, but appears to be a suite of foliated rocks in the northern Beaver Bay Complex that includes the Houghtaling Creek troctolite, the Dam Five gabbronorite, the Wilson Lake ferrogabbro, and the Fourmile Lake ferrogabbro. Some of these units clearly cut the Cabin Creek porphyritic diorite and Shoepack Lake diorite, but their relationship to other Beaver Bay Complex intrusions can only be inferred from ambiguous and somewhat contradictory aeromagnetic data (Miller and Chandler, 1997). The earliest intrusion of the foliated suite is the *Wilson Lake ferrogabbro* (units wlod and wlfg, M-119). It is a 1.5 x 3 kilometer stock that is composed of well-foliated olivine oxide gabbro to ferromonzodiorite and intrudes the Whitefish Lake granophyre and the Shoepack Lake diorite (Boerboom and Miller, 1994). Several northeast-trending dikes of ophitic olivine gabbro

Figure 7.3. Shaded-relief image of total magnetic field data over the Brule Lake–Hovland gabbro and generalized geologic map (from M-119) at the same scale. Solid lines denote inter-intrusion contacts; dashed lines denote intra-intrusion contacts. See M-119 for subunits of intrusions. Number labels are NAD 83-based UTM grid coordinates. Labeled intrusions:

BHOG—Brule Lake–Hovland olivine gabbro
BHGD—Brule Lake–Hovland gabbro diabase
BHFG—Brule Lake–Hovland ferrogabbro
HCT—Houghtaling Creek troctolite
LPD—Leveaux porphyritic diorite
SLG—Sawbill Lake gabbro
BRD—Beaver River diabase
LLD—Lichen Lake diabase
MLD—Monker Lake diabase
EMG—Eagle Mountain granophyre
LCD—Lake Clara diabase
PMG—Pine Mountain granophyre

Duluth Complex units:

AS—Anorthositic series
CLG—Cucumber Lake granophyre
MHG—Misquah Hills granophyre

North Shore Volcanic Group units:

LNV—Lower northeast sequence
SLV—Schroeder–Lutsen sequence
UNV—Upper northeast sequence

radiate from the stock. A northwest-trending dike is inferred from aeromagnetic data to project from the northwest margin of the stock to the easternmost extension of the Greenwood Lake intrusion of the Duluth Complex and thus may indicate a possible comagmatic relationship (M-119).

The southeastern margin of the Wilson Lake ferrogabbro is cut by the *Dam Five gabbronorite*—a well-layered and well-foliated sequence of gabbronoritic to olivine gabbroic cumulates that monoclinally dip at 35° to 45° to the southeast (unit dfgn, M-119; Boerboom and Miller, 1994; Miller and others, 1994). These rocks occur in a northeast-trending, one-kilometer-wide band that can be traced in outcrop for 10 kilometers and can be inferred from aeromagnetic data and one drill core to extend a total of 30 kilometers along strike. The gabbronorite is in intrusive contact with the Shoepack Lake diorite and felsic volcanic rocks on its northwestern margin and is cut by the *Houghtaling Creek troctolite* on its southeastern side. The Houghtaling Creek troctolite forms a macrodike composed mostly of well-foliated olivine-plagioclase cumulates (unit hct, M-119; Boerboom and Miller, 1994; Miller and others, 1994). Foliation and rare modal layering indicate a gently dipping, asymmetric trough near the surface, and a deeper root is implied by gravity and aeromagnetic data. The intrusion cuts across a variety of rock types and can be traced in outcrop and by its pronounced aeromagnetic signature over a strike length of about 50 kilometers. Limited cryptic and modal variations occur over 300 to 500 meters of stratigraphic section (for example, cumulus olivine ranges from Fo_{68} near the northern margin to Fo_{57} at the highest stratigraphic level, and interstitial pyroxene and oxide increase in modal abundance). The *Fourmile Lake ferrogabbro* (Boerboom and Miller, 1994) occurs as a large inclusion within the Houghtaling Creek troctolite. It is a strongly differentiated layered sequence of gabbro to gabbronorite (unit fmfg, M-119), ferromonzodiorite (unit fmmd, M-119), and melanogranophyre (unit fmgp, M-119). Although nearly conformable with the Houghtaling Creek troctolite, a sharp compositional break occurs between the troctolite and the least differentiated part of the Fourmile Lake ferrogabbro. This implies that the differentiated sequence did not evolve in situ from the Houghtaling Creek troctolite; instead, it is probably a detached part of either the Dam Five gabbronorite or the Wilson Lake ferrogabbro.

The next suite of intrusions is a complex mix of hydrothermally altered, non-cumulate olivine gabbroic to quartz monzodioritic rocks that occur in three main areas of exposure. Southwest of the town of Finland, these rocks are mapped as the *Lax Lake gabbro* (units llog, llgd, and llmd, M-119; Miller, 1988; Miller and others, 1993); northeast of Finland, similar rocks are mapped as the *Blesner Lake diorite* (units blpd, blod, blg, bld, blfc, blmd, and blgp, M-119; Miller and others, 1993); and further north in the Cramer and Cabin Lake quadrangles, these rocks are mapped as the *Upper Manitou River gabbro* (units umg, umd, and umgp, M-119; Miller and others, 1994). The nearly identical range in lithologies and contact relationships within these three units suggests that they originally formed a continuous intrusive mass, which was subsequently separated by younger intrusions, most notably the Beaver River diabase. Because of a paucity of internal structure, it is difficult to determine the shape of this early gabbroic mass, although a shallow, south-dipping lensoid sheet seems likely from its outcrop pattern and the attitude of flanking volcanic rocks. Within the Lax Lake gabbro and Blesner Lake diorite bodies, variations in rock types define a crude concentric zonation with the least evolved rock type, ophitic olivine diabase, at the margins and successive inner zones of intergranular gabbro, apatitic olivine ferrodiorite, ferromonzodiorite, and quartz ferromonzonite. In the Blesner Lake diorite, the apatitic ferrodiorite unit (blfc, M-119) locally is well foliated and somewhat resembles the upper differentiates of the Sonju Lake intrusion. The Upper Manitou River gabbro has a comparable range of rock types, but these occur in more dike-like bodies. Locally abrupt changes in rock types and the lack of cumulate textures (except for the laminated ferrodiorite) imply that these varied rock types resulted from multiple injections of progressively more evolved magma from a deeper source rather than from post-emplacement differentiation. Moreover, moderate to strong hydrothermal alteration and an irregular distribution of interstitial granophyre in all rock types suggest that these early gabbroic intrusions were strongly contaminated by hydrothermal fluids and felsic melts generated from the water-bearing volcanic rocks into which the intrusions were emplaced.

A distinctive concentric aeromagnetic pattern (Fig. 7.2) and limited data from 15 drill holes and a few outcrops define the *Cloquet Lake layered series*. These data imply that the Cloquet Lake layered series is a thick, saucer-shaped intrusion composed of two major differentiation cycles. Each cycle grades from a troctolitic lower section (units clog and cuog, M-119) characterized by a low, subdued magnetic anomaly, to a gabbroic to dioritic middle section (units clgd and cugd, M-119) characterized by bands of busy magnetic highs, and ultimately to a discontinuous monzodioritic upper part (units clmd and cumd, M-119) characterized by a consistent magnetic high. A body of granophyre appears to cap the entire series (unit cugp, M-119) based on one drill hole and a subdued aeromagnetic signature. Some very strong magnetic highs are evidently related to volcanic hornfels, as confirmed in two drill holes. Given that not all mafic hornfels is strongly magnetic, it is likely that the Cloquet Lake layered series is more enriched in volcanic inclusions than shown on map M-119. An interesting feature of the Cloquet Lake layered series is that troctolitic to gabbroic rocks from the northern and western parts commonly display cumulate textures, whereas all exposures and drill core in the southern Cloquet Lake layered series (all gabbroic to dioritic rocks) do not. In the southeast, the Cloquet Lake layered series appears to merge with the Lax Lake gabbro.

The *Finland granophyre* is a zoned, oval-shaped mass of reddish, micrographic leucogranite and quartz ferromonzodiorite (units fggr and fgmd, respectively, M-119). At the scale of field mapping (Miller and others, 1993), the quartz ferromonzodiorite encircles and underlies a core of leucogranite. However, several cores recently drilled to monitor ground water contamination show the zoning to be more complex and cyclical. The Finland granophyre clearly intrudes the Lax Lake gabbro on the south and is intruded by the Beaver River diabase on the east. Its relationship to the Sonju Lake intrusion along a gradational northern boundary is more ambiguous. Given the parallel zonation of the two subunits of the Finland granophyre with the strike of cumulate units of the Sonju Lake intrusion (Fig. 7.2; also see M-119; Miller and others, 1993), and generally smooth compositional variations across these units (see Chapter 8, Fig. 8.9; also see Miller and Ripley, 1996), a comagmatic relationship resulting from crystallization differentiation could be envisioned. Such an interpretation is inconsistent, however, with the large amount of granophyre relative to the layered mafic rocks apparent from the geologic map (Miller and others, 1993) and from gravity modeling (Miller and others, 1990). A more plausible interpretation is that the mafic magma that produced the Sonju Lake intrusion underplated the less dense Finland granophyre. Melting of the lower Finland granophyre and partial mixing of the melt with the underlying mafic magma could have produced the gradational contact observed between these two intrusive bodies. This is consistent with recently acquired U-Pb age data that show the Finland granophyre to be slightly older (1097.8 ± 4.4 Ma; Vervoort, unpub. data, 2001) than the Sonju Lake intrusion (1096.1 ± 0.8 Ma; Paces and Miller, 1993).

The *Sonju Lake intrusion* is the most completely differentiated mafic layered intrusion recognized within the Midcontinent rift (Stevenson, 1974; Weiblen, 1982; Miller and Ripley, 1996). The intrusion is a sheet about 1,200-meters-thick that dips 15° to 30° south to southeast and extends at least 15 kilometers along strike as judged from its aeromagnetic signature (Fig. 7.2). It is abruptly truncated on the east by the Beaver River diabase (Miller and others, 1993). The basal contact zone of the intrusion consists of fine-grained melatroctolite (unit slmt, M-119). This is overlain by an upwardly differentiated sequence of cumulate rocks in which the cumulus assemblages Ol → Pl + Ol → Pl + Cpx + Ol → Pl + Cpx + Ox(-Ol) → Pl + Cpx + Ox + Ap + Ol appear in succession and define the map units sld, slt, slg, slfg, and slad (M-119). The top of the sequence is capped by a non-cumulate olivine monzodiorite (unit slmd, M-119) that irregularly grades into the quartz ferromonzodiorite (unit fgmd, M-119) of the Finland granophyre. The Mg values of mafic silicates and the An contents of plagioclase decrease smoothly from base to top across the cumulate sequence (Fig. 7.4). These characteristics are consistent with its formation by closed-system fractional crystallization of a moderately evolved tholeiitic basaltic magma (Miller and Ripley, 1996). An orthogonal set of felsic-mafic hybrid dikes that intrude the upper part and eastern margin of the Sonju Lake intrusion (unit slbr, M-119) appear to have resulted from mixing of residual felsic magma in the upper differentiates of the layered intrusion with the mafic magma of the adjacent Beaver River diabase.

The *Beaver River diabase* is the most widespread intrusive phase of the Beaver Bay Complex (units brd, brod, brg, brfd, and brfc, M119). It occurs as an interconnected suite of dikes, sills, and sheets of predominantly ophitic olivine gabbro (unit brod, M-119). Its western and northern extent is defined by a continuous dike (or dike set) traceable in outcrop and by its aeromagnetic signature along

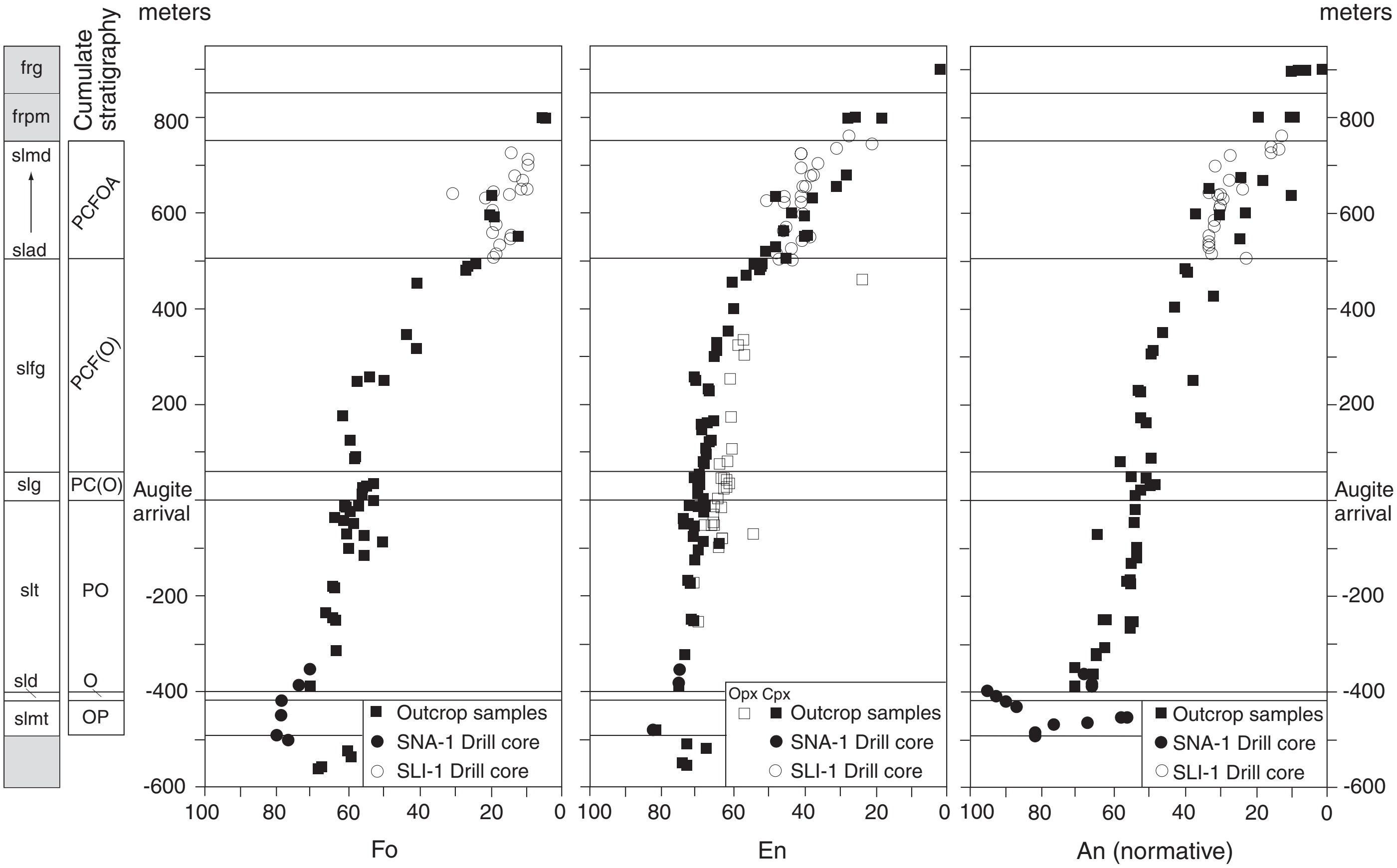


Figure 7.4. Stratigraphic variations in average Fo, En, and An contents of olivine, pyroxene, and plagioclase through the Sonju Lake intrusion. Olivine and pyroxene data are based on averages of 5 to 12 microprobe analyses per sample (Miller, unpub. data). Plagioclase data are based on normative An content (An/An + Ab + Or) of whole rock analyses. Outcrop and drill core samples are distinguished. Drill core SLI-1 is located at T. 58 N., R. 8 W., sec. 35, CDDBDD (see Meints and others, 1993) and drill core SNA-1 is located at T. 58 N., R. 7 W., sec. 22, BBAC (see Miller, 1999).

a 110-kilometer-long arcuate path (Figs. 7.2 and 7.3; M-119). Within the arc of this bounding dike are several other large, bifurcating dikes and several large sheets that dip gently southeast. The complex of sheets holding up tabletop highlands in the southern Beaver Bay Complex (Fig. 7.3) may be part of an originally continuous, nearly horizontal sheet that has locally been eroded through to expose volcanic rocks of the footwall. In many areas, the Beaver River diabase contains composite intrusions of olivine gabbro, ferrodiorite, quartz ferromonzodiorite, and melanogranophyre. In the southern Beaver Bay Complex, these intrusions are distinguished as the Silver Bay intrusions. Locally, the Beaver River diabase contains large inclusions of granophyric granite and anorthosite (units brdg and brda, respectively, M-119).

Inclusions of nearly pure anorthosite are particularly common in the upper and lower margins of the larger diabase sheets. They are typically composed of more than 95 percent labradoritic to bytownitic plagioclase and minor interstitial orthopyroxene, olivine, and/or clinopyroxene. They are as large as several hundred meters in diameter and locally display igneous foliation, brecciation, and recrystallization textures (Morrison and others, 1983). The absence of any discernible chill of the diabase against the anorthosite blocks suggests that the inclusions were derived from a deeper source. Grout and Schwartz (1939) believed that the anorthositic gabbros of the Duluth Complex supplied the inclusions, though they noted several inconsistencies such as the coarser nature and lighter color of the inclusions. Using ambiguous isotopic data, Morrison and others (1983) analyzed the petrographic and geochemical compositions of the inclusions and suggested that they were probably derived from an older (~1.9 Ma), deep crustal source. X-ray diffraction analyses (Miller, 1986) indicated that plagioclase from the inclusions has a significantly higher state of structural disorder compared to plagioclase from the Duluth Complex anorthositic rocks, further confirming a deep crustal source for the inclusions. Miller suggested (Miller, 1986; Miller and Weiblen, 1990; Miller and Chandler, 1997) that these inclusions may be Keweenawan in age and related to the accumulation of plagioclase in the roof zones of lower crustal magma chambers. Miller and Vervoort (1996) speculated that most of these lower crustal magma chambers developed during the latent magmatic stage of the Midcontinent rift (1107 to 1102 Ma). During this time of extensive crustal underplating, significant interaction and assimilation of the lower crust would have occurred, giving rise to the contaminated isotopic compositions of anorthositic cumulates that were later incorporated into Beaver Bay Complex magmas.

The youngest intrusions recognized in the southern Beaver Bay Complex are small, isolated bodies of varied shape and size, collectively termed the *Silver Bay intrusions* (Miller, 1988; Miller and others, 1989). The bodies are intermediate in composition and form composite intrusions into the Beaver River diabase dikes and sheets. The largest of these, located southwest of Beaver Bay, is a gently southeast-dipping, concentrically-zoned, lensoid body emplaced into the upper part of a thick Beaver River diabase sheet. The two major zones of the body—an outer ring of coarse, varitextured ferromonzodiorite (unit sbg, M-119) and an inner core of strongly laminated and locally layered olivine ferrogabbro, gabbronorite, and ferromonzodiorite (units sbfc and sbpg, M-119)—were interpreted by Gehman (1957) as two distinct intrusions. However, mapping (Miller, 1988) and petrologic studies (Shank, 1989; Chalokwu and Miller, 1992) showed that the outer unit is a marginal facies to the inner sequence of iron-rich cumulates. Petrologic studies of this intrusion and a smaller body near Silver Bay reveal an in situ differentiation trend toward extreme iron enrichment. In the southern Beaver Bay Complex, six such zoned bodies and several smaller massive bodies span a considerable range of intermediate compositions, suggesting that these bodies were derived from a deeper fractionating magma chamber at various stages of differentiation. Geochemical modeling demonstrates that fractional crystallization of the Beaver River diabase could have generated the magma compositions that gave rise to the various Silver Bay intrusions.

Several other minor intrusions also occur in the southern Beaver Bay Complex; however, their temporal and comagmatic relationships to the major intrusive units are unclear. The most extensive of these is the *Victor Head diabase*, a 50- to 65-meter-thick sill of fine- to medium-grained, ophitic olivine diabase that can be traced over a strike length of at least 17 kilometers (unit vhod, M-119; Miller, 1988; Miller and others, 1989, 1993). Although older than the Beaver River diabase that intrudes it, the Victor Head diabase is not in contact with any older units. Another small intrusion called the *Milepost 7 sill* is a fine-grained intergranular ferrodiorite that cuts the Gooseberry River basalts and the southern Lax Lake gabbro (unit mpfd, M-119; Green, 1982; Miller, 1988). Also, several isolated masses of micrographic and locally spherulitic leucogranite are intrusive into the Blesner Lake diorite and a Silver Bay intrusion. The former mass may represent satellite intrusions that emanate from the Finland granophyre. The Silver Bay body may have formed by localized melting of felsic volcanic rocks in the footwall of the Beaver River diabase and Silver Bay intrusions.

Structural geology and mechanisms of emplacement

The shapes of Beaver Bay Complex intrusions differ noticeably over its arcuate extent. Whereas dike-like bodies are most common in the northern Beaver Bay Complex, a mix of dikes and sheetlike intrusions are present in the southern and eastern areas (the sheetlike intrusions are especially common among the earlier intrusions). This change in intrusion shape is readily apparent in the aeromagnetic anomaly patterns over the Beaver Bay Complex, where concentric anomalies of the southern Beaver Bay Complex give way to northeast-trending linear anomalies in the northern Beaver Bay Complex (Chapter 3, Figs. 3.5 and 3.6). These differences in intrusion shapes may be related to the presence of the Schroeder–Forest Center ridge (Miller and Chandler, 1997; Chapter 3), which contains Archean footwall rocks that extend to shallow depths beneath Keweenawan igneous rocks.

The Schroeder–Forest Center ridge roughly corresponds to the pronounced saddle in the Bouguer gravity over northeastern Minnesota (Chapter 3, Fig. 3.3). In his geophysical study of western Lake Superior, White (1966) concluded that this saddle represents an extension of a basement ridge that projects northward from the Bayfield Peninsula and acted as a divide between two thick basins of lava accumulation. Davidson (1972), attempting to explain the abundance of granophyre bodies in the roof zone of the Duluth Complex, speculated that the gravity saddle represented the buried projection of the granitic rocks of the Archean Giants Range batholith. Chandler (1990) concluded that the saddle represents a structural thinning of Keweenawan intrusions over granitic crust, a preponderance of low-density anorthositic rock, or both. Other direct geologic evidence that older crust exists at shallow to moderate depths beneath the northern Beaver Bay Complex includes the discovery of migmatite, granite gneiss, amphibolite, and biotite schist inclusions in the Shoepack Lake diorite in the Wanless area (Boerboom, 1994; Boerboom and Miller, 1994; Miller and others, 1994).

The focusing of northeast-trending dikes in the northern Beaver Bay Complex suggests that repeated magma intrusions followed the same narrow conduit through the crustal ridge. This conduit may have been along the abrupt southeastern margin of the ridge, or it may have followed an early-formed fault through the ridge (Miller and Chandler, 1997). The ponding of Beaver Bay Complex magmas into sheetlike bodies on the southwestern side of the crustal ridge suggests that the ridge acted as a barrier to rift-parallel migration of magma in the upper crust. Gravity and magnetic modeling over the Cloquet Lake layered series, situated over the Bouguer gravity anomaly southwest of the ridge, indicate that mafic intrusive rocks extend to depths of about 13 kilometers (Allen and others, 1997). The role of the crustal ridge as a magma deflector is also evident in the volcanic rocks. Green (Chapter 5) noted that the volcanic sequences forming the northeastern and southwestern limbs of the North Shore Volcanic Group do not obviously correlate, especially where the sequence crosses the gravity saddle (Chapter 3, Fig. 3.3). Peterson and Severson (Chapter 4) noted that the projection of the Giants Range beneath the Duluth Complex seems to have acted as a rampart that deflected or truncated the formation of various intrusions (see Chapter 4, Fig. 4.6).

The sheetlike intrusions of the southern Beaver Bay Complex demonstrate a successive overplating and eastward migration of magmatic activity toward the axis of the Midcontinent rift. Within the Cloquet Lake layered series, the anomaly patterns indicate that successively younger intrusions were emplaced above and east of previous intrusions. The Sonju Lake intrusion sheet appears to have sliced through the eastern part of the Cloquet Lake layered series and separated the Lax Lake gabbro, the Blesner Lake diorite, and Finland granophyre from it. Subsequently, further east the Beaver River diabase and its composite Silver Bay intrusions truncated the eastern extension of the Sonju Lake intrusion and displaced the Blesner Lake diorite from the Lax Lake gabbro. The eastward and up-section migration of successive Beaver Bay Complex intrusions may represent a continuation of the same process of overplating evident in the layered series intrusions of the Duluth Complex (Chapter 6). Miller and Chandler (1997) suggested that the shift in the focus of intrusion toward the rift axis might be a consequence of plate separation over a fixed source of magma. They also suggested that the emplacement of sheetlike Beaver Bay Complex intrusions into progressively higher levels of the volcanic pile probably represents magma ponding at a constant depth in a continuously thickening volcanic pile. An important factor controlling the specific level of emplacement is the occurrence of low-density bodies in the volcanic pile. It is clear that many magmas plated out into sheeted intrusions beneath felsic lava flows (Beaver River diabase sheets are locally capped by the Palisade Head porphyritic rhyolite) and granophyre bodies (the Sonju Lake intrusion beneath the Finland granophyre).

HYPABYSSAL INTRUSIONS IN THE NORTHEAST VOLCANIC SEQUENCE

Subvolcanic intrusions of several types are common in the lower and upper northeastern sequences of the North Shore Volcanic Group and in Paleoproterozoic sedimentary rocks forming the northern footwall of the volcanic edifice. The intrusions span a broad range of compositions from primitive olivine tholeiitic diabase to granophyre. They generally occur as sills and sheets of varied thickness that are roughly conformable with the shallow southerly dip of the country rocks. An exception to this is the Pigeon River dikes in the northeastern part of the map area (M-119). Evidence of their hypabyssal setting is inferred from the noncumulate, diabasic textures displayed by most mafic intrusions and by the presence of miarolitic cavities in the granophyre bodies. Cumulate textures are displayed in thicker intrusions that are overlain by felsic bodies (such as the olivine gabbro phase of the Brule Lake–Hovland gabbro).

As noted in Chapter 6, certain gabbroic and granophyric rocks previously assigned to the eastern part of the Duluth Complex (Davidson, 1972) have been classified as miscellaneous intrusions on map M-119. These rocks, which are intrusive into the northeastern sequence of the North Shore Volcanic Group, include olivine gabbro and diabase/gabbro units of the Brule Lake–Hovland gabbro (bhog and bhdg, respectively, M-119), the Sawbill Lake gabbro (sbgb, M-119), the Eagle Mountain granophyre (emgp, M-119), and the Pine Mountain granophyre (pmgp, M-119). These intrusions are situated stratigraphically above the assemblage of granophyre, anorthositic rocks, and volcanic hornfels that characterizes the roof zone of Duluth Complex and are generally younger than the main phases of the Duluth Complex.

Geologic mapping of these hypabyssal intrusions has generally been at a reconnaissance level. In many areas of the northeastern volcanic sequence, generalized geologic mapping by F.F. Grout (Grout and others, 1959) remains the only information available. The distribution of Logan intrusions was mapped in some detail in four 7.5-minute quadrangles (Mathez and others, 1977; Morey and Nathan, 1977, 1978; Morey and others, 1981). Davidson (1977a-h) and Davidson and Burnell (1977) reconnaissance-mapped the central and western parts of the Brule Lake–Hovland gabbro, and Jones (1963) mapped its eastern extension near the Lake Superior shoreline in detail. Near-shore exposures of intrusive rocks between Grand Marais and the Canadian border were also reconnaissance-mapped by Green (1972; unpub. data). Petrologic studies of these intrusions have similarly been at a cursory level (Davidson, 1972; Green, 1972), although some detailed petrologic studies have been conducted locally (the Hovland area by Jones, 1963; the Pigeon Point sill by Mudrey, 1973; the Logan intrusions by Jones, 1984; and the Eagle Mountain granophyre by Nelson, 1991). The areal extent, structure, and lithologic characteristics of the various intrusions in the northeastern sequence of the North Shore Volcanic Group are described below.

Description of intrusions

Near the Canadian border east of Gunflint Lake, a dramatic sawtooth topography reflects the presence of southward-dipping, sill-like bodies of Keweenawan diabase within argillaceous sedimentary rocks of the Paleoproterozoic Rove Formation. These diabase sheets are known as the *Logan intrusions* (unit lsdb, M-119) and can be traced from the Gunflint Lake area northeastward to Thunder Bay (Geul, 1970), and from there northward to the Lake Nipigon area where they are intrusive into the Sibley Group sedimentary rocks (Sutcliffe, 1987). The Logan intrusions have a reversed magnetic polarity (Palmer, 1970), and a sample from the Lake Nipigon area yields a U-Pb zircon age of 1108.8 +4/-2 Ma (Davis and Sutcliffe, 1985), one of the oldest Keweenawan ages in the Lake Superior region. An early intrusive age is supported by field relations in the Long Island Lake (Morey and others, 1981), Gunflint Lake (Morey and Nathan, 1978), South Lake (Morey and Nathan, 1977), and Hungry Jack Lake (Mathez and others, 1977) quadrangles where Logan intrusions are cut by the Poplar Lake intrusion (formerly Nathan's layered series) of the Duluth Complex (U-Pb age of 1107.9 ± 0.3 Ma, Paces and Miller, 1993).

In Minnesota, the Logan intrusions are generally sill-like within the well-bedded Rove Formation, but may locally vary in thickness, branch, and pinch out (Weiblen and others, 1972; Jones, 1984). Eight intrusive sheets in the Rose Lake, Long Island Lake, and Gunflint Lake areas range in thickness from 22 to 280 meters (Weiblen and others, 1972), and four intrusions in the South Lake area range from 56 to 192 meters in thickness (Jones, 1984). Near the Canadian border, the sheets generally dip about 10° to the south, but within about a half-kilometer of the Duluth Complex, the diabase sheets and the enclosing slates and graywackes become inclined to about 50° from horizontal (Weiblen and others, 1972). The branching of the diabase sheets occurs on a variety of scales and locally, intrusive contacts can have as much as 25° discordance with bedding (Jones, 1984).

