

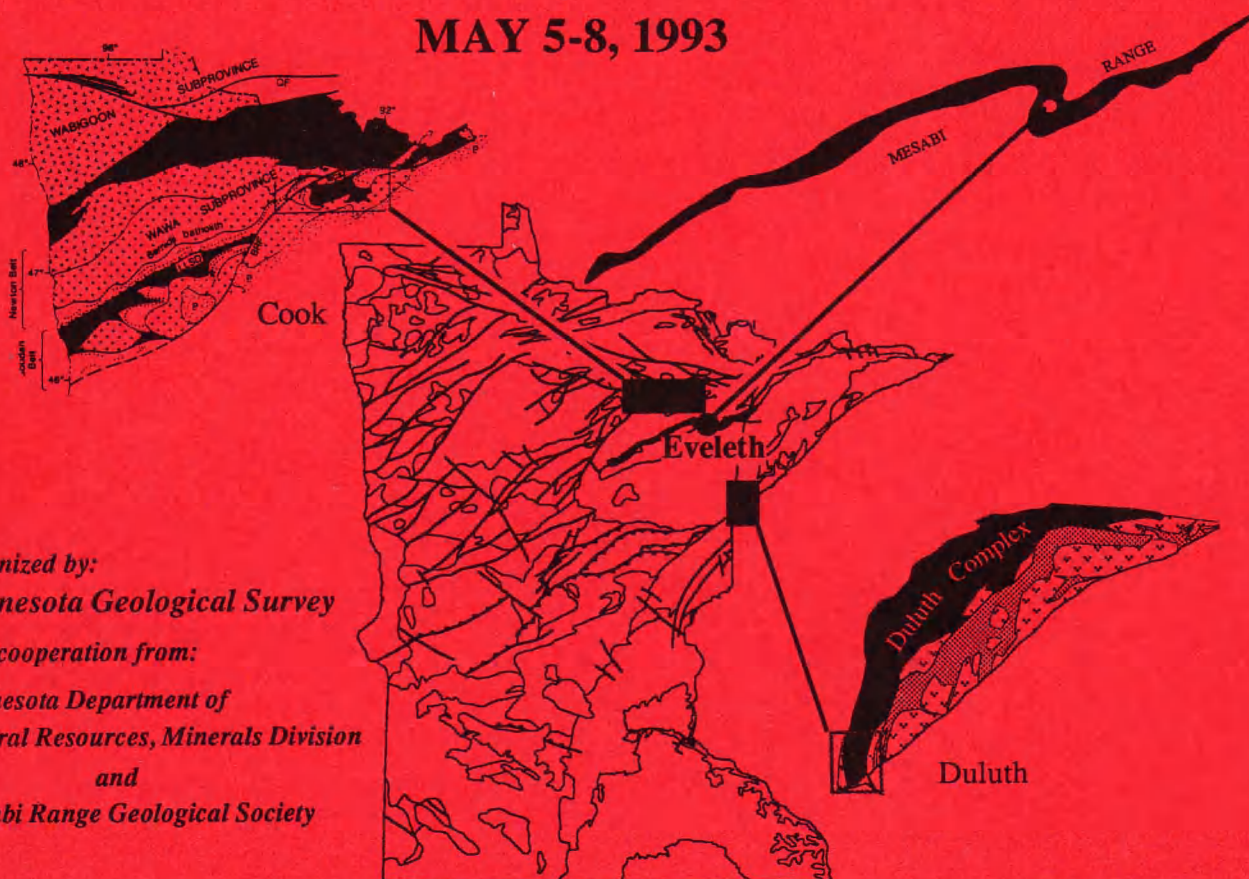
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INSTITUTE ON LAKE SUPERIOR GEOLOGY

EVELETH, MINNESOTA

MAY 5-8, 1993



Organized by:
Minnesota Geological Survey
with cooperation from:
**Minnesota Department of
Natural Resources, Minerals Division
and
Mesabi Range Geological Society**

Proceedings Volume 39, Part 2 - Field Trips

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**INSTITUTE ON
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General Chair: David L. Southwick

Program Chair: Jane Cleland

Field Trip Chair: Mark Jirsa

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FIELD TRIP 1

GEOLOGY AND TACONITE MINES OF THE MESABI RANGE

Field trip organized and guidebook prepared by

Mesabi Range Geological Society

David Meineke, lead editor
Meriden Engineering

Field trip leaders:

Ronald G. Graber
Cliffs Mining Services Company

Richard W. Ojakangas
University of Minnesota-Duluth

Robert J. Waidler
Eveleth Mines

with contributions by

G.B. Morey
Minnesota Geological Survey

FIELD TRIP 1

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Taconite By Any Other Name...Nomenclatural Oddities

Historically, no group of rocks better illustrates the geologist's problem with nomenclature than that of the iron-rich sedimentary rocks. The current untidy nomenclatural situation is due partly to our obsession with naming every kind of rock, in a situation where there is an immense diversity of rock types on one hand, and a continuum between those different rock types on the other. In the late nineteenth century, the nomenclature was quite simple. Iron-rich strata in Wisconsin and Michigan were classified as "ferruginous cherts" with appropriate modifying adjectives (slaty, carbonate-bearing, amphibole-bearing, etc.). At the same time, iron-rich, granular strata, composed of chert, iron oxides, carbonates and silicates on the Mesabi range were classified as "taconyte." The term taconyte was first proposed by N.H. Winchell, who held that the iron-rich strata of the Mesabi range could be correlated with a system of rocks that crop out in the Taconic Mountains in northern New England. The Taconic System was thought to contain primitive fossil forms that predated those found in the Cambrian System. The idea of a Taconic System and its correlatives in the Lake Superior region was soon discredited, but in Minnesota the term taconyte was retained for iron-bearing rocks in general.

The term "iron-formation" is a contraction from "iron-bearing formation," a term used as a lithostratigraphic descriptor by the U.S. Geological Survey in the early twentieth Century. In the classic reports of that period, "iron-bearing formation" came to replace and include earlier rock names such as jaspilite, ferruginous chert, and taconyte. In modern usage, "iron-formation" is a precisely defined term that refers to sedimentary sequences of layered, bedded, or laminated rock that contain 15 percent or more iron, and in which the iron minerals form monomineralic or polyminerallc beds that commonly are interlayered with monomineral or polyminerallc beds of quartz, chert, or carbonate. That definition is very much like the original definition of taconyte, but today "taconite" is used strictly as an economic term, generally in a mining context, for iron-formation from which iron can be profitably extracted and beneficiated after fine grinding.

All this is confused by formal stratigraphic nomenclatural procedures. According to the North American Code, the Biwabik Iron Formation is a formal lithostratigraphic unit, distinguished from surrounding bodies of rock because it consists mostly, but not entirely, of iron-formation. Furthermore, the name "Biwabik" is an Ojibway name that means iron. Thus the iron Iron Formation of the Mesabi range consists mostly of iron-formation, parts of which are taconite.

G.B. Morey

Field Trip 1

GEOLOGY OF THE MESABI RANGE

G.B. Morey
Minnesota Geological Survey

INTRODUCTION

The Mesabi Iron Range in northern Minnesota is one of the most important mining districts in the world (see Geologic Map of Mesabi Iron Range in back pocket). Except for a few mines developed in residual ores of Cretaceous age, production has been entirely from the Biwabik Iron Formation of Early Proterozoic age. In 1992, the Biwabik produced 41.5 million metric tons of iron-ore concentrate—74 percent of the total United States production (56 million metric tons) or 7 percent of the estimated total world production (844 million metric tons). In all, the Range has produced slightly more than 3.4 billion metric tons of ore since the first shipment in 1892. Of that total, 2.4 billion metric tons of direct shipping or gravity concentrate ores were produced from over 500 separately-named mines from 1892 to 1993. After 1955, natural ore production was supplemented and has now been nearly replaced by an iron-ore concentrate produced from taconite (see "Taconite By Any Other Name" on p. 1). Between 1950 and 1992, slightly less than 1 billion metric tons of concentrate have been shipped from eight operations. Currently, seven mines are still in production.

The Mesabi range will continue to be an important producer well into the twenty-first century. Marsden (1978) estimated that the Range has a reserve in excess of 48 billion metric tons of taconite ore, which could yield 8.8 billion metric tons of iron-ore concentrate using then-current techniques. Since that time, recovery of iron-ore concentrate has improved considerably, extending the life of the identified reserve even further into the future.

This field trip provides a unique opportunity to examine the Biwabik Iron Formation at the Thunderbird Mine, operated near Eveleth by Eveleth Mines (Oglebay Norton Company), and the Hoyt Lakes and Dunka River operations of LTV Steel Mining Company. We are indebted to these and other mining companies on the Range, as well as to the members of the Mesabi Range Geological Society, who have made the field trip possible.

Regional Geologic Setting

Supracrustal rocks of Early Proterozoic age constitute a discontinuous linear fold belt along the southern margin of the Archean Superior province of the Canadian Shield (Fig. 1). The strata comprise a major part of the so-called Southern province of the Canadian Shield in Canada and are referred to in the United States as part of the Penokean orogen. In the Lake Superior region, the orogen consists of a deformed, south-facing, passive continental margin assemblage overlying Archean basement that is juxtaposed on the south with accreted magmatic arc terranes termed the Wisconsin magmatic terranes.

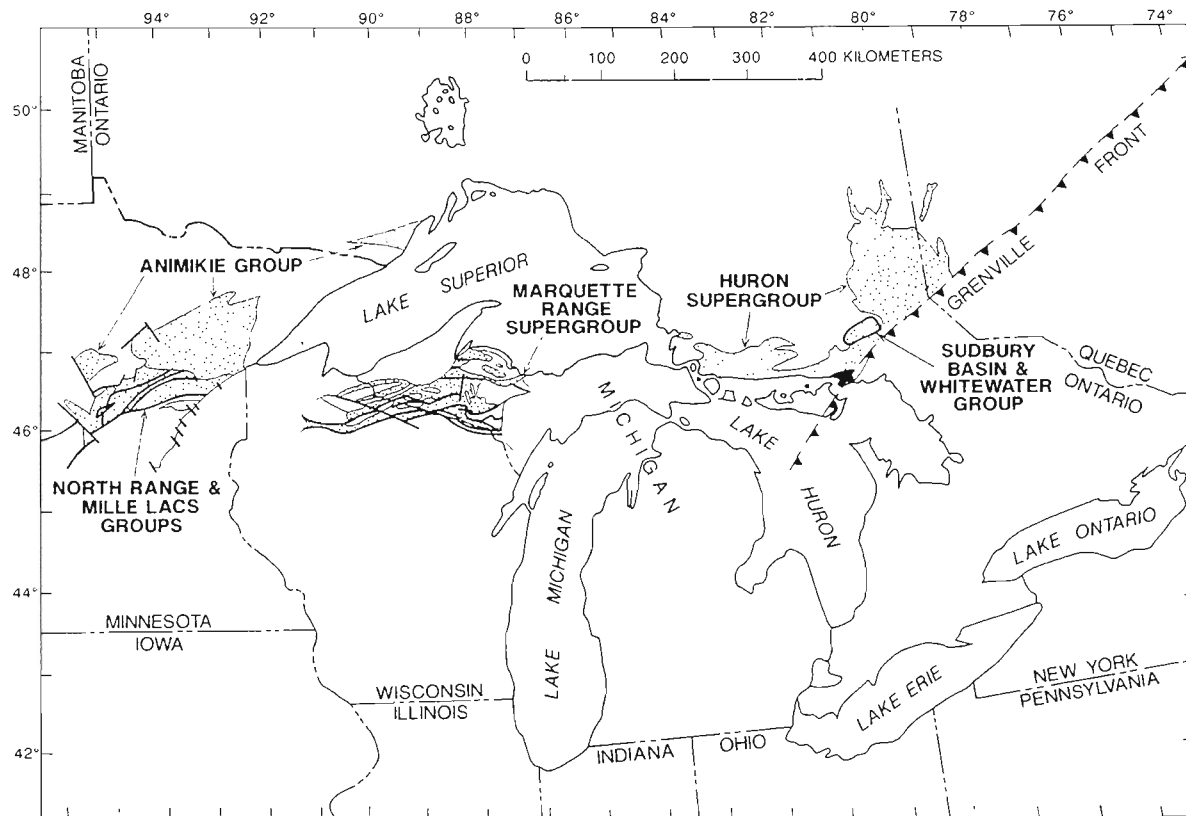


Figure 1 Generalized geologic map showing distribution of Early Proterozoic stratified rocks in the western Great Lakes region. The stratified rocks of the Penokean orogen include the Huron Supergroup in Ontario; the Marquette Range Supergroup in Michigan and Wisconsin; and the Mille Lacs, North Range, and Animikie Groups in Minnesota.

