GEOLOGY AND SEDEX POTENTIAL OF EARLY PROTEROZOIC ROCKS, EAST-CENTRAL MINNESOTA

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ABSTRACT

Many stratiform sedimentary exhalative deposits (SEDEX), specifically those in Canada and Australia, are hosted by Paleoproterozoic sedimentary rocks that were deposited in intracratonic or intra-rift tectonic settings. Rocks of similar age and tectonic settings are also found within east-central Minnesota and include the Animikie Basin and the Fold-and-Thrust Belt. However, exploration for SEDEX deposits has been very limited in Minnesota due to an almost complete lack of outcrop. While extensive drilling for iron-formation took place in these same areas, little drill core exists for examination. In lieu of this paucity of information, there are specific areas in the Animikie Basin and the adjacent Fold-and-Thrust Belt that exhibit many features that are indicative of SEDEX mineralization.

This report covers the regional geology and SEDEX potential of Paleoproterozoic rocks in Aitkin, Carlton, Cass, Crow Wing, Itasca, and St. Louis counties. The detailed geology of 24 specific areas, as determined by the relogging of 1,200 holes (150,630 feet of drill core), are discussed in the report. All base metal analyses, from drill core samples in the above mentioned counties, have been compiled (pre-2001) and are included and evaluated on a site-by-site basis. Areas with the most anomalous zinc values include the following: Siphon Fault area of St. Louis County (up to 2.65% Zn); Kalevala Township of Carlton County (up to 2.5% Zn); Kettle River area of Carlton County (maximum of 0.74% Zn); and Glen Township of Aitkin County (only a maximum of 0.39% Zn but visible sphalerite is present in several drill holes).

All whole rock analyses, for both mafic volcanic and metasedimentary rocks, are also provided and are evaluated in terms of possible depositional/tectonic environments. The plotted positions of the mafic volcanic samples on various diagrams indicates that the mafic rocks are dominantly high-Fe tholeiitic basalts that formed in either an island arc, ocean floor, within plate, or continental settings. Not surprisingly, these plots reiterate the findings of Southwick et al. (2001); wherein, they concluded that these types of rock compositions are often associated with SEDEX deposits, and that they were deposited in basins that may have been extensional and lain in a forearc position. Geochemistry for Paleoproterozoic rocks from other counties outside of the area of this investigation are also included, but are not discussed, in this report.

Sulfur isotopes were determined for various sedimentary and volcanic rock types in this investigation. Isotopic $\delta^{34}S$ values for sequences of carbonaceous argillite exhibit differences from one geographic location to another location that are probably originally related to either euxinic closed basin conditions, magmatic (volcanic) input conditions, or combinations of the two. For example, extremely high $\delta^{34}S$ values (closed basin) are associated with a sedimentary unit of the Virginia Formation (BDD PO Unit) in the Siphon Fault area; whereas, extremely low values $\delta^{34}S$ (magmatic input) are associated with a sulfide-rich carbonaceous argillite in the Glen Township area. Overall, the range of isotopic $\delta^{34}S$ values found in the various carbonaceous argillite sequences show good comparisons with the host-rock $\delta^{34}S$ values of several known SEDEX deposits.

Carbon and oxygen isotope values were also determined for several different rock types. These data suggest that a thick dolomite sequence, intersected in deep drill holes in Carlton County,

could probably be correlated with the Denham Formation exposed to the south in Pine County. However, carbon and oxygen isotopic values of another dolomite sequence, the Trout Lake Formation of the Emily District (Crow Wing County), exhibit marked differences, and thus, the Trout Lake and Denham Formations are probably not correlative.

Microprobe compositions are present for tourmaline found at the Glen Township and the Siphon Fault area. The tourmaline compositions are characteristic of metapelites and metapsammites, and fall within the field defined by tourmalines in host-rocks at the Sullivan and Broken Hill deposits. These relationships suggests that the Glen Township and Siphon Fault area have some potential to host a SEDEX deposit, especially if it can be demonstrated that the presence of a tourmaline-bearing feeder vents are essential.

Also included in this report, but not discussed, are rock property data consisting of magnetic susceptibility readings (5,480 readings from 98 holes) and density readings (1,085 readings - mostly reorganized from previously collected data).

All of the data assembled for this investigation, when viewed collectively, suggests that the best SEDEX potential is present in several areas that include:

Kalevala Township, Fold-and-Thrust Belt, Carlton County -

- Up to 2.5% zinc, as well as visible sphalerite in core, is present.
- Locally present in some holes are thin beds of delicately-bedded semi-massive sulfide (referred to as "brown beds") with very fine-grained syngenetic sphalerite.
- Overall, the rocks exhibit abrupt sedimentary facies changes from coarse-grained clastic sediments up-section to deep water euxinic sediments = possible fault zones (proper plumbing?) within smaller second and third order basins.
- Mafic volcanics (flows and hypabyssal sills) are present in a nearby structural panel.

Glen Township Sulfide - South Body, Fold-and-Thrust Belt, Aitkin County -

- The area contains a thick package of carbonaceous, sulfide-rich argillite in close associated with Fe-carbonate bearing sediments and chemical iron-formation. The sulfide-content in the carbonaceous argillite sequence increases upward indicating a closed basin.
- $\delta^{34}S$ isotope values show a very crude upward increase within the carbonaceous argillite; however, isotope values are low overall (1.6 to 6.4 ‰ $\delta^{34}S$) indicating that a magmatic (hydrothermal?) component was probably active - the argillite is capped by mafic volcanics.
- Gabbroic sills, possible heat sources, are present in all rock units.
- Carbonate alteration, related to hydrothermal activity(?), is present in localized zones in the mafic volcanics.
- Tourmalines, with a composition similar to tourmalines in the host-rock at the Sullivan deposit, are present within an argillite interbed within the overlying mafic volcanics.
- There are numerous sedimentological facies changes in many of the metasediments indicating that localized faulting (growth faults?) may have been important.
- Visible sphalerite is present in several drill holes; unfortunately, limited zinc analyses indicate a maximum of only 0.39% zinc.

- Delicately-bedded, thin, semi-massive sulfide beds (“brown beds”) are locally present (one drill hole) and contain microscopic syngenetic sphalerite, but zinc assays are not particularly encouraging.

North Range of the Cuyuna District, Fold-and-Thrust Belt, Aitkin County -
- The most encouraging evidence for SEDEX mineralization is the presence of tourmaline in four drill holes that suggests that there may be several hydrothermal vent areas in the North Range. However, the tourmalines have higher FeO/(FeO+MgO+MnO) ratios than tourmalines at the Sullivan deposit.
- The presence of aegirine, hyalophane, and Sr-rich barite, in addition to the tourmaline, suggests the presence of a hydrothermal system (Cleland et al., 1996).
- Sulfide-bearing iron-formation and sulfide-rich argillite are locally documented.
- “Anomalous” Ba and B values, based on very limited geochemistry, are common to the west of the Portsmouth Mine. Barite is reported in the Portsmouth Mine and in other mines to the immediate west.
- The geometry of the iron-formations suggests the presence of second and third order basins.
- Mafic volcanic rocks are locally present.

Siphon Fault area, northeastern edge of Animikie Basin, St. Louis County -
- The Siphon Fault is a growth fault that has been documented to have locally exerted control on the thickness of the Biwabik Iron Formation.
- Some fairly high zinc values (0.61%, 1.03%, and 1.67-2.65 % Zn) have been obtained from three drill holes to the east of the Siphon Fault.
- A 1.6 foot thick semi-massive sulfide layer is present in a hornfels inclusion in drill hole B1-117 at the Babbitt Cu-Ni deposit (1.67-2.65% Zn). The semi-massive sulfide consists of pyrrhotite (30%) and syngenetic sphalerite (20%) with occasional remobilized, discontinuous, lensoidal, sphalerite-rich veinlets up to 1.0 cm thick A sulfur isotope value obtained for this zone is 10.7 ‰.
- Visible sphalerite is observed in several holes to the south of the now inactive LTV Taconite Mine. The sphalerite is present at the very base of the Virginia Formation and very top of the Biwabik Iron Formation to the west of the Siphon Fault.
- Traces of sphalerite, from both megascopic and microscopic observations, are found in another seven drill holes in the same general vicinity of the Siphon Fault.
- A large zoned tourmaline crystal (indicative of a hydrothermal system?) was found in a drill hole in the footwall rocks at the Babbitt Cu-Ni deposit. Microprobe analysis of the tourmaline suggest that it is similar to tourmalines at the Sullivan Mine.
- $\delta^{34}S$ isotope values in the Virginia Formation indicate that the BDD PO units were deposited in closed third order basins.
- The Cr-rich Sill at the base of the Virginia Formation could have been emplaced during(??) sedimentation of the Virginia Formation, and **if** so, the sills could represent a potential heat engine as envisioned for the Moyie sills at the Sullivan deposit.

Arrowhead Mine, southeastern edge of Animikie Basin, Carlton County -
- Carbonaceous, sulfide-bearing argillite is present.
- $\delta^{34}S$ isotope values indicate deposition in a closed third order basin.

- Anomalous zinc value, up to 0.5% Zn, are present in many drill holes - however, many of the holes with anomalous zinc are rotary holes and are suspect.
- The area is within one mile of the Fold-and-Thrust Belt. Possible faults (growth faults?) and the proper plumbing for hydrothermal systems can easily be envisioned along the northern (leading) edge of the Fold-and-Thrust Belt.

While the above listed areas contain many features indicative of potential SEDEX mineralization, there are several more areas that also exhibit some of the same features; albeit, the evidence is less evident and more sparse overall. The areas with lower but still some potential for SEDEX deposits include:

- North and South Emily District, southwestern edge of the Animikie Basin, Crow Wing County;
- Glen Township Sulfide - North Body, Fold-and-Thrust Belt, Carlton County;
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INTRODUCTION

Stratiform sedimentary exhalative (SEDEX) deposits are a major worldwide source of zinc and lead. They constitute about 40% of the world's zinc production and 60% of the world's lead production (Tikkannen, 1986). Many of the SEDEX deposits, specifically those present in Canada and Australia, are hosted by Proterozoic sedimentary rocks that were deposited in intracratonic or intra-rift tectonic settings. Rocks of similar age (Paleoproterozoic) and tectonic settings are also found within east-central Minnesota, and include the Animikie Basin and a Fold-and-Thrust Belt to its south. Both of these areas have been extensively explored and drilled for iron-formation. Historically, vast amounts of iron ore have been mined from the Cuyuna North Range (within the Fold-and-Thrust Belt), and are still mined from the Mesabi Range (northern edge of Animikie Basin). Both the Animikie Basin and Fold-and-Thrust Belt have been considered to potentially host SEDEX deposits. However, exploration for this type of ore deposit has been very limited in these same areas due to an almost complete lack of outcrop and the fact that only limited core exists for the thousands of holes that were drilled in search of iron-formation. This investigation is a summary of the types of rocks, and potential SEDEX depositional environments, that are present within the Paleoproterozoic (2,500 - 1,600 Ma) rocks of east-central Minnesota.

DESCRIPTION OF SEDEX ORE DEPOSITS

SEDEX deposits are a type of submarine massive sulfide deposit that formed by the discharge of, or exhalation of, hydrothermal fluids or heated saline brines onto the sea floor. They are almost exclusively associated with marine sedimentary rocks that range from carbonaceous shales, or other fine-grained clastic rocks, to shelf carbonates. Volcanic rocks are generally absent, but very minor proportions of tuffaceous rocks may be locally present. When present in more voluminous amounts, volcanic rocks may occur in the lower portions of stratigraphic sections that host SEDEX deposits, or they may be distally present in spatially contemporaneous sequences. SEDEX deposits are often referred to as "syngenetic" in that they apparently formed at about the same time as their host sedimentary rocks; however, in some cases, they may have formed by replacement of sedimentary rocks during the early stages of diagenesis (Wilton, 1998). Many SEDEX deposits are world class metal depositories in that they host huge volumes of lead-zinc ore (40-460 Mt). Some of the larger and/or more well known deposits include: Broken Hill, McArthur River (HYC), Mount Isa, Dugald River, Century, and Lady Loretta in Proterozoic rocks in Australia; Sullivan in Proterozoic rocks in Canada; Faro, Howards Pass, Cirque, and Red Dog in Phanerozoic rocks in Canada and Alaska, respectively; Meggan and Rammelsberg in Phanerozoic rocks in Germany; and Navan in Phanerozoic rocks in Ireland.

Large (1980) reviewed the geology of several SEDEX deposits and summarized their characteristic features. He found that most SEDEX deposits are associated with:

- First-order basins (in excess of 100 km) in either an epicratonic or intracratonic setting that are usually fault-bounded half-graben features that were active during deposition of the ore zone.

- Second-order basins (restricted to several tens of kilometers) that reflect abrupt changes and cessations in sedimentary facies and thicknesses.
- Syndepositional growth faults at the margins of first- and second-order basins that provided the proper “plumbing” system.
- Sudden changes in the regional sedimentary facies that may be associated with a regional tectonic event.
- Minor contemporaneous igneous activity - in the form of thin tuffite horizons or small intrusive bodies, e.g., Moyie sills at Sullivan.
- Local third-order basins in which an euxinic environment developed.
- Contemporaneous, stratiform, hydrothermal hematitic chert, with minor pyrite, that often occur adjacent to the SEDEX mineralization.
- Sulfur isotope values that are indicative of both a deep-seated (hydrothermal) source “... as well as a biogenically reduced sea water sulphate source...”(Large, 1980, p.61).
- Geochemical halos (stratiform enrichments in Mn and/or Zn) and footwall silicification, that are present in some SEDEX systems.

Lydon (1996) later reiterated that SEDEX deposits generally occur in sedimentary basins situated in either an intracratonic or epicratonic rift-related setting. Goodfellow et al. (1993) suggest that most SEDEX deposits formed within rift-related half-grabens where “seismic pumping” (Sibson et al., 1975) of hydrothermal solutions and brines took place along fault zones. Many of these fault zones appear to be synsedimentary faults, or growth faults. Goodfellow et al. (1993) also suggest that the rift system subsided to the point of allowing a marine transgression. Because the rift system was long-lived, it allowed for alternating open and closed conditions with respect to seawater and “... formed during a period in the Earth’s history when the oxygen content of the oceans and atmosphere was low (Holland, 1984) ... these deposits very probably formed under anoxic bottom water conditions” (Goodfellow et al., 1993, p. 213-214).

“SEDEX deposits first appear in the Early Proterozoic ... the time distribution corresponds to the build-up of sulphur in the oceans in the Early Proterozoic (following the removal of iron in the form of banded iron-formations) and the possible establishment of stratified oceans with reduced and H_2S-rich bottom waters...” (Goodfellow et al., 1993, p. 243). Other features Goodfellow et al. (1993) attributed to SEDEX deposits include:

- Hydrothermally-derived chert is ubiquitous in most deposits.
- Carbonate, in the form of calcite, ankerite, siderite and barium carbonates, is a relatively major hydrothermal component.
- A feeder pipe associated with a synsedimentary fault zone is not always present, but when found, the sedimentary rocks within the pipe are commonly altered, veined, and brecciated.
- Alteration minerals present within the pipe include tourmaline (as at Sullivan), quartz, muscovite, chlorite, ankerite, siderite, and sulfides.
- Hanging wall alteration is either absent or too subtle to be recognized.

Sangster and Hillary (2000) have recently subdivided SEDEX deposits into three sub-types that include:

- Type 1 - median size; grade is generally 7 Mt of 9-10% Pb + Zn ore; sulfide minerals are the only exhalative products added to the host sedimentary rocks (53.5% of all SEDEX deposits);
- Type 2 - median size; grade is generally 8 Mt of 9-10% Pb + Zn ore; in addition to sulfides, chert, siderite/ankerite, and/or barite are also exhalative products (33.1% of all SEDEX deposits); and
- Type 3 - median size; grade is generally 33 Mt of 1-20% Pb + Zn ore; contains attributes of Types 1 and 2 but the SEDEX deposit is also associated with iron oxide-rich sedimentary rocks such as oxide-facies iron-formation (13.4% of all SEDEX deposits).

Gradations between these three sub-types are common. Within this data set, almost 64% of SEDEX deposits occur within Proterozoic strata; with the vast majority of these deposits occurring in both the Paleoproterozoic and Mesoproterozoic. Sangster and Hillary (2000) found that the majority of the world's SEDEX deposits (84%) are **not** underlain by a discordant feeder pipe. Some of the deposits are apparently more distal to a vent area and exhibit a delicately-bedded and fine-grained nature over large distances, because they formed from dense brines that spread out along basinal depressions from a vent site (Goodfellow et al., 1993).

Although no actual age dates for these deposits are given by Sangster and Hillary (2000), a review of other sources (Goodfellow et al., 1993; Lydon, 1996) give constraints of 1800-1650 Ma. The Sullivan deposit has recently been dated at 1470 Ma (Jing et al., 2000).

From the above observations, many of the geologic attributes that characterize SEDEX deposits can also be found within the Early Proterozoic rocks of east-central Minnesota - or more specifically, in the rocks of the Animikie Basin, and the Fold-and-Thrust Belt to its south. Some of the more pertinent characteristics include:

- Both the Animikie Basin and Fold-and-Thrust Belt represent epicratonic basins - the later has been intensely folded and thrusted to the north.
- Smaller intra-rift and rift-related basins are locally documented in the stratigraphic record.
- The rocks were deposited in basins (first-order?) that contain second- and third-order sub-basins that contain sulfur-rich, carbonaceous, shale-argillite sequences that overlie, and locally interfinger with, chemical sedimentary iron-formations. Some of these sub-basins represent euxinic, starved, semi-restricted basins.
- Local tourmaline-rich sedimentary rocks, associated with iron-formation, have been documented (Boerboom, 1989; McSwiggen et al., 1994, 1995; Cleland et al., 1996).
- Syndepositional growth faults are known to be present in localized areas.
- Carbonate-rich sedimentary rocks, overlying various iron-formation facies, are always present.

Even more similarities may be evident, but as the geology of most of this region of Minnesota is conceptualized mainly from drill hole data (both core and drill logs of non-existent core), many of the details are lost. A brief description of the regional geology concerning the Animikie Basin and Fold-and-Thrust Belt is summarized in the following section.

REGIONAL GEOLOGY

Concepts pertaining to the geology of the Paleoproterozoic rocks of east-central Minnesota have changed continuously during the 20th century. One major reason for this "instability" is that the area in question is very poorly exposed, and most of the known geologic data has been obtained from drill core, logs of old drill holes (for which core are no longer preserved), scattered pit exposures, scattered outcrops, and aeromagnetic data. In some small isolated areas, there is an abundance of all of these types of information, e.g., the Cuyuna North Range; whereas in other areas, the data are meager at best. Because the data are present in a variety of forms, of variable quantity and quality, one has to "shift through" piles of information in order to gain an understanding of the overall geologic picture.

Initially, the areas comprising the Animikie Basin and the Fold-and-Thrust Belt were intensively explored for iron-ore at the turn of the 20th century. Numerous iron-formations were discovered during this exploratory phase and include the Mesabi Range (Biwabik Iron Formation), Cuyuna North Range (Trommald Formation), Cuyuna South Range, the Emily District (which was extensively drilled in 1950s), and Glen Township of Aitkin County. All of these iron-formations, and other Paleoproterozoic iron-formations that are present within the Lake Superior region (Fig. 1), were "... believed to represent a unique temporal event that could be used to correlate [all of the] isolated [iron-formation related] sequences .... The idea of a [single] principal episode of iron-rich deposition persisted into the 1980's" (Morey, 1996, p. 30). Under this concept, the rocks of the east-central Minnesota were divided into two different stratigraphic groups: 1. an older Mille Lacs Group and; 2. a younger Animikie Group that includes the various iron-formations and associated clastic sediments (Morey, 1983). However, recently obtained age dates (see discussion below) suggest that the earlier concept of one temporal event for all of the iron-formations in the Lake Superior region may still be viable.

With the advent of more recent plate tectonic interpretations, this simple two-fold stratigraphic concept (Mille Lacs Group versus Animikie Group) was challenged in the late 1980s by Drs. D.L. Southwick and G.B. Morey of the Minnesota Geological Survey. Their observations and conclusions regarding the regional geology are well documented in numerous papers that include: Southwick et al., 1988; Morey et al., 1989; Morey and Southwick, 1995; and Morey, 1996. Because their work serves as a foundation to understanding the geology of east-central Minnesota, most of the following summary relies heavily on the aforementioned papers and the reader is encouraged to review them for a more detailed analysis. According to their model, the Animikie Basin represents a migrating foreland basin that developed "... as a flexural response to loading of the continental lithosphere by stacked thrust sheets ... [thus, the basin is] ... paired with a fold and thrust terrane [to the south] that contains the tectonically interdigitated remains of island arcs, intra-arc basins, accretionary prisms [etc.] ... that were emplaced onto a continental margin during attempted subduction of continental crust" (Southwick et al., 1988, p. 2). Rocks of the Fold-and-Thrust Belt (Fig. 2) are older than the Animikie Basin and consist of several tectonically dismembered structural panels, each separated by geophysically-defined thrust faults, that were tectonically stacked on top of each other during the Penokean orogeny. Each of the structural panels has its own stratigraphy, and rocks of the Mille Lacs Group **do not** present a panel-wide cohesive stratigraphic sequence; rather, portions of the Mille Lacs Group are present in some of the structural panels and absent in

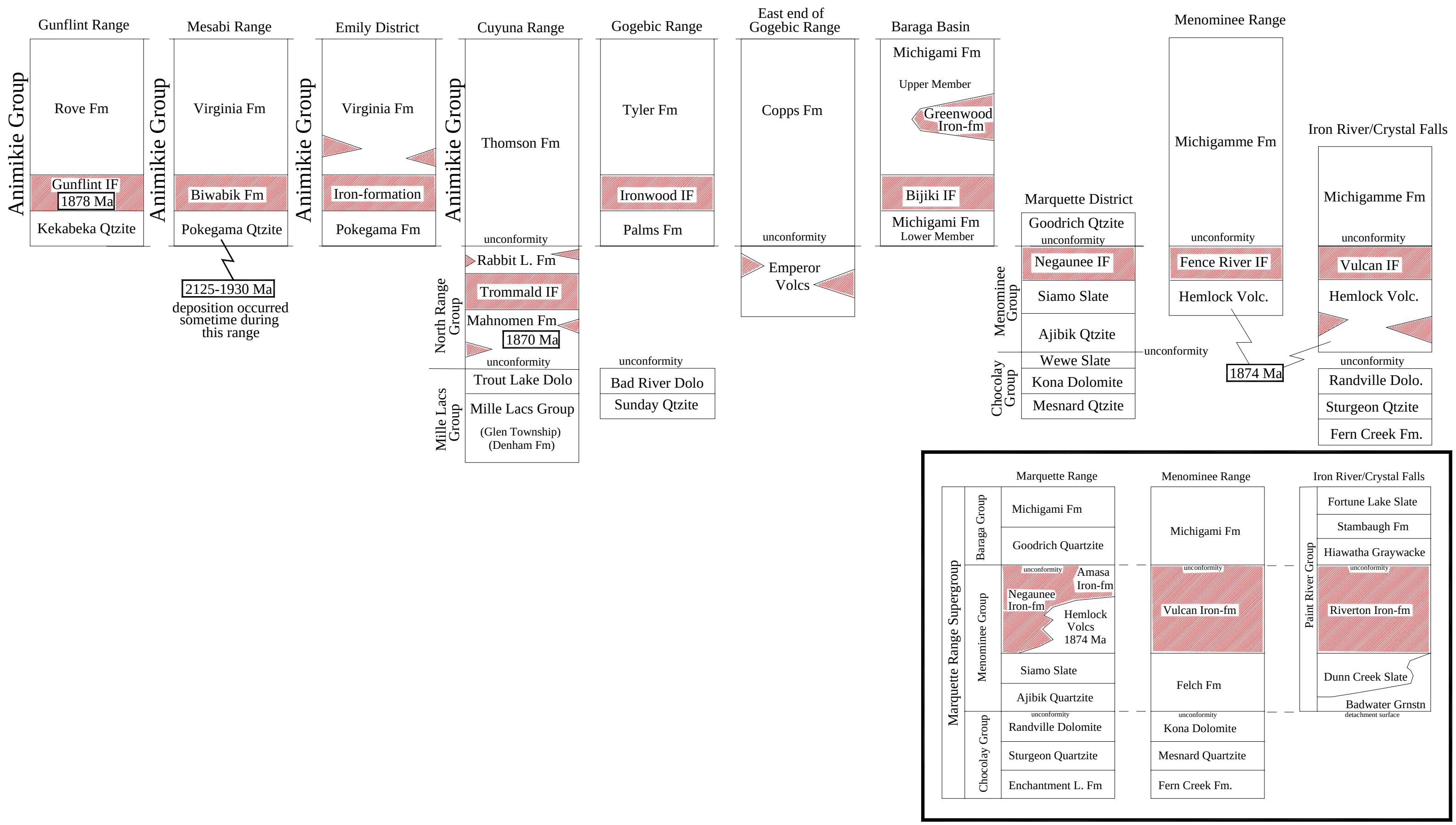

Figure 1 - Generalized correlation chart of Paleoproterozoic strata in the Lake Superior region (after Morey and Southwick, 1995). Note that recently obtained age dates are shown for the Gunflint Formation, Mahnomen Formation, and Hemlock Volcanics (see text for references). Also included for comparison is a correlation chart (lower right quarter of figure) of strata in Menominee, Iron River-Crystal Falls, and surrounding terranes (LaBerge et al., 2003 - includes changes to previous usage not yet officially adopted by the USGS). Iron-formations are shaded in red.

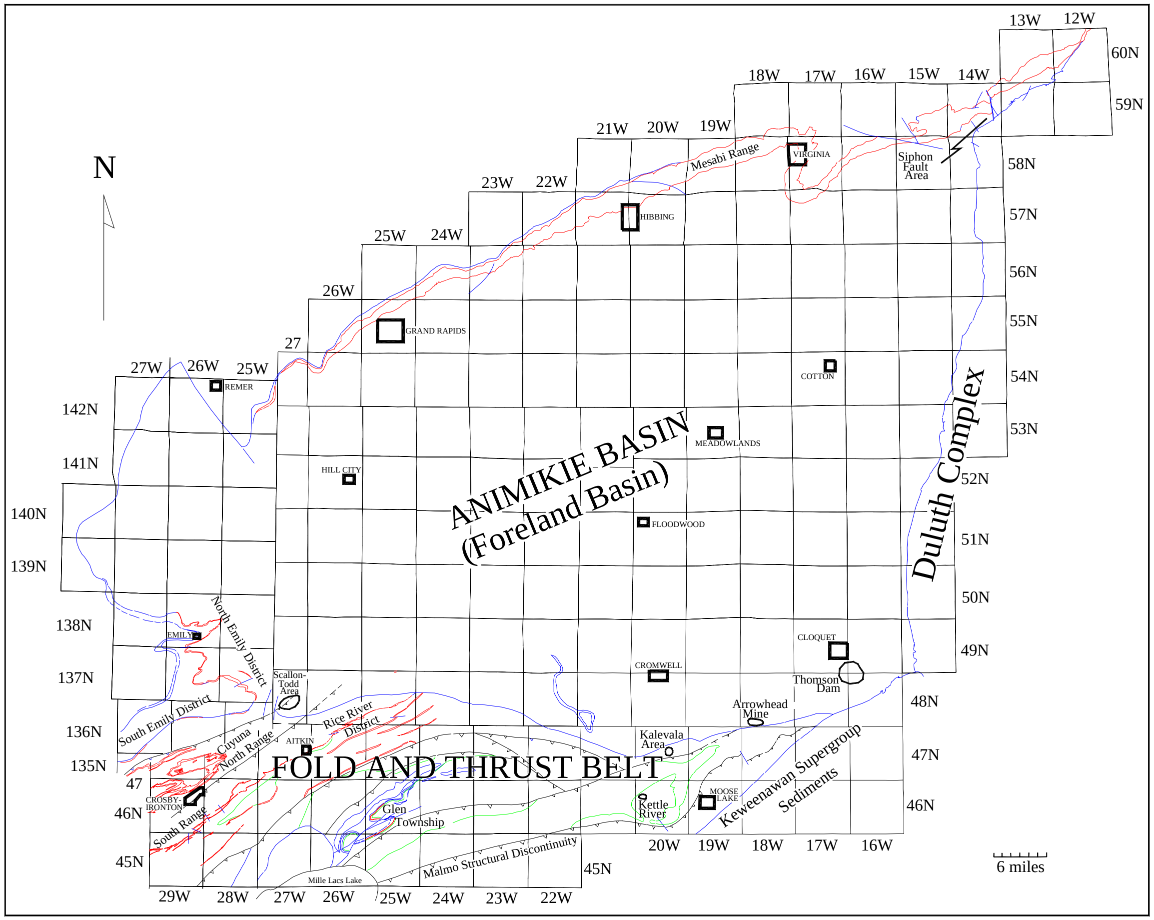

Figure 2 - Simplified geology of the area of this investigation (modified from Boerboom et al., 1999a; 1999b). Specific subareas within the Animikie Basin and Fold-and Thrust Belt are shown and discussed in this report.

others. “It is likely that tectonism has separated some stratigraphic intervals that originally were conformable, and combined others that originally were separated in time and space” (Southwick et al., 1988, p. 10). For these reasons, Southwick et al. (1988) de-emphasized the stratigraphic unity implied by the Mille Lacs Group within the Fold-and-Thrust Belt.

The Mille Lacs Group may be roughly correlated with the Chocolay Group (Fig. 1) in the Upper Peninsula of Michigan (Morey, 1996). Another stratigraphic sequence, the North Range Group of Southwick et al. (1988), is also present within a portion of the Fold-and-Thrust Belt. This sequence of rocks consists of (from bottom to top) the Mahnomen Formation, Trommald Formation (iron-formation), and Rabbit Lake Formation (slate-turbidite sequence). The North Range Group is inferred to be correlative with the Menominee Group (Fig. 1) in the Upper Peninsula of Michigan (Morey, 1996).

Rocks of the Animikie Basin (Fig. 2) are envisioned to have been deposited in the remnants of a migrating foredeep or foreland basin adjacent to its causitive, and older, Fold-and-Thrust Belt. Rocks of the Animikie Group include (from bottom to top): Pokegama Quartzite, Biwabik Iron Formation (and iron-formations in the Emily District), and the Virginia and Thomson Formations (slate-turbidite sequences). The Kakabeka Quartzite, Gunflint Formation (iron-formation), and Rove Formation are the stratigraphic equivalents to the northeast along the Canadian border (Fig. 1). The Animikie Group is inferred to be correlative with the Baraga Group (Morey, 1996) in both Wisconsin (Palms Formation, Ironwood Iron-Formation, Tyler Formation) and the Upper Peninsula of Michigan (Michigamme Formation with a lower Bijiki iron-formation member).

Magnetic depth estimates (Chandler et al., 1982; Carlson, 1985) suggest that the Animikie Basin gradually increases to a depth of about 1 km thick at a distance of 20 km south of the Mesabi Range. Further southward, the basin abruptly steepens to depths in excess of 2 km, and in excess of 3 km to the south of 47° N (Chandler et al., 1982).

Within Minnesota, deformation of the Virginia and Thomson Formations systematically increases from a north to south direction. Slaty cleavage is weakly evident about 10-15 miles south of the Mesabi Range. Much further to the south, outcrops of the Thomson Formation, at Thomson Dam in Carlton County, exhibit upright, moderately tight, east-striking folds with well-developed pervasive axial planar cleavage (Southwick et al., 1988). Still further to the south of Thomson Dam, there are even more pronounced increases in metamorphism and structural complexity. There, the Thomson Formation “... has undergone subhorizontal recumbent folding followed by a second folding of upright style. These doubly folded slaty rocks pass southward into higher grade doubly foliated muscovite schist, muscovite-chlorite phyllite, and ... metavolcanic rocks” (Morey et al., 1989, p. 47). Holst (1984, 1985) suggests that the doubly folded rocks were the result of northward-directed nappes (early folding period) followed by upright folding that produced a pervasive, near-vertical cleavage. Sun et al. (1995) suggest an alternate explanation for the deformation of the Thomson Formation that involves development of S_1 cleavage subparallel to bedding that was formed during N-S shortening and N-directed shear; and with continued regional shortening, the development of a steeply-dipping S_2 crenulation cleavage.

Deformation associated with the Animikie Basin and the Fold-and-Thrust Belt took place during the Penokean orogeny which is restricted to "... the deformational and intrusive events of generally collisional nature that occurred toward the end of the evolutionary history of the Penokean orogen. In time terms, the Penokean orogeny is generally understood to have occurred between about 1900 and 1760 Ma, with the most intense activity having centered in the interval 1870-1850 Ma" (Southwick et al., 1988, p. 2). Morey (1996, p. 31) further states that "... the Penokean orogen can be generally divided into an early extensional phase, when sedimentary rocks, including iron-formation, were deposited on an evolving continental margin, and a subsequent compressional phase, when these continental margin deposits were folded and metamorphosed and partly overridden by one or more northward-migrating foredeep basins ...." Within a tectonic framework, rocks of the Mille Lacs Group are associated with an intracratonic or intra-rift stage, rocks of the North Range Group are associated with a rift stage, and rocks of the Animikie Group are associated with a post-breakup stage (Morey, 1996). Each of these groups represent allostratigraphic packages of rock bounded by, or separated by, unconformities (Morey and Southwick, 1995).

Age dates within the Penokean orogen are limited. The stratigraphic package of rocks from Glen Township, within the Fold-and-Thrust Belt, have yielded a Sm-Nd isochron age of 2,197±39 Ma and a Rb-Sr isochron age (interpreted as a metamorphic age) of 1,746±86 Ma (Beck, 1988). To the north of the Mesabi Range, the Pokegama Quartzite rests unconformably on undeformed diabase dikes of the Kenora-Kabetogama dike swarm that give a Rb-Sr isochron age of 2,125±45 Ma (Beck, 1988). This gives a maximum age for deposition of the Pokegama Quartzite at the base of the Animikie Group. A minimum age of 1,930±25 Ma for deposition of the Pokegama Quartzite was obtained by Hemming et al. (1990) from quartz veins that cut the Pokegama. A Pb/U zircon age from an ash layer within the Gunflint Formation (iron-formation) yields a depositional age of 1,878±2 Ma (Fig. 1 - Fralick and Kissin, 1998; Fralick et al., 2002). A similar age of 1,874±9 Ma has been obtained from the age correlative Hemlock Formation of Michigan (Schneider et al., 2002). An age of 1,821±16 Ma has been obtained from a volcanic ash layer in the Rove Formation that is about 70 meters stratigraphically above the Gunflint Formation (Kissin et al., 2003). Xenotime from drill core of the Mahnomen Formation revealed ages of about 1,870 Ma (recycled detrital grains) and 1,770 Ma (regional epigenetic event - Vallini et al., 2003). Other ages, though less instructional, from the Penokean orogen include metamorphic ages of 1,738±16 Ma for the Thomson Formation (Keighin et al., 1972), and 1,870 Ma for the Cuyuna North Range (Peterman, 1966).

Many of the above age dates indicate that portions of the stratigraphic correlation chart (Fig. 1) may be incorrect and that many of the iron-formations in the Lake Superior region may be time-synchronous after all. Note that the ages for the Gunflint Formation, Mahnomen Formation, and Hemlock Volcanics are shown in Fig. 1, and that many of the portrayed stratigraphic correlations need to be "reshuffled." However, it is well beyond the scope of this investigation to revise the regional Paleoproterozoic stratigraphy.

In summary, the age dates as applied to east-central Minnesota, " ... suggest that some of the volcanic rocks now in the fold-and-thrust belt were extruded at about 2,200 Ma and compressionally reassembled into nappes prior to about 1,740 Ma" (Southwick and Morey, 1991, p. C10). Deposition of the Animikie Group began sometime between 2,125 to 1,930 Ma and continued beyond 1,821 Ma.. Deformation of the Fold-and-Thrust Belt was underway by 1,870 Ma when syntectonic granitic bodies where emplaced to the south (Morey and Southwick, 1995). Postorogenic granites, also south of the Fold-and-Thrust Belt, were emplaced between 1,812 and 1,760 Ma (Morey and Southwick, 1995; Holm et al., 1998), followed by episodic postorogenic collapse at around 1,755 Ma and 1,700 Ma (Holm and Lux, 1995; 1996).

Recent neodymium and lead isotope data suggests a wide variation in provenance areas relative to both the Animikie Basin and Fold-and-Thrust Belt. Nd model ages for all the sedimentary rocks of the North Range Group suggest an Archean (3.0 - 2.6 Ga) source (Hemming et al., 1995); presumably to the northwest. However, a progression of sources is recorded for the Animikie Group. The Pokegama Quartzite contains Archean (2.9 Ga) detritus that was presumably derived from a northern source (Hemming et al., 1995). Ojakangas (1983) suggests that lower "shaly" facies and upper "sandstone" facies of the Pokegama were deposited in a low-energy tidal flat and subtidal high-energy environments, respectively. The Biwabik Iron Formation appears to contain detritus from both Archean and Paleoproterozoic sources (2.8-2.5 Ga; Hemming et al., 1995). "Cherty" and "slaty" members of the Biwabik Iron Formation were deposited on a continental shelf in "shallower" and "deeper" water, respectively (Ojakangas, 1983). Limited sampling of the Virginia Formation (deep water pelagic mud and turbidite sequence) suggests that its detritus was derived from a Paleoproterozoic source (2.32-1.86 Ga; Hemming et al., 1995); presumably from a southern source area. This relationship is consistent with an observed southward increase in turbiditic graywacke beds in the Thomson Formation at Thomson Dam (Southwick et al., 1988). However, paleocurrent studies of cross laminations in Bouma-C sequences at Thomson Dam (Morey and Ojakangas, 1970; Hyrkas, 1982) reveal a contradictory north-to-south component of flow and suggest a northern source. Southwick et al. (1988) offer an alternative explanation for this difference that envisions the north-to-south component as reflecting the waning stages of density-current events on the north slope of a postulated bathymetric trough; an explanation they consider to be *ad hoc* and requiring further testing. In summary, "the transition from continental margin sedimentation [preserved in the Fold-and-Thrust Belt] to foredeep sedimentation [preserved in the Animikie basin] is a transition from a northern provenance supplying detritus of Archean age to a southern provenance supplying detritus of Early Proterozoic age. The boundary separating the two sources is time-transgressive, migrating to the north as the foredeep basin itself migrated in that direction" (Morey and Southwick, 1995, p. 1991).

PRESENT INVESTIGATION

Introduction

The area of this investigation, including the Animikie Basin and Fold-and-Thrust Belt (to the north of the Malmo Structural Discontinuity) is shown in Figures 2 and 3. The area covers portions of Aitkin, Carlton, Cass, Crow Wing, Itasca, and St. Louis counties. These maps are largely based on the maps of Boerboom et al. (1999a, 1999b), which in turn, are based on the map of Southwick et al. (1988). The geology portrayed for the maps that accompany this report (Fig. 3, see CD) differ slightly, in small specific areas, from the maps of Boerboom et al. (1999a, 1999b) and reflect the biases of the primary author. The map units of Boerboom et al. (1999a, 1999b) are referred to throughout this report.

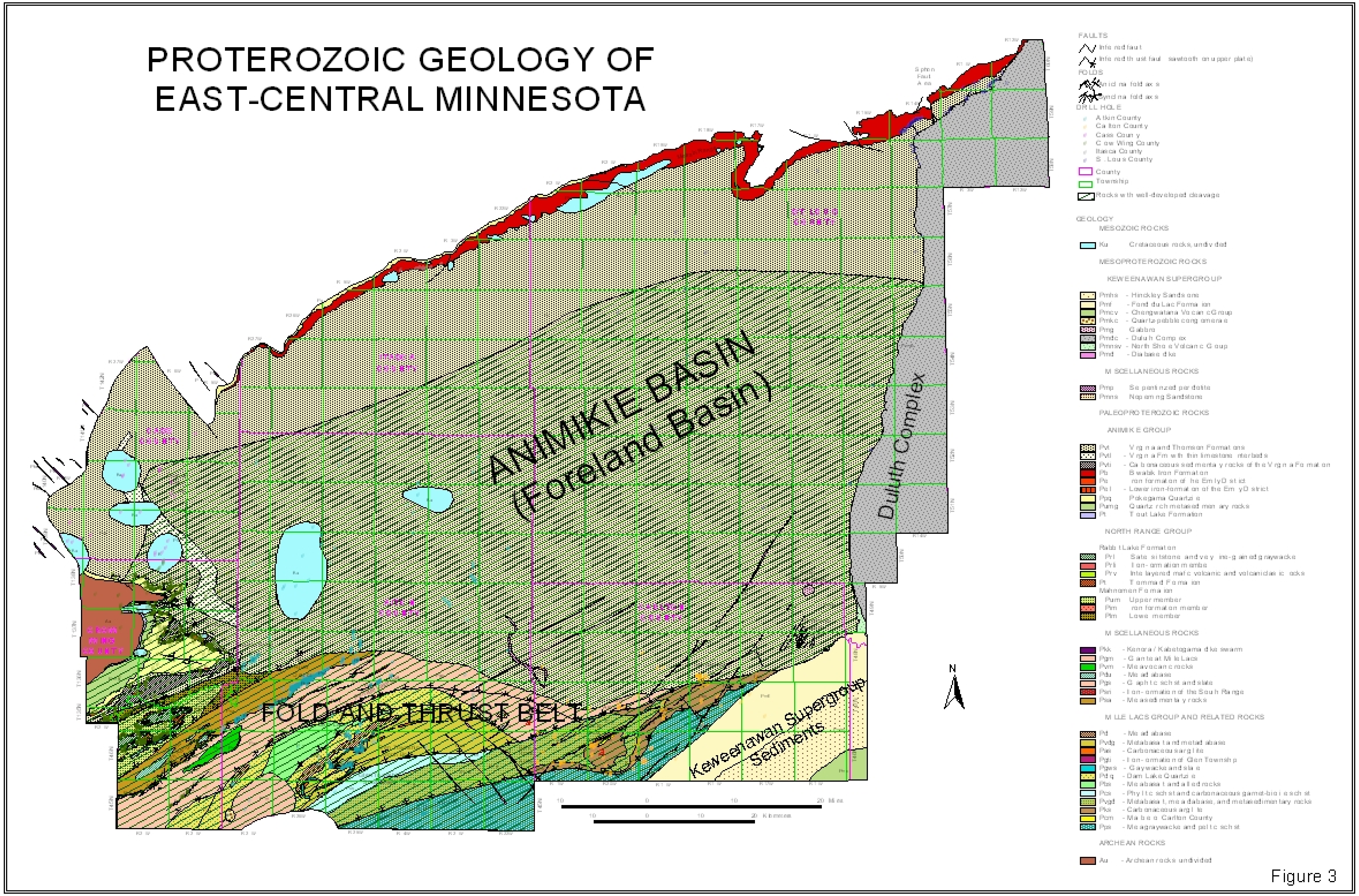

Figure 3 - Detailed geology of the area of this investigation (modified from Boerboom et al., 1999a; 199b). An Arc view-based version of this map is on the CD in the back pocket of this report and on the enclosed CD, or it can be downloaded at www.nrri.umn.edu/cartd/egg .

Drill Hole Locations

In the course of assembling all the data to produce the geologic maps and plates of this report, considerable time and attention were spent in attempts to accurately locate all drill holes for which drill core still exists (1,297 holes). In total, the locations for over 2,100 holes (with or without preserved core) have been determined to varying degrees. The locations of most of these drill holes are listed as UTM-NAD27 coordinates in Appendix 1 and on the CD in the back pocket of this report (*basinholesco.xls*). Abbreviated geologic drill logs for these same holes are listed in Appendix 2 (*basinchemco.xls* data file). Drill hole locations were compiled from several sources at the MDNR that include:

- Recent exploration files that generally show hole locations on either a topographic base (1 : 24,000) or on plat sheets (locations to the nearest 40 acre parcel = worst case scenario).
- Old exploration files (pre-1950s) that exhibit hole locations within square outlines that represent 40 acre parcels (typically at a scale of 1 inch = 200 feet).
- Old M.A. Hanna Company mine maps (1 inch = 50 feet scale) and exploration sheets.
- Old exploration sheets of "competitor" activity also within the Hanna files.
- A 1949 report by Carl Zapffe on file at the MDNR.
- United States Bureau of Mines reports.
- An internal United States Steel (USS) report pertaining to the Emily District (Strong, 1959) on file at the MDNR.
- Additional sources for drill hole locations were obtained from the private corporate files of: Cleveland Cliffs, Incorporated (Ishpeming, MI); Pickens Mather and Company (also at Cleveland Cliffs); and Great Northern Iron Ore Properties (Hibbing, MN).

All of these various-scaled maps were digitized, in AutoCAD (version 14), onto NAD27-referenced county drawing files, and specific hole locations (UTM coordinates) were determined within the drawing file. Because the drill hole data are present in myriads of forms, the following is a listing of what, and how much, drill hole data were determined for each of the respective counties within the study area:

<u>Aitkin County</u> - All known holes (966) within this county have been located in regards to UTM coordinates. Holes included in this category include holes with core, holes with cuttings, holes with no core or cuttings, but with a geologic log, and holes with very abbreviated geologic logs, but no core or cuttings. Specific areas drilled within Aitkin County include: the Rice River District of the Cuyuna South Range; Glen Township area (North and South sulfide bodies); Dam Lake area (few holes are preserved); Scallon-Todd area; Portage Lake Belt area (drill cuttings); Kimberly Belt area; and scattered holes (GN-series holes) along the southern edge of the Animikie "bowl."

<u>Cass County</u> - All known holes (28), with core and/or geologic logs, that were drilled into Paleoproterozoic rocks within this county have been located. These holes were widely scattered and were drilled in attempts to find southwestern extensions of the Mesabi Range. A few holes are clustered in the Thunder Lake area.

Carlton County - All known holes (115), with core, cuttings, and/or geologic logs, that were drilled into Paleoproterozoic rocks within this county have been located. Several holes have very approximate UTM coordinates as their locations are shown as large dots on plat sheets; thus, they are located to the nearest 40 acre parcel. Most of the drilling within this county took place in the late 1970s during uranium exploration. Specific small areas that were drilled include: Arrowhead mine area; Kettle River area; Split Rock area; and the recently drilled Kalevala Township area.

Crow Wing County - The drill holes into Paleoproterozoic rocks of this county are broken into two categories that include: 1) UTM coordinates were determined for all known holes (410 - with or without preserved core) to the north of the Mississippi River (Emily District area); and 2) to the south of the Mississippi River, UTM coordinates for only holes with preserved drill core were determined. The latter area contains the North Range of the Cuyuna District where literally thousands of holes have been drilled since 1900. The thousands of holes (with or without core) in the North Range have been previously located and are shown on the map of Morey and Morey (1986). However, no drill hole number designations are shown on their map. In this investigation, actual UTM coordinates have only been determined for holes with preserved drill core (460) in the North Range; no attempt was made to locate holes with no drill core (thousands), or holes that are only preserved as cuttings (711).

Several methods were employed in order to locate the Cuyuna District holes with preserved core. Most of these holes are shown on Hanna mine maps, on file at the MDNR, and are easily transferred to a UTM-based drawing file. However, some holes are only described as being "X" feet north or south, and "X" feet east or west, of a particular section corner or quarter corner. These holes were transferred to a UTM-based drawing file with less confidence and are probably within 50-200 feet of their actual location. The locations of still another group of holes are listed relative to a particular mine grid. In some instances, the actual grid was found for the specified mine and the drill hole was located with relative ease. However, in most instances, the grid was only found on an adjacent mine map, and this grid had to be extended beyond the limits of the mine map (within the drawing file) in order to gain some idea as to UTM coordinates for individual holes. This category of holes (see Appendix 1 - designated as "grid coords") are probably within 100-400 feet of their actual location. In the end, most of the preserved core holes (460) from the North Range of Cuyuna District were located in regards to corresponding UTM coordinates, but 80 holes out of this group could not be located any closer than to the nearest 40-acre parcel.

Itasca County - Within Itasca County, there are thousands of holes that were drilled prior to, and during, mining of the Paleoproterozoic Biwabik Iron Formation. However, in this investigation, UTM coordinates were determined for only holes with preserved core (38) that were drilled to the south of the Mesabi Range. These holes were collared in the Paleoproterozoic Virginia Formation.

St. Louis County - Several thousand drill holes within this county also intersect Paleoproterozoic rocks along the Mesabi Range (the holes intersect mostly the Biwabik Iron Formation with lesser amounts of the overlying Virginia Formation). Several hundred additional holes intersect varying amounts of Virginia Formation beneath, or adjacent to, the Mesoproterozoic Duluth Complex, which was explored for Cu-Ni deposits. Out of this large group, only holes with preserved core (108) that were drilled to the south of the Mesabi Range, or intersect a fairly thick sequence of the Virginia

Formation beneath, or adjacent to, the Complex, were located in regards to determining UTM coordinates.

Drill Core Logging

Core for the drill holes, that are situated within the confines of this investigation, are stored at several locations that include:

- Minnesota Department of Natural Resources (MDNR), Division of Lands and Minerals - Hibbing, MN;
- Minnesota Geological Survey (MGS) - St. Paul, MN;
- Natural Resources Research Institute (NRRI) - Duluth, MN;
- Cleveland Cliffs, Incorporated - Ishpeming, MI; and
- United States Steel (USS), Ore Operations, USX Corporation - Mt. Iron and Coleraine, MN.

Out of 1,297 holes with preserved drill core, 1,200 holes (150,630 feet of core) have been logged for this investigation. Only a cursory review of the core was made for eight of the holes that are stored at the MGS. An additional unknown amount of skeletonized core, from the Cuyuna District, is also preserved at the MGS, but were not looked at for this investigation. While it would be impossible to describe the geology of each individual drill hole, several observations can be construed regarding stratigraphic packages and types of mineralization for individual areas or counties. These relationships are discussed in later sections of this report.

Geochemical, Thin Section, and Isotope Samples

In addition to relogging drill holes, core samples were also collected for thin-section description, geochemistry (whole rock, REE, and base/precious metal analyses), carbon and sulfur isotopes, and microprobe analyses of tourmaline and carbonates. All of the geochemical results of this investigation (Appendix 2 - *1999bm.xls* and *1999wr.xls*) were added to: 1) previous geochemical results that are on file at the MDNR that have been compiled by Larry Zanko of the NRRI; 2) previous geochemical results from recent MDNR and MGS drilling campaigns; and 3) geochemical results of Southwick et al. (2001). All of these data are compiled and can be found on the CD in the back pocket of this report (Appendix 2 - *basinchemco.xls* data file). Microprobe analyses were conducted by Dr. Peter McSwiggen and Nick Bulloss at the University of Minnesota (Twin Cities Campus) on a JEOL 8900 electron microprobe at an accelerating voltage of 15-20 kV.

Magnetic Susceptibility Readings

Magnetic susceptibility readings (in 10^{-3} SI units) were taken on drill core, at five-foot intervals, with an Exploranium KT-9 instrument manufactured by Terraplus USA Inc., Littleton, CO. Readings were collected from 98 drill holes that are scattered throughout the study area.

Results of these magnetic drill core surveys can be found in Appendix 3 on the CD in the back pocket of this report. Each drill hole with magnetic readings is listed as a separate data base file in Appendix 3.

Density Determinations

Also included on the CD are the results of 1,085 density (g/cm^3) determinations that were conducted on drill core samples. These determinations were made by Tom Lawler and Darold "Ricco" Riihiluoma of the MDNR, with a Mettler 33360 210260 density determination kit, using a Mettler H43 balance. A summary of their data is included in Frey and Lawler (1997), but individual density determinations are not included in their report. The primary author obtained a data disk from the MDNR that contained these individual measurements, and then reorganized the data and assigned formation names and rock type names to the each of the individual samples. Eleven density determinations, made at the NRRI with a Jolly Balance, were added to the data base. The results are presented in Appendix 4 - the *DensityReadings.xls* data file on the CD.

ArcView Map

The ArcView map of the Proterozoic Geology of East-Central Minnesota is presented in datum NAD83. Built from shapefiles containing geologic rock units, faults, folds, inferred domal structures, and drill hole locations, this map can be utilized to acquire such drill hole- / drill hole interval-specific data as location information, coordinates, rock type, brief drill log description, chemistry, mag readings, densities, and isotopes. The aforementioned AutoCad (version 14) drawing of digitized maps and drill hole locations, done in NAD27, served as the basis for the ArcView map.

<u>Geologic Rock Units (polygon theme)</u> - Each geologic rock unit had been assigned to an individual layer in the AutoCad drawing, as had structural features (faults, folds) and other map components. Entities with areal extent (all rock units) were drawn as closed polylines (polygons). Working in AutoCad Map 2000, the individual rock unit layers were exported and added as polygon themes to an ArcView 3.2 drawing. The themes were arranged in chronological order from youngest to oldest, including bedrock occurrences of Mesozoic Cretaceous rocks. This sequential layering was used to go back into AutoCad, where the "copy to layer".lsp file feature was used to create new entities, as necessary, in each rock unit layer to allow for "cutting out" in ArcView to expose older bedrock types contained within polygon entities of younger bedrock. The edited layers were again exported and brought as themes into ArcView. In shapefile format, these themes were edited to create "donuts", i.e., holes, in the polygons to expose an underlying theme (older bedrock type). The theme tables were also edited for consistency and to maintain the integrity of the data file. With editing complete, each layer was converted from NAD27 to NAD83 by means of ArcView's projector extension. Finally, all forty-seven rock unit themes were merged, using ArcView's geoprocessing extension, to create one geologic rock unit shapefile. An additional shapefile was similarly created to show the areal extent of bedrock displaying well-developed cleavage.

Structural Features (line themes) – Inferred faults, inferred thrust faults, anticlines, and synclines had been drawn on individual layers in AutoCad as polylines. These layers were exported and brought into ArcView 3.2 as line themes. They were converted, as above, from NAD27 to NAD83. The two fault themes were merged into one fault shapefile and the anticline and syncline themes were merged into one fold shapefile. A fifth structural feature, inferred domal structures, was exported and brought into ArcView 3.2 as a point theme. This theme was subsequently converted from NAD27 to NAD83 as above.