The average rock type composing the Logan intrusions is an intergranular to subophitic, locally plagioclase-phyric, variably granophyric olivine-poor oxide gabbro (Mathez, 1971; Weiblen and others, 1972; Jones, 1984). Chilled-margin rocks and calculated bulk intrusion estimates have evolved quartz tholeiitic compositions (mg# of 30 to 40; TiO_2 of 3.2 to 3.8 percent). Most sheets are texturally zoned, having upper and lower fine-grained chilled margins, medium- to coarse-grained interiors, and plagioclase ($\sim An_{55}$) porphyritic zones beneath the upper chill. Other than irregular increases in the amount of felsic mesostasis (granophyre) upward in most sheets, the intrusions generally show little stratigraphic variation in mineralogy (except for increased plagioclase in the porphyritic zones), mineral chemistry, and whole rock composition. These observations suggest minimal in situ differentiation of the parental magmas. However, the evolved nature of the parental magmas implies considerable differentiation (and possible contamination) in deeper staging chambers prior to emplacement.

In the vicinity of Brule Lake in west-central Cook County, a series of anastomosing sheets of porphyritic diabase known as the *Brule Lake porphyry intrusions* (unit `bppd`, M-119) cuts the reversed-polarity Hovland lavas (Burnell, 1976; Davidson and Burnell, 1977). The intrusions also show reversed magnetic polarity (Davidson and others, 1976). Seven sheets are mapped, trending east–west, with a roughly 10° southerly dip, but some cut the enclosing volcanic rocks at angles up to 35°. The sheets are approximately 100- to 300-meters-thick. They are cut off to the west by the anorthositic series rocks of the Duluth Complex. Topographically resistant, they form cuestas, with the lavas occupying the intervening low ground. The porphyritic intrusions contain about 25 to 60 percent plagioclase phenocrysts, which are generally 1- to 3-centimeters-long. The composition, texture, and magnetic polarity suggest that these intrusions are closely related to the Logan intrusions.

Cutting the reversed-polarity Grand Portage and Hovland lavas is a swarm of similarly reversed mafic to intermediate dikes called the *Grand Portage diabase dikes* (unit `gpdb`, M-119; Green and others, 1987). About 20 dikes have been mapped in the Grand Portage area; a few others have been seen farther to the west. These dikes range from less than one to over 45 meters in thickness. Most strike east–northeasterly to east–west and dip steeply to the north. Because of the scarcity of outcrop away from the lakeshore, lengths of individual dikes cannot be determined without a detailed magnetic survey. The Grand Portage dikes have intersertal or intergranular, but not ophitic, texture; some are plagioclase-phyric, as are most of the Hovland lavas they intrude. They may represent feeders for those reversed flows. Compositionally they are transitional basalts, trachyandesites, and icelandites.

The *Pigeon River diabase* (unit `prdb`, M-119) consists of a complex network of large, near-vertical dikes and a few associated sheets in the northeasternmost part of the map area. Many of the dikes are over 100-meters-thick and several trend for up to 40 kilometers along strike into Ontario (Geul, 1970; Green and others, 1987). These dikes cut both the Paleoproterozoic Rove Formation and the Keweenawan Puckwunge Sandstone, Grand Portage basalts, and Hovland lavas. Although the volcanic rocks cut by the Pigeon River diabase have reversed magnetic polarity, the dikes themselves show normal polarity. They are resistant to erosion and form dramatic topographic ridges. The dikes are of moderately evolved olivine tholeiite composition, and inboard of chilled margins have ophitic to less commonly intersertal texture.

The *Pigeon Point sill* (unit `ppgb`, M-119) is a 100- to 120-meter-thick, zoned sheet intrusion that is semi-conformable with gently (8° to 15°) south-dipping argillaceous rocks of the Paleoproterozoic Rove Formation at the very northeast corner of the map area. As described by Mudrey (1973, 1977), the lower half to three quarters of the sill is composed of a medium- to coarse-grained, ophitic olivine gabbro. This gabbro grades up into to a narrow (10- to 20-meter) interval of olivine-poor, quartz-bearing gabbro that is locally rich in amphibole. The upper part of the intrusion is composed of a granophyre which is up to 50-meters-thick at the western end of the sill but absent at the east end. Mudrey (1973) concluded that the granophyre is too abundant to be entirely a differentiate of the gabbro and must have incorporated magma derived from partial melting of the Rove Formation. The normal magnetic polarity and olivine tholeiitic composition of the sill suggest that it may be related to the Pigeon River diabase dike swarm.

The *Brule Lake–Hovland gabbro* is a generalized intrusive unit composed of an unknown number of separate intrusions. These intrusions occupy a similar structural position above the Duluth Complex and reversed-polarity lavas of the North Shore Volcanic Group, and beneath the Eagle Mountain and Pine Mountain granophyre sheets. Its main portion trends east–west across central Cook County. It has not been extensively studied except in the Hovland area (Jones, 1963). The gabbro has been divided into three portions for this study.

In west-central Cook County, the western part of the Brule Lake–Hovland gabbro consists of a large body of layered olivine gabbro cumulates (unit bhog, M-119). Davidson (1977b, c, e) described it as a medium- to coarse-grained olivine gabbro. Foliation and layering in the gabbro define a large synclinal structure that plunges about 30° to the southeast. A striped aeromagnetic pattern (Fig. 7.3) coincides with this structure and suggests that the gabbro is macrocyclically layered, possibly being composed of multiple differentiation cycles and/or multiple intrusions. Some direct evidence of internal variability is an interval of layered oxide-rich gabbro (unit bhfg, M-119) in the medial part of the body, which Grout (1949-1950) termed the South Range oxide gabbro. The internal structure and map area of the western part of the Brule Lake–Hovland gabbro imply a thickness of up to 4 kilometers in the central portion of this unit. Contact relations with the overlying Eagle Mountain granophyre are unknown.

East of a septum of anorthositic rocks of the Duluth Complex, the Brule Lake–Hovland gabbro occurs as a two-pronged strip of diabase and gabbroic rocks that extends to the Lake Superior shore near Hovland (unit bhdg, M-119; unit olg of Davidson, 1977d, g, h). Along most of its extent, this diabase/gabbro unit underlies the Eagle Mountain and Pine Mountain granophyres. Its topographic expression implies the presence of both sill-like and dike-like portions that clearly cut across the volcanic rocks. It does not display a striped aeromagnetic pattern like the western gabbro, but local variations in rock type based on reconnaissance mapping (Grout and others, 1959; Nelson, 1991; Green, unpub. data) suggest that it is composed of an unknown number of composite intrusions. The rocks in this area are generally medium-grained, ophitic olivine gabbro, but in some places (such as south of Lima Mountain near the South Brule River and north of Eagle Mountain), the gabbro is foliated with cumulate texture. Farther east (about 5 kilometers northwest of Hovland), the unit consists of locally foliated olivine gabbro and ferromonzodiorite.

The easternmost part of the Brule Lake–Hovland gabbro in the vicinity of Hovland was mapped by Jones (1963) as the Hovland diabase complex. The undifferentiated diabase unit of Jones is included in the main bhdg unit on M-119. However, two other units noted by Jones (1963) and Green (1972) are distinguished here. Northeast of Hovland along the shore is a gently dipping sheet of ophitic olivine gabbro/diabase and minor ferromonzonite that cuts across reversed-polarity volcanic rocks at a low angle. This unit is known as the Reservation River diabase (unit bhrd, M-119). Its relationship to the gabbroic rocks of the undifferentiated diabase complex and to the Pigeon River diabase dikes that project into the area from the northeast is unclear. Between the Brule River and Chicago Bay at Hovland, the Lake Superior shore is underlain by a ferrodioritic unit (unit bhfd, M-119) called the Hovland sill (Grout and others, 1959; Jones, 1963). This sheetlike body is approximately 450-meters-thick, strikes east–northeast, and dips about 10° to the southeast (Jones, 1963). In some outcrops, the rock is foliated and contains cumulus plagioclase, augite, olivine, and magnetite, but most commonly it is decussate and intergranular or intersertal. Although Jones determined the plagioclase to be fairly calcic (An_{72-54}), this sill is otherwise rather evolved, with Fe-rich olivine, up to 15 percent interstitial granophyre, and abundant apatite. Much detailed mapping is required to further subdivide and characterize the many intrusive phases of this compound Brule Lake–Hovland map unit.

The *Eagle Mountain granophyre* (unit emgp, M-119) is a large, tabular, east–west-trending body approximately 35-kilometers-long in central Cook County. Stretching from Kelly Lake on the west to Junco Creek on the east, it overlies gabbroic rocks of the Brule Lake–Hovland gabbro and underlies normal-polarity lavas of the North Shore Volcanic Group. It may be equivalent to the Pine Mountain granophyre to the east, from which it is apparently separated by volcanic rocks (Davidson, 1977b, e). However, Vervoort (unpub. data, 2001) acquired a somewhat older U-Pb age for the Eagle Mountain body (1098.5 ± 4 Ma compared to 1095.4 ± 3.7 Ma for the Pine Mountain granophyre). The petrology of the Eagle Mountain granophyre has been studied in the vicinity of Eagle Mountain (Nelson, 1991), the highest point (2,301 feet [701 meters]) in Minnesota. It is a red-brown, fine-grained, porphyritic, micrographic leucogranite. At Eagle Mountain, the granophyre grades sharply downward into cumulate ferrodiorite and gabbro of the Brule Lake–Hovland gabbro unit. Elsewhere along this contact, Davidson (1977c, d, g) and Davidson and Burnell (1977) mapped a narrow zone of ferromonzodiorite (unit emmd, M-119) between the granophyre and the Brule Lake–Hovland gabbro. Its upper contact in this locality intrudes a slightly metamorphosed gabbro that in turn underlies both rhyolite of the North Shore Volcanic Group and an associated miarolitic granophyre body. Sm-Nd isotopic analyses (Vervoort and Green, 1997) show a moderately negative value ($\varepsilon_{\mathrm{Nd}}$ –7.7), suggesting that the granophyre magma was derived at least in part from partial melting of basement rocks. Modeling indicates that either a relatively small contribution from Archean sources or more substantial melts from possible Paleoproterozoic crustal underplating could produce the observed isotope ratios.

The *Pine Mountain granophyre* (unit pmgp, M-119) is an elongate, tabular body in east-central Cook County. Its relations to volcanic and gabbroic country rocks are similar to those of the Eagle Mountain granophyre to its west because it overlies the Brule Lake–Hovland gabbro and underlies the North Shore Volcanic Group. It is predominantly a micrographic leucogranite and is probably the eastern part of an originally more extensive body that included the Eagle Mountain granophyre. Like the Eagle Mountain granophyre, it is resistant and tends to hold up higher elevations. Its basal contact is somewhat gradational, with a zone of ferromonzodiorite to ferromonzonite (unit pmmd, M-119) that may represent partial melting and hybridization by the underlying gabbro (Davidson, 1972, 1977g, h). Little is known about its upper contact with the volcanic rocks.

The *Lake Clara, Monker Lake, Lichen Lake,* and miscellaneous *diabase* units are large dikes in eastern and central Cook County (units lcdb, mldb, lldb, and diab, respectively, M-119). They vary from being parallel to the regional North Shore Volcanic Group flows to being sharply crosscutting. They are typically 200- to 500-meters-thick. Most have a strong positive aeromagnetic signature that allows correlation between isolated outcrops. These rocks are most commonly fine- to medium-grained, subophitic to ophitic olivine diabase, and contain augite oikocrysts from 4 to 10 millimeters across. Locally they contain sparse, rectangular plagioclase phenocrysts.

HYPABYSSAL INTRUSIONS IN THE SOUTHWEST VOLCANIC SEQUENCE

Several sills and sheetlike intrusions occur within the 7-kilometer-thick section of volcanic rocks exposed along the Lake Superior shoreline from Duluth to Split Rock Point. Upsection (northeast) from Duluth, the succession of intrusions are the Endion sill, the Northland sill, the Lester River sill, the Stony Point/Knife Island sill, the Silver Creek diabase/gabbro, the Lafayette Bluff diabase, and the Split Rock River intrusive felsite. Because they are generally well exposed within 10 kilometers of the shoreline, these intrusions have been the focus of many mapping and petrologic studies including Schwartz and Sandberg (1940), Ernst (1960), Pope (1976), Oestrike (1983), and Jerde (1991). These semi-conformable sheets generally dip gently to the east and hold up cuesta-like ridges. They range in thickness from tens of meters to over 500 meters.

Further inland, exposure becomes very poor and the topographic expression of the sills and sheets disappears. From very sparse exposures (Bonnichsen, 1971; Green and others, 1977) and interpretations of aeromagnetic data, much of this area appears to be composed of gabbroic rocks, granophyre, and volcanic hornfels. On map M-119, two large intrusive bodies are inferred to occur north of Two Harbors, the Sawmill Lake gabbro/granophyre and the Silver Creek diabase/granophyre intrusions. The latter body is interpreted to project to the well-exposed diabase intrusion forming Silver Cliff at the shoreline northeast of Two Harbors. A brief description of the individual hypabyssal intrusions of the southwest volcanic sequence is given below.

Description of intrusions

In the footwall of the Duluth Complex at Duluth, a swarm of fine-grained diabase dikes called the *St. Louis River diabase dikes* (units sldn and sldr, M-119) cuts both the Ely's Peak basalt and the Paleoproterozoic Thomson Formation. Most dikes within the Thomson Formation have reversed magnetic polarity (30 of 34 dikes sampled by Reichhoff [1987] are reversed). These diabase dikes tend to display an intergranular to subophitic texture and range up to 18 meters across (Green and others, 1987; Reichhoff, 1987). Those cutting the Ely's Peak basalts tend to have normal polarity and subophitic to ophitic textures (Kilburg, 1972). North of the Adolph quadrangle, no dikes are exposed but many larger dikes of both normal and reversed magnetic polarity can be inferred from the aeromagnetic data (M-119). On the very edge of the map area, a small, intense, circular anomaly occurs at the junction of two reversed-polarity dikes. A drill core into the body indicated that it is composed of an oxide-rich gabbro (unit mif, M-119).

The *Endion sill* is the lowest hypabyssal intrusion in the volcanic rocks overlying the Duluth Complex at Duluth (Ernst, 1960; Oestrike, 1983). It is a 425-meter-thick diabase sheet that can be traced inland to the north for about 17 kilometers. Although outcrop is poor, aeromagnetic data are interpreted to indicate that the sill projects as two prongs into the Duluth Complex (see M-119). The sill is composed principally of medium-grained, ophitic to intergranular olivine gabbro (unit endb, M-119), but contains in its upper part up to 40 percent intermediate to felsic material (unit engp, M-119). These facies show gradational contacts with the diabase as well as with each other. The sill underlies a large rhyolite flow, and much of the felsic material in it may have been derived from the melting of its roof.

The *Northland sill* (unit nldb, M-119) is another diabase sheet that cuts the North Shore Volcanic Group lavas in the Lakeside area of eastern Duluth (Schwartz and Sandberg, 1940). Very narrow and dike-like at the Lake Superior shore, it widens to the north and northeast to form a large topographic ridge where it is estimated to be about 300-meters-thick. It can be traced about 10 kilometers along strike. Although the lower part of this somewhat crosscutting sheet is a mafic diabase, it contains large amounts of intermediate to felsic material (ferrodiorite to quartz monzodiorite).

Abundant outcrops starting just east of the mouth of the Lester River in eastern Duluth form the southern exposed end of the *Lester River sill* (unit lrdb, M-119; Schwartz and Sandberg, 1940; Jerde, 1991). This sill is a conspicuous ridge-former, and can be traced for about 15 kilometers to the northeast, intermittently offset by faults. It is about 300-meters-thick near the lakeshore. It consists mostly of ophitic to intergranular olivine diabase, but it also contains abundant local zones of intermediate rocks. Jerde (1991) showed that the sill has an inverse zonation, with the most primitive diabase in the central portion. He interpreted this to indicate a composite intrusion of initially primitive olivine tholeiite, which underplated and partially melted a rhyolite flow to locally create a granophyre upper unit. The ophitic olivine diabase formed from this initial intrusion was then underplated by a more evolved tholeiitic magma that crystallized an intergranular gabbro in the lower half of the intrusion.

The *Stony Point diabase* (unit spdb, M-119) is a crosscutting sheet at least 35-meters-thick that holds up “Granite Point” at Knife River, Stony Point to the southwest, and an intervening ridge. It is medium-grained and ophitic, and cuts across local basalt flows at a shallow angle.

The *Sawmill Lake gabbro/granophyre* map unit northwest of Two Harbors is poorly exposed and inferred principally from its aeromagnetic anomaly pattern (see Chapter 6, Fig. 6.5). Observed outcrops include cumulate olivine gabbro (2 to 4 kilometers northwest of Two Harbors), olivine diabase, ferrodiorite, and granophyre (Bonnichsen, 1971; Green and others, 1977; Green, unpub. data). Its relationships with other intrusive units are unknown. Based on aeromagnetic data and topographic considerations, the Sawmill Lake gabbro phase (unit smgb, M-119) is inferred to be cut by the Lester River sill. The granophyre body inferred to core the intrusion (unit smgp, M-119) is interpreted from rare outcrop (Bonnichsen, 1971) and a subdued aeromagnetic expression.

Northeast of Two Harbors is another large, compound intrusion named the *Silver Creek diabase/granophyre*. The best exposures of this body occur near the Lake Superior shoreline. Here Pope (1976) described a large diabase sill, which he called the Silver Creek Cliff sill from that prominent topographic feature. The sill is predominantly composed of a fine- to medium-grained ophitic olivine diabase. It is approximately 60-meters-thick and forms a large tableland that extends about 7 kilometers to the north and northeast from the lakeshore and, in intermittent exposures, for several kilometers beyond. Based on aeromagnetic data (see Chapter 6, Fig. 6.5), this diabase sill appears to be linked to a larger area of intrusive rocks that is poorly exposed except for scattered exposures of gabbro and granophyre (Bonnichsen, 1971; Green and others, 1977). The widely scattered inland exposures of mafic rocks assigned to this (unit scdg, M-119) include troctolite, ophitic olivine diabase and gabbro, and ferromonzonite, which may involve several separate intrusive phases. The large area of granophyre interpreted to core the Silver Creek diabase/granophyre body (unit scgp, M-119) is based on a few exposures in the southern part of the area that are related to a subdued aeromagnetic anomaly pattern.

Between Two Harbors and Castle Danger in southern Lake County, the *Lafayette Bluff diabase* (unit lbdb, M-119), a black, medium-grained, porphyritic diabase sheet, cuts the North Shore Volcanic Group (Pope, 1976). Many outcrops of this rock are deeply weathered to a brown grus, and the rock commonly shows spheroidal weathering. In many areas it contains scattered, small amygdules that contain radial, acicular zeolites. It occurs in two north–south belts of outcrop, and shows complex intrusive and structural relations. Although it is chemically a high-Al olivine tholeiite, its appearance contrasts with most north shore hypabyssal intrusions of that composition (such as the nearby Silver Creek diabase and the Beaver River diabase) in its black, altered, amygdaloidal character and in much less obvious ophitic texture.

The *Split Rock intrusive felsite* (unit srif, M-119) is a pink, fine-grained, sparsely porphyritic rock also described as rhyolite that shows local flow banding. It can be traced for at least 3.4 kilometers northward along strike from the Lake Superior shore. The rock splits readily into shingle, and locally has columnar jointing; these allow it to be relatively easily eroded by waves. Its structural relations are unusual because the sheet jointing defines a synformal structure. At its basal contact, both at its upstream and downstream margins, it is intruded by a thin layer of black, fine-grained ferrodiabase, beyond which are ordinary basalt lava flows. The ferrodiabase and granophyre may be a compound intrusion. Compositionally, it is a quartz monzodiorite to granite. About 5 kilometers northeast of the Split Rock intrusive felsite, the Beaver Bay Complex begins.

REFERENCES

Allen, D.J., Hinze, W.J., Dickas, A.B., and Mudrey, M.G., Jr., 1997, Integrated geophysical modeling of the North American Midcontinent rift system: New interpretations for western Lake Superior, northwestern Wisconsin, and eastern Minnesota, *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. 47-72.

Boerboom, T.J., 1994, Archean crustal xenoliths in a Keweenawan hypabyssal sill, northeastern Minnesota. White was right!: Institute on Lake Superior Geology, 40th Annual Meeting, Houghton, Mich., Proceedings, v. 40, Program and Abstracts, pt. 1, p. 5-6.

Boerboom, T.J., and Miller, J.D., Jr., 1994, Bedrock geologic map of the Silver Island Lake, Wilson Lake, and western Toohey Lake quadrangles, Cook and Lake Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-81, scale 1:24,000.

Bonnichsen, B., 1971, Outcrop map of southern part of Duluth Complex and associated Keweenawan rocks, St. Louis and Lake Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-11, scale 1:125,000.

Burnell, J.R., Jr., 1976, Petrology and structural relations of the Brule Lake intrusions, Cook County, Minnesota: Minneapolis, University of Minnesota, M.S. thesis, 105 p., 1 pl.

Chalokwu, C.I., and Miller, J.D., Jr., 1992, Differentiation of Keweenawan Silver Bay intrusions, Beaver Bay Complex, northeastern Minnesota: Geological Society of America Abstracts with Programs, v. 24, no. 7, p. A86.

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.

Davidson, D.M., Jr., 1972, Eastern part of Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 354-360.

———1977a, Reconnaissance geologic map of the Alice Lake quadrangle, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-33, scale 1:24,000.

———1977b, Reconnaissance geologic map of the Beth Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-26, scale 1:24,000.

———1977c, Reconnaissance geologic map of the Cherokee Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-30, scale 1:24,000.

———1977d, Reconnaissance geologic map of the Eagle Mountain quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-28, scale 1:24,000.

———1977e, Reconnaissance geologic map of the Kelso Mountain quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-27, scale 1:24,000.

———1977f, Reconnaissance geologic map of the Lake Polly quadrangle, Lake and Cook Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-34, scale 1:24,000.

———1977g, Reconnaissance geologic map of the Lima Mountain quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-32, scale 1:24,000.

———1977h, Reconnaissance geologic map of the Pine Mountain quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-31, scale 1:24,000.

Davidson, D.M., Jr., and Burnell, J.R., Jr., 1977, Reconnaissance geologic map of the Brule Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-29, scale 1:24,000.

Davidson, D.M., Jr., Halls, H.C., and Burnell, J.R., Jr., 1976, Paleomagnetism of the Late Precambrian Brule Lake intrusions, Cook Co., Minnesota [abs.]: Institute on Lake Superior Geology, 22nd Annual Meeting, Minneapolis, Minnesota, Proceedings, p. 18.

Davis, D.W., and Green, J.C., 1997, Geochronology of the North American Midcontinent rift in western Lake Superior and implications for its geodynamic evolution: Canadian Journal of Earth Sciences, v. 34, no. 4, p. 476-488.

Davis, D.W., and Sutcliffe, R.H., 1985, U-Pb ages from the Nipigon plate and northern Lake Superior: Geological Society of America Bulletin, v. 96, no. 12, p. 1572-1579.

Elftman, A.H., 1898, Geology of the Keweenawan area in northeastern Minnesota. II: American Geologist, v. 21, p. 175-188.

Ernst, W.G., 1960, Diabase-granophyre relations in the Endion sill, Duluth, Minnesota: Journal of Petrology, v. 1, no. 3, p. 286-303.

Gehman, H.M., Jr., 1957, The petrology of the Beaver Bay Complex, Lake County, Minnesota: Minneapolis, University of Minnesota, Ph.D. dissertation, 92 p.

Geul, J.J.C., 1970, Geology of Devon and Pardee Townships and the Stuart location, District of Thunder Bay: Ontario Geological Survey, Mines and Minerals Division Report 87, 52 p.

Green, J.C., 1972, North Shore Volcanic Group, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 294-332.

———1982, Geology of the Milepost 7 area, Lake County, Minnesota: Minnesota Geological Survey Report of Investigations 26, 12 p.

———1992, Geologic map of the north shore of Lake Superior, Lake and Cook Counties, Minnesota: Part 1. Little Marais to Tofte: Minnesota Geological Survey Miscellaneous Map M-71, scale 1:24,000.

Green, J.C., Bornhorst, T.J., Chandler, V.W., Mudrey, M.G., Jr., Myers, P.R., Pesonen, L.J., and Wilband, J.T., 1987, Keweenawan dykes of the Lake Superior region: Evidence for evolution of the Middle Proterozoic Midcontinent rift of North America, *in* Halls, H.C., and Farhig, W.F., eds., Mafic dyke swarms: Geological Association of Canada Special Paper 34, p. 289-302.

Green, J.C., Jirsa, M.A., and Moss, C.M., 1977, Environmental geology of the north shore: Minnesota Geological Survey, 99 p.

Grout, F.F., 1949-1950, The titaniferous magnetites of Minnesota: St. Paul, Minn., Office of the Commissioner of the Iron Range Resources and Rehabilitation, 117 p.

Grout, F.F., and Schwartz, G.M., 1939, The geology of anorthosites of the Minnesota coast of Lake Superior: Minnesota Geological Survey Bulletin 28, 119 p., 6 pls.

Grout, F.F., Sharp, R.P., and Schwartz, G.M., 1959, The geology of Cook County Minnesota: Minnesota Geological Survey Bulletin 39, 163 p., 16 pls.

Irving, R.D., 1883, The copper-bearing rocks of Lake Superior: U.S. Geological Survey Monograph 5, 464 p.

Jerde, E.A., 1991, Geochemistry and petrology of hypabyssal rocks associated with the Midcontinent rift, northeastern Minnesota: Los Angeles, University of California, Los Angeles, Ph.D. dissertation, 305 p.

Jones, N.W., 1963, The relationships between the Duluth gabbro and the dikes and sills in the vicinity of Hovland, Minnesota: Minneapolis, University of Minnesota, M.S. thesis, 90 p.

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

Kilburg, J.A., 1972, Petrology, structure, and correlation of the Upper Precambrian Ely's Peak basalts: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 97 p.

Lawson, A.C., 1893, The anorthosytes of the Minnesota coast of Lake Superior: Geological and Natural History Survey of Minnesota Bulletin 8, p. 1-23.

Mathez, E.A., 1971, Geology and petrology of the Logan intrusives of the Hungry Jack Lake quadrangle, Cook County, Minnesota: Tucson, University of Arizona, M.S. thesis, 111 p.

Mathez, E.A., Nathan, H.D., and Morey, G.B., 1977, Geologic map of the Hungry Jack Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-39, scale 1:24,000.

Meints, J.P., Jirsa, M.A., Chandler, V.W., and Miller, J.D., Jr., 1993, Scientific core drilling in parts of Itasca, St. Louis, and Lake Counties, northeastern Minnesota, 1989-1991: Summary of lithologic, geochemical, and geophysical results: Minnesota Geological Survey Information Circular 37, 159 p.

Miller, J.D., Jr., 1986, The geology and petrology of anorthositic rocks in the Duluth Complex, Snowbank Lake quadrangle, northeastern Minnesota: Minneapolis, University of Minnesota, Ph.D. dissertation, 585 p.

———1988, Geologic map of the Silver Bay and Split Rock Point NE quadrangles, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-65, scale 1:24,000.

———1999, Geochemical evaluation of platinum group element (PGE) mineralization in the Sonju Lake intrusion, Finland, Minnesota: Minnesota Geological Survey Information Circular 44, 32 p.

Miller, J.D., Jr., Boerboom, T.J., and Jerde, E.A., 1994, Bedrock geologic map of the Cabin Lake and Cramer 7.5-minute quadrangles, Lake and Cook Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-82, scale 1:24,000.

Miller, J.D., Jr., and Chandler, V.W., 1997, Geology, petrology, and tectonic significance of the Beaver Bay Complex, northeastern Minnesota, *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. 73-96.

Miller, J.D., Jr., Green, J.C., and Boerboom, T.J., 1989, Geologic map of the Illgen City quadrangle, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-66, scale 1:24,000.

Miller, J.D., Jr., Green, J.C., Boerboom, T.J., and Chandler, V.W., 1993, Geology of the Doyle Lake and Finland quadrangles, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-72, scale 1:24,000.

Miller, J.D., Jr., and Ripley, E.M., 1996, Layered intrusions of the Duluth Complex, Minnesota, USA, *in* Cawthorn, R.G., ed., Layered intrusions: Amsterdam, Elsevier Science, p. 257-301.

Miller, J.D., Jr., Schaap, B.D., and Chandler, V.W., 1990, The Sonju Lake intrusion and associated Keweenawan rocks: Geochemical and geophysical evidence of petrogenetic relationships [abs.]: Institute on Lake Superior Geology, 36th Annual Meeting, Thunder Bay, Ontario, Proceedings, v. 36, Program and Abstracts, pt. 1, p. 66-68.

Miller, J.D., Jr., and Vervoort, J.D., 1996, The latent magmatic stage of the Midcontinent rift: A period of magmatic underplating and melting of the lower crust: Institute on Lake Superior Geology, 42nd Annual Meeting, Cable, Wis., Proceedings, v. 42, Program and Abstracts, pt. 1, p. 33-35.

Miller, J.D., Jr., and Weiblen, P.W., 1990, Anorthositic rocks of the Duluth Complex: Examples of rocks formed from plagioclase crystal mush: Journal of Petrology, v. 31, no. 2, p. 295-339.

Morey, G.B., and Nathan, H.D., 1977, Geologic map of the South Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-38, scale 1:24,000.

———1978, Geologic map of the Gunflint Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-42, scale 1:24,000.

Morey, G.B., Weiblen, P.W., Papike, J.J., and Anderson, D.H., 1981, Geologic map of the Long Island Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-46, scale 1:24,000.

Morrison, D.A., Ashwal, L.D., Phinney, W.C., Shih, C., and Wooden, J.L., 1983, Pre-Keweenawan anorthosite inclusions in the Keweenawan Beaver Bay and Duluth Complexes, northeastern Minnesota: Geological Society of America Bulletin, v. 94, no. 2, p. 206-221.

Mudrey, M.G., Jr., 1973, Structure and petrology of the sill on Pigeon Point, Cook County, Minnesota: Minneapolis, University of Minnesota, Ph.D. dissertation, 310 p.

———1977, Geologic map of Pigeon Point quadrangle, Cook County, Minnesota:

Minnesota Geological Survey Miscellaneous Map M-36, scale 1:24,000.

Nelson, N., 1991, A petrologic and geochemical study of granophyric granite in the roof of the Keweenawan Duluth Complex, Eagle Mountain, Cook County, Minnesota: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 151 p., 1 pl.

Oestrike, R.W., Jr., 1983, The Endion sill, Duluth, Minnesota: Mineralogy and Petrology of a composite intrusion: Champaign, Ill., University of Illinois at Urbana-Champaign, M.S. thesis, 142 p.

Paces, J.B., and Miller, J.D., Jr., 1993, Precise U-Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: Geochonological insights to physical, petrogenetic, paleomagnetic and tectonomagmatic processes associated with the 1.1 Ga Midcontinent rift system: Journal of Geophysical Research, v. 98, no. B8, p. 13997-14013.

Palmer, H.C., 1970, Paleomagnetism and correlation of some middle Keweenawan rocks, Lake Superior: Canadian Journal of Earth Sciences, v. 7, no. 6, p. 1410-1436.