In the Lake Superior region, the continental margin assemblage consists of a lower rifted passive margin sequence (Schulz, 1991) overstepped northward by one or more synorogenic foredeep sequences (Southwick and others, 1988; Barovich and others, 1989; Southwick and Morey, 1991) (Fig. 2). A thick-skinned foreland fold-and-thrust belt north of the Niagara suture in Wisconsin and Michigan (Klasner and Sims, 1993) passes cratonward (northward) into autochthonous Early Proterozoic sedimentary rocks. The suture that juxtaposes rocks of the Wisconsin magmatic terranes with the continental margin trends eastward and overrides the deformed continental margin assemblage; suturing occurred at about 1,850 Ma (Sims and others, 1989). In Minnesota the presumed equivalent of the Niagara suture, the Malmo discontinuity (Southwick and others, 1988), makes a conspicuous oroclinal bend to the south and is inferred to continue southward through northwest Iowa as the Spirit Lake trend (Anderson and Black, 1983).

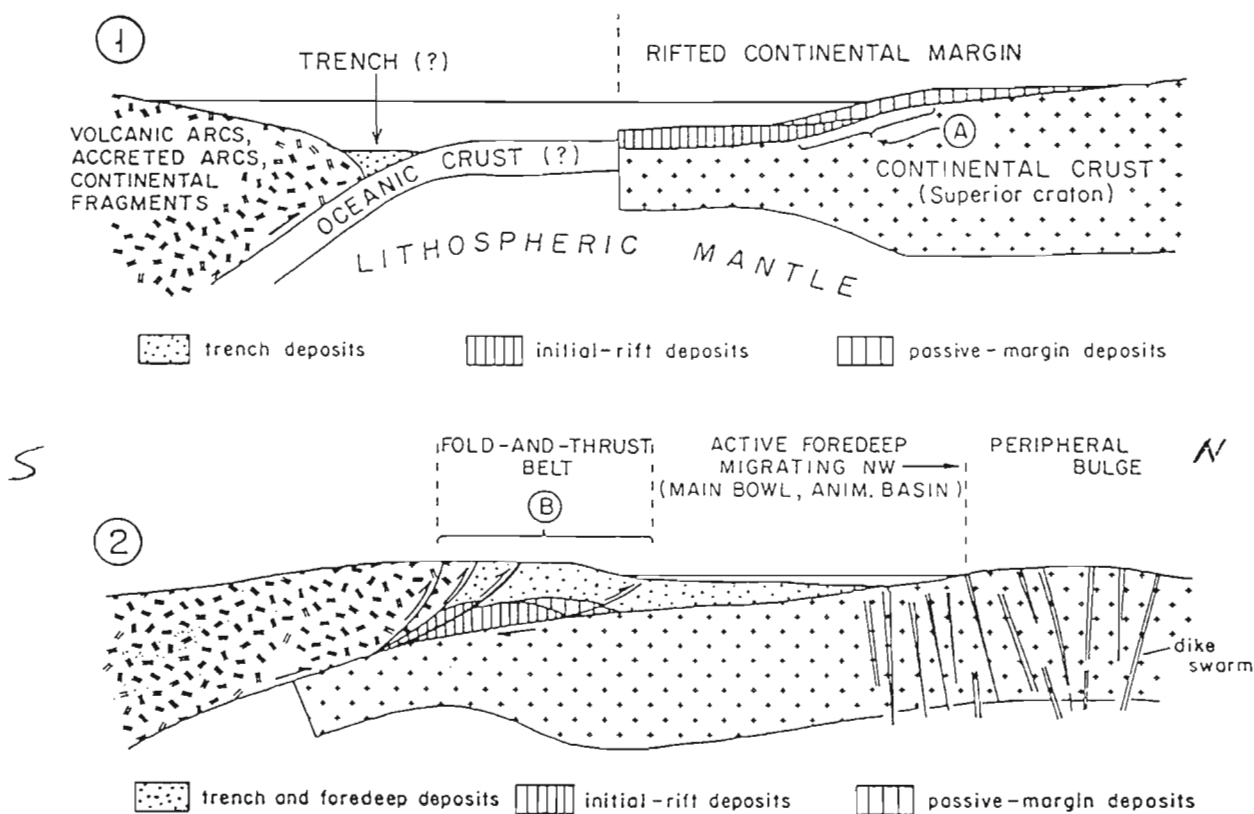


Figure 2 Highly schematic diagram adapted from Hoffman (1987), showing the evolution of an oceanic trench (stage 1) into a foredeep (stage 2). With respect to the Penokean orogen in Minnesota, stage 1 could represent the rifted margin of the Superior craton approaching a southeast-dipping subduction zone in Early Proterozoic time. Initial-rift deposits laid down earlier are riding on the continental edge; passive-margin deposits, possibly preserved in the Denham Formation and other quartzose units of the Mille Lacs Group, are accumulating near (A). Stage 2 represents active subduction of the continental margin. Crustal loading by the ensuing fold-and-thrust mass has occurred, generating as a flexural response an actively-migrating foredeep (main bowl of the Animikie basin) on the continental side. Various volcanic and sedimentary rocks and their stratigraphic basement are involved in fold-and-thrust nappes near (B), representing elements such as island arcs, accretionary wedge deposits, and continental fragments that have been swept together tectonically. The marginal deposits from (A), as well as early deposits laid down toward the rear of the foredeep, also may be incorporated in the deforming mass. In the Penokean of Minnesota there is no unequivocal evidence for the prior existence of oceanic crust, trench deposits, or volcanic rocks of arc affinity within the fold-and-thrust belt. Therefore, this diagram must be considered as a possible model of foredeep generations that has not been fully documented for the Penokean case (from Southwick and others, 1988).

In Minnesota, the stratified rocks of the continental margin sequence are assigned to the Mille Lacs and North Range Groups, whereas the overlying foredeep deposits are assigned to the Animikie Group. They were all deposited in the approximate interval of 2,200 - 1,870 Ma.

PENOKEAN OROGEN IN MINNESOTA

Supracrustal rocks of Early Proterozoic age underlie a broad area in east-central and northern Minnesota (Fig. 3); correlative rocks also underlie a much smaller area in far northeastern Minnesota and adjoining parts of Ontario north of Lake Superior. Except for those of the Gunflint Iron Range in northeastern Minnesota and Ontario and the Mesabi range in northern Minnesota, the rocks are very poorly exposed and the stratigraphic inferences summarized here rely largely on geophysical techniques and supplementary drilling. However, a combined drilling/geophysical approach has had a long tradition in Minnesota. Indeed, the Cuyuna Iron Range was one of the first, if not the first, major mining district to be discovered in the United States by geophysical techniques followed by drilling.

That early exploratory work clearly established the existence of two structurally distinct iron-mining districts—the Mesabi and Cuyuna ranges. The Cuyuna Range was further subdivided into three structurally distinct entities—the Emily district, the North Range, and the South Range. Starting with the early ideas of Van Hise and Leith (1911), and continuing until just a few years ago (e.g., Morey, 1983), most geologic studies were founded on the idea that a single major iron-rich interval tied together the diverse structural elements into a single stratotectonic entity (for

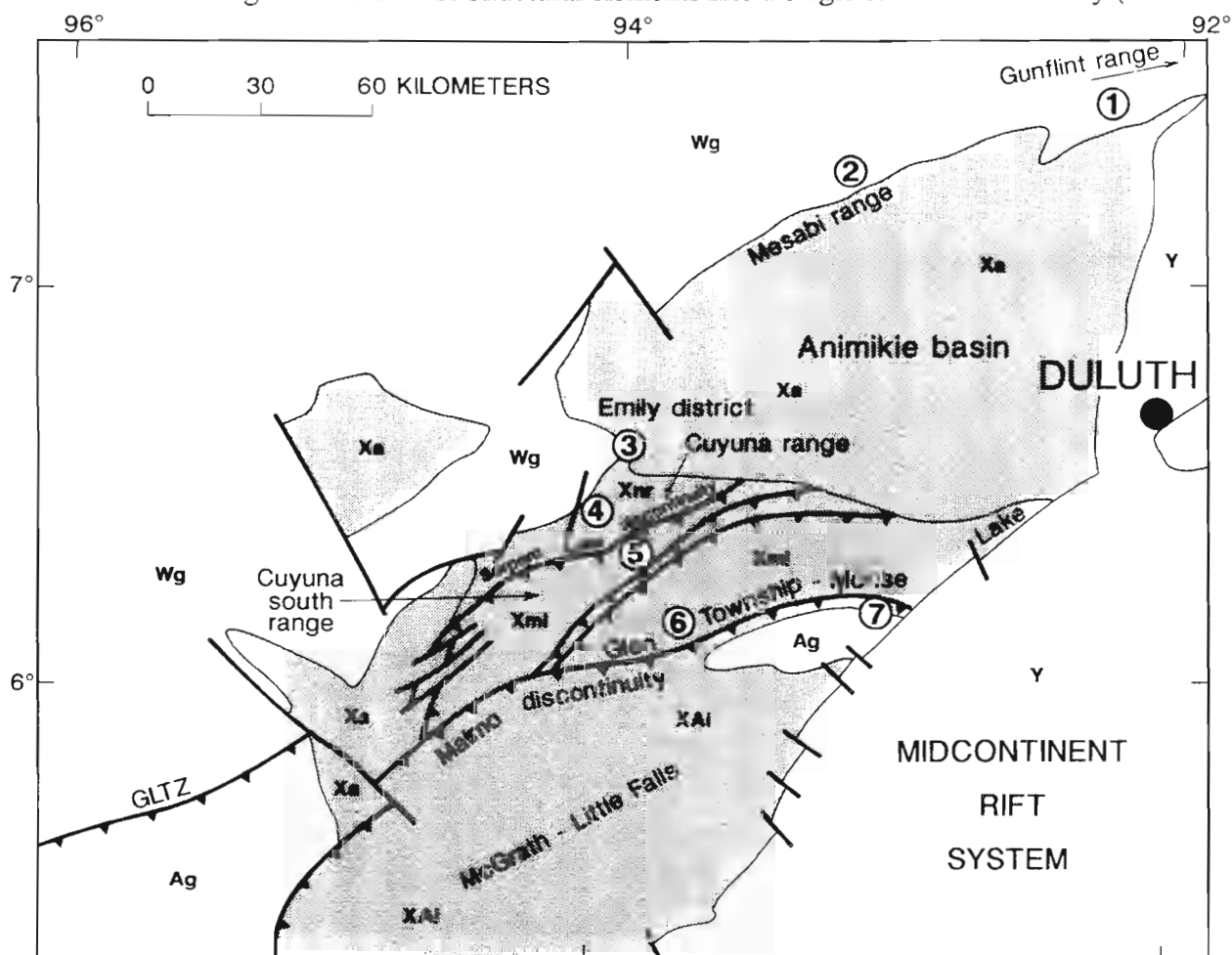


Figure 3 Sketch map showing distribution of Early Proterozoic stratified rocks in the Penokean orogen of Minnesota (modified from Southwick and Morey, 1991).

summary, see Morey, 1978). At the same time, the Early Proterozoic tectonic framework was envisioned in terms of pre-plate-tectonic concepts wherein vertical tectonism was interpreted to have produced synclines and anticlines in a pattern of superimposed interference folds.