Drill Holes (point theme) – NAD27 coordinates for each drill hole located in the map area, where available, are contained in the file basinholes.xls. Using the U.S. Army Corps of Engineers' datum conversion program, Corpscon, these coordinates were converted from NAD27 to NAD83. The NAD83 coordinates were added to the basinholes.xls file, which was renamed basinholesNAD83.xls. BasinholesNAD83.xls was saved in dBASE IV format (.dbf) and brought into ArcView 3.2 as a table. The drill hole locations, using the NAD83 coordinates, were added to the map drawing as an Event Theme and converted to a shapefile. Data files basinchem.xls, basin_isotopes.xls, all_basin_mag.xls, and DensityReadings.xls were also saved in dBASE IV format (.dbf) and added to the ArcView drawing as tables. These tables have been linked to the drill hole theme table. Clicking on a drill hole with the ID tool accesses the data in these tables, as well as that in the basinholeNAD83 table. All of the data is available for querying.

ACKNOWLEDGMENTS

This project was funded by the Mineral Diversification Plan of the Minnesota Legislature administered by the Minerals Coordinating Committee and the Natural Resources Research Institute. Special thanks are extended to the following corporations and individuals for providing access to drill core and private company records: Cleveland Cliffs, Incorporated - Mr. Ronald Graber and Mr. Alan Strandlie; Great Lakes Exploration, Incorporated - Mr. Thomas Quigley; Great Northern Iron Ore Operations; and United States Steel Corporation (USS, a division of USX Corporation) - Mr. Dennis Hendricks.

Special thanks are extended to Mr. Al Dzuck of the MDNR for his constant aid in retrieving core and unraveling inconsistencies in the exploration files. Dr. Edward M. Ripley provided sulfur and carbon isotope analyses. Mr. Larry Zanko (NRRI) began the monumental task of assembling and compiling all of the geochemical data pertaining to the Paleoproterozoic rocks of east-central Minnesota. Linda Lindberg (NRRI) aided Larry Zanko in this compilation project and entered most of the geochemistry values into various spreadsheets. This data was latter updated by Mr. Barry Frey of the MDNR (Frey and Lawler, 1997), and was further updated for this investigation.

Discussions with Mr. Terry Boerboom and Dr. David Southwick (MGS) proved extremely valuable in understanding the complicated geology of east-central Minnesota. Conversations with Mr. Cedric Iverson (deceased - USS), while the primary author was employed by USS, were also extremely helpful in understanding the reams of geological material that have been generated in the exploration for iron-formation in Minnesota during the last 100 years. Mr. Iverson was also one of the first to recognize the SEDEX potential of the Animikie Basin and convinced USS to conduct an airborne survey and drill three holes in an area near Meadowlands, MN.

GEOLOGY OF SPECIFIC AREAS WITHIN THE ANIMIKIE BASIN AND FOLD-AND-THRUST BELT IN CARLTON COUNTY, MINNESOTA

INTRODUCTION

Most of the drilling in Carlton County took place during exploration for uranium in the late 1970s. A total of 115 holes are known to have been drilled within the county since the 1950s; only 30 were drilled in exploration for commodities other than uranium. Out of the 115 holes, 77 holes are preserved as core, and the remainder are only preserved as cuttings. Only 54 of the core holes were logged for this investigation. For the most part, the rocks present in the core holes reflect a progressive increase in grade of metamorphism and deformation in a north-to-south direction; as do limited rock exposures within the same area. Some of the northern-most holes in the county intersect sedimentary rocks of the Animikie Basin, while the remaining holes, in the southern portion of the county, intersect sedimentary and volcanic rocks of the Fold-and-Thrust Belt.

The division, or unconformity, between these two allostratigraphic packages (Animikie Basin versus Fold-and-Thrust Belt) within Carlton County is difficult to pinpoint on a map with accuracy due to its spatially transitional nature that reflects a time-transgressive, northward-migrating boundary (Morey and Southwick, 1995). In areas with outcrop, this unconformity may be confined, with some certainty, to an area a few miles south of Thomson Dam, or a short distance south of Otter Creek (Southwick et al., 1988). However, tracing this same unconformity towards the west, where outcrops are absent and drill holes are widely scattered, becomes extremely problematic. In this investigation, and as on the map of Southwick et al. (1988), an east-west-trending aeromagnetic high is inferred to represent this unconformity and marks the southern edge of the Animikie Basin. Specific areas that were drilled within Carlton County are described below.

ARROWHEAD MINE AREA

Introduction

Small workings dug into the Thomson Formation around 1910, within Section 32, T.48N., R.18W., are referred to as the Arrowhead Mine (Fig. 4a). These workings are situated at the extreme southern edge of the Animikie Basin. Rocks at the "mine" site consist of black carbonaceous slate that is heavily fractured, brecciated, and impregnated with quartz and pyrite (Ojakangas, 1976; Morey and Davidson, 1979). Bedding trends within the area are generally east-west, but the fracture system exhibits a northerly trend. The carbonaceous slate was mined to be used as coal, and at one time, may have been "mined" for gold (Morey and Davidson, 1979). Anomalous uranium concentrations in a grab sample from the mine were discovered by Ojakangas (1976), and the area was subsequently explored for uranium by Rocky Mountain Energy, of Denver, CO, in the late 1970s. Rocky Mountain drilled 14 rotary holes (ML-series holes), and four core holes (MLCH-series holes), to the east of the Arrowhead Mine site (Fig. 4a). They also drilled three core holes within 1.5 miles to the south of the

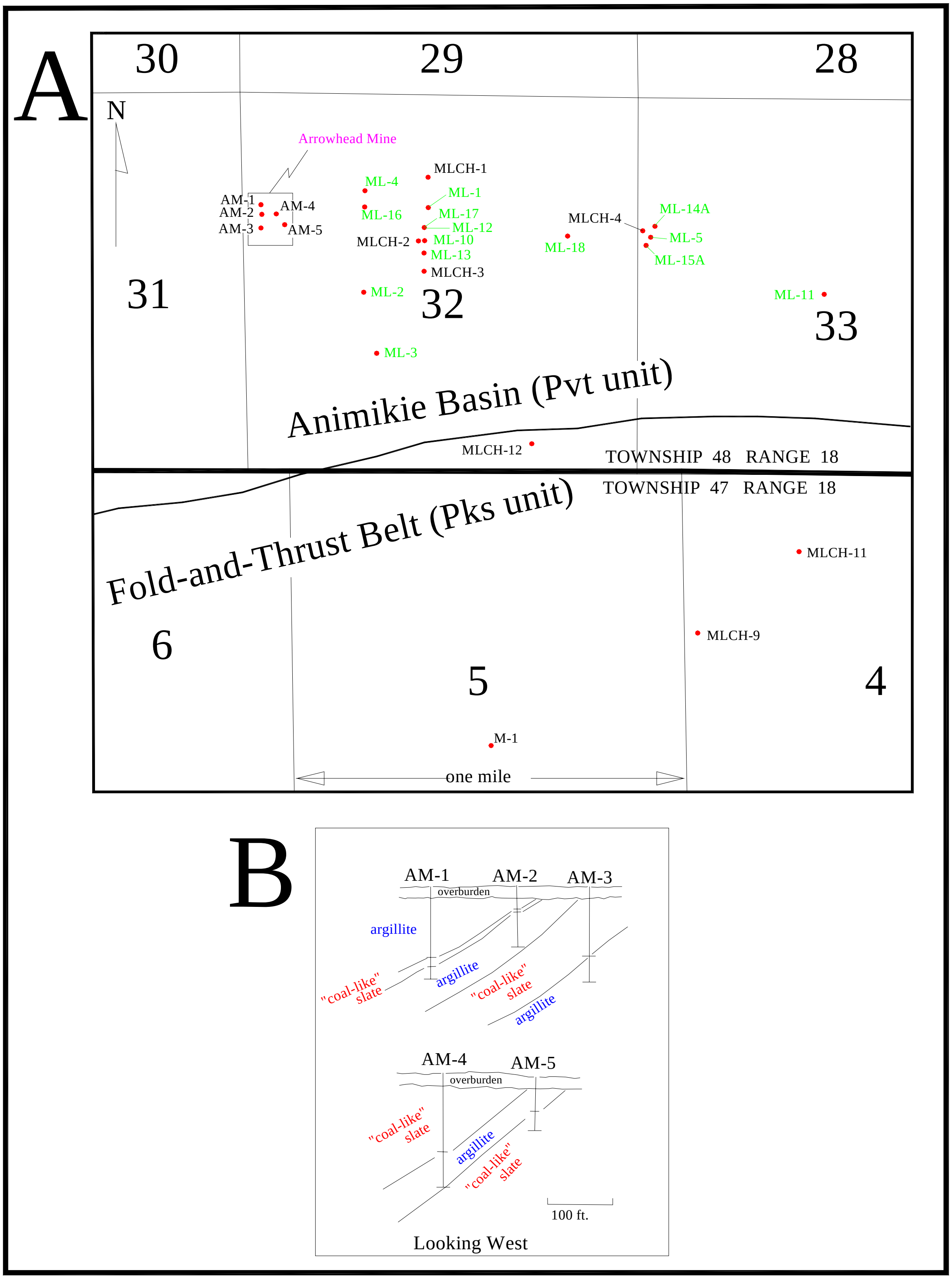

Figure 4 - (A) Drill hole location map - Arrowhead Mine and vicinity, Carlton County, Minnesota. (B) Cross-sections (looking east) showing general geologic relationships at the Arrowhead Mine.

mine area. These three holes are located within the northern edge of the Fold-and-Thrust Belt rather than the Animikie Basin. In the late 1980s, Great Lakes Exploration, Incorporated drilled an additional five core holes at the mine site (AM-series holes).

Geology

Rock types intersected in drill holes at the mine site (AM-1 through AM-5) consist of interbedded, fine-grained argillaceous metasediments of the Thomson Formation (Pvt unit) and "coal-like" carbonaceous slate. The latter is often highly brecciated and contains a network of quartz and/or pyrite veins; the amount of pyrite varies from 5% to 35% (visual estimate). Bedding within these holes is variable due to folding and is often overprinted by a later penetrative cleavage that exhibits steep dips of 70-90°, but is locally as shallow as 30°. Inferred cross-sectional relationships (Fig. 4b) indicate that the overall dip of bedding at the mine site is on the order of 35° to the south.

Raman microprobe spectroscopy analyses of three drill core samples for this investigation indicates that the "coal-like" carbonaceous material is unstructured and "...characteristic of graphite in pelitic rocks metamorphosed in the chlorite zone of greenschist facies metamorphism. In other words, ... [the] carbonaceous materials are well beyond the "kerogen stage" but do not appear to have reached the chlorite/biotite zone" (Dr. Jill Dill Pasteris, Feb. 1999, pers. comm., and Appendix 7). McSwiggen and Morey (1989) noted that the rocks at the Arrowhead mine exhibit a low degree of crystallinity and contain 20.80% to 26.10% carbon (total). A carbon isotope value obtained by McSwiggen and Morey (1989) from an outcrop at the Arrowhead Mine (sample Arrow-1) is -32.18 ‰. Additional isotope samples were collected in this investigation and are discussed at the end of this report.

Rock types intersected in four core holes to the east of the mine site (MLCH-1 through MLCH-4) also consist of argillaceous metasediments (Pvt unit) with "coal-like" slate; however, brecciation and quartz veining is less evident. Sulfides are also less evident and generally average about 5% (as cubes up to 1.5 cm) with most of the pyrite occurring in the carbonaceous slate. Sedimentary bedding is better preserved in these four holes and exhibits dips of 10-60°. A penetrative cleavage is generally perpendicular to bedding and exhibits dips of 60-80°.

To the south of the mine area, and within the Fold-and-Thrust Belt, a more intensely deformed argillaceous package (Pks unit) is intersected in four core holes (MLCH-9, MLCH-11, MLCH-12, and M-1). Additional differences that are intersected in this group of southern holes include:

- Calcareous zones are exceedingly common.
- Very thin (<2 cm) quartz arenite beds are present and are preserved as boudinages
- Some possible tuffaceous units are present.
- Graphite-bearing argillite is present, but the "coal-like" slate that is common to the north is absent.

Bedding planes in drill core are often obliterated and overprinted by a penetrative cleavage that itself is folded and exhibits dips of 10-60°. A crenulation cleavage is also observed in some holes. Phosphate-rich sedimentary rocks are reported to occur in: drill hole MLCH-11 at 44.3-45 ft. (see MDNR open files; no core is preserved for this interval), two test pits in the NE-NW, Section 4, T.47N., R.18W.; and in glacial boulders in NE-SE Section 4 , T.47N., R.18W. (Hyrkas, 1982).

Zinc assays

Other than anomalous uranium concentrations and "fraudulent" gold, rocks in the Arrowhead Mine area also contain anomalous zinc values (>1,000 ppm). Four grab samples from the mine area, collected by the MGS (McSwiggen and Morey, 1989), contain from 120-1,300 ppm Zn. In addition, many of the holes in the vicinity intersect thick intervals (30-135 feet thick) that contain semi-continuous anomalous zinc values (see Appendix 2 - *basinchemco.xls*). Anomalous zinc values are present in 12 out of 13 holes where zinc analyses were routinely run. It is important to note that the holes with the most anomalous zinc values are rotary holes (ML-series holes), and thus, it is difficult to speculate on the type of rock that is associated with the zinc mineralization. Also, because these holes were rotary holes, the validity of such thick semi-continuous zones with zinc are questionable as some of the zinc values could be related to contamination that occurred during drilling(?). Interestingly, all but one of the analyzed rotary holes have thick (>30 feet thick) anomalous zinc-bearing zones. Another factor to consider when viewing the viability of the zinc values is that extremely high concentrations of silver (up to 24 oz./ton in one instance) were also commonly reported by the same lab. When duplicate samples were re-run for silver, none of the original values could be verified.

With regard to core holes, anomalous zinc values (>1,000 ppm) are present in the following:

- MLCH-1 - 10 feet with up to 1,550 ppm Zn;
- MLCH-2 - one small sample with 1,600 ppm Zn;
- MLCH-3 - 135 feet with up to 4,200 ppm Zn;
- MLCH-4 - 40 feet with up to 5,500 ppm Zn;
- AM-1 - 3.5 feet with 1,045 ppm Zn;
- AM-3 - 6.5 and 6.0 feet with 1,916 ppm and 1,363 ppm zinc, respectively; and
- AM-4 - 6.5 feet with 3,762 ppm zinc and 5,133 ppm Pb; and 2.0 feet with 3,009 ppm zinc.

For the most part, these high zinc values are associated with the "coal-like" carbonaceous slate with highly variable concentrations of pyrite (<1% to 10%; visual estimate). Again, it is interesting to note that in one instance, a core hole with only minor anomalous zinc values (MLCH-2) is **right next to** a rotary hole (ML-10) that has 75 feet of anomalous zinc. Overall, the zinc analyses conducted during the late 1970s are suspect. However, the scattered presence of anomalous zinc values indicated by more recent MDNR and MGS sampling campaigns suggests that anomalous zinc concentrations are indeed present in the area and a potential for SEDEX mineralization does exist.

The location of the Arrowhead Mine area, relative to the tectonically active Fold-and-Thrust Belt, also suggests a potential for growth faults and a potential SEDEX plumbing system.

Zinc analyses were rarely conducted on the core holes within the Fold-and-Thrust Belt to the south of the Arrowhead Mine area (see Fig. 4a). Where conducted, zinc values in excess of 200 ppm Zn are rare, except in MLCH-12 (1,050 ppm Zn at a depth of 125-130 feet), MLCH-9 (594 ppm Zn at 469-472 feet), and MLCH-11 (2,419 ppm Zn at 334-335 feet).

MDNR Drill Hole BM-1

Introduction

An extremely deep hole (BM-1, down to a depth of 3,143 feet) was drilled by the MDNR within the Fold-and-Thrust Belt in 1985. Drill hole BM-1 is located in Section 16, T.47N., R.19W. (Fig. 3) and was drilled at an angle of 45° to the north. The hole was initially drilled to test an inferred fault zone (based on geophysics) that was speculated to host Carlin-type Au or Sullivan-type Zn-Pb mineralization (Sellner et al., 1985). Although no significant mineralization was encountered in the hole, it did intersect a thick stratigraphic package of rock that is worth a brief discussion.

Geology

The top half of the hole, down to a depth of 1,248 feet, is characterized by massive mafic volcanic rocks (Pvgd unit), with possible medium-grained gabbroic zones, and common calcareous zones. Present within the mafic volcanic package are argillaceous interbeds that vary from less than one inch to 130 feet thick (as at 636-762 feet which is graphite-bearing), and possible reworked tuffaceous beds (762-845 feet). Beneath the mafic volcanic package, a sequence of argillite interbedded with reworked tuffs(?) and arkosic metasediments is intersected at a depth of 1,248-1,545 feet. The bottom of the hole, from 1,545-3,143 feet, is characterized by a recrystallized siliceous dolomite. Bedding within the siliceous dolomite is beautifully preserved and intricate folds and micro-shear zones are evident throughout the rock and increase in intensity with depth. The dolomite in drill hole BM-1 may correlate with dolomite beds within the Denham Formation (Pdam unit) of the Mille Lacs Group, exposed about 10-12 miles to the south of the hole. Similar dolomite beds that may also be correlative occur in the bottom of the Hattenberger hole (see later discussion), and to a lesser extent, the Trout Lake Formation of the North Emily District.

KALEVALA TOWNSHIP AREA

Introduction

Interest in the Kalevala Township area was sparked by the reported anomalous presence of zinc in an old reconnaissance core hole that was drilled by the M.A. Hanna Company in the 1950s.

This hole, K-1 (Fig. 5), was drilled on a magnetic high in exploration for either sulfide-rich metasediments (for a potential sulfur source) or for iron-formation. The top 92 feet of K-1 averages 0.8% zinc with a maximum of 1.6% zinc (Owens, 1984). Recent analyses conducted on core from K-1 by the MDNR indicate the presence of up to 2.25% zinc in a five-foot thick interval (see Appendix 2 - *basinchemco.xls* data file).

The MDNR drilled a core hole (BM-2 in Fig. 5) to the east of K-1 in 1984. Further exploration for SEDEX deposits in the area has been conducted by Great Lakes Exploration, Incorporated (GLE), along with various joint venture partners. Five core holes (KL-1 through KL-5 in Fig. 5) were drilled in 1995-1996. More recent drilling has also been conducted by GLE, but the results of their efforts are unknown at this time.

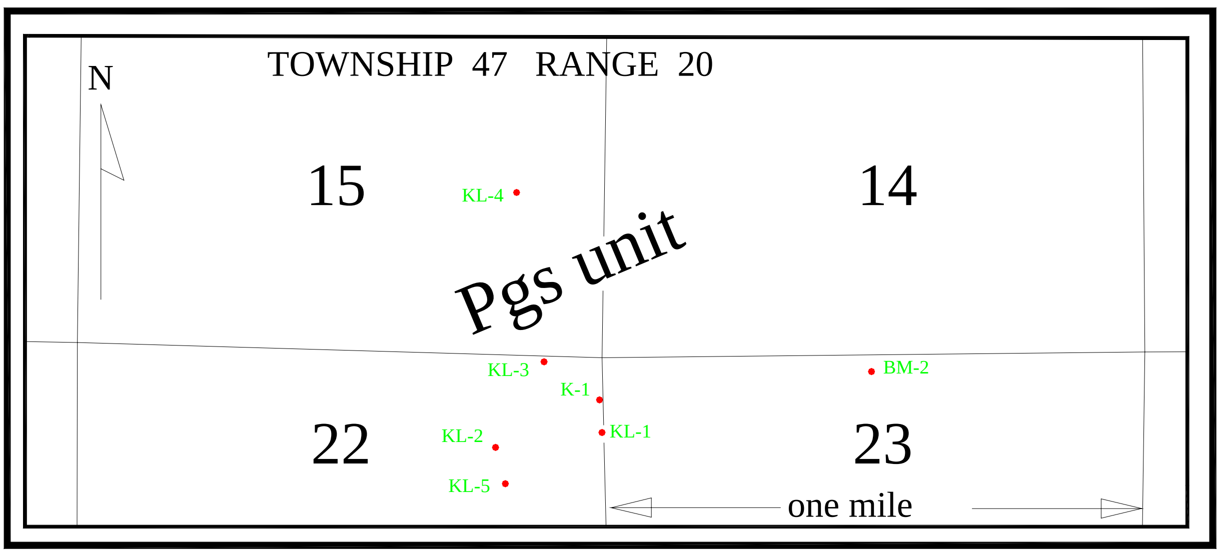

Figure 5 - Location of pre-1999 drill holes at the Kalevala Township area, Carlton County, Minnesota.

Geology

The dominant rock type intersected in the holes consists of thin-bedded argillite and carbonaceous argillite with lesser amounts of light-gray mudstone/siltstone, calcareous argillite, dolomitic marble, and reworked tuff (Pgs unit). Beneath the argillite-dominated sequence, drill hole BM-2 intersects a thick unit of coarser-grained clastic rock. This clastic unit consists of interbedded quartz-grain (granule-sized) wacke (>15% matrix) and quartz-pebble conglomerate that is both matrix- and clast-supported. In addition to quartz pebbles, the conglomerate locally contains granitic clasts and lensoidal-shaped argillite fragments (soft-sediment rip-ups?). Gradations from quartz-granule wacke to quartz-pebble conglomerate are present throughout this unit. Also present within this unit are thin interbeds of argillite and carbonaceous argillite. The presence of such a thick clastic unit in the bottom of drill hole BM-2 is certainly intriguing, and its place within the allostratigraphic record is unknown. At present, this thick clastic unit is interpreted as representing an abrupt change to rapid shedding of detritus from a more proximal source (the overlying argillites represent a deeper water depositional environment). This rapid change may be related to the presence of a growth fault at the margin of a third order basin.

Structure

The rocks are generally well-cleaved (S_1), and only locally are the original bedding planes (S_0) preserved. In these instances, the bedding planes readily define fold axes (that range in drill core from six inches to over several feet in amplitude) with axial planar cleavage (S_1). Small offsets in bedding (< 5 cm) along micro-faults are also commonly developed along the S_1 cleavage. Wherever both S_0 and S_1 are subparallel, S_1 is dominant and overprints S_0. Also present in some of the holes is a preserved crenulation cleavage (S_2) that is axial planar to very small folds defined by S_1.

Sulfide Mineralization

Drill holes K-1 and KL-1 intersect a unique rock type, referred to as “brown beds,” that contain very fine-grained sphalerite (observed at both macro and microscopic scales). These “brown beds” occur as thin interbeds (<2 cm) within carbonaceous argillite. Upon close inspection, especially when polished sections are made, these brown beds are found to be rich in <u>extremely</u> fine-grained pyrrhotite, with a range of 30-80% (semi-massive to massive sulfide), with variable lesser amounts of sphalerite and/or chalcopyrite. The overall appearance of these delicately-bedded “brown beds” in thin section suggests that they are syngenetic with sedimentary deposition and could represent the outermost, or more distal, portions of a SEDEX deposit.

Zinc Assays

In regards to zinc mineralization, anomalous values are certainly present within drill hole K-1 (2.25% zinc), and private GLE data indicates that hole KL-1 also contains anomalous values; many of the high Zn values appear to be related to syngenetic sulfides. In addition to the syngenetic sulfides, there are obvious late veins (<1 cm) that are rich in visible sphalerite and/or chalcopyrite that cross-cut the S_1 cleavage. The extremely high value of 2.25% zinc in drill hole K-1 is probably related to a vein that contains secondary sphalerite. [The core that remains for this zone in K-1 does not contain any obvious sphalerite mineralization (one-quarter core), and it is possible that the portion of the core with the suspect vein was consumed during sampling for base metal analyses].

KETTLE RIVER AREA

Introduction

The Kettle River area (Section 7, T.46N., R.20W.) was initially drilled by the United States Bureau of Mines (USBM) in 1951 to check on the reported presence of a large sulfide body (details unknown). This sulfide body, and similarly known sulfide bodies in nearby Glen Township of Aitkin County, was considered to be potential sulfur sources. Three holes (BM-1 through BM-3 in Fig. 6a) were drilled by the USBM, but only one of the holes intersected material with sufficient quantities of sulfides to be of interest (Pennington and Davis, 1953). The USBM drilled two additional holes in the area (BM-4 and BM-5 in Fig. 6a) at some unknown later date. These two holes were collared close to two of the earliest holes, but were drilled deeper in order to intersect more sulfide-bearing materials at depth (see cross-sections in Fig. 6a). A nearby core hole (KR-1) was drilled in the vicinity by Energy Reserves Corporation in 1978 in search of uranium. Three inclined core holes (MG-5 through MG-7 in Fig. 6a) were put down in 1980 by Anaconda during a uranium exploration campaign.

Geology

Highly deformed and metamorphosed, garnet-bearing, schistose rocks of the Fold-and-Thrust Belt are intersected in this group of holes. Rock types consist of near equal amounts of metasedimentary rocks (quartz-mica schist - Pks unit) and mafic metavolcanic rocks (chlorite±actinolite schist - Pvgd unit). Various types of metasedimentary rocks that are intersected in the holes include: argillaceous schist; graphitic schist; sulfide-rich (5-30%) graphitic schist; Fe-carbonate-quartz-mica schist; minor recrystallized dolomite (especially in drill hole KR-1; Fig 6); and minor quartz arenite. All rock types are interbedded at various scales. The mafic metavolcanic rocks (Pvgd unit) are characterized by well-cleaved, fine- to medium-grained rocks with common calcareous zones, common gabbroic zones, and minor vesicle-bearing zones.

Structure

All rock types appear to be doubly deformed. Original bedding plane surfaces (S_0) appear to be subparallel to a well-developed cleavage (S_1), and when seen, S_0 is best preserved in the hinge zones of small folds. The dominant planar feature in the holes is a penetrative cleavage (S_1) which exhibits extreme variations in dip (10-50°). Folds defined by the S_1 cleavage are also common in many holes. Late stage quartz veins are common and cut both S_0 and S_1. The overall dip of the rock units at Kettle River is subhorizontal (Fig 6b).

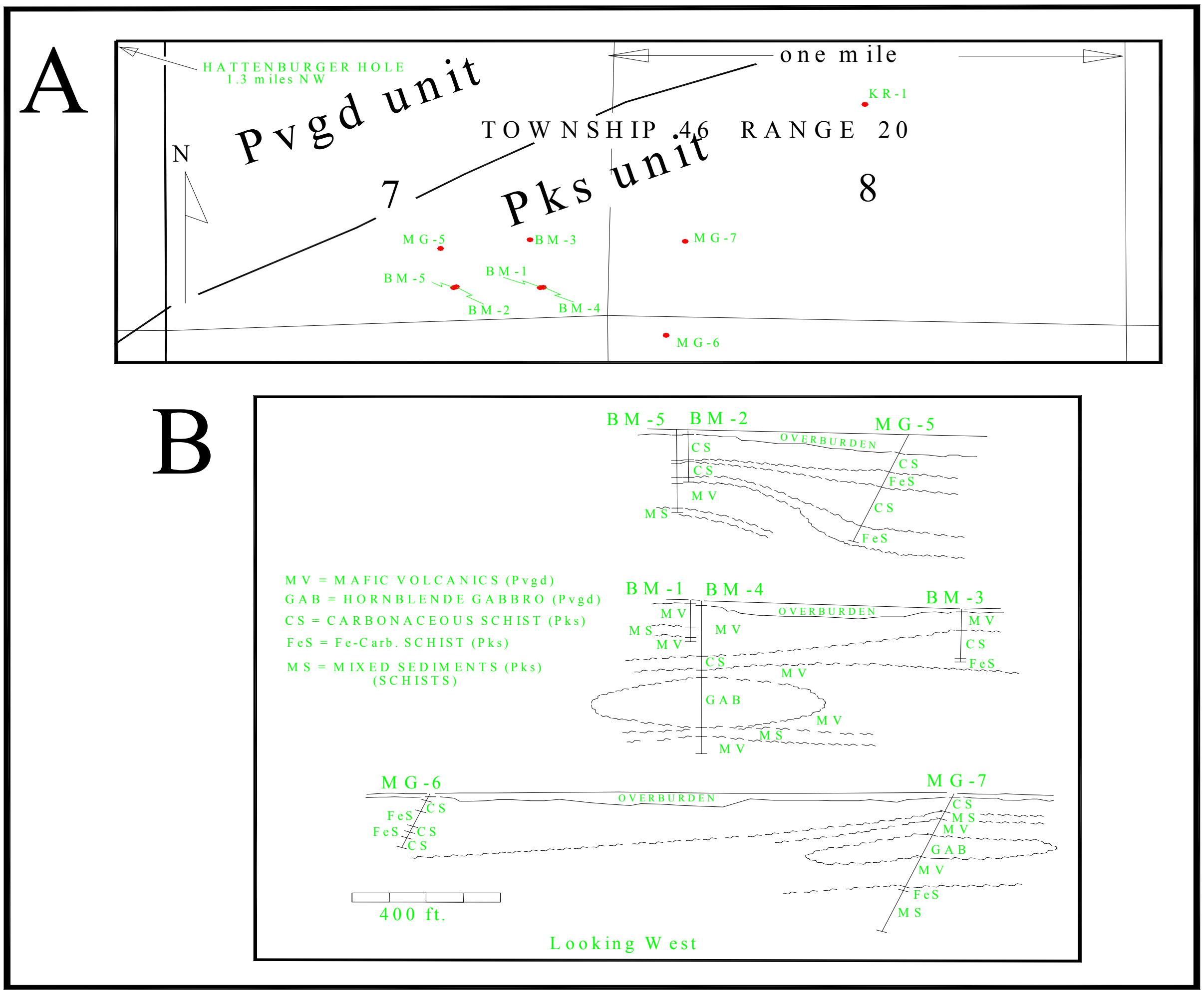

Figure 6 - (A) Location of drill holes at the Kettle River area, Carlton County, Minnesota. (B) Generalized geologic cross-sections (looking west) showing overall relationships of highly cleaved and folded rock units.

Sulfide Mineralization

Both pyrrhotite and pyrite are common within the more carbonaceous metasedimentary rocks and exhibit values as high as 30% sulfides (visual estimate). The sulfides occur as bands and irregular masses along S_1, and possibly along S_0. In some small areas in the drill core, it appears that the sulfides acted as a "grease" during deformation, and the sulfides became more concentrated in dilatant zones during the deformation event. The highest sulfides seen in core occur in hole MG-5 (329-362 feet) where values over 50% are common.

Zinc Assays

Only four holes from the Kettle River area were analyzed for zinc. Holes that contain anomalous zinc values (>1,000 ppm) are:

- MG-5 at 317 feet (a few inches were sampled) = 3,300 ppm Zn;
- MG-5 at 329-331 feet = 1,350 ppm Zn;
- MG-5 at 339-340 feet = 7,400 ppm Zn;
- MG-7 at 68 feet (a few inches sampled) = 1,400 ppm;
- MG-7 at 79-80 feet = 1050 ppm Zn;
- BM-2 at 150-155 feet = 1,008 ppm Zn;
- BM-5 at 107-117 feet = 4,717 ppm Zn; and
- BM-5 at 137.5-138.7 feet = 2,204 ppm Zn.

HATTENBERGER DRILL HOLE

Introduction

Located within two miles to the northwest of the Kettle River area is the site of the deepest core hole (7,440 feet) drilled in Minnesota. The Hattenberger hole, located in Section 2, T.46N., R.21W. (Fig. 3), has an exceptionally interesting story that has been recounted by Cleland and Morey (1993) and Southwick (2002). The story began in 1976 when Lee Hattenberger discovered methane in his domestic water supply after a small explosion (presumably in his toilet) was ignited by a candle during a power outage. The source of the methane was his water well which was drilled to a depth of 803 feet. "In an attempt to develop a commercially producing well, Mr. Hattenberger, a number of neighbors, and ultimately a local exploration company — Turmoil Inc. contracted with E.J. Longyear Co. to further develop the original water well.... subsequently deepened [the water well] to 2,391 feet ... and subsequently deepened to 5,062 feet ... in early January of 1979. Drilling resumed in April 1979 and continued intermittently until a depth of 7,440 feet was attained on August 2, 1979. At that time Hattenberger No. 1 was the second deepest continuously cored drill hole in the world.... the core was stored ... in the nearby barn of a partner in the drilling venture, where it remained until it was donated to the Minnesota Geological Survey in May 1994" (Cleland and Morey, 1993).

Geology

At present, there is no detailed log for the core, but publication of one is planned for the future (Dr. D.L. Southwick, pers. comm., March, 1999). General descriptions of the core, by Southwick (2002), indicate that quartz-rich mica schist, carbonaceous mica schist, carbonaceous (graphitic)-silicate-carbonate-sulfide iron-formation, calcareous mica schist, and dolomitic marble are present. Also present are mafic volcanic rock (both flows and fragmental types) and an assortment of mafic volcanic rocks that are thinly interbedded with the metasedimentary components. Sills of metadiabase, that are chemically identical to the volcanic rocks, are present throughout the core (Southwick, 2002). According to Cleland and Morey (1993) "... sulfides—mainly pyrite and pyrrhotite—occur throughout the core, but are particularly abundant in the carbonaceous intervals. Deformation is extreme throughout the core. There is evidence for two and in places three periods of folding.... Deformation was accompanied by several carbonate phases and abundant quartz veins. According to graded bedded sequences throughout the core and the lack of evidence for major faulting, the section appears to represent an original upward-younging stratigraphic sequence."

Only portions of the core were looked at for this investigation (799-2,707 feet). Massive-textured mafic volcanic rocks (Pvgd unit) with localized vesicular zones, pillowed zones and gabbroic zones are the dominant rock types down to at least 2,280 feet. Southwick (2002) states that iron-formation, containing the assemblage stilpnomelane+chert+graphite+Fe-rich amphibole, is interbedded with carbonaceous argillite at 2,280-3,190 feet. [Note that the primary author of this study did not classify any of this material as iron-formation; rather, felt that the interval consists of mixed carbonaceous argillite, reworked tuff and turbidites]. The hole bottoms in a thick quartzite and dolomite unit (4,779-7,440 feet). The dolomite bears many similarities to the dolomite encountered in MDNR drill hole BM-1 (see above) and may also be correlative with dolomitic rocks in the Denham Formation (Pdam unit) of the Mille Lacs Group, and to a lesser extent, the Trout Lake Formation in the North Emily District.

Zinc Assays

There are no published base or precious metal assay results for the Hattenberger drill hole. Talks given by Dr. Dave Southwick (Southwick, 2002) leads the primary author to believe that whole rock analyses are available at the MGS.

SPLIT ROCK AREA

Introduction

The Split Rock area (Fig. 7) was initially drilled by the M.A. Hanna Company in 1952. Three close-spaced holes (SR-1 through SR-3) were drilled in search of sulfide bodies to be used as a source for sulfur. A similar sulfide body, in the Glen Township area of Aitkin County (see later discussions), was also drilled by Hanna during this same time period. Additional holes were drilled 2-3 miles to the east (Fig. 7) during exploration for uranium and include four core holes (MG-1 through MG-4) by Anaconda in 1980, and five rotary holes (CK-1 through CK-5) by Rusc Incorporated (?) in 1986.

Geology

All three of the Hanna holes are extremely shallow (<116 feet) and intersect chlorite schist (mafic volcanics - Pvgd unit) with minor carbonaceous argillite. Three of the four core holes (MG-1,

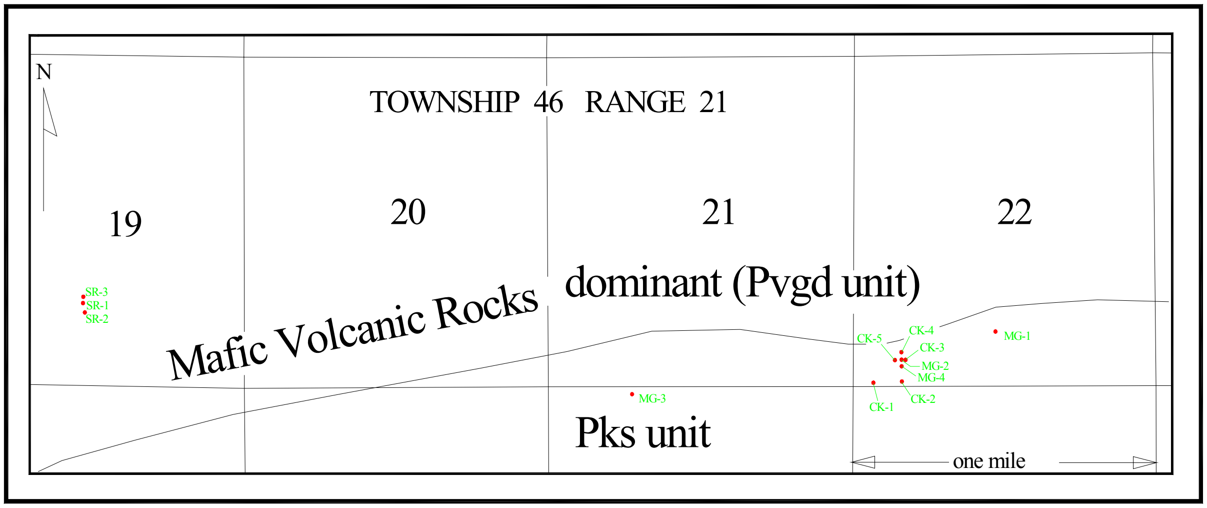

Figure 7 - Location of drill holes in the Split Rock area, Carlton County, Minnesota.

MG-3, and MG-4) were looked at for this investigation. This group of holes intersects a predominantly metasedimentary sequence (Pks unit) consisting of well-cleaved and interbedded argillite, graphite-bearing argillite, siltstone, graywacke, reworked tuffaceous(?) beds, and minor thin quartz arenite beds (that occur as small boudinages). Bedding (S_0) and cleavage (S_1) are subparallel, but small highly folded zones, with an axial planar crenulation cleavage (S_2), are present throughout the core. Sulfide mineralization is weak at best with most of the sulfides (up to 5%) associated with the more carbonaceous rocks.

Zinc Assays

Out of 70 samples analyzed for zinc in seven holes, only two sampled intervals contain anomalous zinc(>1,000 ppm Zn):

- drill hole MG-3 at 272-274 feet = 2,151 ppm Zn; and
- drill hole MG-3 at 374-382 feet = 1,100 ppm Zn.

GEOLOGY OF SPECIFIC AREAS WITHIN THE ANIMIKIE BASIN AND FOLD-AND-THRUST BELT IN AITKIN COUNTY, MINNESOTA

INTRODUCTION

Most of the drilling in Aitkin County took place during exploration for both iron-formation, as in the Cuyuna South Range, or for potential sulfur sources, as in the Glen Township area. At least 961 holes are known to have been drilled since the early 1900s, but the actual number of holes could be considerably higher. Core is preserved for 323 drill holes; most of which are stored at the MDNR. All but two of the core holes (stored at the MGS) from Aitkin County have been looked at for this investigation. Many of these holes were drilled in specific small areas and are described in the following sections.

GLEN TOWNSHIP SULFIDE - SOUTH BODY

Introduction

Glen Township (Fig. 2 - T.46N., R.25W.) has experienced a considerable amount of exploratory drilling in search of iron-formation, sulfur in sulfide-rich carbonaceous rocks, and more recently, iron-formation-hosted gold. Both reconnaissance drill holes and closely-spaced drill holes are present within the township (Plate I). Two small areas were intensively drilled and include Glen Township Sulfide - South Body and Glen Township Sulfide - North Body.

Initial drilling of strongly magnetic belts in Glen Township, in exploration of iron-formation, was conducted in 1922-23 by the Berrigh Magoffin Jr. of Deerwood, MN (Pennington and Davis, 1953). Considerable iron-sulfides, but no iron-formation, were cut in many of Magoffin's holes. The holes were drilled in at least two areas that are referred to as the South Body and North Body in this report. No accurate records of the drill holes were kept by Magoffin, nor were any analyses conducted on the core or cuttings.

In 1941, C.J. O'Connell became interested in the reported presence of iron sulfides as potential sources of sulfur and iron and acquired mineral rights in various sections within Glen Township Sulfide - South Body. In 1942, the Defense Plant Corporation announced plans to construct a manganese leaching plant in Trommald, MN (Zapffe, 1949). Because sulfur and sulfuric acid would be required in the leaching plant, Butler Brothers took an option on some of O'Connell's property in Glen Township and drilled 15 holes in Sections 28 and 29 in 1941. However, when the order to build the plant was canceled, they released their option in 1943 (Zapffe, 1949; Pennington and Davis, 1953). O'Connell remained optimistic, retained the property, and organized the Glen Development Company in 1945.

Additional holes were drilled at the Glen Township Sulfide - South Body in 1946 by the Minnesota Iron Range and Resources and Rehabilitation Commission (Pennington and Davis, 1953).

They drilled 19 holes to further delineate the sulfide body and to determine the potential sulfur and iron reserves. The M.A. Hanna Company became interested in the property (details are unknown) and drilled an additional 54 holes. In summary, a total of 89 holes have been drilled into sulfide-rich carbonaceous rocks at the Glen Township - South Body (73 holes have preserved core). Hanna estimated (Hanna exploration files at MDNR) that this body contains 20,372,000 crude tons of material averaging 15% S (using an 8% S cutoff) or 11,632,000 crude tons of material averaging 17.8% S (using a 15% S cutoff).

While all this activity was taking place in Sections 28 and 29, similar exploration efforts were taking place on a magnetic high in nearby Section 30 of the same township (Plate I). In 1914, N. Vladimiroff, a jeweler from Crosby, MN, acquired an option on the property and drilled at least seven holes into iron-formation (Zapffe, 1949). Oliver Iron Mining Company (a division of USS) drilled five holes in the area (18,000-series holes in Plate I) in 1951-52. Two of the holes intersected thin-bedded "slaty" iron-formation and another two holes intersected sulfide-rich carbonaceous rocks. Core from the USS holes were looked at and sampled for geochemical analyses in the 1980s and anomalous gold values (up to 1.41 ppm gold) were obtained from the iron-formation (Eldougdoug, 1984). A comparison was drawn between these iron-formation-hosted gold values and "similar" Homestake-type iron-formation-hosted gold deposits (Eldougdoug, 1984). A flurry of core sampling campaigns followed, and these same holes were re-sampled; however, **all** attempts at duplicating even weakly anomalous gold values proved to be futile, and the initial high gold values are suspect. During this same time period, the MDNR drilled two very deep core holes (A-2 and A-6 in Plate I) to the immediate north of the Glen Township Sulfide - South Body. The holes intersect down-dip extensions of both sulfide-rich carbonaceous rocks and "slaty" iron-formation at depth.

Geology

The core for 80 holes from the South Body, and the nearby vicinity, are still preserved and stored at the MDNR. Locations of the drill holes are portrayed in Plate I. Seventy-nine of the core holes have been relogged for this investigation, and each drill core is used to systematically build a stratigraphic section. A portrayal of the stratigraphic package intersected in the South Body area is shown on Figure 8. Drill holes that intersect specific portions of the stratigraphy are portrayed on Figure 9. There are at least six major units within the stratigraphic package at the South Body (Fig. 8). Within each of these major units are localized differences that are expressed as interbeds (numbers 1-17 in Fig. 8). From the top, down towards the bottom, a brief description of the stratigraphy the South Body follows:

<u>Mafic Volcanics (Pvdg unit)</u> - At the top of the stratigraphic column is a mafic volcanic unit consisting of flows and sills. The flows are characterized by a green-colored, chlorite-amphibole±feldspar-sericite schist (variably cleaved) with common calcareous zones and local pillows and calcite-filled vesicles. Fine- to medium-grained gabbroic sills, with chilled margins, are locally present in the volcanic rocks. Locally, and especially near the base of the mafic volcanic unit, the rocks are strongly carbonate altered, and protolith recognition is more difficult. Thin interbedded packages of argillite, carbonaceous argillite, and/or quartz arenite are locally present in the mafic volcanics. Tourmaline is present in some of the interbeds within the mafic volcanic unit in drill hole

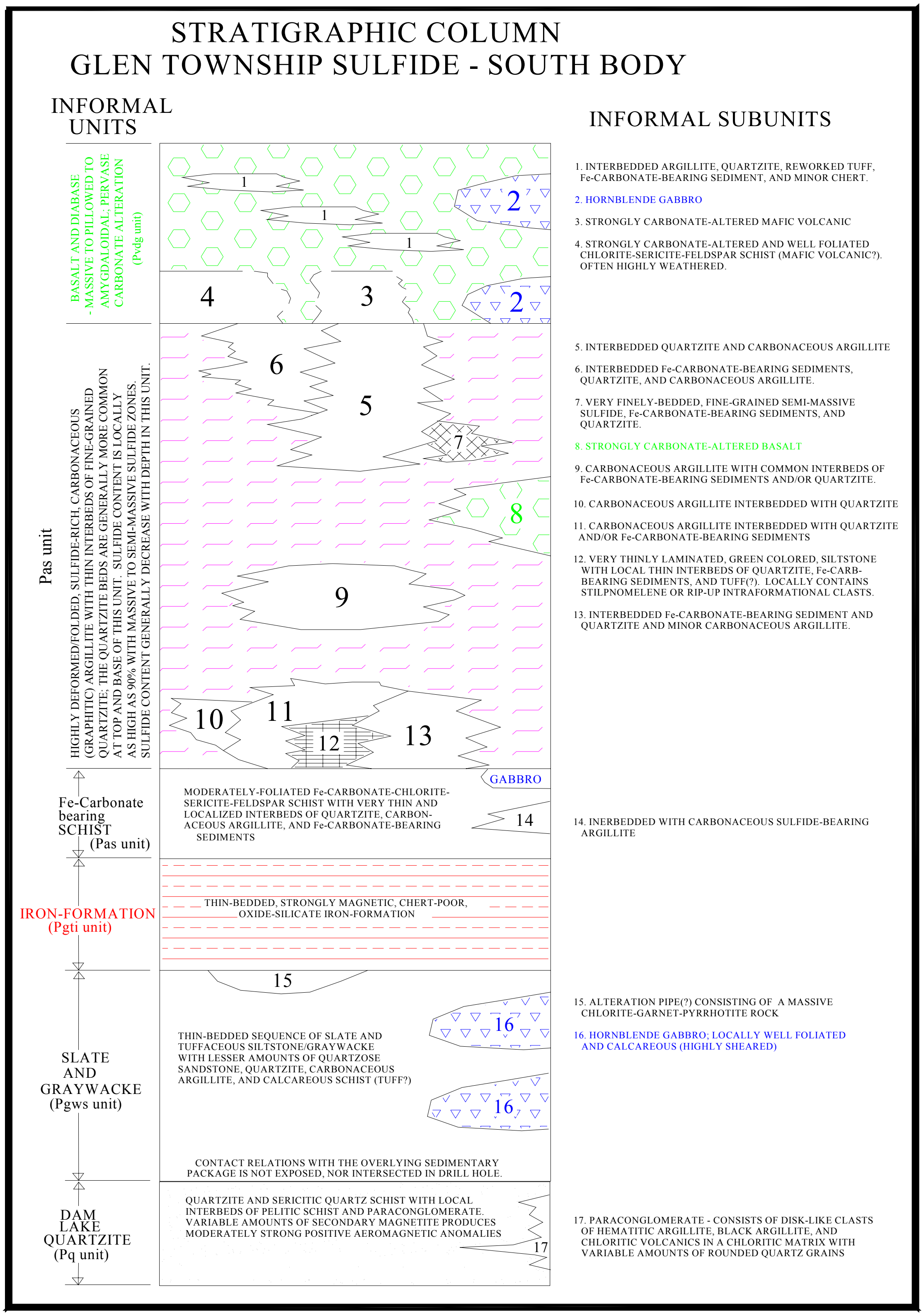

Figure 8 - Stratigraphic sequence of rocks as determined by drill hole logging at the Glen Township Sulfide - South Body, Aitkin County, Minnesota. No scale implied.

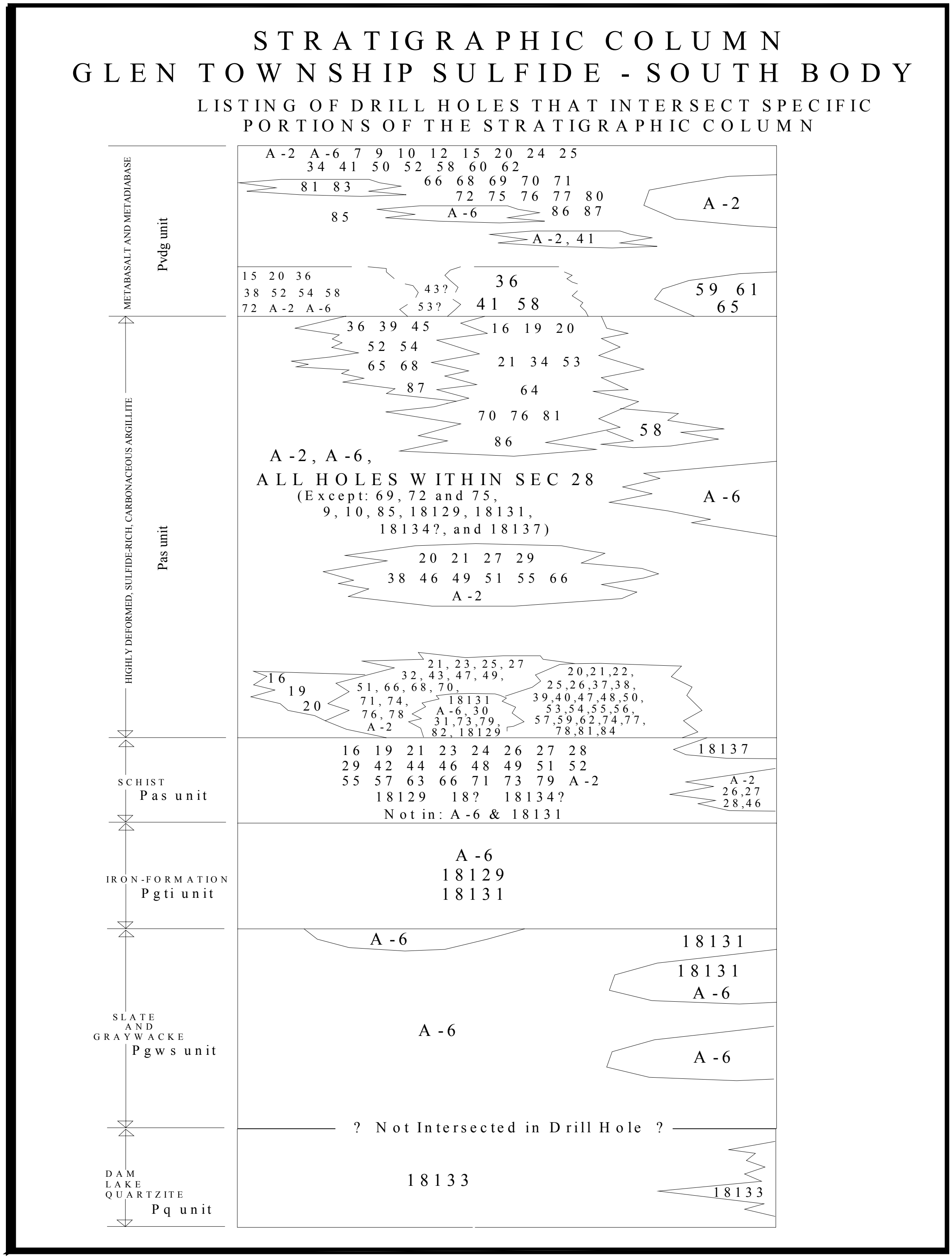

Figure 9 - Listing of drill holes that intersect specific portions of the stratigraphic sequence at the Glen Township Sulfide - South Body, Aitkin County, Minnesota. Compare with Figure 8.

A-6 (Dahlberg et al., 1987). Microprobe analyses for four tourmaline grains within a sedimentary interbed in hole A-6 (564.5 feet) are shown in Table 1.

Sulfide-rich, Carbonaceous Argillite (Pas unit) - Beneath the mafic volcanic unit are the sulfide-rich rocks that were originally drilled for their sulfur content. These rocks consist of highly folded, black, carbonaceous, sulfide-rich argillite with lesser amounts of interbedded argillite, quartz arenite, and Fe-carbonate bearing metasediments. This unit is the most highly deformed rock unit in the South body due to its "greased," highly carbonaceous nature. Folds, defined by bedding (S_0) and cleavage(S_1), are common throughout the core at scales ranging from a few inches to several feet wide. Thin interbeds of white, fine-grained, quartz arenite are common throughout this unit, but they are more numerous, and thicker, at the top and bottom of the package (see Fig. 8).

Also present within this unit, especially near the top and bottom, are Fe-carbonate-bearing metasedimentary rocks that are characterized by light-brown to pale yellow-green to cream-colored schistose rocks. The color of these rocks suggests that ankerite and/or siderite are present. In thin section, these rocks are carbonate-rich, but it is difficult to tell what type of carbonates are present without staining. In lieu of staining, microprobe analyses were conducted on one sample (Table 2). The analyses indicate that magnesian siderite is present. X-ray diffraction analysis on another sample (hole 48 at 46 feet - Fig. 10) indicates the presence of ankerite and dolomite. Magnetite-rich bands are locally associated with the Fe-carbonate beds and have been observed in three holes (holes 20, 36, and 52). In addition to the Fe-carbonate interbeds, a package of very finely laminated, pale-olive green, siltstone beds (number 12 subunit on Fig. 8) is also present at the base of the carbonaceous argillite package. These siltstone beds contain Fe-carbonates, and in three holes (30, 31, and A-6) stilpnomelane was noted. Both the Fe-carbonate-bearing metasedimentary rocks and green siltstone beds could collectively be interpreted to represent carbonate facies iron-formation - an observation also made by Eldougdoug (1984). These Fe-carbonate-bearing metasediments are often interbedded with quartz arenite and argillite (Fig. 8) and exhibit a transitional contact with the underlying unit, which is also Fe-carbonate-bearing.