Pope, N.M., 1976, Petrology and structure of the Late Precambrian mafic sills east of Silver Creek, Lake County, Minnesota: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 157 p.

Reichhoff, J.A., 1987, Two Keweenawan basaltic dike swarms in the Duluth area, Minnesota: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 168 p., 5 pls.

Schwartz, G.M., and Sandberg, A.E., 1940, Rock series in diabase sills at Duluth, Minnesota: Geological Society of America Bulletin, v. 51, no. 8, p. 1135-1171.

Shank, S.G., 1989, The petrology of the Beaver Bay Complex near Silver Bay, northeastern Minnesota: Minneapolis, University of Minnesota, M.S. thesis, 127 p., 1 pl.

Stevenson, R.J., 1974, A mafic layered intrusion of Keweenawan age near Finland, Lake County, Minnesota: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 160 p.

Sutcliffe, R.H., 1987, Petrology of Middle Proterozoic diabases and picrites from Lake Nipigon, Canada: Contributions to Mineralogy and Petrology, v. 96, no. 2, p. 201-211.

Vervoort, J.D., and Green, J.C., 1997, Origin of evolved magmas in the Midcontinent rift system, northeast Minnesota: Nd-isotope evidence for melting of Archean crust: Canadian Journal of Earth Sciences, v. 34, no. 4, p. 521-535.

Weiblen, P.W., 1982, Keweenawan intrusive igneous rocks, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 57-82.

Weiblen, P.W., Mathez, E.A., and Morey, G.B., 1972, Logan intrusions, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 394-406.

White, W.S., 1966, Tectonics of the Keweenawan basin, western Lake Superior region: U.S. Geological Survey Professional Paper 524-E, 23 p.

Winchell, N.H., 1899, The geology of Minnesota: Geological and Natural History Survey of Minnesota, Final Report, v. 4, 629 p., 100 pls.

Chapter 8

MINERAL POTENTIAL OF THE DULUTH COMPLEX AND RELATED INTRUSIONS

Mark J. Severson, James D. Miller, Jr., Dean M. Peterson, John C. Green, and Steven A. Hauck

As discussed in Chapter 2, increased demand and commodity prices for platinum group elements (PGEs) have recently reinvigorated exploration activity in the Duluth Complex and related Keweenawan intrusions in northeastern Minnesota. Known copper-nickel deposits along the base of the complex are being reassessed for their PGE concentrations, and intrusions stratigraphically higher in the Duluth and Beaver Bay Complexes are being evaluated using new models for stratiform PGE mineralization within well-differentiated tholeiitic systems. A principal objective of geologic map M-119 is to aid identification of new exploration targets by providing an improved geologic picture of the Duluth Complex and related Keweenawan intrusions.

In this chapter, we document the known mineral deposits of the Duluth Complex and related rocks and assess the potential for discovering similar deposits elsewhere in explorable areas of northeastern Minnesota. The types of mineral deposits considered here include copper-nickel-(PGE) sulfide, stratabound and stratiform PGE, iron-titanium ± vanadium oxide, and silver-cobalt fissure veins. We also discuss the economic significance of the North Shore Volcanic Group in terms of the potential for rare metal mineralization of felsic rocks and, indirectly, the regional potential for sulfide deposits implied by copper and nickel concentrations in mafic volcanic rocks. The following discussion focuses on copper-nickel sulfide and stratabound and stratiform PGE deposits because they hold the greatest potential for an economic discovery.

COPPER-NICKEL-(PGE) SULFIDE MINERALIZATION

The fundamental characteristics of this style of mineralization involve sulfur contamination of mafic magmas by pre-Keweenawan footwall rocks, and mineralization occurring in the vicinity of the basal contact of mafic intrusions. The variants of this style of mineralization that may potentially exist in the Duluth Complex include:

- Disseminated copper-nickel-(PGE) sulfide mineralization in basal contact zones of mafic intrusions
- Massive sulfide mineralization at the basal intrusive contact and in footwall rocks
- Sulfide mineralization in major feeder zones (Noril'sk/Voisey's Bay-type; Naldrett, 1997)

Only disseminated copper-nickel sulfide mineralization and basal massive sulfide mineralization are presently known to occur in the Duluth Complex and will be described. In the final part of this section, we will discuss the potential for other occurrences of these two types of mineralization and the potential for Noril'sk/Voisey's Bay-type copper-nickel-(PGE) massive sulfide mineralization in intrusion feeder zones.

Disseminated sulfide mineralization

Large resources of low-grade copper-nickel sulfide ore that locally contain anomalous PGE concentrations are well documented by drilling in the basal zones of the South Kawishiwi and Partridge River intrusions. At least nine subeconomic deposits (Chapter 2, Fig. 2.3) have been delineated in the basal 100 to 300 meters of both intrusions. The mineralization consists predominantly of disseminated sulfides that collectively constitute over 4.4 billion tons of material averaging 0.66 percent copper and 0.2 percent nickel (Listerud and Meineke, 1977). Overall, the copper to nickel ratio averages 3.3:1, ranging from 2.4:1 to 4.11:1 (Chapter 2, Table 2.2). PGE concentrations average about 10 parts per million platinum + palladium (recalculated to 100 percent sulfide), but may range as high as 50 parts per million platinum + palladium (recalculated to 100 percent sulfide) in associated stratabound zones, such as the Birch Lake and Dunka Road deposits. Sulfur isotope analyses consistently indicate that the source of sulfur was from the pelitic country-rocks of the Virginia Formation, which form much of the footwall to the Partridge River intrusion and locally to the South Kawishiwi intrusion (Ripley, 1986).

The sulfide deposits are hosted by taxitic troctolitic to gabbroic rocks that contain abundant inclusions of the various footwall rock types. Within the Partridge River intrusion, the basal unit (Unit I of Severson and Hauck, 1990; see Chapter 6, Fig. 6.10) hosts the vast majority of the disseminated sulfides. Similarly, mineralization within the South Kawishiwi intrusion is confined to the basal heterogeneous (BH), ultramafic 3 (U3), basal augite troctolite/norite (BAN), and updip wedge (UW) units (Severson, 1994; see Chapter 6, Fig. 6.12). The disseminated sulfide minerals occur as interstitial grains that make up between trace amounts and 10 percent of the rock by volume (visual estimation). The average sulfide mineral content is between 1 and 5 percent. Major sulfide minerals are pyrrhotite, chalcopyrite, cubanite, and pentlandite. Pyrrhotite is generally the dominant sulfide, especially closer to the basal contact. Chalcopyrite is generally the dominant copper-sulfide with variable amounts of cubanite. Also present are minor amounts of bornite, talnakhite, chalcocite, digenite, mackinawite, valleriite, violarite, native copper, and platinum group minerals.

Although this mineralization type is described as being present within the basal units of the South Kawishiwi and Partridge River intrusions, the basal zones do not contain sulfides in all areas. Mineralized zones are extremely erratic in their spatial extent and ore grades. Zones that are barren of sulfides commonly interfinger with mineralized zones in a random pattern. This erratic pattern of mineralization, in part, mirrors the lithologic heterogeneity of the basal units. The only exception to this random mineralization pattern is the Maturi deposit (and its downdip eastward extension), where the upper portion of the basal heterogeneous (BH) unit consistently exhibits copper values in excess of 1.0 percent that gradually decrease with depth toward the basal contact. The change to more consistent mineralization at Maturi may be related to a thinning of the basal heterogeneous unit in the area and thus the sulfides are more restricted to a specific horizon. Although the style of mineralization in all of the deposits is dominated by disseminated copper-nickel sulfides, differences occur between the deposits in copper-nickel and PGE grade, thickness, and tonnage. Mineralization profiles from single drill holes within each of the deposits of the South Kawishiwi intrusion are presented in Figure 8.1. Peterson (2001) attributed the higher-grade, sheetlike mineralization of the Maturi and Maturi Extension deposits to confined magma flow of the lower South Kawishiwi intrusion beneath a large pillar of older anorthositic series rocks.

Contrasting with this heterogeneity of rock types and mineralization, some internal PGE-

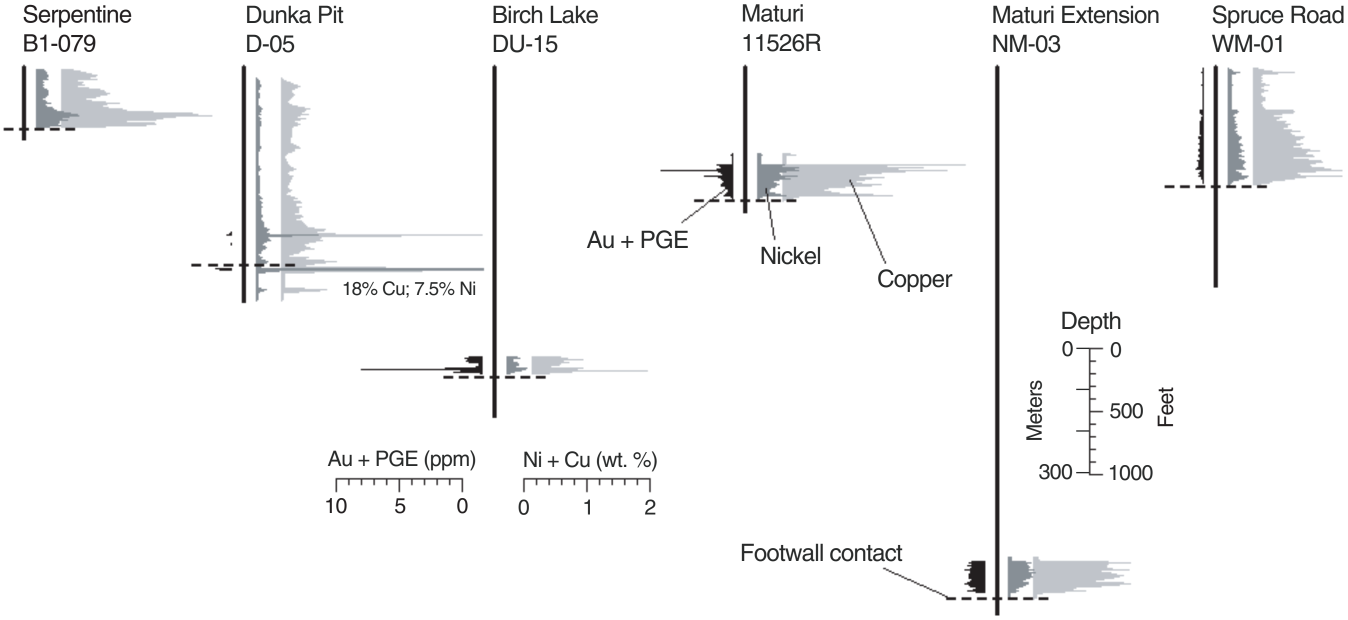


Figure 8.1. Assays from drill holes in each of the copper-nickel deposits of the South Kawishiwi intrusion (Peterson, 2001).

bearing sulfide zones within the lower units exhibit a stratabound relationship to the igneous stratigraphic section. For example, at the Dunka Road (Geerts, 1991) and Babbitt deposits, the top of Unit I immediately beneath an ultramafic layer (Fig. 8.2) commonly exhibits increased copper-PGE grades. These PGE-bearing zones are often copper-enriched. Two other stratabound copper-rich (± PGE) zones are present beneath discontinuous ultramafic horizons within the interior of Unit I at Dunka Road (Fig. 8.2). At the Maturi deposit, a copper-enriched (and possibly PGE-enriched) zone also occurs immediately beneath an ultramafic unit (U3) at the top of the basal heterogeneous unit.

Copper-enrichment often occurs locally near fault zones as in the Wyman Creek, Wetlegs, and Dunka Road deposits close to the basal contact (Severson and Hauck, 1997), and at the South Filson Creek deposit, 670 meters above the basal contact (Kuhns and others, 1990). The causes of

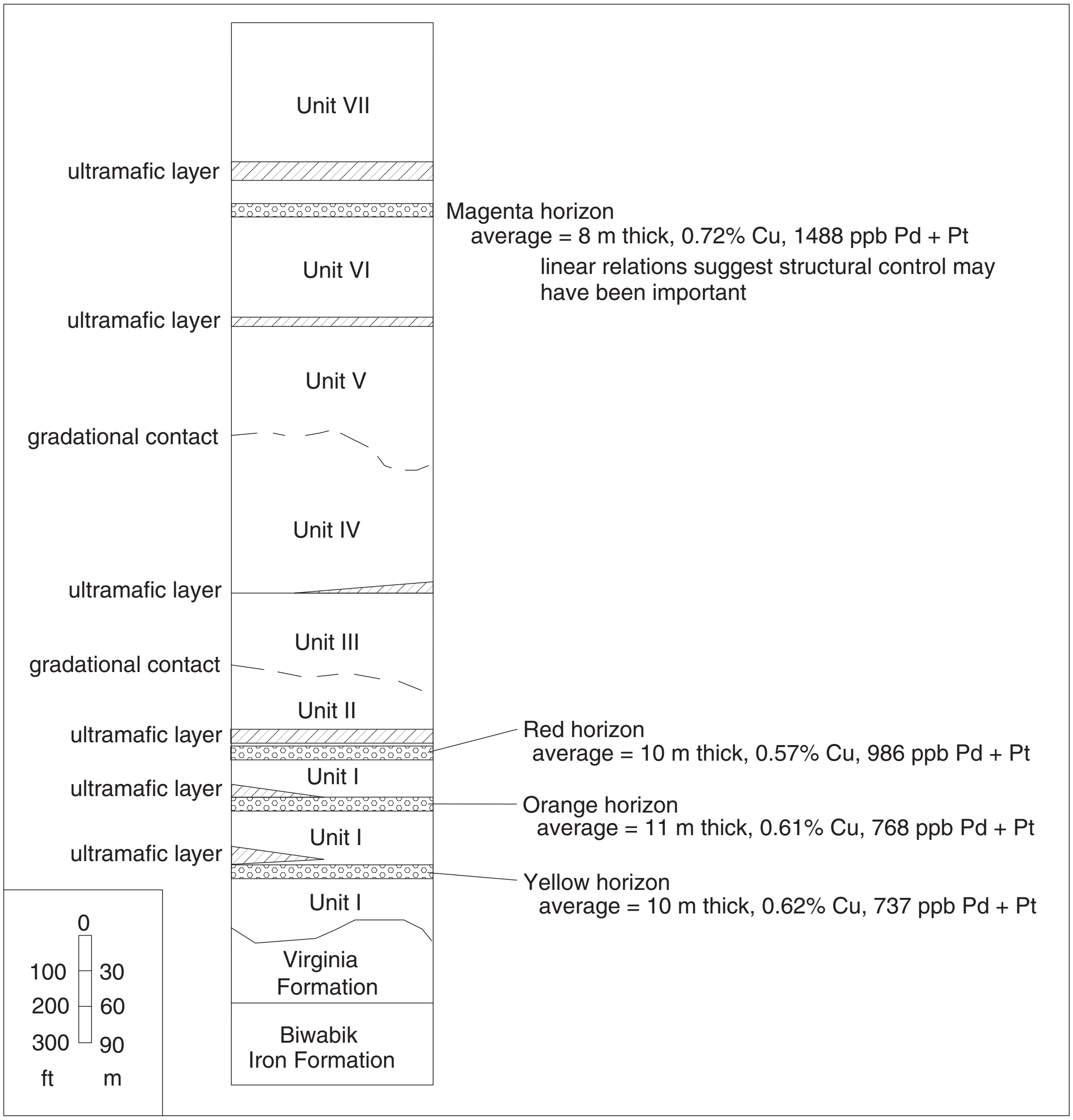


Figure 8.2. Distribution of PGE-bearing stratabound horizons relative to the igneous stratigraphy at the Dunka Road deposit (modified from Geerts, 1991).

copper-PGE enrichment along faults are not entirely clear, but probably involve the remobilization and redeposition of copper and PGEs by circulating chlorine-rich hydrothermal fluids, possibly during the latest stages of magmatic crystallization. Evidence for such fluids is given by the presence of chlorine-rich brown liquid drops that commonly coat the surfaces of drill core after exposure to air. These drops form by a deliquescent process and are found on core from the Fish Lake area north to the Spruce Road deposit (Chapter 2, Fig. 2.3) and the Gunflint Trail area. Analyses of the drops indicate high chlorine content values up to 3,000 parts per million (Dahlberg 1987; Dahlberg and others, 1988; Dahlberg and Saini-Eidukat, 1991). The drops are most common on core from the ultramafic layers (variably serpentinized) and the oxide ultramafic intrusions (OUI). They are also locally associated with disseminated sulfide zones, massive sulfides at the Local Boy ore zone of the Babbitt deposit, massive oxides and ultramafic layers from the U3 unit of the South Kawishiwi intrusion, pre-Duluth Complex sills (Logan-type sill and Cr-sill), and olivine-bearing portions of the metamorphosed footwall Biwabik Iron Formation (submembers C and P; see Chapter 4, Fig. 4.3). In addition to the liquid drops, chlorine-rich coatings on the core occur in a variety of colors and precipitate forms. A complete listing of these drill core coatings is included in Hauck and others (1997a).

In summary, the disseminated sulfide mineralization at each of the copper-nickel deposits, with the exception of the Maturi deposit, can be classified as chaotic with diverse ore grades that are unevenly distributed throughout the basal mineralized units. This diverse nature makes it difficult to predict the overall spatial distribution of ore zones based on widely scattered drill holes and little to no outcrop. More in-fill drilling is needed in order to address ore controls. The cause of the erratic mineralization is probably related to a variety of factors that include:

- The nature of magma emplacement (turbulent versus quiescent)
- The mode of emplacement (along bedding planes in the footwall rocks versus overplating previous magma pulses)
- The volume of magmatic inputs (small incremental batches versus wide-spaced and large-volume batches)
- The total sulfide content of the magma prior to final emplacement
- The sulfide content of the footwall rocks (in situ source)
- The secondary enrichment/depletion of copper and PGEs along faults

Magma pulses in the basal heterogeneous units appear to have formed dispersed sulfides that were unable to coalesce and form massive sulfides. Exceptions include pyrrhotite-rich massive sulfides at the Serpentine and Dunka Pit deposits; however, in these two cases a local sulfur source is also present in the footwall Virginia Formation. Most of the disseminated mineralization appears to have formed from a sulfide melt that interacted with low volumes of silicate magma, as indicated by low to moderate R-factors ranging from 50 to 3,000 (Thériault and others, 1997, 2000). The low R-factors are probably the result of close-spaced magma inputs of limited volume in progressively developing magma chambers accompanied by contamination from the footwall rocks. Conversely, the copper-PGE-enriched zones beneath ultramafic horizons formed from a sulfide melt that apparently interacted with large volumes of silicate magma as indicated by high R-factors in the range of 5,000 to 17,000 (Thériault and others, 1997, 2000). The high R-factors of these zones are indicative of more turbulent magma conditions following a new magma input that crystallized the ultramafic layers. Overall, copper- and PGE-enriched zones within the disseminated sulfide mineralization are associated with a dynamic changeover in the style of emplacement from close-spaced, low-volume, and contaminated pulses to wide-spaced, large-volume, and uncontaminated pulses. Some late hydrothermal secondary enrichment of copper and PGEs also took place adjacent to faults during later stages of emplacement.

Basal massive sulfide mineralization

In a few localized areas along the basal zones of the South Kawishiwi and Partridge River intrusions, semi-massive to massive sulfide mineralization is present at the basal contact. In most cases, the massive to semi-massive sulfide is proximal to either sulfide-rich footwall rocks or structures such as faults and pre-complex folds. Massive sulfide zones that are spatially related to sulfide-rich footwall rocks are intersected in scattered drill holes in the Dunka Pit, Babbitt, and Serpentine deposits (Severson, 1994; Severson and others, 1994; and Zanko and others, 1994, respectively). All of these massive sulfides are pyrrhotite-rich (with generally less than 2 percent copper) and are present at, or slightly above, the basal contact. In all cases, a pyrrhotite-rich member of the footwall Virginia Formation (bedded pyrrhotite unit) is located at the basal contact and is situated updip of the massive sulfide occurrences. This relationship suggests that the bedded pyrrhotite unit acted as a local sulfur source that generated a copper-poor, sulfide-rich melt that was concentrated downdip along the basal contact, via gravity settling. An example of this relationship is portrayed in Figure 8.3 for the Serpentine deposit. Pyrrhotite-rich massive sulfides are also present at Water Hen (in both the OUI and troctolitic rocks), Central Boulder Lake, and Fish Lake exploration areas (Chapter 2, Fig. 2.3).

The massive sulfide occurrence in the Local Boy ore zone of the Babbitt deposit (Fig. 8.4) is clearly structurally controlled. At this locality, the massive sulfide zones are copper-rich (generally 5 to 25 percent copper) and are situated along the axis of an anticline defined by the footwall rock units. The highest PGE values (11 parts per million

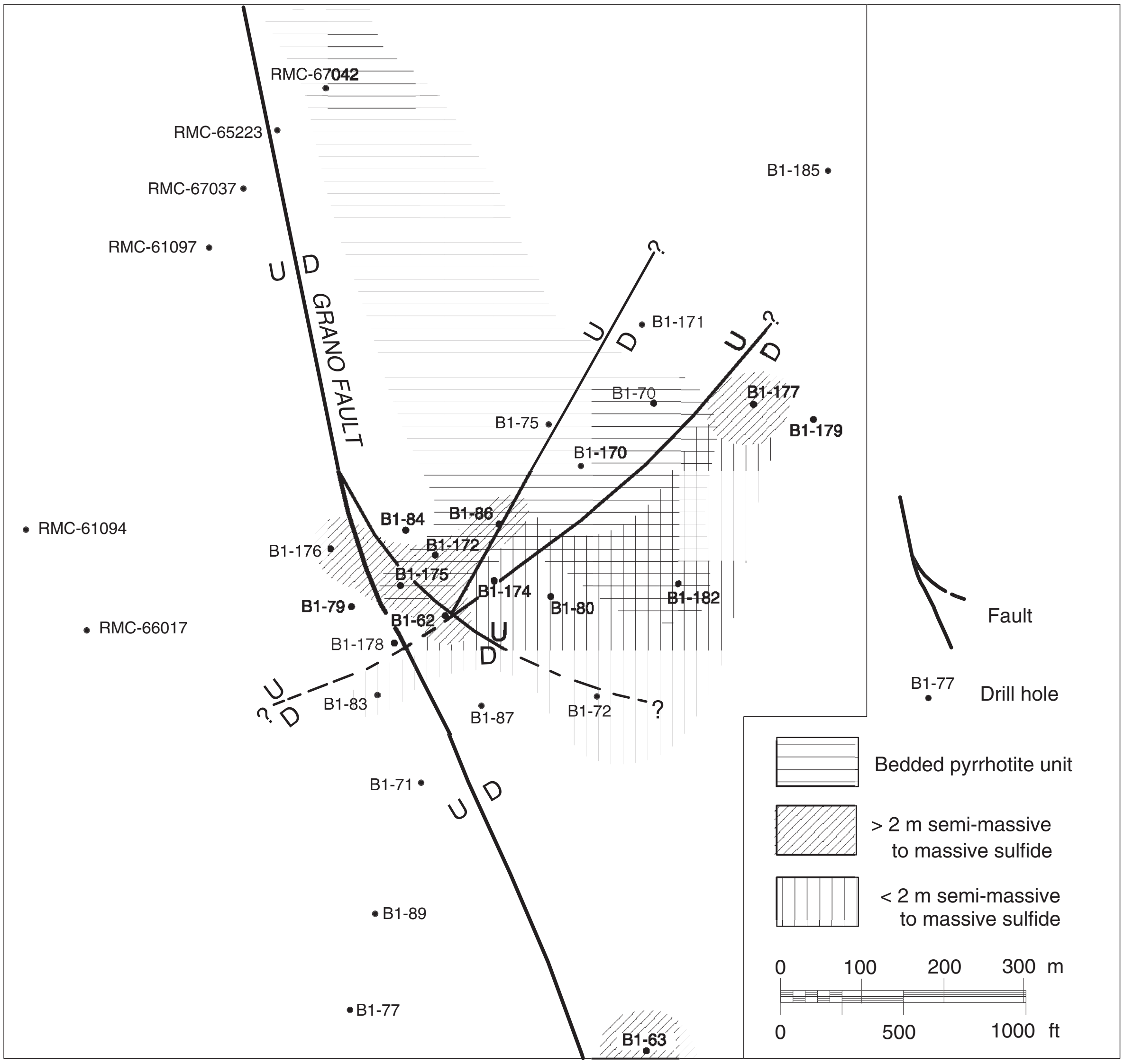


Figure 8.3. Distribution of semi-massive to massive sulfide zones in drill holes relative to the bedded pyrrhotite member within the Virginia Formation at the Serpentine deposit (modified from Zanko and others, 1994).

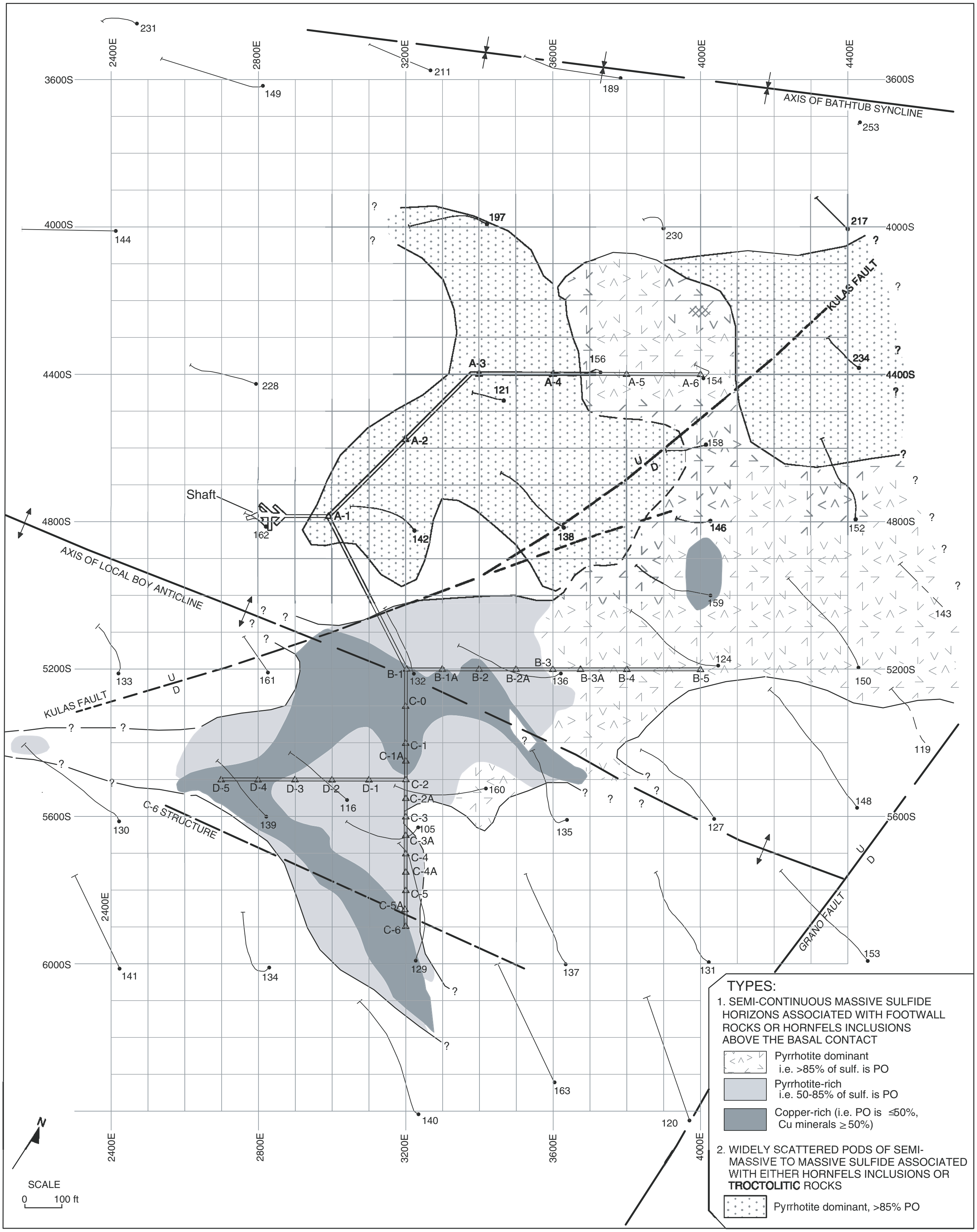


Figure 8.4. Potential distribution of semi-massive to massive sulfide types relative to the Grano fault and Local Boy anticlinal axis at the Local Boy ore zone of the Babbitt deposit (modified from Severson and Zanko, unpub. data).

palladium and 8 parts per million platinum) found to date within the Duluth Complex are associated with these structurally controlled, copper-rich, massive sulfides. The massive sulfides are almost exclusively hosted by the Virginia Formation, present as both inclusions above the basal contact and in the footwall rocks below the basal contact, while interfingering intrusive rocks are relatively barren of massive sulfide. These relationships, plus sulfide textures that are indicative of structural preparation, suggest that the massive sulfides were "injected" into the footwall rocks. Ripley (1986) and Severson and Barnes (1991) proposed that an immiscible sulfide melt, formed in an auxiliary magma chamber at depth, was injected into structurally prepared zones in the footwall rocks along the anticline to form the Local Boy ores. Late movement of chlorine-rich fluids along the axis of the anticline further redistributed and concentrated the PGEs (Severson and Barnes, 1991). Recent studies (Severson and Zanko, unpub. data) indicated that there is an overall increase in the copper-PGE content of the massive sulfide in an east-to-west direction (Fig. 8.4); this is possibly the result of fractional crystallization of immiscible sulfide melt as it migrated into the footwall rocks. In this scenario, the north–south-trending Grano fault is inferred to be a potential feeder zone.

Structurally controlled veins and irregular pods of massive sulfide are locally present within granitic footwall rocks immediately beneath the South Kawishiwi intrusion. These occurrences are intersected in scattered holes that outline two northeast-trending belts (Fig. 8.5). The linearity of the belts suggests they are fault controlled. One of these belts crudely aligns with the Birch Lake fault zone that trends through the Birch Lake PGE prospect. The massive sulfide veins were probably formed by the downward expulsion of a basal immiscible sulfide melt into fractured and faulted footwall rocks (Bonnichsen and others, 1980; Severson, 1994). The veins are moderately copper-enriched due to fractional crystallization of the sulfide melt as it moved down through the footwall rocks.