Our view of the stratotectonic evolution has changed considerably in the last few years (Southwick and others, 1988). The tectonic framework is now envisioned as the product of a collisional event—the Penokean orogeny of Goldich and others (1961)—that occurred between 1900 and 1760 m.y., with most activity in the interval between 1870 and 1850 m.y. (Morey and Van Schmus, 1988). In this view, the Penokean orogen consists of an allochthonous fold-and-thrust belt that includes the South Range and contiguous areas to the south and east. The belt contains several structural discontinuities that bound discrete structural panels or enclaves that possess small-scale structural features consistent with large-scale north-northwest-verging nappes (Holst, 1984; Southwick and Morey, 1991). The fold-and-thrust belt flanks a tectonic foredeep that extends to the Mesabi and Gunflint ranges in northern and northeastern Minnesota where rocks of the well-known Animikie Group are exposed.

The structural studies of Southwick and others (1988) also showed that iron-formation was deposited at different times in different parts of the Penokean orogen (Fig. 4). This change in stratigraphic thinking is of considerable importance in understanding the origin of the iron-formation. Prior to 1972, the time of the last major field excursion to the Mesabi range (Marsden, 1972b), the entire Early Proterozoic succession in Minnesota was assigned to the Animikie Group. On the Mesabi and Gunflint ranges the Animikie Group forms a coherent stratigraphic entity that unconformably overlies Archean basement. On the Cuyuna Range and environs, however, Marsden recognized an older Early Proterozoic sequence between Early Proterozoic strata of the North Range and Archean basement. Subsequently, Morey (1978) subdivided the older sequence into several formations that he collectively assigned to his Mille Lacs Group.

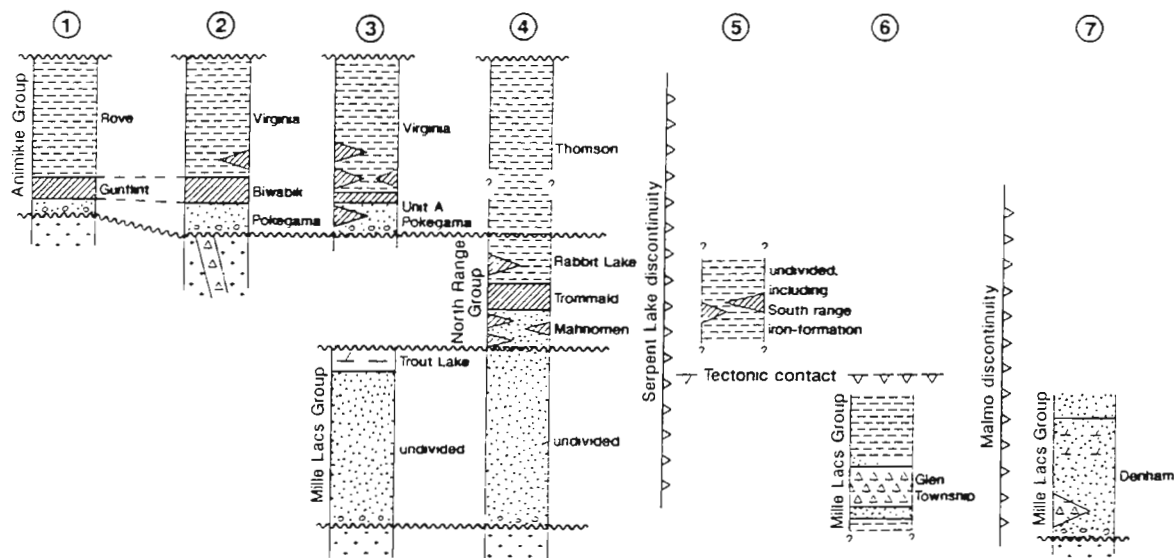


Figure 4 Lithostratigraphic correlations of Early Proterozoic stratified rocks of the Penokean orogen of Minnesota (modified from Southwick and Morey, 1991). Column locations shown in Figure 3.

The stratigraphic interpretation of Morey (1978) relied greatly on the concept of a single iron-formation of regional extent, but the structural interpretation of Southwick and others (1988) has required several changes to the existing nomenclature. In general, rocks south of the Serpent Lake discontinuity (Fig. 3) can still be assigned to the Mille Lacs Group, although the folded and faulted terrane is broken into at least four fault-bounded structural panels, and the rocks cannot be correlated from one panel to another.

Rocks north of the Serpent Lake discontinuity form a structurally coherent stratigraphic package consisting of the Mille Lacs, North Range, and Animikie Groups. Very little is known about the Mille Lacs Group in this area. Sparse drilling indicates that it unconformably overlies Archean basement and consists dominantly of quartz arenite, siltstone, and shale, topped by a mappable interval of limestone and dolomite named the Trout Lake Formation (Marsden, 1972).

The term "North Range Group" was proposed by Southwick and others (1988) for rocks unconformably above the Mille Lacs Group and unconformably below the Animikie Group. Units of the North Range Group were first described and named by Schmidt (1963), who recognized three formations: (1) Mahnomen Formation, a lower quartz-rich sandstone-siltstone sequence, (2) Trommald Formation, a middle iron-rich and locally manganese-rich sequence, and (3) Rabbit Lake Formation, an upper black shale-graywacke interval. In addition, Southwick and others (1988) have recognized at least two other major iron-rich intervals in the middle part of the Mahnomen Formation and a third smaller interval in the upper part.

The Animikie Group on the Mesabi and Gunflint ranges consists of a basal quartz arenitic sequence, the Kakabeka and Pokegama Quartzites; an intermediate iron-rich sequence, the Gunflint and Biwabik Iron Formations; and an upper thick graywacke-shale sequence, the Rove and Virginia Formations. The Thomson Formation (in the strict sense of the definition) in east-central Minnesota also comprises part of the upper graywacke-shale sequence.

Stratigraphic relationships between the Animikian rocks at the western end of the Mesabi range and those of the Emily district are imperfectly known. However, in the Emily district proper, the stratigraphic position of the Biwabik is occupied by four broadly lenticular units of iron-formation that are separated from one another by intervening sequences of epiclastic rocks, either quartz arenite like the Pokegama Quartzite or black shale like the Virginia Formation (Fig. 4). Thus, the simple, three-fold scheme of stratigraphic nomenclature for the Mesabi range cannot be applied with confidence to rocks of the Emily district. Therefore, to eliminate unnecessary conjecture and to simplify the nomenclature, Morey and others (1991) used the term "Unit A of the Ruth Lake area" for the thickest and most persistent of the iron-formations in the Emily district.

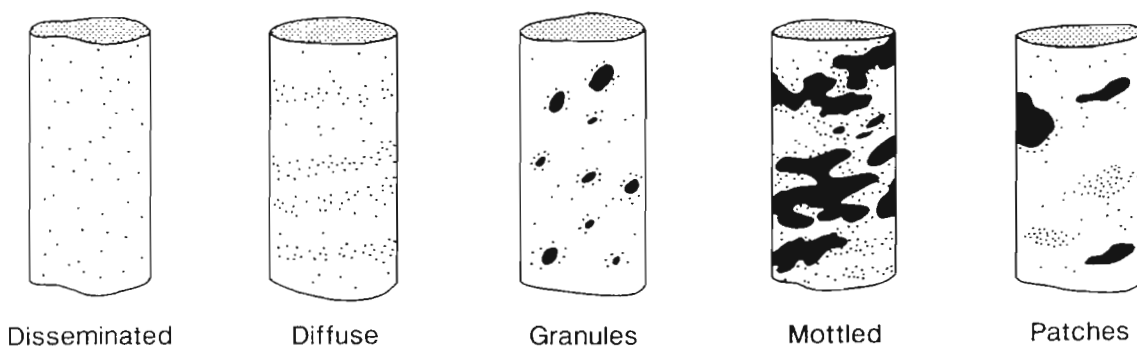
THE BIWABIK IRON FORMATION

The Biwabik Iron Formation is one of the major iron-bearing formations in the world and the largest in the United States. It crops out as a narrow belt, 0.40 to 4.8 km wide, that extends for 193 km along strike in northern Minnesota. It is about 213 to 229 m thick. Strata are classified by texture into two kinds of iron-formation, (1) cherty materials, which are granular, massive, and typically but not always rich in quartz and iron oxides; and (2) slaty materials, which are generally finely laminated, fine grained, and composed mostly of iron silicates and iron carbonates. In reality, both types contain about the same amount of silica. Therefore, the terms *granular* and *laminated* are used here for rocks having cherty or slaty attributes, respectively. Some characteristic textures are illustrated in Figure 5. Beds or groups of beds having granular or laminated attributes are interlayered on all scales. Despite the heterogeneity of the formation, it has been divided into four lithostratigraphic entities, which are, from bottom to top (Fig. 6): (1) Lower Cherty, (2) Lower Slaty, (3) Upper Cherty, and (4) Upper Slaty. Wolff (1917) termed these entities "Divisions," and that usage is still followed by some mining companies on the range.

However, since the work of White (1954), the cherty and slaty units have generally been referred to as informal members. Except for an ash-fall tuff—called the Intermediate Slate—at the Lower Cherty-Lower Slaty contact, contacts between adjacent members are gradational and arbitrary. Stratigraphic units in the slaty members generally contain 40 percent or more laminated strata; locally that proportion may be less. The cherty members contain 10 to 30 percent laminated material. The members contain several unnamed subunits in the eastern half of the Mesabi range. Two are hematite-rich, stromatolite-bearing intervals a meter to a few tens of meters thick. The thickest and most persistent is at the base of the Lower Cherty member; a second interval occurs in the middle part of the Upper Cherty member.

The upper few meters of the Upper Slaty member contain beds of limestone and dolomite, about half a meter thick. The calcareous rocks are intercalated with iron-rich slaty strata toward the bottom of the interval and with shale toward the top.