Fe-Carbonate Bearing Unit (within Pas Unit) - The next major unit in the stratigraphic column at the South Body is a potential "carbonate facies iron-formation" unit. This schistose unit is characterized by a pale yellowish-green to cream-colored, fine- to medium-grained, crystalline, schistose rock with minor interbeds of quartz arenite and argillite. The schist contains variable amounts of Fe-carbonate, carbonate, chlorite, sericite, and feldspar. A pervasive cleavage (S_1) is exceptionally well-developed in the rock, and its crystalline character is related to small rhombs (<2 mm) of siderite, ankerite, dolomite, and calcite (Table 2). These carbonates are present in varying amounts, and thus the rock exhibits a variable reaction with HCl acid. Microprobe analytical results for two samples from this unit confirm the presence of ankerite (Table 3) and calcite (Table 4). Wherever the Fe-carbonate bearing unit is collared in the tops of drill holes, it is easily weathered and typically contains small (<2 mm), square-shaped, brown pits with porous limonite that formed by oxidation of the Fe-carbonates. This unit could be interpreted to represent carbonate facies iron-formation. Eldougdoug (1984) variably classified the protolith of this rock type as: ankerite-bearing graywacke (three times); carbonate iron-formation (once); graywacke (once); and metavolcanic (once). A fine-grained gabbroic sill is intersected within this unit in one hole (18138).

A-6 564.5 ft. - Four Different Tourmaline Grains													
Weight %													
No.	**SiO2**	**Al2O3**	**FeO**	**B2O3**	**MgO**	**CaO**	**MnO**	**K2O**	**F**	**Na2O**	**H2O**	**Li**	**Total**
1	35.328	31.028	9.771	9.395	6.247	1.008	0.048	0.012	0.000	2.030	?	?	94.867
2	35.564	31.510	9.767	9.157	6.288	0.905	0.075	0.024	0.000	2.086	?	?	95.376
3	35.558	31.374	9.885	9.454	6.304	0.867	0.073	0.018	0.000	2.053	?	?	95.586
4	35.981	31.561	9.560	9.626	6.310	0.966	0.048	0.023	0.013	2.089	?	?	96.172
Cation													
O = 12.0													
No.	**Si**	**Al**	**Fe**	**B**	**Mg**	**Ca**	**Mn**	**K**	**F**	**Na**	**H2O**	**Li**	**Total**
1	2.4875	2.5752	0.5754	1.1420	0.6557	0.0760	0.0029	0.0011	0.0000	0.2772	?	?	7.7931
2	2.4934	2.6039	0.5727	1.1082	0.6571	0.0680	0.0044	0.0021	0.0000	0.2836	?	?	7.7934
3	2.4848	2.5842	0.5777	1.1404	0.6567	0.0649	0.0043	0.0016	0.0000	0.2782	?	?	7.7929
4	2.4922	2.5767	0.5538	1.1509	0.6516	0.0717	0.0028	0.0020	0.0029	0.2806	?	?	7.7853

Note: H2O could not be analyzed

Table 1 - Microprobe analyses for tourmaline grains from a metasedimentary interbed in the mafic volcanic unit (hanging wall) at the Glen Township Sulfide - South Body, Aitkin County, Minnesota. Sample from drill hole A-6 at 564.5 feet.

DH-77 177.5 ft. - three magnesian siderite grains							
Weight %							
No.	**CaO**	**MgO**	**FeO**	**MnO**	**SrO**	**CO2**	**Total**
1	0.603	6.423	53.875	0.481	0	38.617	99.999
2	0.703	6.320	53.345	0.664	0	38.969	100.001
3	1.171	6.459	52.399	1.214	0	38.757	100.000
Cation, O = 12.0							
No.	**Ca**	**Mg**	**Fe**	**Mn**	**Sr**	**C**	**Total**
1	0.0481	0.7131	3.3554	0.0304	0	3.9265	8.0735
2	0.0559	0.6989	3.3095	0.0417	0	3.947	8.0530
3	0.0932	0.7151	3.2548	0.0763	0	3.9303	8.0697

Note: CO2% determined by difference (remainder of 100% - major cations%)

Table 2 - Microprobe analyses of three coarse-grained Fe-carbonate grains (magnesian siderite) in an interbed of the "Fe-carbonate-bearing unit" (subunit 13 in Fig. 8). Sample from drill hole 77 at 177.5 feet; Glen Township Sulfide - South Body, Aitkin County, Minnesota.

MAG-51 234.3 ft. - four ankerite grains							
Weight %							
No.	**CaO**	**MgO**	**FeO**	**MnO**	**SrO**	**CO2**	**Total**
1	29.642	12.985	12.588	0.884	0.168	43.733	100.000
2	29.678	12.277	13.909	0.606	0.185	43.345	100.000
3	28.910	11.166	16.447	0.331	0.220	42.925	99.999
4	29.212	12.623	13.328	0.755	0.164	43.919	100.001
Cation, O = 12.0							
No.	**Ca**	**Mg**	**Fe**	**Mn**	**Sr**	**C**	**Total**
1	2.0951	1.2768	0.6944	0.0494	0.0064	3.9389	8.0610
2	2.1116	1.2153	0.7724	0.0341	0.0071	3.9298	8.0703
3	2.0767	1.1159	0.9221	0.0188	0.0086	3.9290	8.0711
4	2.0645	1.2411	0.7352	0.0422	0.0063	3.9553	8.0447

Note: CO2 determined by difference (remainder of 100% - major cations%)

Table 3 - Microprobe analyses of four Fe-carbonate grains (ankerite) from the "Fe-carbonate-bearing unit" (Fig. 8) at the Glen Township Sulfide - South Body. Sample from drill hole 51 at 234.3 feet.

BM-21 266 ft. - nine fine- to medium-grained calcite grains							
Weight percent							
No.	**CaO**	**MgO**	**FeO**	**MnO**	**SrO**	**CO2**	**Total**
1	53.871	0.217	0.959	0.121	0.282	44.55	100.000
2	53.475	0.579	0.925	0.269	0.271	44.481	100.000
3	54.486	0.122	0.700	0.092	0.334	44.267	100.001
4	51.503	2.320	4.281	0.308	0.314	41.274	100.000
5	54.820	0.325	1.157	0.357	0.332	43.010	100.001
6	54.959	0.322	0.995	0.153	0.331	43.241	100.001
7	55.522	0.158	0.538	0.404	0.235	43.142	99.999
8	54.697	0.114	1.205	0.470	0.284	43.228	99.998
9	54.573	0.340	1.244	0.306	0.300	43.237	100.000
Cation, O = 12.0							
No.	**Ca**	**Mg**	**Fe**	**Mn**	**Sr**	**C**	**Total**
1	3.8319	0.0214	0.0532	0.0068	0.0109	4.0379	7.9622
2	3.8033	0.0573	0.0513	0.0151	0.0104	4.0313	7.9688
3	3.8856	0.0121	0.0390	0.0052	0.0129	4.0226	7.9775
4	3.7761	0.2366	0.2450	0.0179	0.0124	3.8560	8.1440
5	3.9570	0.0326	0.0652	0.0204	0.0130	3.9560	8.0442
6	3.9567	0.0322	0.0559	0.0087	0.0129	3.9668	8.0332
7	4.0003	0.0159	0.0303	0.0230	0.0092	3.9607	8.0394
8	3.9424	0.0114	0.0678	0.0268	0.0111	3.9703	8.0298
9	3.9306	0.0341	0.0699	0.0174	0.0117	3.9681	8.0318

Note: CO2% determined by difference (remainder of 100% - major cations%)

Table 4 - Microprobe analyses of both fine-grained and medium-grained calcite grains in a sample collected from the "Fe-carbonate0bearing unit" (Fig. 8) at the Glen Township Sulfide - South Body. Note that no Fe-carbonate is present within this particular sample. Sample collected from drill hole BM-21 at 266 feet.

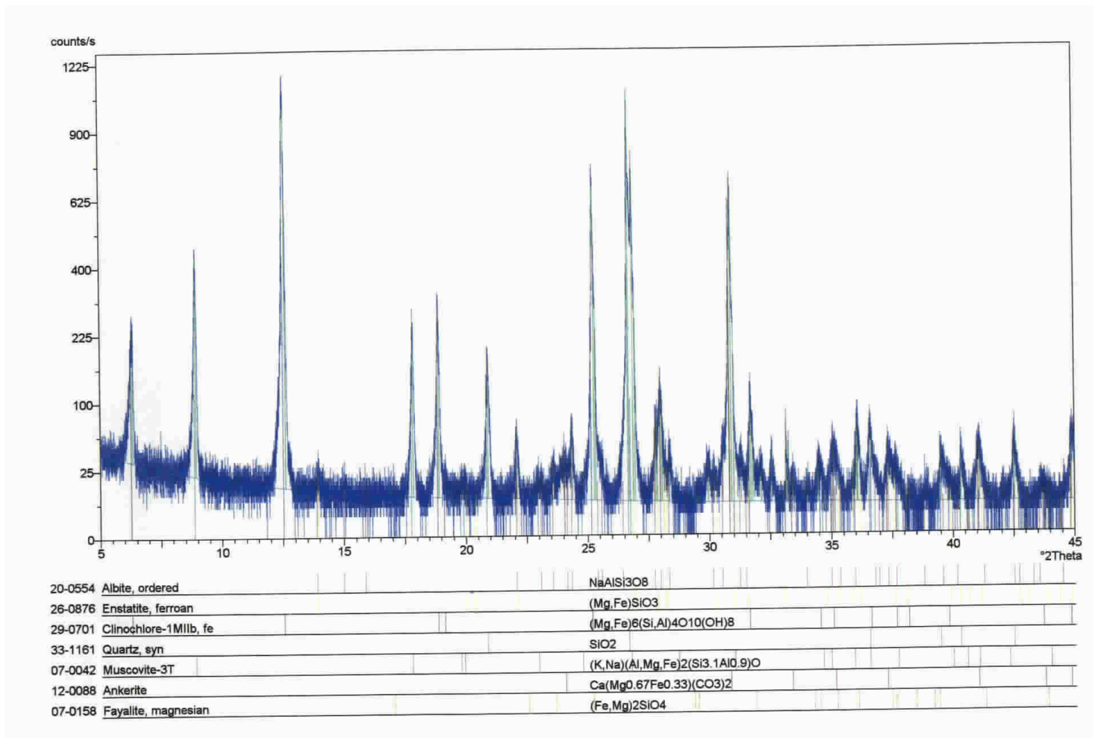

Figure 10 - X-ray analysis of a core sample from the Fe-carbonate-bearing unit in drill hole 46 (178.5 feet) at the Glen Township Sulfide - South Body. Ankerite is confirmed to be present in the rock, along with quartz, clinochlore, muscovite, and lesser amounts of feldspar, enstatite, and fayalite.

Iron-Formation (Pgti unit) - Beneath the "carbonate facies iron-formation" is a thin-bedded (0.5-5.0 mm thick beds), "slaty", magnetic, variably green- to gray-colored, silicate-carbonate-oxide facies iron-formation. The iron-formation is intersected in only three holes (A-6, 18129, and 18131 in Fig. 9) and is approximately 230 feet thick in hole A-6. The rock is fine-grained and consists of alternating dark magnetite-rich bands, greenish Fe-silicate/Fe-carbonate bands, and lesser amounts of light gray quartzose bands. Gray chert beds, up to 3.0 cm are only locally present. Thin beds of black argillite are also locally present. Bedding is generally straight and planar, but small folds and micro-faults are locally present. A four foot thick chlorite-garnet-sulfide alteration zone is present beneath the iron-formation in drill hole A-6. A pervasive cleavage (S_1) is poorly developed within the iron-formation due to its more competent nature.

Metasediments (Pgws unit) - Below the iron-formation is a thick sequence of thinly-bedded metasediments consisting of black mudstone, light-gray siltstone, sandy-textured tuffaceous graywacke, quartz arenite, and minor dolomite. Intersected in hole A-6 are three hornblende-bearing gabbroic sills that are locally uralitized and carbonate altered. Highly altered sills may be present in the bottom of another two drill holes (18131 and 18134). Bedding planes (S_0) within the metasediments, in drill hole A-6, are straight and planar, but exhibit abundant folds with depth. A moderately-developed cleavage (S_1) is present in the top portion of this unit and becomes more well-developed with depth. A crenulation cleavage (S_2) is also better developed at depth. The S_1 cleavage both parallels, and is perpendicular to, S_0 in alternating thick zones. Whenever folds are observed, S_1 is axial planar to the fold axes.

Dam Lake quartzite (Pq unit) (informal name) - At the bottom of the stratigraphic column is a clastic sequence of interbedded quartz arenite, argillite, and paraconglomerate. This unit is intersected in only one hole (18133) and is presumed to be correlative with nearby outcrops of the Dam Lake quartzite. Contact relations with the overlying rocks are not intersected in any hole. The paraconglomerate is characterized by 5-40% clasts of black argillite, reddish hematitic material (iron-formation?), and chloritic "siltstone." The clasts are elongated to disk-shaped (up to one inch long) with moderately-rounded edges. The matrix of the conglomerate consists of variable amounts of rounded quartz grains in a chloritic "mud."

Age Dates

A Sm-Nd isochron age of 2,197±39 Ma has been obtained for the package of rocks in the Glen Township area (Beck, 1988). Rock samples were collected from what was referred to as "metavolcanic rocks" in the USS drill core by both Eldougdoug (1984) and Beck (1988). However, neither investigator clearly defines what holes and footages were actually sampled! Several attempts by NRRI personnel to confirm the actual footages of the samples have been fruitless. A crude "reckoning" of what rock type was actually sampled suggests that several rock types, including altered sills within the metasedimentary rocks, were sampled for age dating. No samples were collected from the two MDNR drill holes (A-2 and A-6) that intersect a clearly-recognizable mafic volcanic unit at the top of the stratigraphic column (Fig. 8) - this is because neither of the holes were available for sampling at that time. In summary, the age date obtained by Beck (1988) can only be considered to represent a **stratigraphic** date for the Glen Township area (Dr. D.L. Southwick, pers.

comm., October, 2000). Clearly, additional age dates are needed for the volcanic rocks of Glen Township.

Structure

Rocks of the South Body are structurally complex as exemplified by structures and folds within the black, carbonaceous, sulfide-rich argillite. The folds are well-defined within this "greased" and easily deformed rock type. Structural deformation is also defined in the carbonaceous argillite by sulfides that appear to have plastically flowed into dilatant zones to form semi-massive to massive sulfide zones up to 10 cm thick. The quartz arenite beds, which represent more competent rocks within the incompetent carbonaceous argillite, define folds and are present in a variety of features that include boudinages, patches, stringers, irregular beds, and lensoidal flaser-like beds. Quartz veins are present in many of the rock units, and when present, the veins are often boudinaged and/or folded. Cross-sectional relationships (Figs. 11 and 12) indicate that the South Body is situated on the crest of an anticline, which explains the amount of deformation recorded in the carbonaceous argillite unit.

Sulfide Mineralization

Sulfides are present in many of the rock types, but they are the most prolific within the carbonaceous argillite sequence. The sulfides consist of pyrrhotite, pyrite, and marcasite (Thiel, 1924). Pyrrhotite, which is the most dominant, generally occurs as fine-grained masses that exhibit plastic deformation to varying degrees. Pyrite appears to be late, as it is present as fine to coarse-grained cubes within structurally deformed rocks. In general, the amount of sulfides decrease downward within the carbonaceous argillite unit from 5-50% (visual estimate) in the upper portion to 5-10% in the lower-most portion. This relationship is also born out by the sulfur analyses; a maximum of 31% sulfur is present in drill hole 37 at 80-85 feet. The upper portion of the carbonaceous argillite unit contains a sulfur percentage in the upper teens to lower twenties which gradually decreases to around 10% sulfur in the bottom of the unit. Semi-massive to massive sulfide zones are present in most of the holes, but they are the most common, and generally thicker, in at least three holes (39, 50, and 52).

An interoffice Hanna memo (see Severson and Heine, 2003) states that pyrite appears to be early and late (replaces other sulfides). Some pyrrhotite replaces early pyrite, and in turn, is cross-cut by chalcopyrite veins, and in one case sphalerite(?). All of these observations are reminiscent of an "overcooked" volcanogenic massive sulfide; wherein, the order of sulfide replacement suggests that copper and zinc were leached and vented/deposited elsewhere (Severson and Heine, 2003).

Zinc Assays

In regards to zinc mineralization, very few of the South Body holes were ever analyzed for zinc, except for scattered analyses conducted during the 1980s. Out of this limited data set, only seven holes contain zinc values in excess of 1,000 ppm (see Appendix 2 - *basinchemco.xls*). These

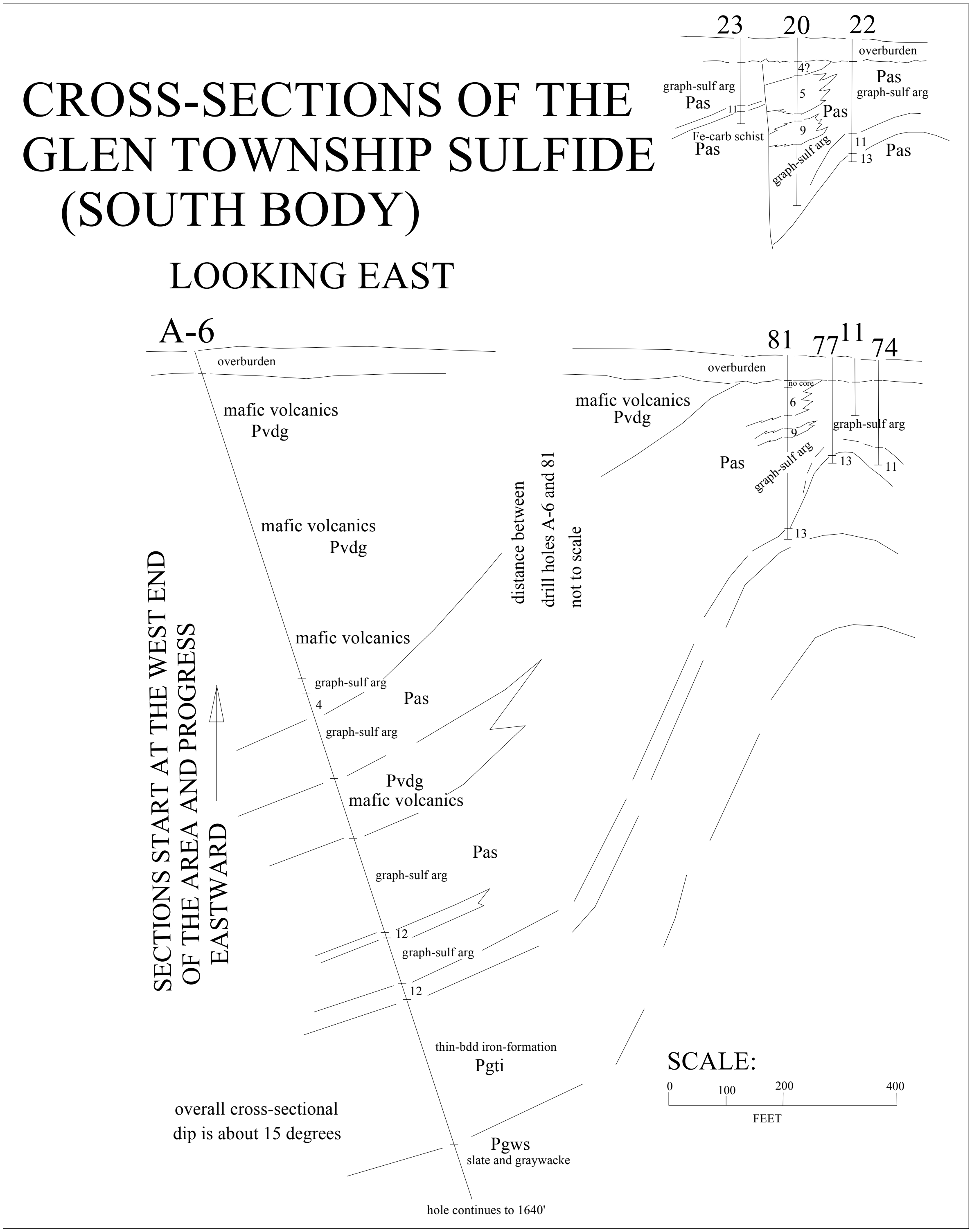

Figure 11 - Two cross-sections (looking east) that illustrate the overall geologic relationships of units at the Glen Township Sulfide - South Body. See Plate I for location of drill holes.

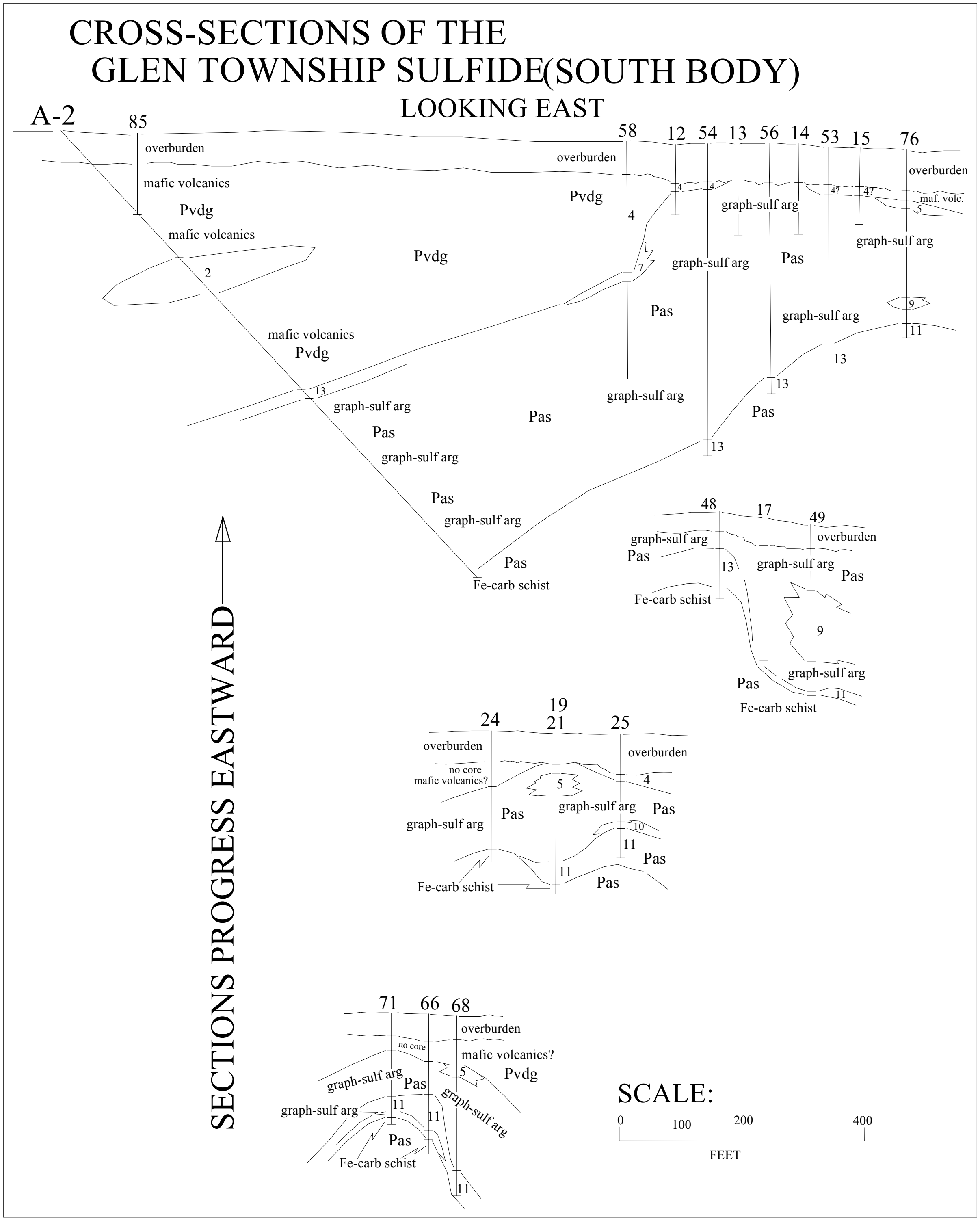

Figure 12 - Four cross-sections (looking east) that illustrate the overall geologic relationships of units at the Glen Township Sulfide - South Body. See Plate I for location of drill holes.

holes are: A-6 (two intervals), 20 (maximum of 3,900 ppm in one interval), 30, 33 (three intervals), and 50. These anomalous values are associated with the carbonaceous, sulfide-rich argillite. Visible sphalerite, which is related to remobilization during deformation, was noted in a few holes that include 42, 46(?), 51, 52, 54, and 58. The best indication of SEDEX mineralization is present in drill hole 58 where delicately-bedded (distal?) sulfide-rich (10-35%) beds are present at 182-218 feet (subunit number 7 on Fig. 8). While this interval did not contain anomalous zinc values (sampled for this investigation), sphalerite is very common in polished thin section samples.

SEDEX Potential

Collectively, the holes with visible sphalerite, anomalous zinc values, and the delicate sulfide-rich beds of hole 58, are all crudely clustered in an area in the extreme northeast corner of Section 28, T.46N., R.25W. Using all of the available data, the best potential for SEDEX mineralization lies to the north and northeast of this clustering. Self potential surveys conducted by M.A. Hanna Company indicated that "The high crest at Glen was found north of the ore body..." (Zimmer, 1953, p. 2). The presence of tourmaline in drill hole A-6 is also suggestive of a potential SEDEX system.

GLEN TOWNSHIP SULFIDE - NORTH BODY

Introduction

Like the South Body, the North Body (Sections 14 and 15, T.46N., R.25W.) was also initially drilled by Berrigh Magoffin Jr. in 1922-23. The USBM drilled an additional twelve holes (BM-1 through BM-12 on Plate I) during 1950-51 to better define the iron and sulfur resources known to be present (Pennington and Davis, 1953). An estimated 13,766,000 crude tons of material averaging 13.9% S are calculated to be present at the North Body (Morey, 1972).

Geology

The stratigraphic section at the North Body is probably very similar to that defined at the South Body, as the two areas are continuations of the same geology as traced out by aeromagnetics and drilling (Plate I). Limited drilling at the North Body indicates that the carbonaceous sulfide-bearing argillite sequence (Pas unit) is overlain by a mafic volcanic sequence (Pvdg unit) of flows and sills. Beneath the carbonaceous argillite is a sequence of intimately interbedded Fe-carbonate-bearing metasediments (see Table 5 for microprobe analyses of the Fe-carbonate), pale-green siltstone, quartz arenite, argillite, and carbonaceous argillite - all of which are present at the base of the carbonaceous argillite unit at the South Body. Holes at the North Body were not drilled deep enough to confirm the presence of a "slaty" magnetic iron-formation, as is present at the South Body. However, thin-bedded, magnetic iron-formation is intersected within the carbonaceous argillite sequence in two holes that include BM-11 (70.5-85 feet) and BM-12 (150-160 feet). Another magnetite-bearing zone is intersected within the Fe-carbonate-bearing sequence in drill hole BM-3 (197-199 feet).

BM-7 144.2 ft. - three grains of magnesian siderite							
Weight %							
No.	**CaO**	**MgO**	**FeO**	**MnO**	**SrO**	**CO2**	**Total**
1	0.650	5.662	54.529	0.108	0	39.052	100.001
2	0.666	5.759	54.476	0.051	0	39.048	100.000
3	0.722	5.785	53.312	0.094	0	40.087	100.000
Cation, O = 12.0							
No.	**Ca**	**Mg**	**Fe**	**Mn**	**Sr**	**C**	**Total**
1	0.0517	0.6272	3.3891	0.0068	0	3.9626	8.0374
2	0.0530	0.6377	3.3846	0.0032	0	3.9607	8.0392
3	0.0567	0.6328	3.2718	0.0058	0	4.0164	7.9835

Note: CO2% determined by difference (remainder of 100% - major cations%)

Table 5 - Microprobe analyses of three grains of Fe-carbonate (magnesium siderite) from "Fe-carbonate-bearing interbeds" at the base of the sulfide-bearing carbonaceous argillite at the Glen Township Sulfide - North Body, Aitkin County, Minnesota. Sample collected from drill hole BM-7 at 144.2 feet.

Structure

Deformation of rocks at the North Body is substantially less than at the South Body. Dips of bedding in core are generally shallow (10-40°), and folds only become evident with depth in four drill holes. Cross-sectional relationships indicate that the carbonaceous sequence dips to the south at 12° (Fig. 13a) to 50° (Fig. 13b). Intersection of the stratigraphic sequence in holes BM-11 and BM-12, is inferred to be a repetition that is related to a fault, as is shown in Fig. 13b. Boerboom et al. (1999b) interpret the BM-11 and BM-12 intersections to represent a different lensoidal stratigraphic sequence, and not related to faulting.

Sulfide Mineralization

Sulfides are present in less quantities at the North Body than at the South Body. There are generally <5% sulfides (visual estimate) in the holes at the North Body, but locally present are maximum sulfide values of 10-15% that are associated with folded and/or brecciated zones. Sulfur contents are generally the highest at the top of carbonaceous unit and decrease with depth. Maximum sulfur content is 19.5%. The overall lack of sulfides at the North Body, relative to the South Body, may be a function of either: 1) differences in the original deposition environment (euxinic third order basins?); and/or 2) differences in degree of deformation - the sulfides were not as "actively" concentrated in dilatant zones during limited folding at the North Body. The principal ore minerals

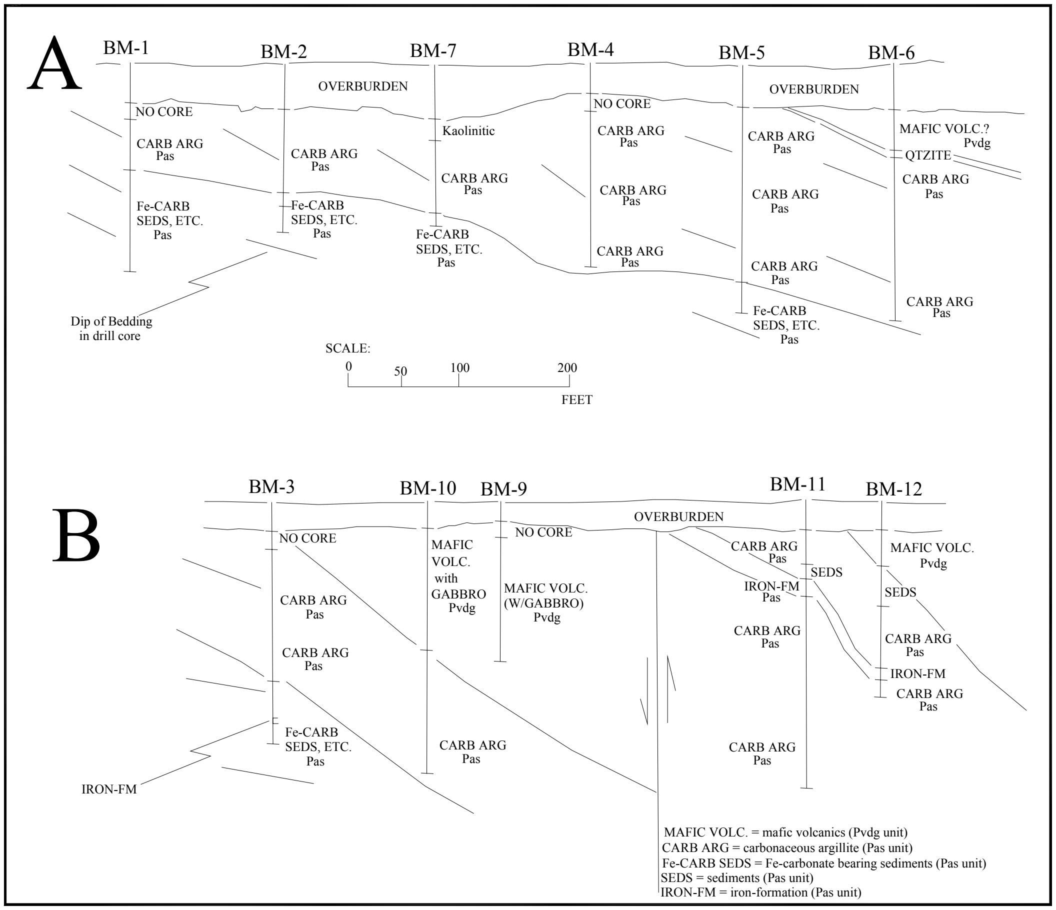

Figure 13 - (A) Cross-section (looking east) showing geologic relationships at the Glen Township Sulfide - North Body. (B) Cross-section (looking east) showing geologic relationships at the Glen Township Sulfide - North Body. See Plate I for drill hole locations.

are pyrrhotite and pyrite with subordinate amounts of magnetite and marcasite (Han, 1968). Present in minor quantities are sphalerite, chalcopyrite, arsenopyrite, ilmenite, covellite, hematite, and goethite (Han, 1968). Although all of the sulfides are metamorphosed, Han (1968) noted that there are four generations of pyrite, two generations of marcasite, and three generations of magnetite.

Zinc Assays

Only thirty-one samples from the core of the North Body were run for zinc analyses. Out of this data set, the highest value is 694 ppm zinc. Two anomalous zinc values (>1,000 ppm) are present in drill hole G-1, which is located about one mile to the west of the North Body (Plate I).

DAM LAKE AREA

Introduction

Near the shore of Dam Lake are two areas of outcrop and test pits of a massive to thick-bedded quartzite that has been informally referred to as the Dam Lake quartzite (Pq unit). In 1902, C.K. Leith proposed that the quartzite may be related to the Pokegama Quartzite of the Mesabi Range to the north, and thus, a Biwabik Iron Formation equivalent should be present in the vicinity of Dam Lake (Zapffe, 1949). Weak and spotty magnetic highs also seemingly supported this concept. However, drilling in the early 1900s, by the Oliver Iron Mining Company (USS), Jamison and Peacock (or Crosby Exploration Company), and other individuals, failed to intersect any iron-formation in 39 shallow drill holes (Zapffe, 1949). Most of these holes were drilled to the south of the quartzite outcrops in Sections 3 and 4 (Fig. 14). Additional drilling was conducted in 1950 to the north of the outcrop area by W.S. Moore Co.(?) in Section 34, T.47N., R.25W (holes DL-1 through DL-4).

Geology

Out of a possible 43 drill holes (Fig. 14), core are only preserved for the DL-series drill holes, and even these holes consist of skeletonized core. Rocks encountered in all of the holes are reported to consist of quartzite, and variably-colored sericitic schist, with locally up to 10% magnetite. The outcrops are reported to be quartzite with no bedding features.

SOUTH RANGE OF THE CUYUNA DISTRICT - AITKIN COUNTY

Introduction

As early as 1882, serious attempts at exploration for iron-formation took place in central Minnesota. In 1904, Cuyler Adams spotted the first hole that was drilled into iron-formation near Rabbit Lake in Crow Wing County. This "find" eventually lead to the drilling of thousands of holes into the iron-formations of what became known as the Cuyuna District (Cuyler Adams coined the name by combining the first syllable of Cuyler with the name of his dog - Una). Traditionally, the Cuyuna District has been broken into three subdistricts or ranges - the North Range, the South Range and the Emily District. Only the South Range extends into Aitkin County (Fig. 15). The South Range consists of several northeast-trending lenses of iron-formation that are present along a strike-length of some 65 miles extending from Randall, MN, in Crow Wing County, to within about 6 miles south of Palisade, MN, in Aitkin County. Although exploratory drilling was intense along the South Range, very little ore was ever mined; whereas, the North Range had many producing mines.

Until the 1980s, rocks of both the North and South Ranges were considered to be time synchronous (Morey, 1983). The constant reappearance of a single iron-formation in many localities was inferred to be related to a highly-folded nature. This concept was challenged by Southwick et al. (1988), and the North and South Ranges were interpreted to be within two different structurally-

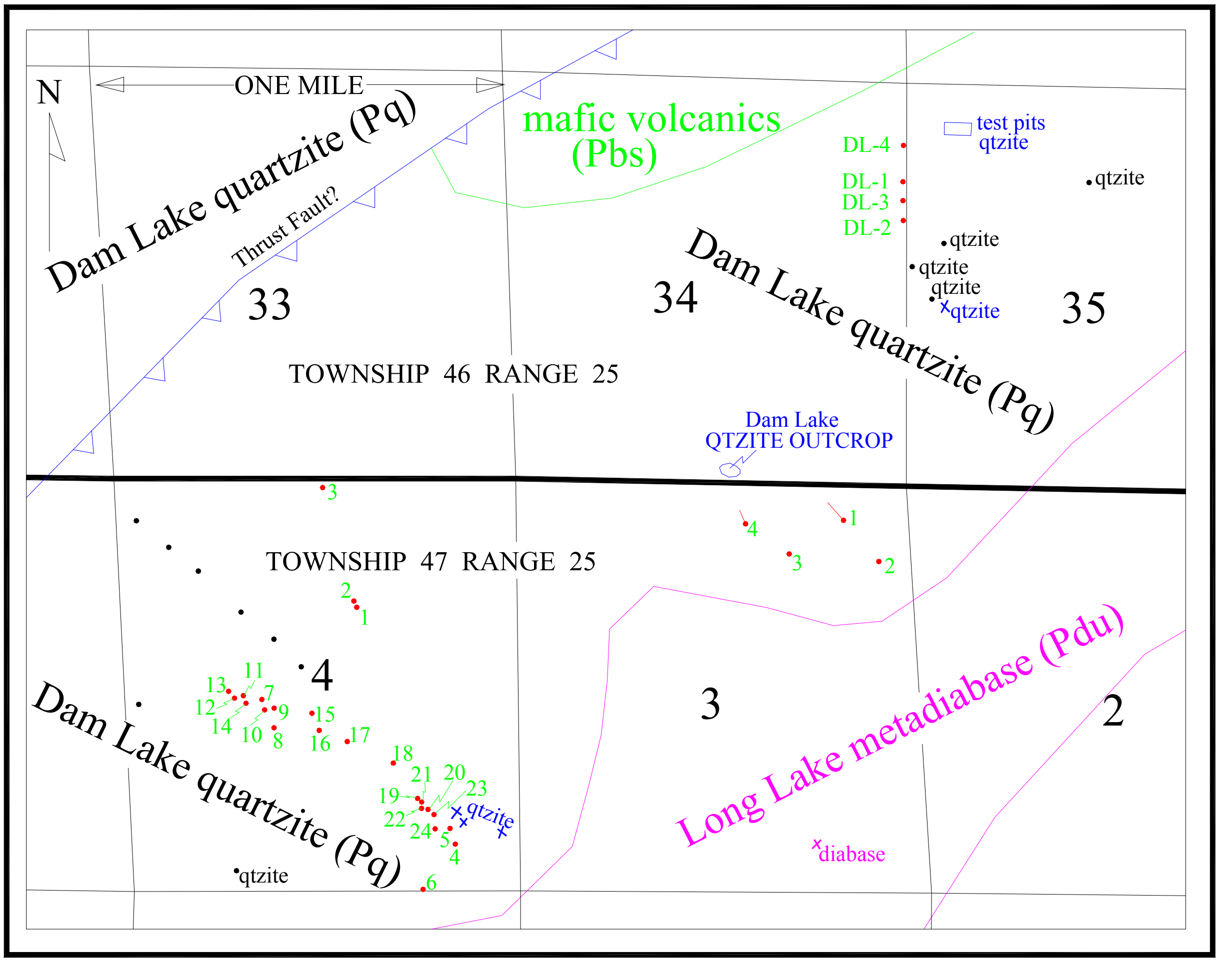

Figure 14 - Locations of drill holes, outcrops (x), and test pits in the Dam Lake area, Aitkin County, Minnesota. Drill hole numbers are known for the USS holes (Section 4), Crosby Exploration Company holes (Section 3), and W.S. Moore holes (DL-series holes).

separated panels within the Fold-and-Thrust Belt. Even though the rocks of both panels are somewhat similar, there are also fundamental differences that suggest that they are not correlative. One major difference is that mafic volcanic rocks (Pvm unit) are commonly associated with the iron-formations of the South Range. Another difference is the lensoidal nature of the iron-formations of the South Range. These differences in the South Range suggested that "The rather large number of places where iron-formation lenses terminate within a stratigraphic sequence of green metavolcanic rocks and black carbonaceous slate (Morey and Morey, 1986) suggests to us that the deposition of iron-formation was closely allied with volcanic activity ... specific to small basins of accumulation. In some respects the stratigraphic setting resembles that of the so-called Algoma-type iron-formations..." (Southwick et al., 1988, p. 14).

Geology

Within Aitkin County, at least 524 holes were drilled into rocks of the South Range. Most of these holes were drilled in an area that was referred to as the Rice River District (see below description). Excluding the Rice River District, 159 holes were put down into the South Range in Aitkin County. Out of this data set, there are only seven holes that have preserved core in Aitkin County (Fig. 15). A breakdown of rock types in these holes is as follows:

- Mafic volcanic rocks (Pvm unit) are intersected in four holes (S-225, S-240, S-247, and S-257). The volcanics occur above the iron-formation, and are characterized by massive, green, chloritic, variably-weathered metabasalt.
- Iron-formation (Psri unit) is intersected and preserved in only two core holes (S-208 and S-247).
- Footwall metasedimentary rocks (Psa unit) are present in MGS hole AB-25.
- Hanging wall carbonaceous metasediments (Pgvi unit) are present in MGS hole AB-27.

Descriptions of the iron-formation and metasedimentary rocks are presented in the next section pertaining to the Rice River District.

SOUTH RANGE - RICE RIVER DISTRICT

Introduction

The Rice River District is situated at the extreme northeast end of the South Range (Figs. 2 and 15). This area was extensively drilled for oxidized iron-formation and at least 365 holes are known to have been drilled in the area (Plate II). Most of the drilling was conducted by M.A. Hanna Company in the late 1940s and early 1950s. These holes are often preserved as both cuttings and/or skeletonized core (S-series holes). Out of this group, core is preserved for 162 holes, all of which have been looked at for this investigation (10,590 feet of skeletonized core). No mafic volcanic rocks are intersected in any of the Rice River holes; however, iron-formation and other metasedimentary rocks (both footwall and hanging wall to the iron-formation) are intersected in the holes. Locations of drill holes, and the distribution of rock types present in the collars of the holes, are shown on Plate II.

Geology

Three main geological units are intersected in drill hole at the Rice River District of the South Range. All are metasedimentary packages and consist of the following:

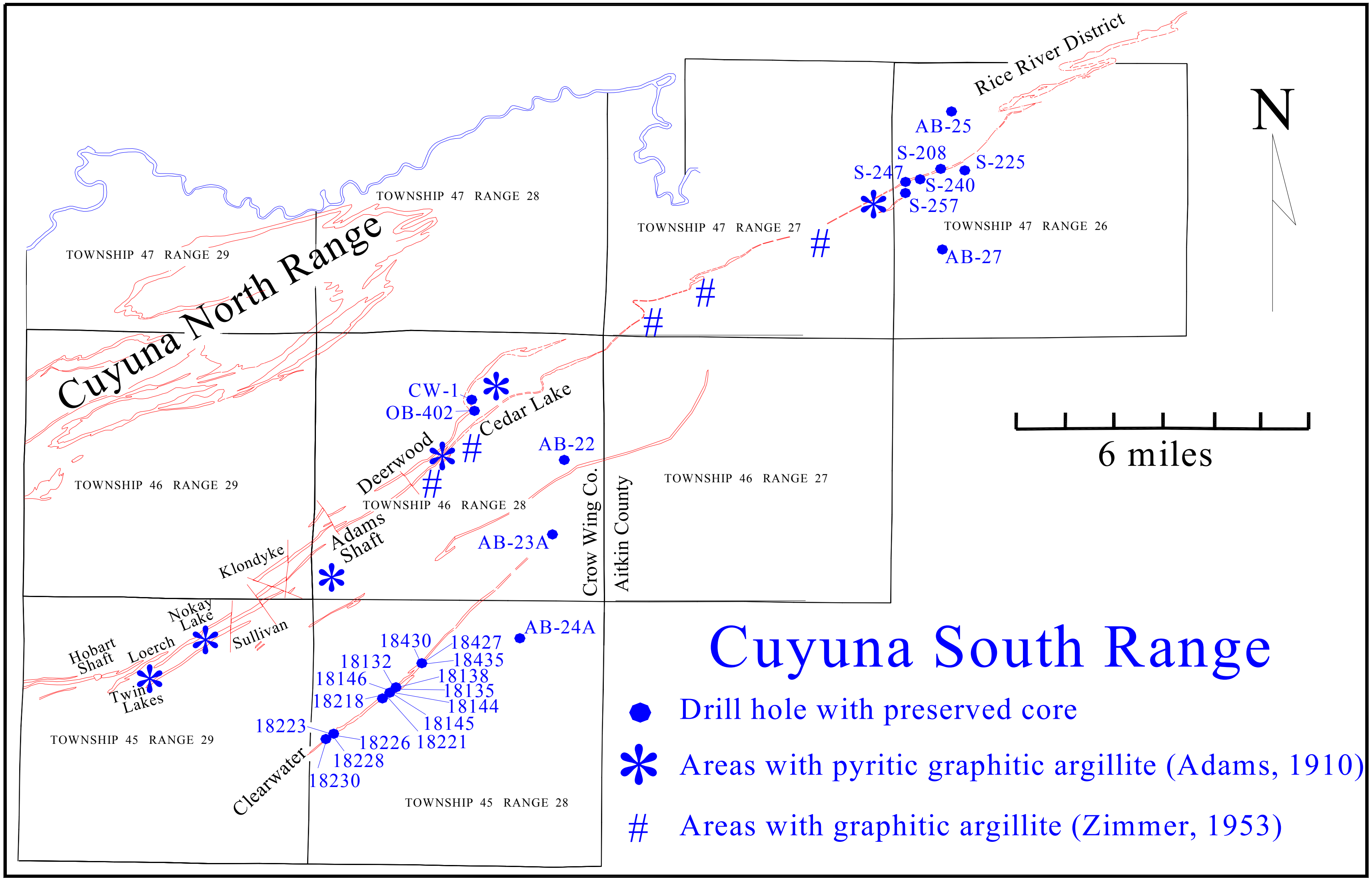

Figure 15 - Simplified geology of a portion of the Cuyuna South Range, showing trends of iron-formations in Aitkin and Crow Wing Counties. Drill holes with preserved core are shown on the figure; except for the Rice River District where numerous cores are available (see below discussion). Names of subareas along the iron-formation trend are from Zapffe (1949).

Footwall Metasedimentary Rocks (Psa unit) - Pelitic rocks beneath the iron-formation are intersected in 27 holes at Rice River. These footwall rocks are characterized by thinly-bedded, gray-colored, interbedded siltstone, mudstone, and weakly-graded, distal graywacke. Bedding is highly variable in drill core due to the presence of abundant folded zones that vary from a few inches to several feet across. The rock is moderately- to well-cleaved. The cleavage is axial planar to fold axes and locally exhibits some shearing and/or micro-faulting. The most highly sheared, brecciated (syn- to post-S_1), and micro-faulted zones are present in the vicinity of major anticlines and synclines (see inset - Plate II). The footwall rocks are often variably Fe-stained; especially when moderately weathered and/or in close proximity to the overlying iron-formation. A transitional contact into the overlying iron-formation is expressed by a 5-20 foot thick interval of non-magnetic, green- and gray-colored, argillaceous, silicate facies iron-formation.

Thin-bedded Iron-formation (Psri unit) - The iron-formation intersected in most of the holes at Rice River is generally oxidized and characterized by mixtures of: thin-bedded limonitic rock, porous limonitic rock, thin-bedded sideritic rock, thin-bedded hematitic rock, hematitic “paint rock”, and highly broken-up oxidized zones. Unoxidized iron-formation is intersected in at least 16 holes. In these holes, the iron-formation is fine-grained and thin-bedded (0.5-15mm) with alternating green beds (Fe-silicates and Fe-carbonates), dark beds (magnetite), and lesser light-gray quartzose beds. A pervasive cleavage is not developed within these structurally more competent rocks. Chert beds are locally present and are less than 2-3 cm thick. The iron-formation is generally magnetic, but weakly-magnetic to non-magnetic zones are common at the base of the unit. Small-scale folds are not evident in the core, but weak variations in the bedding (<20°) within a single hole probably define larger-scale (tens of feet?) weakly undulating folds. In drill hole A-5, the iron-formation is about 210 feet thick and dips steeply (85°) to the south.

Hanging Wall Metasedimentary Rocks (Pgvi unit) - Rocks above the iron-formation are intersected in only eight core holes. All but one of these holes intersect very short intervals of variably weathered and Fe-stained slate and/or schist. Drill hole A-5, which is inclined at 45° to the south, is the exception and intersects about 500 feet of the hanging wall. In this drill hole, the rocks are characterized by well-cleaved and thin-bedded, carbonaceous slate, with common pyrite laminae (1-20 mm thick). Bedding (S_0) is highly variable (10-50° to the core axis) with locally preserved small folds with axial planar cleavage (S_1). A pervasive cleavage (S_1) is well-developed in these rocks (30-70° to the core axis). It is generally subparallel to S_0, but becomes sub-perpendicular to S_0 with depth in the hole. The pyrite bands appear to be coincident with S_0, but some remobilization of pyrite along S_1 or into small folds is also evident. Arsenopyrite was noted in one polished thin section sample taken from a pyritic band in drill hole A-5 at 1,006 feet. A thin siliceous tuff(?) bed was noted in the hanging wall rocks in drill hole S-39.

Structure

The configuration of the iron-formation in Plate II defines several northeast-trending anticlines and synclines with shallow plunges to the east. The distribution of bedding plane dips seen in drill core are shown in the top half of Plate II. Dips within the iron-formation are generally 50-90° to the south, except in fold noses where the bedding plane dips are both subvertical and subhorizontal (10-45°). A penetrative cleavage (S_1) is best developed in the footwall and hanging wall rocks, and is generally near vertical (60-88°). The stratigraphic package in the Rice River District appears to be south-facing. Topping directions are present within the footwall rocks in some core holes, but these are generally in highly folded zones and are not very instructive. In holes that exhibit shallow bedding plane dips, the stratigraphic sequence suggests that pelitic rocks are footwall to the iron-formation, and carbonaceous argillitic rocks are hanging wall to the iron-formation. All three of these rock units are intersected in a hole (A-5), which was drilled by the MDNR in 1984-85.

Sulfide Mineralization

Pyrite bands are common within the hanging wall carbonaceous slate unit. Arsenopyrite was noted in a pyrite band in drill hole A-5 at 1,006 feet. Late quartz veins (± pyrite and/or chalcopyrite) and late pyrite veins are present in a few of the core holes. A pyrite "seam" is reported in one of the holes that is preserved as cuttings. The distribution of these veins (and seam) are portrayed on the small inset map within Plate III.

Zinc Assays

Zinc analyses were conducted on only about 150 samples collected from various holes in the Rice River District. Mildly anomalous zinc values (550–2,800 ppm Zn) are present in drill hole A-5 (817-827 feet) at a transition zone between iron-formation and the overlying carbonaceous slate. Within this zone, chert and slate are interbedded, and the chert bands appear to be boudinaged while the slate appears to have flowed around, and into, the chert bands (soft-sediment deformation?).

SOUTH RANGE - PORTAGE LAKE BELT

Exploration for iron-formation took place along a northeast-trending magnetic high that was indicated by dip needle surveys, in the Portage Lake belt (Zapffe, 1949). This belt, the Portage Lake Belt (Figs. 15 and 16), is located in Section 1, T.47N., R.25W. and Section 6, T.47N., R.24W. Jamison and Peacock of Duluth, MN, (also referred to as the Crow Wing Land Company or Crosby Exploration Company) drilled 36 holes in 1912-13. The holes are reported to have intersected mostly iron-formation (South Range type?) along with lesser amounts of lean ore, ferruginous slate, variably-colored slate, siliceous slate, iron-carbonate, and sulfide-bearing slate (Zapffe, 1949; and files in the Hanna collection at the MDNR). Cuttings for 20 of the holes are stored at the MDNR. In 1914, the Quinnesec Mining Company drilled four holes at the northeast end of the Portage Lake Belt in Section 33, T.48N., R.24W. Iron-formation ("iron and schist") is reported to be present in the holes (Zapffe, 1949), but no core or cuttings are available for inspection.

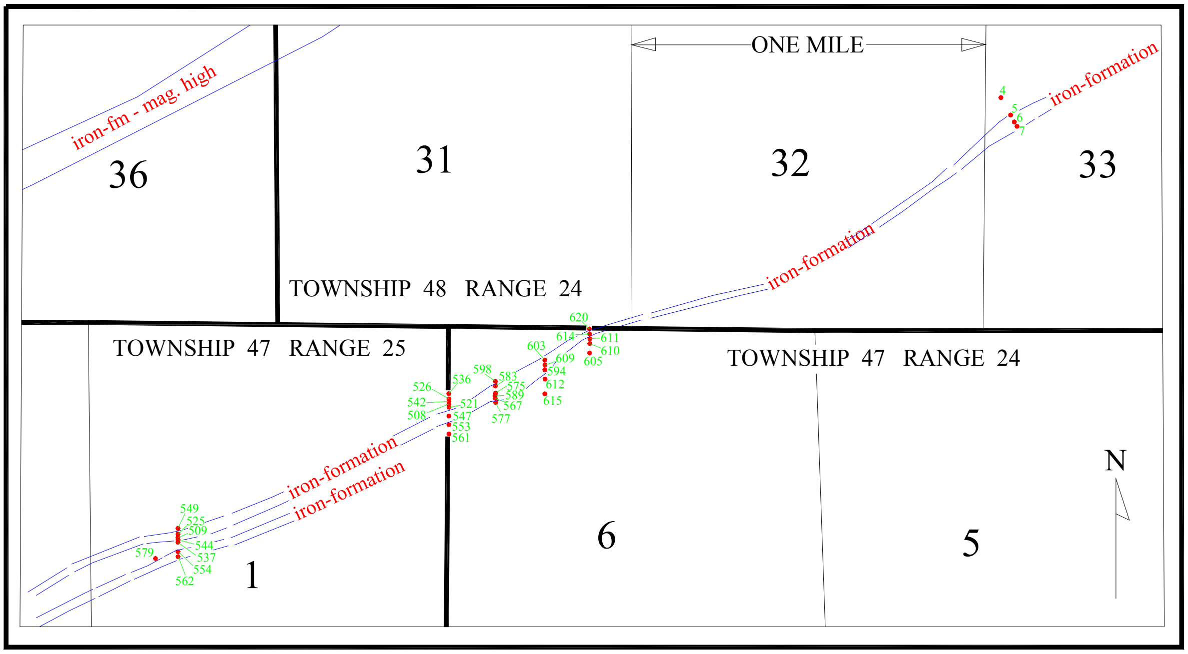

Figure 16 - Locations of drill holes (only cuttings preserved) in the Portage Lake Belt, Aitkin County, Minnesota. "Black pyritic slate" is reported (Zapffe, 1949) to be present in three holes: 536, 576, and 598.