At the Water Hen area (Chapter 2, Fig. 2.3), orthopyroxenite dikelets (possibly structurally controlled) within fine-grained intrusive rocks above the basal contact contain up to greater than 3 parts per million combined palladium + platinum + gold (Morton and Hauck, 1987). Although these occurrences are not massive sulfide, most of the orthopyroxenites are sulfide-enriched, and chalcopyrite is the dominant sulfide. Severson (1995) compared the orthopyroxenite dikelets at Water Hen to the high-grade footwall veins at the Strathcona mine in the Sudbury Complex, Canada. In the Skibo area, there are massive sulfide veins with maximum values of 11.23 percent copper and 6.42 percent nickel that are associated with troctolitic rocks near the basal contact (Severson, 1995).

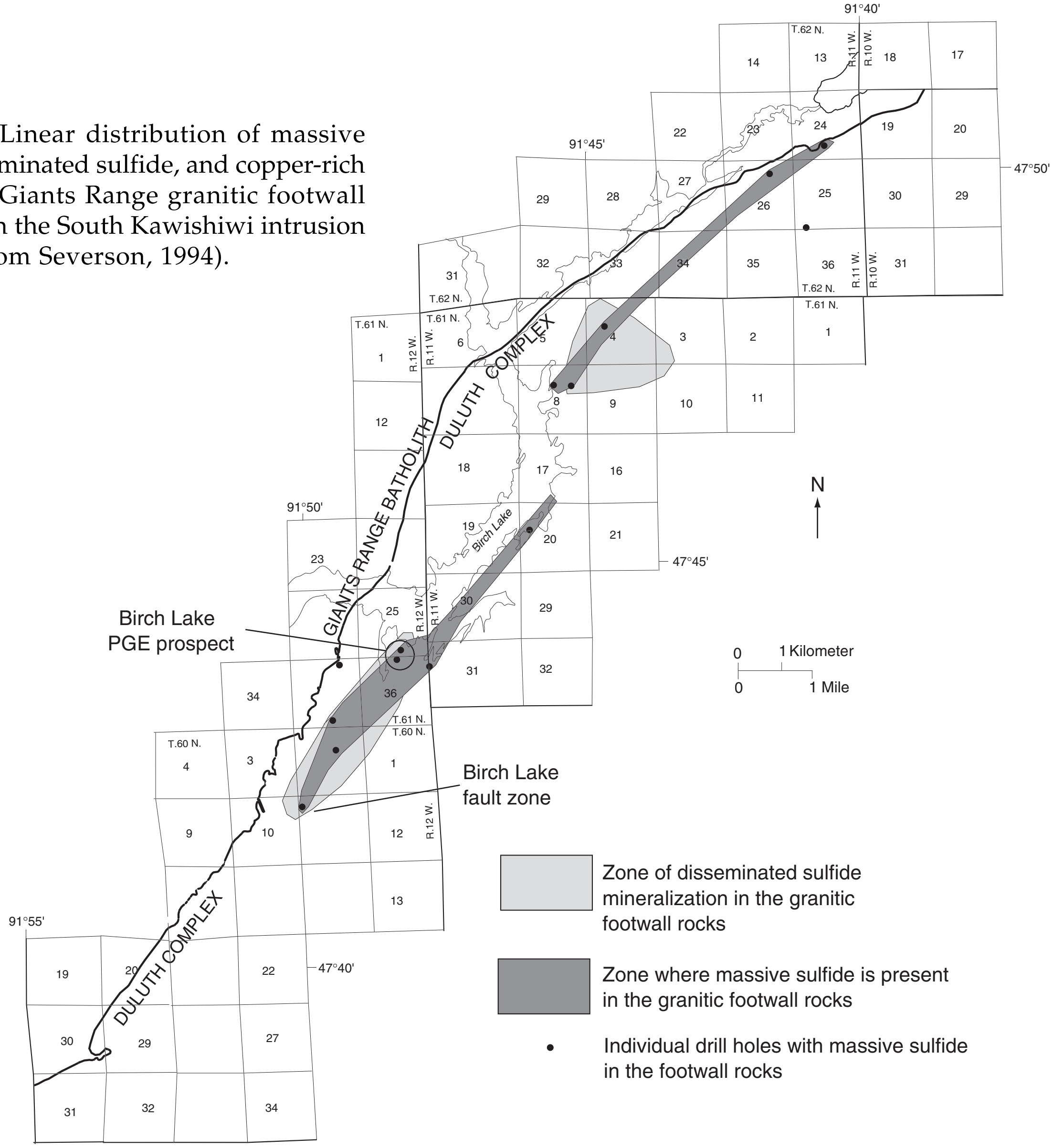
The occurrence of local massive sulfide veins near and below the basal contact of the Duluth Complex is an indication that larger, potentially economic footwall massive sulfide deposits may yet be found. In the Sudbury Complex, pooling of a monosulfide solid solution (mss) melt at the basal contact appears to be an important prerequisite to the injection of fractionated sulfide melts (Naldrett, 1997). Exploration drilling for basal mineralization rarely penetrated far into footwall rocks beneath the Duluth Complex and therefore data are lacking on the petrochemical attributes of footwall massive sulfides. Peterson (1997) compiled the available copper-nickel data for the lower 500 feet of the South Kawishiwi and Partridge River intrusions to evaluate if copper-rich sulfide melts were generated by fractionation of monosulfide solid solution. He defined some interesting target areas, but a more rigorous evaluation of the database and test drilling into the footwall are needed.

Feeder zone sulfide mineralization

Some of the attributes of the Duluth Complex copper-nickel-PGE sulfide deposits resemble those of deposits at Noril'sk, Russia and Voisey's Bay, Canada that are associated with sulfide mineralization in intrusive feeder zones. The common attributes include occurrence in shallow tholeiitic intrusions associated with plateau basalt volcanism, an external sedimentary source of sulfur, and openness to repeated magma influx and expulsion. A critical attribute of the high-grade Noril'sk–Talnakh and Voisey's Bay deposits, not yet positively identified in the Duluth Complex deposits, is the location of a magma conduit. A conduit that experienced repeated influxes of magma appears to be key to the formation of high-grade copper-nickel-PGE deposits (Naldrett, 1997). One of the difficulties in evaluating the potential for feeder zone mineralization in the Duluth Complex is determining whether intrusions were fed one-by-one by local magma conduits or by master conduits that sequentially fed several intrusions.

Several geologists have identified possible conduits that may have fed the South Kawishiwi and Partridge River intrusions. Severson and Zanko (unpub. data) suggested that the Grano fault might mark a possible feeder zone for the Local Boy ore zone at the northeast end of the Partridge River intrusion (Fig. 8.4 and Chapter 2, Fig. 2.3). Thériault and others (2000) postulated that a conduit was present somewhere between the Wetlegs and Dunka Road deposits. Another possible feeder zone may have been along the prolongation of the Siphon fault, which is a Paleoproterozoic growth fault (Graber, 1993) that may have been reactivated during emplacement of the Duluth Complex (Severson and Hauck, 1997). Several authors have suggested the presence of a feeder beneath the Bald Eagle intrusion based on field relations (Weiblen and Morey, 1980) and geophysical attributes (Chandler, 1990). A model relating the emplacement of the South Kawishiwi and Bald Eagle intrusions to this single magma feeder is presented in Chapter 6 (Fig. 6.15). At a more detailed level, Peterson (2001) interpreted the copper-PGE mineralization in the Maturi deposit and its extension to the east (Maturi Extension deposit) as indicative of magma input from the northwest via an arcing macrodike that connects the Bald Eagle and South Kawishiwi intrusions (M-

Figure 8.5. Linear distribution of massive sulfide, disseminated sulfide, and copper-rich veins in the Giants Range granitic footwall rocks beneath the South Kawishiwi intrusion (modified from Severson, 1994).



119). Peterson (2001) envisioned a confined magma flow model that invokes a change from laminar to turbulent flow beneath a pillar of older anorthositic series rocks, increasing the R-factor of the entrained sulfides, and resulting in higher metal contents of the exited (Maturi deposit) and remaining (Maturi Extension deposit) sulfide fraction (Fig. 8.6). A downdip view of the three-dimensional model along the northern margin of the South Kawishiwi intrusion is presented in Figure 8.7. If correct, this model predicts that a Voisey's Bay-type copper-nickel-PGE massive sulfide body may exist in an area south of the Spruce Road deposit.

Taking a more regional view, it is also possible that the two major Bouguer anomalies record the positions of major conduits that fed layered series intrusions in the Duluth Complex and some hypabyssal intrusions in the Beaver Bay Complex (Chapter 3, Fig. 3.5 and Chapter 4, Fig. 4.6). Geophysical models indicate depths of mafic rocks to more than 10 kilometers over these anomalies (Allen and others, 1997). If these intrusive roots represent the master conduits to most Duluth

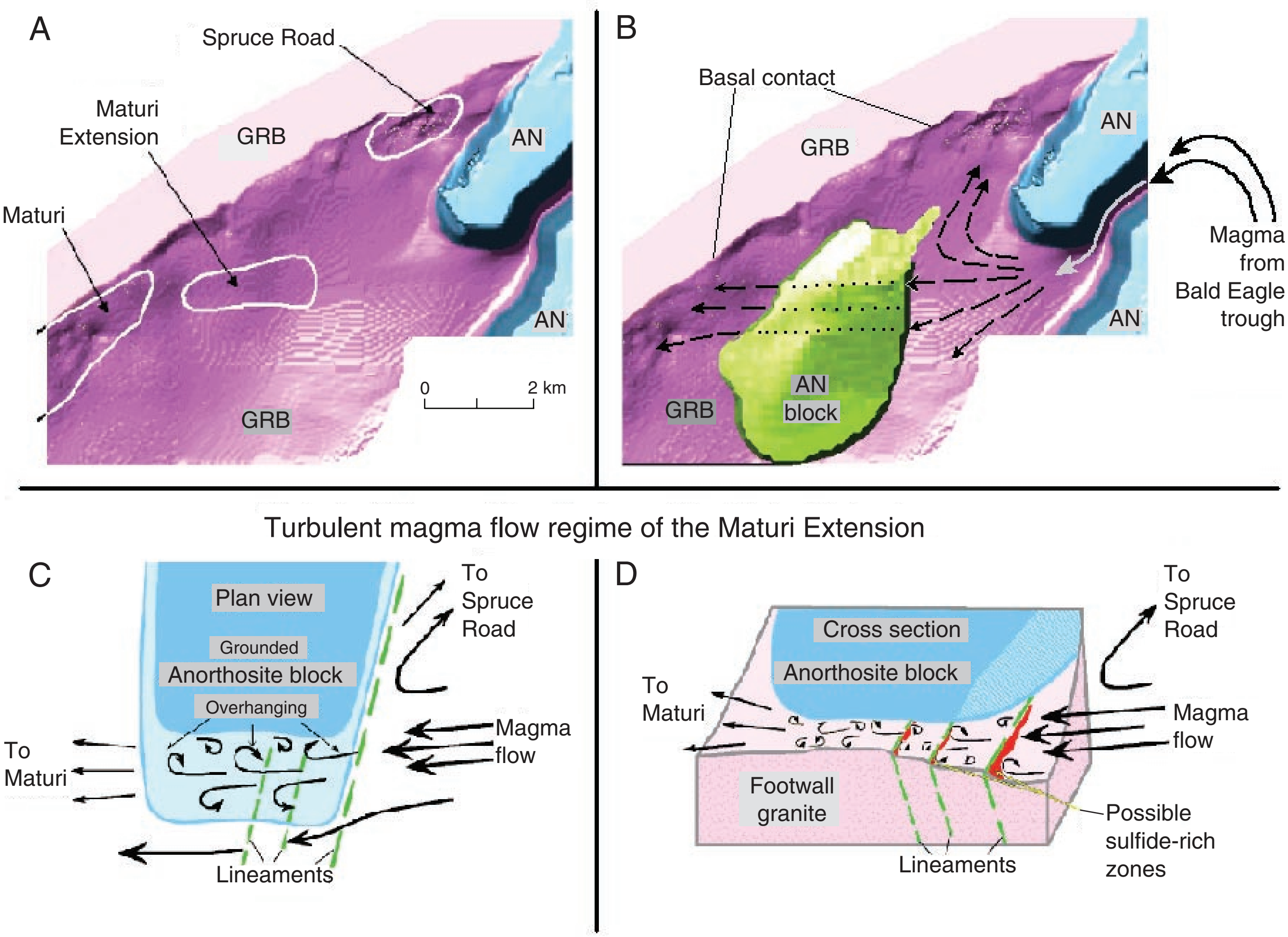


Figure 8.6. Simplified conceptual model of magma flow and copper-nickel-PGE deposits for the northern South Kawishiwi intrusion.

A. Copper-nickel deposit location map overlain on a three-dimensional model of the basal contact of the South Kawishiwi intrusion (Peterson, unpub. data).

B. Magma flow model.

C. Plan view of the turbulent magma flow under the anorthositic series pillar (AN Block).

D. Cross-section of the turbulent magma flow under the anorthositic series pillar (AN Block).

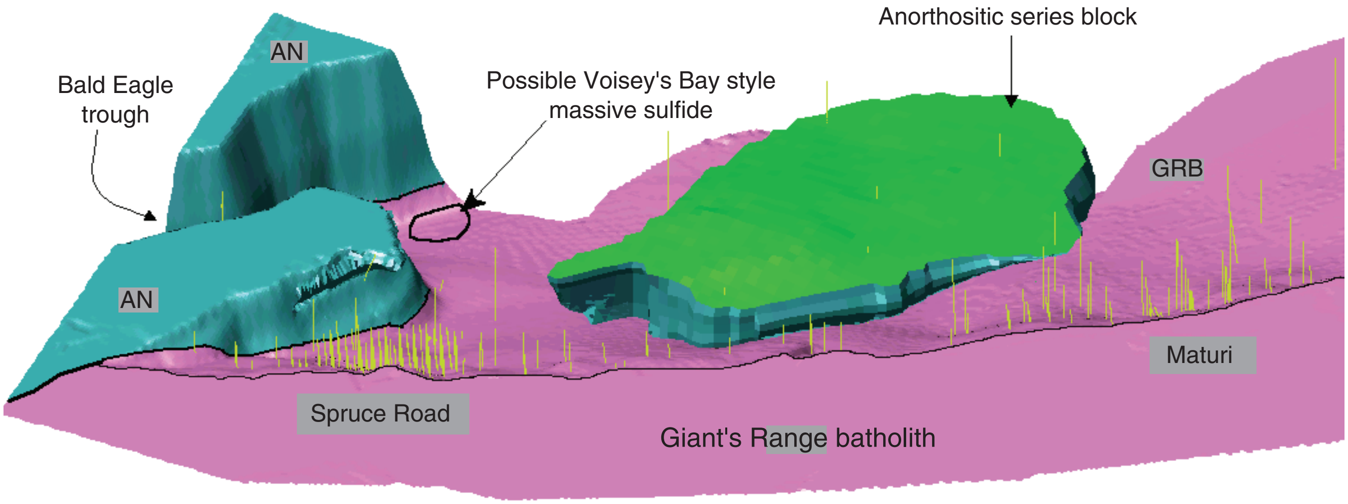


Figure 8.7. View to the south–southeast down the dip of the basal contact of the northern margin of the South Kawishiwi intrusion. A possible Voisey's Bay copper-nickel-PGE massive sulfide target is interpreted to occur at the western end of the macrodike connecting the Bald Eagle and South Kawishiwi intrusions.

Complex intrusions, it suggests that potential feeder-zone sulfide mineralization may exist at prohibitive depths.

New copper-nickel-(PGE) sulfide mineralization targets

Most of the mineral exploration conducted along the base of the Duluth Complex over the past 60 years has focused on copper-nickel potential. As mentioned earlier, many of the established copper-nickel sulfide deposits (Chapter 2, Fig. 2.3) are presently being reevaluated for their PGE concentrations (see Chapter 2), but this work is only beginning. In addition to this reevaluation of known areas of mineralization, other underexplored and unexplored areas of the Duluth and Beaver Bay Complexes hold potential for copper-nickel-(PGE) sulfide mineralization.

Intriguing exploration targets in the otherwise heavily explored basal contact zone of the Duluth Complex are the Sudbury-like copper + PGE-rich sulfide offshoot veins in footwall rocks. Most prior exploration drilling, being focused on copper-nickel sulfide mineralization within the intrusive rocks, stopped when the footwall was reached. As mentioned above, a few longer drill holes and reconnaissance mapping have shown the presence of footwall sulfide vein systems in the Giants Range granite (Severson, 1994). A study of copper-nickel concentrations in the basal zones of the Partridge River and South Kawishiwi intrusions (Peterson, 1997) showed areas of copper enrichment and depletion that may imply fractionation and mobilization of sulfide melt. Peterson (1997) speculated that zones of copper depletion may indicate downward migration of copper + PGE-rich sulfide melt, and therefore the footwall beneath such depleted areas may host offshoot veins. Such targets may be especially inviting where the depletion overlies known footwall structures.

Farther into the Duluth Complex, intrusions were emplaced largely within volcanic rocks or previously formed intrusions. Thus, potential sources of sulfur contamination are lacking, at least at the level of emplacement. Possible exceptions to this are those intrusions emplaced adjacent to the northwest-trending Schroeder–Forest Center ridge that gives rise to the pronounced saddle in the Bouguer anomaly over northeastern Minnesota (Chapter 3, Fig. 3.3). This crustal ridge, which is probably a projection of the Archean Giants Range batholith, appears to have acted as a deflecting rampart to several layered series intrusions (the Bald Eagle, Wilder Lake, and Greenwood Lake intrusions; see Chapter 4, Fig. 4.6). In the northern Beaver Bay Complex, successive dike-like intrusions appear to have intruded along the southeast termination of the ridge or along the same breach in the ridge. Although the general composition of this ridge appears to be granitic, it also contains metavolcanic and metasedimentary rocks, indicated by the presence of inclusions of amphibolite and biotite schist in the Shoepack Lake diorite (Boerboom, 1994)—the earliest intrusion of the Beaver Bay Complex (Chapter 7). Consequently, the potential exists for this crustal ridge to have been a source of extramagmatic sulfur for some Duluth Complex and Beaver Bay Complex intrusions.

Duluth Complex intrusions that may have developed basal zone sulfide mineralization due to interaction with the Schroeder–Forest Center crustal ridge include the Bald Eagle intrusion (northern margin), the Wilder Lake intrusion (basal zone), and the Greenwood Lake intrusion (eastern extension). Of these, only the Greenwood Lake intrusion is in an explorable area outside the Boundary Waters Canoe Area Wilderness. Of the intrusions of the northern Beaver Bay Complex, the basal zones of the Wilson Lake ferrogabbro and offshoot dike, the Dam Five gabbronorite, the Elbow Lake olivine gabbro, and the northwestern margin of the Houghtaling Creek troctolite may be potential targets where they cut across the crustal ridge. These intrusions may also have derived sulfur from the Whitefish Lake granophyre body in the roof zone of the Duluth Complex.

STRATABOUND AND STRATIFORM PGE MINERALIZATION

PGE-enriched zones in the Duluth Complex and related intrusions can be classified into two categories—stratabound and stratiform. The term *stratabound* refers to PGE-enriched horizons that are restricted to a general stratigraphic unit; however, the PGE-enriched zones are often transgressive relative to the enclosing stratigraphy because they are associated with a wide variety of internal rock types that characterize the stratigraphic unit. The term *stratiform* denotes specific PGE-enriched horizons that are sheetlike in form, concordant, and strictly coextensive with laterally persistent igneous layers. Stratabound PGE horizons are located within the lower portions of the intrusions where they are intimately associated with copper-nickel sulfide mineralization and with one or more ultramafic layers that indicate magma recharge events. The stratiform PGE horizons differ from the stratabound ones because they are consistently sulfide-poor and tend to occur at midlevels of well-differentiated intrusions. The origins of the two types also differ because stratabound PGE horizons appear to be related to magma mixing and hydrothermal remobilization, whereas stratiform PGE horizons tend to form by the saturation of magmas in sulfide caused by orthomagmatic processes of fractional crystallization, decompression due to magma venting, cumulus phase changes, as well as magma recharge.

Stratabound PGE mineralization

Stratabound PGE-enriched horizons, with low to moderate sulfide concentrations (0.05 to 1.0 weight percent sulfur), are commonly associated with ultramafic layers in the Dunka Road, Babbitt, Wetlegs, and Birch Lake deposits (Chapter 2, Fig. 2.3). Elevated copper and PGE concentrations at the Dunka Road deposit, and to a lesser extent the Babbitt and Wetlegs deposits, occur at the extreme top of Unit I immediately beneath a laterally persistent ultramafic layer. At Dunka Road, this stratabound horizon (red horizon of Geerts, 1991, 1994) averages about 10-meters-thick and contains an average of 1.0 part per million palladium + platinum (Fig. 8.2). Recent work by Thériault and others (1997, 2000) suggested that the sulfur was largely derived from the mafic magma and that this stratabound horizon was formed as a result of magma mixing. Two similar stratabound PGE-enriched horizons, related to laterally discontinuous ultramafic layers (Fig. 8.2), occur toward the middle of Unit I at Dunka Road (orange and yellow horizons of Geerts, 1991, 1994). To the west of Dunka Road, the stratabound PGE horizon at the top of Unit I is also present at the Wetlegs and Wyman Creek deposits. In those areas, however, the overall palladium content in this horizon exhibits a definite decrease in an east-to-west direction, suggesting that as the magma was intruded it became progressively impoverished with respect to PGEs (Severson and Hauck, 1997; Thériault and others, 1997).

PGE-enriched stratabound horizons associated with ultramafic layers situated above the basal contact also occur at the Dunka Road and Wetlegs deposits (Geerts 1991, 1994; Severson and Hauck, 1997). Both of these occurrences span across the ultramafic layer that separates Units VI and VII (Fig. 8.2). Further to the south in the Water Hen area, one drill hole intersected a layered ultramafic package that contains a 20-centimeter-thick semi-massive oxide (chromium titanomagnetite) layer assaying 780 parts per billion platinum. This occurrence is also positioned well above the basal contact. A similar semi-massive oxide occurrence associated with ultramafic layers with anomalous PGEs was also cut by a drill hole in the Fish Lake area, located near the base of the Duluth layered series (Sassani, 1992; Severson, 1995).

Another example of a PGE stratabound horizon is at the Birch Lake PGE prospect within the South Kawishiwi intrusion. There, PGE contents as high as 9 parts per million palladium + platinum, and Cr_2O_3 contents locally as high as 10 weight percent are associated with a wide variety of rock types within the U3 unit. The U3 unit consists of alternating troctolitic and ultramafic layers in which variably sulfide-mineralized zones and discontinuous pods of Cr-bearing massive oxide both occur (Severson, 1994). As stated in Chapter 6, the massive oxide pods are interpreted based on empirical relationships to have been produced by assimilation and partial melting of the Biwabik Iron Formation. This oxide-rich partial melt may have initially acted as a trap that concentrated chromium and titanium, and through further assimilation and contamination of the magma, may have led to precipitation of PGEs. However, because the ultramafic layers of the U3 unit are interpreted to record new influxes of more primitive magma (Severson, 1994), magma mixing may have had a more significant effect on PGE mineralization. Stable and radiogenic isotope data suggest that both magmatic and footwall contamination processes were active at Birch Lake (Hauck and others, 1997b).

Furthermore, the presence of chlorine-rich drops on the surface of drill core from the Birch Lake area suggests that a hydrothermal model of concentrating the PGE could also be invoked. A model involving ascending chlorine-rich hydrothermal fluids, depicted in Figure 8.8 and similar to a model proposed by Boudreau and McCallum (1992), may have remobilized and further concentrated the PGE along the northeast-trending Birch Lake fault (Severson, 1994). The model of Boudreau and McCallum (1992) seems to reasonably explain why anomalous PGE values (greater than 100 parts per billion palladium and greater than 50 parts per billion platinum) are common in the U3 unit of the South Kawishiwi intrusion. According to the model as applied to the South Kawishiwi intrusion, an upward-moving, chlorine-rich, intrusion-wide hydrothermal front was capable of remobilizing PGEs from the basal heterogeneous unit and depositing them in the U3 unit, which represents the lowest potential stratigraphic trap. However, this model does not account for the presence of significantly higher PGE contents in the U3 unit at the Birch Lake area if an intrusion-wide front is envisioned. Rather, specific drill holes in the Birch Lake area contain higher PGE values (greater than 1 part per million palladium) while other holes outside of the Birch Lake area are void of similar high values even though the geologic setting of all the holes is the same. In essence, a straightforward application of the model of Boudreau and McCallum (1992) may be incorrect. A possible explanation, depicted in Figure 8.8, is that the Birch Lake area represents an area where there was a local increase in the amount of upward-moving, chlorine-rich solutions that were concentrated, or funneled, along the Birch Lake fault. Late granophyre bodies and footwall massive sulfide veins (Fig. 8.5) situated preferentially along the fault zone imply that the fault was repeatedly reactivated during emplacement of the South Kawishiwi intrusion (Severson, 1994; Hauck and others, 1997a).

Dahlberg (1987) suggested that PGE-mineralizing fluids at the Birch Lake area were structurally controlled not by the Birch Lake fault but by inferred northwest–southeast crosscutting structures that are evident in the regional gravity and aeromagnetic data. In summary, the mineralization style in the U3 unit at the Birch Lake area is still poorly understood and appears to be related to a magmatic process, coupled with footwall contamination, that was later modified by hydrothermal activity along a northeast- and/or northwest-trending fault zone. Exploratory drilling is ongoing at Birch Lake and concepts pertaining to the origin of the PGEs change as new information is collected.

Stratiform PGE mineralization

Model

Recent discoveries of gold- and PGE-enriched horizons (or PGE reefs) in the upper part of the Skaergaard intrusion (Bird and others, 1991; Andersen and others, 1998) and related Tertiary intrusions of east Greenland (Aranson and others, 1997) have stimulated exploration for such deposits in other tholeiitic layered intrusions such as those comprising the Duluth Complex. Stratiform PGE mineralization in well-differentiated tholeiitic intrusions are similar to classic PGE reef deposits hosted by ultramafic-mafic complexes, such as the Bushveld and Stillwater Complexes, in that they occur as sulfide-poor (less than 1 weight percent),

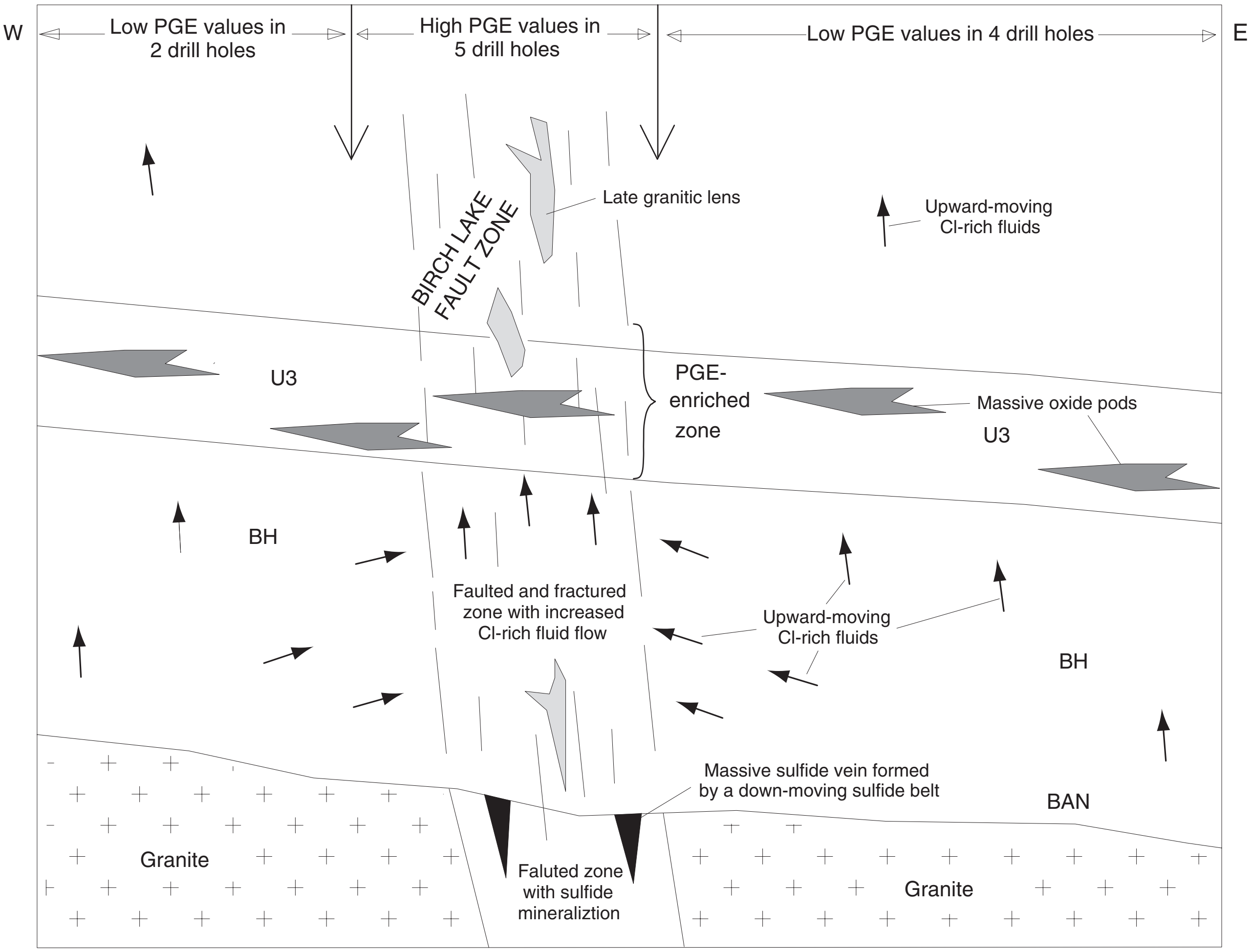


Figure 8.8. Schematic diagram showing the possible role that the Birch Lake fault may have played in funneling upward-moving, chlorine-rich solutions and the resultant re-concentration of significant magmatic PGEs within the U3 unit at the Birch Lake PGE area within the South Kawishiwi intrusion (modified from Severson, 1994). BH—Basal heterogeneous unit, BAN—Basal augite troctolite/norite unit, U3—ultramafic 3 unit.