Textures associated with granular rocks



Textures associated with laminated rocks

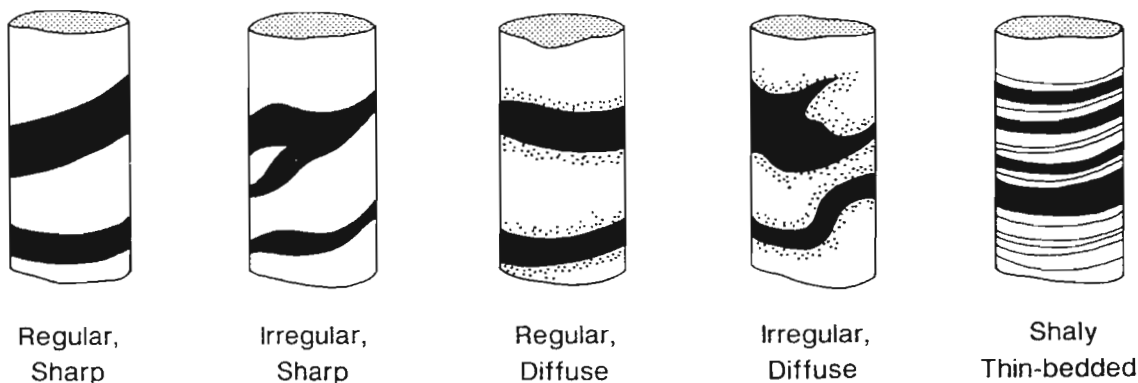


Figure 5 Textural characteristics of the Biwabik Iron Formation (modified by Pfleider and others, 1968, from a classification scheme developed by geologists of the Hanna Mining Company). Developed initially to characterize magnetite, the scheme has been used subsequently for other mineral phases.

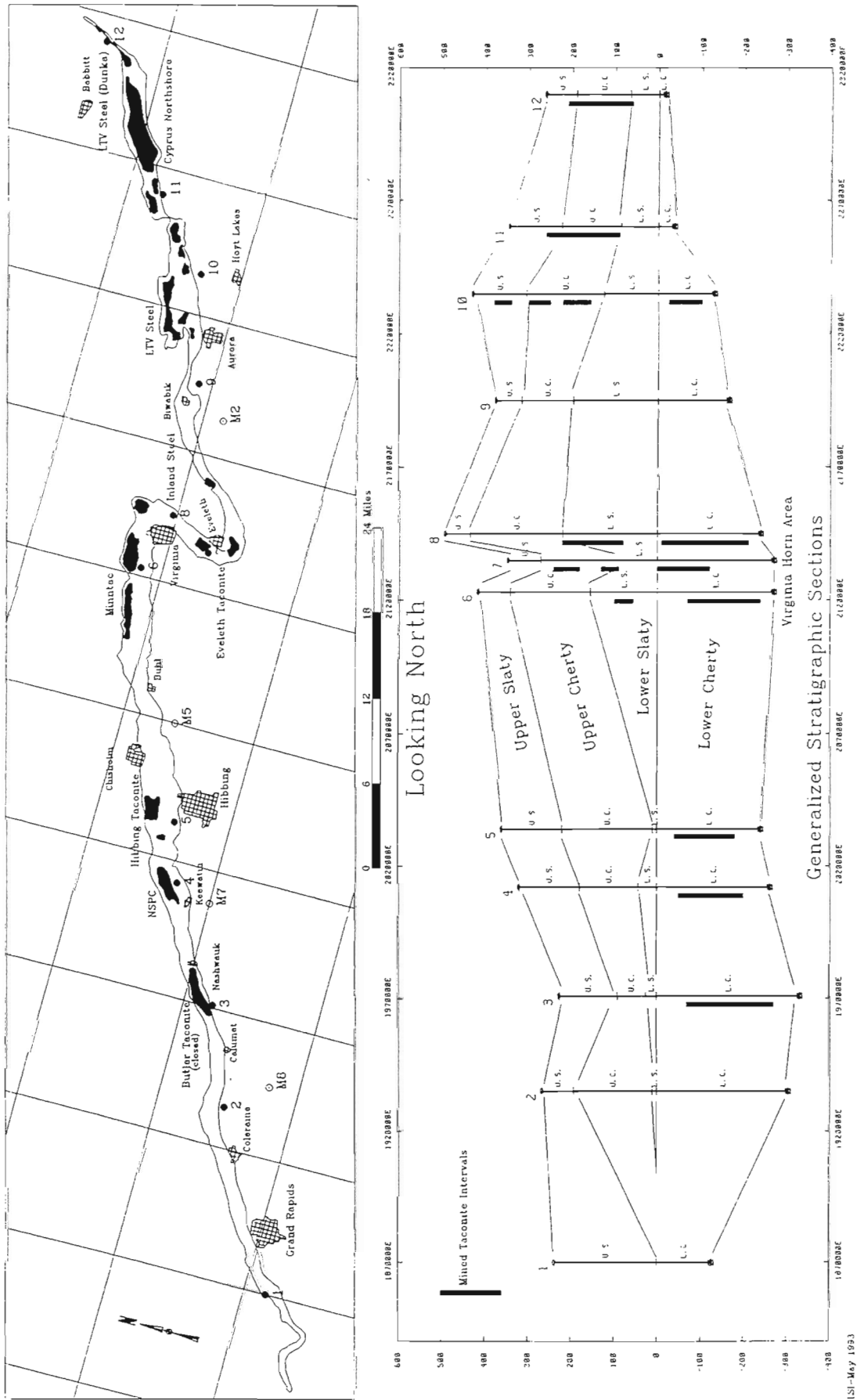


Figure 6 Generalized map and longitudinal section of the Mesabi Range-Biwabik Iron Formation (compiled by Henry Djerlev, 1993). Mined taconite intervals are shown as black columns adjacent to sections.

The limestone-bearing interval, both subunits of stromatolitic chert, and the Intermediate Slate thin to zero thickness just west of Nashwauk. Magnetite- and silicate-rich strata give way to units dominated by siderite and quartz. Farther west, near Grand Rapids, the Lower Slaty member disappears, and the Lower and Upper Cherty members merge into a unit dominated by granular chert and siderite. There the Upper Slaty member consists of intervals of laminated chert and siderite intercalated with intervals of black, iron-rich argillite.

The Biwabik Iron Formation from Mesaba eastward (Fig. 3) was metamorphosed in Middle Proterozoic time with the emplacement of the Duluth Complex, a large batholithic body of generally mafic composition related to the midcontinent rift. Metamorphism was essentially isochemical, except for the loss of volatiles, including water and carbon dioxide, and the addition of TiO₂ near the contact of the Duluth Complex (Ref. to be added by Morey). Broad features of the metamorphic aureole of the complex include mineral assemblages in the iron-formation that are dominated by fibrous amphiboles on the fringes, and by olivine and pyroxene near the complex. West of Mesaba, much of the Biwabik Iron Formation was oxidized and leached by ground water and surficial weathering. Oxidation is so pervasive throughout much of the western Mesabi range—where the dominant iron-bearing mineral was siderite—that it is difficult to find stratigraphic intervals of appreciable thickness where the original iron-formation is preserved.

Sedimentological Attributes

Stratigraphic interpretations in the Biwabik Iron Formation are in one way or another dependent on the concept of intercalated cherty and slaty members. Although detailed sedimentological interpretations have been hindered by the uneven application of stratigraphic terminology, there is a consensus that the Biwabik reflects a gradual change over time from predominantly epiclastic sedimentation in shallow water through a period of predominantly chemical precipitation of silica and iron, to a second period of epiclastic sedimentation in deeper water. This broad trend from shallower water to deeper water deposition can in turn be divided into two subcycles, 1) Lower Cherty member (shallower)—Lower Slaty member (deeper), and 2) Upper Cherty member (shallower)—Upper Slaty member (deeper). These can be recognized across much of the range.

Physical Sedimentary Processes

White (1954) suggested that granular sediments of the cherty members were deposited in a shallow-water, agitated environment, and that the laminated sediments of the slaty members were deposited in deeper, less active water. The vertical repetition of intercalated units of cherty and slaty suggested to White a depositional environment near an alternately transgressing and regressing strandline. Although his observational evidence was consistent with a moving strandline, he did not have a mechanism that could explain why the strandline moved. At about the same time, Goodwin (1956) emphasized the importance of volcanic materials in the Gunflint Iron Formation in Ontario and suggested that intercalated granular and laminated materials there were related to episodic tectonism. In this view, the floor of the depositional basin sloped more or less uniformly away from a strandline during periods of crustal stability. During episodes of crustal instability, however, the basin floor subsided, and the shallow-water units were then covered by deeper water materials that gradually filled the basin and eventually restored shallow-water conditions. These ideas were further expanded by Ojakangas (1983), who established with certainty a shallow-water tidal flat to subtidal depositional regime for the Pokegama Quartzite. He proposed a model where quartz arenite, iron-formation, and black shale were deposited more or less simultaneously on a shelf that deepened to the south. At about the same time, Lucente and Morey (1983) showed that the upper part of the Biwabik Iron Formation was cut in places by graywacke-filled channels that formed as the headwaters for turbiditic fan deposits in the Virginia Formation. Subsequently, Morey and others (1991) developed a model where sedimentation in the

Emily district occurred in an environment broadly analogous to pretidal-platform/carbonate-ramp/shale-filled basin sequences in rocks of Phanerozoic age (Fig. 7).

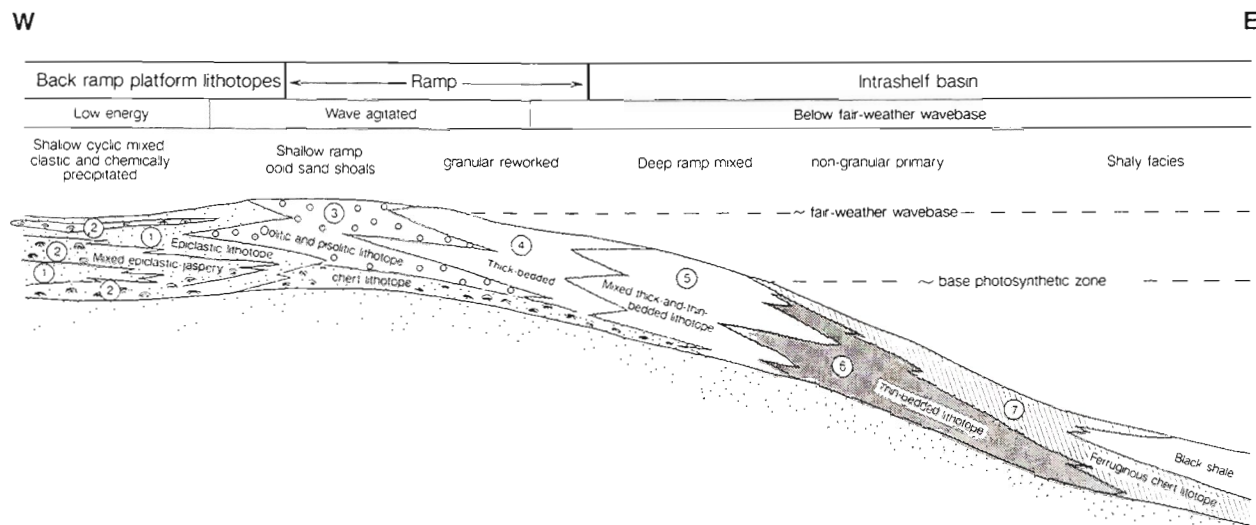


Figure 7 Schematic sedimentological interpretation of lithotopes in Unit A of the Emily district (modified from Morey and others, 1991). The Biwabik Iron Formation contains components equivalent to lithofacies 3, 4, and 5.