SOUTH RANGE - KIMBERLY BELT

Dip needle surveys in Section 11, T.47N., R.25W. (Fig. 15), indicated a northeast-trending magnetic high. Three holes were drilled in the area in 1909 by Jamison and Peacock of Duluth, MN (Zapffe, 1949). "Greenish crystalline slates," interpreted by Zapffe (1949) to represent unoxidized carbonate iron-formation (South Range type?) were intersected in the holes (no core or cuttings preserved).

ANIMIKIE BASIN RECONNAISSANCE HOLES

Introduction

Approximately 170 holes have been drilled into metasedimentary rocks of the Animikie Basin, since the early 1900s, in search of an equivalent Mesabi Range iron-formation. These holes were drilled in specific areas (Fig. 17), often associated with magnetic highs, and are discussed below.

Great Northern Holes (GN-series)

Discovery of quartzite outcrops at Dam Lake (see above Dam Lake discussion) prompted some exploration for a Mesabi Range iron-formation equivalent along the southern edge of the Animikie Basin in Aitkin County. Based on this premise, H.J. Kruse persuaded Great Northern Iron Ore Properties to drill 20 scattered reconnaissance holes (GN-series holes) in northern Aitkin County in 1929 (Zapffe, 1949). Skeletonized core, along with cuttings, are preserved for 18 of the holes and were looked at for this investigation (Fig. 17). Locations of the drill holes are shown on the ArcView map submitted with this report; brief geologic logs are included in Appendix 2 (*basinholeco.xls* data base on CD in back pocket). Rocks intersected in these holes consists of an unknown amount of Cretaceous material and/or regolith overlying cleaved and well-bedded metasedimentary rocks of the Thomson Formation (slate with minor graywacke). Iron-formation, with up to 25% Fe, was reported to be present in one of the holes (GN-16), but a review of the preserved cuttings and core pieces indicates that hematitic cuttings are prevalent (Cretaceous and/or regolith?) along with minor core pieces of gray-colored slate.

Scallon-Todd area

<u>Introduction</u>

The Scallon-Todd area, located in Sections 23 and 27, T. 48N. R.27W. (Fig. 17), is apparently situated at the southern edge of the Animikie Basin. To the immediate southwest of this area are prominent northeast-trending aeromagnetic highs that probably correspond to rocks of the North Range Group (Southwick et al., 1988). However, in the Scallon-Todd area, and continuing for several miles toward the northeast, this same magnetic high becomes more subdued. This relationship suggests that the subdued magnetic high is caused by older rocks of the North Range Group that are overlain by younger Animikie Basin rocks.

In 1915, this same magnetic high was traced by dip-needle surveys, over a distance of 15-20 miles, into the Scallon-Todd area (Zapffe, 1949). Coincidently, George S. Carson had previously drilled (1913-14) ten holes into this area in Section 23, solely as a matter of attempting to discover what mineral value was present beneath the glacial cover of his property (Zapffe, 1949). Manganese values in the holes were exceptionally high (9-25%), but iron values were not particularly significant (<25%). In 1916-17, the Crosby Exploration Company became interested in the property and drilled an additional 35 holes (1,000-series holes in Fig. 18). Similar high manganese values were encountered in the holes and crude tonnage estimates indicated that 3.4 Mt of material averaging 19.4% Fe and 11.13% Mn were present (Zapffe, 1949). Because the manganese was so high, M.A. Hanna Mining Company drilled an additional five holes (S-100 through S-104 in Fig. 18) in 1949. Their manganese values were much lower (average of about 4% with maximum values up to 12%), and Hanna abandoned the project.

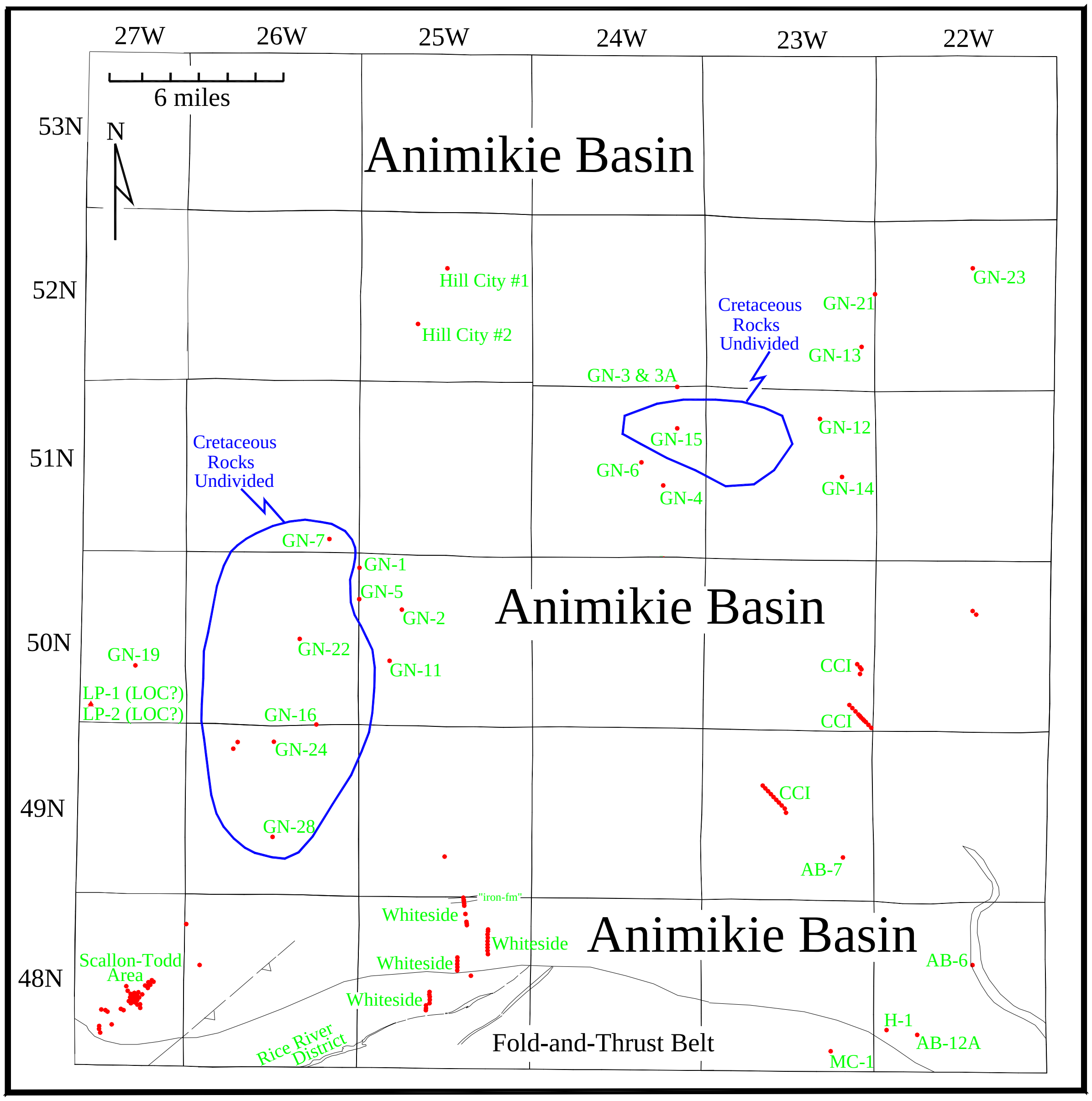

Figure 17 - Distribution of exploration drill holes into the Animikie Basin in the northern portion of Aitkin County, Minnesota. GN-series holes were drilled by Great Northern Iron Ore Properties. Several drill hole traverses across various Sections were drilled by Cleveland-Cliffs Iron Company (CCI) and by R.B. Whiteside. The scattered unlabeled holes in this figure represent exploration holes for which little information is available.

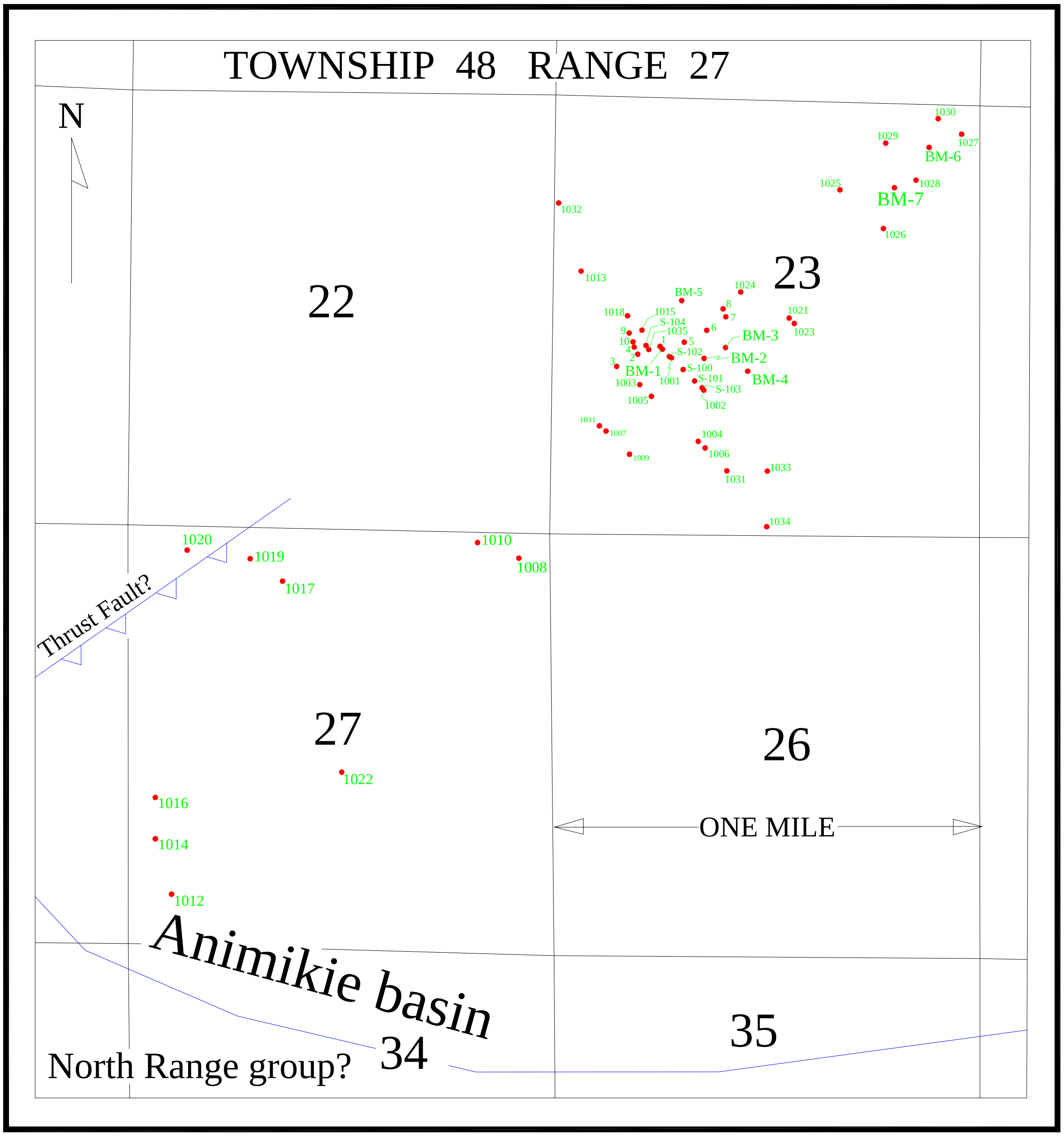

Figure 18 - Locations of known drill holes in the Scallon-Todd area, Animikie Basin, Aitkin County, Minnesota.

The USBM became aware of the Scallon-Todd area and the high manganese values, including the much lower Hanna values, while conducting a compilation of manganese resources for the nearby Cuyuna District (Grosh et al., 1953). In order to obtain material for check analyses and beneficiation tests, the USBM drilled a test hole (BM-1) in the spring of 1950, followed by continued drilling of another six holes in the fall of 1950 (BM-2 through BM-7; Fig. 18). The core was analyzed and found to contain an average of about 3% Mn with isolated extremely high values of 10-21% Mn. These values substantiated the results previously obtained by Hanna. The USBM concluded that a substantial tonnage of low-grade manganese material is present at the Scallon-Todd area (Grosh et al., 1953).

Geology

Out of the 57 holes that were drilled at the Scallon-Todd area (Fig. 18), drill core is only preserved for the seven USBM holes. All of these holes were looked at for this investigation (BM-1 through BM-7). Rocks intersected in the holes consist of soft, clay-rich, reddish, hematitic, thin-bedded (<1 cm) argillite that appears to be a highly weathered/altered equivalent of the Virginia and Thomson Formations (Pvt unit). Bedding planes are planar and dips are constant throughout each individual drill hole. No small-scale folds are apparent in the core. However, there are two trends in the dips of bedding that include: 20-40° dips in BM-1, BM-3, and BM-4; and 40-60° dips in the remaining four holes. These broad variations in dip probably reflect broad, large-scale folds. A near vertical pervasive cleavage is only evident in one hole (BM-4). Thin chert interbeds, 1-6 inches thick, are intersected in BM-6 and BM-7.

The clay-rich nature of the core, if related to weathering and/or alteration, persists down to depths of 180-220 feet beneath the glacial and/or Cretaceous(?) cover. This weathering/alteration gradually diminishes with depth in most of the holes, except BM-1 and BM-3. Only one hole out of the group (BM-2) was drilled deep enough to intersect "fresh" gray argillite at depth.

Manganese mineralization

Most of the manganese in these holes consists of hard, impure psilomelane associated with vuggy zones that cross-cut bedding in the highly weathered/altered material. Manganese contents are generally much higher in the altered material, with spotty values as high as 21%; whereas, manganese contents in excess of 2.5% are rare in the less altered material at depth. The origin of the manganese in these rock is clearly-related to a post-sedimentation process, but the details are unknown. Perhaps the manganese was concentrated during intense and deep weathering of the rocks during the Cretaceous period. Alternatively, high concentrations of manganese in the iron-formations of the Emily District, located within 6 miles west of the Scallon-Todd area, have been inferred to be related to a reflux remobilization event (Morey and Southwick, 1993). A similar mechanism may be responsible for the manganese concentrations at Scallon-Todd. According to the reflux model of Morey and Southwick (1993), anaerobic ground waters dissolved manganese from the iron-formations of the North Range during the Paleoproterozoic, which then migrated northward into the Animikie Basin. As the ground water moved into the basin, it reprecipitated manganese at or very close to the sediment-water interface when the anaerobic solutions encountered oxidizing conditions. The model further suggests that the precipitation of manganese took place in more porous zones of the final host rock, where both anaerobic and aerobic solutions would meet and commingle.

Cleveland-Cliff Holes

In 1914, Cleveland-Cliffs Iron Company drilled three series of holes in northwest-trending traverses (Fig. 17) across Section 16, T.49N., R.23W. (ten holes) and across Sections 24 (four holes) and 36 (eleven holes), T.50N., R.23W. The holes intersect metasedimentary rocks of the Thomson Formation (Pvt unit). Core for these holes is preserved in Ishpeming, MI, but were not looked at for this investigation.

Whiteside Holes

In 1912, R.B. Whiteside drilled several series of drill hole traverses (Fig. 17) across Sections 3, 11, and 15, T.48N., R.25W. (12 holes, 17 holes, and 10 holes, respectively). Another drilling traverse was conducted across rock of the Fold-and-Thrust Belt in Section 21, T.48N., R.25W. (Fig. 17 - 11 holes). No core or cuttings are preserved for any of these holes. Drill records in the Hanna collection at the MDNR indicate that "red schist and paint rock" (regolith?) were commonly encountered along with slate in all of the drilled traverses. The four northern-most holes that were put down in Section 3 are reported to have intersected "jasper, ore, and lean ore."

Recent Holes

Recent reconnaissance holes drilled within, or to the immediate south of, the Animikie Basin (Fig. 17) include H-1, AB-7, AB-12A, and AB-6 (the AB-series holes were drilled by the Minnesota Geological Survey for mapping purposes). Core for these holes are preserved at the MDNR. Drill hole AB-6 intersected a Keweenawan intrusive (peridotite), which has since been drilled (3+ holes) by Kennecott Mining Company. The remainder of the reconnaissance holes intersected moderately-cleaved, weakly-deformed, thin-bedded, argillite, and graphitic argillite. A well-developed cleavage, which overprints original bedding, is present in hole AB-12A. Drill hole MC-1 reportedly intersected a mafic volcanic unit within a metasedimentary rock package (core not available for inspection).

Miscellaneous Holes

Fourteen miscellaneous holes (see Appendix 1 - *basinholesco.xls* data base) were drilled in scattered locations throughout the Animikie Basin in Aitkin County (Fig. 17). Records for most of these drill holes are meager, and for the most part, only the location of the holes are known. Core are only preserved for holes in the Little Pine area (LP-series holes in Section 33, T.50N., R.27W.) and Hill City area (two holes in Sections 15 and 20, T.52N., R.25W. - core stored at the Minnesota Geological Survey).

THE ANIMIKIE BASIN AND FOLD-AND-THRUST BELT IN CROW WING COUNTY, MINNESOTA

INTRODUCTION

After the initial discovery of iron-formation in the Cuyuna District, in 1904 by Cuyler Adams, literally thousands of holes were drilled in Crow Wing County in attempts to trace out the various iron-formation horizons. This drilling was also conducted to: 1) locate oxidized ore zones in the magnetic iron-formation; and 2) extend the limits of producing mines. Mining of the iron ore, some with appreciable amounts of manganese, took place from 1911 to 1984 when over 106 million tons of ore (Skillings, 1998, Minnesota Mining Directory) were shipped from the Cuyuna District. The Cuyuna District has traditionally been divided into two to three smaller districts in Crow Wing County that include: the North Range; the South Range; and the Emily District (which is further subdivided in this report into the North Emily District and the South Emily District). These smaller districts are distinct geographic units (Fig. 2), and most importantly, they each contain distinctly different stratigraphic rock packages of presumably different ages. Extensive mining of iron ore took place in the North Range; whereas, only a few underground mines were operated in the South Range in the 1910s and 1920s (Morey, 1990). No mining took place in the Emily District. Locations for 1,016 drill holes within Crow Wing County, some with preserved core, were determined for this investigation (see Appendix 1 - *basinholesco.xls*). Geologic descriptions for each of the four districts within Crow Wing County are presented below.

SOUTH RANGE OF THE CUYUNA DISTRICT - CROW WING COUNTY

Introduction

Rocks of the South Range are distinct from the rocks of the other districts in Crow Wing County. As has been discussed previously, major differences adherent to the South Range are that the iron-formations are lensoidal and, in places, they are closely allied with volcanic rocks that are present as both flows and hypabyssal sills. However, the South Range is also similar to the other iron-formations of the Lake Superior region, in that carbonaceous argillite with pyrite-rich laminae is common to the rocks above the iron-formation (Adams, 1910; Severson and Heine, 2003).

Geology

Out of the hundreds of holes drilled in the South Range of Crow Wing County, only 23 holes are still preserved as core at the MDNR (Fig. 17). Out of this set, only nine holes were looked at for this investigation. The rocks in these holes consist of mafic volcanics, thin-bedded iron-formation, carbonaceous argillite, and argillite. Holes within the South Range that were not looked at for this investigation, include a reconnaissance hole drilled by the MDNR (OB-402), an exploratory hole drilled by the MDNR (CW-1); and some of the holes in the Clearwater Lake area (Fig. 17). Rocks within these holes consist of an interbedded package of variably-foliated and sheared metagabbro, iron-formation, and mafic fragmental rocks, with lesser amounts of graphitic schist, argillite, and chert (Boerboom, pers. comm., March, 1998).

Several close-spaced holes were drilled by USS (1951-52 and 1958) in the Clearwater Lake area of the South Range. The holes were put down in Sections 9, 17, and 19 in T.45N, R.28W. along an iron-formation that can be traced magnetically for at least six miles. Rocks intersected in the USS holes (Boerboom, pers. comm., March, 1998) consist of interbedded:

- thin-bedded silicate-oxide-carbonate iron-formation;
- oxidized ore and lean ore;
- variably foliated/sheared metagabbro and mafic flows;
- slate and argillite; and
- lesser amounts of graphitic-pyritic argillite.

NORTH RANGE OF THE CUYUNA DISTRICT

Introduction

During the period of 1911-1984, numerous mines were developed within the North Range of the Cuyuna District. Over 45 mines, both open pit and underground, shipped varying amounts of iron ore and manganiferous iron ore. Unfortunately, all of the mines are now inactive, have long since filled with water, and only a small amount of drill core exists for inspection. Thus a geologic description of the North Range is almost wholly dependant on previous reports and paper copies of drill logs. Only 438 holes, out of the thousands of holes that were drilled, are still preserved as core at the MDNR and MGS. Locations for these drill holes with core are portrayed in Plate III (note that UTM coordinates (NAD27) were determined for all but 84 of the core holes). All of the core holes, except for four holes at the MGS, were looked at for this investigation (21,380 feet of core and skeletonized core).

Geology

The geology of the North Range of the Cuyuna District (Fig. 2) was first described in detail by Harder and Johnston (1918). They believed that the iron-formations occurred as several lenses within an argillite sequence. Wolff (1919) correlated the North Range iron-formations with the four members of the Biwabik Iron Formation on the Mesabi Range to the north. Later work, by Grout and Wolff (1955) further stressed the Mesabi-Cuyuna Range connection. They conducted a drilling campaign in the North Range (four holes - stored at the MGS) to further define the four-fold division analogous to that on the Mesabi Range. However, Grout felt that “Attempts to correlate the formations in the three deep drill holes are not wholly satisfactory” (Grout and Wolff, 1955, p. 47), and “None of [the drilling] reached the Lower Cherty member as was hoped...” (Grout and Wolff, 1955, p. 52). Both authors reconciled these, and other, differences to a thickening of the iron-formation and remained optimistic that the four-fold division was present.

Schmidt (1963) conducted later detailed work in the area. He was doubtful of this division and stated “Specific correlations were made by Wolff without much regard to the structure and the changes in sedimentary facies in the district; then faults were inserted where the geology of the adjacent areas seemed incompatible” (Schmidt, 1963, p.8). Much of the following descriptions of the rock units present at the North Range are from Schmidt (1963). A generalized geologic map of the North Range is presented in Figure 19 and Plate III. The term “North range group” was suggested by Southwick et al. (1998) as an informal designation for the stratigraphy as described by Schmidt (1963).

Mahnomen Formation (Pm unit) - At the base of the North Range Group are metasedimentary rocks of the Mahnomen Formation. Schmidt (1963) roughly estimated that the Mahnomen Formation is at least 2,000 feet thick; the base of the formation has not yet been drilled. Rock types consist of sericitic argillite, slate, siltstone, and quartzite; schist and phyllite occur close to faulted or folded zones. Minor amounts of shale, graywacke, and limestone were also observed by Schmidt (1963). Quartzite is generally more common at the top of the Mahnomen Formation in the western part of the North Range (Schmidt, 1963).

Minor amounts of magnetite or martite octahedra are present within the Mahnomen Formation in some areas (Schmidt, 1963). Also present are lenses of ferruginous argillite and thin-bedded iron-formation. These rock units are responsible for localized, weak magnetic anomalies, many of which, were drilled for iron-formation. On the basis of aeromagnetic data, Southwick et al.(1988) divided the Mahnomen Formation into an upper more magnetic member and a lower, less magnetic member. This same division is also adopted in this investigation and by Boerboom et al.(1999a).

The Mahnomen Formation is preserved in at least 41 core holes from the North Range (see Plate III). The thickest intersections of this formation are in the Northland, North Hillcrest, and Merritt holes (stored at the MGS), and drill hole G-1 which was recently drilled by the USBM in the Gloria Mine area (Fig. 19). Rock types in these four holes consist of variably-foliated argillite and graywacke, with minor tuffaceous beds and amphibole-bearing volcaniclastic beds (McSwiggen et al., 1995). Both tourmaline-bearing beds and tourmalinites are associated with the Mahnomen in all four of these holes (McSwiggen et al., 1994, 1995; Cleland et al., 1996). Other holes that intersect the Mahnomen Formation include (see Severson and Heine, 2003 for a more detailed list):

- five holes into Fe-stained sandstone at the Millford Mine (Section 23, T.47N., R.29W.);
- 16 holes into quartzite with ore zones, and four holes into argillite, at the Merritt #2 Mine (Section 33, T.47N. R.29W.);
- three holes into schist (Section 22, T.47N., R.28W.);
- one hole (S-104) into sandstone (Section 23, T.47N., R29W.);
- four holes into schist (Section 36, T.47N., R.29W.);
- four holes into schist and metasedimentary rocks at the Section 6 Mine (T.46N. R.29W.)

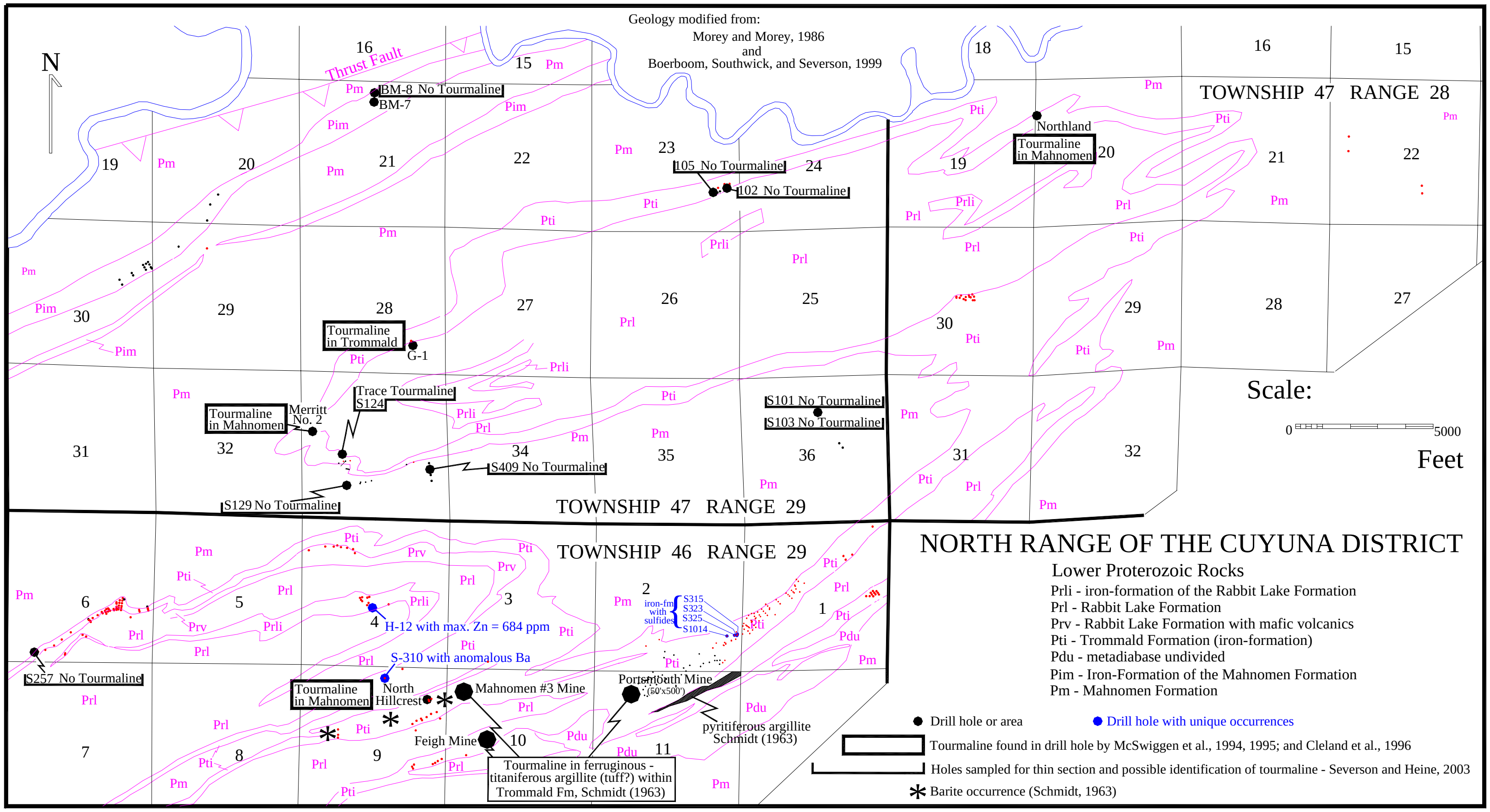

Figure 19 - Simplified geology of the Cuyuna North Range (after Morey and Morey, 1986; and Boerboom et al., 1999a) showing distribution of drill holes and areas with (and without) tourmaline, sulfide-bearing units, barite occurrences, and location of the maximum zinc value for the district (as defined by very limited sampling for zinc!). Locations of all drill holes with preserved core are indicated by very small dots.

Another group of core holes, which intersect an iron-formation member within the Mahnomen Formation, are also preserved as core at the MDNR. At least eleven holes were drilled by M.A. Hanna Co. (S-series holes), and another eight holes were drilled by the USBM (BM-series holes), in Sections 20, 21, 29, and 30, T.47N., R.29W. to the immediate northwest of the North Range (see Plate III and Fig. 19). The USBM holes were drilled to determine the manganese concentrations in an unoxidized iron-formation (Heising et al., 1959). Rocks of the Mahnomen Formation that are intersected in 18 of the holes consist of weakly oxidized to unoxidized, green to gray to black, thinly-foliated and/or thin-bedded, variably magnetic, silicate-carbonate-oxide iron-formation. Bedding (S_0) is generally overprinted by a pervasive cleavage (S_1) and is locally well-preserved in the noses of small folds. Other than the well-developed foliation that is imparted to the rocks, the iron-formation in this group of holes looks remarkably like the Trommald Formation. One of the USBM holes (BM-6) did not intersect iron-formation; rather, it intersected black, well-cleaved, argillaceous rock of the Mahnomen Formation.

<u>Trommald Formation (Pti unit)</u> - Most of the iron-ore ± manganese ore of the North Range was formed as a result of the alteration/oxidation of this iron-formation unit. Schmidt (1963) estimated that the Trommald Formation is 45-500 feet thick, and divided it into two major groups - a lower thin-bedded facies and an upper thick-bedded facies. Schmidt (1963) also noted that "The thick-bedded facies constitutes the entire Trommald Formation in part of the North range; the thin-bedded facies makes up the entire formation in another part; and in about a third of the North range, the thick-bedded facies overlies the thin-bedded facies ... and grades downward into it " (Schmidt, 1963, p. 20). "Where only the thick-bedded facies is present, the iron-formation is thinner ... The formation is thickest where only the thin-bedded ... facies was deposited" (Schmidt, 1963, p. 31).

The thin-bedded iron-formation is the dominant rock type preserved in drill core, and when unoxidized, it exhibits alternating ≤1 mm to 5 mm beds that vary from black to gray to green. The thin laminae are characterized by varying amounts of quartz, manganiferous siderite, dolomite-like carbonate, ferroan kutnahorite (McSwiggen et al., 1995), magnetite, hematite, stilpnomelane, chamosite, minnesotaite, and chlorite with localized amounts of grunerite and tourmaline (Schmidt, 1963; McSwiggen et al., 1995). Aegirine-bearing beds (sodic pyroxene) and tourmaline-bearing beds are also present (McSwiggen et al., 1995; Cleland et al., 1996). Chert beds are generally absent, but when present locally, vary from three inches to ten feet thick. Thin-bedded argillaceous beds are also locally present. In some areas, the argillaceous rocks have high titania contents (1-2%), and are thought to be a reworked volcanic ash (Schmidt, 1963).

Present at the top of the Trommald Formation is the thick-bedded facies. This facies is characterized by massive chert beds, with intermixed iron oxides and interbeds of more thin-bedded iron-formation. The massive chert beds vary from a few inches to six feet thick. Two bedding types were recognized by Schmidt (1963) within the thick-bedded facies - straight-bedded rock and wavy-bedded rock. Localized spheroidal features described as algal structures, oolites and oncolites (Schmidt, 1963), and/or micronodules of uncertain origin (McSwiggen et al., 1995), are present in the thick-bedded facies at the Merritt Mine (Section 33, T.47N., R.29W.) and the Maroco Mine (Section 4, T.46N., R.29W.).

Most of the drill core that is still preserved consists of various ore types (see descriptions in Schmidt, 1963), and variably-oxidized to unoxidized, thin-bedded iron-formation. The thick-bedded facies iron-formation is preserved in only sixteen holes, most of which, are in Section 5, T46N., R.29W. A complete stratigraphic section of the iron-formation is cut in the Merritt drill hole (at the MGS) and drill hole G-1. Disseminated syngenetic sulfides, associated with thin-bedded, unoxidized iron-formation, are preserved in at least four core holes (S-315, S-323, S-325, and S-1014; Fig. 19 and Plate III) from the northeast end of the Portsmouth Mine (Section 2, T.46N., R.29W.). A tourmaline-bearing zone is present near the base of the Trommald Formation in drill hole G-1 (Fig. 19 - McSwiggen et al., 1995; Cleland et al., 1996).

<u>Rabbit Lake Formation (Prl unit)</u> - Overlying the Trommald Formation are black to dark-gray, carbonaceous argillites and interbedded light-gray siltstone of the Rabbit Lake Formation. Pyrite is common within the carbonaceous rocks where it is present as thin laminae (generally <0.5 mm thick, but locally up to 1.0 cm thick) and as fillings in cross-cutting joints. Schmidt (1963) noted that there are several minor variations to the Rabbit Lake Formation that include: 1) tuffaceous rocks at the base of the formation with about 2.0% titania; 2) basalt flows near the base of the formation in the vicinity of the Section 6 Mine (T.46N., R.29W.) and Maroco Mine (Section 4, T.46N., R.29W.); 3) small lenses and thin beds of chert and ferruginous chert; and 4) iron-formations, up to several hundred feet thick, occur from 500 feet to 2,000 feet above the base of the formation. The iron-formations within the Rabbit Lake Formation are thin-bedded and siliceous with abundant interbedded argillaceous material (Schmidt, 1963) and scattered thin chert layers. They tend to be strongly oxidized (hematite and limonite), altered, and folded. The only known exposures of this type of iron-formation are within the now idle and water-filled Virginia Mine, and possibly in the Snowshoe Mine.

Core from the Rabbit Lake Formation are preserved in about 40 drill holes stored at the MDNR. Rocks intersected in the various holes are as follows:

- drill hole G-1 at the Gloria Mine - gray argillite and lesser phyllite;
- Merritt drill hole at the Merritt Mine (core stored at MGS) - gray argillite and lesser phyllite;
- seven S-series holes from Lot 9, Section 4, T.46N., R.29W. - gray argillite and lesser phyllite;
- five S-series holes (S-1018, -1019, -1031, -1045, -1047) from Section 10, T46N., R.29W - gray argillite and lesser phyllite;
- two holes (S-801 and S-804) from Section 9, T.46N., R.29W. - gray argillite and lesser phyllite;
- two holes (S-501 and S-502) from the Snowshoe Mine - gray argillite and lesser phyllite;
- drill hole S-257 from Section 6, T.46N., R.29W. - argillite with chert beds;
- four S-series holes (S-260, -261, -263, -266) from Section 6, T.46N., R.29W. - iron-formation within the Rabbit Lake Formation;
- six S-series holes (S-13, -15, -16, -17, -19, -20, -21) - iron-formation within the Rabbit Lake Formation;

- twelve H-series holes (H-2, -3, -4, -5, -6, -12, -15, -17, -18, -19, -20, -21) from Section 4, T.46N., R.29W. - iron-formation within the Rabbit Lake Formation;
- two holes (S-205 and S-247) from the Section 6 Mine - massive mafic flows (Prv unit).

Chlorite Schist - Though not a particular formation within the North Range Group, chloritic schists are commonly scattered throughout the Mahnomen and Trommald formations. On the map of Morey and Morey (1986), the chloritic schists are grouped with "igneous rocks of generally dioritic to gabbroic composition ... that occur as dikes and sills." Chlorite schist that is intersected in drill hole and preserved as core is present in at least six holes that include: S-286, S-346, and S-347 from the Section 6 Mine (Prv unit); and S-213, S-214, and S-216 from the Portsmouth Mine (Pdu unit).

Structure

Throughout the North Range, folding of the rocks is clearly evident at all scales that include folds in drill core, folds in pit faces, and folds at the map scale (see Plate III and Fig. 19). At least four major synclines and one anticline were recognized in the North Range by Schmidt (1963). Drag folds near the axes of major folds were also observed. "Structurally the North range is a complex synclinorium that is inclined toward the northwest (axial surfaces dip southeast) and is doubly plunging on a regional scale (Schmidt, 1963)" (Southwick et al., 1988, p. 10). The North Range Group is inferred to have accumulated in fault-bound basins that formed during a period of rifting, or during a "rift stage" (Morey, 1996). Evidence for this interpretation are indications of extensive hydrothermal fumarolic activity noted by McSwiggen et al. (1994, 1995) and Cleland et al. (1996). The Menominee Group, including the Negaunee Iron-Formation, in the upper peninsula of Michigan is also inferred to have been deposited in a similar tectonic setting (Morey, 1996).

Tourmaline-Bearing Rocks

Indications of a potential SEDEX depositional environment in the North Range was first noted by McSwiggen et al. (1994, 1995) and Cleland et al. (1996). They conducted a detailed study of four drill holes, all of which, penetrate the Trommald Formation and the upper portion of the Mahnomen Formation. Three of the holes that they reviewed were originally drilled by the University of Minnesota to better define the stratigraphy of the Trommald Formation (Grout and Wolff, 1955) - no mention of tourmaline was initially recorded in these drill cores. However, a close inspection of thin sections by McSwiggen et al. (1994, 1995) and Cleland et al. (1996) revealed the presence of tourmaline-bearing layers, as well as the presence of aegirine and hyalophane (Ba-feldspar), in layers within the Trommald Formation (one hole), and layers within the footwall Mahnomen Formation (four holes). Because these indicators are present mostly in the footwall rocks and in four widely-spaced holes (Fig. 19), a very large hydrothermal system was inferred to be present somewhere beneath the iron-formation of the North Range. However, because little exploration has taken place within the footwall rocks, it was difficult to further define the spatial limits of such a system.

A review of the preserved core of the footwall rocks in the North Range, for this investigation, has not been helpful in further defining a SEDEX system. No additional tourmaline-bearing zones were noted during macroscopic viewing of the core (Fig. 19). However, this apparent lack of tourmaline may be related to its very fine-grained nature. Microscopic study of additional samples collected from core of the Mahnomen Formation (Severson and Heine, 2003) showed that tourmaline is not equally present within the North Range. Its limited distribution could be related to: 1) tourmaline is present in only small areas in close proximity to localized exhalative "vent" areas (for only the holes defined by McSwiggen et al. (1994, 1995) and Cleland et al. (1996); or 2) much more extensive thin section sampling for tourmaline in the Mahnomen Formation is needed in the North Range.

Zinc Assays and Other Geochemical Indicators

Indications of a SEDEX system are not readily apparent in the drill core that is preserved. Recent analyses for zinc were conducted on numerous drill cores and cuttings from the North Range. A maximum of 684 ppm Zn is present in drill hole H-12 (Fig. 19 - Section 4, T.46N., R.29W.) where it is associated with an iron-formation horizon within the Rabbit Lake Formation. Barium analyses have also been conducted on numerous samples, but many were conducted with an upper detection limit of 2,800 ppm Ba (listed as 1,000,000 ppm Ba in the *basinchemco.xls* data file). Boron analyses are limited to only 57 samples from the North Range. In reviewing these data, drill hole S-310 (Fig. 19; Section 9, T.46N., R.29W.) stands out as unique in that it contains several anomalous Ba values (>2,800 ppm), and several anomalous B values (up to 215 ppm) that are associated with the Trommald Formation. [Note that the boron content in rocks specifically sampled because they contain abundant tourmaline averages about 2,000 ppm B (Cleland et al., 1996)].

Interestingly, <u>most</u> of the holes with either tourmaline-bearing zones or holes with anomalous B values (>100 ppm) are situated in the western half of the North Range in Sections 28 and 33 (T.47N., R.29W.) and Sections 4-6, and 9-11 (T.46N., R.29W.). Unique sulfide-bearing rocks are present in Sections 2 and 11 (T.46N., R.29W.). Out of this group, the vast majority of unique holes, unique areas, and unique occurrences are situated in Sections 2, 4, 9, 10, and 11 of T.46N., R.29W. (Fig. 19). These areas appear to present the best potential for SEDEX mineralization in the Cuyuna North Range.

EMILY DISTRICT

Introduction

The Emily District is located to the north of the Cuyuna North Range and is positioned along the southwestern margin of the Animikie Basin (Fig. 2). Because the Emily District and the North Range areas are so close together geographically, many early workers (Grout and Wolff, 1955; Schmidt, 1963; Marsden, 1972; Morey, 1983) considered their iron-formations to be continuations of the same geologic unit. They also recognized that specific sedimentary features in the iron-formation of the Emily District mirrored similar features in the Biwabik Iron Formation of the western Mesabi Range. Thus, in essence, the iron-formation of the Emily District eventually became the “missing link” between the Mesabi and Cuyuna ranges, and all three were portrayed as one continuous iron-formation. However, differences in the stratigraphy from one area to the next were also recognized (to be discussed below). Within the Emily District, there are at least three (probably more) broadly lenticular lenses of iron-formation that are separated by more argillaceous material (Morey, 1990). Marsden (1972) believed that the lowermost of these was equivalent to the Biwabik Iron Formation and referred to the other two upper lenses as the Emily iron-formation member of the Rabbit Lake Formation. Morey (1978) suggested that Marsden’s Biwabik of the Emily District could be correlated with the Trommald Formation and that the upper iron-formations were unnamed units in the Virginia Formation. More recently, Southwick et al. (1988) suggested that all three lenses of the Emily District roughly occupy the same stratigraphic position as the Biwabik Iron Formation of the Mesabi Range. They also proposed that any correlation of the Biwabik Iron Formation to the Trommald Formation was no longer valid.

Some of the earliest known drilling took place in the Emily District in 1913. Several companies continued exploration efforts in search of iron-formation throughout the 1940s. The most concerted effort to trace the iron-formation in the Emily District was conducted by the Oliver Iron Mining Division (USS) from 1951 to 1958 when they drilled over 230 holes (Strong, 1959). The MGS conducted a limited reconnaissance drilling program during the 1980s. Recent holes were drilled by the USBM (drill hole E-1) in 1990 and the Minnesota Manganese Resources Company in 1995 to obtain manganiferous material for *in situ* leach tests. Out of this set of holes, drill core is still preserved for 275 holes; 231 of these holes were looked at for this investigation (44,792 feet of core). Locations of all known holes drilled in the Emily District are shown on Plate IV.

NORTH EMILY DISTRICT

Introduction

For the sake of discussion, the Emily District has been subdivided in this investigation into the North Emily District, where most of the drilling took place, and the South Emily District, where more widely scattered holes were put down. The geology of the North Emily District is discussed below - the geology of the South Emily District is discussed in a later section.

Geology

A description of the stratigraphy of the iron-formation in the North Emily District is presented in several articles that include: Morey (1990); Morey et al. (1991); and Morey and Southwick (1993). Most of their detailed descriptions of the stratigraphy pertain to the Ruth Lake area in Sections 20 and 21, T.138N., R.26W., and the reader is encouraged to obtain the articles for further study. Their stratigraphic observations, coupled with observations made during core logging for this investigation, are summarized below.

Trout Lake Formation (Ptl unit) - Silicified dolomite of the Trout Lake Formation (TLF) of Marsden (1972) is intersected in at least five holes; core is still preserved for three of these holes. Each of the holes begins and ends in the dolomite, and thus the stratigraphic position of this formation relative to adjacent formations is largely unknown. Marsden (1972) suggested that the TLF is present at the base of the stratigraphic section and compared it to the Bad River Dolomite in Wisconsin and Michigan. More recently, Morey and Southwick (1995) have placed the TLF at the top of the Mille Lacs Group (Fig. 1), which includes the Denham Formation, and have correlated it with similar formations in the Lake Superior area that include the Bad River Dolomite, Kona Dolomite, and Randville Dolomite. Bekker (1998) conducted an isotope study of all these formations and interpreted the Kona Dolomite to be slightly younger than the other dolomite formations based on carbon isotope systematics - no attempt was made to determine if the Trout Lake and Denham formations can be correlated.

In drill core, the TLF is characterized by a variably-colored (red to tan to gray to white), thick to thin-bedded, "cherty" dolomite with variable bedding dips (steep to shallow) and local small folds. Cherty or quartzose interbeds are present in drill holes 18224 and 18225. Limited chemical analyses of the TLF indicate that it varies from a dolomite to a dolomitic limestone (Marsden, 1972).

Quartz-Rich Metasedimentary Rocks (Pumg unit) - To the east of the TLF, and probably overlying the TLF, are quartz-rich metasedimentary rocks that may also be correlative with rocks of the Mille Lacs Group. Core is preserved for only five holes located in this unit (Plate IV). Rocks intersected in four of the drill holes are dominantly thick-bedded, gray quartz arenite, and thin-bedded, red to green mudstone. Bedding plane dips are generally shallow (10-30°) in this group of holes, except in hole 18448, which is near an anticlinal axis (Plate IV), and exhibits dips of 30-50°. Unusual rocks are present in one drill hole (18693) that intersected a variety of rocks that include schist, phyllite, sheared quartzite, oxidized thin-bedded iron-formation, and chert. The foliation in this hole is quite steep (55°), and may be related to its proximity to a major fault (Plate IV). The rocks in all of the holes, except 18693, are very similar to rocks of the nearby Pokegama Quartzite, and thus, this unit may not truly be correlative with the Mille Lacs Group.

Pokegama Quartzite (Ppq unit) - Rocks of the Pokegama Quartzite are characterized by either:

- thick-bedded or thin-bedded, gray to red, medium- to fine-grained, quartz arenite (±mudstone interbeds);
- thin-bedded to locally thick-bedded, variably hematite-stained, green mudstone ± local interbeds of quartz arenite, gray argillite, and distal graywacke; and
- thinly-interbedded mudstone and quartz arenite.

Only one of these rock types is present in some holes; whereas, in other holes, all three of the rock types are present. There appears to be no systematic vertical pattern to the rock units - quartz arenite overlies mudstone in some holes, and the reverse is true in other holes. Even when a drill hole cuts the overlying iron-formation and penetrates the Pokegama Quartzite, mudstone is present directly beneath the iron-formation in 37 holes, while quartzite is present directly beneath the iron-formation in 31 holes.

The base of the Pokegama, to the west of the Emily District (Plate IV), is defined by a curvilinear, moderate positive magnetic anomaly that is inferred to represent concentrations of heavy minerals (Boerboom et al., 1999a). Higher than "normal" amounts of magnetite crystals (<0.5 mm across) are present in drill hole18954, which was drilled near the base of the Pokegama. The top of the Pokegama is generally in sharp contact with the overlying iron-formation. However, in some holes a highly gradational contact is present. In these cases, the Pokegama is characterized by clastic metasediments with a hematitic cement that increases upward into a porous, hematitic "mud" with a sprinkling of detrital quartz grains (referred to as the "purple Pokegama" in this report).

Bedding plane dips within the Pokegama Quartzite (see Fig. 20) are generally shallow (10-45°), but dips as steep as 80-90° are locally present indicating the presence of large-scale folds. Small-scale folds are evident in some drill holes. Minor conglomerate beds and local cross-bedding are reported by Strong (1959). A pervasive cleavage is generally not well-developed within the Pokegama Quartzite, but phyllite (originally mudstone) is present in close proximity to faults and folds. Strong (1959) estimated that the Pokegama Quartzite (called the Mahnomen Formation in his report) is at least 200 feet thick.

<u>Iron-Formation (Pei unit)</u> - Most of the iron-formation in the North Emily District has been pervasively oxidized and leached, which commonly caused problems in drill core recovery. Many drilled intervals consist of broken-up core pieces and/or soft and earthy, hematite-rich, "paint rock" pieces. On top of this problem, most of the drill holes do not intersect the entire stratigraphic section of the iron-formation. Some holes start at the base of the iron-formation, while others start at the top or middle of the iron-formation, and may or may not fully penetrate the entire iron-formation section. This condition results in "piece meal" drill hole intercepts that are difficult to correlate with other nearby "piece meal" drill hole intercepts. However, even in the face of these core recovery obstacles and "piece meal" obstacles, there have been attempts to subdivide the iron-formation. Strong (1959) divided the iron-formation into several subtypes that include: quartzitic iron-formation ("purple Pokegama" of this report); unoxidized thin-bedded iron-formation; sandy-banded facies (thick-bedded granular chert); interbedded ferruginous chert; thin-bedded iron-formation; and an "unusually thin iron-formation" (wherein the entire iron-formation, while thin overall, consists of only barren ferruginous chert). All of these subtypes were noted in this investigation, but most of them are complexly interbedded throughout the North Emily District. Morey et al. (1991) subdivide the bottom-most iron-formation unit, which they informally refer to as Unit A, in the Ruth Lake area into six lithotopes that include:

- Clastic lithotope = hematitic quartz-rich siltstone interbedded with quartz arenite;
- Mixed epiclastic-jaspery chert lithotope = manganese-oxide-cemented quartz arenite with interbeds of jasper exhibiting either algal stromatolitic structures and/or jasper clast-bearing intraformational conglomerate;
- Oolitic and pisolitic lithotope;
- Thick-bedded lithotope = granular "cherty" iron-formation;
- Mixed thick- and thin-bedded lithotope = similar to the thick-bedded lithotope, but with intervals of thin-bedded "slaty" iron-formation; and

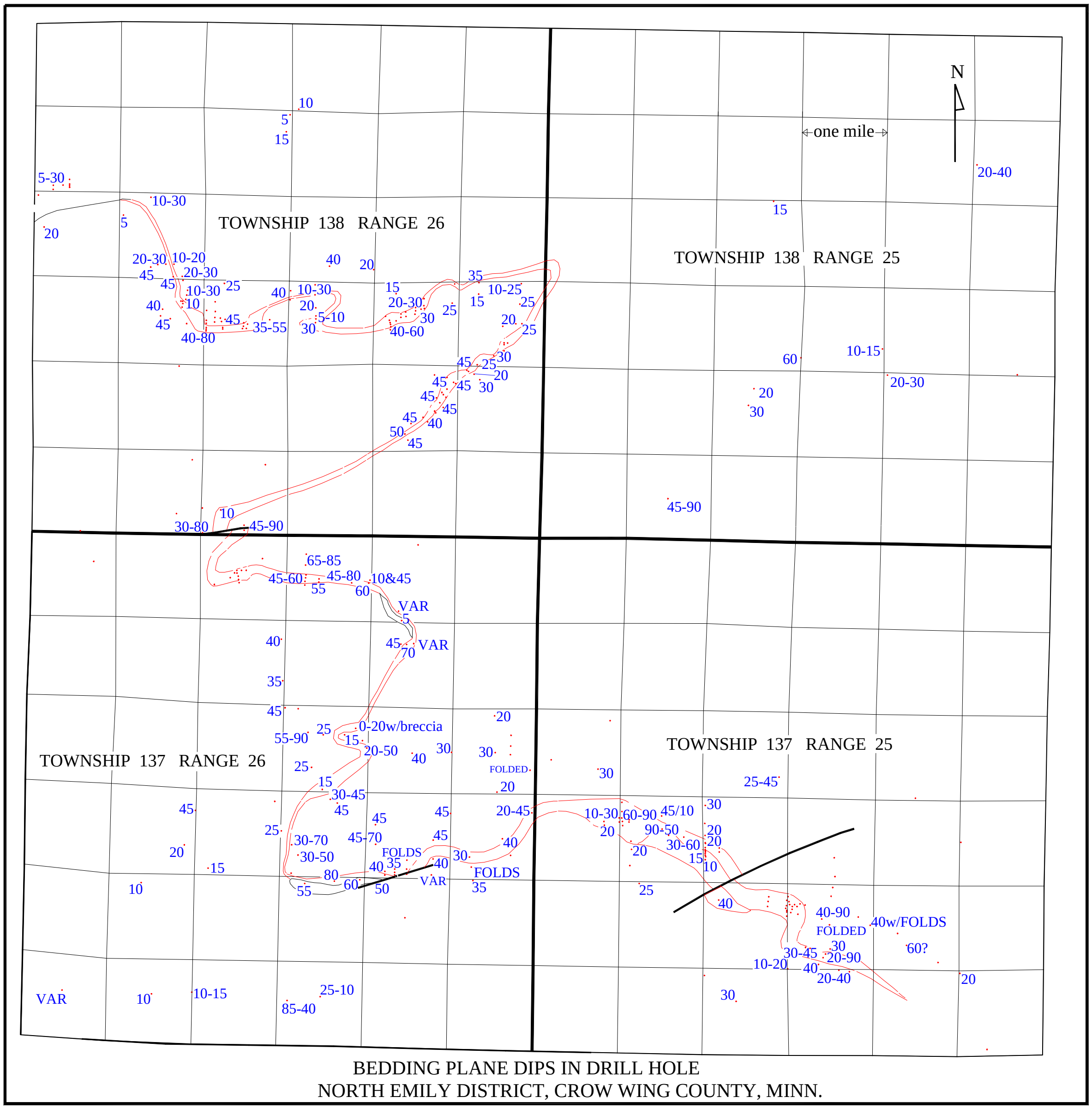

Figure 20 - Bedding plane dips of the Pokegama Quartzite, iron-formation, and Virginia Formation in the North Emily District, Crow Wing County, Minnesota. Dips shown on this figure have been corrected from drill hole dips to apparent dips. VAR = variable dips.

- Ferruginous chert lithotope = thin-bedded jasper, chert, and hematite that passes upward into the overlying Virginia Formation.

Again, many of these lithotope types were noted in this investigation, but outside of the Ruth Lake area, many of these lithotopes are lacking, or complexly interbedded, or additional iron-formation types are present.