PGE-rich intervals that are several meters thick and are conformable with igneous layering. However, stratiform PGE mineralization in tholeiitic intrusions, termed Skaergaard-type PGE mineralization by Prendergast (2000), differs from the classic PGE reefs because it is:

- Exclusively associated with mantle plume-influenced, continental rift environments
- Of Middle Proterozoic age or younger
- Associated with aluminous, olivine tholeiitic parent magma compositions that experience Fenner-type crystallization differentiation
- Hosted by ferrogabbroic cumulate rocks
- Associated with copper-rich, nickel-poor sulfide
- Associated with significant gold that is stratigraphically offset above peak PGE concentrations

Although there is considerable disagreement about how classic PGE reefs formed (Cawthorn, 1999), most believe that Skaergaard-type reefs are orthomagmatic (formation by the saturation, exsolution, and settling of sulfide melt from silicate magma). Boudreau and Meurer (1999) gave the only notable objection to an orthomagmatic model for Skaergaard-type PGE mineralization, arguing instead for a hydrothermal origin.

The key requirements for the orthomagmatic formation of an economic PGE reef in a tholeiitic intrusion are:

- The parent magma must be initially sulfide-undersaturated
- The parent magma must have a high initial PGE concentration and/or experience a considerable amount of fractional crystallization to build up noble metal concentrations prior to sulfide saturation
- The initial segregation of sulfide melt must be associated with a large R-factor (silicate/sulfide melt ratio)

These required conditions imply that the best chance for significant stratiform PGE mineralization in a tholeiitic intrusion should be at a mid- to upper-level horizon that marks the first "cumulus arrival" of immiscible sulfide melt.

Given a well-differentiated, initially sulfide-undersaturated tholeiitic intrusion, its ability to form an economic PGE reef depends on the manner by which sulfide becomes saturated in the magma. To maximize the PGE grade, sulfide saturation should be triggered in such a way that the exsolved sulfide melt is exposed to the greatest volume of silicate melt (Naldrett, 1989b). In this way, dense droplets of sulfide melt can efficiently scavenge PGEs and other chalcophile metals from the silicate magma as they settle to the cumulate floor of the magma chamber to form a stratiform horizon. Chlorine-bearing deuteric fluids may have an important effect on improving the PGE tenor of sulfide ore, and such a hydrothermal process is most effective where it acts on a magmatically generated sulfide-enriched horizon. Mechanisms that may trigger sulfide saturation include:

Fractional crystallization—Because sulfur is an incompatible element in silicate minerals, sulfide will become enriched in differentiating magmas ultimately to the point of saturation and exsolution.

Magma recharge and mixing—Unlike variable sulfide solubility in ultramafic-mafic magmas that produce classic PGE reefs (Naldrett, 1989b), sulfide solubility in differentiating tholeiitic magmas remains fairly constant over the course of fractional crystallization due to the offsetting effects of temperature and Fe-enrichment (Haughton and others, 1974; Naldrett, 1989a; Poulson and Ohmoto, 1990). Therefore, mixing of magmas with comparable sulfide solubilities is unlikely to produce sulfide saturation or oversaturation. Magma mixing probably works in the formation of stratabound PGE mineralization described above because it also involves sulfide contamination in recharging PGE-rich magmas by basal sulfide-bearing units.

Decompression due to magma venting—At shallow crustal depths, sulfide solubility appears to positively correlate with pressure (Carroll and Rutherford, 1985; Naldrett, 1989a). Consequently, in a magma that is close to sulfide saturation, decompression due to magma venting can potentially trigger system-wide exsolution of sulfide melt.

Phase changes—The cumulus arrival of a mineral phase that abruptly lowers the iron content of the magma can potentially trigger sulfide saturation. Magnetite crystallization would be the most effective phase change. This was the apparent trigger for sulfide saturation in the Rincón del Tigre magma system (Prendergast, 2000).

Most intrusions of the Duluth and Beaver Bay Complexes formed from initially sulfide-undersaturated magmas and show evidence of having undergone one or more of the above-mentioned processes during crystallization. Two of these intrusions, the Sonju Lake intrusion (Miller, 1999) and the layered series at Duluth (Miller, 1998a, b), have been studied for their potential to host stratiform PGE mineralization, and subeconomic mineralization has been found in both areas. The Sonju Lake intrusion was a closed magmatic system and the layered series at Duluth was a more open magmatic system. Studies conducted thus far provide exploration guides for finding PGE reefs in associated Keweenawan intrusions. The salient features of PGE mineralization in these two intrusion types are outlined below and the section concludes with guides for stratiform PGE mineralization exploration.

Stratiform PGE mineralization in the Sonju Lake intrusion

The Sonju Lake intrusion is a 1,200-meter-thick, shallow-dipping, sheetlike intrusion that forms part of the Beaver Bay Complex (Chapter 7). Although its exposed strike-length is only about 3 kilometers, the Sonju Lake intrusion has a distinctive aeromagnetic signature that can be traced for at least 20 kilometers beneath a cover of glacial drift (Chapter 7, Fig. 7.2). The nearly constant width of its aeromagnetic anomaly suggests that the intrusive sheet retains a fairly uniform thickness and dip angle over most of this distance. The eastern margin of the Sonju Lake intrusion is abruptly truncated by a Beaver River diabase dike. The base of the Sonju Lake intrusion is in intrusive contact with a complex mixture of gabbroic to dioritic rocks, granophyre, and volcanic hornfels. The top of the Sonju Lake intrusion is in gradational contact with a granophyric quartz ferromonzodiorite phase of the Finland granite. The granite is thought to have acted as a density barrier that caused the Sonju Lake intrusion mafic magma to underplate it (Miller and Chandler, 1997).

The Sonju Lake intrusion is predominantly composed of well-laminated, mafic mesocumulates that define a unidirectionally differentiated sequence. Between a lower contact zone of fine-grained melatroctolite cumulates (unit slmt—OP cumulate, M-119) and an upper zone of unlaminated olivine ferromonzodiorite (unit slmd, M-119), five units are distinguished on the basis of cumulus mineral assemblages (Fig. 8.9) and are shown on map M-119. In ascending order these units are: sld—dunite (O), slt—troctolite (PO), slg—gabbro (POC), slfg—ferrogabbro (PCF ± O), and slad—apatite olivine ferrodiorite (PCFOA). This cumulus stratigraphy is complemented by a smooth cryptic variation in mineral compositions (Chapter 7, Fig. 7.4).

The parent magma composition of the Sonju Lake intrusion is estimated to be an uncontaminated, moderately evolved olivine tholeiite. Miller and Ripley (1996) calculated the bulk composition of the Sonju Lake intrusion by a weighted sum of its chemostratigraphy, and by using fractional crystallization models (for example Nielsen, 1990), they demonstrated that this composition is a reasonable estimate of the parent magma. Similar modeling of the cumulus stratigraphy and cryptic variation suggests that the Sonju Lake intrusion formed by unidirectional fractional crystallization under nearly closed conditions.

To determine the possible location of a stratiform PGE reef in the Sonju Lake intrusion, a total of 67 outcrop and drill core samples that profile the intrusion were analyzed for platinum, palladium, gold, sulfur, copper, and other major and trace elements (Miller, 1999). These data indicate that a narrow PGE-enriched interval exists within the ferrogabbro unit (slfg, M-119) and lies immediately below the stratigraphic level marking the initial saturation of sulfide melt in the Sonju Lake intrusion magma. Measuring stratigraphic height in the Sonju Lake intrusion relative to the horizon where cumulus augite appears (slt–slg unit boundary, Fig. 8.9), initial saturation and segregation of sulfide melt is inferred to occur at the +322-meter level, where an increase in copper abundance is recognized (Fig. 8.9). Copper content increases from consistently less than 100 parts per million below the +322-meter level to greater than 500 parts per million above, and then gradually decreases to below 100 parts per million in the upper part of the intrusion. This pattern is consistent with:

- Sulfide undersaturated conditions below the +322-meter level
- The saturation and "cumulus" segregation of sulfide melt at the +322-meter level
- The gradual depletion of copper abundance due to continued exsolution of sulfide melt above the +322-meter level

Nickel was strongly depleted in the magma at the time of inferred sulfide saturation, presumably by prolonged olivine crystallization.

Interestingly, the onset of sulfide saturation at the +322-meter level implied by the abrupt increase in copper abundance is not reflected in the sulfur data (Fig. 8.9). Theoretically, a gabbro cumulate saturated in sulfide melt should contain a minimum of 400 parts per million sulfur based on sulfide solubility of 0.1 weight percent for a moderately evolved mafic magma (Haughton and others, 1974; Boudreau and McCallum, 1992). The sulfur abundance in cumulates below the +322-meter level are consistently less than the theoretical saturation benchmark. However, sulfur concentrations above the +322-meter level vary unsystematically between less than 100 and 500 parts per million, and only sustain greater than 400 parts per million sulfur concentrations above about +460 meters. Petrographic observations confirm that this zone of presumed sulfide saturation is locally poor in modal sulfide and where present, the sulfide is dominated by copper-rich varieties (chalcopyrite, bornite, and digenite). A possible explanation for the high copper, low sulfur samples in the zone between +322 meters and +460 meters is that oxidizing deuteric fluids caused dissolution of sulfur without mobilizing copper. A similar oxidation/desulfurization process has been noted in the low-sulfide PGE reefs in eastern Greenland intrusions (Skaergaard,

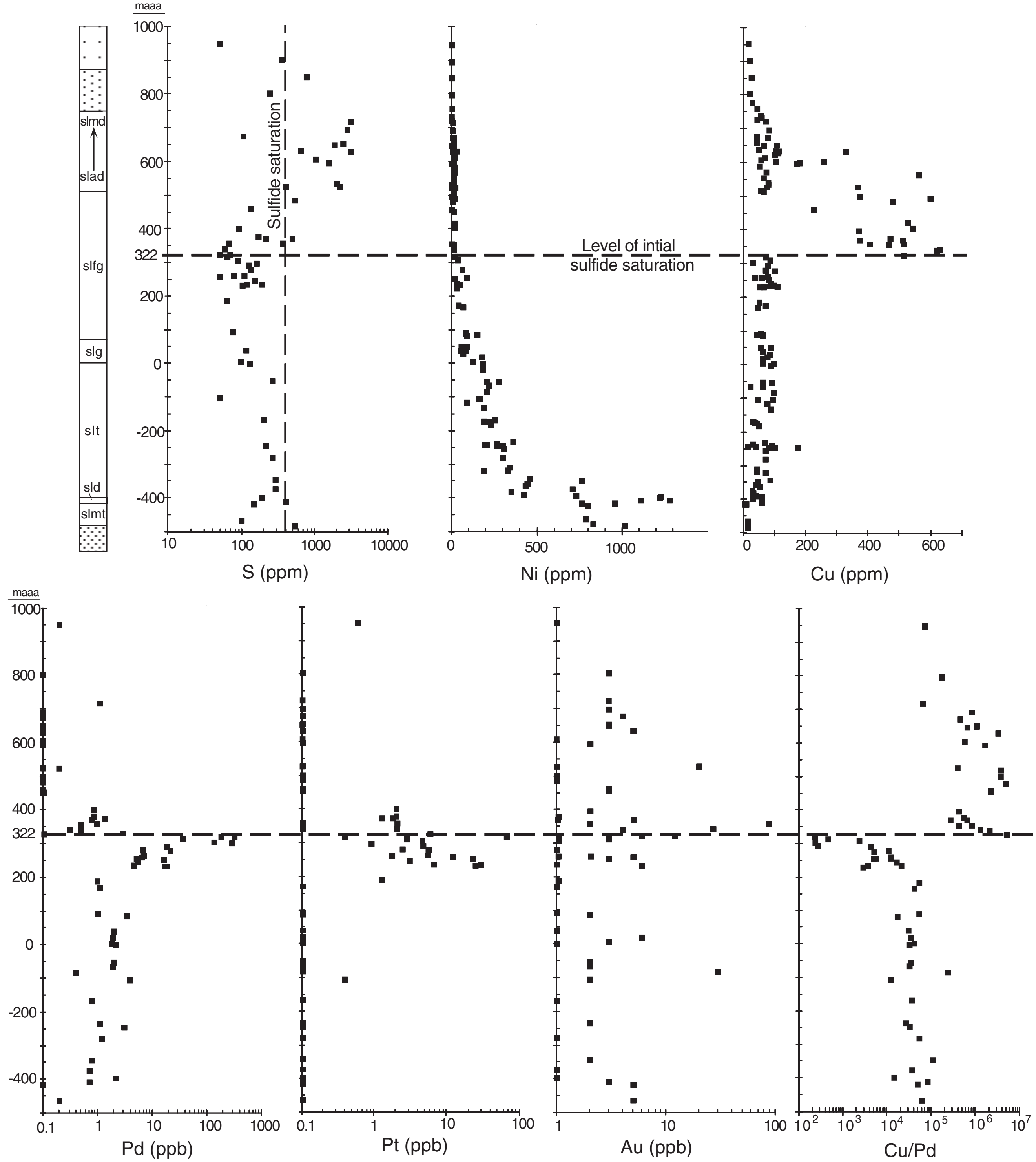


Figure 8.9. Chemostratigraphic variations in whole rock concentrations of sulfur, nickel, copper, palladium, platinum, gold, and copper/palladium through the Sonju Lake intrusion. Sample height is measured relative to the level of cumulus augite arrival (maaa—meters above cumulus augite arrival). The abrupt increase in copper concentration at the 322-meter level is interpreted to indicate sulfide. Data from Miller (1999).

Andersen and others, 1998; Kap Edvard Holm, Aranson and Bird, 2000). The Sonju Lake intrusion displays several features that are consistent with such a process of oxidation and desulfurization:

- Moderate degrees of chloritic and uralitic alteration of pyroxene are common in ferrogabbroic cumulates of the ferrogabbro (slfg, M-119) unit
- Copper-rich sulfides (chalcopyrite, bornite, and digenite) predominate in samples near the +322-meter level
- Secondary veins of pyrite with hematite occur locally above the +322-meter level

If deuteric desulfurization is a widespread phenomenon in mafic layered intrusions, variations in copper abundance rather than total sulfur may be better indicators of magmatic sulfide saturation.

There are no overt changes in lithology evident from field observations across the horizon of increased copper abundance (and PGE enrichment) that would suggest sulfide saturation was triggered by a significant perturbation to the magma system (such as magma recharge, assimilation, or venting). The only notable change observed across the horizon of initial sulfide saturation is the gradual changeover from titanomagnetite-dominated to ilmenite-dominated cumulus oxide phases. However, this also seems an unlikely triggering mechanism because such a change should have minimal effect on the FeO content of the magma and thus sulfide solubility. Rather, given the well-differentiated and closed nature of the Sonju Lake intrusion system, it is concluded that simple crystallization differentiation was the process primarily responsible for not only driving the magma to sulfide saturation, but also for triggering the initial sulfide exsolution event.

Palladium consistently peaks in abundance and the ratio of copper to palladium shows an abrupt increase near the +322-meter horizon of initial sulfide saturation (Fig. 8.9). Concentrations of platinum and gold show similar though less regular trends. In the lower two-thirds of the intrusion, where copper values are consistently less than 100 parts per million, palladium values average around 2 parts per billion and range between 0.7 and 5 parts per billion. Estimating that the lower Sonju Lake intrusion mesocumulates contain about 30 weight percent trapped liquid component (Miller and Ripley, 1996), the average 1 to 3 parts per billion concentrations of palladium observed in the cumulates below +230 meters (Fig. 8.9) imply a parent magma concentration of 3 to 10 parts per billion. This is an undepleted concentration that is consistent with observed abundances in plume-related basalts (~7.6 parts per billion palladium, Barnes and others, 1993). Upward from about the +230-meter level, palladium abundance increases regularly to a peak concentration of 320 parts per billion in the sample just below the first known sample to display an abrupt jump in copper to greater than 500 parts per million (see Miller, 1999, Table 1). This high palladium sample also yields the greatest platinum concentration (66 parts per billion), although a secondary platinum peak (less than 30 parts per billion) seems to exist about 90 meters below the sulfide saturation level. The highest gold concentration (85 parts per billion) occurs 35 meters above the level of initial sulfur saturation, although its variation is less systematic than palladium and platinum (Fig. 8.9). In the first high-concentration copper sample (greater than 500 parts per billion) and in most overlying samples, palladium and platinum abundances drop to below detection limits (less than 0.1 part per billion).

The efficiency with which PGEs were scavenged from the Sonju Lake intrusion magma with the “cumulus arrival” of sulfide melt is indicated by the 10^4 increase in copper/palladium observed across the +322-meter horizon (Fig. 8.9). Changes in the copper/palladium ratio reflect the fact that the sulfide melt/silicate magma partition coefficient for palladium is several orders-of-magnitude greater than that for copper (Peach and others, 1990). The copper/palladium versus palladium variation in the Sonju Lake intrusion (see Miller, 1999, Fig. 7) implies that each aliquot of sulfide melt in the initial sulfide segregation event encountered over 10^5 times that volume of silicate magma. Such an implied R-factor suggests that an even more PGE-enriched horizon may exist in the 7-meter-thick interval between the sample with peak palladium concentration and the overlying sample with increased copper abundances. Detailed geochemical sampling must be conducted to ascertain the thickness and peak grade of the Sonju Lake intrusion reef.

When directly comparing the Sonju Lake and Skaergaard intrusions, not only are their petrologic similarities evident, but also when comparably scaled, their patterns of precious metal and sulfide mineralization are remarkably similar (Fig. 8.10).

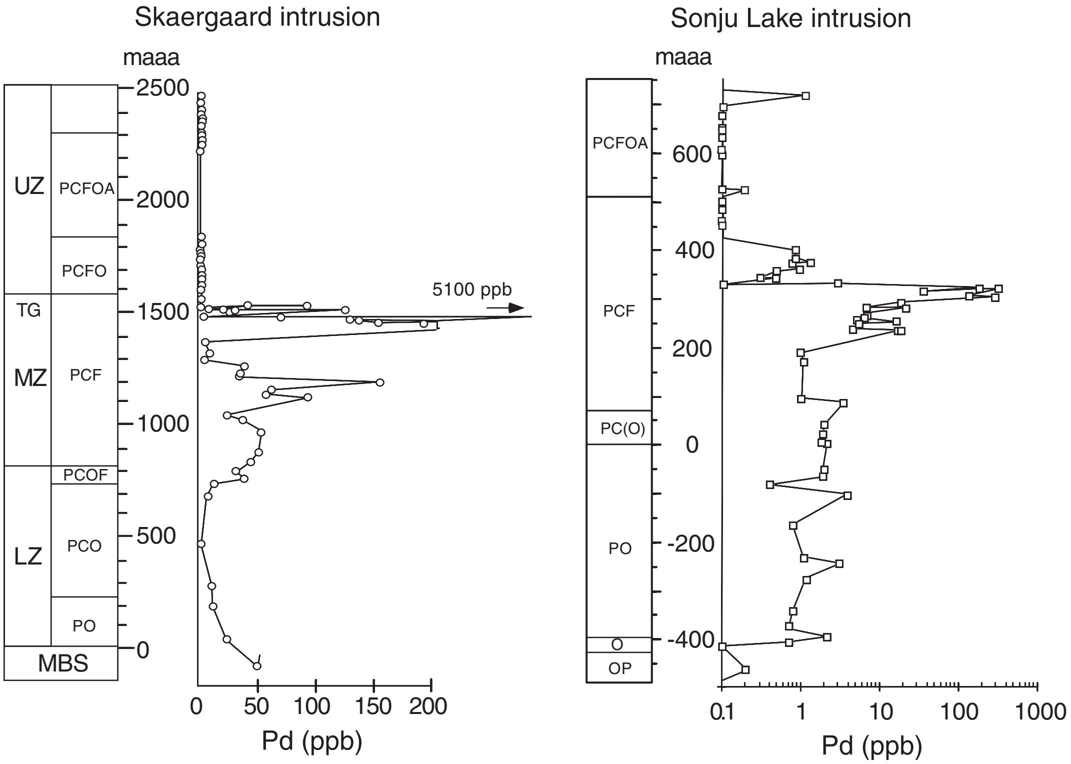


Figure 8.10. Comparison of generalized igneous stratigraphy and stratigraphic variation of palladium concentration in the Skaergaard and Sonju Lake intrusions. Note scaling differences in stratigraphic height and in palladium concentration. The columns show the cumulate stratigraphies of the two intrusions. Unit abbreviations for the Skaergaard intrusions are LZ-lower zone, MZ-middle zone, UZ upper zone, and TG, triple group. Skaergaard data from Andersen and others (1998).

Their similar paragenetic sequences of cumulus minerals imply comparable closed-system crystallization differentiation of aluminous, olivine tholeiitic parent magmas. Based on a 400 parts per million sulfur benchmark and/or increases in copper abundance, both parent magmas were initially sulfide-undersaturated and became saturated at proportionally similar levels in their crystallization histories. Both intrusions were crystallizing a cumulus mineral assemblage of plagioclase + augite + iron oxide at the time of sulfide saturation. Both show peak PGE concentrations at or just below the level of initial sulfide saturation. Both show low and variable levels of palladium in the lower sulfide-undersaturated part of the intrusions (related to variable amounts of trapped undepleted magma) and almost complete and persistent palladium depletion above the sulfide saturation horizon (Fig. 8.10). Finally, both show an upward displacement of peak gold concentration from the PGE peak.

Stratiform PGE mineralization in the layered series at Duluth

The layered series at Duluth is a 3.5- to 5-kilometer-thick, sheetlike, mafic layered intrusion that was emplaced into the base of a 4- to 5-kilometer-thick edifice of comagmatic flood basalts, and forms the southernmost layered series intrusion of the Duluth Complex. Intrusion of the layered series at Duluth was preceded by the emplacement of plagioclase crystal mushes that statically crystallized anorthositic series rocks now forming the hanging wall to the layered series at Duluth. The igneous stratigraphy of the layered series at Duluth is divided into five major zones shown on map M-119. Above a basal contact zone of taxitic olivine gabbro and troctolite (unit dlsb, M-119), the main cumulate sequence of the layered series at Duluth progresses upward from PO cumulates of the troctolitic zone (unit dlst, M-119) to multiphase PCF ± O ± A cumulates of the gabbro zone (unit dlsg, M-119). This cumulate progression occurs in a cyclical manner across a 1-kilometer-thick interval termed the cyclic zone (unit dlsc, M-119). Upper gabbroic cumulates, in turn, grade upward into unlaminated (noncumulate) apatitic quartz ferromonzodiorite, which composes most of the upper contact zone (unit dlsu, M-119). The ferromonzodiorite complexly mixes with a fine-grained biotitic ilmenite ferrodiorite, which ultimately forms the "chilled" contact with anorthositic series rocks. A body of melanogranophyre (unit dlsm, M-119) that cuts irregularly through the anorthositic series probably represents the uppermost differentiate of the layered series at Duluth. This igneous stratigraphy is complemented by cryptic layering of cumulus mineral compositions (Chapter 6, Fig. 6.8 and Fig. 8.11) and together these imply the layered series at Duluth generally formed by bottom-up fractional crystallization of a moderately evolved, olivine tholeiitic parent magma.

The repeated progression from troctolitic to gabbroic cumulates in the cyclic zone (Fig. 8.12) indicates that the layered series at Duluth, unlike the Sonju Lake intrusion, did not crystallize as a closed system. The cyclic zone consists of at least six major macrocycles (each 50- to 200-meters-thick) within which troctolitic (PO) cumulates grade upward to gabbroic (PCFO) cumulates. Macrocycle boundaries are marked by the abrupt regression in the cumulus paragenesis from gabbroic back to troctolitic cumulate assemblages. The gabbroic parts of the macrocycles commonly contain anorthositic series inclusions and the very uppermost parts of the macrocycles locally have discontinuous layers of fine-grained gabbroic adcumulate (microgabbro). This cyclicity in phase layering does not correspond to a complimentary cryptic variation in mineral chemistry (Miller and Ripley, 1996). Based on these characteristics, Miller and Ripley (1996) suggested that the macrocyclic

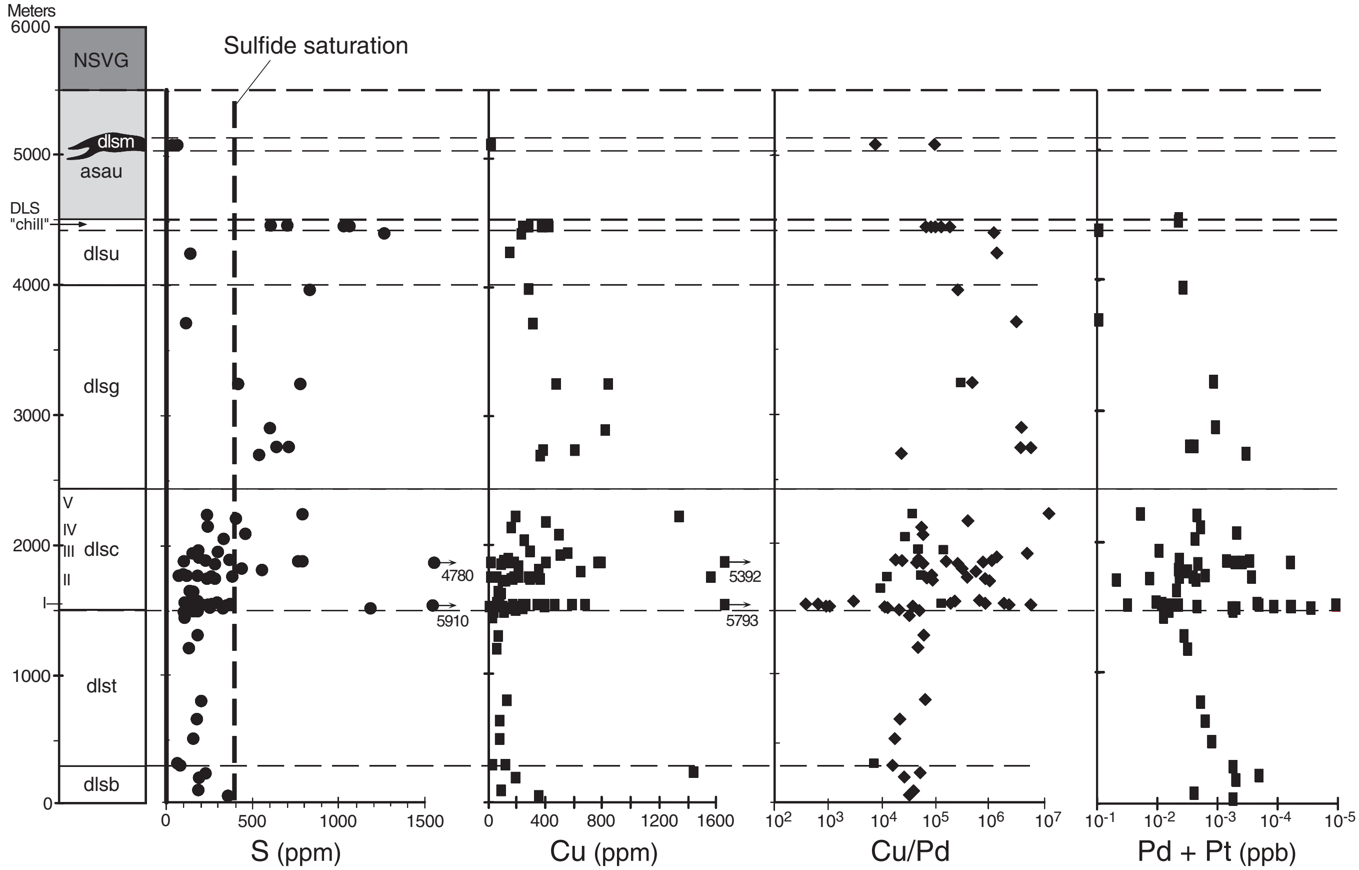


Figure 8.11. Stratigraphic variation in sulfur, copper, copper/palladium, and palladium + platinum abundances through the layered series at Duluth.

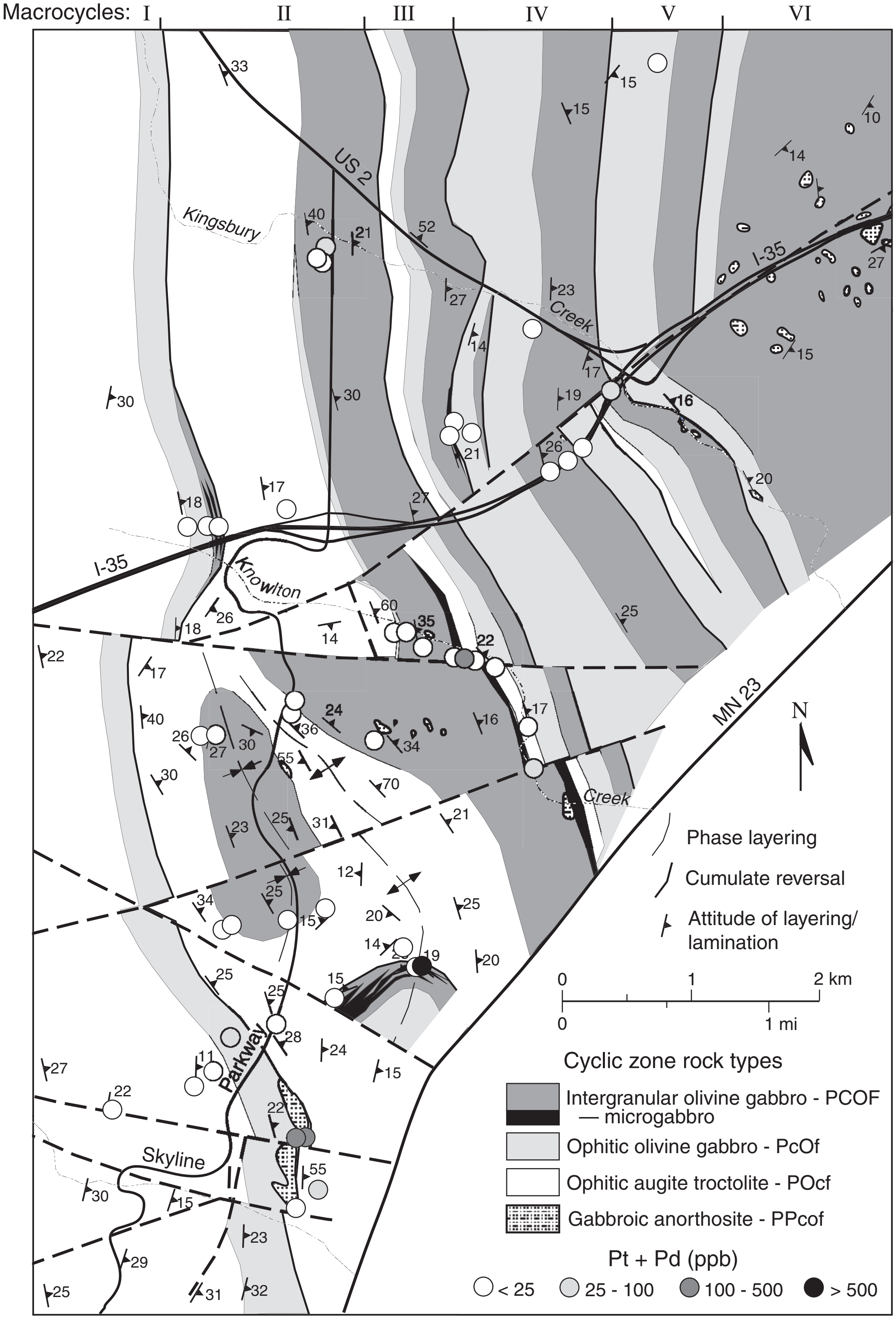


Figure 8.12. Geology and internal structure of the southern part of the layered series at Duluth cyclic zone showing locations and platinum + palladium concentrations in hand samples. Cyclical alternations between three general cumulate rock types define six macrocycles (I-VI).

phase layering is predominantly related to devolatilization and decompression that attended magma venting events from a shallow (less than 5 kilometers) chamber, with magma recharge possibly having a secondary affect.