The idea of periodic crustal instability in the Biwabik Iron Formation is central to the foredeep interpretation of the Animikie basin proposed by Hoffman (1987) and developed by Southwick and Morey (1991). The foredeep units lapped onto the northern and northwestern cratonic foreland in response to tectonic loading in the hinterland to the south and southeast. Because tectonic processes tend to be episodic rather than continuous over time, the model predicts that the sedimentary responses on the cratonic basin margin also should be episodic.

Chemical Sedimentary Processes

Although there is still considerable controversy, it is likely that Proterozoic iron-formations like the Biwabik Iron Formation formed by processes broadly similar to those illustrated in Figure 8. In the model, silica and ferrous iron from both anoxic weathering and volcanic sources accumulate in an extensive anaerobic marine basin. Upwelling of water rich in silica and iron from such a basin onto a shallow-water shelf leads to three separate but interrelated processes. First, the waters are warmed and carbon dioxide is lost, triggering the precipitation of siderite (FeCO_3). Second, nutrients in the upwelling waters stimulate the growth of protoalgae and cyanobacteria, and consequently the production of photosynthetic oxygen. The presence of that oxygen leads to the conversion of ferrous iron to ferric iron and the precipitation of insoluble ferric hydroxides, which ultimately are converted to hematite. Unlike siderite and hematite, which are syngenetic minerals, magnetite is produced in this setting by the diagenetic breakdown of hematite (Han, 1978, 1982) via the reaction hematite + organic carbon yields magnetite + carbon dioxide (Perry and others, 1973). This reaction shows that the amount of magnetite that can form is controlled by the amount of organic carbon available in the diagenetic system. The amount of available carbon would have been controlled in turn by the organic productivity of the photosynthetic zone and the extent to which dead organisms were oxidized and destroyed, or were reduced and preserved in the near-bottom environment. Consequently, the lack of magnetite and siderite in cherty parts of the Biwabik could be taken to mean (1) that precipitation occurred well within the photosynthetic zone and (2) that oxygen was sufficiently abundant in the photosynthetic zone to destroy organic material before it could accumulate in the diagenetic environment.

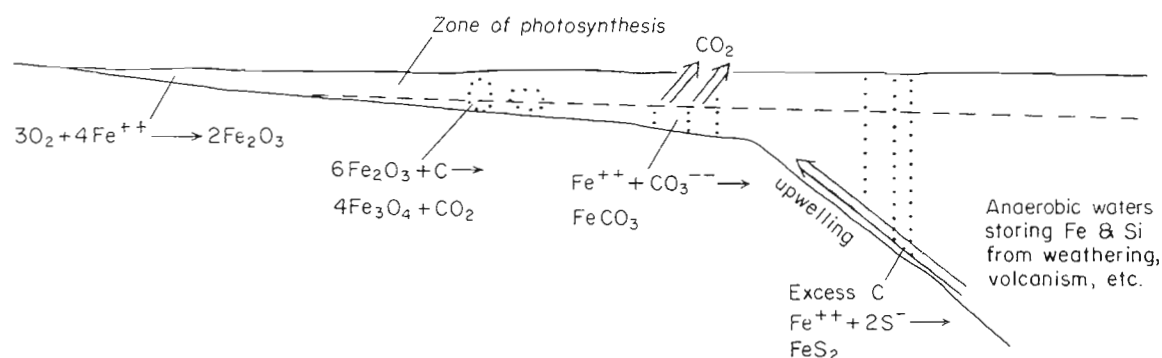


Figure 8 Schematic diagram summarizing the relationships between the precipitation of various iron-bearing minerals and subsequent diagenetic modifications relative to the amount of organic carbon in the depositional system.

Finally, it is generally held that organisms capable of building silica into their internal skeletons did not exist in Early Proterozoic time. Consequently, the amount of silica in any given solution was controlled by the solubility of either amorphous silica or a hydrous silicate such as magadiite or greenalite. Considerable experimental work has shown that the solubility of silica is favored in cold, alkaline solutions. Thus silica will precipitate in response to warming on a shallow-water shelf, a process that is enhanced when warming causes evaporation to occur. Probably more important to the precipitation of silica, however, is the fact that the precipitation of iron, whether by oxidation of the ferrous to the ferric state and subsequent hydrolysis to a ferric oxide, or by forming carbonates or silicates, constitutes a release of acid and a trend toward a solution that is neutral to slightly alkaline, a condition that also favors the precipitation of silica.

In summary, both the physical and chemical sedimentological features of the iron-rich strata in the Biwabik Iron Formation can be attributed to a south-sloping shallow-water shelf environment where oxic conditions prevailed because of extensive photosynthetic activity by protoalgae and cyanobacteria.

Facies Attributes

At about the same time as White (1954), James (1954) proposed a four-fold subdivision of iron-formation into "facies" on the bases of the dominant original iron mineral: sulfide, carbonate, silicate, and oxide. James (1954, Fig. 3) published a diagrammatic cross-section of a conceptual basin in which the facies are presented as integrated lateral equivalents deposited simultaneously in the deep, intermediate, and shallow parts of the basin, respectively. He related the different iron minerals characteristic of deposition at these different depths to parallel, depth-related variations in Eh and pH.

Although James (1954) used the words "highly diagrammatic" in the caption to his Figure 3 and stated (p. 242), "it is doubtful if the pattern of precipitation indicated is ever actually obtained in nature...", the facies concept became almost universally accepted as a sedimentological standard, against which all iron-formations should be compared. Thus Morey (1972) built on White's earlier model and suggested that the Biwabik east of Nashauk could be assigned to a silicate-carbonate facies deposited mostly inboard of the transition between the silicate and carbonate facies, whereas west of Nashauk the rocks were deposited mostly outboard of that transition. Thus the iron-

formation west of Nashwauk was thought to have been deposited in water deeper than east of Nashwauk.

The view that diagnostic mineral assemblages are primary chemical precipitates was challenged by Gruner (1956), who recognized abrupt changes over wide areas from oxide facies to carbonate facies, and vice versa, in various parts of the Biwabik Iron Formation. Gruner held that many minerals, but especially magnetite and the silicates, were diagenetic rather than primary precipitates. Recent petrographic studies of other iron-formations have confirmed Gruner's view that the mineralogy of granular iron-formation reflects a significant diagenetic component. We now conclude that those rock types having textural attributes indicative of shallow water"such as the red taconite toward the base of the Lower Cherty member and the algal interval in the middle of the Upper Cherty member"have hematite that most likely is primary in origin. Except for some very fine grained magnetite, which may be primary, magnetite is a diagenetic product.

The origin of rocks with abundant carbonate and silicate minerals, e.g., rocks of James's (1954) carbonate and silicate facies" is more problematic. These materials could have been precipitated either at the sediment-water interface, or anywhere in the water column between the lower boundary of the photosynthetic layer and the sediment-water interface where they accumulated in their final resting place. Thus the Eh-pH condition under which these minerals precipitated could reflect either the diagenetic or a depositional environment.

Given the above, it seems best to abandon the term "facies" in descriptions such as "oxide-facies iron-formation," insofar as the words are associated in a particular depositional model. Nonetheless, terms such as oxide iron-formation and carbonate iron-formation remain good descriptive terms indicating the dominant iron-bearing mineral assemblage.

Because of the diagenetic nature of many mineral assemblages, Gruner (1946, 1956) championed the view that the major element composition of the Biwabik Iron Formation was the best indication of the chemical environment under which it formed. Moreover, he thought that it was unlikely that the chemical attributes would change significantly with time, except where the iron-formation was subjected to subsequent metamorphic or supergene processes.

The ideas of Gruner were subsequently expanded by Henry Lepp (see Morey, 1992 for a complete reference list), who, among other things, showed that there was little chemical difference between granular and laminated iron-formations, regardless of geographic locality or stratigraphic age. In support of that idea, Lepp (1966) published average compositions for the cherty and slaty members in the Biwabik and, from those, calculated an "average composition" for silicate-carbonate strata. Morey (1992) subsequently expanded on that work and substantiated the long-held position that the Biwabik is characterized by the prevalence of SiO_2 , the major iron species FeO and Fe_2O_3 and, to a lesser extent, carbon dioxide (Gruner, 1946). These constituents are 64 to 94 percent of the total whole-rock composition. The amounts of other major element constituents vary greatly. The iron-formation contains 0.85 to 24.2 wt percent CaO , 8.42 to 24.20 wt percent MgO , 0.18 to 2.20 wt percent P_2O_5 , 0.60 to 4.70 wt percent water, and 0.02 to 4.74 wt percent Al_2O_3 . Other constituents are present in negligible amounts.

Table 1. Some average compositions for the Biwabik Iron Formation

	Lepp (1966)	Morey (1992) ¹
SiO ₂	46.12	43.61 [$\pm$ 6.36] (23.60 - 56.20)
Al ₂ O ₃	0.86	1.24 [$\pm$ 1.70] (0.02 - 4.74)
TiO ₂	0.04	0.12 [$\pm$ 0.191] (0.01 - 0.76)
Fe ₂ O ₃	19.47	16.74 [$\pm$ 9.61] (1.28 - 31.8)
FeO	19.26	19.28 [$\pm$ 6.82] (3.90 - 32.40)
MnO	0.66	0.88 [$\pm$ 0.71] (0.18 - 2.20)
MgO	2.88	3.04 [$\pm$ 1.49]
CaO	1.79	2.71 [$\pm$ 3.31] (0.85 - 24.20)
Na ₂ O	0.05	0.07 [$\pm$ 0.04] (<0.01 - 0.17)
K ₂ O	0.14	0.19 [$\pm$ 0.46] (<0.01 - 0.65)
P ₂ O ₅	0.07	0.09 [$\pm$ 0.46] (0.03 - 0.50)
S	-	0.05 [$\pm$ 0.02] (<0.01 - 12.80)
CO ₂	6.79	10.42 [$\pm$ 6.01] (1.30 - 32.50)
H ₂ O	1.68	1.74 [$\pm$ 1.08] (0.60 - 4.70)

[Major elements in wt percent; — = not analyzed; bold face = arithmetic average; brackets = standard deviation]

¹Number of samples analyzed: 67

Much of the observed variability may be due to compositional differences between cherty and slaty strata (Morey, 1992). For example, the cherty members contain on average somewhat more silica than the slaty members. They also contain appreciable quantities of both ferrous and ferric iron—not surprising, given that the magnetite, which is a dominant mineral in cherty strata, contains 31.0 percent FeO and 69.0 percent Fe₂O₃ by weight. The slaty members contain appreciable Al₂O₃, reflecting the presence of stilpnomelane, the only significant alumina-bearing silicate in the iron-formation.

Other major element constituents such as TiO₂, Na₂O and K₂O, are present in minor quantities and show no obvious relationship to silica, ferrous or ferric iron, or carbon dioxide. However, there is positive correlation between TiO₂ and Al₂O₃, implying that the stilpnomelane may be titanium-bearing. The titanium-bearing silicates in the Trommald Formation on the Cuyuna Range are in part of volcanic derivation (Schmidt, 1958), and a volcanic component also may be present in the Biwabik Iron Formation.