While logging the core for this investigation, it quickly became obvious that the presence of only three lenticular iron-formations in the Emily District is an understatement. Within just the bottom-most iron-formation, presumably Unit A of Morey et al. (1991), there are constant lateral and vertical gradational changes within the iron-formation. In many areas, "slaty" iron-formation grades laterally into argillaceous iron-formation, that in turn, laterally grades into clastic rocks of the Virginia Formation. Within the Virginia Formation itself, there are multitudinous horizons with chert bands, thin-bedded iron-formation, and argillaceous iron-formation. Because of all these common gradational changes, it is extremely difficult to describe a "typical" stratigraphic section of the iron-formation in the Emily District. Thus, Figure 21 is offered as a crude rendering of the rock types that are present in the main iron-formation unit (Unit A) from one end of the North Emily District to the other. It is important to note that since this project was intended to define potential SEDEX environments, minimal time was spent logging drill holes in the iron-formation.

It is readily apparent in Figure 21 that a thick-bedded, granular chert is generally present at the base of the iron-formation (unit C in Fig. 21). In some areas, this chert unit is underlain by, or interbedded with, a porous hematitic material with detrital quartz grains ("purple Pokegama" unit - PP unit in Fig. 21). Algal stromatolites are common at the top of the granular chert unit in the Ruth Lake area, but they are rarely encountered elsewhere in the North Emily District. Thin-bedded "slaty" iron-formation (unit T in Fig. 21) generally occupies the middle portion of the iron-formation and is characterized by thin beds (<5 mm) of red/hematitic to brown/limonitic material with highly variable amounts of fine-grained chert beds up to a few feet thick. There are constant lateral and vertical gradational changes of the "slaty" iron-formation into a hematite-bearing, argillaceous, "red bed" iron-formation (unit A in Fig. 21), which in turn, exhibits gradational changes into argillaceous metasediments of the Virginia Formation (unit VF in Fig. 21). Mixed zones of alternating beds of "slaty" iron-formation and granular chert (unit M in Fig. 21) are locally present within the middle of the iron-formation. Lenses of granular cherty iron-formation (also unit C on Fig. 21 - but well above the base of the iron-formation) are common near the top of the iron-formation; however in some areas the intervening material between the bottom chert and an upper chert are Fe-poor argillaceous rocks rather than iron-formation. Because there are many lateral facies changes within the iron-formation to more argillaceous rock, it is next to impossible to determine an overall thickness for the iron-formation. In some areas, only a thin cherty iron-formation represents the entire iron-formation section (as described by Strong, 1959); whereas in other areas, a much thicker section is present, and consists of alternating thin-bedded "slaty" zones and thick-bedded granular "cherty" zones.

Bedding plane dips within the iron-formation of the North Emily District (Fig. 20) are generally shallow (5-45°), but localized steep dips (45-90°) are also present in clusters of drill holes, e.g., Sections 22 and 23, T.137N., R.26W. in Figure 20. In some cases, highly variable dips (0-90°) are present within the same hole; small-scale folds are also evident in some holes. The overall trend

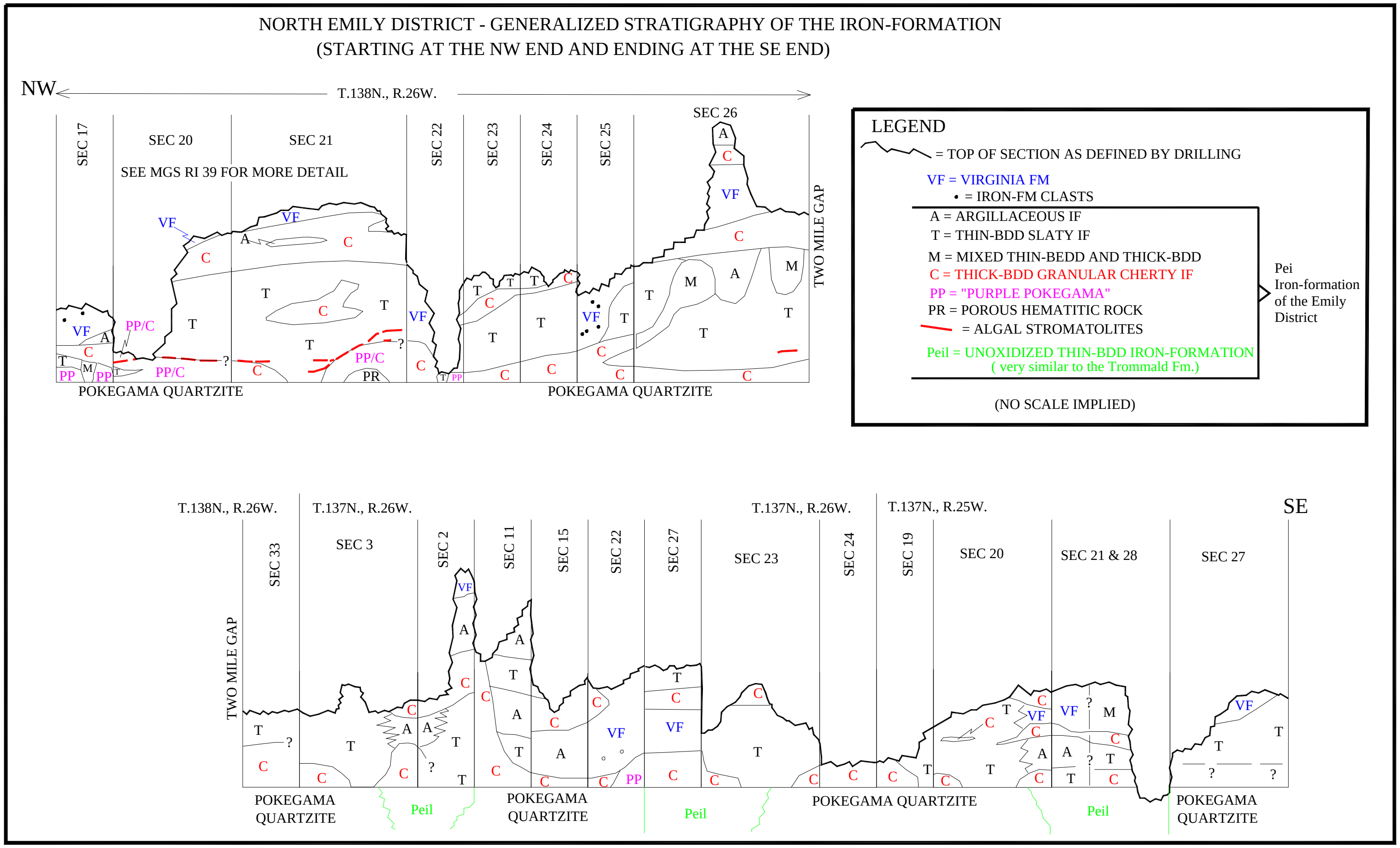

Figure 21 - Crude stratigraphic relationships and facies changes in the iron-formation of the North Emily District, Crow Wing County, Minnesota.

of the iron-formation in the North Emily District defines a series of broad, open, eastward-plunging folds with near-vertical axial planes (Morey, 1990). High concentrations of manganese are locally present within the oxidized and leached iron-formation. Morey and Southwick (1993) suggest that these high concentrations are related to a reflux remobilization model; whereby, manganese-rich anaerobic ground water migrated north from the Cuyuna North Range and reprecipitated the manganese in the Emily District as the ground water mixed with oxygenated waters in the porous, granular, cherty zones.

<u>Lower Thin-Bedded Iron Formation (Peil Unit)</u> - Probably the most important and recent finding in this investigation, from a stratigraphic correlation standpoint, is the localized presence of unoxidized, thin-bedded, magnetic, silicate-carbonate-oxide facies iron-formation at the very base of the iron-formation (Peil unit on Fig. 21 and Plate IV). The presence of the Peil Unit at the base of the iron-formation in specific areas of the Emily District is quite perplexing. The Peil unit is characterized by extremely thin beds (<1 mm to 5 mm) of alternating dark bands (with magnetite), green to greenish-black to olive-green bands (with Fe-carbonates and Fe-silicates) and **rare** chert bands. Chemical analyses conducted by USS (Strong, 1949) indicate that the rock contains 20-50% carbonate (probably as siderite, ankerite, and manganosiderite?). Relatively consistent Mn values are associated with the Peil unit and exhibit variations from 2% to 8% Mn.

In all of the above respects, the Peil unit is extremely similar to the Trommald Formation! Cross-section relationships (Plate V), while meager, suggest that in places the Peil unit exhibits a drastic thickening down dip. Over 815 feet of the Peil unit are intersected in drill hole18290 which was terminated within the unit! Such drastic increases in the thickness of this unit suggests that this unit, like the Trommald Formation to the south, was deposited in a deep water environment within small fault-bounded basins.

The Peil unit was eventually covered by shallow water clastic iron-formation as exhibited by the thick-bedded, granular, cherty iron-formation (unit C on Fig. 21). Again, there is a striking parallelism to the Trommald Formation, which is characterized by thick-bedded iron-formation, with "stromatolite-like" features, overlying a package of thin-bedded iron-formation. It may be possible that the Peil unit of the Emily District could be correlative with the Trommald Formation; however, this concept would "set the clock back" on the recent stratigraphic thinking (Southwick et al., 1988; and Morey and Southwick, 1995, to name a few) and would require much more detailed work that is beyond the scope of this study.

<u>Lower Virginia Formation (Pvt unit)</u> - The Virginia Formation, immediately above the iron-formation in the North Emily District is characterized by thin-bedded, dark-gray, argillite, and fine-grained, graded graywacke. Both rock types are variably hematite-stained, and the core often consists of alternating gray beds and hematite-rich "red beds." In some holes, the "red beds" appear to be the result of primary hematite deposition (derived from weathering of spatially-related iron-formation?); whereas in other holes, the Fe-staining appears to be the result of more recent weathering and oxidation of Fe-carbonate bearing beds - in some of these holes the "red beds" exhibit oxidation fronts that cross-cut bedding. Also interbedded with the argillite, graywacke, and "red beds" are lesser amounts of :

- Moderate-gray siltstone;
- Light-gray, fine-grained quartz arenite;
- Black (organic-rich?) argillite;
- Chert beds that vary from 1 cm to 5 cm thick (locally up to 15 cm thick); and
- Crumbly, red, hematitic "paint rock" zones.

Quartz arenite interbeds are extremely common within T.138N., R.26W. as are soft-sediment deformed features, thin conglomerate beds, and beds containing what appear to be rip-up fragments of hematitic iron-formation(?). These same features are also present in Section 22, T.137N., R.26W. The conglomerate is matrix-supported and contains sub-rounded, but elongate clasts of chert, hematite-rich fragments(iron-formation?), quartz arenite, and black argillite. Soft-sediment deformed features, due to slumpage(?), include chaotic small folds, small folds overlain by planar/straight bedding, and high-angle dipping beds obliquely overlain by more horizontal beds.

Bedding plane dips of the Virginia Formation in the Emily District (Fig. 20) are generally shallow (5-30°) but steep dips (45-90°) are locally present, especially in the vicinity of major fold axes. Well cleaved phyllite is also present in the vicinity of faults and folds.

<u>Carbonaceous Argillite of the Virginia Formation with Iron-Formation Lenses (Pvti unit)</u> - Positioned about 100-500 feet above the base of the Virginia Formation is a highly variable unit (Pvti unit on Plate IV) characterized by:

- Carbonaceous (graphitic), black argillite;
- Thin-bedded, pale green to brown, carbonate facies iron-formation; and
- Hematite-rich "red beds."

The volume of each of these three rock types is extremely variable in drill hole. All three of the rock types are present as either individual beds, that are <1 inch, or repeated beds in zones that are several tens of feet thick. Locally interbedded with these three rock types are lesser amounts of:

- Sulfide-bearing carbonaceous argillite;
- Thin bands of fine-grained, and internally-brecciated, chert (<2 inches thick);
- Locally thick bands of cherty iron-formation (20-50 feet thick); and
- Locally thick packages of oxidized argillaceous iron-formation (40-150 feet thick) that is characterized by abundant "red-beds," and/or "paint rock," with minor chert beds (1 inch to a few feet thick).

All of the above rock types can be intricately interbedded at very small scales. For example, three different rock types (carbonate iron-formation, carbonaceous argillite, and "red beds") are present in alternating <2 inch-thick beds in drill holes 18130 (Section 36, T.137N., R.25W.), and 18302 and 18401 (Section 27, T.137N., R.25W.). In these examples, deep water reducing conditions are evident by deposition of carbonate iron-formation and carbonaceous argillite; whereas, the "red beds" are indicative of periodic influxes of oxidized allogenic material that may have been deposited via turbidity currents (Morey, pers. comm., March, 1999).

Thick intersections of the carbonaceous argillite are present in at least ten drill holes. Out of this set, only five of the holes contain sulfide-bearing zones with highly variable amounts of sulfides that range from trace amounts to 10%. Holes with sulfides include:

- 18130 = trace to 3% late pyrite;
- 18141 = core is coated by gypsum crystals and actual amount of sulfides is difficult to estimate;
- 18298 = 1% pyrite nodules at the bottom of the hole;
- 18302 = with 10% pyrite at 500-503 feet; and
- 18450 = rare pyrite.

Two holes (18297 and 18302 in Section 26 and 27, T.137N., R.25W.) exhibit thin zones with malachite coatings on the core (one inch thick zone at 475 feet and one inch thick zone at 502 feet, respectively).

The overall thickness of this unit is quite variable and difficult to estimate because no drill hole penetrates the entire section, and more importantly, this unit exhibits constant lateral facies changes that are probably related to drastic changes in thickness. A minimum of 300 feet is penetrated in drill hole 18423. To the extreme northwest of the North Emily District (Sections 7 and 18, T.138N., R.26W.), this unit is characterized by only brown, sideritic, carbonate facies iron-formation beds; no carbonaceous argillite is present.

<u>Upper Virginia Formation (Pvt unit)</u> - Rocks of the Virginia Formation that overlie the Pvti unit (described above) are characterized by a monotonous sequence of thin-bedded argillite with occasional thin limestone bands (< 3 inches thick). **No** "red beds," quartz arenite beds, chert beds, nor even soft-sediment deformed features, which are so common at the base of the Virginia Formation, are present within this upper monotonous sequence.

<u>Regolith and Weathered Bedrock</u> - Highly weathered bedrock, overlain in some instances by Cretaceous sediments, is intersected in at least 16 holes. The material varies from red, hematite-rich, clay-rich rocks that are locally pisolitic to weathered and friable kaolinitic sandstone (derived from the Pokegama Quartzite). Some of this material has been evaluated for kaolin potential (Heine et al., 1998). Varying amounts of regolith are probably present throughout the area, but it was rarely cored in the drill holes.

<u>Cretaceous Rocks</u> - Cretaceous rocks are intersected in at least 18 holes in the area. Wherever these rocks are cored, they are characterized by various rock types that include:

- White to variably-colored, kaolinitic, clay-rich material;
- Gray clay-rich shale ± lignite fragments;
- Local conglomerate with hematite-rich clasts (in 3 holes); and
- Rare lignite (one hole).

Some of this material has been evaluated for kaolin potential (Heine et al., 1998).

Structure

The overall structure of the North Emily District, as defined by the surface trace of the iron-formation, consists of a series of broad, open, eastward-plunging folds with near-vertical axial planes. In some small areas, evidence of more extreme deformation is readily evident in a group of drill holes. For example:

- In Section 33, T.138N., R.26W., two drill holes intersect unusual structural features that include:
  - near-vertical dips are present in hole18614; and
  - well-cleaved phyllite and a fault zone are associated with hole 18624.

- In Section 15, T.137N., R.26W., unusual structures in drill holes include:
  - near-vertical dips and phyllite are present in hole 18586;
  - near-vertical dips, along with breccia and phyllite are present in hole 18590; and
  - near-vertical dips are present in hole18592.

Sulfide Mineralization and Other Features

Regarding potential SEDEX mineralization, the Pvti unit appears to be the most prospective rock type. It is the main sulfide-bearing unit in the North Emily District (five holes - see above). Faint malachite staining is present over thin intervals in two holes (see above). Overall, the Pvti unit is characterized by abrupt and often highly localized changes in the types of sediment deposited. A close association with iron-formations and euxinic environments is also indicated for this unit. However, out of 31 samples collected mostly from the Pvti unit, which were analyzed for Cu, Pb, and Zn, a disappointing maximum value of 87 ppm Zn is all that has been indicated to date.

SOUTH EMILY DISTRICT

Introduction

The South Emily District is discussed separately for two reasons. First, the geology is defined by a very limited amount of holes (65 - of which 25 are still preserved as core at the MDNR) that are widely scattered in T.136N., Ranges 25 through 27 W. (Plate IV). Second, correlation of rock types present in the South Emily District with similar counterparts in the North Emily District could be disputed. Boerboom et al. (1999a) suggest that the iron-formation of the North Emily District (Pei unit) is present in the south Emily District (Pei unit). In the South Emily District, this same iron-formation is overlain by a unit that is very similar to the Pvti unit (to the north), but it is not designated as such by Boerboom et al. (Pqgi unit - 1999a). In this investigation, the Pvti unit designator for rocks above the iron-formation is used in both the North and South Emily Districts.

Geology

Most of the rocks of the South Emily District are similar to rocks of the North Emily District and will not be redefined in this section. However, two rock units deserve special mention and are described below.

Iron-Formation (Pei unit) - This iron-formation is preserved as core for only four holes. Some of the holes intersected "paint rock" and recovery was poor. The best intersections of this unit are in holes:

- 18720 - intersected an oxidized "purple Pokegama" type iron-formation; and
- 18951 - intersected several oxidized zones of thick-bedded, granular, "cherty" iron-formation, and thin-bedded, "slaty" iron-formation with thin chert bands. The rocks intersected in hole 18951 are almost exact "dead ringers" for the iron-formation that is "typically" intersected in the holes in the North Emily District.

Carbonaceous Argillite of the Virginia Formation with Iron-Formation Lenses (Pvti unit) - This unit is very similar to the package of rocks that are present above the main iron-formation unit in the North Emily District. The rocks are characterized by thin-bedded, black, carbonaceous (graphitic) argillite with common iron-formation layers that contain varying amounts of:

- Oxidized thin-bedded chert;
- Oxidized thick-bedded granular chert (minor);
- Oxidized thin-bedded iron-formation;
- Oxidized thin-bedded argillaceous iron-formation ("red beds" with chert beds);
- Paint rock; and
- Unoxidized thin-bedded carbonate facies iron-formation.

Structure

Bedding within the Pvti unit is generally 30-60°, but variations within a single drill hole are evident. Drill hole 18721 exhibits folded and brecciated rock with late calcite veins. Meager data from cross-sections (not included in this report) suggest that the rocks of the South Emily District have an overall dip of 30-45° to the south.

Sulfide Mineralization

Pyrite is present in seven out of eight holes that intersect carbonaceous argillite (Pvti unit). The pyrite occurs as either disseminations, as very fine-grained sulfides (<5%) in "brown beds" (less than six inches thick), semi-massive beds (less than six inches thick), and occasionally as late pyrite veins. In some of the holes, gypsum crystals are growing on the core surface and along bedding planes causing the core to expand and literally "self destruct." Only 21 samples from the Pvti unit have been analyzed for zinc, with maximum values of 258-291 ppm Zn present in holes 18721 and 18965.

THE ANIMIKIE BASIN
IN CASS COUNTY, MINNESOTA

INTRODUCTION

At least 29 holes (2,840 feet of core) were drilled into the Paleoproterozoic rocks within Cass County (Fig. 22) in attempts to trace out a southwestern extension of the Biwabik Iron Formation, or for reconnaissance geologic mapping purposes (LV-series holes). Twenty-four of the holes intersect the Virginia Formation (Pvt unit), along with variable amounts of overlying regolith and/or Cretaceous materials.

MESABI RANGE HOLES - CASS COUNTY

Geology

Four holes were drilled on the extreme western end of the Mesabi Range (see Fig. 22 and Appendix 1 - *basinholesco.xls* data base). These four holes intersect:

- carbonaceous argillite of the Virginia Formation (holes 3795 and 4072) with sulfides (present within gypsum-coated and self-destructing core);
- thin-bedded "slaty" silicate-carbonate facies Biwabik Iron Formation (3795, 3796, and 4072); and
- the Pokegama Quartzite (3987).

ANIMIKIE BASIN HOLES - CASS COUNTY

Geology

At least 25 holes were drilled into the Animikie Basin of southeastern Cass County (Fig. 22). Rock types intersected in the holes are described below (see also *basinholesco.xls* data base).

<u>Virginia Formation (Pvt unit)</u> - This formation is dominated by thin-bedded, gray to black (locally green), argillite with lesser interbeds of pale-gray siltstone and distal graywacke. The siltstone often exhibits load casts and micro cross-bedding. Sharp bases, with some grading, are characteristic of the fine-grained/distal graywacke. Some thin limestone beds (1-7 cm thick), and/or calcite concretions, are widely distributed in a group of holes that defines a northwest-trending belt (see geologic map). Thin chert bands, and possibly sericitic reworked tuffaceous bands, are locally present in the Thunder Lake area in one drill hole (TL-4). Thin-bedded silicate-carbonate facies iron-formation, with a nine inch-thick chert band, is intersected in the bottom of hole LV-2A (over eleven feet-thick).

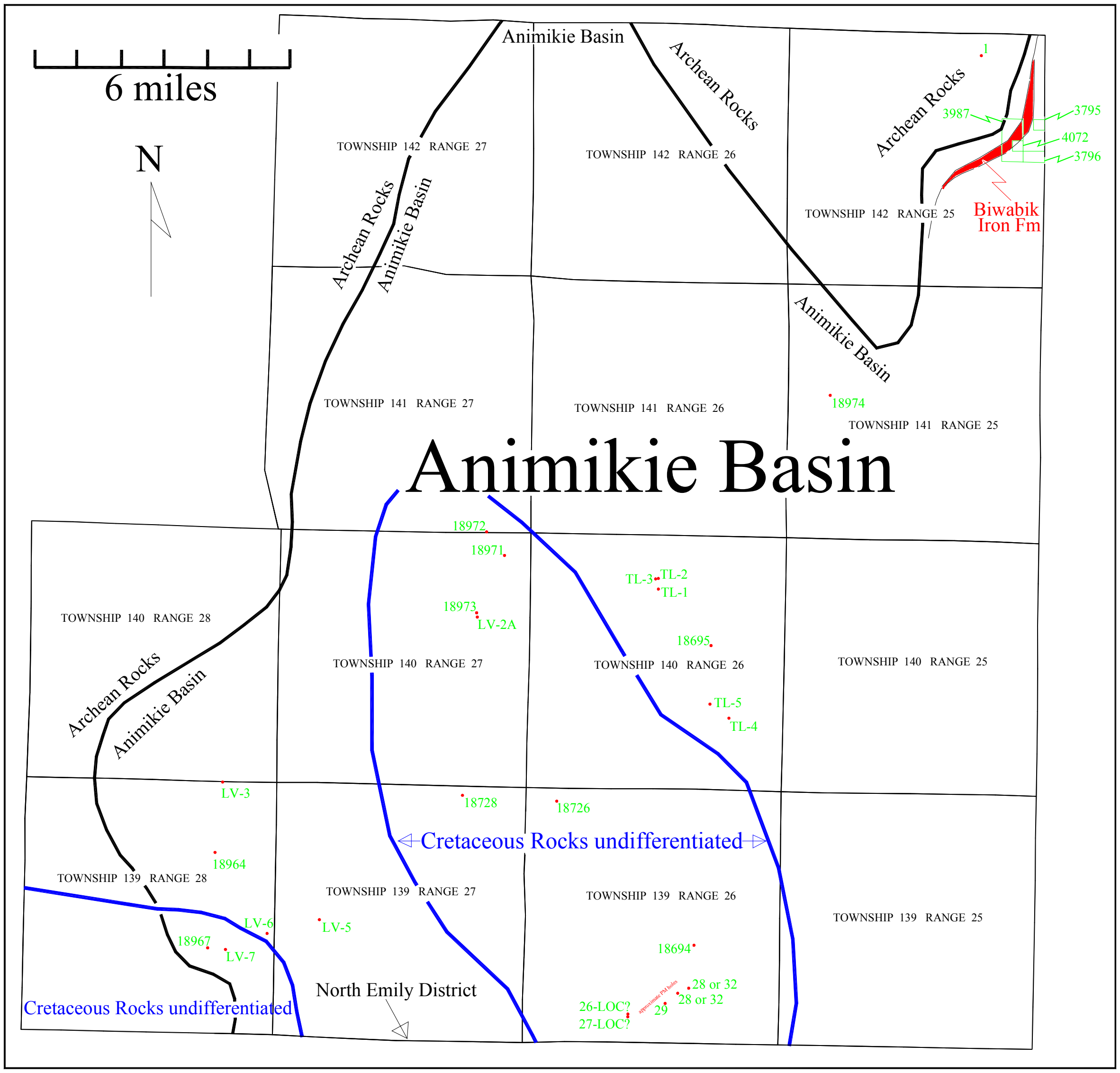

Figure 22 - Location of exploration drill holes into the Mesabi Range and Animikie Basin in the southeastern portion of Cass County, Minnesota. Drill holes in the upper right corner of the figure (western end of the Mesabi Range) are holes with generalized location descriptions (usually to the nearest 40 acre parcel).

Bedding of the Virginia Formation in Cass County is generally 5-20° with localized steeper dips of 30°. Much steeper dips (up to 45°), along with a well-developed cleavage and small-scale folds, are evident in some of the holes in the Thunder Lake area (north half of T.140N., R.26W.).

Regolith - Variable amounts of clay-rich, highly weathered bedrock, or regolith, are preserved as core for 14 drill holes. The regolith in these holes varies from 3-132 feet thick. The clays are variably-colored and grade with depth into less weathered rock to "fresh" bedrock. The clays in some of the holes have been evaluated for kaolin potential (Heine et al., 1998).

Drill hole LV-7 was reported (Southwick et al., 1986) to have intersected 255 ft. of regolith with irregular iron-formation bands at a depth of 604-686 feet (based on cuttings - the hole was not cored). However, a USS core hole (18967), located about 1,500 feet to the west of LV-7, intersected an extremely thick package of Cretaceous sediments (described below) at a depth of 434-729 feet. This relationship suggests that the cuttings of hole LV-7 were incorrectly interpreted.

Cretaceous - Cretaceous material (4-354 ft. thick) is preserved as core for at least six holes in Cass County. Five of the holes intersect variably-colored claystone ± lignite fragments and minor lignite beds up to three feet-thick. Friable, variably hematite-cemented, orange-colored, medium-grained sandstone is intersected in two holes (LV-2A and 18967). Drill hole 18967 intersected over 295 feet of Cretaceous sandstone (the hole was terminated in this unit). Also within the Cretaceous sandstone of hole18697 are interbeds of hematite-rich mudstone (545-555 feet), siltstone beds ± small rock fragments, and strongly Fe-stained sandstone. The Cretaceous materials in some of the holes has been evaluated for kaolin potential (Heine et al., 1998).

Zinc Assays

Only 43 zinc assays are available for the drill holes in the south-eastern portion of Cass County. A maximum of 399 ppm Zn is present in one interval from one hole.

THE ANIMIKIE BASIN
IN ITASCA COUNTY, MINNESOTA

Introduction

Within Itasca County there are thousands of holes that were drilled into the Paleoproterozoic Biwabik Iron Formation of the Mesabi Range. Only 38 known drill holes intersect the overlying Virginia Formation (Fig. 23). All but two of the holes (MDDP-7 and MDDP-8 - described by Lucente and Morey,1983) were looked at for this investigation.

Geology

A total of 36 holes into the Virginia Formation have been looked at for this investigation (8,824 feet of core) and for a project concerning the oxidized taconite potential of the Biwabik Iron Formation in the vicinity of Coleraine, MN (Zanko et al., 2003). The Virginia Formation intersected in the holes corresponds to the lower argillaceous lithosome of Lucente and Morey (1983) and is described below.

<u>Virginia Formation (Pvt unit)</u> - Only the basal 300 feet of the Virginia Formation was logged for this investigation. The major rock types, portrayed for six holes in Figure 24, include:

- gray- to green-colored argillite;
- black, "organic-rich," carbonaceous argillite; and
- brown to tan to pale-green carbonate facies iron-formation.

All three rock types are thin-bedded and each can be present as either: alternating thin beds (½ to 6 inches thick); or thick packages (10-90 feet thick) where one rock type is more dominant. Also included within these three major rock types are lesser interbeds of:

- gray to green thin-bedded siltstone (locally with sharp bases and gradational tops);
- rare distal graywacke;
- rare sericitic tuffaceous(?) beds; and
- fairly common, but widely scattered, chert beds and/or nodules.

The chert beds are very fine-grained and range from 1 cm to 7 cm thick. For the most part, the chert beds are straight and planar, but they locally exhibit: pinch-and-swell thickness changes; internal brecciation; draped argillaceous beds over the top of nodules; and evidence of the nodules settling into the underlying argillaceous rock.

Thin sulfide-bearing zones are present in five drill holes at 35-45 feet and 65-75 feet above the base of the Virginia Formation (Fig. 24). Sulfide-bearing zones are also present in four holes that are located to the west of the holes portrayed in Figure 24. These holes (3681, 3742, 3954, and 3961

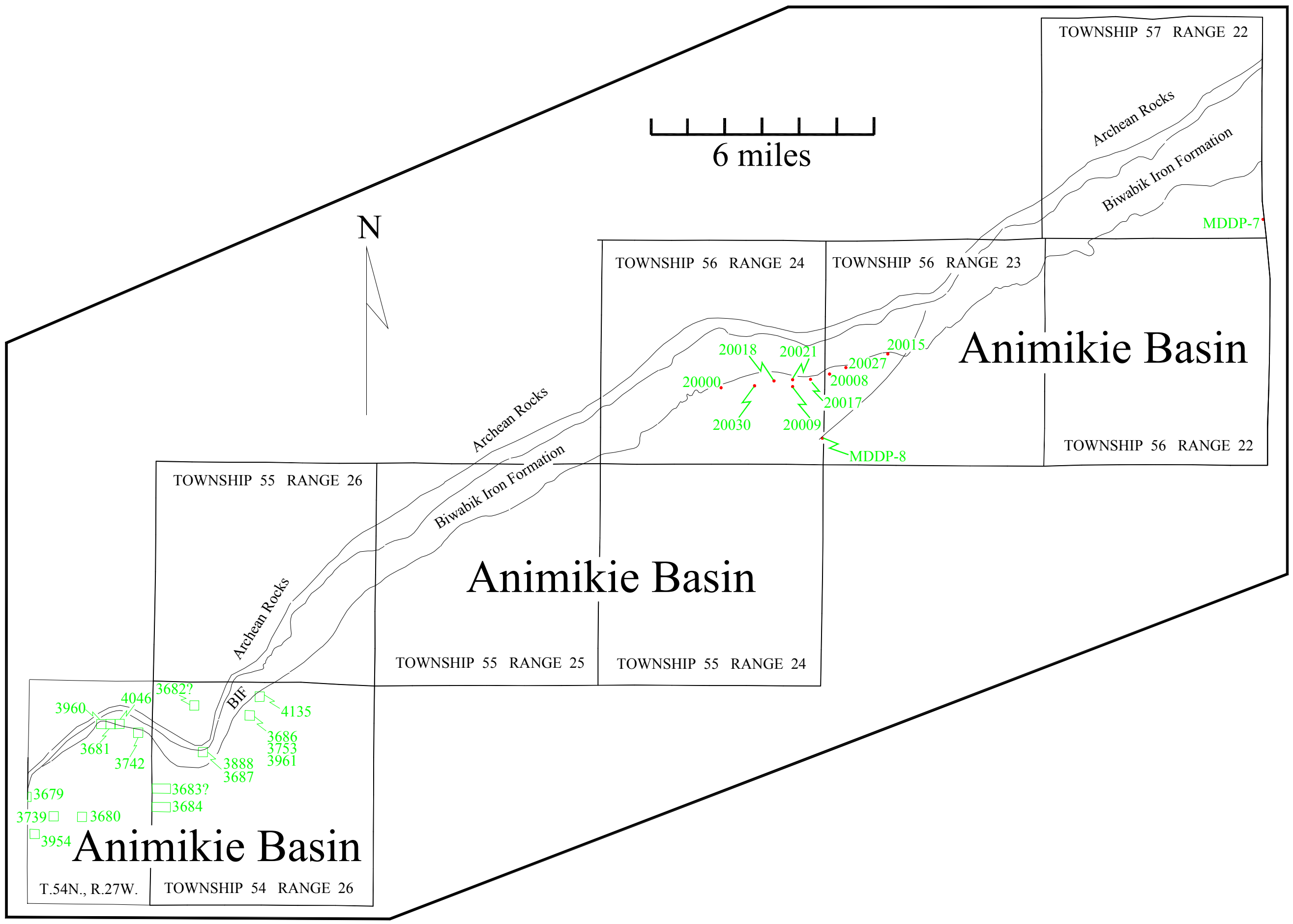

Figure 23 - Location of exploration drill holes into the Animikie Basin in the southern portion of Itasca County, Minnesota, that were looked at for this investigation (except the MDDP-series holes). Drill holes in the lower left corner of the figure are holes with generalized location descriptions (usually to the nearest 40 acre parcel). Drill hole MDDP-7 and MDDP-8 (stands for Mesabi Deep Drilling Project) are also referred to as MGS-7 and MGS-8.

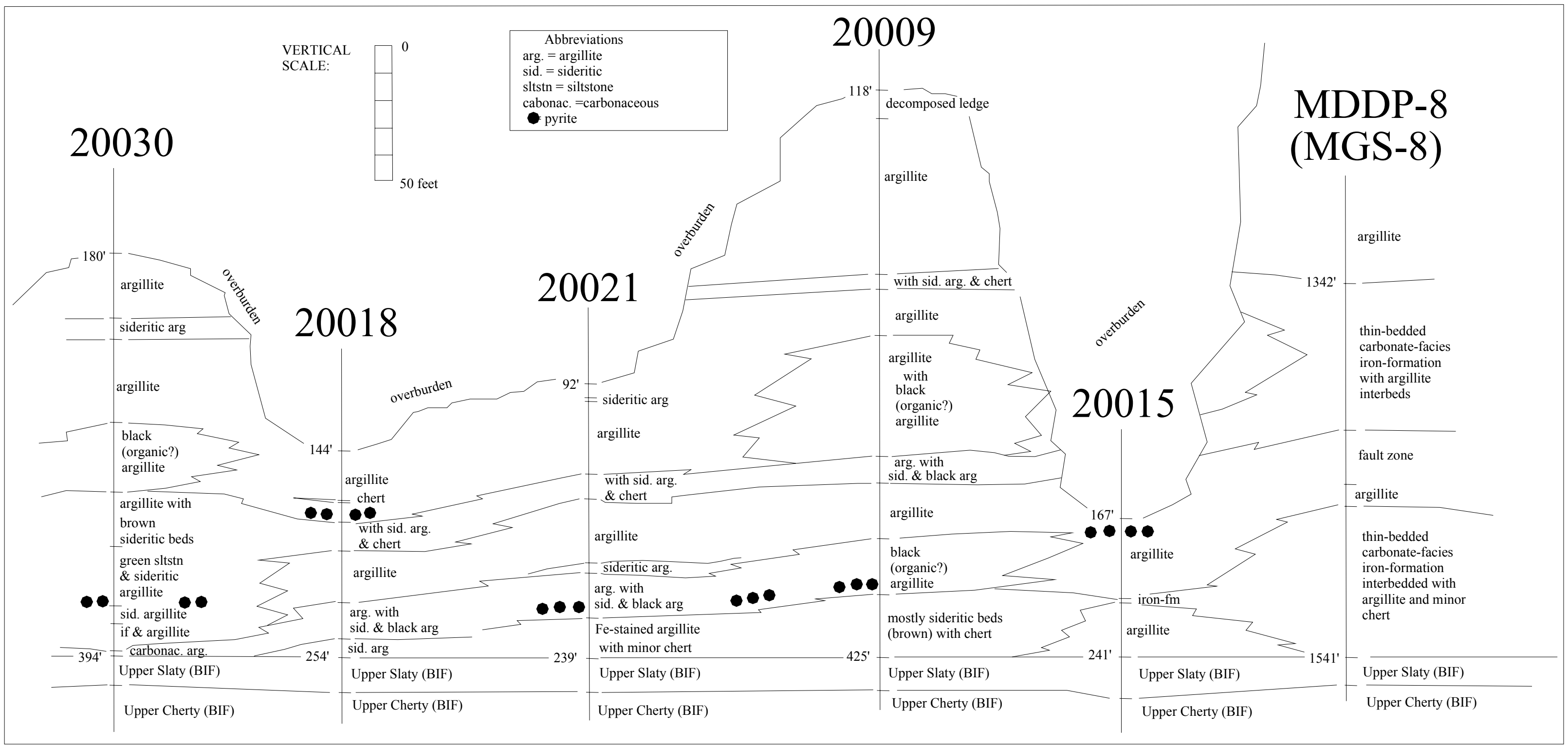

Figure 24 - Distribution of sedimentary units in drill hole within the lower 300 feet of the Virginia Formation, Itasca County, Minnesota (modified from Zanko et al., 2003). Note that all the holes are hung on the top of the Biwabik Iron Formation (BIF).

- Fig. 23) are characterized by gypsum-coated, self-destructing core; the actual amount of sulfides that are present is difficult to estimate. The sulfide-bearing material in these four holes is probably positioned at, or near, the base of the Virginia Formation.

The basal contact of the Virginia Formation with the underlying Upper Slaty member of the Biwabik Iron Formation is highly transitional in most of the drill holes. This transitional nature is characterized by carbonate facies iron-formation beds in the Virginia Formation that increase with depth toward the Biwabik Iron Formation; however, the iron-formation in the Virginia Formation contains common argillite interbeds. In this investigation, the base of the deepest argillaceous interbed, associated with the carbonate iron-formation, marks the base of the Virginia Formation. The top member of the iron-formation, the Upper Slaty member, is almost always hematitic and oxidized in the holes in Itasca County; whereas, the carbonate facies iron-formations within the Virginia Formation are rarely oxidized.

Zinc Assays

Only 18 zinc assays are available for the drill holes in the southern portion of Itasca County. A maximum of 212 ppm Zn is present in one interval from one hole.

THE ANIMIKIE BASIN
IN ST. LOUIS COUNTY, MINNESOTA

Introduction

Many drill holes, probably on the order of thousands of holes, have been put down into the rocks of the Paleoproterozoic Animikie Group in St. Louis County. This includes holes drilled on the Mesabi Range and holes drilled in the vicinity of the Mesoproterozoic Duluth Complex in search of Cu-Ni deposits. The distribution of exploration holes with preserved core of the Virginia Formation are shown on Figure 25.

Geology

At the base of the Virginia Formation, or the lower argillaceous lithosome of Lucente and Morey (1983), the rocks are characterized by thin-bedded argillite and carbonaceous argillite (locally sulfide-bearing) with lesser amounts of siltstone, chert, tuffaceous(?) beds, and limestone beds. However, in close proximity to the Duluth Complex, the grade of metamorphism, and associated deformation, progressively increases, and several metamorphic varieties and textures are superimposed on the original sedimentary package. A description of the Virginia Formation and the more prevalent metamorphic varieties in close contact with the Duluth Complex follows.

Virginia Formation (Pvt unit) - Core from 33 drill holes, located to the south of the now inactive LTV mine, were looked at for this investigation (2700, 2800, 7400, and 7500-series holes on Plate VI). This core represents the basal 125 feet of the Virginia Formation. The major rock types consist of interbedded dark-gray argillite and black (organic-rich?) carbonaceous argillite. The carbonaceous argillite is the dominant rock type in the bottom-most portion (8-65 feet) of the Virginia Formation. Pyrite cubes and marcasite-rich laminae (up to 2 mm thick) are common in the carbonaceous argillite, but the overall sulfide content varies from hole to hole (trace to 5%). Sulfide content also shows some spatial variation in that some clusters of holes have more sulfides than other clusters of drill holes (Severson, in prep.). This relationship indicates the presence of small third-order(?) euxinic basins. At least seven thin limestone beds (less than one foot-thick) are intermittently present at the base of the Virginia and can be traced out in several groups of drill holes (Severson, in prep.).

Visible sphalerite, associated with thin discontinuous calcite veins near the base of the Virginia Formation, is present in six holes (Plate VI) that include 2840, 2842, 2858, 2859, 2860, and 7557. Visible sphalerite (rare amounts to 1%) is present in the top 1-1.5 inches of the Biwabik Iron Formation in four holes that include 2753, 2836, 2853, and 2859 (Plate VI).

Recrystallized Unit (RXTAL) - In close proximity to the Duluth Complex, the thin-bedded metasediments of the Virginia Formation were heated enough to produce up to 20%-30% pervasive partial melts that enabled the rock to literally flow in response to stresses applied during emplacement of the Duluth Complex. All bedding planes are completely obliterated in the RXTAL unit, or diatexite (Sawyer, 1999), and what remains is a recrystallized rock that contains medium-grained biotite flakes

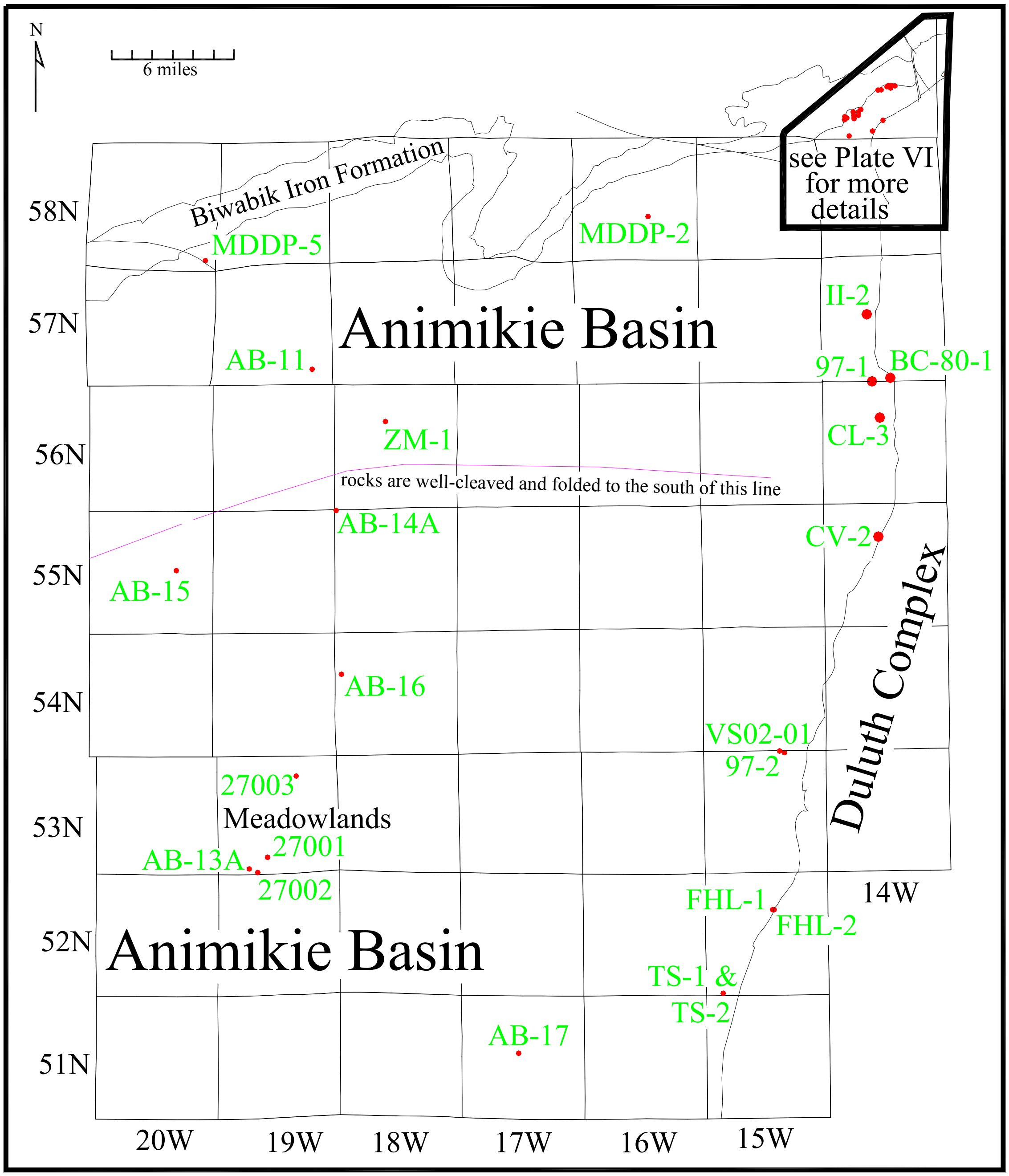

Figure 25 - Distribution of exploration holes, with preserved core, within the Animikie Basin in the southern portion of St. Louis County, Minnesota. Note that the Mesabi Deep Drilling Project holes (MDDP-holes) are also referred to as the MGS-series holes. Recent holes (3) drilled by BHP along the northern margin of the Animikie Basin are not included in this figure.

that are arranged in a decussate manner. Floating within this recrystallized matrix are blocks/boudins of more structurally competent siltstone and calc-silicate beds. The RXTAL unit is generally the metamorphic variant that is most often observed close to the Duluth Complex. The DISRUPT unit (see below) is generally positioned slightly farther away from the basal contact of the Complex.

Disrupted Unit (DISRUPT) - Well-bedded argillites of the Virginia Formation are commonly transformed into a highly deformed rock, or 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 micro-folding, micro-faulting, and micro-brecciation. Superimposed on this chaotic pattern are abundant partial melt zones that are also chaotic and micro-folded. The overall texture of the DISRUPT unit appears to be a result of a combination of partial melting and intense pervasive structural deformation (both in response to emplacement of the Duluth Complex).

Calc-Silicate Beds - Close to the Duluth Complex, the limestone beds of the Virginia Formation are metamorphosed to calc-silicate beds and pods that contain wollastonite, plagioclase, grossular garnet, idocrase, and variable amounts of diopside (Kirstein, 1979). Some hornfels inclusions within the Duluth Complex contain numerous layers of calc-silicate, some of which, are closely associated with chert beds and diopsidic chert beds. There is an overall increase in the abundance of calc-silicate and chert beds within the Virginia Formation in a west-to-east direction toward the Duluth Complex. This relationship indicates a change in the sedimentary environment of the Virginia Formation in the vicinity of the Duluth Complex. Unfortunately, the stratigraphic section of Virginia Formation in this vicinity is incomplete as it is only preserved in discombobulated random hornfels inclusions.

Graphitic Argillite - Carbonaceous argillite is preserved as hornfelsed graphitic argillite in close proximity to the Duluth Complex. Several horizons are known to be present at the base of the Virginia Formation (Severson, 1991). The graphitic argillite horizons often pinch-out and then "reappear" at the same stratigraphic level. Graphitic argillite horizons are not only confined to the base of the Virginia Formation as they are present well to the south (and thus much higher up in the stratigraphy) in drill holes in the Fish Lake area near the city of Duluth, MN (Severson, 1995).

Bedded Pyrrhotite Unit (BDD PO) - Wherever the graphitic argillite exhibits regular-spaced pyrrhotite laminae (up to 2 mm thick), it is referred to as the BDD PO unit. This unit is also present as several horizons in the Virginia Formation in an area that spans from the Dunka Pit and Babbitt Cu-Ni deposits (T.60N., R.12W.), through the Dunka Road and Wetlegs deposits (T.59N., R.13W.), and then sporadically toward the south to the Fish Lake area. The spatial distribution of BDD PO units suggests that there are numerous isolated horizons that reflect deposition in restricted euxinic basins. Limited sulfur isotope studies (Severson, 1994; Zanko et al., 1994) indicate that some of the BDD PO units were deposited in closed basin settings.

Very fine-grained chalcopyrite and sphalerite are occasionally seen in the BDD PO unit, but Zn analyses were rarely conducted by the exploration companies. However, routine Cu-Ni analyses were conducted on the BDD PO unit in the Babbitt deposit area, and copper values up to 0.61% are locally present. Contouring of the Cu values for the BDD PO unit in the Babbitt deposit area (inset - Plate VI) indicates that the copper values increase in a north-to-south direction toward the Duluth Complex. At this time, it is difficult to determine if this copper increase is related to the original Cu-content in the BDD PO, or if the increase is related to emplacement of the Complex and some secondary enrichment of Cu in the footwall rocks.

<u>Sill at the Base of the Virginia Formation</u> - In the vicinity of the Duluth Complex, a fine-grained sill is present at the very base of the Virginia Formation (Severson, 1991; Severson et al., 1996; Hauck et al., 1997; Park et al., 1999). The sill exhibits consistent Cr contents >800 ppm and has been informally referred to as the Cr-rich Sill (Hauck et al., 1997). The age of the Cr-rich Sill is inferred to be early Mesoproterozoic, but a much older age (1.8 Ga?) is also possible. If the sill is older, it could be compared to the Moyie sills at the Sullivan Zn-Pb deposit, which are inferred to be related to a larger magmatic source at depth that acted as a heat engine for fluids that formed the Sullivan ore body (Turner et al., 1992).

SIPHON FAULT AREA

Geology and mineralization

Most of the above geologic discussion pertains to an area, shown in Plate VI, that is bordered by the Duluth Complex (to the east) and contains the Siphon Fault. There are several features associated with the Virginia Formation in the vicinity of the Duluth Complex and the Siphon Fault that suggest the area has potential for SEDEX mineralization that include:

- The Siphon Fault represents a growth fault, across which, the Biwabik Iron Formation decreases from 560 feet thick to the west of the fault to 435 feet thick to the immediate east of the fault (Graber, 1993).
- Sedimentary structures (cross-beds and load casts), in meager outcrops of the Virginia Formation in the immediate vicinity of the Siphon fault, suggest that a submarine channel was present along the fault trace during deposition of the Virginia Formation (Severson and Hauck, 1997). This inferred channel could have been related to continued motion along the Siphon "growth" fault.
- Some fairly high zinc values have been obtained from three drill holes to the east of the Siphon Fault. These holes are shown in Plate VI and include:
    - zinc values up to 2.65% associated with a 1.6 foot thick semi-massive sulfide layer in a hornfels inclusion in drill hole B1-117 (Severson et al., 1996);
    - a zinc value of 1.08% associated with a three foot thick zone in a graphitic argillite in drill hole 26024 (Severson et al., 1996); and
    - a crumbly one foot thick zone with 0.61% zinc in hole B1-201 (this investigation).
- Visible sphalerite is observed in several of the LTV holes at the very base of the Virginia Formation and very top of the Biwabik Iron Formation (described above) to the west of the Siphon Fault.

- Traces of sphalerite, from both megascopic and microscopic observations, are found in another seven drill holes in the general vicinity of the Siphon Fault (shown in Plate VI).
- A large zoned tourmaline crystal (indicative of a hydrothermal system?) was found in drill hole B1-374 in the footwall rocks at the Babbitt Cu-Ni deposit (Plate VI). Microprobe analysis of the tourmaline are presented in Table 6.
- Some of the BDD PO units contain high copper values (up to 0.6%) - the copper content appears to increase toward the Duluth Complex.
- The Cr-rich Sill at the base of the Virginia Formation could have been emplaced during(??) sedimentation of the Virginia Formation, and **if** so, the sills could represent a potential heat engine as envisioned for the Moyie sills at the Sullivan deposit.

All of these relationships indicate that a SEDEX system was present somewhere in the vicinity of the Siphon Fault; however, it is unknown if the system was vigorous enough to produce a large deposit, and if so, is such a deposit still present, or was it assimilated during emplacement of the Duluth Complex?

SKIBO SOUTH AND LINWOOD LAKE AREAS

Geology and Mineralization

The Skibo South area (Severson, 1995) is located about eight miles to the south of the Siphon Fault area in Section 16, T.57N., R.14W. Six holes were drilled in this area during exploration for Cu-Ni mineralization at the base of the Duluth Complex. One of the holes (II-2) was collared in the Virginia Formation and intersected numerous BDD PO horizons. These horizons range from <1 inch to 10 feet thick. The BDD PO layers contain 0.01-0.03% Cu; Zn analyses were not conducted. Tourmaline, associated with thin partial melt veins in the Virginia Formation, is present in a few locations in this same hole. Microprobe analyses from four zoned tourmaline grains are presented in Tables 7 and 8.

The Linwood Lake area (Severson, 1995) is located about seven miles to the south of Skibo South in Section 22, T.56N., R.14W. Several outcrops of the Virginia Formation are present there and are described by Severson (1995). Tourmaline grains were noted in one thin section collected from the RXTAL unit; no microprobe analyses are available.

Other than the presence of tourmaline, it is difficult to ascertain the potential for SEDEX mineralization in either the Skibo South or Linwood Lake areas. The BDD PO unit is present at Skibo South and is suggestive of either 2nd or 3rd order basins. There are no zinc analyses of the Virginia Formation from either area.

B1-374 293 ft. - Four analyses from one large/zoned tourmaline grain														
Weight %														
No.	**SiO2**	**Al2O3**	**FeO**	**B2O3**	**MgO**	**CaO**	**MnO**	**K2O**	**F**	**Na2O**	**H20**	**Li**	**Total**	**Comment**
1	35.441	32.939	6.087	10.055	7.103	0.847	0.000	0.058	0.007	1.946	?	?	94.480	outer zone 1
2	35.521	32.981	5.748	9.5920	6.901	0.761	0.017	0.052	0.004	1.971	?	?	93.546	outer zone 2
3	35.496	32.504	6.013	10.135	7.038	0.983	0.035	0.044	0.000	1.900	?	?	94.148	inner zone 1
4	35.619	34.369	5.898	10.833	6.521	0.592	0.000	0.030	0.004	1.819	?	?	95.683	inner zone 2
Cation, O = 12.0														
No.	**Si**	**Al**	**Fe**	**B**	**Mg**	**Ca**	**Mn**	**K**	**F**	**Na**	**H20**	**Li**	**Total**	**Comment**
1	2.4486	2.6824	0.3517	1.1992	0.7316	0.0627	0.0000	0.0051	0.0015	0.2607	?	?	7.7435	outer zone 1
2	2.4772	2.7110	0.3353	1.1547	0.7175	0.0569	0.0010	0.0047	0.0009	0.2665	?	?	7.7257	outer zone 2
3	2.4596	2.6548	0.3485	1.2123	0.7270	0.0730	0.0021	0.0039	0.000	0.2553	?	?	7.7365	inner zone 1
4	2.4130	2.7443	0.3341	1.2669	0.6586	0.0430	0.000	0.0026	0.0009	0.2389	?	?	7.7024	inner zone 2

Note: H2O content could not be analyzed.