Geochemical data were acquired from 83 hand samples that profile the general stratigraphy of the layered series at Duluth. The sampling focused on specific horizons, particularly in the cyclic zone, that contain visible sulfide mineralization or appear to represent perturbations to the magmatic system (Fig. 8.11). Most of the samples have platinum + palladium concentrations below 15 parts per billion, 14 samples have concentrations between 15 and 150 parts per billion, and five samples have concentrations greater than 150 parts per billion. Whole rock sulfur and copper concentrations (Fig. 8.11) imply that the layered series at Duluth magma was consistently sulfide-undersaturated during troctolite-zone crystallization, achieved intermittent saturation during crystallization of the cyclic zone, and was fairly consistently saturated as the gabbro zone accumulated. In contrast to the singular large increase in copper abundance and copper/palladium ratio observed in the Sonju Lake intrusion system (Fig. 8.9), the layered series at Duluth shows erratic variability in these parameters (Fig. 8.11). Such variability probably reflects the openness of the layered series at Duluth system to magmatic recharge. Nevertheless, a 2- to 3-orders-of-magnitude range in the copper/palladium ratio through the cyclic zone indicates at least a low level of efficiency in the ability of sulfide melt to extract PGEs from silicate magma (for example Maier and others, 1996).

Six hand samples that contain the most enriched platinum + palladium and sulfide concentrations come from the upper portions of macrocycles I and II (Figs. 8.11 and 8.12), and the two highest values are associated with gabbro-microgabbro interfaces. The model of magma venting to explain the phase layering of the cyclic zone (Miller and Ripley, 1996) also can explain the elevated concentrations of sulfide and PGE at cyclic zone boundaries of cumulus regression. Experimental data at low pressures (1 to 2 kb) suggest a positive correlation between pressure and sulfide solubility in hydrous tholeiitic magmas (Carroll and Rutherford, 1985). If valid, this implies that magma decompression due to venting from shallow differentiated magma chambers may trigger sulfide saturation (or oversaturation in a saturated magma). Devolatilization resulting from the venting of a volatile-rich magma would also cause an abrupt increase in fO_2, which would have a compounding effect on reducing sulfur solubility (Poulson and Ohmoto, 1990). The attractiveness of magma venting as a trigger for sulfide saturation in terms of PGE enrichment is that it would promote chamber-wide sulfide segregation if the system was well-mixed, or a rain of sulfide out of the roof zone if the magma chamber was compositionally zoned. Both situations would promote high R-factors, although the second scenario would require enough overproduction of sulfide to withstand the descent to the cumulate floor.

Exploration for stratiform PGE deposits in northeastern Minnesota

The basic conditions required to generate stratiform PGE mineralization imply that all initially sulfide-undersaturated, well-differentiated, tholeiitic mafic layered intrusions can potentially host PGE reef deposits. This is true whether the magma systems are open or closed. Intrusions related to igneous provinces generated by mantle plumes appear to hold the greatest potential to make PGE reefs by virtue of their more PGE-rich composition; however, prolonged fractional crystallization prior to sulfide saturation can theoretically compensate for intrusions formed from parent magma with low initial PGE concentrations.

The stratigraphic position of sulfide saturation and a possible PGE reef in a mafic layered intrusion is difficult to discern by field observations because a sulfide-saturated gabbro need only contain 0.1 weight percent sulfide (Boudreau and McCallum, 1992). As geochemical studies of the Sonju Lake intrusion and layered series at Duluth show, the stratigraphic variability of copper and sulfur can be used as indicators to where sulfide saturation occurred in the crystallization history of an intrusion and may alone be sufficient to locate a favorable horizon for a PGE reef. However, because iron-sulfide may be readily mobilized by deuteric fluids, copper variability may be a better indicator of primary sulfide saturation. Parameters such as the copper/palladium ratio (Fig. 8.11) provide qualitative indicators of the efficiency with which PGEs were scavenged from the magma (Barnes and others, 1993; Maier and others, 1996). Absolute abundances of PGEs have limited use in identifying horizons of initial sulfide saturation because their anomalous concentration will be tightly bound to the horizon itself, and because evidence of depleted concentrations will require high-resolution analyses (0.1 to 0.5 part per billion detection limits). To properly evaluate any chemostratigraphic data, however, it is important to understand the petrologic history of each intrusion.

For intrusions that fractionally crystallized under generally closed conditions, exploration for stratiform PGE mineralization involves a fairly straightforward process of identifying the level at which the magma became initially saturated in sulfide. If the system is truly closed, the highest PGE concentrations possible should occur at the horizon of initial sulfide saturation. This is certainly the case for stratiform PGE mineralization in the Sonju Lake and Skaergaard intrusions. However, it is unlikely that any intrusive system is completely closed. Even the Skaergaard intrusion, considered the prime example of a closed magmatic system, may have been open to minor recharge or venting events given the cyclical nature of the PGE mineralization and cumulate lithologies associated with the Platinova reefs (Anderson and others, 1998).

In open magmatic systems, exploration should also focus on locating the horizon of initial sulfide saturation. The first significant sulfide saturation/exsolution event has the greatest chance of encountering the most PGE-enriched silicate magma. Moreover, the lowermost sulfide-rich horizon would be best situated to having its PGE tenor upgraded by the fluxing of a deuteric, chlorine-bearing fluid devolved from the cooling cumulate pile below (for example Barnes and Campbell, 1988; Boudreau and McCallum, 1992). The higher this horizon of initial sulfide saturation is stratigraphically, the greater the likelihood that the primary PGE tenor of the magma was high and the greater the thickness of lower cumulates that could have been scavenged. However, such a horizon may be difficult to identify if sulfide saturation was triggered by a short-term perturbation to the system (such as venting or recharge). Where intrusive systems are known to be approaching sulfide saturation, petrologic indicators of such perturbations should be evaluated (such as abrupt changes in cumulus mineralogy or texture, and the appearance of modal layering). Such an approach was successful in identifying stratiform PGE and sulfide mineralized horizons in the cyclic zone of the layered series at Duluth.

Although the lowest stratigraphic horizon marking sulfide saturation may be the first place to seek out PGE mineralization in an open magmatic system, a lack of significant PGE enrichment at that level should not discourage exploration at higher levels. What matters more to forming a high-grade PGE reef than the overall PGE tenor of the magma at the time of a particular sulfide saturation event is the fluid dynamics of how and over what stratigraphic distance the sulfide melt settled to the floor of the intrusion. In an open magma system where multiple sulfide saturation events may occur, it may be that the fluid dynamics of a later (stratigraphically higher) saturation event was triggered by a process that was more conducive to efficiently scavenging PGEs. Such a situation apparently occurred in the Great Dyke, where the high-grade PGE reef is associated with the Main Sulfide Zone, located some 50 meters above the first sulfide saturation event that formed the PGE-poor Lower Sulfide Zone (Prendergast and Wilson, 1989). Clearly, a full understanding of the crystallization history of a layered intrusion is as important to evaluating its potential for stratiform PGE mineralization as is a thorough geochemical profiling.

Other exploration targets for stratiform PGE mineralization in northeastern Minnesota

In addition to the Sonju Lake intrusion and layered series at Duluth, northeastern Minnesota contains a number of well-differentiated, tholeiitic intrusions that are also possible exploration targets for stratiform PGE mineralization. Given that such distinct intrusions as the layered series at Duluth and the Sonju Lake intrusion were both initially sulfide undersaturated, it can be reasonably presumed that most intrusions of the Duluth and Beaver Bay Complexes were similarly undersaturated at the time of their emplacement. The well-differentiated intrusions that occur in explorable areas of northeastern Minnesota include:

- The large, layered series at Duluth-like Greenwood Lake intrusion in the upper-central part of the Duluth Complex
- The small, plug-like Osier Lake intrusion also in the central Duluth Complex
- The Boulder Lake intrusion in the south-central part of the Duluth Complex with its two major differentiation cycles
- The Cloquet Lake layered series forming the western part of the Beaver Bay Complex,

which also appears to be composed of two major differentiation cycles

- The Houghtaling Creek troctolite macrodike, which contains a differentiated sequence in its northeastern extent

With the exception of the Houghtaling Creek troctolite, which is fairly well exposed in the northern Beaver Bay Complex (Boerboom and Miller, 1994; Miller and others, 1994), all other intrusions are poorly exposed to unexposed and are known mainly from their aeromagnetic signatures and scattered drilling (Meints and others, 1993; Miller and Chandler, 1999; Chandler, 2001). Although some hesitancy may exist for exploring such unexposed intrusions, the stratiform nature of this style of mineralization may require only a single geochemical profile to evaluate the sulfide-saturation character of an intrusion and to focus on a favorable horizon for detailed sampling. It might also be possible to conduct geophysical surveys across the igneous stratigraphy of these intrusions to delineate changes in sulfide and/or oxide content.

In early 2002, the Minnesota Geological Survey will conduct a shallow drilling program across the Greenwood Lake intrusion to better determine its igneous stratigraphy and to approximate where sulfide saturation may have occurred in the magma system. The Greenwood Lake intrusion is 6- to 7-kilometers-thick and has aeromagnetic signatures akin to the layered series at Duluth. Therefore, an open magma system model, like the layered series at Duluth, will be used to evaluate its chemostratigraphy. The results of this study will be released in 2002.

Ironically, the two intrusions where most PGE exploration activity has been focused until now, the Partridge River and South Kawishiwi, may hold the least potential for the type of stratiform PGE mineralization described here. These open-system intrusions apparently did not differentiate beyond olivine-plagioclase (troctolite) crystallization (Miller and Ripley, 1996) and were contaminated by extramagmatic sulfur upon emplacement. The stratabound PGE mineralization found at the Birch Lake prospect in the South Kawishiwi intrusion and others noted in the preceding section is not the same type of mineralization described here. Rather, its formation appears to have involved processes of magma recharge, iron-formation assimilation, and late stage remobilization by chlorine-brines along fault zones.

Fe-Ti (± V) MINERALIZATION

Titaniferous iron oxide bodies were first discovered in the Duluth Complex around 1867, at about the same time as the initial discovery of the Mesabi range iron ores (Winchell, 1897). Over the last 100 years, demands for iron and titanium have periodically stimulated small exploration efforts in the form of outcrop examinations and drilling campaigns. Most of these efforts have taken place along the base of the Duluth Complex. The earliest discoveries took place along the northern margin of the complex in Cook County. Grout (1949-1950) estimated that along the northern margin there are 81.6 million tons of low-grade titaniferous magnetite ore (in 14 bodies) with an average grade of 12 to 14 percent TiO_2 (Hauck and others, 1997a). Oxide mineralization is also associated with late plug-like oxide ultramafic intrusions (OUIs) along the western margin of the Duluth Complex. The oxide ultramafic intrusions were initially discovered by drilling rocks associated with magnetic highs during copper-nickel exploration (Bonnichsen, 1972; Hauck and others, 1997a). Listerud and Meineke (1977) estimated that 220 million tons of oxide material, with greater than 10 percent TiO_2, are present in at least three of the oxide ultramafic intrusions. However, nine additional areas portrayed as oxide ultramafic intrusions in Figure 2.3 (Chapter 2) are known to contain titaniferous iron ores and are not included in their original estimate. Hauck and others (1997a) have classified the titaniferous ores, composed principally of ilmenite and/or titanomagnetite, into three general types: iron-rich metasedimentary inclusions, magmatic banded oxide segregations, and oxide ultramafic inclusions.

Iron-rich metasedimentary inclusions

This category pertains to titanium-bearing inclusions of the Biwabik and Gunflint Iron Formations that occur along the northwestern and northern margin of the Duluth Complex. The inclusions range from those that possess easily recognizable metasedimentary attributes to those that are featureless, pod-like bodies of massive oxide (Hauck and others, 1997a). Examples of the latter are the “restite” pods of Biwabik Iron Formation within the U3 unit of the South Kawishiwi intrusion. Several authors (Broderick, 1917; Grout, 1949-1950; Grout and others, 1959; Muhich, 1993) have concluded that the titanium in the inclusions was added from the surrounding magma during emplacement of the Duluth Complex. However, not all of the massive oxide zones within the Duluth Complex can be attributed to iron-formation inclusions. Isotope work by Hauck and others (1997b) suggested that some of the oxide-rich zones within the U3 unit, especially the uppermost oxide-rich zones of the unit, might be magmatic in origin. In addition, the spatial relations of subhorizontal oxide-rich horizons located well above the basal contact of the Duluth Complex at the Wetlegs, Water Hen, and Fish Lake deposits (Severson, 1995; Severson and Hauck, 1997) also suggest a magmatic origin. In summary, the effects of partial melting and recrystallization on the iron-formation inclusions may make them extremely difficult to distinguish from magmatic oxide-rich layers. Because these inclusions are of limited extent and thickness, and because they are scattered randomly throughout the basal margin of the Duluth Complex, there have been no attempts to calculate the potential Fe-Ti resources they contain.

Magmatic banded oxide segregations

Massive to semi-massive oxide layers of ilmenite and/or titanomagnetite that range in thickness from a few centimeters to 3 meters occur in many places within the Duluth Complex. These layers commonly alternate with plagioclase-rich bands and ferrogabbroic cumulate layers. Both the oxide layers and the enclosing cumulate rocks generally exhibit a primary igneous plagioclase foliation. Individually, the oxide layers commonly grade into gabbroic cumulates both vertically and laterally. Collectively, the oxide layers form a quasi-continuous megalayer, or series, of overlapping lenses that is several kilometers in strike length and dips slightly to the southeast. As mentioned above, this type of oxide occurrence overlaps with the recrystallized iron-formation inclusions, and at some localities it is difficult to discriminate between the two. However, spatial relationships (great thicknesses above the basal contact) indicate that magmatic semi-massive oxide layers are present within the Boulder Lake, Western Margin, and Poplar Lake intrusions, and the Brule Lake–Hovland gabbro. The known oxide-rich horizons contained within each of these intrusions are briefly discussed below.

Probably the best-known occurrences of this category are the Fe-Ti oxide-rich layers within the Poplar Lake intrusion and Brule Lake–Hovland gabbro. Broderick (1917) was the first to make detailed descriptions of oxide-rich zones within the Duluth Complex. Much of his work is included in a later, more detailed study by Grout (1949-1950), who described the geology and conducted a small drilling campaign in 1947 to calculate possible titaniferous resources. Grout (1949-1950) referred to the oxide-rich belt in the Poplar Lake intrusion as the "North Range" and the oxide-rich belt of the Brule Lake–Hovland gabbro as the "South Range." The North Range encompasses a 24-kilometer-long belt south of the Gunflint Trail and includes exposures along the shores of Poplar and Tucker Lakes (unit plox, M-119). Several test pits were dug into titaniferous-rich material near both lakes, but the exposures on Tucker Lake appeared to be more Fe-Ti rich, and exploratory holes were drilled by the Johnson Nickel Mining Company as early as 1899 (Grout, 1949-1950). However, the early drilling was inadequate to define the grade and amount of material in the deposit and Grout (1949-1950) drilled an additional eight holes at Tucker Lake. Many of these holes intersected variably mineralized "ore zones" that contained as much as 25 percent TiO_2. Even though Grout (1949-1950) believed that the mineralized zones were erratic both mineralogically and spatially, he calculated that the drilling defined a combined 25 million tons of material in a main zone (average grade of 22 percent TiO_2) and two low-grade zones (average grade of 12 percent TiO_2). Today most of the North Range is surrounded by the Boundary Waters Canoe Area Wilderness, and it is unlikely that mining could ever take place on this belt.

Fe-Ti oxide-rich layers of the South Range were also explored by test pits at the same time as the North Range. Rocks of the South Range (unit bhfg, M-119) are exposed in a 10-kilometer-long belt that extends from Smoke Lake on the west to Homer Lake on the east. Grout (1949-1950) drilled two holes at Smoke Lake in 1947, mainly to illustrate that the oxide-rich rocks of the South Range dip to the south, and continue to an unknown depth beneath a large sill-like granite body of the felsic series (unit fgpu, M-119). He estimated that collective resources of the South Range amount to 14 million tons (grades were not specified). However, today this area is also located entirely within the Boundary Waters Canoe Area Wilderness and is not open to mining. Even though Grout (1949-1950) considered the titaniferous ores of the South Range to be magmatic, he noted that outcrops at the east end of the belt might have been contaminated by the Gunflint Iron Formation. A map in his report showed a belt of "altered Animikie sediments" (unit `Psh`, M-119) to the immediate north of the South Range at its eastern end. Davidson (1977d) and Davidson and Burnell (1977) also noted these same metasedimentary rocks and, on the basis of chemical analyses, suggested they are similar to the Virginia Formation. As discussed in Chapter 4, a footwall ridge of pre-Keweenawan rock may extend into this area and may have contributed Paleoproterozoic xenoliths to superjacent Duluth Complex intrusions.

Semi-massive to massive oxide layers have been intersected by drilling in the Boulder Lake intrusion at the Boulder Lake North area (Chapter 2, Fig. 2.3). The oxide layers are titanomagnetite-rich, range from 0.02- to 1.5-meters-thick, and are associated with ferrogabbroic cumulates that contain clinopyroxenite lenses (Severson, 1995). Ferrogabbroic cumulates that contain 5 to 10 percent titanomagnetite are also present in the Western Margin intrusion at the Boulder Creek exploration area. Magmatic semi-massive oxide layers from 0.06- to 2.0-meters-thick are also present at the Wetlegs, Water Hen, and Fish Lake areas (Severson, 1995; Severson and Hauck, 1997). There are no known calculations pertaining to Fe-Ti resources for any of these oxide occurrences.

Oxide ultramafic intrusions (OUIs)

Exploratory drilling for copper-nickel mineralization encountered several oxide ultramafic intrusions that later were evaluated for their Fe-Ti ± V potential. Many of the oxide ultramafic intrusions are expressed as aeromagnetic highs, commonly with an associated electromagnetic conductor, and thus they were initially drilled in search of conductive sulfide mineralization. At least thirteen oxide ultramafic intrusions have been intersected in drill holes along the basal contact of the Duluth Complex. Detailed drilling to define potential Fe-Ti ± V resources has taken place at only the Longnose and Water Hen localities, and to a much lesser extent at the Section 34 locality. Resources are only known for the Longnose oxide ultramafic intrusion and total approximately 25 million tons of material with greater than 15 percent TiO_2 (Hauck and others, 1997a). Detailed descriptions of the oxide ultramafic intrusions are found in Mainwaring (1975), Mainwaring and Naldrett (1977), Severson and Hauck (1990), Linscheid (1991), Miner and Pasteris (1994), Miner (1995), and Severson (1995).

The oxide ultramafic intrusions are plugs or pipe-like bodies that commonly have irregular apophyses. They intrude troctolitic rocks of the Partridge River, Western Margin, and Boulder Lake intrusions. The Water Hen oxide ultramafic intrusion appears to be rootless as defined by detailed drilling (Fig. 8.13); the three-dimensional configurations of the other oxide ultramafic intrusions are unknown due to insufficient drilling (Hauck and others, 1997a). In general, the oxide ultramafic intrusions are spatially arranged along linear trends, suggesting that structural control was important to their genesis. All of the oxide ultramafic intrusions are crosscutting with the exception of the oxide ultramafic intrusion at Boulder Creek, which is roughly stratabound with a crosscutting feeder zone. Rock types include coarse-grained to pegmatitic clinopyroxenite, dunite, peridotite, melatroctolite, and minor melagabbro; all rock types are oxide bearing. Some oxide ultramafic intrusions exhibit a crude zonation from an olivine-rich core (dunite, peridotite, and melatroctolite) to an outer clinopyroxenite margin, whereas others consist of only one dominant rock type. A thick saprolite cap, presumably formed by weathering during the Cretaceous period, is present at the Water Hen oxide ultramafic intrusion.

Oxide content is variable in the oxide ultramafic intrusions and ranges from 15 percent in disseminated zones to 100 percent in localized massive oxide zones. Oxide ultramafic intrusions that contain thick intervals of massive oxide include Longnose (up to 30-meters-thick; Linscheid, 1991) and Section 34 (up to 40-meters-thick; Severson, 1995). Titanomagnetite is dominant in some of the oxide ultramafic intrusions, whereas ilmenite is dominant in other oxide ultramafic intrusions. Sulfide minerals (predominantly pyrrhotite) are ubiquitous in all the oxide ultramafic intrusions and range from trace amounts to 5 percent in disseminated zones to greater than 70 percent in localized net-textured and massive sulfide zones, such as Water Hen and Boulder Lake South (Chapter 2, Fig. 2.3).

Average and maximum TiO_2 values for each of the thirteen oxide ultramafic intrusions that have been drilled are listed in Table 8.1. In this table, the oxide ultramafic intrusions are divided into two major groups, a northern group (N-OUI) that contains oxide ultramafic intrusions located within the Partridge River intrusion, and a southern group (S-OUI) that contains oxide ultramafic intrusions located in the Western Margin and Boulder Lake intrusions. The N-OUI group do not differ

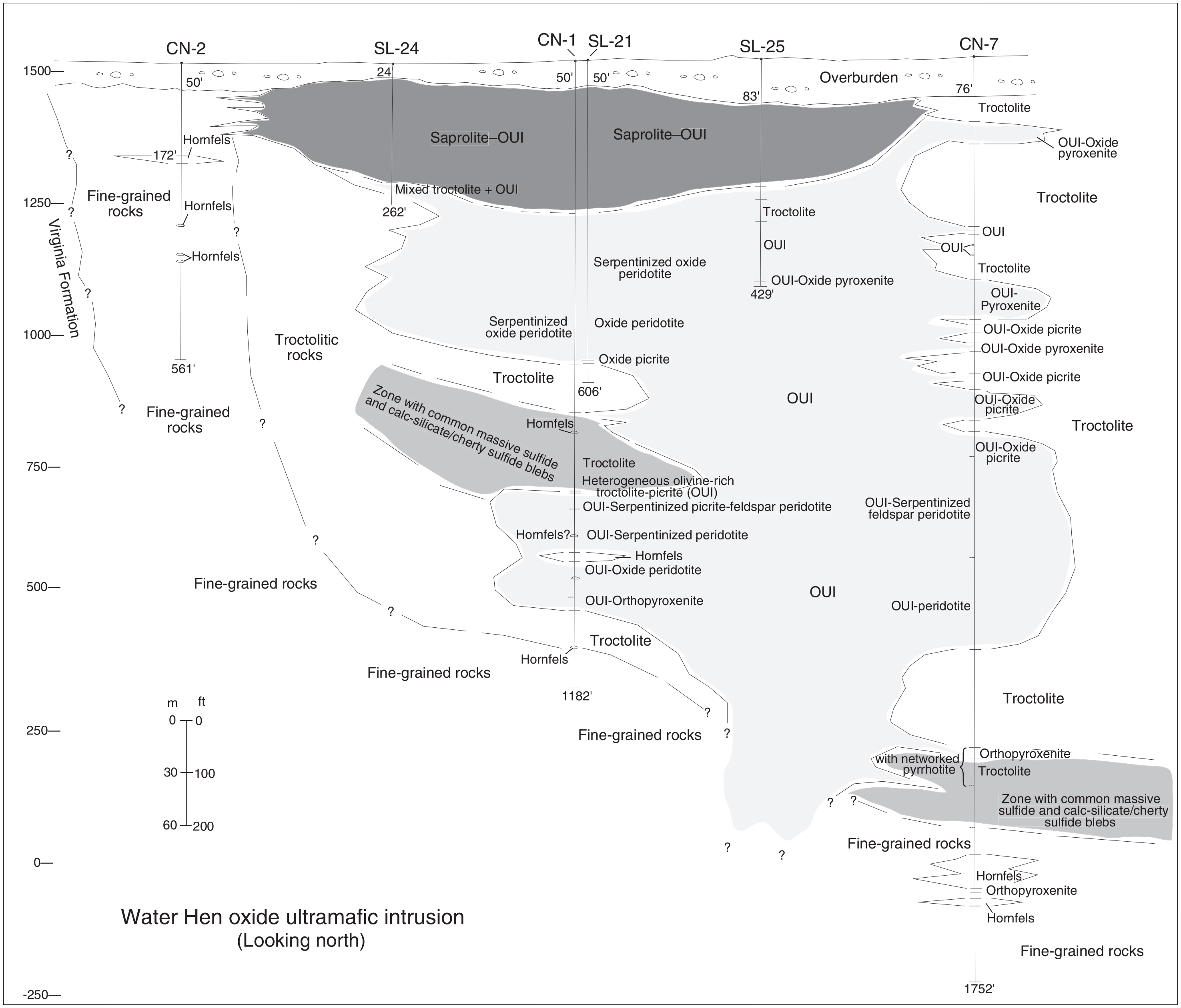


Figure 8.13. Simplified cross-section of the Water Hen area showing the crosscutting relationship of the oxide ultramafic intrusion to the troctolitic host rocks of the Partridge River intrusion. Also shown are massive sulfide zones and the saprolite cap (modified from Severson, 1995).

Table 8.1. Average and maximum known TiO_2 contents for the oxide ultramafic intrusions along the western margin of the Duluth Complex. Note the extreme variability in sampling density (for TiO_2) within each of the various OUI bodies. These data are from corporate files that are either on open-file at the Minnesota Department of Natural Resources, or are supplied from private corporate files (United States Steel Corporation, American Shield Corporation, and BHP Minerals), and are included in Severson (1995).

	Oxide ultramafic intrusion	Intrusion	no. TiO_2 analyses	Avg. TiO_2 (wt. %)	Max. TiO_2 (wt. %)	Avg. V (ppm)	Max. V (ppm)	Avg. Cr (ppm)	Max. Cr (ppm)	Max. Cu (wt. %)	Max. Ni (wt. %)	Max. Pt (ppb)	Max. Pd (ppb)
N-OUI GROUP	Section 17	Partridge River	33	10.92	14.66	790	950	490	820	0.15	0.10	25	30
	Longear	"	1045	12.49	30.70	1325	4400	-	341	0.33	0.06	-	-
	Longnose	"	1149	18.06	50.50	580	3590	-	1843	0.39	0.10	-	-
	Wyman Creek	"	10	17.63	28.65	-	540	1500	3285	0.16	0.08	50	25
	Section 22	"	62	10.74	28.72	1130	2790	1200	7000	0.25	0.12	139	445
	Skibo	"	18	14.33	25.28	165	220	134	185	0.34	0.31	230	300
	Skibo-South	"	3	-	12.60	1100	1346	1340	1700	0.24	0.16	-	-
	Water Hen	"	608	11.15	29.30	1065*	2285*	863*	1750*	1.97	0.64	127	205
S-OUI GROUP	Section 34	Western Margin	204	15.66	26.74	2610	4035	250	370	0.16	0.03	14	20
	Boulder Creek	"	8	14.80	19.09	4630	8125	440	791	0.40	0.07	360	320
	Boulder Lake North	Boulder Lake	6	20.58	35.20	4045	6835	925	2000	0.22	0.07	-	-
	Central Boulder Lake	"	none	-	-	-	-	-	-	-	-	-	-
	Boulder Lake South	"	2	-	16.03	-	787	-	260	0.18	0.02	-	-

(-) unavailable

* Excludes a unique Cr-V-rich zone in drill hole CH-7.

appreciably in content of TiO_2 from the S-OUI group. The N-OUI group appears to contain somewhat more chromium than the S-OUI group, and somewhat less vanadium. However, the sampling campaigns have differed significantly from one oxide ultramafic intrusion to another, and the data should be interpreted cautiously. Copper values are generally low (less than 0.4 percent) for both the N-OUI and S-OUI groups with the exception of the Water Hen body, which has copper values as high as 1.97 percent associated with massive sulfide intervals.

Other major differences and similarities between the N-OUI and S-OUI groups are listed in Table 8.2. One major difference is the dominant oxide type. Ilmenite is dominant in the N-OUI and titanomagnetite is dominant in the S-OUI (with the exception of the Boulder Lake South oxide ultramafic intrusion). This difference may be related to the mode of origin for specific groups of oxide ultramafic intrusions.

The genesis of the N-OUI group has been empirically linked to intrusion and assimilation of the Biwabik Iron Formation at depth followed by upward movement of an Fe-rich partial melt along fault zones. The Section 17, Longear, and Longnose oxide ultramafic intrusions occur along a northeast-trending fault where the iron-formation is in direct contact with the Duluth Complex (Severson and Hauck, 1990). The oxide ultramafic intrusions from the Wyman Creek deposit southward to the Water Hen oxide ultramafic intrusion (Chapter 2, Fig. 2.3) are associated with a north-trending magnetic high that is interpreted to reflect a strong magnetic overprint caused by heating of the Biwabik Iron Formation (Bath, 1962;

Table 8.2. Summary of major features relative to the oxide ultramafic intrusions (OUIs) in the Partridge River, Western Margin, and Boulder Lake intrusions.

	Oxide ultramafic intrusion	Oxides, I = ilmenite, M = magnetite	Chromium titnomagnetite	Graphite	Sulfides (in addition to pyrrhotite, cubanite chalcopyrite, pentlandite)	Apatite	Dominant rock type	Host rock
N-OUI GROUP	Section 17	I ≥ M		no	bornite	no	pyroxenite	Units VI, VII of prmz*
	Longear	I ≥ M		no	bornite, pyrite	no	pyroxenite	Units VI, VII of prmz
	Longnose	I ≥ M		no	bornite	no	dunite-core, pyroxenite-rind	Units VI, VII of prmz
	Wyman Creek	I > M	yes	no		no	peridotite, pyroxenite	Unit I of prmz
	Section 22	I > M	yes	no	maucherite, parkerite	no	peridotite	Unit V of prmz
	Skibo	I > M	yes	yes		no	peridotite	Unit V? of prmz
	Skibo-South	I > M	yes	yes	maucherite, safflorite, cobaltite, sphalerite	no	peridotite, pyroxenite	Unit V? of prmz
	Water Hen	I > M	yes	abundant	maucherite, pyrite, mackinawite, sphalerite, bornite	no	pyroxene-upper half, peridotite-lower half	Unit V? of prmz
S-OUI GROUP	Section 34	M > I		no	bornite, pyrite, sphalerite	no	peridotite, pyroxenite	anorthosite
	Boulder Creek	M > I		common	bornite, sphalerite	no	peridotite	troctolite
	Boulder Lake North	M > I		no		common	peridotite, pyroxenite	ferrogabbro, troctolite, anorthosite
	Boulder Lake South	I > M		yes		common	peridotite, pyroxenite	troctolite, basalt

*prmz is the Partridge River intrusion marginal zone; unit numbers correspond to Chapter 6, Figure 6.10.