The slaty members also are somewhat enriched on the average with Li, V, Co, Cu, Zn, Y, Zr, Ba and Nb. Robinson (1984) concluded that the elemental association Fe-Mn-Mg-Ca-Co was chemically precipitated in a silicate facies iron-formation in Canada, whereas the elemental association Al-Ti-Zr-V-P-Nb had a volcanoclastic origin. Ewers and Morris (1981) identified two groups of components in the Dales Gorge Member of the Brockman Iron Formation in Australia, where the elemental association Ca-Mg-Mn-CO₂ had the attributes of a chemical sediment, and the association Al-Ti-V had a composite origin, involving clastic material derived from a volcanic source. Thus the Biwabik Iron Formation, like many other Precambrian iron-formations, is probably a composite lithostratigraphic entity composed of materials derived from a mixture of chemical, volcanic, and epiclastic sources. The challenge now is to explain the distribution of these materials in more than the most general way.

NATURAL ORES

Natural ore bodies in the Biwabik have a wide variety of shapes and sizes, but in general can be classed into one of three types: trough, fissure, or flat-lying (Figure 9 and Geologic Map of Mesabi Iron Range in back pocket). Trough ore bodies are as much as 1.6 km long, 300 m wide, and 60-120 m deep. Fissure ore bodies are similar but smaller. Both types are elongate ore bodies with steep and sharply defined walls. They occur locally in parallel swarms. Individual ore bodies may converge, diverge, or intersect so as to leave numerous rock islands or horses, which represent blocks of unaltered iron-formation within the natural ore bodies. Flat-lying ore bodies have a relatively great horizontal extent compared with their thickness. In these, alteration appears to have been localized by bedding planes rather than by joints or fractures.

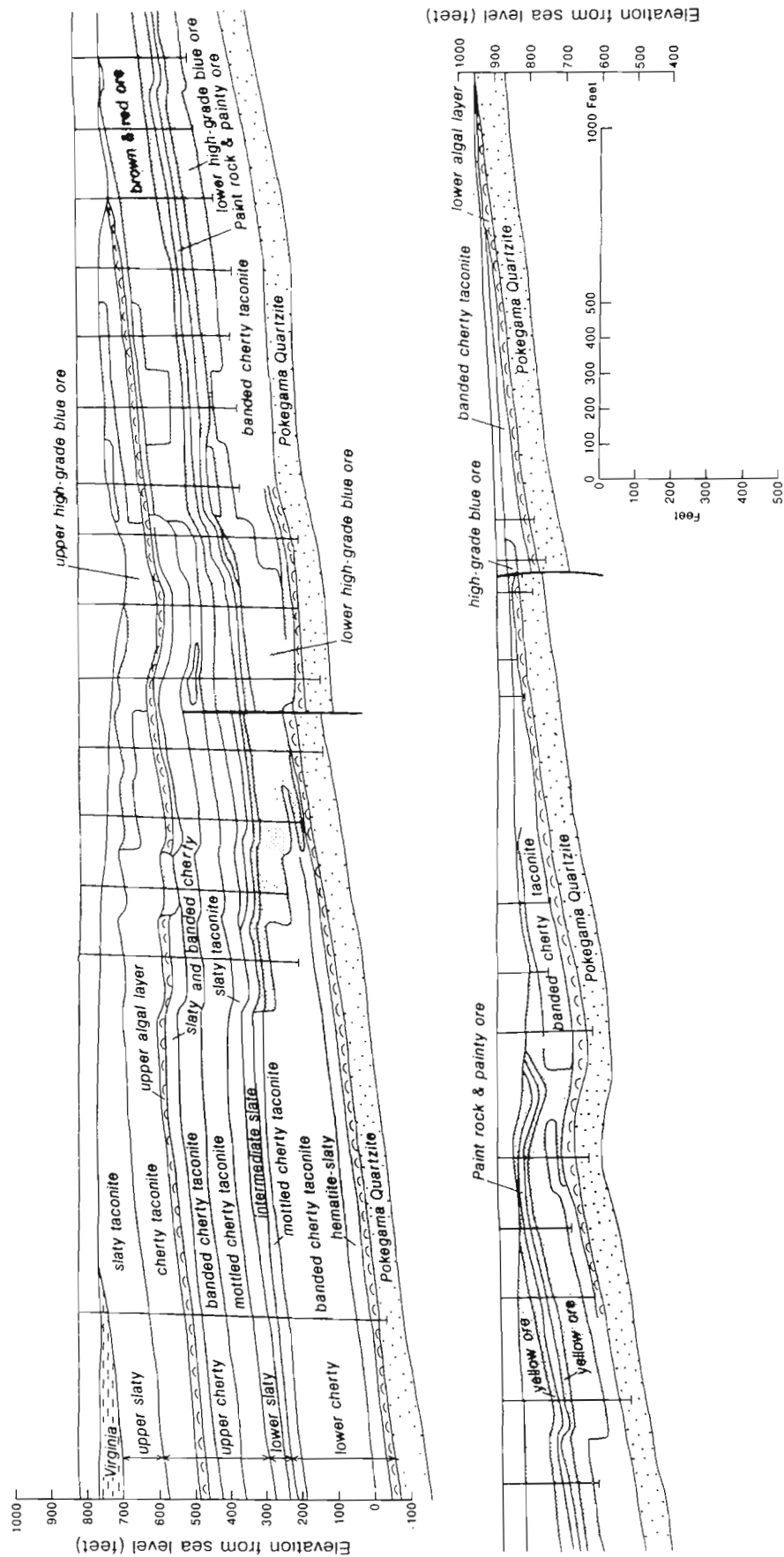


Figure 9 Longitudinal cross section of a large trough orebody and related features, showing the kinds of ore derived from various stratigraphic units in the Biwabik Iron formation (modified from Wolff, 1917).

The major controls of ore localization are considered to be both structural and lithologic on the central Mesabi range and dominantly lithologic on the remainder of the range. Intense fracturing, including both joints and faults, localized in areas of abundant folding, seems to account for about 80 percent of the ore bodies on the central Mesabi range. East of Gilbert, most ore bodies trend N40°-50°W, parallel to the strike of a major joint set and perpendicular to the strike of the iron-formation. In that area, most bodies are of the fissure type and appear to be distributed throughout the iron-formation without regard to the stratigraphy. Between Gilbert and Mountain Iron, as in the central Mesabi range, the ore bodies appear to be localized by monoclinal flexures and by fractures of a major joint set that is perpendicular to the strike of the iron-formation. The ore bodies are of both trough and fissure types, and are deep. Some extend vertically through the entire iron-formation, but most are confined to texturally, compositionally, or structurally more favorable parts of the iron-formation. Between Mountain Iron and a hypothetical line about midway between Keewatin and Nashwauk, the ore bodies trend either northwest or west, parallel to a major fracture set. Commonly, several parallel troughs coalesce to form fairly large bodies, particularly near the hanging wall. At depth, the ore bodies resemble those between Gilbert and Mountain Iron in that they contain large horses of unaltered iron-formation. From east of Nashwauk westward, fissure- or trough-type ore bodies are inconspicuous, and most of the ore bodies are of the relatively shallow, flat-lying type. There the ore appears to be controlled by the lithologic character of the iron-formation. All the ore bodies reach or closely approach the present erosion surface, and none is completely covered by the Virginia Formation. Ore zones may extend beneath the Virginia Formation, and where this occurs, the overlying rocks are kaolinized and bleached.

There is little doubt that the natural ores are the products of two largely concurrent processes. One process involves the oxidation and hydration of primary mineral assemblages to various oxides, coupled with loss of volume and coincident increase in secondary porosity—typically, magnetite altered to martite, minnesotaite and greenalite to goethite, siderite to hematite or goethite, and stilpnomelane to goethite, hematite, and kaolinite. The resulting oxidized iron-formation is in itself not of ore grade, but the increased porosity and permeability greatly enhanced the ability of through-flowing solutions to leach silica, phosphorus, magnesium, and calcium. Leaching in turn led to even more porosity and permeability and to ore deposits that, in some places, formed many hundreds of meters away from the original channelways.

There is a consensus that oxidation and leaching occurred through action of large volumes of water that flowed through the iron-formation along previously prepared channelways. There is, however, no consensus as to the source or sources of those large volumes of water. Two principal hypotheses have been proposed: (1) oxidation and leaching resulting from downward-moving supergene waters, and (2) oxidation and leaching resulting from upward-moving hydrothermal or hypogene solutions.

One of the earliest supergene models was that of Irving (1886), who suggested that the flow of meteoric water led to a combination of in situ oxidation and precipitation of iron oxides from solution. Van Hise and Bayley (1897) apparently were inspired by this model when they suggested that meteoric waters decomposed iron carbonate and carried ferrous iron deep into the strata. This iron was reprecipitated at depth by the confluence with oxygen-bearing water flowing directly from the surface. By 1911, Van Hise and Leith had developed the often-cited hypothesis that high-grade ores resulted from supergene processes involving often-cited meteoric waters.

Gruner (1926, 1930) is probably best known for hypogene models for the formation of the natural ores. His basic model visualized the oxidation and concentration of iron minerals by the leaching of silica in hot magmatic waters. Gruner (1937) subsequently modified his model by envisaging hot gases from deep igneous intrusions that heated oxygenated ground water, which dissolved silica and oxidized the iron minerals. Enrichment also occurred by replacement of quartz by hematite. However, no supporting evidence, such as conduits, hydrothermal minerals, or an

adequate magmatic source, has been identified; and there is a tendency today to believe that the natural ores formed by supergene weathering processes in Late Jurassic to pre-Late Cretaceous time. Neither field nor experimental and theoretical evidence is conclusive for either a supergene or hypogene mechanism.

MAGNETITE TACONITE ORE

Magnetite occurs throughout the unoxidized iron-formation in widely-varying amounts. It occurs as disseminated individual octahedra, aggregates of octahedra, and layered clusters formed by interconnecting aggregates of grains. Very fine grained magnetite, which occurs in both granules and matrix as disseminated and diffuse crystals 5 microns or less in size, could be a primary precipitate. Definite secondary magnetite euhedra, 0.05 to 0.1 mm in diameter, commonly replace earlier iron silicates in granules, and also surround and embay fine-grained siderite in the thin intervals of laminated strata within granular iron-formation. Replacement by magnetite is most common at granule margins, yielding an inner core of greenalite or minnesotaite surrounded by a rim of coarser magnetite that generally preserves the outline of the granule; more rarely, an entire granule is pseudomorphously replaced by magnetite. Thus, magnetite appears to have been one of the last minerals formed.

Thick layers from which magnetite can be mined and concentrated, using present technological methods, occur principally in two areas: the central Mesabi range between the towns of Nashwauk and Mesaba (now abandoned), and the east Mesabi district, from Hoyt Lakes to Dunka (Fig. 6). The distinction between these two areas also has a geological basis, as east of Hoyt Lakes, the Biwabik Iron Formation was modified through metamorphism by the Duluth Complex.