Table 6 - Microprobe analyses of a large (> 1 inch across) zoned tourmaline crystal collected from the footwall Virginia Formation at the Babbitt Cu-Ni deposit, St. Louis County, Minnesota. Sample collected from drill hole B1-374 at 293 feet.

II-2, 872.6 ft. - analyses of two zoned tourmaline grains														
Weight %														
No.	**SiO2**	**Al2O3**	**FeO**	**B2O3**	**MgO**	**CaO**	**MnO**	**K2O**	**F**	**Na2O**	**H2O**	**Li**	**Total**	
1	35.188	32.84	6.924	10.419	6.346	0.926	0.000	0.061	0.000	1.897	?	?	94.601	interior of #1
2	35.237	32.408	6.848	9.228	6.673	1.104	0.010	0.044	0.004	1.899	?	?	93.453	middle of #1
3	35.347	33.075	7.184	10.011	6.379	0.946	0.034	0.056	0.001	1.894	?	?	94.927	exterior of #1
4	35.096	32.929	7.038	10.432	6.551	0.980	0.000	0.052	0.014	1.885	?	?	94.971	interior of #2
5	35.284	32.971	6.920	10.234	6.508	0.960	0.000	0.058	0.012	1.990	?	?	94.932	middle of #2
6	35.313	33.454	7.009	9.547	6.528	0.953	0.002	0.100	0.000	2.008	?	?	94.914	middle of #2
7	35.105	33.040	7.283	10.086	6.606	1.210	0.010	0.063	0.022	1.893	?	?	95.309	exterior of #2
Cation, O = 12.0														
No.	**Si**	**Al**	**Fe**	**B**	**Mg**	**Ca**	**Mn**	**K**	**F**	**Na**	**H2O**	**Li**	**Total**	
1	2.4332	2.6767	0.4004	1.2437	0.6541	0.0686	0.0000	0.0054	0.0000	0.2543	?	?	7.7365	interior of #1
2	2.4813	2.6898	0.4033	1.1217	0.7004	0.0833	0.0006	0.0040	0.0009	0.2593	?	?	7.7447	middle of #1
3	2.4443	2.6960	0.4155	1.1950	0.6575	0.0701	0.0020	0.0050	0.0003	0.2539	?	?	7.7397	exterior of #1
4	2.4200	2.6763	0.4058	1.2417	0.6734	0.0724	0.0000	0.0046	0.0030	0.2520	?	?	7.7492	interior of #2
5	2.4350	2.6819	0.3994	1.2192	0.6695	0.0710	0.0000	0.0051	0.0027	0.2663	?	?	7.7502	middle of #2
6	2.4478	2.7333	0.4063	1.1423	0.6745	0.0708	0.0001	0.0088	0.0000	0.2699	?	?	7.7538	middle of #2
7	2.4220	2.6869	0.4202	1.2013	0.6794	0.0895	0.0006	0.0056	0.0048	0.2532	?	?	7.7635	exterior of #2

Note: H2O content could not be analyzed.

Table 7 - Microprobe analyses of two zoned tourmaline grains from the Virginia Formation at the Skibo South area. Sample collected from drill hole II-2 at 872.6 feet.

II-2, 883.8 ft. - analyses of two zoned tourmaline grains														
Weight %														
No.	**SiO2**	**Al2O3**	**FeO**	**B2O3**	**MgO**	**CaO**	**MnO**	**K2O**	**F**	**Na2O**	**H2O**	**Li**	**Total**	
1	35.336	32.049	7.304	9.903	6.724	1.140	0.011	0.035	0.000	1.758	?	?	94.260	interior of #1
2	35.568	32.952	7.237	9.707	6.486	0.897	0.029	0.047	0.000	1.883	?	?	94.806	middle of #1
3	36.309	34.396	6.708	10.612	5.983	0.520	0.033	0.022	0.014	1.756	?	?	96.347	middle of #1
4	35.436	34.238	9.866	10.022	3.918	0.616	0.056	0.045	0.000	1.782	?	?	95.979	exterior of #1
5	35.591	32.853	7.047	9.734	6.540	0.977	0.020	0.039	0.000	1.883	?	?	94.684	interior of #2
6	35.528	32.356	7.595	12.024	6.499	1.200	0.031	0.051	0.000	1.850	?	?	97.134	middle of #2
7	35.890	33.160	7.218	9.578	6.534	1.056	0.000	0.060	0.000	1.839	?	?	95.335	middle of #2
8	35.414	32.005	7.126	11.660	6.822	1.170	0.020	0.044	0.011	1.742	?	?	96.009	exterior of #2
Cation, O = 12.0														
No.	**Si**	**Al**	**Fe**	**B**	**Mg**	**Ca**	**Mn**	**K**	**F**	**Na**	**H2O**	**Li**	**Total**	
1	2.4643	2.6345	0.4260	1.1922	0.6991	0.0852	0.0006	0.0031	0.0000	0.2378	?	?	7.7428	interior of #1
2	2.4658	2.6927	0.4196	1.1617	0.6703	0.0667	0.0017	0.0041	0.0000	0.2531	?	?	7.7357	middle of #1
3	2.4508	2.7365	0.3787	1.2364	0.6020	0.0376	0.0019	0.0019	0.0029	0.2299	?	?	7.6787	middle of #1
4	2.4451	2.7846	0.5694	1.1937	0.4030	0.0455	0.0033	0.0040	0.0000	0.2384	?	?	7.6870	exterior of #1
5	2.4683	2.6856	0.4088	1.1654	0.6761	0.0726	0.0011	0.0034	0.0000	0.2532	?	?	7.7346	interior of #2
6	2.3874	2.5629	0.4269	1.3948	0.6510	0.0864	0.0018	0.0044	0.0000	0.2411	?	?	7.7568	middle of #2
7	2.4760	2.6965	0.4164	1.1407	0.6720	0.0781	0.0000	0.0053	0.0000	0.2459	?	?	7.7310	middle of #2
8	2.4043	2.5611	0.4046	1.3665	0.6904	0.0851	0.0011	0.0038	0.0024	0.2293	?	?	7.7487	exterior of #2

Note: H2O could not be analyzed.

Table 8 - Microprobe analyses of two zoned tourmaline grains from the Virginia Formation at the Skibo South area. Sample collected from drill hole II-2 at 883.8 feet.

MEADOWLANDS AREA

Introduction

In 1974, United States Steel Corporation (USS) flew a large airborne survey over the central portion of the Animikie Basin in southwestern St. Louis County. Abundant EM conductors were located by the survey in the vicinity of the town of Meadowlands (recollections of the primary author). USS drilled three holes in the area (Fig. 25) to test some of the EM conductors.

Geology and Mineralization

Rock types of the Virginia Formation intersected in the three USS holes consist mainly of alternating thin beds of gray and black (organic-rich?) argillite. Cleavage is moderately developed in all the holes and is best developed in the black argillite beds. Overall bedding trends are different in each of the holes suggesting that some large-scale folds are present.

Sulfides are only locally present in each of the holes and consist mainly of marcasite/pyrite. When present, the sulfides are more common in the black argillite beds where up to 1-2% disseminated cubes (up to 1.0 mm across) are concentrated in widely scattered 1-3 cm thick zones. Within the gray argillite, sulfides are generally rare, except as thin coatings along cleavage and fractures (often associated with calcite veined and brecciated zones).

WHOLE ROCK GEOCHEMISTRY

INTRODUCTION

Geochemical characterization of rock types within the confines of the study area have been severely hampered by a general lack of outcrop - most of the known geology is based on scattered drill hole information and interpretations of regional aeromagnetic patterns. Many of the holes have been sampled for precious and base metal assays, but there are only a limited amount of whole rock analyses. Some of the early archived whole rock analyses that are available have to be used with great care as the samples were either collected from improperly classified rock types, highly altered rocks, sampled intervals that cross contacts, or analytical results that are poorly documented. These problems have often lead to ambiguities in interpreting the geochemical data (Southwick et al., 2001). Furthermore, the original content of the igneous rocks, with respect to Ca, Na, K, and lithophile trace elements, have been modified by metamorphic processes (Southwick et al., 1988). In lieu of these problems, Southwick et al. (2001) have established several new "benchmark" analyses that can be used to classify igneous rock types within the Fold-and-Thrust Belt. The geochemical results of Southwick et al. (2001), as well as geochemical results obtained in this study and for all of the archived data, are included in this report regardless of the above listed ambiguities. However, only a select group of whole rock analyses are used in this report to categorize the various igneous rock types of the Animikie Basin and Fold-and-Thrust Belt.

PREVIOUS INVESTIGATIONS

Southwick et al. (1988) offer the first real attempt to classify the igneous rocks of the Fold-and-Thrust Belt. They found that the volcanic rocks are mainly tholeiitic with a continental affinity; whereas, calc-alkaline, orogenic, or island-arc compositions are minor. More recent geochemical characterization (Southwick et al., 2001) suggests that volcanic and hypabyssal rocks in four areas of the Fold-and-Thrust Belt (North and South Ranges, Glen Township, and Kettle River area) are high-Ti primitive-arc or continental tholeiites. Mafic rocks of the Denham Formation tend toward calc-alkaline composition. Southwick et al. (2001) further suggest that the continental tholeiites, associated with thick accumulations of clastic and chemical sedimentary rocks, were deposited in basins that were removed from an active magmatic arc, and that the basins may have been extensional and lain in a forearc position.

GEOCHEMICAL SAMPLES - THIS INVESTIGATION

Seventy-one samples from drill core were selected for geochemical analyses in this investigation. The samples were divided into two groups and sent to XRAL Laboratories in Don Mills, Ontario, Canada, where they were analyzed as follows.

- A multi-element package (whole rock, 53 elements, FeO, C (by Leco), and CO_2) was conducted on 42 samples. Two standards were included with this group (Mount Royal

Gabbro standard = MRG-1; and an argillaceous limestone standard = 1C). The samples were milled using tungsten carbide.

- A 31-element package, including B, S (by Leco), and Au (fire assay), was conducted on 28 variably sulfide-mineralized samples. One standard was included with this group (Zn-Sn-Cu-Pb ore standard = MP-1a). In the event that any zinc values were greater than 1.0%, the lab was instructed to conduct a follow-up zinc assay. The samples were milled using tungsten carbide.
- One sample of crumbled core, from drill hole RMC-65260 (170-170.8 feet), was submitted for Zn assay only. The crumbled material was suspected to be sphalerite-rich and assayed 1.59% Zn.

Results of the geochemical analyses are included in Appendix 2 - *1999wr.xls* data base for the whole rock analysis package (multi-element package) and *1999bm.xls* data base for the base metal package (31-element package). In regards to base metal assays, seven samples contained >1,000 ppm Zn and include:

- 1,030 ppm Zn in drill hole A-6 at 1153-1154.9 feet - Glen Township Sulfide - South Body;
- 1,460 ppm Zn in drill hole A-6 at 1163.1-1164 feet - Glen Township Sulfide - South Body;
- 2,540 ppm Zn in drill hole 50 (referred to as MAG-50) at 414.3-417.4 feet - Glen Township Sulfide - South Body;
- 2.51% and 2.65% Zn in drill hole B1-117 at 965.4-966.4 feet - associated with a hornfels inclusion of Virginia Formation within the Duluth Complex at the Babbitt Cu-Ni deposit;
- 1,160 ppm Zn in drill hole A4-15 at 113.3-116.1 feet - footwall Virginia Formation at the Wetlegs Cu-Ni deposit in the Duluth Complex;
- 1,220 ppm Zn in drill hole A4-18 at 238.2-240.2 feet - footwall Virginia Formation at the Wetlegs Cu-Ni deposit in the Duluth Complex; and
- 1.59% Zn in drill hole RMC-65260 at 170-170.8 feet - footwall Virginia Formation between Babbitt Cu-Ni deposit and the Peter Mitchell taconite mine on the east end of the Mesabi Range.

GEOCHEMICAL COMPILATION

Included in this report is a data base (Appendix 2 - *basinchemco.xls*) that lists the results of almost all geochemical analyses that have been conducted on drill core (and cuttings) within the confines of the study area; only minimal outcrop samples are included in the data base. This data base was initially prepared in1994 by Larry Zanko, of the Natural Resources Research Institute (NRRI), for a project to compile all the geochemical results of east-central Minnesota. [Note that all of the results of the 1994 project are included in this report]. Zanko originally compiled the results from a variety of sources that included: 1) mineral exploration sampling campaigns (on file at the MDNR); 2) academic studies (M.S. theses and Ph.D. dissertations); and 3) state agency related sampling campaigns. Data that was omitted during this compilation included: 1) poorly documented sample intervals; 2) poorly documented results that could not be confirmed by later sampling endeavors; and 3) analyses that included only Fe, Si, and Mn results.

The entire data set of Zanko was then obtained by the MDNR, and the results of their sampling campaigns, prior to 1997, were added to the compilation (Frey and Lawler, 1997). In turn, the data base of Frey and Lawler (1997) was then acquired by the primary author and samples collected for this investigation (Appendix 2 - *1999bm.xls* and *1999wr.xls*) were added to the data base in 1999. Lastly, the most recent geochemical results for the area (Southwick et al., 2001) were added to the data base in 2003.

Thus, the geochemical results presented in Appendix 2 (*basinchemco.xls* data file on the CD in the back pocket of this report) represents the most up-to-date compilation of results for Paleoproterozoic rocks in: Aitkin; Carlton; Cass; Crow Wing; Itasca; and St. Louis counties. The results of this sample group are discussed in this report. Geochemical results from other Paleoproterozoic rocks intersected in drill hole, from counties that are peripheral to this study area (Benton, Kanabec, Meeker, Mille Lacs, Morrison, Otter Tail, Pine, Stearns, and Todd counties), are supplied by Zanko and are also included in this report (Appendix 2). Note that results of this latter group are not discussed in this report.

WHOLE ROCK COMPILATION

Introduction

All of the whole rock data for rocks in the study area, gleaned from the *basinchemco.xls* data base, are presented separately in the *allbasinwr.xls* data base of Appendix 2 (on the CD in the back pocket of this report). This includes all samples from both igneous and metasedimentary rocks.

The *allbasinwr.xls* whole rock data has been further pared down, to include only whole rock analyses of volcanic and plutonic rocks within the Fold-and-Thrust Belt, and is also included in Appendix 2 as the *allbasinplot.xls* data file. The *allbasinplot.xls* file, which contains 82 individual whole rock analyses, is organized according to the map units of Boerboom et al. (1999a and 1999b). This file, and the Igpet99 plotting program of Carr (1999) were used to prepare the various geochemistry plots for this report. Locations of drill holes that contain whole rock geochemistry are shown in Figure 26.

X-Y Plots of Mafic Igneous Rock Units

Only two X-Y plots (Figs. 27 and 28) are included to show trends of how the various mafic volcanic and hypabyssal units can (and cannot) be grouped. These plots can also be used to "filter" out whole rock analyses that are anomalous with respect to plotted positions. These anomalous samples probably do not represent "benchmark" samples, and they should be used with care; however, they are still displayed on the various plots to further illustrate these ambiguities.

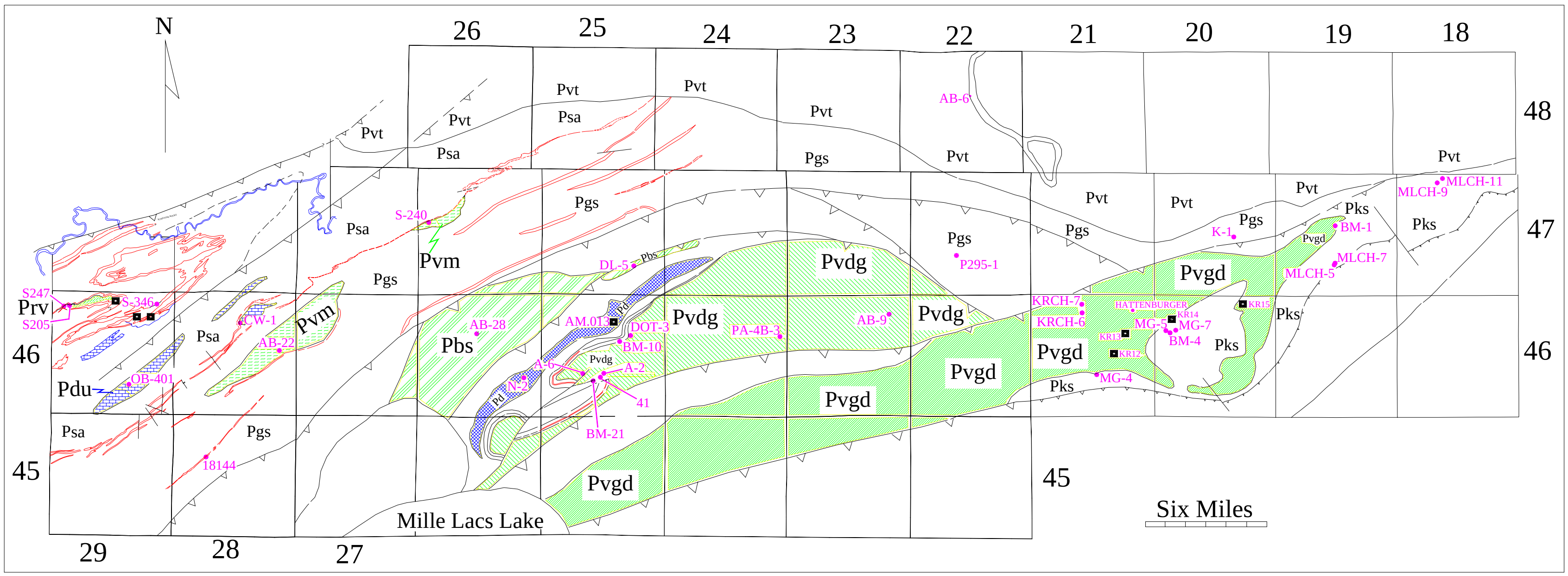

Figure 26 - Location of drill holes with whole rock geochemistry that are used in classifying the various igneous rocks within the study area. Geologic units are from Boerboom et al. (1999a; 1999b). Areas than consist of dominantly mafic volcanic rocks are shaded in green (Pvgd, Pvdg, Pbs, Pvm, and Prv units). Intrusive gabbroic rocks are shaded blue (Pdu and Pd units). Iron-formation trends are shown in red. Drill hole locations are shown as magenta dots, and outcrop samples are shown as black boxes. Note that the geochemical sample from drill hole AB-6 is from a Keweenawan intrusive and is not discussed in this report.

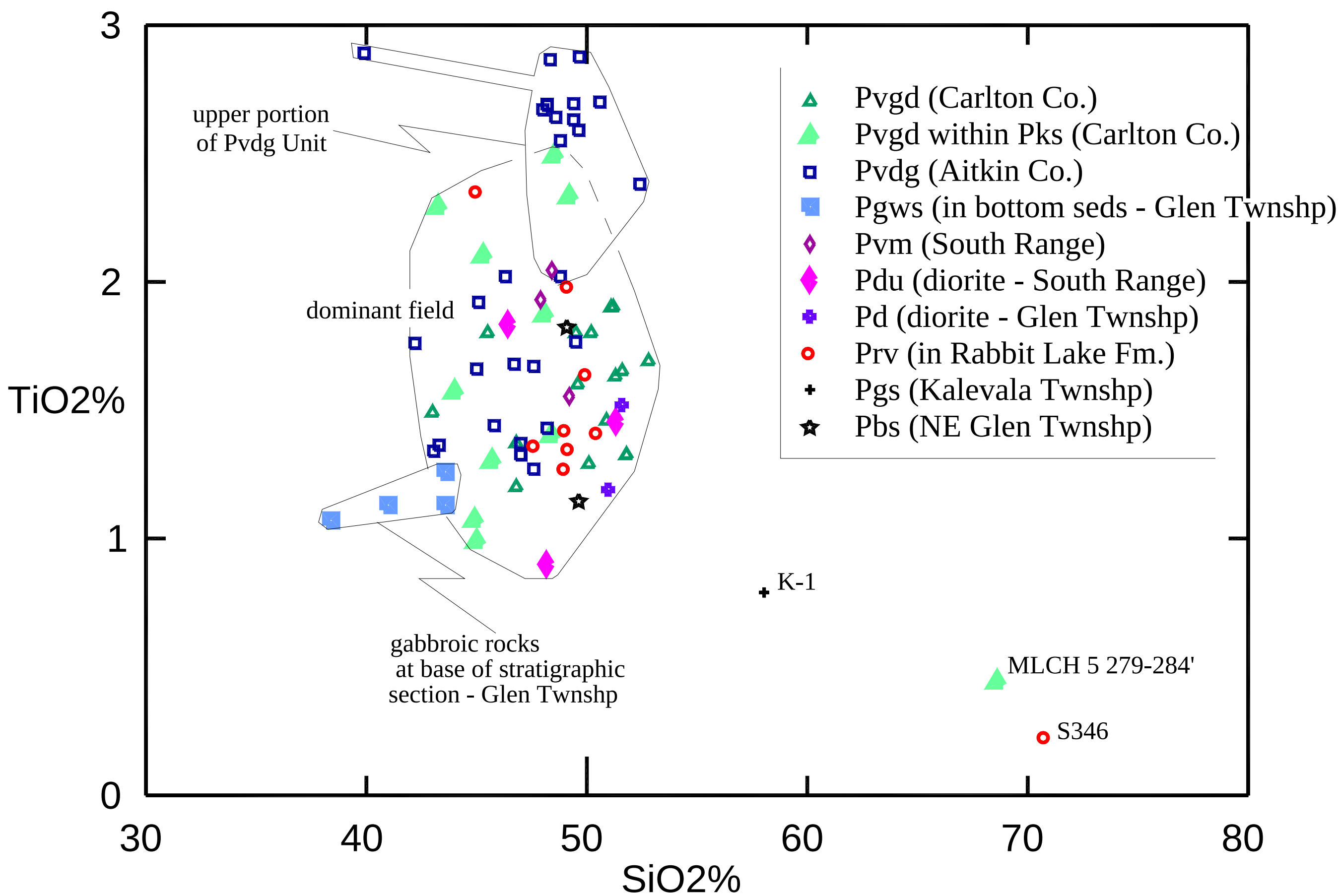

Figure 27 - X-Y plot of SiO_2 to TiO_2 for mafic volcanic and hypabyssal rocks in the study area. Units are from Boerboom et al. (1999a; 1999b). The Pvdg and Pvgd units are indistinguishable in the field and are divided into two units based mainly on geographical location. The "Pvgd within Pks unit" = mafic volcanic rocks (of Pvdg unit affinity) that are intersected in holes that are collared in the Pks unit - note the plotted positions relative to the plotted Pvgd unit. The three isolated samples in the lower right corner of the diagram exhibit "suspect" geochemical values.

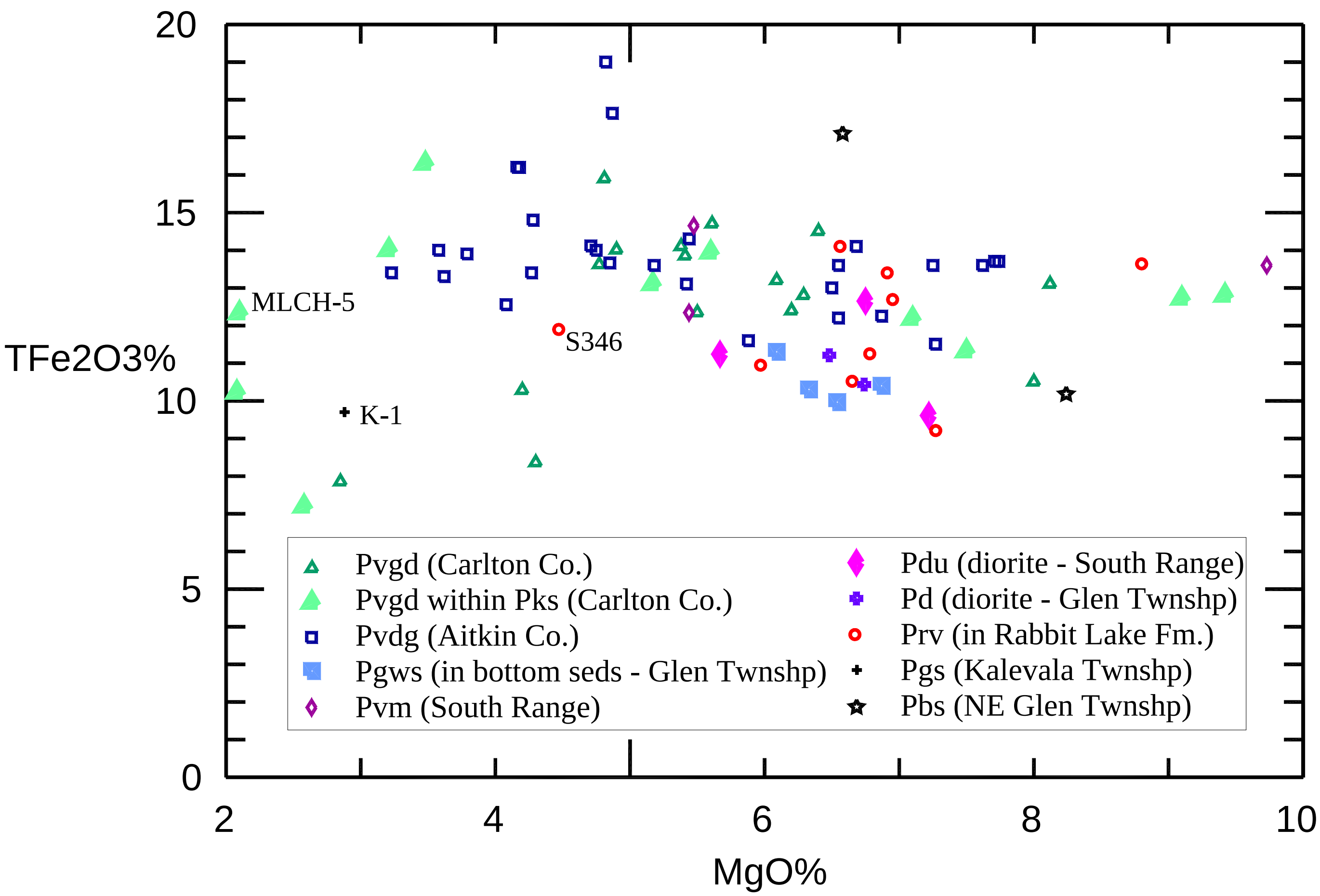

Figure 28 - X-Y plot of MgO to TFe_2O_3 for mafic volcanic and hypabyssal rocks in the study area. Units are from Boerboom et al. (1999a; 1999b).

In Figure 27, almost all of the mafic volcanic and hypabyssal rocks plot within the same general field regardless of map unit or location. However, it is interesting to note that the upper portion of the mafic volcanic and hypabyssal rocks in the Glen Township area (Pvdg unit) are consistently TiO_2-enriched relative to all of the other samples. Also, gabbroic intrusions that are emplaced into the bottom of the stratigraphic section at Glen Township plot as a close-knit cluster. Samples that plot well away from the trend (K-1, MLCH-5, and S346 samples) are probably related to altered or poorly analyzed samples and should be used with caution.

In Figure 28, a wide variation in plotted positions for the units is evident. Gabbroic intrusions within the basal portion of the stratigraphy (Pgws) at Glen Township show a good clustering of plotted positions. Some crude clustering is evident for the mafic volcanic and hypabyssal rocks associated with the Rabbit Lake Formation (Prv unit). It is interesting to note that the plotted positions for the three "suspect" samples are lost in this mix.

Discrimination Plots of Mafic Igneous Rock Units

Several geochemical comparison plots can be used to interpret the mafic volcanic and hypabyssal rocks of east-central Minnesota. The plotted positions of the samples in the various plots (Figs. 29 through 34) indicates that the mafic rocks are geochemically similar and are dominantly high-Fe tholeiitic basalts that formed in an island arc, ocean floor, within plate, or continental settings. Not surprisingly, these plots reiterate the findings of Southwick et al. (2001); wherein, they concluded that these types of rock compositions are often associated with SEDEX deposits.

X-Y Plots of Metasedimentary Rock Units

In the course of compiling all of the geochemistry for the study area, numerous whole rock analyses were found for metasedimentary rocks within the Fold-and-Thrust Belt and Animikie Basin. These data, along with whole rock analyses collected from metasedimentary rocks for this investigation, are included in Appendix 2 (*basinchemco.xls* and *allbasinwr.xls* data bases on CD in back pocket of this report). The location of drill holes, from which whole rock analyses of metasedimentary rocks are available, are shown in Figure 35.

Two X-Y plots (Figs. 36 and 37) are included in this report to show the wide variation in chemical compositions for metasedimentary rocks of the Fold-and-Thrust Belt (as to be expected). For example, the Trommald Formation (iron-formation) displays the widest range of variation regardless of rock type (thin-bedded versus thick-bedded, and oxidized versus unoxidized). However, the iron-formation in Glen Township (Pgti unit), and Fe-carbonate-bearing metasediments (carbonate facies iron-formation) in Glen Township, both plot as tight clusters.

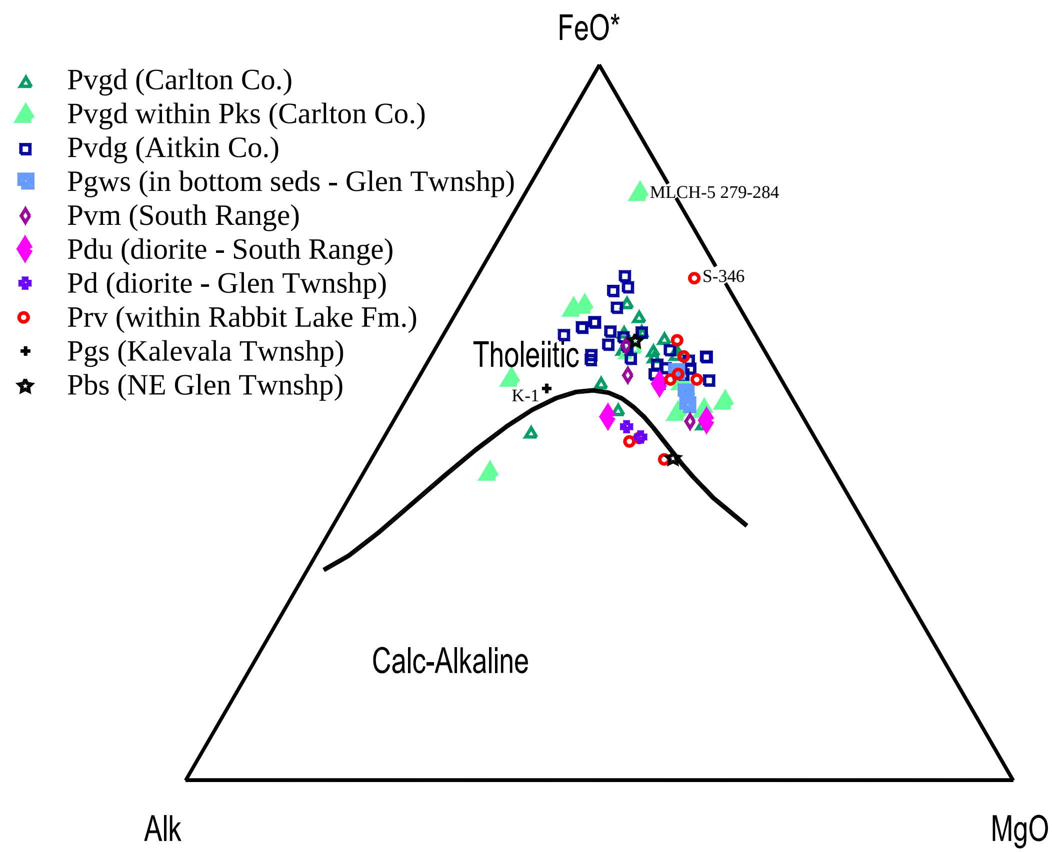

Figure 29 - AFM triangular plot for mafic volcanic and hypabyssal rocks in the Fold-and-Thrust Belt. The mafic rocks from the various map units generally plot within a tight cluster in the tholeiitic field, except for two very anomalous samples (S346 and MLCH-5 279-284 ft. = two of the three “suspect” samples). The anomalous nature of these two “suspect” samples probably reflects that either highly altered rocks were sampled, or the geochemistry results are flawed. *FeO = Total Iron.

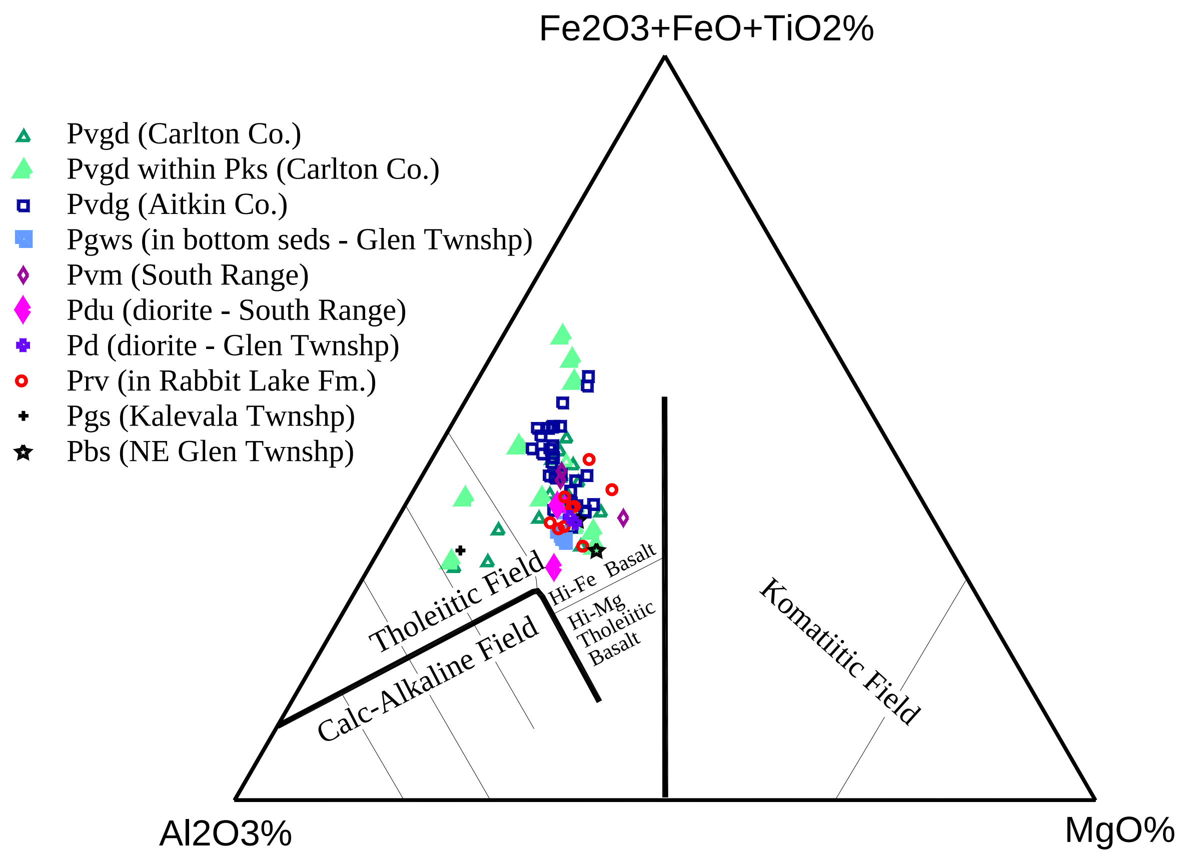

Figure 30 - Jensen Cation plot (Jensen, 1976) for mafic volcanic and hypabyssal rocks in the Fold-and-Thrust Belt. Note that mafic volcanic rocks of the Denham Formation (not shown) in Pine County also plot as calc-alkaline (Southwick et al., 2001).

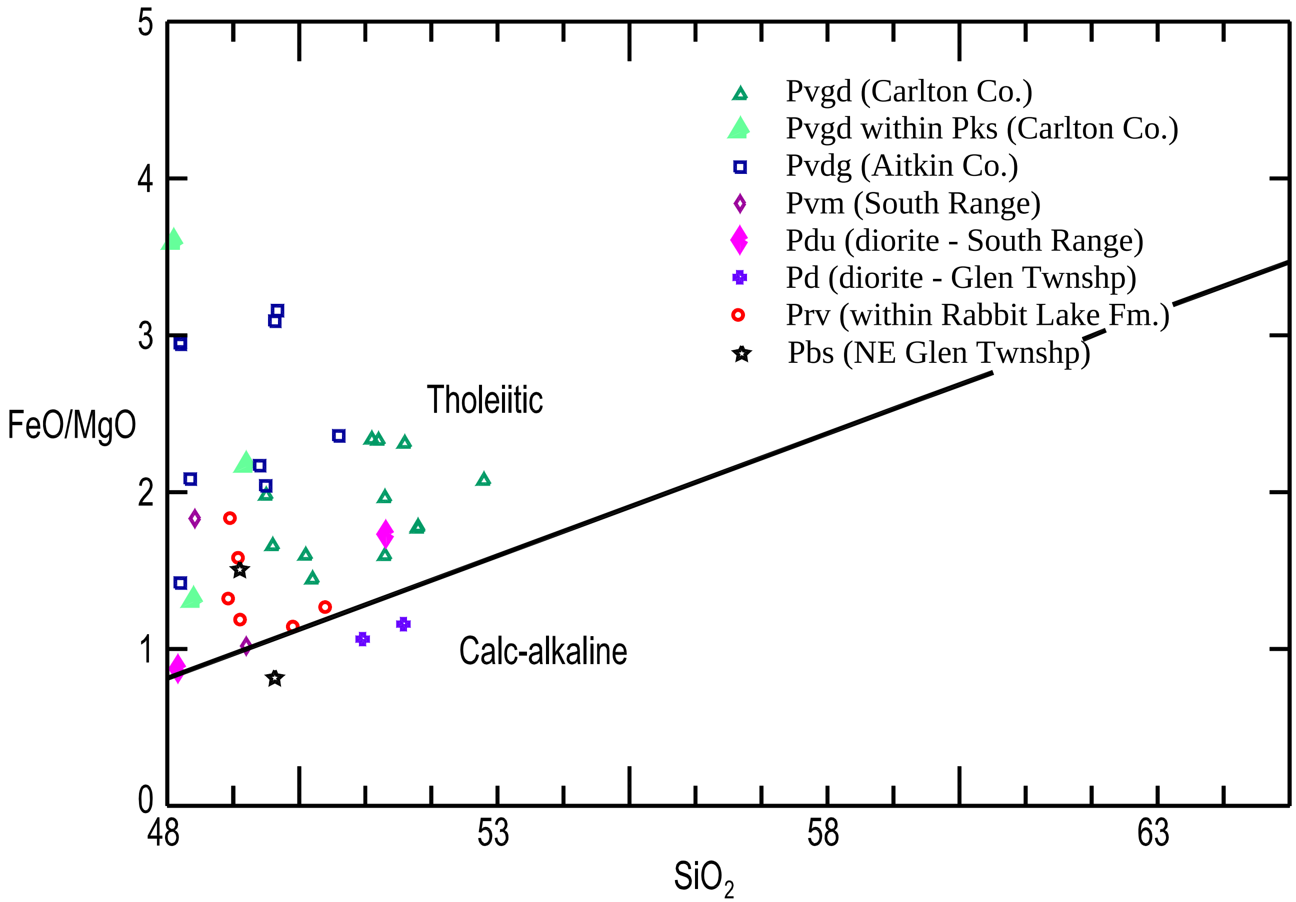

Figure 31 - Miyashiro diagram (Miyashiro, 1974) for mafic volcanic and hypabyssal rocks in the Fold-and-Thrust Belt.

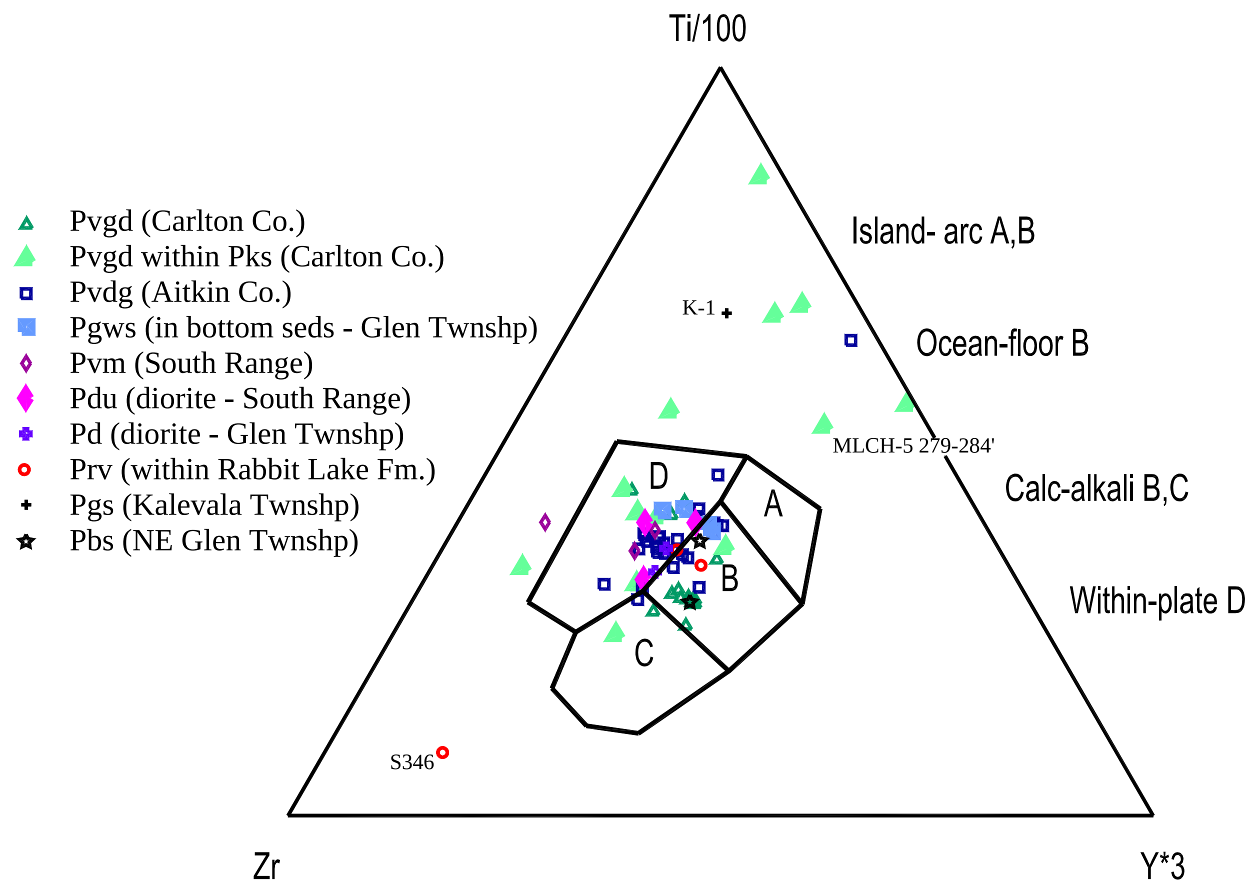

Figure 32a - Pearce-Cann diagrams (A and B; Pearce and Cann, 1973) for mafic volcanic and hypabyssal rocks in the Fold-and-Thrust Belt. Note the plotted positions of the three "suspect" samples (K-1, MLCH-5, and S346), as well as other anomalous plotted positions (the latter do not exhibit anomalous positions on the other plots).

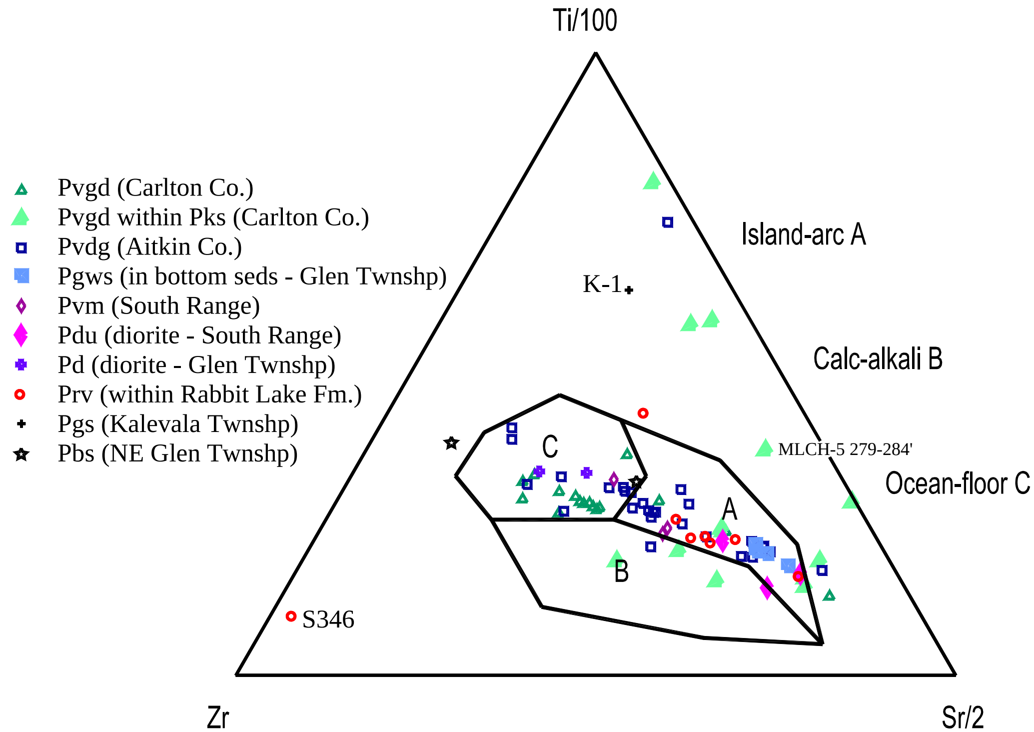

Figure 32b - Pearce-Cann diagrams (A and B; Pearce and Cann, 1973) for mafic volcanic and hypabyssal rocks in the Fold-and-Thrust Belt. Note the plotted positions of the three "suspect" samples (K-1, MLCH-5, and S346), as well as other anomalous plotted positions

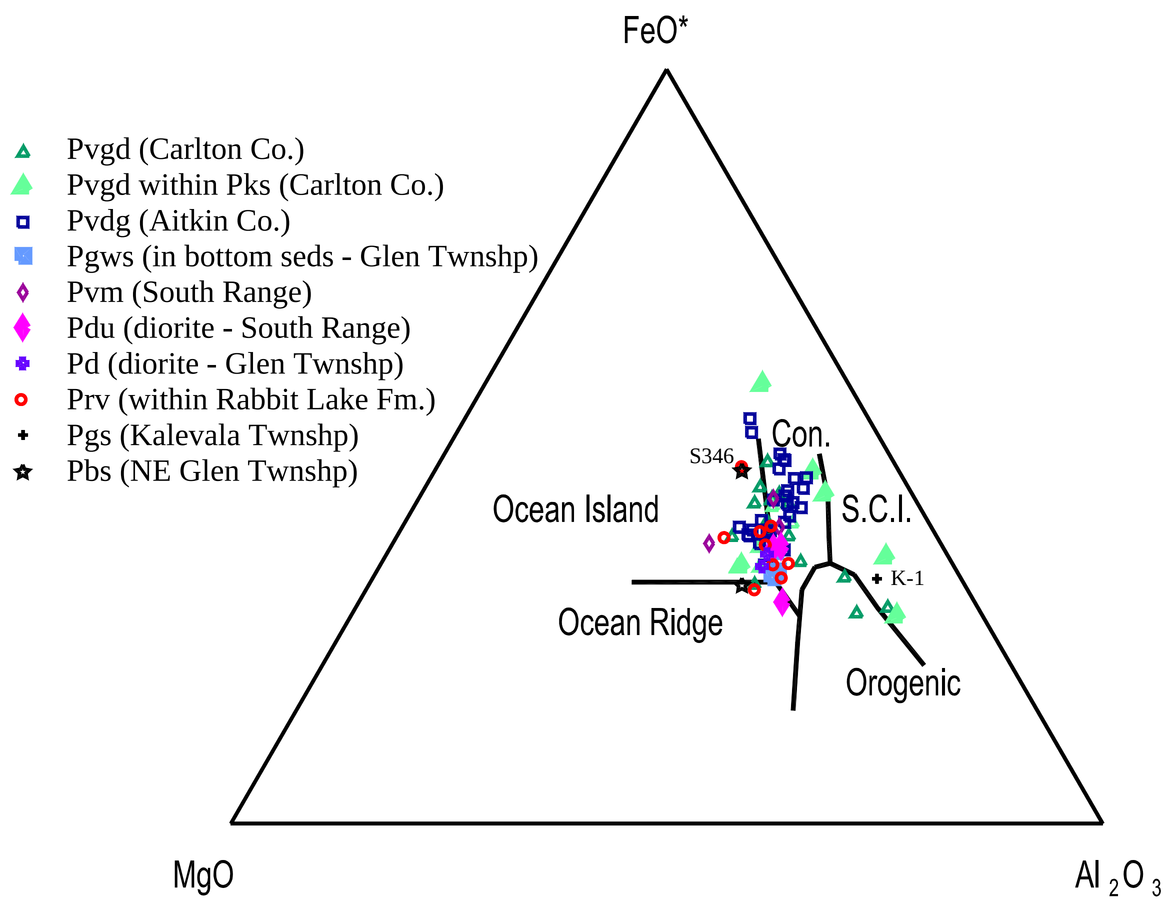

Figure 33 - Pearce diagram (Pearce et al.,1977) for mafic volcanic and hypabyssal rocks in the Fold-and-Thrust Belt. Con. = Continental; *FeO as Total Iron.

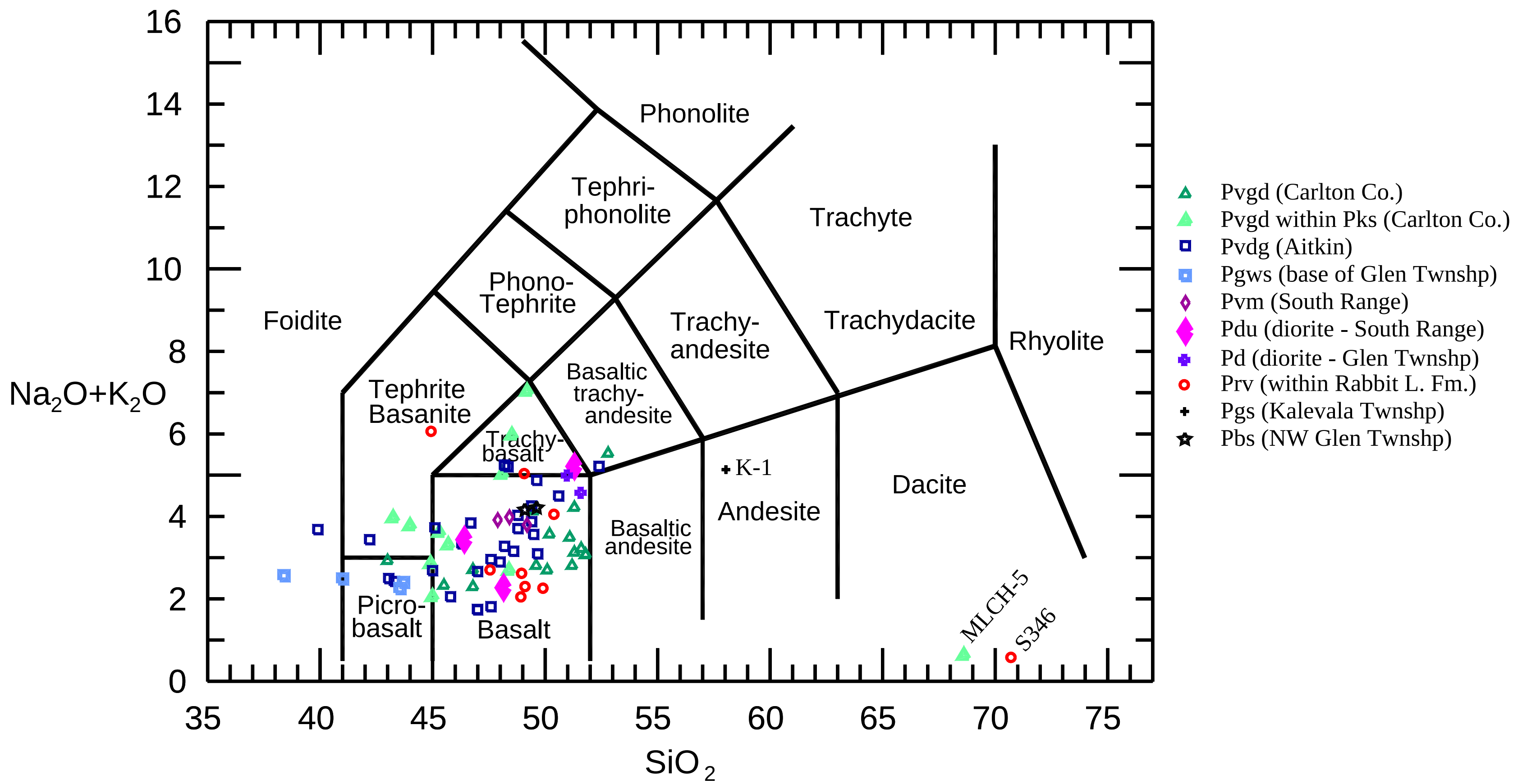

Figure 34 - Volcanic fields (LeBas et al., 1986) for mafic volcanic and hypabyssal rocks in the Fold-and-Thrust Belt. Note the plotted positions of the three “suspect” samples (K-1, MLCH-5, and S346).