Chandler and Ferderer, 1989; Chandler, 1990). The position of these oxide ultramafic intrusions relative to the magnetic high suggests that they may have also formed by a mechanism of intrusion and assimilation of the iron-formation (Severson, 1995). There are two potential problems concerning an origin that involves assimilated Biwabik Iron Formation. First, the high TiO_2 content of the oxide ultramafic intrusions is difficult to reconcile because the iron-formation contains only 0.03 to 0.19 percent TiO_2 (Morey, 1992). Muhich (1993) documented elevated TiO_2 contents (up to 6.0 percent in magnetic concentrates produced from taconite) at Dunka Pit where the iron-formation is in direct contact with the Duluth Complex. He suggested that the titanium was metasomatically transferred across the contact from the intruding silicate magmas. However, the titanium content in this example is still much lower than TiO_2 concentrations in the oxide ultramafic intrusions. The second problem is if the iron-formation is a potential source, it is difficult to reconcile how a dense, iron-rich, partial melt could have been forced upward along a fault. The dynamics involved in regard to the second problem have not been investigated. Miner (1995) offered an alternative explanation for the origin of the Longnose oxide ultramafic intrusion that involves formation of a magmatic iron-rich melt along a fault to form a pipe-like body that was further modified by localized metasomatic replacement. Clearly, additional work is needed to further understand the origin of the N-OUI group.

The S-OUI group is not related to iron-formation assimilation because pelitic rocks of the Thomson Formation, rather than iron-formation, are present at the basal contact. These oxide ultramafic intrusions may be related to ferrogabbroic cumulates that are present above or at the same stratigraphic level. The S-OUI group may have formed by development of an iron-rich residual melt at the top of a crystallizing cumulate pile that drained down into the pile along faults (Severson, 1995). A similar origin of metasomatic replacement in response to downward percolating, iron-rich residual melts has been presented for iron-rich pegmatites in the Bushveld Complex of South Africa (Scoon and Mitchell, 1994).

In the above discussion on the origin of the oxide ultramafic intrusions, there is an obvious dichotomy regarding the relative movement of oxide ultramafic intrusion magma—upward in one case and downward in the other case. At present, there are no reliable indicators regarding the potential direction that the magma migrated. The same dichotomy applies to similar bodies in the Bushveld Complex. Stumpfl and Rucklidge (1982) suggested the bodies formed by the upward movement of magma, and Scoon and Mitchell (1994) envisioned formation from the downward movement of an iron-rich melt.

FISSURE VEIN POTENTIAL—LOGAN SILLS

Several types of fissure vein deposits that contain lead, zinc, copper, and silver minerals are known to occur across the Canadian border in the Thunder Bay district of Ontario. There, the deposits are associated with veins and fractures that crosscut rocks of the Animikie Group (Rove Formation and Gunflint Iron Formation) and Logan sills (Mudrey and Morey, 1972). The Thunder Bay district was first discovered in 1846 and sporadically produced almost $5,000,000 worth of silver ore prior to 1900 (Mudrey and Morey, 1972). Similar deposits have been searched for in Cook County, Minnesota, but none have proved to be commercial.

Along the Gunflint Trail in Minnesota, small sulfide veins with significant copper and cobalt values were reported at the Blankenburg–Whiteside prospect on the south shore of Loon Lake (T. 65 N., R. 3 W., sec. 34). The mineralized veins, which contain abundant arsenopyrite, occur at the base of the Logan sill (unit lsdb, M-119) near its contact with the Rove Formation. Reports by Hubert (1954), Engen (1968), Johnson (1968), and Coyner (1974) stated that in the early 1930s, a prospector first brought the mineralization to the attention of lodge-owner R. Blankenburg. The mineralization was evident at the base of a cliff and Blankenburg dug several test pits attempting to trace the mineralization. At the cliff locale, where an adit was dug, the mineralization consists of branching arsenopyrite-quartz veins that contain abundant chalcopyrite and lesser amounts of pyrrhotite, magnetite, ilmenite, and hematite. The veins, as thick as several centimeters, strike approximately east–west and dip steeply to the south. There appear to be no sulfide veins higher than 9 meters above the base of the cliff.

Prospecting was eventually discontinued and did not resume until the 1950s when Blankenburg and R. Whiteside of Duluth conducted a drilling program of eight holes. Two holes struck arsenopyrite veins as wide as 5 centimeters and returned assays as much as 6.48 percent cobalt (Johnson, 1968). No core or drill logs are preserved from this early period of drilling. A second drilling program was undertaken between 1967 and 1971. Eighteen holes were drilled, the core of which is stored at the Minnesota Department of Natural Resources. Coyner (1974) suggested that the mineralization is associated with an east–west-trending monoclinal hinge line where the dip of both the Rove Formation and Logan sill increases from 25° to 65° to the south. Coyner (1974) reported grab samples that assayed 5.04 percent copper and 1.08 percent cobalt. Johnson (1968) reported values as high as 10.28 percent copper, 3.86 percent cobalt, and 1.51-ounce/ton silver.

A prospect on Susie Island in Lake Superior, south of Pigeon Point, consists of veins in a Grand Portage diabase dike (unit gpdb, M-119). The veins contain calcite and barite with minute inclusions of chalcocite and bornite, and lesser amounts of pyrite, chalcopyrite, and covellite (Mudrey and Morey, 1972). High-grade grab samples assayed as much as 6.22 percent copper (Grout and Schwartz, 1933). The Green prospect near Mineral Center, Minnesota (T. 63 N., R. 5 E.) is a vein deposit localized within fractured, brecciated, and altered rocks of the Pigeon River diabase (unit prdb, M-119). Primary sulfides in the veins are pentlandite, pyrrhotite, and chalcopyrite (Schwartz, 1924, 1925). A sulfide concentrate from the Green prospect assayed 18.26 percent copper and 0.52 percent nickel (Mudrey, 1972).

ECONOMIC SIGNIFICANCE OF THE NORTH SHORE VOLCANIC GROUP AND RELATED HYPABYSSAL INTRUSIONS

At present, the only economic use of the volcanic and hypabyssal rocks along the north shore is as industrial quarry rock. One large, traprock quarry is operating in the Ely's Peak basalts southwest of Duluth, but there is considerable potential for other such developments in the area, assuming a favorable market, economical transportation, and other factors. A quarry in the southeast side of Carlton Peak near Tofte is now inactive; it exploited the massive, widely-jointed anorthosite xenoliths contained in diabase for use as riprap. Large blocks of diabase removed from State Highway 61 tunnels northeast of Two Harbors are stockpiled at Castle Danger and are used as riprap for occasional erosion-control projects in the area. Anorthosite in the Beaver Bay Complex was briefly quarried in several places near the shore of Lake Superior early in the 1900s in the mistaken belief that it was corundum (Grout and Schwartz, 1939). The area was extensively explored for metallic deposits, especially copper, in the late nineteenth and early twentieth centuries (Green, 1972), but no viable deposits have been found.

The felsic rocks, both rhyolites and granophyres, might have some potential for hosting a number of metals of interest, such as base metals (including copper, zinc, or tin), precious metals (silver or gold), rare earth elements, tungsten, and uranium. A geochemical survey (Green, 1989) of felsic samples showed generally low values of these and other indicator elements (Table 8.3). However, there were a few more elevated values (greater than ten times the mean) for arsenic, gold, and tungsten, and one each for copper and zinc. Most of the material available for sampling (in outcrop) is relatively unaltered, whereas mineralization is more likely to be found in hydrothermally altered rocks such as permeable zones in flowtop breccias, tuffs, or shear zones. Such altered rocks, unless silicified, are typically more susceptible to erosion, and in this terrane are generally covered by glacial drift. An attempt was made to sample and analyze as many of these as feasible (where exposed in streambeds, shore cliffs, or road cuts), but most are inaccessible. In order to fully investigate the economic potential of these felsic rocks, it would be useful to conduct soil, stream sediment, or drift geochemical surveys, and a drilling/sampling program to investigate the

Table 8.3. Selected trace-element values of economic interest in Keweenawan felsic rocks. Values in parts per million except for Au (parts per billion).

Element	As	Sb	Au	Ag	Cu	Zn	Mo	U	W	Sn	Ce
Number of analyses	73	64	80	72	76	73	77	77	90	36	76
Number above detection limit	58	58	37	19	73	73	13	77	56	28	76
Detection limit(s)	1,2	0.1,0.2	2,10	0.5	1	0.5	2	0.1	1	2,3	1
Average, at or above detection limit	12.3	0.50	28	0.85	41	135	4.2	3.6	6.05	10.8	175
Average, all analyses*	9.8	0.46	13	0.24	40	135	0.7	3.6	3.8	8.4	175
Five highest values	110	1.7	170	1.5	430	1400	13	10.4	210	39	470
	100	1.5	130	1.5	226	290	7	8	42	25	448
	62	1.4	110	1.5	210	250	6	7	7	22	290
	51	1.4	110	1.5	160	240	5	7	3	21	266
	43	1.0	95	1.0	120	210	3	6.8	3	20	256

* Values below detection limit counted as 0

typically unexposed top zones of the large felsic volcanic flows.

The mafic rocks (basalt, diabase) also have economic significance as potential indicators of metal concentrations in associated intrusions. This results from the conditions associated with the separation of immiscible sulfide liquid from the mafic magma during crystallization. This can happen during closed-system crystallization, when the time of sulfide separation would be relatively late because of the generally low sulfur content of tholeiitic magmas; it can be promoted by assimilation of sulfur from adjacent country rocks; or it can be triggered by the assimilation of more siliceous wallrock, changing the liquidus relations (Irvine, 1975). Such a silicate liquid would tend to scavenge chalcophile elements, such as the base metals, from the magma. Thus nickel, which without a sulfide liquid present would be fractionated into olivine, would be depleted from the magma along with copper. This relationship presents a tool for regional exploration for sulfide or PGE ores (Lightfoot and others, 1997). If basaltic or diabasic rocks are depleted in copper and nickel, this suggests that somewhere in comagmatic plutonic intrusions there may be a concentrated sulfide deposit. This is well illustrated by the Noril'sk copper-nickel-PGE district associated with the Siberian Traps (Lightfoot and others, 1994). Alternatively, if the basalts have "normal" elevated values of these chalcophile elements, it suggests that no sulfide separation and scavenging have taken place. Isotopic or other geochemical evidence for crustal contamination can also be used to infer the potential for sulfide exsolution by that mechanism (Lightfoot and others, 1997).

To evaluate this relationship for the North Shore area, nickel values were compared with MgO for 65 mafic dikes and mafic volcanic rocks of the North Shore Volcanic Group (Fig. 8.14). For the dikes, there is a clear positive correlation between nickel and MgO, with nickel values in the most magnesian dikes reaching 250 parts per million (Fig. 8.14a). Copper values are also high, with an average of 233 parts per million for the 42 samples with copper data. These imply that little scavenging has taken place, and the nickel is contained principally in the olivine. Brannon (1984) produced a consistent set of analyses of North Shore Volcanic Group lavas for a 4-kilometer section between Duluth and Two Harbors. Her 51 basaltic analyses also showed a strong positive correlation between nickel and MgO (Fig. 8.14b); no sample contained less than 62 parts per million nickel. No copper data for these flows are available. Fifty-four other basaltic North Shore Volcanic Group analyses contain data for nickel, 27 for the northeast limb and 27 for the southwest

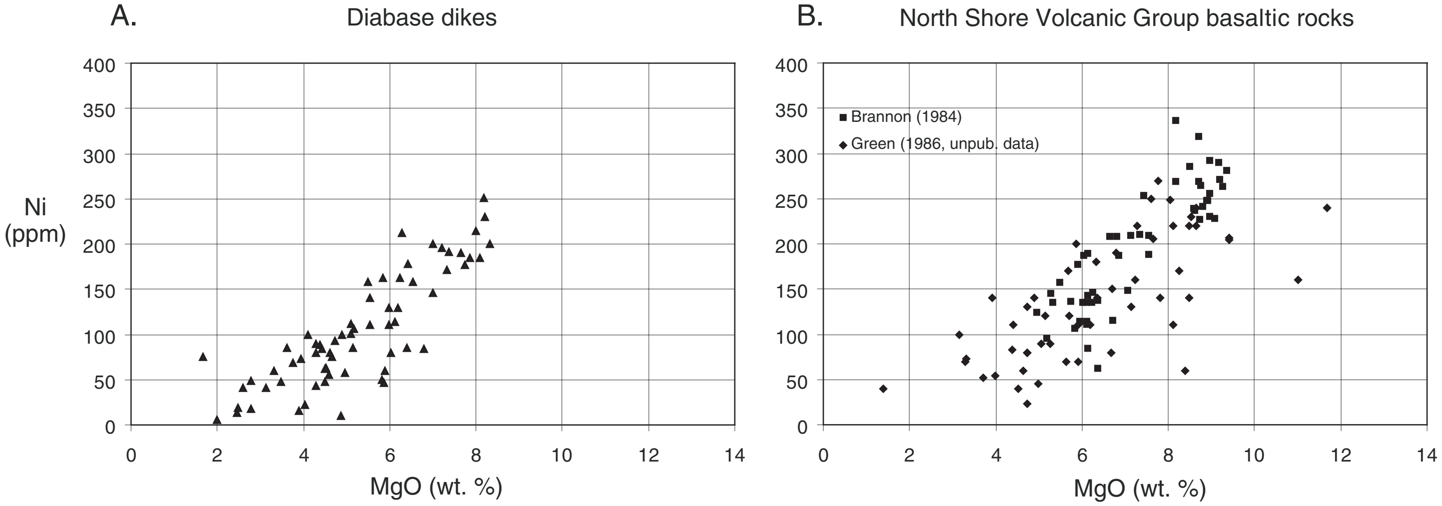


Figure 8.14. A. Variation in nickel and MgO in diabase dikes (Green, 1986, unpub. data).

B. Variation in nickel and MgO in North Shore Volcanic Group basalts from the upper southwest sequence (Brannon, 1984) and various North Shore Volcanic Group basalts from the northeast and southwest sequences (Green, 1986; unpub. data).

limb. Both sets again show a "normal," non-depleted trend of nickel and MgO; they are combined in Fig. 8.14b. A comparison of normal versus reversed magnetic polarity shows no significant difference in the MgO/nickel relationship. An average of 152 parts per million copper was found for the 17 analyses available.

These data imply that the magma sources that supplied these lavas and associated dikes experienced "normal," olivine-controlled fractionation without appreciable scavenging by immiscible sulfide liquids at depth. This conclusion is supported by the available lead, rubidium/strontium, and Sm/Nd isotope data for the basalts that indicate that little, if any crustal assimilation has affected these mafic liquids (Green, 1983; Dosso, 1984; Nicholson and others, 1997). It should be noted that the samples for these analyses were mostly collected in the general north shore area, although some came from inland localities. These are nearly all tens of kilometers from exposed plutons of the Duluth Complex, and may not have been connected to the intrusions of interest. Thus, it is not known how applicable these geochemical relations are to metallic exploration in the complex itself.

REFERENCES

Allen, D.J., Hinze, W.J., Dickas, A.B., and Mudrey, M.G., Jr., 1997, Integrated geophysical modeling of the North American Midcontinent rift system: New interpretations for western Lake Superior, northwestern Wisconsin, and eastern Minnesota, *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. 47-72.

Andersen, J.C.Ø., Rasmussen, H., Neilsen, T.F.D., and Rønsbo, J.G., 1998, The Triple Group and the Platinova gold and palladium reefs in the Skaergaard intrusion: Stratigraphic and petrographic relations: Economic Geology, v. 93, no. 4, p. 488-509.

Aranson, J.G., and Bird, D.K., 2000, A gold- and platinum-mineralized layer in gabbros of the Kap Edvard Holm Complex: Field, petrologic, and geochemical relations: Economic Geology, v. 95, no. 5, p. 945-970.

Aranson, J.G., Bird, D.K., Bernstein, S., and Kelemen, P.B., 1997, Gold and platinum-group element mineralization in the Kruuse Fjord Gabbro Complex, east Greenland: Economic Geology, v. 92, no. 4, p. 490-501.

Barnes, S.J., and Campbell, I.H., 1988, Role of late magmatic fluids in Merensky-type platinum deposits: A discussion: Geology, v. 16, no. 6, p. 488-491.

Barnes, S.J., Couture, J.F., Sawyer, E.W., and Bouchaib, C., 1993, Nickel-copper occurrences in the Belleterre-Angliers belt of the Pontiac Subprovince and the use of Cu-Pd ratios in interpreting platinum-group element distributions: Economic Geology, v. 88, no. 6, p. 1402-1418.

Bath, G.D., 1962, Magnetic anomalies and magnetizations of the Biwabik Iron Formation, Mesabi area, Minnesota: Geophysics, v. 27, no. 5, p. 627-650.

Bird, D.K., Brooks, C.K., Gannicott, R.A., and Turner, P.A., 1991, A gold-bearing horizon in the Skaergaard intrusion, east Greenland: Economic Geology, v. 86, no. 5, p. 1083-1092.

Boerboom, T.J., 1994, Archean crustal xenoliths in a Keweenawan hypabyssal sill, northeastern Minnesota. White was right!: Institute on Lake Superior Geology, 40th Annual Meeting, Houghton, Mich., Proceedings, v. 40, Program and Abstracts, pt. 1, p. 5-6.

Boerboom, T.J., and Miller, J.D., Jr., 1994, Bedrock geologic map of the Silver Island Lake, Wilson Lake, and western Toohey Lake quadrangles, Cook and Lake Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-81, scale 1:24,000.

Bonnichsen, B., 1972, Southern part of the Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 361-387.

Bonnichsen, B., Fukui, L.M., and Chang, L.Y., 1980, Geologic setting, mineralogy, and geochemistry of magmatic sulfide deposits, Duluth Complex, U.S.A.: Proceedings, 5th quadrennial International Association on the Genesis of Ore Deposits Symposium, Stuttgart, Germany, p. 545-565.

Boudreau, A.E., and McCallum, I.S., 1992, Concentration of platinum-group elements by magmatic fluids in layered intrusions: Economic Geology, v. 87, no. 7, p. 1830-1848.

Boudreau, A.E., and Meurer, W.P., 1999, Chromatographic separation of platinum-group elements, gold, base metals and sulfur during degassing of a compacting and solidifying igneous crystal pile: Contributions to Mineralogy and Petrology, v. 134, p. 174-185.

Brannon, J.C., 1984, Geochemistry of successive lava flows of Keweenawan North Shore Volcanic Group: St. Louis, Mo., Washington University, Ph.D. dissertation, 312 p.

Broderick, T.M., 1917, The relation of the titaniferous magnetites of northeastern Minnesota to the Duluth Gabbro: Economic Geology, v. 12, p. 663-696.

Carroll, M.R., and Rutherford, M.J., 1985, Sulfide and sulfate saturation in hydrous silicate melts: Journal of Geophysical Research, v. 90C, p. 601-612.

Cawthorn, R.G., 1999, Platinum-group element mineralization in the Bushveld Complex—A critical reassessment of geochemical models: South African Journal of Geology, v. 102, no. 3, p. 268-281.

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.

———2001, Superimposed magnetic on gravity anomaly map of the central Duluth Complex and western part of the Beaver Bay Complex, Lake and St. Louis Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-117, scale 1:100,000.

Chandler, V.W., and Ferderer, R.J., 1989, Copper-nickel mineralization of the Duluth Complex, Minnesota—A gravity and magnetic perspective: Economic Geology, v. 84, no. 6, p. 1690-1696.

Coyner, A.R., 1974, Geology of copper and cobalt veins, Loon Lake, Minnesota [abs.]: Institute on Lake Superior Geology, 20th Annual Meeting, Sault Ste. Marie, Ontario, Proceedings and Abstracts, v. 20, p. 10.

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 Minerals Report 255, 60 p.

Dahlberg, E.H., and Saini-Eidukat, B., 1991, A chlorine-bearing phase in drill core of serpentinized troctolitic rocks of the Duluth Complex, Minnesota: The Canadian Mineralogist, v. 29, pt. 2, p. 239-244.

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.]: Institute on Lake Superior Geology, 34th Annual Meeting, Marquette, Mich., handout.

Davidson, D.M., Jr., 1977, Reconnaissance geologic map of the Cherokee Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-30, scale 1:24,000.

Davidson, D.M., Jr., and Burnell, J.R., Jr., 1977, Reconnaissance geologic map of the Brule Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-29, scale 1:24,000.

Dosso, L., 1984, The nature of the Precambrian subcontinental mantle: Isotopic study (Sr, Pb, Nd) of the Keweenawan volcanism of the North Shore of Lake Superior: Minneapolis, University of Minnesota, Ph.D. dissertation, 220 p.

Engen, C.A., 1968, An informal report on the geology of the Blankenburg-Whiteside Prospect: Report supplied by A.R. Coyner, 2000.

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

———1994, Petrography and geochemistry of a platinum group element-bearing horizon in the Dunka Road prospect, (Keweenawan) Duluth Complex, northeastern Minnesota: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 157 p., 8 pls.

Graber, R.G., 1993, LTV Steel Mining Company: Institute on Lake Superior Geology, 39th Annual Meeting, Eveleth, Minn., Proceedings, v. 39, Fieldtrips, pt. 2, p. 39-42, 52-59.

Green, J.C., 1972, North Shore Volcanic Group, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 294-332.

———1983, Geologic and geochemical evidence for the nature and development of the middle Proterozoic (Keweenawan) Midcontinent rift of North America: Tectonophysics, v. 94, p. 413-437.

———1986, Lithogeochemistry of Keweenawan igneous rocks: Minnesota Department of Natural Resources, Division of Minerals Project 241-4, 94 p.

———1989, Mineral potential of felsic Keweenawan rocks in northeastern Minnesota: Final report: Unpublished Report, Basic Research Program, Minnesota Minerals Diversification Plan, 12 p.

Grout, F.F., 1949-1950, The titaniferous magnetites of Minnesota: St. Paul, Minn., Office of the Commissioner of the Department of Iron Range Resources and Rehabilitation, 117 p.

Grout, F.F., and Schwartz, G.M., 1933, The geology of the Rove Formation and associated intrusives of northeastern Minnesota: Minnesota Geological Survey Bulletin 24, 103 p., 20 pls.

———1939, The geology of anorthosites of the Minnesota coast of Lake Superior: Minnesota Geological Survey Bulletin 28, 119 p., 6 pls.

Grout, F.F., Sharp, R.P., and Schwartz, G.M., 1959, The geology of Cook County Minnesota: Minnesota Geological Survey Bulletin 39, 163 p., 16 pls.

Hauck, S.A., Severson, M.J., Ripley, E.M., Goldberg, S., and Alapieti, T., 1997a, Geology and Cr-PGE mineralization of the Birch Lake area, South Kawishiwi intrusion, Duluth Complex: Natural Resources Research Institute, Technical Report NRRI/TR-97/13, 32 p.

Hauck, S.A., Severson, M.J., Zanko, L.M., Barnes, S.J., Morton, P., Aliminas, H.V., Foord, E.E., and Dahlberg, E.H., 1997b, 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.

Haughton, D.R., Roeder, P.L., and Skinner, B.J., 1974, Solubility of sulfur in mafic magmas: Economic Geology, v. 69, no. 4, p. 451-467.

Hubert, J., 1954, Cobalt-copper showings of Loon Lake, northeastern Minnesota: Report supplied by A.R. Coyner, 2000.

Irvine, T.N., 1975, Primary precipitation of concentrated deposits of magmatic ores: Geological Survey of Canada Paper 75-1B, p. 73-79.

Johnson, R.G., 1968, Copper-nickel mineralization in the basal Duluth gabbro complex, northeastern Minnesota: A case study: Iowa City, University of Iowa, M.S. thesis, 91 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: Natural Resources Research Institute, Technical Report NRRI/GMIN-TR-89-15, 60 p., 3 pls.

Lightfoot, P.C., Naldrett, A.J., Gorbachev, N.S., Fedorenko, V.A., Hawkesworth, C.J., Hergt, J., and Doherty, W., 1994, Chemostratigraphy of Siberian trap lavas, Noril'sk District: Implications for the source of flood basalt magmas and their associated Ni-Cu mineralization, *in* Lightfoot, P.C., and Naldrett, A.J., eds., Proceedings of the Sudbury–Noril'sk symposium: Ontario Geological Survey Special Volume 5, p. 283-312.

Lightfoot, P.C., Hawkesworth, C.J., Olshefsky, K., Green, T., Doherty, W., and Keays, R.R., 1997, Geochemistry of Tertiary tholeiites and picrites from Qeqertarssuaq (Disko Island) and Nuussuaq, west Greenland with implications for the mineral potential of comagmatic intrusions: Contributions to Mineralogy and Petrology, v. 128, p. 139-163.

Linscheid, E.K., 1991, The petrology of the Longnose peridotite deposit and its relationship to the Duluth Complex: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 121 p., 2 pls.

Listerud, W.H., and Meineke, D.G., 1977, Mineral resources of a portion of the Duluth Complex and adjacent rocks in St. Louis and Lake Counties, northeastern Minnesota: Hibbing, Minn., Minnesota Department of Natural Resources, Division of Minerals Report 93, 74 p.

Maier, W.D., Barnes, S.J., De Klerk, W.J., Teigler, B., and Mitchell, A.A., 1996, Cu/Pd and Cu/Pt of silicate rocks in the Bushveld Complex: Implications for platinum-group element exploration: Economic Geology, v. 91, no. 6, p. 1151-1158.

Mainwaring, P.R., 1975, The petrology of a sulfide-bearing layered intrusion at the base of the Duluth Complex, St. Louis County, Minnesota: Toronto, University of Toronto, Ph.D. dissertation, 251 p.

Mainwaring, P.R., and Naldrett, A.J., 1977, Country rock assimilation and the genesis of Cu-Ni sulfides in the Water Hen intrusion, Duluth Complex, Minnesota: Economic Geology, v. 72, no. 7, p. 1269-1284.

Meints, J.P., Jirsa, M.A., Chandler, V.W., and Miller, J.D., Jr., 1993, Scientific core drilling in parts of Itasca, St. Louis, and Lake Counties, northeastern Minnesota, 1989-1991: Summary of lithologic, geochemical, and geophysical results: Minnesota Geological Survey Information Circular 37, 159 p.

Miller, J.D., Jr., 1998a, Potential for stratiform PGE deposits in sulfide-undersaturated, tholeiitic layered intrusions of the Duluth Complex, Minnesota, USA: 8th International Platinum Symposium Abstracts, Rustenburg, South Africa, GSSA and SAIMM Symposium Series S18, p. 263-266.

———1998b, Potential for reef-type PGE mineralization in the Duluth Complex: Evidence from the layered series at Duluth: The Minnesota Prospector, Special Issue, p. 8-12.

———1999, Geochemical evaluation of platinum group element (PGE) mineralization in the Sonju Lake intrusion, Finland, Minnesota: Minnesota Geological Survey Information Circular 44, 32 p.

Miller, J.D., Jr., Boerboom, T.J., and Jerde, E.A., 1994, Bedrock geologic map of the Cabin Lake and Cramer 7.5-minute quadrangles, Lake and Cook Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-82, scale 1:24,000.

Miller, J.D., Jr., and Chandler, V.W., 1997, Geology, petrology, and tectonic significance of the Beaver Bay Complex, northeastern Minnesota, *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. 73-96.

———1999, Bedrock geologic map of the central Duluth Complex and western part of the Beaver Bay Complex, Lake and St. Louis Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-101, scale 1:100,000.

Miller, J.D., Jr., Green, J.C., Boerboom, T.J., and Chandler, V.W., 1993, Geology of the Doyle Lake and Finland quadrangles, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-72, scale 1:24,000.

Miller, J.D., Jr., and Ripley, E.M., 1996, Layered intrusions of the Duluth Complex, Minnesota, USA, *in* Cawthorn, R.G., ed., Layered intrusions: Amsterdam, Elsevier Science, p. 257-301.

Miner, G.C., 1995, Aspects of the petrogenesis of the Longnose Fe-Ti-oxide-rich ultramafic body, Duluth Complex, Minnesota: St. Louis, Mo., Washington University, M.S. thesis, 243 p.

Miner, G.C., and Pasteris, J.D., 1994, Longnose Fe-Ti-oxide ultramafic body, Duluth Complex, MN: Evidence for magmatic and metasomatic development [abs.]: Geological Society of America Abstracts with Program, v. 26, no. 7, p. A-294.

Morey, G.B., 1992, Chemical composition of the eastern Biwabik Iron-Formation (Early Proterozoic), Mesabi range, Minnesota: Economic Geology, v. 87, no. 6, p. 1649-1658.

Morton, P., and Hauck, S.A., 1987, PGE, Au, and Ag contents of Cu-Ni sulfides found at the base of the Duluth Complex, northeastern Minnesota: Natural Resources Research Institute, Technical Report NRRI/GMIN-TR-87-04, 81 p.

Mudrey, M.G., Jr., 1972, Magmatic sulfides and associated fissure vein deposit at the Green prospect, Cook County, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 411.

Mudrey, M.G., Jr., and Morey, G.B., 1972, Cook County fissure vein deposits, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 407-410.

Muhich, T.G., 1993, Movement of titanium across the Duluth Complex–Biwabik Iron Formation contact at Dunka Pit, Mesabi Iron Range, northeastern Minnesota: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 154 p.

Naldrett, A.J., 1989a, Sulfide melts: Crystallization temperatures, solubilities in silicate melts, and Fe, Ni, and Cu partitioning between basaltic magmas and olivine, *in* Whitney, J.A., and Naldrett, A.J., eds., Ore deposition associated with magmas: Reviews in Economic Geology, v. 4, p. 5-20.

———1989b, Stratiform PGE deposits in layered intrusions, *in* Whitney, J.A., and Naldrett, A.J., eds., Ore deposition associated with magmas: Reviews in Economic Geology, v. 4, p. 135-165.

———1997, Key factors in the genesis of Noril'sk, Sudbury, Jinchuan, Voisey's Bay and other world-class Ni-Cu-PGE deposits: Implications for exploration: Australian Journal of Earth Sciences, v. 44, no. 3, p. 283-315.