In the area between Nashwauk and Mesaba on the central Mesabi range, ore bodies of mineable magnetite occur chiefly within the cherty members: The slaty members are either too thin or too lean to be mineable. The ore zones are tabular bodies whose vertical extent is defined by a more or less arbitrary magnetite content, and whose lateral extent is limited by superposed oxidation patterns. The middle part of the Lower Cherty member is a major ore zone, inasmuch as it has the greatest extent and is fairly uniform in magnetite content. In contrast, the Upper Cherty member is much more variable in lithology; consequently, it has a much less uniform iron content and the magnetite is distributed erratically.

West of Nashwauk, there is a profound lateral change from magnetite- and silicate- bearing to carbonate-bearing iron-formation and, as a consequence, only relatively small horses or tongues of unoxidized magnetite-bearing strata exist here. In general, the magnetite ore occurs primarily in the Lower Cherty member in the southern part of the outcrop belt, where overlying strata protected the iron-formation from the pervasive, near-surface oxidation. In contrast, the Lower Cherty member is relatively thin in the East Mesabi district, and mineable magnetite deposits are restricted to the Upper Cherty member and the lower part of the Upper Slaty member.

POKEGAMA QUARTZITE

Richard W. Ojakangas

The Pokegama Quartzite has been studied briefly by various workers since it was named by Winchell (1893) for exposures at the west end of the Mesabi range. Much of the previous work has been summarized by Morey (1972, 1973).

Distribution and Thickness

Few natural exposures exist, as thick glacial drift generally covers the formation. Outcrops, roadcuts, and mine cuts occur at a few places over the length of the Mesabi range, a distance of about 130 km, but most exposures are restricted to the central part of the range. Only two drill holes, one located just south of Eveleth (NE1/4-NE1/4, Section 5, T.57N, R.17W,) and the other southwest of Mountain Iron (SE1/4-SE1/4, Section 8, T.58N, R.18W), separated by 12 km, are known to transect the entire formation, which is 51 m thick and 26 m thick, respectively, at these two points (Fig. 10). Several other drill holes have penetrated the upper part of the formation, but most drilling on the Mesabi range was performed in relation to iron ore exploration and development and barely penetrated the Pokegama beneath the Biwabik Iron Formation. The Pokegama is thought to thicken from the eastern end of the Mesabi range, where it is only a few meters thick, to the western end of the range, where it may be as much as 100 m thick (White, 1954 and Morey, 1979) (see Geologic Map of Mesabi Iron Range in back pocket). It also thickens to the south in the central part of the range.

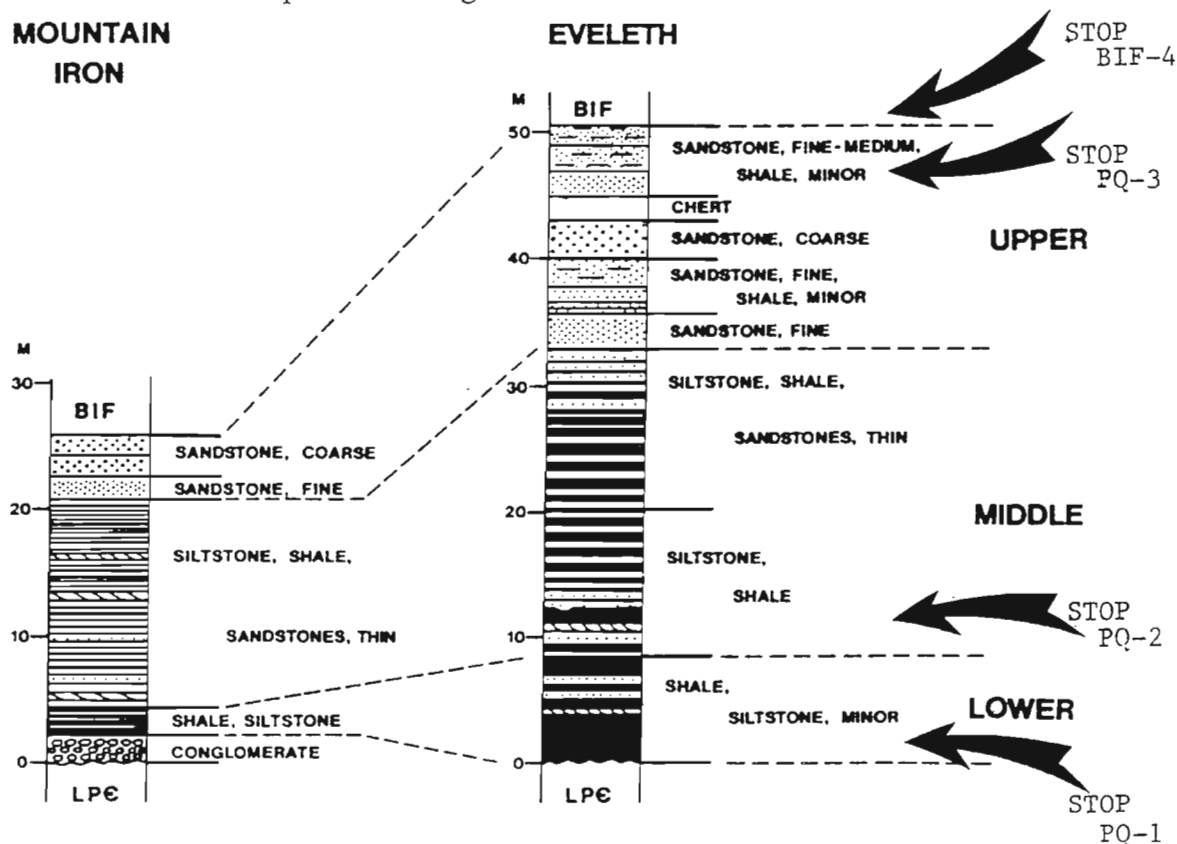


Figure 10 Measured sections from drill cores of the Pokegama Quartzite in the area of field trip. Dark shading represents shale, thin blank units represent siltstone, and dotted pattern represents sandstone. BIF is Biwabik Iron Formation and LPE is Lower Precambrian (Archean) basement. The terms "lower," "middle," and "upper" refer to the members. Arrows indicate stratigraphic positions of field trip stops PQ-1, PQ-2, PQ-3, and BIF-4, which are shown on Figure 21 (after Ojakangas, 1983).

Contact Relationships

The Pokegama Quartzite unconformably overlies Archean metavolcanic, metasedimentary, and plutonic rocks. There may be as much as 30 m of relief on the Archean surface beneath the quartzite (Grout and Broderick, 1919); but the surface was, nevertheless, essentially a peneplain.

The contact between the Pokegama and the overlying Biwabik Iron Formation is conformable, although a chert-fragment conglomerate at the contact has been interpreted as a minor unconformity (Leith, 1903). Dolence (1961) described both gradational and sharp contacts. A cherty zone found 6 m and 12 m beneath the top of the Pokegama in two different drill cores (Dolence, 1961) further signifies a gradation between the Pokegama and the Biwabik (Fig. 10).

General Lithology

The Pokegama Quartzite, despite its name, consists of three main rock types: quartzite, metasiltstone, and argillite. Most exposures consist of massive quartzite just beneath the Biwabik Iron Formation. However, two human-made exposures of lower parts of the formation are made up largely of thin-bedded argillite and metasiltstone.

The drill holes that intersect the entire formation show best the stratigraphy of the formation (Fig. 10). Pre-metamorphic lithologic terms will generally be used in the following descriptions. The top part of the formation consists of sandstone, mostly fine- to medium-grained with thin siltstone and shale layers; the middle portion consists of interbedded siltstone and shale with only minor sandstone; and the lowest consists of shale with minor siltstone and sandstone. Minor basal conglomerate is present locally.

Environment of Deposition

The Pokegama closely resembles the Palms Formation on the Gogebic Range in Michigan and Wisconsin. The Palms is well exposed, and paleocurrent indicators are abundant. The environment of deposition for the Palms was interpreted as tidal on the basis of sedimentary structures and a bimodal-bipolar paleocurrent pattern (Ojakangas, 1983). Three major members were distinguished: a basal argillaceous member; a middle member comprised of thin beds of shale, siltstone, and sandstone; and an upper member of sandstone. The basal argillaceous member was interpreted as having been deposited as the initial unit upon the basement in a transgressing sea, the upper tidal flat. The middle member was interpreted as middle tidal flat, and the sandy upper member as lower tidal flat or subtidal. The striking similarities between the Palms and the Pokegama were utilized in assigning the same environments of deposition to the members of the Pokegama (Fig. 11).

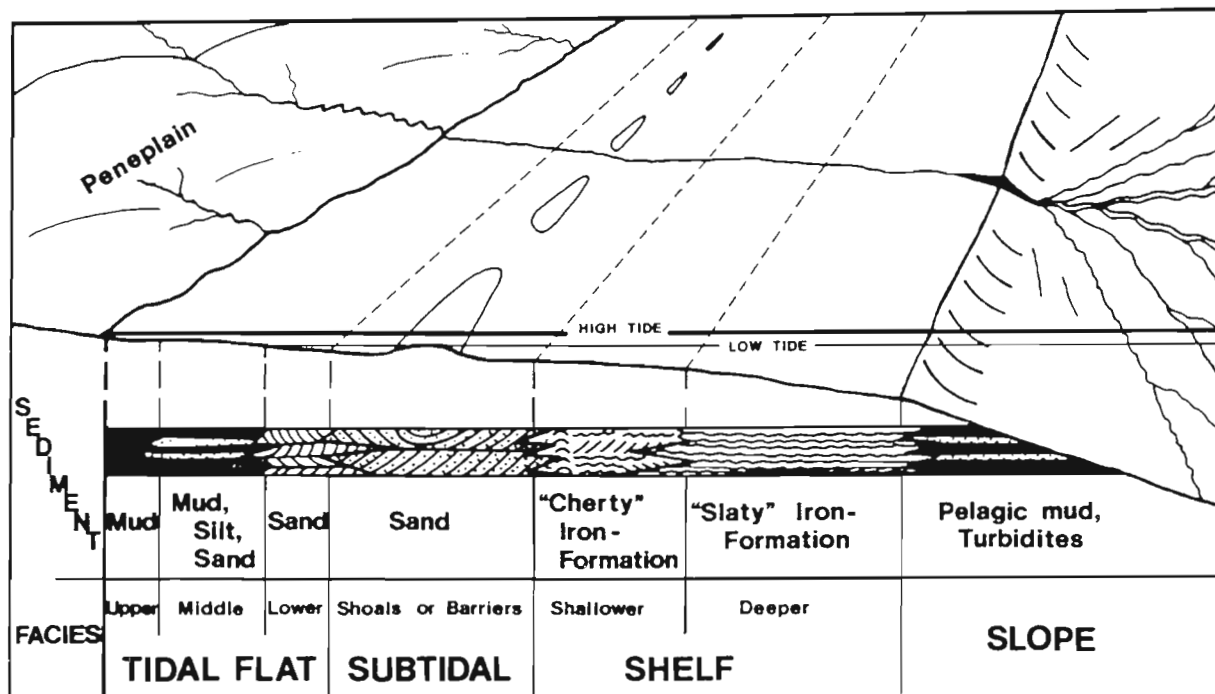


Figure 11 Sedimentational model showing lateral relationships of the siliciclastic tidal facies (Pokegama Quartzite), the iron-formation (Biwabik Iron Formation) on the shelf, and the deeper-water turbidite-mud facies (Virginia Formation). Thickness and geography not to scale (from Ojakangas, 1983).