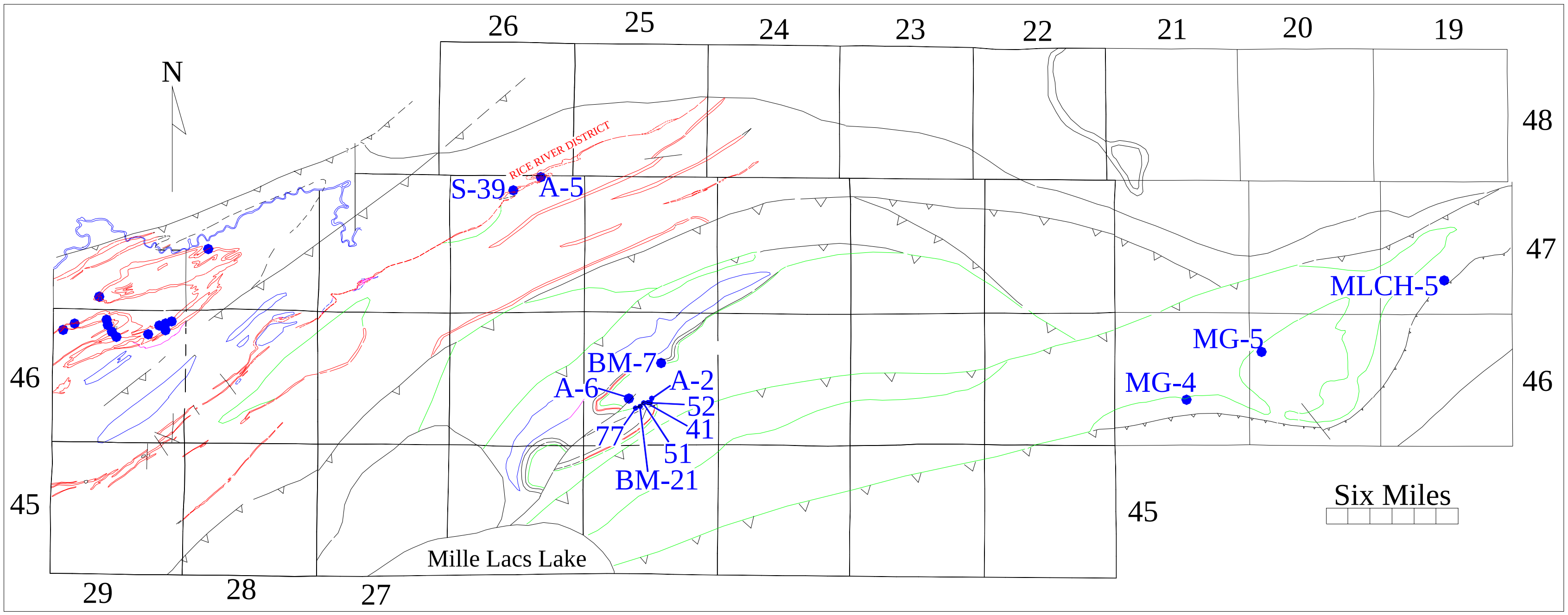

Figure 35 - Locations of drill holes that have whole rock analyses for metasedimentary rocks within the Fold-and-Thrust Belt. Note that holes on the left side of figure (Cuyuna North Range) are not individually labeled due to space considerations. Iron-formations are shown in red; "dioritic" intrusions are outlined in blue; and areas with dominantly mafic volcanic rocks are outlined in green.

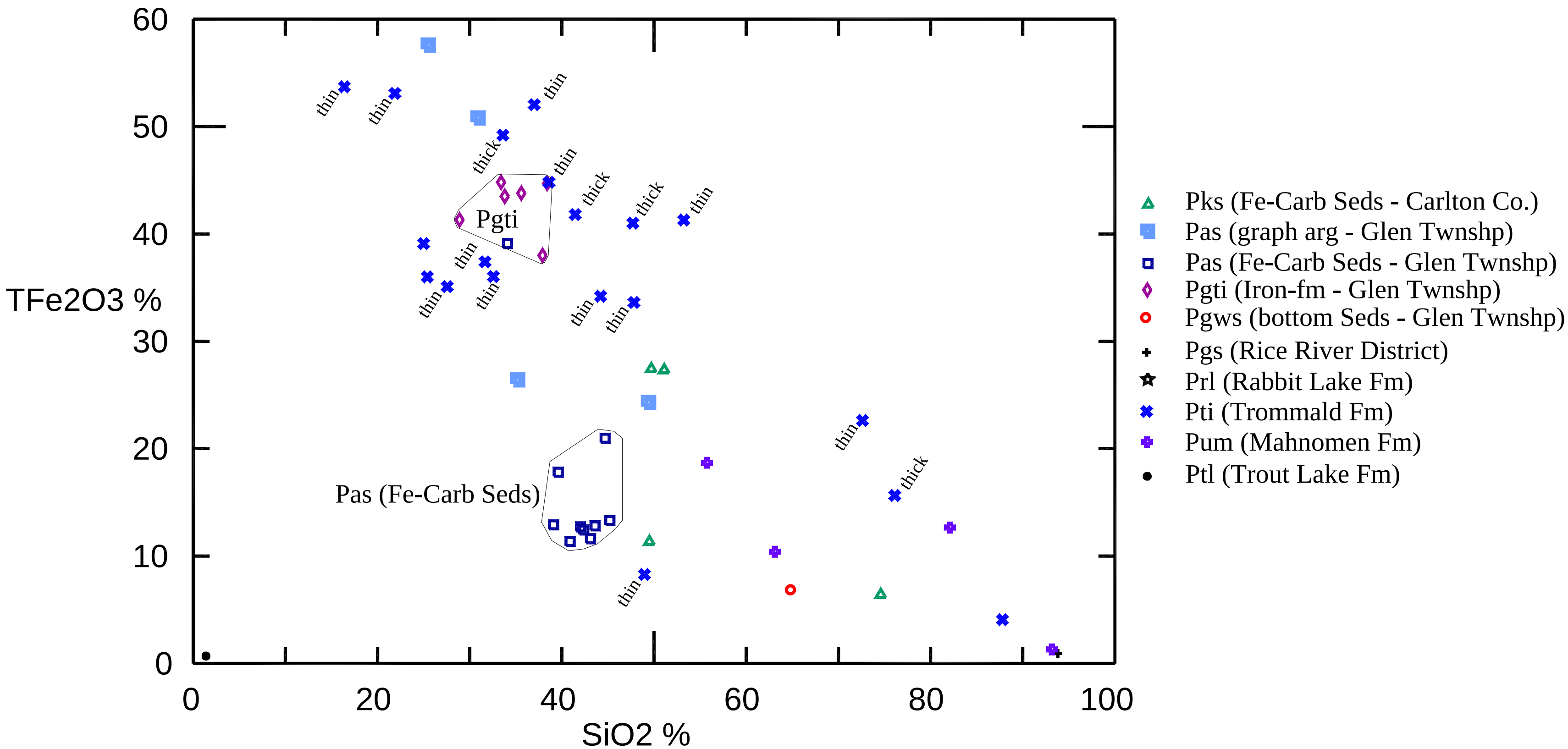

Figure 36 - SiO_2 versus TFe_2O_3 plot for metasedimentary rocks of the Fold-and-Thrust Belt. Only the iron-formation related samples from Glen Township (Pgti = magnetic iron-formation; Pas = "carbonate facies iron-formation") plot as tight clusters. Note that differences in types of Trommald Formation (thin-bedded iron-formation versus thick-bedded iron-formation) show no discernable pattern on this particular diagram.

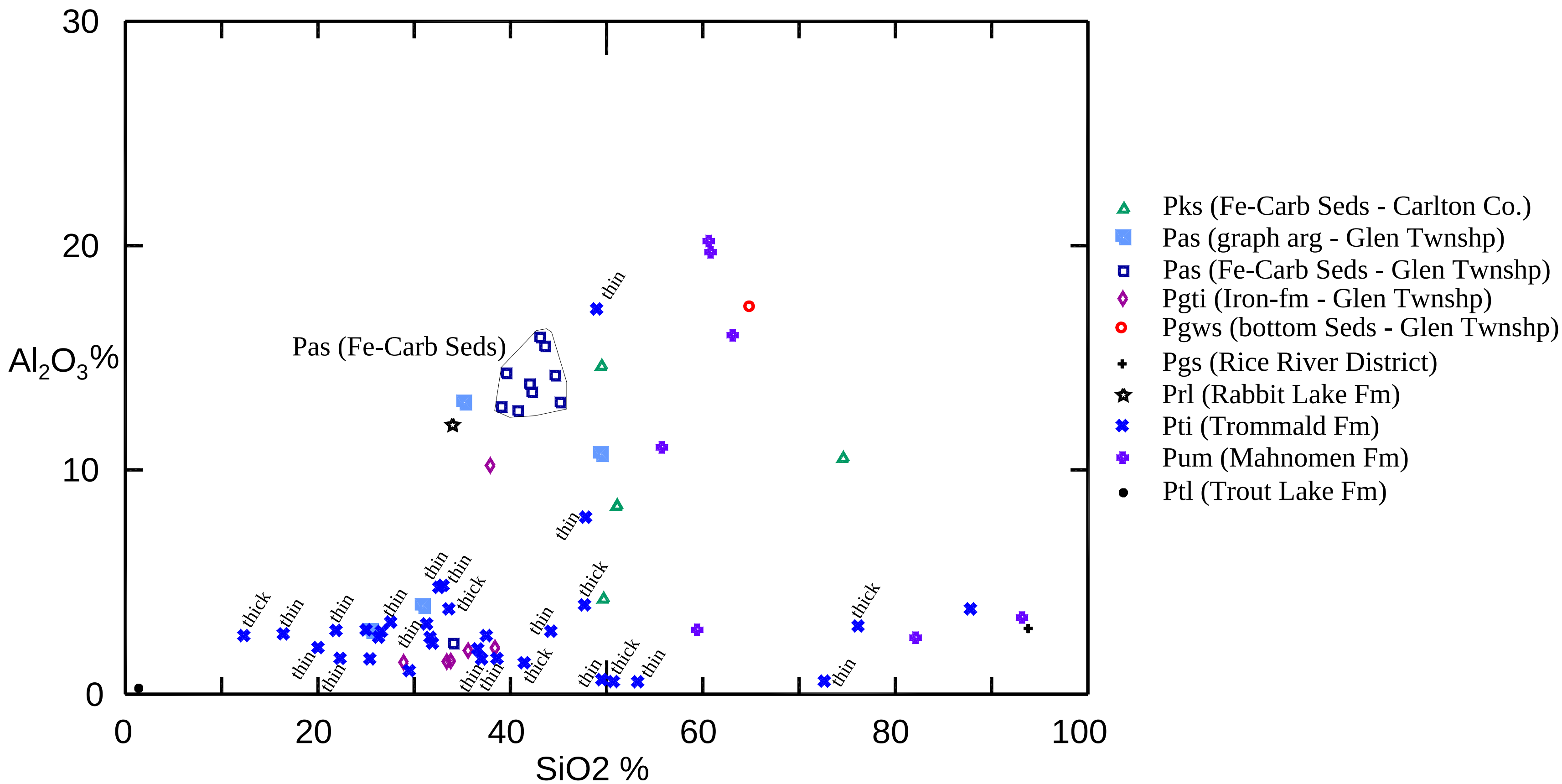

Figure 37 - SiO_2 versus Al_2O_3 plot for metasedimentary rocks of the Fold-and-Thrust Belt. Only the Fe-carbonate bearing metasediments (Pas unit; "carbonate facies iron-formation") from Glen Township plot as a tight cluster. Note that differences in types of Trommald Formation (thin-bedded iron-formation versus thick-bedded iron-formation) show no discernable pattern on this particular diagram.

ISOTOPE GEOCHEMISTRY

INTRODUCTION

Very little work has been done with respect to isotopes in the Animikie Basin and Fold-and-Thrust Belt. The vast bulk of previous isotopic research has been completed on samples of the Virginia Formation from drill holes in the vicinity of the Duluth Complex (Mainwaring and Naldrett, 1977; Ripley, 1981; Ripley and Al-Jassar, 1987; Severson, 1994; Zanko et al., 1994; and Arcuri et al., 1998). Most of this work deals with isotopic systematics between the Virginia Formation and Duluth Complex, and the details will not be discussed here; however, the data are incorporated in some of the various plots of this chapter. Isotopic research within the Fold-and-Thrust Belt is limited to only two studies (McSwiggen and Morey, 1989; Bekker, 1998).

McSwiggen and Morey (1989) conducted a study to estimate the potential energy content of carbonaceous (graphitic) argillaceous rocks intersected in several holes scattered throughout the Fold-and-Thrust Belt. In the course of their study, they obtained carbon isotope values (-22.44 to -32.18 per mil range) for five samples. Bekker (1998) obtained carbon and oxygen isotope values for the Trout Lake Formation and Denham Formation, and compared these two formations to other similar-age dolomite formations in the Lake Superior area (Bad River Dolomite, Kona Dolomite, and Randville Dolomite), as well as formations in Canada and Wyoming. He interpreted the Kona Dolomite to be slightly younger than the other dolomite formations based on carbon isotope systematics; however, no attempt was made to determine if the Trout Lake and Denham formations could be correlative.

THIS INVESTIGATION

Sixty-eight samples were collected for isotopic analyses in this investigation. The samples were selected from drill holes that are located in the Animikie Basin and in some of the structural panels within the Fold-and-Thrust Belt (Fig. 38). A variety of rock types were sampled and are listed in Table 9. The analyses were performed in 1999 by Dr. Edward Ripley at the Department of Geological Sciences, Indiana University, Bloomington, IN. Analyses are included Appendix 5 (*isotopetable.xls* and *Sedex isotope.xls* data bases on the CD in the back pocket of this report).

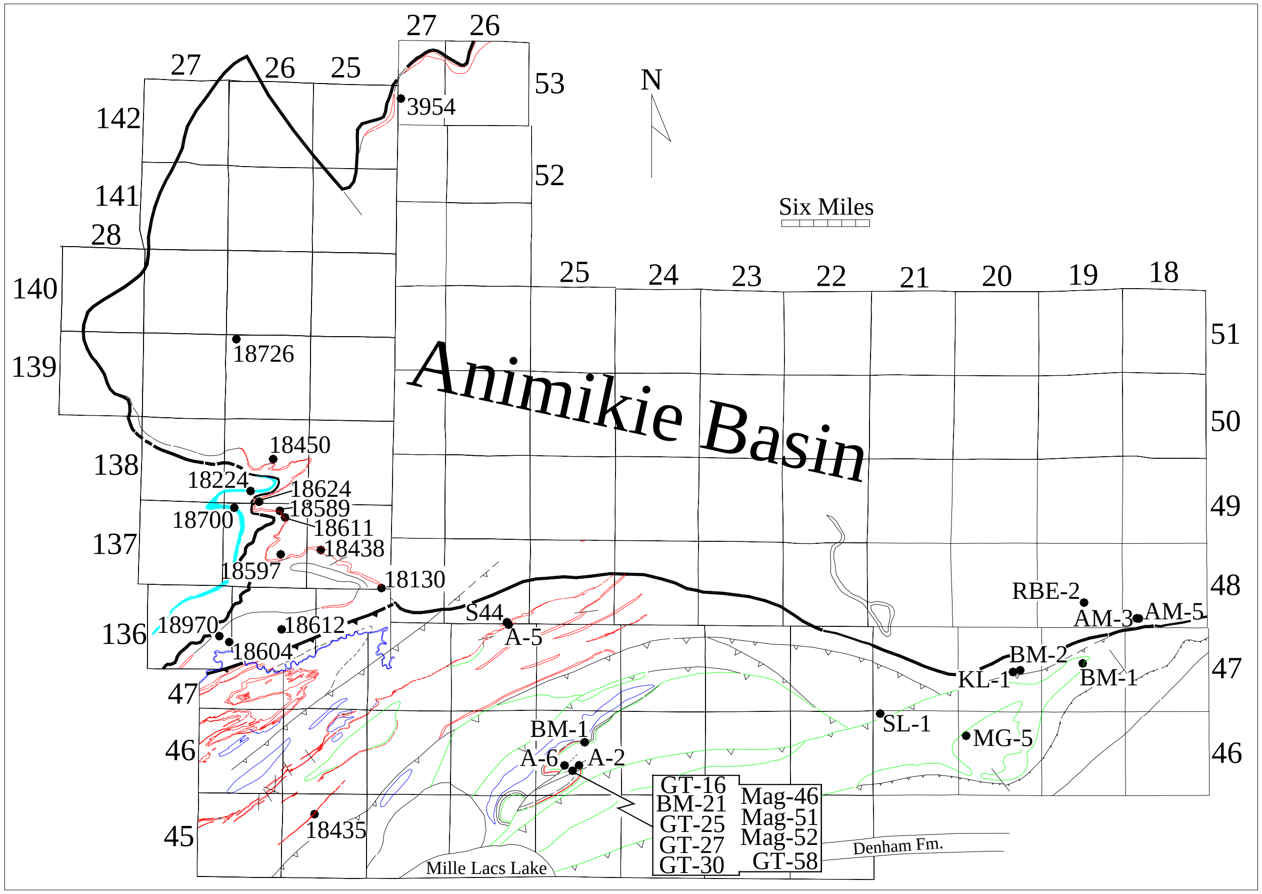

Figure 38 - Locations of drill holes that have been sampled for isotope analyses in this investigation. Samples were collected from several holes in the Glen Township area (T.46N., R.25W.), but they are too close together to show individually on this figure. [Note that the prefix GT- and Mag- are used as "place markers" to denote the Glen Township holes in this study only]. Drill hole 18224, in the North Emily District (center left side of figure), intersects a thick section of the Trout Lake Formation (shown in light blue) and was extensively sampled by Bekker (1998). Additional samples of the Denham Formation also sampled by Bekker (1998) are not shown, and are located to the south of the study area.

Rock Type	No. of Samples	Area	Map Unit
graphitic argillite	8	Emily District	Virginia Fm. (Pvti)
graphitic argillite	1	Western Mesabi (Cass Co.)	Virginia Fm. (Pvt)
graphitic argillite	5	SW edge of Animikie Basin	Thomson Fm. (Pvt)
graphitic argillite	1	Emily District	Pokegama Qtzte (Ppq)
graphitic argillite	15	Glen Township	Pas
graphitic argillite	5	FTB - Kalevala Township	Pgs
graphitic argillite	5	FTB- Kettle River etc.	Pks
graphitic argillite	3	FTB - Rice River District	Pgs
carbonate iron-fm.	2	Emily District	Virginia Fm.
carbonate iron-fm.	2	Emily District	lower iron-fm. (Peil)
ox. gran. iron-fm.	1	Emily District	main iron-fm. (Pei)
magnetic iron-fm.	3	FTB - Glen/Rice R.-So. Range	Pi (Pgti and Psri)
Fe-carb. sediments	4	FTB - Glen Township	Pas
Fe-carb. sediments	1	FTB- Kettle River etc.	Pks
mafic volcanics	4	FTB - Glen Twnshp & Kettle R.	Pvdg & Pvgd
dolomite	4	Emily and FTB - Denham Fm?	Ptl (1) & Pdam? (3)
limestone bed?	1	Western Animikie (Cass Co.)	Pvt (bed or concretion)
sulfides in veinlets	3	Glen, Rice R., Siphon Fault area	mixed
Total	68		

Table 9 - Listing of rock types sampled for isotopic analyses in this investigation. The dolomite that was sampled includes the Trout Lake Formation (Ptl unit - 1 sample) and a dolomite in MDNR drill hole BM-1 (possible Denham Formation? - Pdam unit?). Abbreviations: Co. = County; Fe-carb. = Fe-carbonate-bearing; FTB = Fold-and-Thrust Belt; ox. = oxidized; gran. = granular cherty; Qtzte = Quartzite; Twnshp = Township.

ISOTOPE RESULTS

The range of isotope values obtained in this investigation are included in Appendix 5 and are summarized in Tables 10 through 12. Figures 39 to 41 illustrate the distribution of sulfur, oxygen, carbonate oxygen, and carbon isotopic values in various samples from the Animikie Basin and the Fold-and-Thrust Belt. Stable isotopic data from the Virginia Formation adjacent to the Duluth Complex or hornfels inclusions within the Complex are not included. The sulfur isotopes in Figure 39 illustrate both lighter magmatic sulfur components and heavier closed euxinic basin values.

Area	Map Unit	δ34S sphal.‰ VCDT	δ34S pyrite ‰VCDT	δ34S whole rock ‰VCDT	δ34S sulfide ‰VCDT	δ34S pyrr. ‰VCDT	δ13C whole rock ‰PDB	δ23C low temp ‰PDB	δ13C high temp ‰PDB	dδ13C carb. ‰VDPB	δ18O carb. ‰ VSMOW
Animikie Basin RBE-1	Pvt				6.0	3.5 to 5.2	-26.0 to -30.2				
Animikie Basin Arrowhead mine	Pvt			5.3 to 5.5	8.4		-31.0 to -33.2				
Animikie Basin - No. Emily	Pvt & Pvti			5.6 to 11.0			-17.6 to -30.1	-6.5	-28.8		
Animikie Basin - So. Emily	Pvt & Pvti			6.6 to 6.9			-30.2 to -31.3				
FTB - Glen Twnshp	Pas	5.6	4.7 to 6.4	2.8 to 5.1		1.6 to 4.5	-12.0 to -21.5	-9.9 to -11.4	-22.0 to -27.9	-7.2 to -11.0	12.4 to 20.8
FTB - Kalevala Twnshp	Pgs?	-1.4	-5.6 to -0.4	5.8		-6.1 to -1.1	-13.1 to -26.0				
FTB - Kettle River	Pks			5.6	4.0 to 6.0	4.2	-21.1 to -22.6				
FTB - MNDR hole BM-1	Pks			2.2			-19.7 to -24.3				
FTB - Rice River Dist. - So. Range	Pgs	9.5	7.3	6.6 to 7.1			-22.6	-15.4	-30.5		

Table 10 - Sulfur, carbon, and oxygen isotope values for carbonaceous (graphitic) argillites in the southern half of the Animikie Basin and adjoining Fold-and-Thrust Belt. Drill hole locations are shown in Figure 38. Abreviations: FTB = Fold-and-Thrust Belt; sphal = sphalerite; pyrr = pyrrhotite; carb = carbonate.

Area	Map Unit	δ34S sphal ‰VCDT	δ34S pyrite ‰VCDT	δ34S whole rock ‰VCDT	δ34S sulfide ‰VCDT	δ34S pyrr ‰VCDT	δ13C carb ‰VPDB	δ18O carb ‰ VSMOW	δ18O silicate ‰ VSMOW
Emily Dist Carb. Iron-fm	Pvt & Pvti						-5.7 to -12.2	19.4 to 22.5	
Emily Dist ox. Iron-fm	Pei						-9.9	17.7	
Glen Twhshp Fe-Carb Seds	Pas	5.7	3.4	0.8			-9.2 to 1.8	12.9 to 32.6	
Glen Twnshp magnetic IF	Pgti								13.8
Kettle River Fe-Carb Seds	Pas						-7.0	12.3	
Rice River magnetic IF	Psri								10.7
South Range magnetic IF	Psri								13.0

Table 11 - Sulfur, carbon, and oxygen isotope values for iron-formation and related sediments in the Animikie Basin (Emily District only) and Fold-and-Thrust Belt. Material sampled includes: Carb. Iron-fm. = thin-bedded silicate-oxide-carbonate iron-formation; magnetic Iron-fm. = thin-bedded magnetic silicate-oxide iron-formation; and Fe-Carb Seds = Fe-carbonate-bearing metasediments. Abbreviations: ox = oxidized; sphal = sphalerite; pyrr = pyrrhotite; carb = carbonate.

<u>DOLOMITE</u>	**Map Unit**	**δ34S pyrite ‰VCDT**	**δ34S whole rock ‰VCDT**	**δ34S sulfide ‰VCDT**	**δ13O carbonate ‰VDPB**	**δ18O carbonate ‰VSMOW**
Emily Dist. - Trout L. Fm	Plt				-9.57 to 0.9	21.04 to 23.90
MDNR hole BM-1	Pdam?	28.9	10.0 to 28.9		2.1 to 2.7	18.0 to 20.3
Denham Fm. (Pine Co.)	Pdam				-2.63 to 1.77	14.81 to 20.47

<u>MAFIC VOLC</u>.						
Glen Township	Pvdg		2.1		-6.1 to -9.8	11.7 to 14.3
MDNR hole BM-1	Pvgd			-.01 to1.7	-4.9	11.9

Table 12 - Sulfur, carbon, and oxygen isotope values for dolomite and mafic volcanics in the Fold-and-Thrust Belt and Emily District. Isotope values for the Trout Lake Formation (Ptl) in the Emily District include data from Bekker (1998). Also included are isotope values from dolomite in the Denham Formation (Pdam) in Pine County (Bekker, 1998). A thick dolomite unit, intersected in MDNR drill hole BM-1, may be correlative with the Denham Formation.

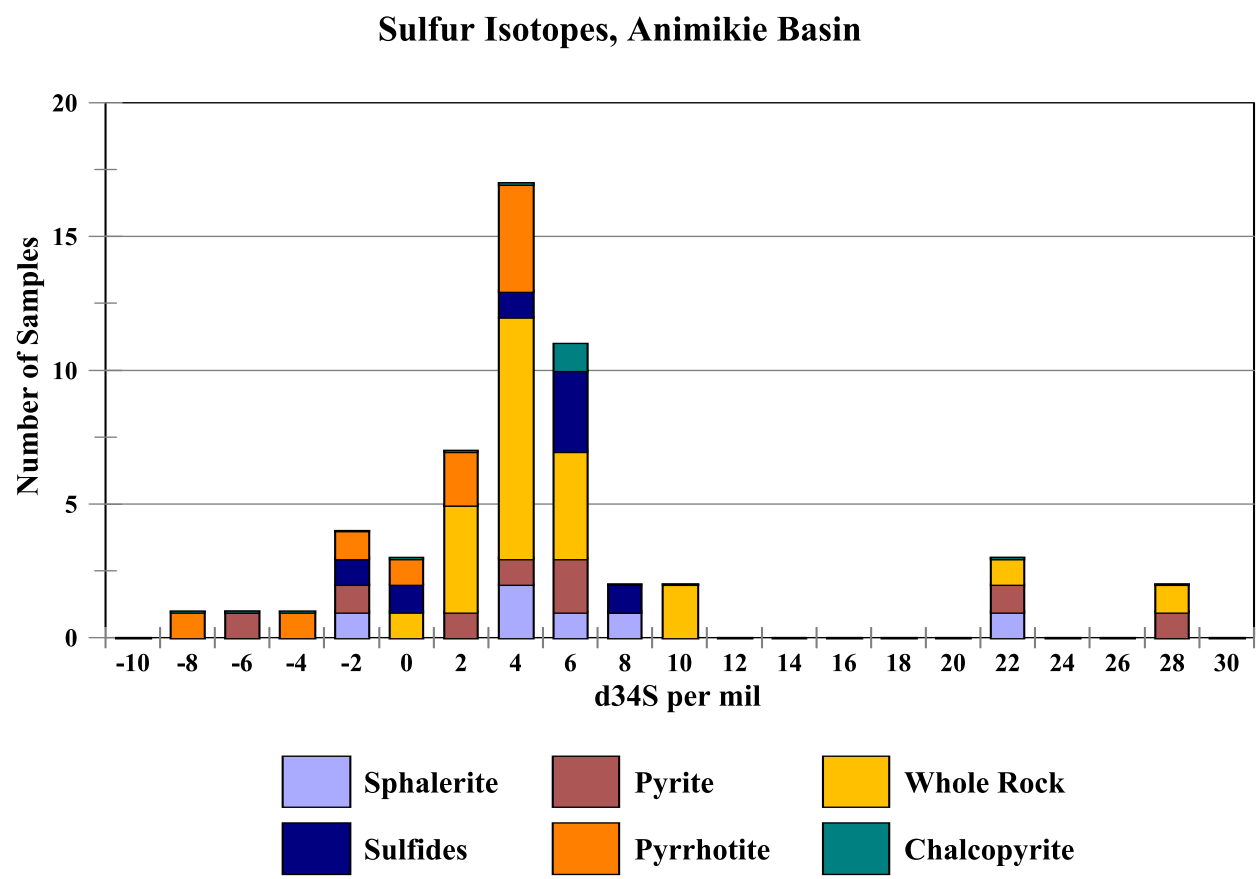

Figure 39 - Histogram of sulfur isotopes in the Animikie Basin and the Fold-and-Thrust Belt by mineralogy and whole rock analysis (all samples). Note presence of heavy "euxinic" isotopes and more volcanic or igneous isotopic values. Most samples are in the 4-6 per mil range suggesting mixing of both components. Samples within hornfels inclusions within the Duluth Complex or adjacent to the Complex are not included.

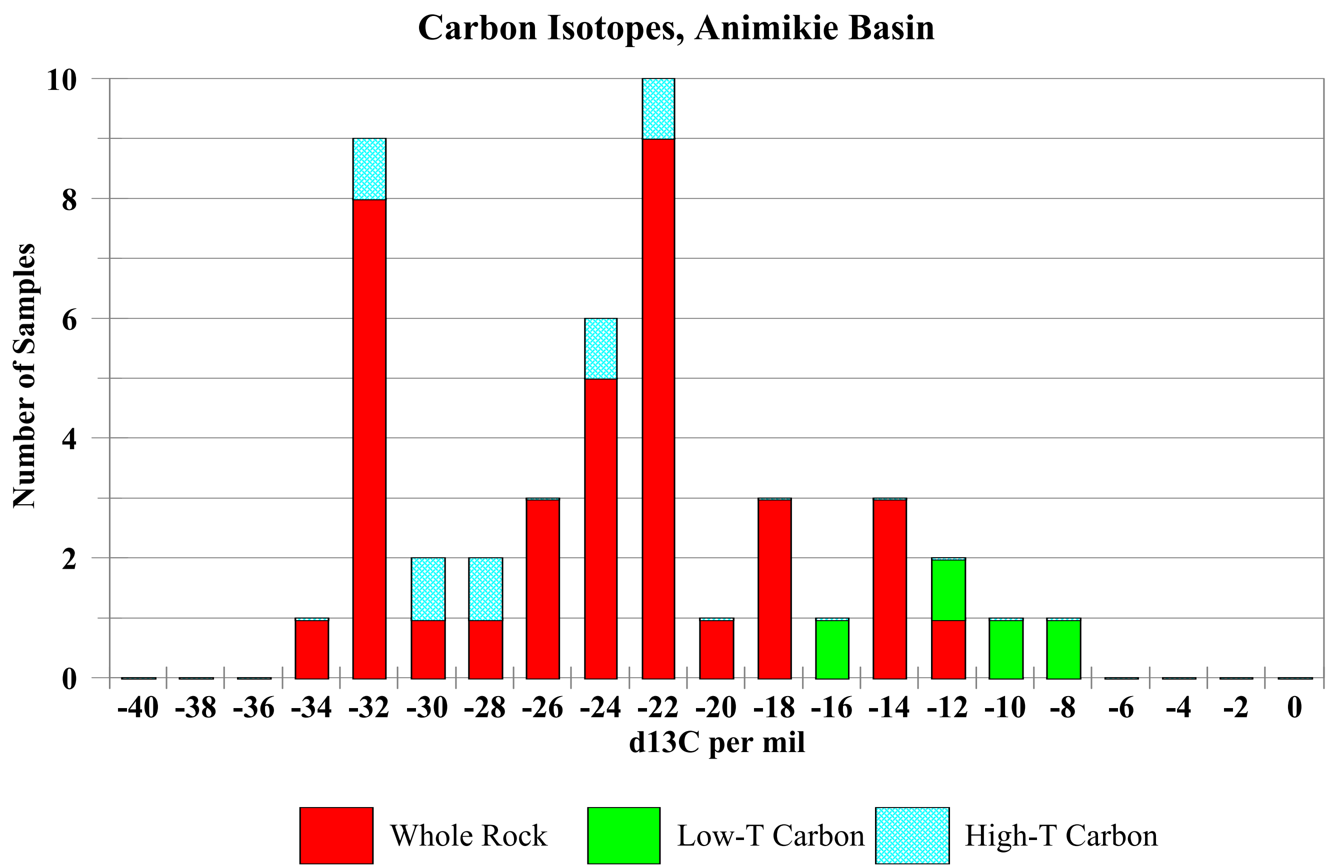

Figure 40 - Histogram of carbon isotopes in the Animikie Basin and the Fold-and-Thrust Belt. Samples within hornfels inclusions within the Duluth Complex or adjacent to the Complex are not included.

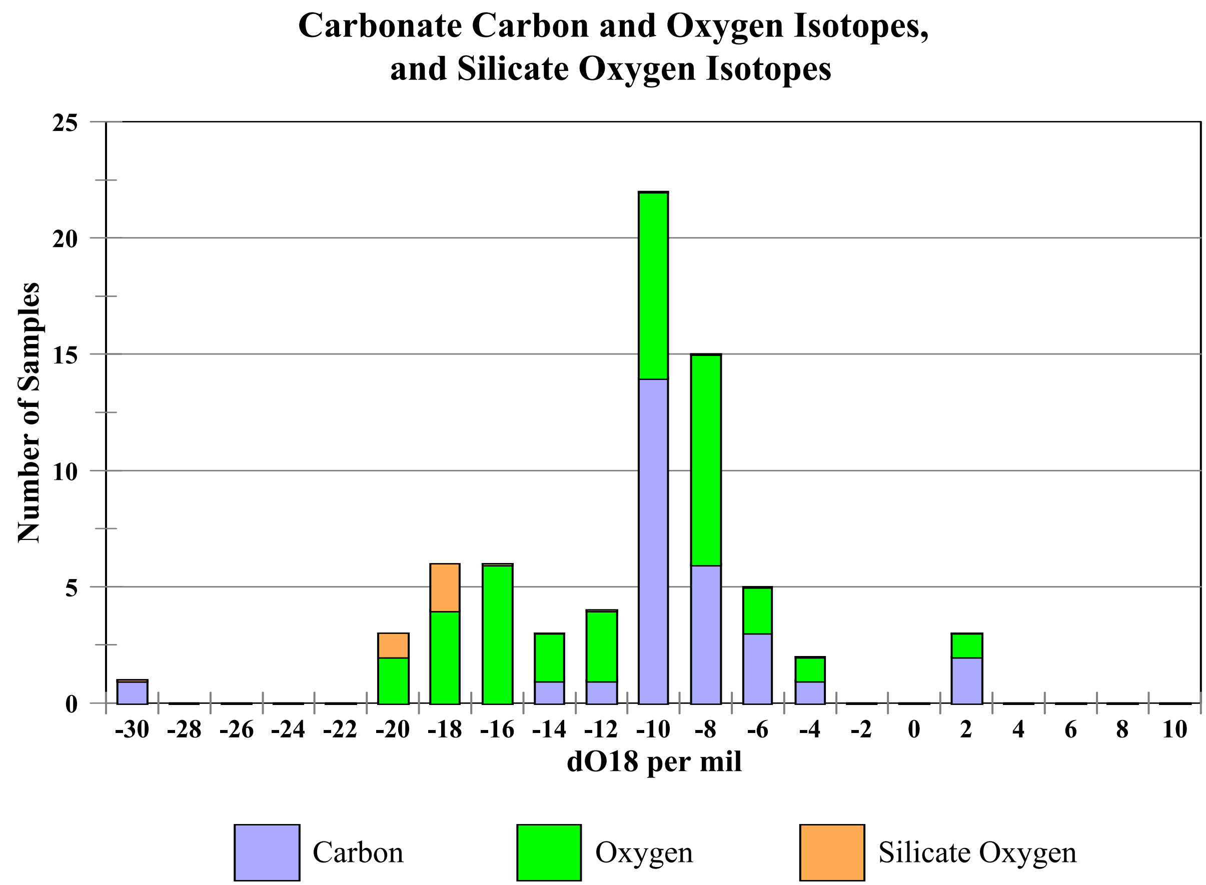

Figure 41 - Histogram of carbon and oxygen isotopes on carbonate samples from the Animikie Basin and the Fold-and-Thrust Belt. Samples within hornfels inclusions within the Duluth Complex or adjacent to the Complex are not included.

DISCUSSION OF ISOTOPE VALUES

The range of isotope values, per rock type and per map unit, are portrayed in Figure 42. As can be seen, the $\delta^{13}C$ whole rock carbonate values for the thin-bedded carbonate facies iron-formation are about the same as values for the Fe-carbonate-bearing metasedimentary rocks (the latter overlie the iron-formation in Glen Township). The same can be said for the $\delta^{18}O$ carbonate isotope values (iron-formation values = Fe-carbonate metasediment values). However, the $\delta^{13}C$, $\delta^{18}O$, and $\delta^{34}S$ values for the various carbonaceous (graphitic) argillite units show much different values than the other two rock types. Futhermore, the isotope values for each of carbonaceous argillite units shows some differences from one geographic location to another location. These differences are probably originally related to either euxinic closed basin conditions, magmatic (volcanic) input conditions, or combinations of the two. For example, the $\delta^{34}S$ values for the Pks (Carlton County) and Pas (Glen Township) units are much lower than all of the other carbonaceous argillite units. This relationship indicates that the Pks and Pas units have much lower $\delta^{34}S$ values due to a strong magmatic component - both of these units are intimately associated with mafic volcanics; whereas, no volcanics are present in any of the other units. The extremely high $\delta^{34}S$ values of the Bdd Po Unit (within the Virginia Formation in the vicinity of the Duluth Complex), indicate that these rock types formed in small closed basins under euxinic conditions. Also shown in Figure 42 are the range of $\delta^{34}S$ values for three Proterozoic SEDEX deposits. The range of isotope values found in carbonaceous argillites of this study show good comparisons with these three SEDEX deposits; however, the range of the three SEDEX deposits is quite large in the first place.

Ten samples of carbonaceous (graphitic) argillite from various holes at the Glen Township Sulfide - South Body were analyzed for $\delta^{34}S$. A profile of these isotope values is portrayed in Figure 43. [Note that the stratigraphic position of each sample in the various holes was determined by “dead reckoning” and should be considered to approximate]. The data crudely indicates that the $\delta^{34}S$ values increase, i.e., get heavier (less magmatic input), with height at Glen Township South. However, the $\delta^{34}S$ values are low overall suggesting that magmatic sulfur was also continually(?) added to the system.

Through the use of carbon and oxygen isotopes, Bekker (1998) interpreted that the Kona Dolomite in Michigan (Fig. 1) to be slightly younger than similar dolomite formations in the Lake Superior area (Trout Lake Formation, dolomite in the Denham Formation, Bad River Dolomite, and Randville Dolomite). However, no attempt was made by Bekker (1998) to determine if the Trout Lake and Denham formations could be correlative. Additional samples of this type of material were collected for this investigation and include the Trout Lake Formation (one sample in drill hole 18700) and a possible Denham Formation dolomite equivalent in MDNR drill hole BM-1 (two samples). The isotope data for this investigation, and for Bekker (1998), are plotted in Figure 44. In this diagram, the two samples from drill hole BM-1 clearly plot within the field defined by the Denham samples collected by Bekker (1998). This indicates that the dolomite in BM-1 could be correlated with the Denham Formation. However, the field defined by samples of the Trout Lake Formation fall within an entirely different position in Figure 44 indicating that the Trout Lake and Denham Formations are probably not correlative.

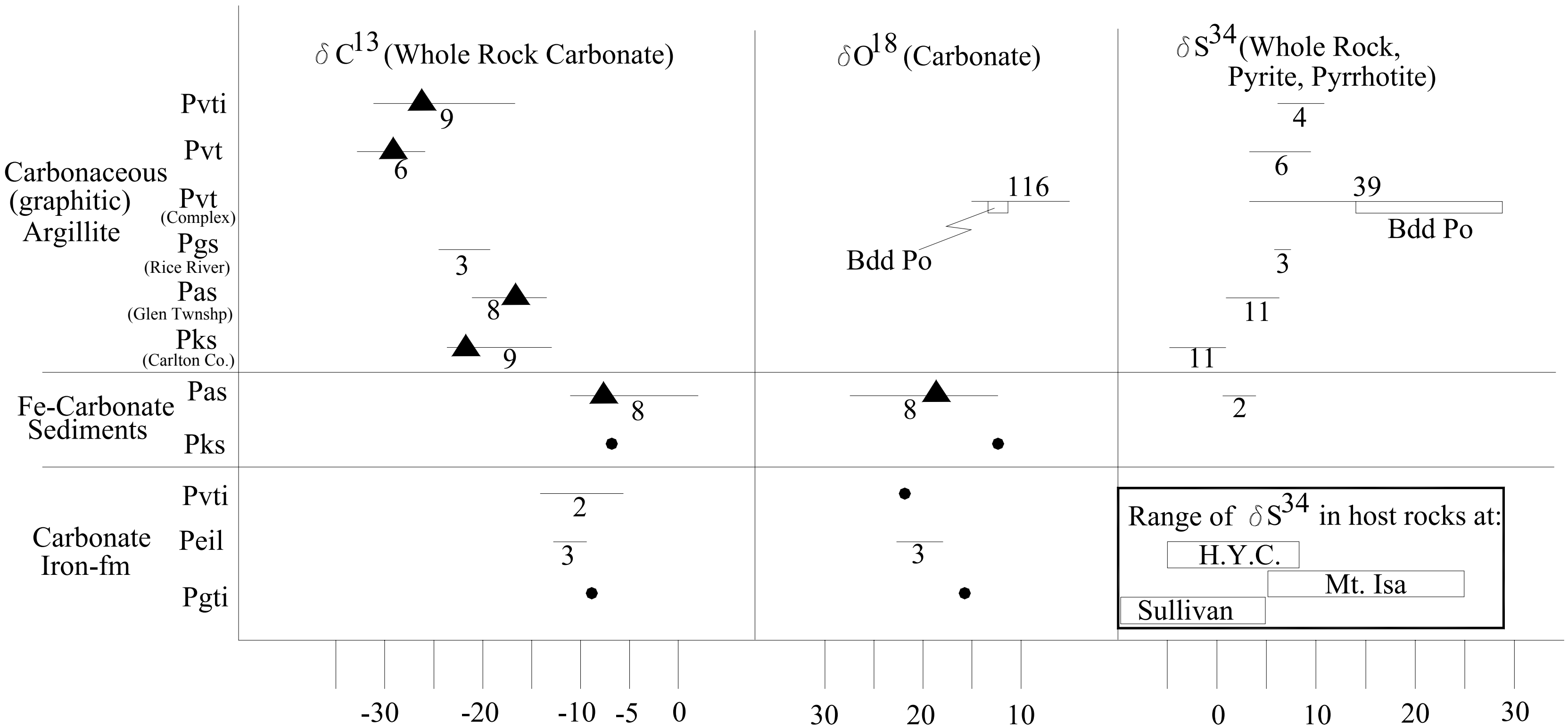

Figure 42 - Range of $\delta^{13}C$, $\delta^{18}O$, and $\delta^{34}S$ isotope values for various rock types and map units within the study area. Horizontal lines indicate the range of isotopic values for particular units; the numbers under the lines represent the total number of analyses for the unit. Triangles represent the average isotope value within a particular range, and single dots represent single isotopic values for a particular unit. The "Pvt (Complex)" unit consists of isotope values recorded for the Virginia Formation in the vicinity of the Duluth Complex (see references listed at the beginning of this chapter). The range of $\delta^{34}S$ isotope values for three Proterozoic SEDEX deposits are shown in the lower right corner of the figure - these data are from Ohmoto et al. (1985) and Large et al. (2001).

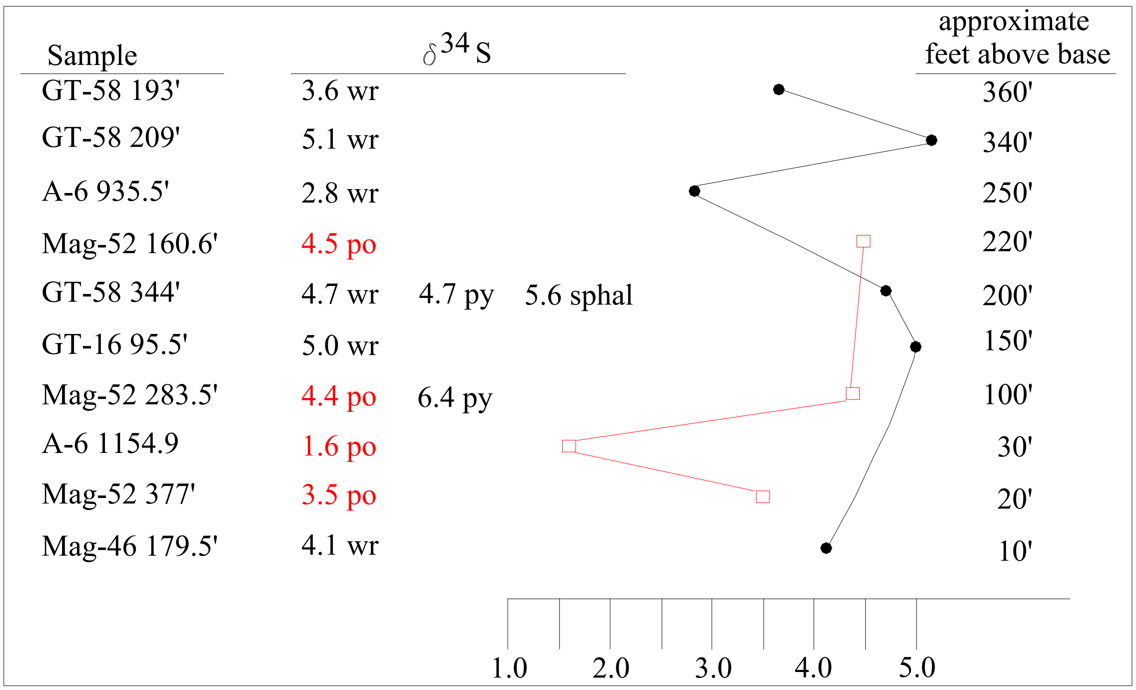

Figure 43 - Profile of $\delta^{34}S$ values with crude stratigraphic height within the carbonaceous (graphitic) argillite (Pas unit) at the Glen Township Sulfide - South Body, Aitkin County, Minnesota. The drill hole prefix GT- and Mag- are only used in this study as "place markers" to denote holes at Glen Township (GT) or Magoffin (Mag) holes - no such prefixes are used for the core that is actually stored at the MDNR in Hibbing, MN.

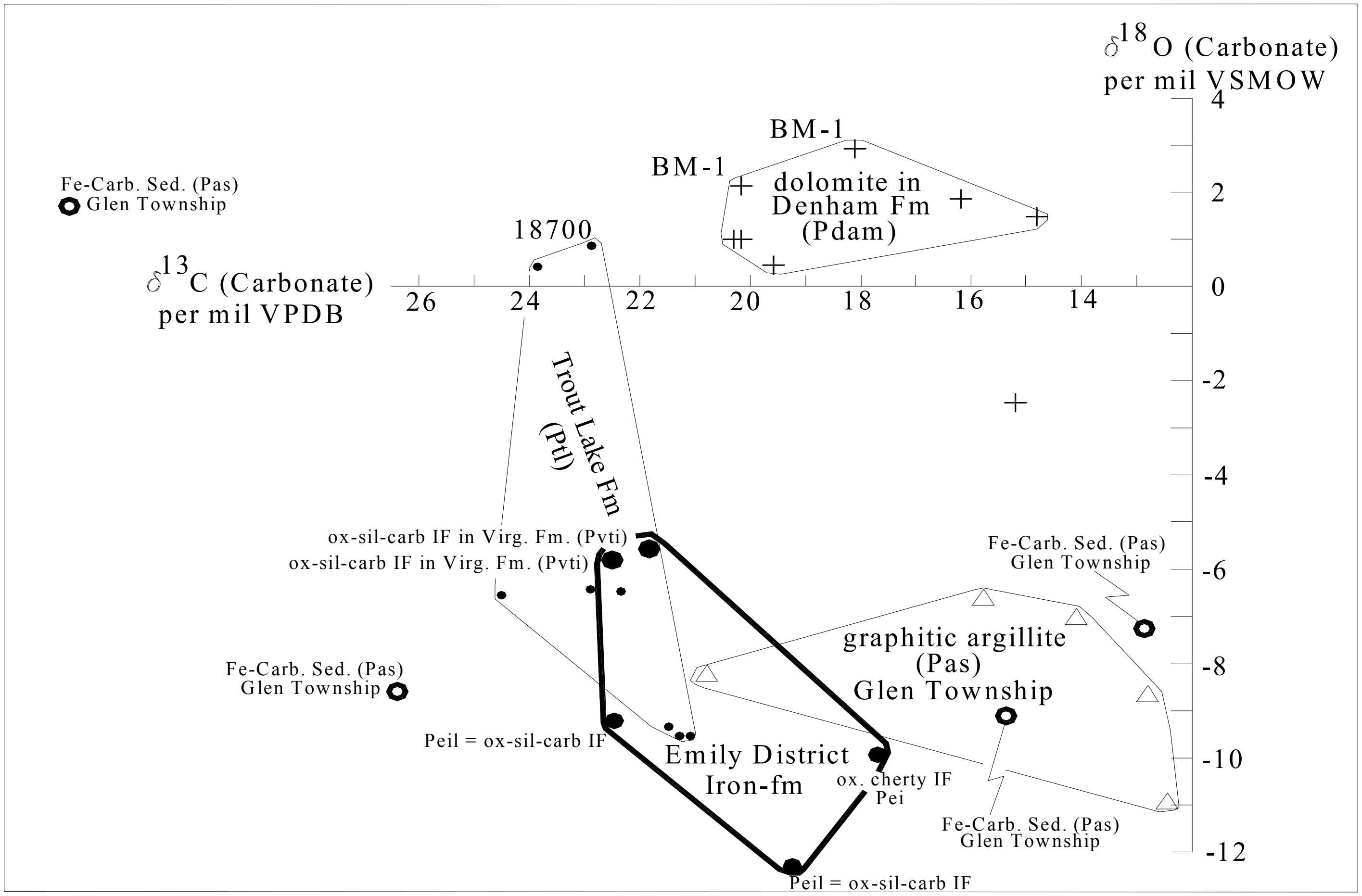

Figure 44 - X-Y plot of carbonate $\delta^{13}C$ versus carbonate $\delta^{18}O$ for five rock types/map units in the Fold-and-Thrust Belt. All but two of the Denham Formation dolomite values are from Bekker (1998); the BM-1 values were obtained in this investigation. All but one of the Trout Lake Formation samples are from Bekker (1998); the 18700 sample was obtained in this investigation. Other material sampled for this investigation includes several iron-formation types in the Emily District (Pvti, Pei, and Peil units), carbonaceous (graphitic) argillite from the Glen Township Sulfide - South Body (Pas unit); and Fe-carbonate-bearing metasediments from both the North and South Glen Township Sulfide bodies (Pas unit).

Other fields defined by the data in Figure 44 are carbonaceous (graphitic) argillite at Glen Township and iron-formation units from the Emily District. These are the first such samples for which carbonate $\delta^{13}C$ and carbonate $\delta^{18}O$ values have been obtained, and only continued sampling will determine whether these fields are unique. Also included in Figure 44 are samples from the Fe-carbonate-bearing metasediments from Glen Township. These samples are widely scattered in the diagram and cannot be used to define a particular field.

TOURMALINE ANALYSES

INTRODUCTION

Concentrations of tourmaline are present in some SEDEX deposits. Notable examples include: Sullivan, Canada; Broken Hill, Australia; Bleikvassli, Norway; Bergslagen, Sweden; Broken Hill, South Africa; Roseberry, Tasmania; and Yindongzi-Tongmugou, China; (Slack, 1996; and references therein). At Sullivan, the tourmaline occurs below the ore zone in the footwall rocks associated with a central vent zone; the tourmaline was deposited at lower levels in the system during exhalative deposition of the Pb-Zn-Ag ores (Slack, 1996). At Broken Hill, Australia, tourmaline occurs in stratabound horizons and as disseminations in a variety of rock types (Slack, 1996). In most of the above cases, the tourmaline is relatively Mg-rich (dravitic tourmaline) and in some greenschist-facies metamorphic terranes, can be used as a prospecting guide (Slack, 1996), e.g., the Sullivan deposit.

The presence of tourmaline, in close association with Paleoproterozoic iron-formations, has been found at several locations in Minnesota and include: Cuyuna North Range (Schmidt, 1963; McSwiggen et al., 1994, 1995; and Cleland et al., 1996); near the town of Philbrook in the Long Prairie Basin, Todd County (Boerboom, 1989); and Glen Township Sulfide - South Body (MDNR Drill Hole A-6; Dahlberg et al., 1987). Tourmaline concentrations have also been found in the Virginia Formation in the eastern Mesabi Range (this investigation). In all but one of these cases, the tourmaline is fine-grained and recognition of it was mainly accomplished through microscopic inspection. Thus, it is entirely possible that more as-yet-to-be-discovered tourmaline is present in other areas of Minnesota.

TOURMALINE COMPOSITIONS

Microprobe analyses of tourmaline from Glen Township (Table 1), the Siphon Fault area (Table 6) and Skibo South area (Tables 7 and 8) have already been presented in this report. These data, along with tourmaline compositions from Boerboom (1989) and Cleland et al. (1996), are included in the following figures and discussion.

In Figure 45, the tourmaline compositions generally fall within the compositional field defined by Henry and Guidotti (1985) as being characteristic of metapelites and metapsammites. Futhermore, the tourmalines from this investigation fall within the field defined by tourmalines in the host rocks at the Sullivan and Broken Hill deposits (fields from Slack, 1996).

In Figure 46, the ratios for tourmaline collected from Glen Township Sulfide - South Body, the Siphon Fault area, Skibo South area, and Philbrook area (Boerboom, 1989) plot within the field defined by tourmaline in the host rocks of the Sullivan deposit. The plotted relationships in Figures 45 and 46 suggests that these specific areas in the Proterozoic rocks of east-central Minnesota have some potential to host a SEDEX deposit, especially if it can be demonstrated that the presence of a tourmaline-bearing feeder vents are essential.