Nicholson, S.W., Shirey, S.B., Schulz, K.J., and Green, J.C., 1997, Rift-wide correlation of 1.1 Ga Midcontinent rift system basalts: Implications for multiple mantle sources during rift development, *in* Bornhorst, T.J., ed., Petrology and metallogeny of intraplate mafic and ultramafic magmatism: Canadian Journal of Earth Sciences, v. 34, no. 4, p. 504-520.

Nielsen, R.L., 1990, Theory and application of a model of open system processes, *in* Nicholls, J., and Russell, J.K., eds., Modern methods of igneous petrology: Understanding magmatic processes: Reviews in Mineralogy, v. 24, p. 56-106.

Peach, C.L., Mathez, E.A., and Keays, R.R., 1990, Sulfide melt—silicate melt distribution coefficients for the noble metals and other chalcophile elements as deduced from MORB: Implications for partial melting: Geochimica et Cosmochimica Acta, v. 54, no. 12, p. 3379-3389.

Peterson, D.M., 1997, Ore deposit modeling of the footwall mineralization of the Duluth Complex: Hibbing, Minn., Minnesota Department of Natural Resources, Division of Minerals Project 317, 55 p., 46 pls.

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

Poulson, S.R. and Ohmoto, H., 1990, An evaluation of the solubility of sulfide sulfur in silicate melts from experimental data and natural samples: Chemical Geology, v. 85, p. 57-75.

Prendergast, M.D., 2000, Layering and precious metals mineralization in the Rincón del Tigre Complex, eastern Bolivia: Economic Geology, v. 95, no. 1, p. 113-130.

Prendergast, M.D., and Wilson, A.H., 1989, The great dyke of Zimbabwe—II. Mineralization and mineral deposits, *in* Prendergast, M.D., and Jones, M.J., eds., Magmatic sulfides—The Zimbabwe volume: London, Institute of Mining and Metallurgy, p. 21-42.

Ripley, E.M., 1986, Origin and concentration mechanisms of copper and nickel in Duluth Complex sulfide zones—a dilemma: Economic Geology, v. 81, no. 4, p. 974-978.

Sassani, D.C., 1992, Petrologic and thermodynamic investigation of the aqueous transport of platinum-group elements during alteration of mafic intrusive rocks: St. Louis, Mo., Washington University, Ph.D. dissertation, 952 p.

Schwartz, G.M., 1924, The contrast in the effect of granite and gabbro intrusions on the Ely Greenstone: Journal of Geology, v. 32, no. 2, p. 89-138.

———1925, A sulfide diabase from Cook County, Minnesota: Economic Geology, v. 20, no. 3, p. 261-265.

Scoon, R.N., and Mitchell, A.A., 1994, Discordant iron-rich ultramafic pegmatites in the Bushveld Complex and their relationship to iron-rich intercumulus and residual liquids: Journal of Petrology, v. 35, no. 4, p. 881-917.

Severson, M.J., 1994, Igneous stratigraphy of the South Kawishiwi intrusion, Duluth Complex, northeastern Minnesota: Natural Resources Research Institute, Technical Report NRRI/TR-93/34, 210 p., 15 pls.

———1995, Geology of the southern portion of the Duluth Complex: 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: 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: Natural Resources Research Institute, Technical Report NRRI/GMIN-TR-89-11, 236 p., 4 pls.

———1997, Igneous stratigraphy and mineralization in the basal portion of the Partridge River intrusion, Duluth Complex, Allen quadrangle, Minnesota: Natural Resources Research Institute, Technical Report NRRI/TR-97/19, 102 p., 4 pls.

Severson, M.J., Patelke, R.L., Hauck, S.A., and Zanko, L.M., 1994, The Babbitt copper-nickel deposit, part B: Structural datums: Natural Resources Research Institute, Technical Report NRRI/TR-94/21b, 48 p., 6 pls.

Stumpfl, E.F., and Rucklidge, J.C., 1982, The platiniferous dunite pipes of the eastern

Bushveld: Economic Geology, v. 77, no. 6, p. 1419-1431.

Thériault, R.D., Barnes, S.J., and Severson, M.J., 1997, The influence of country-rock assimilation and silicate to sulfide ratios (R factor) on the genesis of the Dunka Road Cu-Ni-platinum-group element deposit, Duluth Complex, Minnesota, *in* Bornhorst, T.J., ed., Petrology and metallogeny of intraplate mafic and ultramafic magmatism: Canadian Journal of Earth Sciences, v. 34, no. 4, p. 375-389.

———2000, Origin of Cu-Ni-PGE sulfide mineralization in the Partridge River intrusion, Duluth Complex, Minnesota: Economic Geology, v. 95, no. 5, p. 929-943.

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

Winchell, H.V., 1897, Reputed nickel mines in Minnesota: Engineering and Mining Journal, v. 64, p. 578.

Zanko, L.M., Severson, M.J., and Ripley, E.M., 1994, Geology and mineralization of the Serpentine copper-nickel deposit: Natural Resources Research Institute, Technical Report NRRI/TR-93/52, 90 p., 3 pls.

DATA-BASE CD

Timothy E. Wahl

This appendix describes the contents of the CD that accompanies this report. The data are contained largely in the form of ArcView shapefiles and are intended to provide much of the raw field data, drill hole data, and geophysical data upon which the mapped interpretation was based as well as digital versions of map M-119 itself. The data were compiled in ArcView 3.2 and their use requires either that program or other software capable of converting the ArcView shapefile format. The gridded geophysical data included, both aeromagnetic and gravity, are in ArcInfo grid format. Also included with the data are three ArcView project files that may prove useful for accessing the data via that software, but some familiarity with the use of ArcView is assumed.

Data capture was largely accomplished using the native capabilities of ArcView along with Geologic Mapping System (GeMS)—a data structure and user interface routine developed at the Minnesota Geological Survey. The "gem" prefix on many of the shapefiles refers to this data system. Data capture was mostly done on screen using the U.S. Geological Survey Digital Raster Graphic (DRG) 7.5-minute quadrangle maps as references and for the registration of maps scanned for digitization.

All geographic coordinate data are in the UTM projection, zone 15. The datum used is NAD 83.

ACCESSING THE DATA

The CD contains three zip files. The first of these, "dulcmplx.zip," contains the project data layers and supporting files in a single, compressed directory. The full extracted size of the directory is about 130 MB. The second file on the CD, "drgs.zip," contains the DRGs for the study area in tif format. Extracting all of the DRGs will require about 625 MB of disk space. It is suggested that the dulcmplx.zip files be extracted to disk first. The DRGs are not required for the ArcView project files to run, but if desired, they should be extracted to the drg folder that will exist in the dulcmplx folder after the full dulcmplx directory is installed. The third zip file, "m120.zip," contains all files associated with Minnesota Geological Survey Miscellaneous Map M-120, "Superimposed magnetic on gravity anomaly map of the Duluth Complex and related rocks, northeastern Minnesota," by V.W. Chandler. The contents of m120.zip are documented by files "readme.txt" or "readme.doc," and "m120meta.pdf," which are contained within the m120.zip file.

CONTENTS

The two main ArcView project files included in dulcmplx.zip are "dcmap200x.apr" and "dcmapdetail.apr." The data layers utilized by each project are:

1. Project file: "dcmap200x.apr"—This project file draws on data layers used to generate the printed map M-119.

Data utilized:

shapefiles (.shp):

geologic data layers:

- **gemu200x**—Base geology units for map M-119
- **geml200l**—Linework for gemu200x (faults, contacts, and other linear map features)
- **gemst200x**—Structure measurements appearing on map M-119

cartographic layers:

- patterns—Overlay patterns to provide distinction of different units and circumvent technical difficulties with the printing process
- maplabels—Unit labels
- strlabels—Dip and plunge labels for structural measurements

base layers (provided for general reference):

- quads—U.S. Geological Survey 7.5-minute quadrangle grid of the area
- highways—TIGER major roads
- roads—TIGER minor roads
- lakes—TIGER lakes layer
- hydro—TIGER hydrology layer
- counties—Minnesota Department of Transportation county boundary layer
- papg—Project area polygon outline

2. Project file: "dcmapdetail.apr"—Provides more detailed versions of the geology map layers, some of which were compiled at 1:24,000-scale and others where compiled from previous work at various (smaller) scales. This project file also incorporates the geophysical gridded data (aeromagnetic and gravity) as well as site-specific data not included on map M-119.

Data utilized:

- *shapefiles (.shp):*
  - *geologic data layers:*
    - **gemgeou**—(cf.gemguall) Includes detailed geologic units that were dropped, lumped, or simplified for the 1:200,000-scale map
    - **gemgeol**—(cf.gemglall) Linework for gemgeou (faults, contacts, and other linear map features)
    - **gemstr**—Full structural measurement data set compiled for the project
    - **gemdhl**—All exploration diamond drilling holes compiled
    - **gemoc**—Some 20,000 outcrop polygons digitized for the projects, about half of which include detailed field data attributes
    - **gemsam**—Handsample locations and data compiled for several areas within the mapped region
    - grpt—Gravity station location and attributes for data used to generate the Bouguer and derivative gravity grids
    - rockprop—Rock properties data (density and magnetization) and locations
- *Arc grids:*
  - mgd—Base aeromagnetic anomaly grid
  - mgdhs1—ArcView-generated hillshade of mgd; azimuth 345; elevation 45
  - mgd1vt—First vertical derivative of mgd after reduction to pole
  - ggd—Base Bouguer gravity grid
  - ggd2d—Second vertical derivative of ggd

Both projects make use of a special set of markers for displaying structural data. This marker set requires that a custom font (Mgs_esri.tff), included in the dulcmplx.zip data set, be installed in Windows. The method for installing this font differs among the various versions of Windows, so consult the system documentation for details on this procedure.

The third ArcView project file is "intrusionmap.apr." This project provides a simplified version of the Duluth Complex geology in which the different units have been aggregated by "intrusion." This project file presents the data as shown in the 1:500,000-scale intrusion map on plate 2 of M-119.

Data utilized:

- *shapefiles (.shp):*
  - *geologic data layers:*
    - intrusns—Simplified geology
    - dikes—Dikes
  - *cartographic layer*
    - intrlabs—Map labels
  - *base layers*
    - quads—Grid of U.S. Geological Survey 7.5-minute quadrangles in the study area
    - counties—Minnesota Department of Transportation county boundary layer
    - papg—Project area polygon outline

Digital versions of the M-119 plates in pdf format are included in a folder called "pdfs" within the dulcmplx folder.

Formal metadata for the GIS data layers in this distribution are included in a folder called "Metadata" within the dulcmplx folder.

GEOLOGIC MAPPING SYSTEM (GeMS)

As mentioned above, much of the data capture for this project was accomplished using GeMS, the Geologic Mapping System developed by the Minnesota Geological Survey. The following sections describe the system and give an overview of the interface and its use in examining the attribute information included with project data layers.

GeMS—Background

GeMS consists of a geologic data model, the physical data structures to support the model, and ArcView interface routines to facilitate data capture and retrieval. The underlying goal of GeMS is to provide a framework for storing geologic field data in a geographic information system (GIS) to facilitate geologic mapping.

GeMS data model

GeMS was designed from the perspective of the field geologist. Currently, the model is limited to bedrock geologic mapping, but it will be expanded to include data structures needed to support "surficial" or Quaternary geologic mapping.

The general structure is as follows (model components in italics were not implemented for this project):

- outcrop
  - *detailed attributes*
    - *igneous intrusive rocks*
    - *volcanic rocks*
    - *metamorphic rocks*
    - *sedimentary rocks*
  - *alteration/mineralization/deformation*
- samples
  - *whole rock analyses*
  - *thin sections*
  - *petrography*
  - *microprobe analyses*
    - *silicates*
    - *oxides*
    - *sulfides*
    - *other*
  - rock properties
  - *isotope analyses*
  - *geochronology*
  - *assay data*
- structure
- drill holes
  - general data
    - *interval data*
- geology
  - geologic units (polygons)
  - geologic linear features (such as contacts, faults, and fold axes)

The main geologic data types and their related GIS feature types and associated shapefile or coverage names are:

Geologic data type	GIS topology	Layer name (shapefile/coverage)
outcrop	polygon	gemoc
sample	point	gemsam
structure	point	gemstr
drill holes	point	gemdhl

There are two layers associated with the geologic map as used in GeMS. These are:

Geologic map layer	GIS topology	Layer name (shapefile/coverage)
geologic map units	polygon	gemgeou
geologic map lines (such as contacts, faults, and fold axes)	line	gemgeol

The detailed data structure for the data layers implemented in this project are given at the end of this appendix.

GeMS interface

The main portions of the GeMS model were used for this project and are supported by interface extensions for ArcView version 3.x developed in Avenue. The standard GeMS interface, as distributed in the ArcView project for the Duluth Complex dataset, uses two views—"GeMSindex" and "GeMSview." In practice, only the GeMSview view, which contains the actual data interface routines, is used, and discussion here will be limited to that portion of the interface.

A pull-down menu bar item is added to the main view menu bar of the GeMSview view (Fig. A1).

These menu items provide access to the GeMS data layer attributes for viewing or editing. To view (or edit) data for a given GeMS theme, the theme must be active and one feature of the theme selected. The corresponding item is selected from the GeMS menu, which activates a pop-up window displaying the current attributes for the selected feature. In Figure A2, the GeMS structure theme "gemstr" is active, a structure measurement has been selected, and the "Structure" item has been selected from the GeMS menu displaying the structure measurement attributes.

GeMS interface requirements and customization

The data structure uses a number of codes to store attribute information. The interface routines rely on code tables to expand the codes for the data access windows. These tables must be in a folder (directory) called "codes" in the folder where the ArcView project file using the GeMS interface is located. The format of the code tables is given below. The data within the code tables may be modified through ArcView Tables editing, Excel, FoxPro, or any software capable of editing .dbf

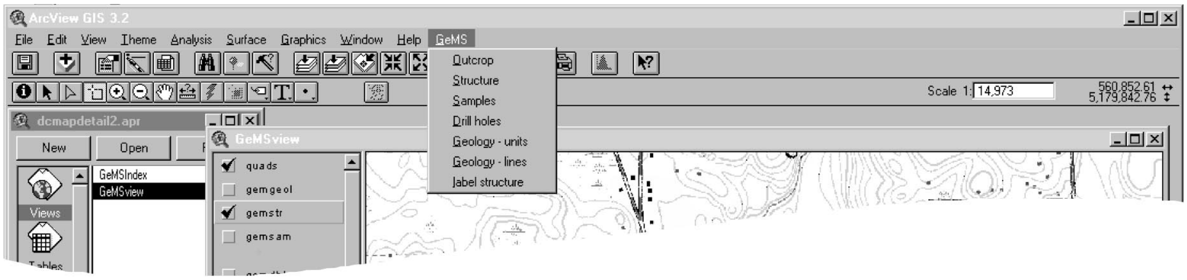
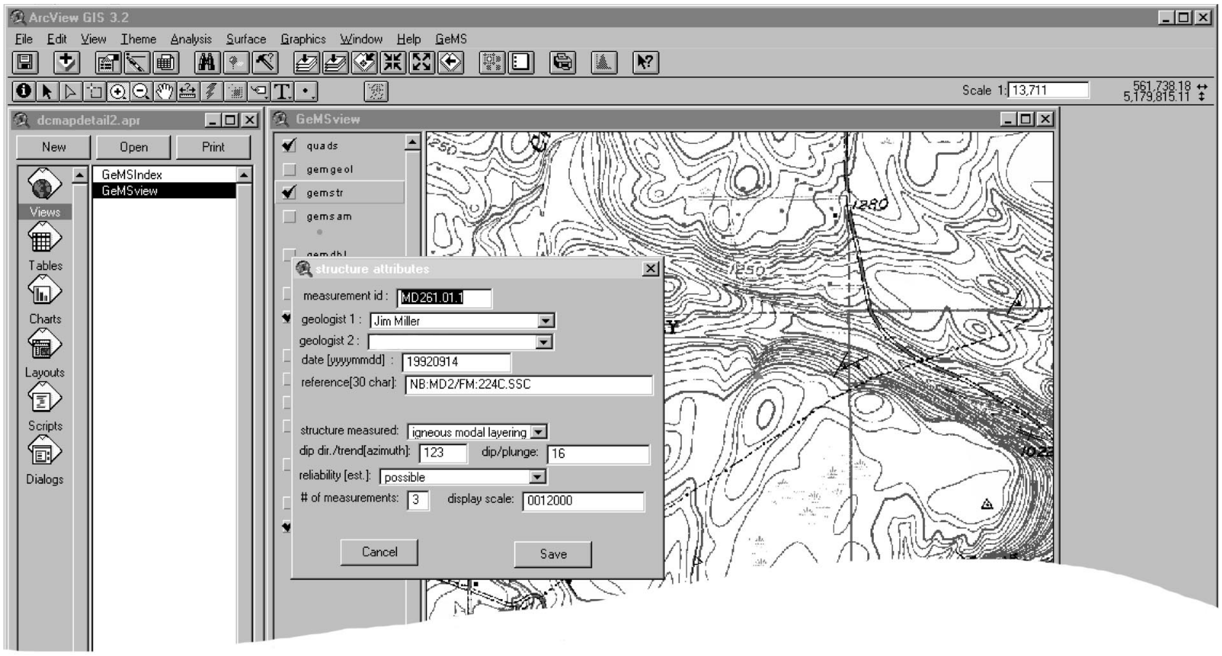


Figure A1. GeMSview interface menu.



structure attributes

measurement id : MD261.01.1

geologist 1 : Jim Miller

geologist 2 :

date [yyyymmdd] : 19920914

reference[30 char]: NB:MD2/FM:224C.SSC

structure measured: igneous modal layering

dip dir./trend[azimuth]: 123

dip/plunge: 16

reliability [est.]: possible

# of measurements: 3

display scale: 0012000

Figure A2. Example showing GeMS data access for the structure theme.

(dBase) files in order to customize the menus for mapping in particular locales, although care must be taken not to alter the structure (field widths, types, or names) of the code files. Additions and modifications to code tables should be made with care because one of the main advantages of using code tables is to standardize and minimize the variety of data stored in the database in order to simplify queries and data retrieval.

GeMS also operates only on themes with specific names (such as “gemoc” and “gemstr”). However, this only refers to the theme name in the view, not the shapefile behind the name. As long as a shapefile has the correct data structure it can be manipulated through GeMS if it is added to GeMSview and the name property of the theme is set appropriately.

Note that GeMS is a data model and defined file structure with an interface to manipulate data elements within that structure, but it does not provide the means to create the geography for the features to which it applies. The actual creation of the points, lines, and polygons in the various layers is accomplished using standard ArcView editing tools.

GeMS attribute tables and reference codes

OUTCROPS

shapefile: **gemoc** type: polygon

Field name	Format	Field	Code lookup table
RELATEID	C 10	relate id	
TYPE	C 2	polygon type	(= OC)
GCM_CODE	C 3	geo-coordinate method	gcmcode.dbf
GEOC_SRC	C 5	geo-coordinate source	geocsrc.dbf
GEOC_DATE	I 8	geo-coordinate date	(yyyymmdd)
UTME	I 6	UTM easting	
UTMN	I 7	UTM northing	
UTM_ZONE	I 2	UTM zone	(= 15)
FIELD_STA	C 8	field station identifier	
GEOL_1	C 3	geologist (1)	gcgeolgs.dbf
GEOL_2	C 3	geologist (2)	gcgeolgs.dbf
OC_DATE	I 8	field date	(yyyymmdd)
REFRNCE	C 30	reference	(field book/map or other)
OBS_DETAIL	C 1	observation detail	gcocobs.dbf
EXP_VIS	C 1	exposure visibility	gcexpvis.dbf
EXP_PCNT	C 1	exposure percent	gcexppct.dbf
OC_TYPE1	C 2	outcrop type (1)	gcoct.dbf
OC_TYPE2	C 2	outcrop type (2)	gcoct.dbf
OC_PHOTOS	C 3	outcrop photo reference	
OC_SAMPLES	C 1	sample take	(y/n/ /#)
ROCK_TYPE1	C 1	primary rock type (1)	(I/V/M/S)
RK_NAME1	C 4	rock name (1)	gcrkn.dbf (gcrkni/v/m/s)
ROCK_TYPE2	C 1	secondary rock type (2)	(I/V/M/S)
RK_NAME2	C 4	rock name (2)	gcrkn.dbf (gcrkni/v/m/s)
ROCK_TYPE3	C 1	additional rock type (3)	(I/V/M/S)
RK_NAME3	C 4	rock name (3)	gcrkn.dbf (gcrkni/v/m/s)
MAPUNIT	C 4	map unit code	
OCFLD_DESC	C 40	outcrop field description	
[CUMULATE1	C 6	cumulate descriptor code – specific to Duluth Complex mapping]	

SAMPLES

shapefile: **gemsam** type: point

Field name	Format	Field	Code lookup table
RELATEID	C 10	relate id	
TYPE	C 2	polygon type	
GCM_CODE	C 3	geo-coordinate method	gcmcode.dbf
GEOC_SRC	C 5	geo-coordinate source	geocsrc.dbf
GEOC_DATE	I 8	geo-coordinate date	(yyyymmdd)
UTME	I 6	UTM easting	
UTMN	I 7	UTM northing	
UTM_ZONE	I 2	UTM zone	(= 15)
FIELD_STA	C 8	field station identifier	
SAMP_ID	C 10	sample identifier	
SAMP_DATE	I 8	sample date	(yyyymmdd)
GEOL_1	C 3	geologist (1)	gcgeolgs.dbf
GEOL_2	C 3	geologist (2)	gcgeolgs.dbf
REFRNCE	C 30	reference	(field book/map or other)
PCORE	C 1	core	(y/n/blank)
PSLAB	C 1	slab	(y/n/blank)
PHNDSMP	C 1	hand sample	(y/n/blank)
PPULP	C 1	pulp	(y/n/blank)
PLOC	C 1	sample location	gcploc.dbf
ROCK_TYPE	C 1	primary rock type (1)	(I/V/M/S)
ROCK_NAME	C 4	rock name (1)	gcrkn.dbf (gcrkni/v/m/s)
MAPUNIT	C 4	map unit code	
FIELD_DESC	C 40	field description	
NTHNSECT	I 1	number of thin sections	
PETROG_TL	C 1	petrography-trans.light	(y/n/blank)
PETROG_RL	C 1	petrography-reflect.light	(y/n/blank)
PETRO_DESC	C 40	petrographic description	
MODE	C 1	modal analysis done?	(y/n/blank)
PROBE_SIL	C 1	probe-silicates done?	(y/n/blank)
PROBE_OX	C 1	probe-oxides done?	(y/n/blank)
PROBE_S	C 1	probe-sulfides done?	(y/n/blank)
PROBE_OTH	C 1	probe-other done?	(y/n/blank)
WRA	C 1	whole-rock done?	(y/n/blank)
ISOTOPE	C 1	isotope analysis done?	(y/n/blank)
ASSAY	C 1	mineral assay done?	(y/n/blank)
GEOCHRON	C 1	geochronology done?	(y/n/blank)
ROCKPROP	C 1	rock properties done?	(y/n/blank)

STRUCTURE

shapefile: **gemstr** type: point

Field name	Format	Field	Code lookup table
RELATEID	C 10	relate id	
TYPE	C 2	polygon type	
GCM_CODE	C 3	geo-coordinate method	gcmcode.dbf
GEOC_SRC	C 5	geo-coordinate source	geocsrc.dbf
GEOC_DATE	I 8	geo-coordinate date	(yyyymmdd)
UTME	I 6	UTM easting	
UTMN	I 7	UTM northing	
UTM_ZONE	I 2	UTM zone	(= 15)
FIELD_STA	C 8	field station identifier	
MEAS_ID	C 10	measurement identifier	
MEAS_DATE	I 8	measurement date	(yyyymmdd)
GEOL_1	C 3	geologist (1)	gcgeolgs.dbf
GEOL_2	C 3	geologist (2)	gcgeolgs.dbf
REFRNCE	C 30	reference	(field book/map or other)
STRUCTURE	C 2	structure measured	gcstr.dbf
STRUC_TYPE	C 1	struct.type-planar or linear	(P/L)
DIPD_TREND	I 3	dip direction or trend	(meas.as azimuth 0-360 from north)
DIP_PLUNGE	I 3	dip or plunge	(neg.indicates overturned)
MRR_RELIAB	C 1	measurement reliability	gcmrr.dbf
N_MEAS	I 1	number of measurements	
SYM_CODE	I 4	symbol code	gcstr.dbf
DISPLAY	I 8	display scale	(smallest at which to display)
AVANGLE	I 3	ArcView angle	

DRILL HOLES

shapefile: **gemdhl** type: point

Field name	Format	Field	Code lookup table
RELATEID	C 10	relate id	
TYPE	C 2	polygon type	
GCM_CODE	C 3	geo-coordinate method	gcmcode.dbf
GEOC_SRC	C 5	geo-coordinate source	geocsrc.dbf
GEOC_DATE	I 8	geo-coordinate date	(yyyymmdd)
UTME	I 6	UTM easting	
UTMN	I 7	UTM northing	
UTM_ZONE	I 2	UTM zone	(= 15)
DHLID	C 10	drill hole identifier	
DHLNAME	C 24	drill hole name	
DATE_DRLLD	I 8	date drilled	(yyyymmdd)
LESSEE	C 20	lease holder	gclessee.dbf (not used)
TWP	I 3	township	
RNG	I 2	range	
RNG_DIR	C 1	range direction	(W/E)
SEC	I 2	section	
SUBSEC	C 6	subsection	
ELEV	I 4	elev. of land surface	
AZ	I 3	azimuth (if angled hole)	
PLUNGE	I 2	plunge (if angled hole)	
DEPTH	I 4	depth (ft.)	
D2BDRK	I 4	depth to bedrock (ft.)	
FRST_BDRK	C 4	first bedrock unit	gcstrat.dbf
LAST_STRAT	C 1	last strat. unit	gcstrat.dbf
CSTORAGE	C 4	core storage location	
CDIAM	C 4	core diameter (in.)	
CINT_TOP	I 4	core int. top depth (ft.)	
CINT_BOT	I 4	core int. bottom depth(ft.)	
GEOL_1	C 3	geologist	gcgeolgs.dbf
GEOL_SRC	C 5	geology source. inst.	gcgeosrc.dbf
DATE_LOGD	I 8	date core was logged	(yyyymmdd)

GEOLOGY—UNITS

shapefile: **gemgeou** type: polygon

Field name	Format	Field	Code lookup table
RELATEID	C 10	relate id	
TYPE	C 2	polygon type	(= GU)
GCM_CODE	C 3	geo-coordinate method	gcmcode.dbf
GEOC_SRC	C 5	geo-coordinate source	geocsrc.dbf
GEOC_DATE	I 8	geo-coordinate date	(yyyymmdd)
UTME	I 6	UTM easting	
UTMN	I 7	UTM northing	
UTM_ZONE	I 2	UTM zone	(= 15)
GEOL_1	C 3	geologist	gcgeolgs.dbf
INTRP_DATE	I 8	interpretation date	(yyyymmdd)
BASIS1	C 4	basis for interp.(1)	gcgbas.dbf
BASIS2	C 1	basis for interp.(2)	gcgbas.dbf
MGSCODE	C 4	internal MGS code	gcgeou.dbf
SYMBOL	C 1	legend symbol number	gcgeou.dbf
MAPLABEL	C 6	map label	gcgeou.dbf
UNIT_CODE	C 4	map unit code	gcgeou.dbf
DESCRIPTION	C 30	description	gcgeou.dbf
REFRNCE	C 30	reference	

GEOLOGY—LINES

shapefile: **gemgeol** type: line

Field name	Format	Field	Code lookup table
RELATEID	C 10	relate id	
TYPE	C 2	polygon type	
GCM_CODE	C 3	geo-coordinate method	gcmcode.dbf
GEOC_SRC	C 5	geo-coordinate source	geocsrc.dbf
GEOC_DATE	I 8	geo-coordinate date	(yyyymmdd)
GEOL_1	C 3	geologist (1)	gcgeolgs.dbf
INTRP_DATE	I 8	interpretation date	(yyyymmdd)
BASIS1	C 3	basis for interp.(1)	gcgbas.dbf
BASIS2	C 3	basis for interp.(2)	gcgbas.dbf
FEATURE	C 4	linear feature	gcgeol.dbf
MGSCODE	I 6	internal MGS code	gcgeol.dbf
SYMBOL	I 3	legend symbol number	gcgeol.dbf
DESCRIPTN	C 30	description	gcgeol.dbf
REFRNCE	C 30	reference	
WIDTH_M	I 4	est. width of feature (m.)	

GeMS code table definitions

The table structure for most code files is:

Field name	Format	Field
code	C xx	code
descriptn	C yy	code expansion

where xx and yy are replaced with widths appropriate for the code and code expansion.

The code file (gcstr.dbf) format for structure features (gemstr) is:

Field name	Format	Field
code	C 2	structure feature code
descriptn	C 30	description
type	C 1	planar or linear
symbol	I 3	symbol number for inclined feature
symbolv	I 3	symbol number for vertical feature
symbolh	I 3	symbol number for horizontal feature
structure	C 2	structure feature code

The code file (gcgeou.dbf and gcgeol.dbf) format for geologic units (gemgeou) and linear geologic features (gemgeol) is:

Field name	Format	Field
mgscode	I 6	internal MGS code
symbol	I 3	symbol number for feature
label	C 6	text label for map display
unit_code	C 4	standard MGS feature code
descriptn	C 30	description

Code files are:

gcexppct.dbf	exposure - percent
gcexpvis.dbf	exposure – visibility
gcgbas.dbf	basis for geologic interpretation
gcgeol.dbf	geologic map linear features
gcgeolgs.dbf	geologists
gcgeosrc.dbf	geologic interpretation source (institution)
gcgeou.dbf	geologic map units
gclessee.dbf	mineral lease holders [not used]
gcmrr.dbf	structure measurement reliability codes
gcocobs.dbf	outcrop observation detail
gcoct.dbf	outcrop type
gcploc.dbf	sample storage location
gcrkn.dbf	rock names
gcrknb.dbf	[rock names-blank]
gcrkni.dbf	rock names-intrusive
gcrknm.dbf	rock names-metamorphic
gcrkns.dbf	rock names-sedimentary
gcrknv.dbf	rock names-volcanic
gcrkt.dbf	rock type
gcscond.dbf	sample surface condition
gcstr.dbf	structure
gcstrat.dbf	stratigraphic units
gcynb.dbf	yes/no/blank
gcmcode.dbf	geographic coordinate method code
geocsrc.dbf	geographic coordinate source (institution)