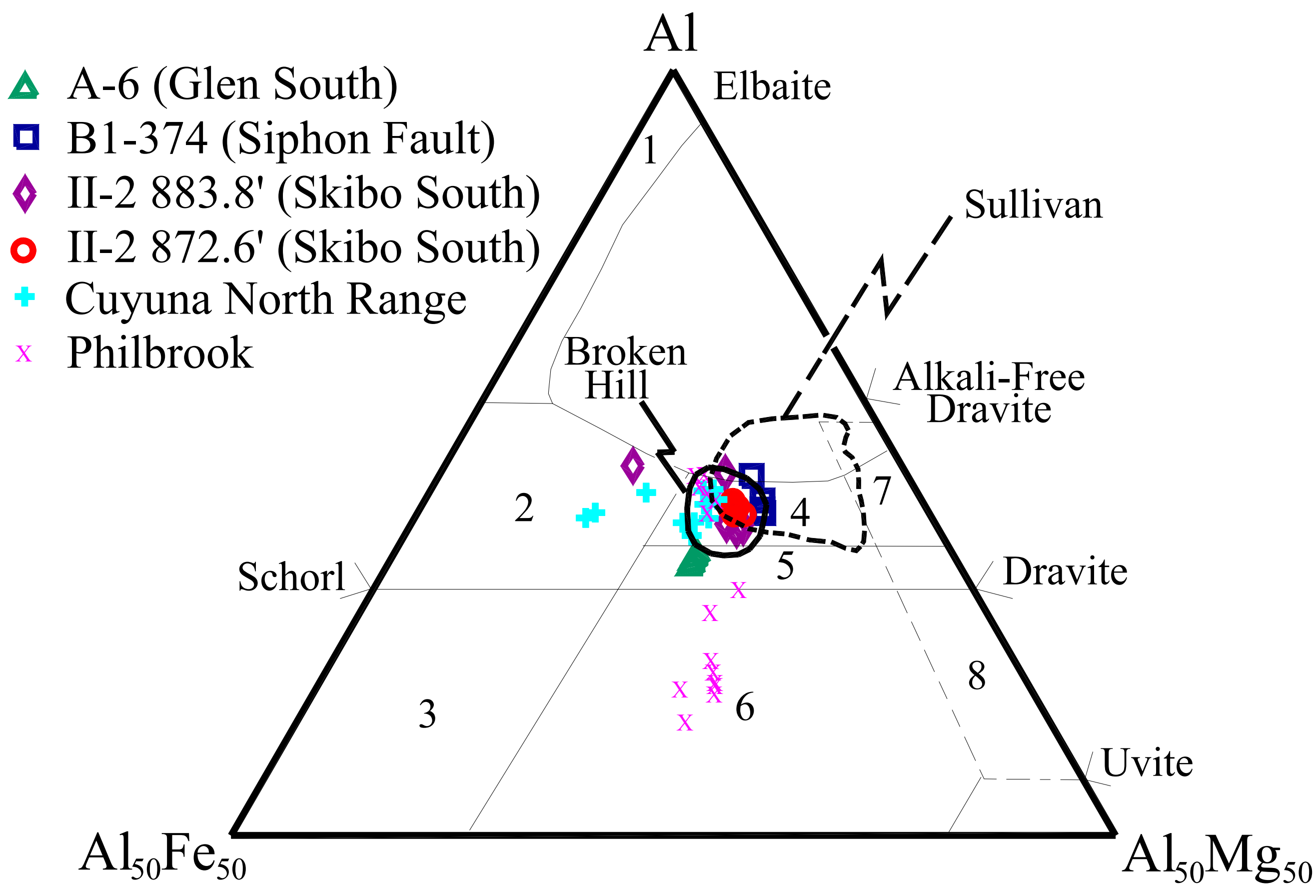

Figure 45 - Cation plot of microprobe analyses of tourmalines from the Glen Township (drill hole A-6), Siphon Fault area (drill hole B1-374) and Skibo South area (drill hole II-2). Diagram modified from Henry and Guidotti (1985) and Cleland et al. (1996). Circled fields outline tourmaline compositions in the host rocks at the Sullivan and Broken Hill deposits and are from Slack (1996). Numbered fields are defined by tourmaline compositions in various host rocks: 1 = Li-rich granitic pegmatites and aplites; 2 = Li-poor granitic pegmatites and aplites; 3 = ferric iron-rich quartz tourmaline rocks (hydrothermally altered): 4 and 5 = metapelites and metapsammites; 6 = ferric iron-rich quartz-tourmaline rocks, calc-silicate rocks, and metapelites; 7 = low Ca meta-ultramafic rocks and Cr- and V-rich metasedimentary rocks; 8 = metacarbonates and metapyroxenites (Henry and Guidotti, 1985).

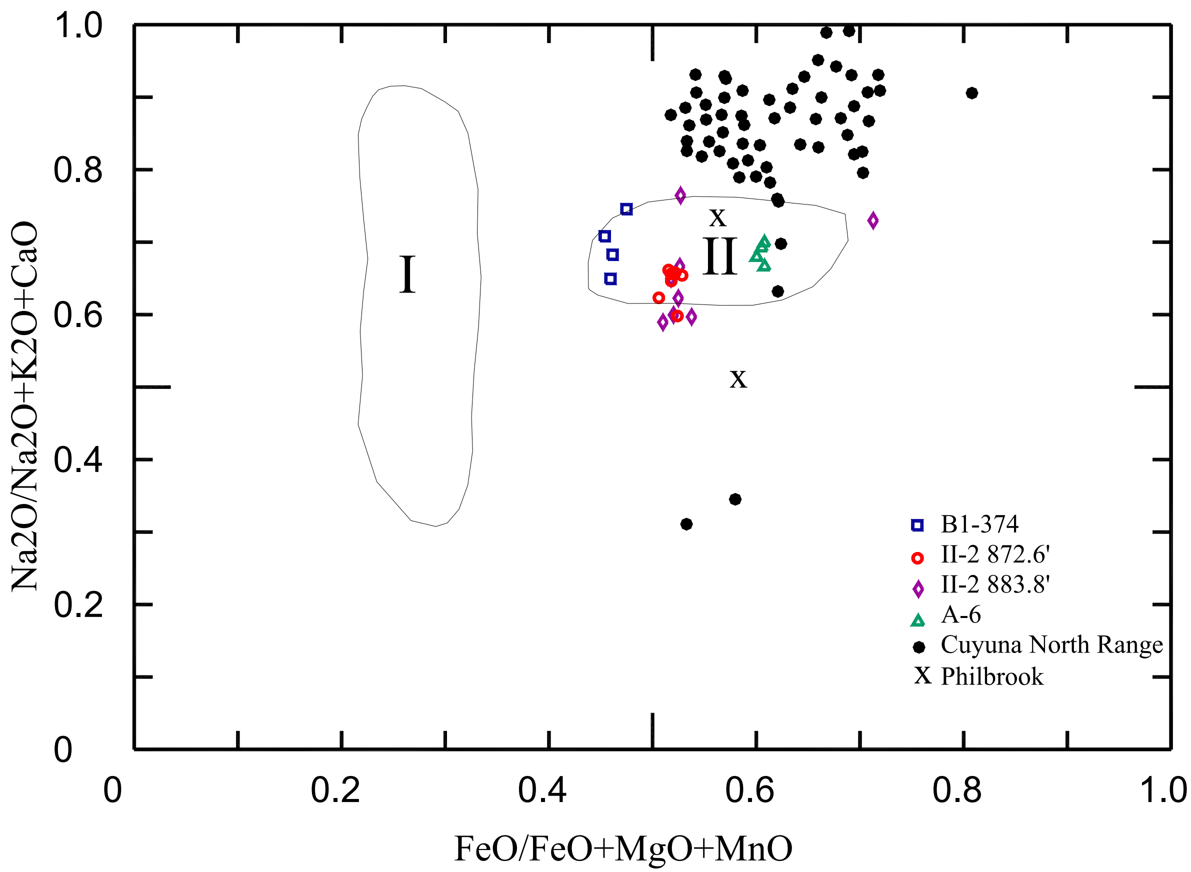

Figure 46 - Tourmaline compositions from Glen Township Sulfide - South Body (drill hole A-6), Siphon Fault area (drill hole B1-374), Skibo South area (drill hole II-2), Cuyuna North Range (Cleland et al., 1996), and Philbrook area (Boerboom, 1989). Outlined areas (I = Sullivan ore body, II = host rocks at Sullivan) are from from Ethier and Campbell (1977).

SUMMARY AND CONCLUSIONS

One major drawback in conducting a regional study for SEDEX potential in east-central Minnesota is that, in an area with very little outcrop, one is often limited to discussions of the geology that is present in much smaller areas where a fair amount of drilling has taken place. Each of these smaller areas can then be evaluated in terms of meeting certain SEDEX criterion; whereas, the vast bulk of the overall area outside of the drilled areas represents uncharted territory. Keeping these conundrums in mind, Table 13 is offered as a means of evaluating the SEDEX potential of several site-specific areas where the available amount of drill holes or geochemical analyses are plentiful. Each of the areas are evaluated as to whether they do or do not contain specific SEDEX indicators, as has been outlined in the first chapter of this report. In some drilled areas (Table 13), there are no known indications of SEDEX mineralization; whereas in other areas, several criteria for potential SEDEX mineralization may be met, or at least hinted at.

Whole rock geochemical data reiterate the conclusion of Southwick et al. (2001) - that the mafic volcanic rocks in the Fold-and-Thrust Belt are high-Ti tholeiites that can be inferred to have been deposited in an extensional setting. Compositions of some of the tourmalines found in close association with iron-formation suggest that some areas have tourmalines that are similar to the tourmalines in the host rocks at the Sullivan deposit, which contains a tourmaline-bearing hydrothermal pipe. In conclusion, areas that exhibit the best potential for hosting a SEDEX deposit include the following.

Kalevala Township, Fold-and-Thrust Belt, Carlton County -

- Up to 2.5% zinc in drill hole K-1.
- Visible sphalerite in core associated with late veins.
- Presence of thin beds of delicately-bedded semi-massive sulfide ("brown beds") with very fine-grained syngenetic sphalerite.
- Abrupt upward sedimentary facies changes from coarse-grained clastic sediments to deep water euxinic sediments indicates possible fault zones (proper plumbing?) and possible smaller second and third order basins.
- Mafic volcanics (Pvgd unit - flows and hypabyssal sills) are present in nearby structural panel to the south.

Glen Township Sulfide - South Body, Fold-and-Thrust Belt, Aitkin County -

- Thick package of carbonaceous, sulfide-rich argillite (Pas unit) in close associated with Fe-carbonate-bearing sediments and chemical iron-formation (Pgti unit). Sulfide-content in the carbonaceous argillite increases upward indicating a closed basin.
- $\delta^{34}S$ isotope values show a very crude upward increase within the carbonaceous argillite (Pas unit); however, isotope values are low overall (1.6 to 6.4 $\delta^{34}S$) indicating that a magmatic (hydrothermal?) component was probably active - the argillite is capped by a mafic volcanic unit (Pvdg unit).
- Gabbroic sills, possible heat sources, are present in all rock units.
- Carbonate alteration, related to hydrothermal activity(?), is present in localized zones in the mafic volcanics.

LEGEND

X	present
(x)	very locally present
-	not present
	can't tell - not enough core
?	possible or probable - not enough core
D	distal
reg	related to regional metamorphism

Lyndon, 1996 (intracratonic/epicratonic); Large, 1980 (first order basins through third order basins); Goodfellow et al., 1996 (third order basins through feeder pipe with alteration); Sangster and Hillary, 2000 (oxide facies iron-formation onward)

Area	intracratonic/epicratonic	first order basins (>100 Km)	second order basins (10s of Km)	sudden sedimentary changes	minor tuff and/or sills	synchronous voluminous volcanics	Range of Sulfur isotopes (d34S) in graphitic agrillite	geochemical halos	third order basins (euxinic environment)	growth faluts	chert	rift-related basins	carbonates (calcite, siderite, ankerite, etc.)	feeder pipe with alteration	oxide facies iron-formation	anomalous zinc	maximum zinc (%)	delicately-bedded sulfides (distal?)	tourmaline	approximate age (Ga)
Arrowhead Mine	X	X		-	-	-	5.3-5.5		X	?						X	0.55			1.8
Kalevala Township	X		?	X	X	X	-6.1 to -0.4		X	?			reg			X	2.25	X		
Kettle River	X		?		X	X	4.0-6.0		?				reg			(x)	0.74			
Split Rock	X		?	?	X	X			?				reg			(x)	0.11			
Glen Township - South	X		?	X	X	X	1.6-6.4		X	?	X		X	?	X	X	0.39	X	X	2.2
Glen Township - North	X		?	?	?	X			X				X		X	(x)	0.07			2.2
Dam Lake	X		?	-	?	D			-		-		-		-	-				
South Range (Aitkin Co.)	X		?	?	X	X			?	?					X					
Rice River District	X		?	-	?	D	6.6-23.4		X	?	X				X	X	.28*			
Portage Lake Belt	X		?	?	?	X			X		?		-	-	X	?		?		
Kimberly Belt	X		?	?	?	X			X		?		-	-	X	?		?		
Scallon-Todd	X	X	-	-	-	-			-		X	-	-	-	D?	-		-		
South Range (Crow Wing Co.)	X	X	?	X	X	X			X	?	X		X		X	?		?		
North Range of Cuyuna District	X	X	X	(x)	X	D		Ba? B?	X	?	X	X	X	X	X	(x)	.07*	(x)	X	1.8-2.2
North Emily District	X	X	X	X	?	?	5.6-11.0		X	?	X		X		X	-	<.01	X		1.8
South Emily District	X	X	X	X	?	?	6.6-6.9		X	?	X		X		X	-	<.01	X		1.8
Cass County	X	X	?	-	-	-			?				-		X	-		-		1.8
Itasca County	X	X	?	-	-	-	8.4		?		X				X	-		-		1.8
Siphon Fault (St. Louis Co.)	X	X	X	?	?	-			X	X	X				X	X	2.65	X	X	1.8

Table 13 - Chart listing specific SEDEX-related features that may, or may not, be present at specific areas within either the Animikie Basin or Fold-and-Thrust Belt of east-central Minnesota. Areas listed are those studied in this investigation - other unstudied areas with SEDEX potential are probably present in undrilled areas or in areas outside of this investigation, e.g., the Philbrook area of Todd County (Boerboom, 1989). * = maximum Zn value based on very limited assays.

- Tourmalines, with a composition similar to tourmalines in the host rock at the Sullivan deposit, are present within an argillite interbed (in drill hole A-6) within the overlying mafic volcanics (Pvdg unit).
- Chlorite-rich rocks are present in a four-foot thick zone beneath the iron-formation in drill hole A-6. The alteration may be indicative of local feeder vents.
- There are numerous sedimentological facies changes in many of the metasediments of the Pas unit indicating that localized faulting (growth faults?) was important.
- Visible sphalerite is present in at least six drill holes (hole numbers 42, 46?, 51, 52, 54, and 58).
- Delicately-bedded, thin, semi-massive sulfide beds ("brown beds") are present in drill hole #58. The beds contain common amounts of microscopic syngenetic sphalerite, but zinc assays are not particularly encouraging.
- Unfortunately, limited zinc analyses to date indicate a maximum of only 0.39% zinc.
- Collectively, the holes with visible sphalerite, "brown beds," and the most "anomalous" zinc values are clustered in the northeastern corner of Section 28, T.46N., R.24W. - this appears to be the best area in the South Body.

North Range of the Cuyuna District -

- The most encouraging evidence for SEDEX mineralization is the presence of tourmaline in four drill holes. This, and data from Severson and Heine (2003), suggests that there may be several hydrothermal vent areas in the North Range. However, the tourmalines have higher FeO/(FeO+MgO+MnO) ratios than tourmalines at the Sullivan deposit.
- The presence of aegirine, hyalophane, and Sr-rich barite, in addition to the tourmaline, suggests the presence of a hydrothermal system (Cleland et al., 1996).
- Sulfide-bearing iron-formation and sulfide-rich argillite are documented in the Portsmouth Mine area.
- "Anomalous" Ba values are common to the west of the Portsmouth Mine. Barite is reported in the Portsmouth Mine and in other mines to the immediate west.
- Based on limited boron analyses (57), the highest B values are present in drill hole S-310 to the west of the Portsmouth Mine.
- The geometry of the iron-formations suggests the presence of second and third order basins.
- Mafic volcanic rocks are locally present within the Rabbit Lake Formation.
- Collectively, the presence of tourmaline; sulfides (in the Trommald and Rabbit Lake formations); barite; and "anomalous" Ba, Zn, and B suggests that the best SEDEX potential resides in Sections 2, 4, 9, 10, and 11, T.46N., R.29W.

Siphon Fault Area, Northeastern Edge of Animikie Basin, St. Louis County -

- The Siphon Fault is a growth fault.
- Some fairly high zinc values (0.61%, 1.03%, and 1.67-2.65 % Zn) have been obtained from three drill holes to the east of the Siphon Fault.
- A 1.6 foot thick semi-massive sulfide layer is present in a hornfels inclusion in drill hole B1-117 at the Babbitt Cu-Ni deposit (1.67-2.65% Zn). The semi-massive sulfide consists of pyrrhotite (30%) and syngenetic sphalerite

(20%) with occasional remobilized, discontinuous, lensoidal, sphalerite-rich veinlets up to 1.0 cm thick (Severson et al., 1996). A sulfur isotope value obtained for this zone is 10.7 ‰.

- Visible sphalerite is observed in several holes to the south of the now inactive LTV Taconite Mine. The sphalerite is present at the very base of the Virginia Formation and very top of the Biwabik Iron Formation to the west of the Siphon Fault.
- Traces of sphalerite, from both megascopic and microscopic observations, are found in another seven drill holes in the same general vicinity of the Siphon Fault.
- A large zoned tourmaline crystal (indicative of a hydrothermal system?) was found in drill hole B1-374 in the footwall rocks at the Babbitt Cu-Ni deposit (Plate VI). Microprobe analysis of the tourmaline suggest that it is similar to tourmalines at the Sullivan Mine.
- Some of the BDD PO units contain high copper values (up to 0.6%) - the copper content appears to increase toward the Duluth Complex. $\delta^{34}S$ isotope values indicate that the BDD PO units were deposited in closed third order basins.
- The Cr-rich Sill at the base of the Virginia Formation could have been emplaced during(??) sedimentation of the Virginia Formation, and **if** so, the sills could represent a potential heat engine as envisioned for the Moyie sills at the Sullivan deposit.

Arrowhead Mine, southeastern edge of Animikie Basin, Carlton County -

- Carbonaceous, sulfide-bearing argillite (Pvt unit) is present.
- $\delta^{34}S$ isotope values indicate deposition in a closed third order basin.
- Anomalous zinc value, up to 0.5% Zn, are present in many drill holes - however, many of the holes with anomalous zinc are rotary holes (many of these values are suspect - see text).
- The area is within one mile of the Fold-and-Thrust Belt. Possible faults (growth faults?) and the proper plumbing for hydrothermal systems can easily be envisioned along the northern (leading) edge of the Fold-and-Thrust Belt.

While the above listed areas contain many features indicative of potential SEDEX mineralization, there are several more areas that also exhibit some of the same features; albeit, the evidence is less evident and more sparse overall. The areas with lower but still some potential for SEDEX deposits, include the following.

North Emily District, Southwestern Edge of Animikie Basin, Crow Wing County -

- The Pvti unit appears to be the most prospective rock type. It is the main sulfide-bearing unit in the North Emily District. Overall, the Pvti unit is characterized by abrupt and often highly localized changes in the types of sediment deposited indicating that faulting (growth faults?) and small basins (third order?) are present. A close association with iron-formations and euxinic environments is also indicated for this unit. Delicately-bedded sulfide-rich beds ("brown beds") are locally present in the Pvti unit.

- However, out of 31 samples collected mostly from the Pvti unit, a disappointing maximum value of 87 ppm Zn is all that has been indicated to date.

South Emily District, Southwestern Edge of Animikie Basin, Crow Wing County -

- The same reasoning for the North Emily District applies to the South Emily District.
- The mapped distribution of the Pvti unit, as determined from scattered drill holes, suggests that this unit is thicker and more widespread in the South Emily District.
- The leading (northern) edge of the Fold-and-Thrust Belt is located to the immediate south. The thrust fault that marks the leading edge may have provided the proper plumbing for hydrothermal fluids.
- Out of 21 samples, only a maximum of 291 ppm Zn is indicated.

Glen Township Sulfide - North Body, Fold-and-Thrust Belt, Aitkin County -

- Both the South and North bodies exhibit the same stratigraphy. Thus the same reasoning for the Glen Township Sulfide - South Body can be applied to the Glen Township Sulfide - North Body. However, sulfide content within the carbonaceous argillite (Pas unit) is generally much lower at the North Body.
- Out of 31 samples, only a maximum of 694 ppm Zn is indicated.

Kettle River and Split Rock Areas, Fold-and-Thrust Belt, Carlton County -

- Sulfide-bearing carbonaceous rocks (Pks unit) are present in both areas. It is difficult to assess the sedimentological depositional environment at either area as structural deformation and metamorphism are more intense in both areas.
- Mafic volcanics (Pvgd unit) are voluminous at both areas.
- Up to 0.74% Zn is present at Kettle River; up to 0.22% Zn is present at Split Rock.

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APPENDICES

APPENDIX 1

DRILL HOLE LOCATIONS
(listed by County)

The next several pages list most of the pertinent data regarding drill hole locations in the following sections.

Appendix 1A – Aitkin County
Appendix 1B – Carlton County
Appendix 1C – Cass County
Appendix 1D – Crow Wing County
Appendix 1E – Itasca County
Appendix 1F - St. Louis County

For more complete information refer to the *basinholeco.xls* data file included on the CD in the back pocket of this report.

Drill hole locations are listed according to UTM (Nad27) coordinates, and according to Section-Township-Range (S-T-R) coordinates. In some cases, a location is known only to the nearest 40 acre parcel, and thus, the UTM coordinates given in the data base are highly generalized (see UTM comment in the last column of the data base). Also included in this data base are:

- location relative to a geographic area or mine where the hole was drilled;
- geologic map unit (adapted from Boerboom et al., 1999a, 1999b; and from maps in this investigation);
- drill core storage location (MDNR, MGS, USS, Cleveland Cliffs, etc.);
- MDNR drill core unique numbers if the hole is stored at the MDNR;
- abbreviated old drill log description (from paper copies of old logs at the MDNR);
- abbreviated drill log description (logged in this investigation);
- attitude of bedding (S_0) relative to drill core axis; and
- attitude of cleavage (S_1) relative to drill core axis.

Note that the first column in the data base lists a specific ID# for each hole. The ID# consists of an abbreviation for the county followed by the drill hole number (abbreviations for counties are: a = Aitkin, cn = Carlton, cs = Cass, cw = Crow Wing, I = Itasca, and sl = St. Louis). For example, *as4* denotes drill hole S-4 in Aitkin County. In some cases there may be two (or more) holes in the same county with the same designation, e.g., two S-4's, and in this case the string "county-hole number-section-township-range" denotes the particular hole. For example, *as4164825* denotes a drill hole S-4 in Aitkin County in Section 16, T.48N., R.25W. This ID numbering system is also used in many of the data files in the other Appendices of this report.

APPENDIX 2

GEOCHEMISTRY

Data files pertaining to geochemical results, on the CD in the back pocket of this investigation, are broken down as follows:

basinchemco.xls - all geochemical results from drill core (arranged by county).

allbasinwr.xls - all whole rock geochemical results for the study area; data was gleaned from the *basinchemco.xls* data file.

allbasinplot.xls - whole rock geochemical data for only volcanic and plutonic rocks within the study area. This file was used in making the geochemical plots of this report.

1999wr.xls - whole rock geochemical results for samples collected in this investigation (these data included in the above two data files).

1999bm.xls - base metal geochemical results for samples collected in this investigation (all of these data are included in the *basinchemco.xls* data file).

Note that the first column in the data base lists a specific ID# for each hole. The ID# consists of an abbreviation for the county followed by the drill hole number (abbreviations for counties are: a = Aitkin, cn = Carlton, cs = Cass, cw = Crow Wing, I = Itasca, and sl = St. Louis). For example, *as4* denotes drill hole S-4 in Aitkin County. In some cases, there may be two (or more) holes in the same county with the same designation, e.g. two S-4's, and in this case the string "county-hole number-section-township-range" denotes the particular hole. For example, *as4164825* denotes a drill hole S-4 in Aitkin County in Section 16, T.48N., R.25W. This ID numbering system is also used in many of the data files in the Appendices of this report.

Zanko_compilation Folder - This file is on the CD in the back pocket of this report under the Appendix 2 heading. Within the *Zanko_compilation* Folder are five data bases that were compiled by Larry Zanko, in 1994, for geochemical results in Benton, Crow Wing, Kanabec, Meeker, Mille Lacs, Morrision, Otter Tail, Pine, Stearns, and Todd counties. Except for the data in the crowwing.xls data base, the geochemical results in all of the other counties are <u>not</u> specifically discussed in this report. A listing of the data bases is as follows:

1) *CROWWINGDATA.xls* - 566 geochemical results are listed. All of these results, except for five geochemical samples from Section 28, T.42N., R.28W.) are included in the *basinchemco.xls* data base.

2) *PINEDATA.xls* - 221 geochemical results from Paleoproterozoic rocks in Pine County.

3) *TODDDATA.xls*- 53 geochemical results from Paleoproterozoic rocks in Todd County.

4) *MORRISONDATA.xls* - 16 geochemical results from Paleoproterozoic rocks in Morrison County.

5) *STEARNSDATA.xls* - 30 geochemical results from Paleoproterozoic rocks in Stearns County.

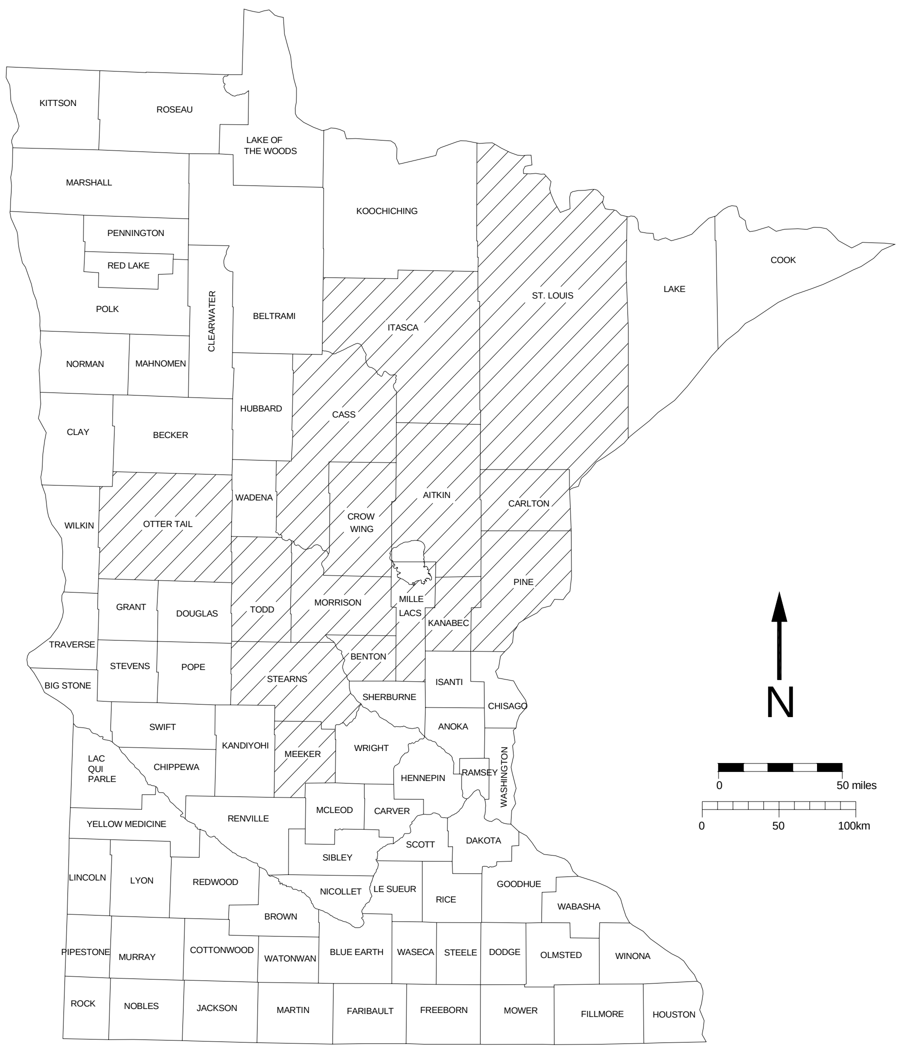
6) *MISCELLANEOUSDATA.xls* - geochemical results from Paleoproterozoic rocks in:
Benton County - 1 sample
Itasca County - 24 samples (all are included in *basinchemco.xls*)
Kanabec County - 3 samples
Meeker County - 21 samples
Mille Lacs County - 1 sample
Otter Tail County - 3 samples

Note that when these data files were originally compiled, the exploration company files at the MDNR were arranged according to Township-Range-Section (T-R-S). Thus, the reference given by Zanko in the each of the data files indicates that a particular geochemical sample result can be found in "File T-R-S." However, the MDNR has since reorganized the system, and one now has to first look for the appropriate exploration company, and then for the T-R-S.

NOTES REGARDING THE GEOCHEMICAL DATABASES COMPILED BY LARRY ZANKO (1996).

Compilation and Location of East-Central Minnesota Geochemistry

A digital database of East-Central Minnesota geochemical data (from drill hole and outcrop samples) has been compiled and assembled in spreadsheet form, with all known sample locations georeferenced in UTM's. Over 60,000 values from more than 3,000 samples are available from 15 counties (see below). A summary of the data shows that verifiable elevated Zn, Cu, and Pb values (>1,000 ppm) and Au values (>500 ppb) are found in Carlton, Aitkin, Crow Wing, St. Louis, and Pine counties. These base and precious metal assays suggest that these locations (and other areas in East-Central Minnesota influenced by the Penokean orogeny) merit further geologic scrutiny, e.g., a more detailed evaluation of the Animikie Basin.



Counties in database.

Interestingly, the study revealed that previously reported anomalous gold values in some Aitkin County drill core samples (Glen Township) were contradicted by follow-up analytical work performed on the same samples. Similar discrepancies in other analyses were discovered. These findings demonstrate that analytical results must be scrutinized before accepting them at face value, and that it is the responsibility of the company and/or agency geoscientist to verify the reliability of analytical results before they are reported. Submitting erroneous or poor analytical data is irresponsible, and can lead to a misdirection of follow-up exploration efforts.

Geographic resolution of location information

The accuracy of the sample location data was limited by the quality and detail of the available references. Therefore, many locations were given "UTM accuracy" values (in meters) that reflect this limitation. When no map existed, and only a legal description was given for a sample or a drill hole's location, the location was assumed to be the center of the smallest legal subdivision.

Eight +/- values were used. The larger the value, the greater the uncertainty, as shown below:

1) 800 m (center of a section; 640 acres; for example, a point located at the center of a section would be approximately 800 meters from the north, south, east, and west boundaries of the section)
2) 400 m (center of a quarter section; 160 acres)
3) 200 m (center of a 40 acre parcel)
4) 100 m (center of a 10 acre parcel)
5) 50 m (center of a 2.5 acre parcel)
6) 25 m (reasonably detailed location map or legal description)
7) 12.5 m (accurate location map)
8) 1 m (specific location provided)

In addition to the geochemical data, digital georeferenced maps have been produced. Very early in the study, Southwick, Morey and McSwiggen's (1988), *"Geologic Map of the Penokean Orogen, East-Central Minnesota"*, was digitized, and GIS-compatible files for the map's polygonal and linear map features were submitted to MDNR (in 1994).

Recommendations

All geochemical data should be entered into a digital database by agency personnel whenever new data is turned over by companies (or anyone else) doing work in Minnesota. It should be a matter of policy that **ABSOLUTELY NO** newly-received data be filed in hard copy form without first verifying its quality and converting it to a digital form. It is difficult and time consuming (and therefore costly) to search through reams of hard copy for geochemical reports and analytical results that are often poorly reproduced, poorly organized, and scattered between multiple files.

Also, the easting, northing, and (if possible) elevation of all new drill hole or sampling sites should be determined using a GPS, and reported with reference to NAD 83 UTMs. Solid geographic control increases everyone's understanding of Minnesota's geology and mineral potential. The technology exists to do this type of work fairly easily. Dots on photocopied maps are notoriously poor location indicators.

APPENDIX 3

MAGNETIC SUSCEPTIBILITY READINGS

Data file information pertaining to Magnetic Susceptibility Readings ($x10^{-3}$ Sl) were collected from 98 drill holes (5,480 individual readings) that are scattered throughout the study area and cover a wide variety of rock types . The data are presented as either QuattroPro files (DH*number*.wb3) or as Excel files (DH*number*.xls). The data files, one for each drill hole, are included in the **zincmag Folder** on the CD in the back pocket of this investigation. The **zincmag Folder** is broken down as follows:

Aitkin_misc Folder (scattered holes in Aitkin County)

Hole #/File Name	Area	Sec-T-R	Major Rock Types in the Hole
DHBM-2 .xls	Scallon-Todd area	23-48-27	"weathered" argillite (Pvt)
DHH-1.xls		30-48-22	graphitic argillite (Pvt)
DHMO-1.xls		8-45-25	graphitic phyllite (Pcs)
DHN-2.xls		25-46-26	metagabbro (Pd)
DHWB-1.xls		14-47-23	graphitic argillite (Pgs)

Carlton Folder (Carlton County)

Hole #/File Name	Area	Sec-T-R	Major Rock Types in the Hole
DHAM-1.xls	Arrowhead Mine	32-48-18	graphitic argillite (Pvt)
DHAM-2.xls	Arrowhead Mine	32-48-18	graphitic argillite (Pvt)
DHAM-3.xls	Arrowhead Mine	32-48-18	graphitic argillite (Pvt)
DHAM-4.xls	Arrowhead Mine	32-48-18	graphitic argillite (Pvt)
DHAM-5.xls	Arrowhead Mine	32-48-18	graphitic argillite (Pvt)
DHAG-2.xls		17-46-19	phyllite (pps)
DHAW-2.xls		19-46-19	phyllite (pps)
DHBM-1dnr.xls	MDNR hole	16-47-19	mafic volc. (Pvgd), sediments (Pks), Denham Fm.?
DHBM2dnr.xls	MDNR hole	23-47-20	mixed sediments (Pks), Denham Fm.?
DHBM-4.xls	Kettle River area	7-46-20	mafic volcanics (Pvgd)
DHBM-5.xls	Kettle River area	7-46-20	sediments (Pks) with diabase (Pvgd)
DHBS-1.xls		13-47-20	phyllite (Pks)
DHCL-1.xls		3-46-20	mixed argillite (Pks)
DHJA-1.xls		7-46-19	mixed phyllite (Pks)
DHK-1.xls		22-47-20	graphitic argillite (Pgs)
DHKR-1.xls	Kettle River area	8-46-20	mixed sediments (Pks)
DHKRCH-6.xls		4-46-21	mafic volcanics (Pvgd)
DHKRCH-9.xls		33-46-20	mixed sediments (Pks)
DHM-1.xls	So. of Arrowhead	5-47-18	graphitic argillite (Pks)

DHMG-4.xls	Kettle River area	22-46-21	mixed sediments (Pks)
DHMG-7.xls	Kettle River area	8-46-20	mixed sediments (Pks) + mafic volcs. (Pvgd)
DHMLCH-11.xls	Arrowhead Mine	4-47-18	mixed sediments and schist (Pks)
DHMLCH-5.xls		28-47-19	schist + phyllite (Pks)
DHMLCH-9.xls	So. of Arrowhead	4-47-18	graphitic argillite (Pks)
DHMM-1.xls		7-46-19	phyllite (Pks)
DHSL-1.xls		6-46-21	mixed sediments (Pgs)
DHSR-1.xls	Split Rock area	19-46-21	mafic volcanics (Pvgd), sediments
DHSR-2.xls	Split Rock area	19-46-21	mafic volcanics (Pvgd)
DHSR-3.xls	Split Rock area	19-46-21	mafic volcanics (Pvgd)
DHWL-1.xls		21-46-20	schist (Pks)

Cuyuna_No.Range Folder

Hole #/File Name	Area	Sec-T-R	Major Rock Types in the Hole
DHBM-4#2.xls	NW North Range	20-47-29	unox. IF in Mahnomen Fm (Pim)
DHG-1.xls	Gloria Mine	28-47-29	Mahnomen, Trommald, Rabbit L.
DHS-1015.xls	Kennedy Mine	30-47-28	ox. Trommald Fm (Pti)
DHS-102.xls	Millford	23-47-29	ox. Trommald Fm (Pti)
DHS-1033.xls	Feigh Mine	10-46-29	unox. Trommald Fm (Pti)
DHS-1047.xls	Portsmouth Mine	2-46-29	unox. Trommald Fm (Pti)
DHS-205.xls	Section 6 Mine	6-46-29	mafic volc? (Prv), Trommald Fm (Pti)
DHS-247.xls	Section 6 Mine	6-46-29	mafic volcanic (Prv)
DHS-323ports.xls	Portsmouth Mine	2-46-29	unox. Trommald Fm (Pti)
DHS-378.xls	Portsmouth Mine	1-46-29	unox. Trommald Fm (Pti)

Glen_Twnshp Folder

Hole #/File Name	Area	Sec-T-R	Major Rock Types in the Hole
DH18131.xls	west of Glen-So.	19-46-25	unoxidized iron-formation (Pgti)
DHA-2.xls	Glen South	21-46-25	mafic volc (Pvdg), graph arg, footwall seds (Pas)
DHA-6.xls	Glen South	20-46-25	as above + unox. IF (Pgti), basal seds (Pgws)
DHBM-10.xls	Glen North	15-46-25	mafic volcanics, graph argillite
DHBM-12.xls	Glen North	14-46-25	footwall metasediments, IF (Pgti)
DHBM-6.xls	Glen North	15-46-25	mafic volc, graph arg, footwall seds
DHG-2.xls	Glen Twnshp	1-46-25	gabbro, etc. (Pvdg)
DHG-3.xls	Glen Twnshp	18-46-25	gabbro (Pvdg)
DHG-5.xls	Glen Twnshp	11-46-25	black argillite (Pas)
DHG-7.xls	Glen Twnshp	16-46-25	graphitic argillite (Pas)
DHG-8.xls	Glen Twnshp	11-46-25	graphitic argillite (Pas)

DHMAG-16.xls	Glen South	28-46-25	Fe-carbonate seds, footwall seds (Pas)
DHMAG-17.xls	Glen South	28-46-25	Fe-carbonate seds, footwall seds (Pas)
DHMAG-19.xls	Glen South	28-46-25	Fe-carbonate seds, footwall seds (Pas)
DHMAG-29.xls	Glen South	28-46-25	Fe-carbonate seds, footwall seds (Pas)
DHMAG-41.xls	Glen South	28-46-25	mafic volcanics (Pvdg)
DHMAG-50.xls	Glen South	28-46-25	graphitic argillite, footwall seds
DHMAG-52.xls	Glen South	28-46-25	mafic volcanics, graphitic argillite
DHMAG-58.xls	Glen South	28-46-25	mafic volc(?), graphitic argillite

[Note that the "MAG" in this series holes denotes holes drilled in the Glen Township Sulfide - South Body (MAG stands for Magoffin holes, regardless of who actually drilled the holes). In actuality, most of these holes were simply called holes 1 through 84 when they were drilled, and are still called as such in the core storage facilities of the MDNR in Hibbing, MN. The MAG prefix is only used in this investigation as a "tag" for the holes in the South Body.]

No.Emily Folder

Hole #/File Name	Sec-T-R	Major Rock Types in the Hole
DH18130.xls	36-137-25	Virginia Fm - Pvti unit
DH18219.xls	21-137-25	iron-fm (Pei), unox. Iron-fm (Peil)
DH18290.xls	21-137-25	unoxidized iron-fm (Peil)
DH18408.xls	28-137-25	unoxidized iron-fm (Peil)
DH18423.xls	21-137-25	Virginia Fm (Pvti), unox. iron-fm (Peil)
DH18426.xls	23-137-25	oxidized iron-fm - Pei unit
DH18450.xls	15-138-26	Virginia Fm with iron-fm, etc. - Pvti unit
DH18589.xls	3-137-26	ox. iron-fm (Pei), unox. iron-fm (Peil)
DH18610.xls	26-138-26	ox. iron-fm (Pei), wkly-oxx iron-fm
DH18611.xls	2-137-26	ox. iron-fm (Pei), unox. iron-fm (Peil)
DH18685.xls	25-138-26	Virginia Fm (Pvt), iron-fm (Pei)
DH18693.xls	31-138-26	regolith, mixed rocks (Pumg - Mille Lacs Group??)
DHE-1.xls	21-138-26	Virginia Fm (Pvt), ox. iron-fm (Pei), Pokegama Quartzite (Ppg)

So.Emily Folder

Hole #/File Name	Sec-T-R	Major Rock Types in the Hole
DH18600.xls	30-136-26	iron-fm (Pvti?)
DH18951.xls	5-135-27	oxidized iron-fm (Pei?), Pokegama Quartzite (Ppg)
DH18970.xls	24-136-27	graphitic argillite (Pvti), fault zone, phyllite

So.Range Folder (Aitkin County only)

Hole #/File Name	Sec-T-R	Major Rock Types in the Hole
DHS-240.xls	18-47-26	mafic volcanics (?)
DHS-257.xls	18-47-26	mafic volcanics

So.Range_Rice_R Folder (Rice River District)

Hole #/File Name	Sec-T-R	Major Rock Types in the Hole
DHA-5.xls	2-47-26	hanging wall (Pgvt), unox. Iron-fm (Psri), footwall (Psa)
DHS-182.xls	3-47-26	unoxidized iron-fm (Psri)
DHS-19.xls	4-47-26	oxidized and unoxidized iron-fm (Psri)
DHS-204.xls	36-48-26	oxidized iron-fm (Psri)
DHS-22.xls	3-47-26	unoxidized iron-fm (Psri)
DHS-250.xls	3-47-26	footwall (Psa)
DHS-27.xls	3-47-26	unoxidized iron-fm (Psri)
DHS-307.xls	30-48-25	unoxidized iron-fm (Psri)
DHS-323aitkin.xls	4-47-26	footwall (Psa)
DHS-36.xls	35-48-26	oxidized iron-fm (Psri)
DHS-40.xls	3-47-26	oxidized iron-fm (Psri)
DHS-43.xls	35-48-26	oxidized iron-fm (Psri)
DHS-44.xls	35-48-26	unoxidized iron-fm (Psri), footwall (Psa)
DHS-52.xls	35-48-26	unoxidized iron-fm (Psri), footwall (Psa)
DHS-64.xls	4-47-26	footwall (Psa)
DHS-94.xls	4-47-26	footwall (Psa)

The top line of each file lists an abbreviation for the county followed by the drill hole number (abbreviations for counties are: a = Aitkin, cn = Carlton, and cw = Crow Wing). For example, *as4* denotes drill hole S-4 in Aitkin County. In some cases, there may be two (or more) holes in the same county with the same designation, e.g., two S-4's, and in this case the string of “county-hole number-section-township-range” denotes the particular hole. For example, *as4164825* denotes a drill hole S-4 in Aitkin County in Section 16, T.48N., R.25W.

APPENDIX 4

DENSITY READINGS
(on CD in the back pocket of this investigation).

DensityReadings.xls - 1,085 individual specific gravity/density readings (in g/cm^3) from various core and chip samples. The density readings are listed according to:

- ID# (see Appendix 1 for a description of the system used for ID#s for drill holes);
- Drill hole number;
- footage (or interval) where reading was taken;
- rock type description (when available for holes logged in this investigation);
- map unit - adapted from geologic maps of Boerboom et al., 1999a; 1999b
- density reading value;
- area - geographical area where hole is located (North Range, Glen Township, etc.); and
- Section-Township-Range (S-T-R) location.

basindensity.qpw - same as above, but in QuattroPro format.

The determinations were originally made by Tom Lawler and Darold "Ricco" Riihiluoma of the MDNR, with a Mettler 33360 210260 density determination kit, using a Mettler H43 balance. A summary of their data is included in Frey and Lawler (1997), but individual density determinations are not included in their report. The primary author obtained a data disk from the MDNR that contained these individual measurements, and then reorganized the data and assigned map formation names and rock type names to the each of the individual samples (for only the holes that were relogged for this investigation). Eleven density determinations, made at the NRRI with a Jolly Balance, were added to the database.

APPENDIX 5

ISOTOPES

isotopetable.xls - a listing of isotopic values for 68 samples obtained in this study is included on the CD in the back pocket of this investigation.

Sedex isotopes.xls - listing of isotopic values, associated with rocks in the Animikie Basin (excluding samples in the vicinity of the Duluth Complex) and the Fold-and-Thrust Belt, included on the CD in the back pocket of this investigation. Samples are mainly from this investigation and Bekker (1998). Samples are categorized into various worksheets in the data base as follows:

- Animikie data = listing of all the isotopes by sample, drill hole (or outcrop), interval, area, etc.
- Glen Township Sulfide - South and North Bodies
- Rice River District of the South Range (Aitkin County)
- Emily District
- Carlton County
- Virginia Formation
- Biwabik Iron Formation
- Trout Lake Formation
- Denham Formation
- Thomson Formation
- Graphitic argillite (Glen Township, Arrowhead Mine, Emily District, etc.)
- Iron Carbonate - Fe-carbonate facies iron-formation at Glen Township, Emily District, Kettle River area, etc.
- Mafic Volcanics - scattered throughout the Fold-and-Thrust Belt
- Some published isotope values from the Century, McArthur River, and Sullivan deposits.
- Data files (arranged by county) that list drill hole locations and rock units intersected in the drill holes. Note that these files are early versions of drill hole location files that were eventually combined into a single data base - the *basinholesco.xls* also on the CD. Worksheets are referred to as:
    - carltondh.xls
    - aitkindh.xls
    - cassdh.xls
    - crowdh.xls
- The results of the first batch of isotopic values obtained at the start of this investigation are listed in the Ripley1 worksheet.

APPENDIX 6

ARCVIEW FILES

The files in this category are duplicates of pre-existing data files, except that unique drill hole numbers have been added to the first column. These files are intended to interact with the ArcView Map that is included on the CD in the back pocket of this report. The data files are as follows:

basinholes.xls (upgraded *basinholesco.xls* file)

basinchem.xls (upgraded *basinchemco.xls* file)

all_basin_mag.xls (all files in Appendix 3 are combined into one file - magnetic susceptibility readings)

DensityReadings.xls (as in Appendix 4)

basin_isotopes.xls (upgraded *isotopestable*.xls as in Appendix 5)

Because there are over 2,100 drill holes within the study area, a system was devised to designate where the drill holes are located. The system consists of an abbreviation for the county in which the hole is located followed by the drill hole number. Abbreviations for counties are as follows: a = Aitkin, cn = Carlton, cs = Cass, cw = Crow Wing, I = Itasca, sl = St. Louis. For example, *as4* denotes drill hole S-4 in Aitkin County. In some cases there may be two (or more) holes in the same county with the same designation, e.g., two S-4s, and in these cases the system used consists of a string of numbers after the county abbreviation to denote a particular drill hole as follows: county abbreviation-hole number-section-township-range. For example, *as4164825* denotes a drill hole S-4 in Aitkin County in Section 16, T.48N., R.25W. In this manner each hole is represented by a unique number that is not repeated elsewhere within the study area.

ARCVIEW MAP AND RELATED FILES

MAP TITLE: Proterozoic Geology of East-Central Minnesota

Project File: sedex2003.apr

View: Proterozoic Geology of East-Central Minnesota

Shapefiles, with accompanying legend (.avl), text (.avt), and metadata files:

GEOLOGIC FEATURES	
sedex_geology83py.shp	Bedrock units
sedex_geology.avl	
sedex_geologytxt.avt	
sedex_geoareastxt.avt	
sedex_cleavage83py.shp	Rocks displaying well-developed cleavage
sedex_cleavage.avl	
sedex_ddhnad83pt.shp	Drill holes (datum NAD83)
sedex_drillholes.avl	
sedex_drillhole_idtxt.avt	
sedex_faults83ln.shp	Inferred faults and inferred thrust faults
sedex_faults.avl	
sedex_fold83ln.shp	Anticline and syncline fold axes
sedex_folds.avl	
sedex_inferred_dome83pt.shp	Inferred domal structures
sedex_inferreddome.avl	
sedex2003.htm	Metadata
BASE MAP FEATURES	
sedex_basinbord83py.shp	Outline of study area
sedex_border.avl	
sedex_basincty83py.shp*	County boundaries
sedex_county.avl	
ctybdne2lt.htm	
sedex_basinsec83py.shp*	Sections
sedex_section.avl	
plsscne3lt.htm	
sedex_basintwp83py.shp*	Townships
twprgne3lt.htm	
sedex_township.avl	
sedex_twptxt.avt	

DATA TABLES

basinholesNAD83.dbf
basinchem.dbf
all_basin_mag.dbf
DensityReadings.dbf
basin_isotopes.dbf

View: Study Area Location Map

Shapefiles, with accompanying legend (.avl), text (.avt), and metadata files:

sedex_basinbord83py.shp	Outline of study area
sedex_border.avl	
ctybdpy2.shp*	Minnesota counties

*County, section, and township shapefiles used in the first view were clipped from full Minnesota coverages provided on the Minnesota.data, Vol. 1, CD (LMIC and MNDNR), available from the Land Management Information Center (LMIC) Minnesota Geographic Data Clearinghouse at http://www.lmic.state.mn.us/chouse/. The full county coverage was used in the second view. The "lite" version of the metadata for these files has been included on the map CD. The full metadata file can be viewed on the Minnesota Department of Natural Resources's GIS Data Deli website: http://deli.dnr.state.mn.us/.

APPENDIX 7

Communication from Dr. Jill D. Pasteris, Washington University, St. Louis, MO, regarding Raman microprobe spectroscopy analyses of carbonaceous argillite from the Arrowhead Mine, Carlton County, Minnesota.

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Department of
Earth and Planetary Sciences

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Dr. Steven Hauck
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Dear Steve:

I have finished the Raman analyses on the three graphitic samples (AM1-118, AM1-124.5, and AM5-67.5) that you sent to me. After examining the rocks themselves and the polished thin sections that Bob Poli made for you, I decided to do the Raman analyses on the thin sections. The graphitic material obviously was inhomogeneous, and I thought that I would have better control of my analyses if I made use of the high optical quality of the thin sections in reflected light. In the Raman analyses, I used only 30% of the normal laser power on the samples in order to avoid possible "burning." I saw no optical evidence for any surficial destruction of the surfaces that I analyzed. The goal of the Raman analyses was to investigate the degree of crystallinity of the graphites (based on the ratio of their spectral "disorder" and "order" peaks) and then to interpret the highest grade of metamorphism of the host samples based on the spectral data.

In my brief observations under reflected light (using my research optical microscope), I found the graphitic material to have interesting, but unexpected, properties. The reflectivity is very inhomogeneous, and none of the material looks like "normal graphite." In other words, except for some areas in sample AM1-124.5, I found no optically anisotropic blades or stringers. Instead, the material looks like a poikylitic intergrowth of two gray phases of low reflectivity. The more highly reflecting of the two phases appears to have a slightly irregular topography. I interpret this phase to be the actual graphitic material. The accompanying, less-reflective, intergrown phase appears smoother (with a more highly polished surface). Because both the more- and less-reflective phases are opaque to transmitted light, I interpret the less-reflective phase to be silicate (or other mineral) material that covers the graphite. My Raman analyses support those optical interpretations.

I did analyses on three kinds of materials that provided Raman spectra of graphite:

1) within the inhomogeneous low-reflecting regions, I analyzed the more highly reflecting, surficially irregular opaque.

2) within the inhomogeneous low-reflecting regions, I analyzed the less-reflective, smoother opaque.

3) beneath the surface of large transparent grains, I analyzed isolated opaque grains.

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The nature of the surface analyzed is important to the interpretation of the spectrum. When graphite is polished, as in a thin section, its surface becomes disrupted. Therefore, the Raman spectrum of a polished graphite surface (type #1 material, above) will indicate the maximum degree of disorder that exists in the body of the graphite grain. Graphite grains that are analyzed below the surfaces of polished transparent mineral grains (types #2 and 3) should give spectra that better indicate their true degree of order/disorder.

I took a total of 14 spectra of the three samples. The within-sample and between-sample ranges are about the same for ratios of the intensities of the disorder:order (D:O) spectral bands. In many, but not all cases, the graphite grains that lie beneath a transparent phase (typically quartz) display spectra with lower D:O ratios (more crystalline) than do graphite grains whose surfaces were disrupted by polishing. The band ratios from the 14 analyses range from D~O (most crystalline) to D>>O (least crystalline). In all cases, the two first-order bands (D and O) were accompanied by one or both of the second-order bands that characterize poorly crystalline graphite (see Fig.2, column A, spectrum 2, of the accompanying reprint of Wopenka and Pasteris, 1993). These first-order and second-order spectral features are characteristic of graphite in pelitic rocks metamorphosed in the chlorite zone of greenschist facies metamorphism. In other words, your carbonaceous materials are well beyond the "kerogen stage" but do not appear to have reached the chlorite/biotite zone. Again, these interpretations are based on the change in crystallinity undergone by graphitic materials in pelitic hosts.

I hope that these analyses are useful. Please let me know if you have any questions.

Best regards,

Jill

Jill Dill Pasteris
Professor of Earth and Planetary Sciences

APPENDIX 8

MICROPROBE RESULTS - AS REPORTED BY THE MICROPROBE LABORATORY
(Also included as tables in the text of the report)

A6,564.xls - Tourmaline compositions (see Table 1), drill hole A-6 (564'), Glen Township-South

B1-374,293.xls - Tourmaline compositions (see Table 6), drill hole B1-374 (293'), Babbitt Cu-Ni Deposit

BM7.xls - Fe-carbonate compositions (see Table 5), drill hole BM-7 (144.2'), Glen Township-North

BM21,266.xls - Fe-carbonate compositions (see Table 4), drill hole BM-21 (266'), Glen Township-North

DH77.xls - Fe-carbonate compositions (see Table 2), drill hole DH-77 (177.5'), Glen Township-South

II2,872.xls - Tourmaline compositions (see Table 7), drill hole II-2 (872'), Skibo South Area

II2,883.xls - Tourmaline compositions (see Table 8), drill hole II-2 (883'), Skibo South Area

Mag-51.xls - Fe-carbonate compositions (see Table 3), drill hole 51 (234.3'), Glen Township-South

APPENDIX 9

METADATA FILE

Sedex 2003.htm - metadata file, pertaining to Plate VII, as prepared via the DataLogr 2.11 C program according to Minnesota Geographic Metadata Guidelines, v. 1.2 (online linkage at http://www.lmic.state.mn.us/gc/stds/metadata.htm).