Tectonic Setting

The Animikie basin, with the Pokegama Quartzite and the Biwabik Iron Formation located on its northern edge, has been interpreted as a northward-migrating foreland basin (Hoffman, 1987; Southwick and Morey, 1991; Holst, 1991; Ojakangas, in press). The basin is located between Archean rocks to the north and 1850-1900 Ma calc-alkaline volcanic rocks and granitic plutons to the south in Wisconsin and east-central Minnesota. In this tectonic model, a fold-and-thrust belt developed to the south as a result of southward subduction of the Archean continent, and a peripheral bulge formed on its northern edge. The Pokegama Quartzite and Biwabik Iron Formation were deposited on the southern edge of this bulge. Alternatively, they may have been deposited on a stable platform prior to the development of the foreland basin; the main fill in this part of the basin is graywacke, siltstone, and mudstone of the Virginia and Thomson Formations.

IRON ORE AND TACONITE MINES OF THE MESABI RANGE

NATURAL IRON ORE MINES

Adapted by D.G. Meineke from Marsden and others, 1968.

The Mesabi range natural iron ores have been well-described by Leith (1903), Wolff (1915), Gruner (1946), White (1954), and others. Commercial natural iron ore bodies occur as irregular deposits within the Biwabik Iron Formation where oxidation has changed the iron minerals of the primary unoxidized taconite to hematite and goethite, and leaching has removed sufficient silica so the material can be shipped to the steel furnaces directly or after rather simple beneficiation

processes. These processes include crushing, screening, washing, and gravity beneficiation methods. The natural iron ore deposits have a spatial distribution in that essentially no deposits occurred in the eastern area where the taconite was metamorphosed by the Duluth Complex; the area between Mesaba and Hibbing contained a very high proportion of direct shipping ore with lesser amounts of partly-leached, concentrating-grade material; and, west of Hibbing, the deposits had a preponderance of concentrating-grade ore and rather small amounts of direct shipping ore (see Geologic Map of Mesabi Iron Range in back pocket).

The first discovery of commercial iron ore on the Mesabi range was in 1890 at Mountain Iron by the Merritt brothers of Duluth. The Mountain Iron deposit was developed in conjunction with construction of the Missabe & Northern Railroad from Duluth to Mountain Iron, and the first shipment of iron ore was in 1892. In 1992, the Northwest Ore division of LTV Steel Company permanently closed the last operating natural iron ore concentrating plant (wash plant), located at the Stephens and Donora Mines on the eastern Mesabi range. LTV continues to produce natural iron ore from the Connie Mine near Inland Steel Mining Company's Minorca taconite mine, with exhaustion of the Connie Mine expected in 1993. The Connie ore is simply crushed before shipment. The Connie is the only natural iron ore mine to operate in 1993 on the Mesabi range.

The natural ore deposits occur in a wide variety of shapes and sizes. In size, they contain from a few thousand tons to hundreds of millions of tons. In shape, the deposits range from narrow fissures of ore following a single fracture, to channel-type deposits following a system of fractures, to blanket-type deposits where extensive areas in favorable stratigraphic horizons formed ore. In some deposits, ore was developed in essentially the entire Biwabik Iron Formation from the Pokegama Quartzite to the Virginia Formation.

All ore bodies are related to erosion surface on Precambrian basement, which generally is the present bedrock surface. The ore bodies commonly lie directly below the glacial drift or, in some areas, below a thin interval of Cretaceous strata. The ore extends to various depths, from a few feet to about 800 feet, but most ore is within 400 feet of the surface. Ore typically occurs in the outcrop area of the Biwabik Iron Formation, although extensions of a few ore bodies reach a short distance under the Virginia Formation, as at the Embarrass and St. James Mines. In a few deposits, such as the Missabe Mountain and Auburn Mines near Virginia, decomposed, kaolinized, and bleached Virginia argillite occurred in the central part of slump synclines over iron ore bodies. The ores may show a more widespread development in certain layers within the Biwabik Iron Formation than in others. One such layer is at the top of the Lower Cherty member, where a 15- to 30-foot portion of the upper silicate-taconite unit forms flat, strata-bound, yellow limonitic ore bodies. This type of ore body was mined extensively at the Godfrey underground mine northeast of Hibbing.

The mineralogy and chemistry of natural ore shows a direct relationship to the taconite from which it was derived. Slaty taconite commonly produced slightly to highly aluminous ores containing from 1.0 to 6.0 percent or more Al_2O_3 . This ore is usually fine grained and red. It typically is sticky, has a high moisture content, and is termed "painty ore" or, if not of ore grade, "Paint Rock." The magnetite-rich middle unit of the Lower Cherty member commonly yields a blue, martitic, high-grade ore that is low in silica, alumina, and phosphorous. The silicate taconite at the top of the Lower Cherty members forms a yellow to brown ore, and the Upper Cherty member produces brown to blue ores that commonly are of non-Bessemer grade, ranging from 0.04 to 0.18 percent phosphorus and from 0.5 to 1.5 percent alumina. The silica content tends to be low in the cherty ores (2-8%) but higher in the painty ores (5-10%). The ores shipped to the steel furnaces are blends of high- and low-silica ores, concentrated ores, and painty ores, designed to meet specific grade requirements.

The natural, direct shipping ores occur in permeable areas where leaching action has been concentrated. There is a common correlation of ore bodies with faults, flexures, and folds that

caused fracturing in the brittle taconite. White (1954) concluded that about 75 percent of the natural ore is related to various types of folds and flexures, 15 percent to faults, and 10 percent to stratigraphic and other factors.

It is thought that oxidation and leaching processes worked together, but that the oxidation of the ferrous iron minerals was easier to accomplish than the removal of the major quantities of silica required to produce high-grade ores. This is shown by the extensive areas of oxidation around some ore bodies.

The removal of 40-60 percent of the taconite by the leaching of silica, with little, if any, introduction of material, created much pore space and the residual mass of iron oxide could not support the overlying ore and rock. The resulting slump often amounted to 35-45 percent of the original thickness of the taconite. In deep channel or trough ore bodies, prominent slump synclines developed and were accompanied by faulting and crumpling in the ore. In a general way, the depth of the ore body is indicated by the extent of slumping observed in its upper parts.

Quartz veins, some up to 15-20 feet wide and 0.5 miles long, are found in some ore bodies. The development of these veins may have had some influence on the ore genesis, but no direct relationship has been proven.

The Upper Cretaceous seas, acting on a shoreline along the Mesabi range, eroded and concentrated the iron-bearing materials of the Biwabik Iron Formation. Where the eroded Biwabik contained ore bodies, the conglomerates in the Cretaceous locally are ore-grade deposits consisting of pebbles and grains of iron ore in a limonitic matrix. Some of these ore bodies resemble stream valley gravels, others appear to have been formed as beach deposits, and some, as at the Enterprise Mine near Virginia, appear to be accumulations of an iron-cemented conglomerate, resembling "Canga," on the pre-Cretaceous surface. The Cretaceous ores are generally higher in sulphur, phosphorus, and alumina than ores formed in the Precambrian iron-formation.

Cretaceous rocks are common in the western Mesabi as far east as Hibbing. East of Hibbing they occur as isolated deposits, as at the Sherman Mine near Chisholm, the Judson Mine near Buhl, and the Enterprise Mine at Virginia. In some areas, as the Judson Mine, the Cretaceous ore conglomerate has been transported and the underlying Precambrian rock is the Virginia argillite.

TACONITE MINES

Introduction

David G. Meineke

The taconites of the Mesabi range (Biwabik Iron Formation) commercially can be divided into two groups: (1) fine-grained magnetite-rich cherty intervals and magnetite-rich slaty intervals for which eight commercial magnetic taconite concentrating plants were originally constructed, and (2) nonmagnetic oxidized cherty taconite composed of fine-grained chert, hematite, and goethite, for which a commercial processing plant has not been constructed on the Mesabi range. Although the magnetite-rich intervals currently being mined are of appreciable thickness, locally they are referred to as "horizon," and that usage is continued here. The magnetic taconite mines and plants, along with production statistics, are described in Table 2. The first magnetic taconite operations on the Mesabi range, Cyprus Northshore Mining Corporation (formerly Reserve Mining Company) and LTV Steel Mining Company (formerly Erie Mining Company), began operations in the 1950s. Butler Taconite was permanently closed in 1985 and has been completely dismantled, leaving seven magnetic taconite plants currently operating on the Mesabi range.

TACONITE OPERATION	OWNERSHIP	START OF OPERATIONS	ANNUAL PELLET CAPACITY (Long Tons)	PRODUCT	MINE PITS	CRUDE TACONITE MINED ¹ (Long Tons)	PELLETS PRODUCED ¹ (Long Tons)	CRUDE TACONITE GRADE (% Mag Fe)	PELLET FE	EMPLOYEES
Butler Taconite	M. A. Hanna Company Inland Steel Mining Company Wheeling Pittsburgh Steel Corporation	1967 (permanently closed in 1985)	2,650,000	Acid Pellets	3	125,389,000	40,500,684	22.2%	65.82% (dry)	500
Cyprus Northshore Mining Corporation (formerly Reserve Mining Company)	Cyprus Minerals Corporation	1955	4,200,000	Acid & Flux Pellets	1	660,393,000	226,566,000	24.0%	65.13% (nat.) Acid 63.25% (nat.) Flux	425
Eveleth Mines	Rouge Steel Company Oglebay Norton Company Armco, Inc. Stelco, Inc.	1965	5,400,000	Partial Flux Pellets	2	277,293,171	89,097,438	23.0%	64.49% (nat.)	740
Hibbing Taconite Company	Bethlehem Steel Corporation Cleveland-Cliffs Iron Company Stelco, Inc.	1976	5,270,000	Acid Pellets	2	367,467,000	103,882,000	20.0%	66.30% (dry)	950
LTV Steel Mining Company (formerly Erie Mining Company)	LTV Steel Company	1957	3,000,000	Acid Pellets	5	799,731,175	268,724,478	22.5%	65.6% (dry)	1,500
Mammetac	USX Corporation	1967	13,500,000	Acid & Flux Pellets	2	829,251,919	252,116,535	20.61%	64.38% (dry) Acid 62.22% (dry) Flux	1,600
Minorca	Inland Steel Mining Company	1977	2,500,000	Acid & Flux Pellets	2	106,868,000	19,821,000 12,512,000	24.0%	65.18% (nat.) Acid 61.69% (nat.) Flux	300
National Steel Pellet Company	National Steel Corporation	1967	5,000,000	Acid Pellets	2	301,900,000	86,900,000	18.6%	65.4% (nat.)	710

¹Start of operations through December 31, 1992

Table 2 Mesabi Range magnetic taconite operations (compiled by D.G. Meineke, 1993, with information provided by J.L. Arola, H. Djerlev, R.G. Graber, J.E. Hanttula, L.A. Mattson, P.L. Pastika, F. Pezzuto, R.J. Waidler, and R.L. Winston).

Figure 6, compiled by Henry Djerlev for this guidebook, is a longitudinal section of the Mesabi Range Biwabik Iron Formation showing the magnetic taconite operations at nine localities. The longitudinal section shows the four major members of the Biwabik Iron Formation (Upper Slaty, Upper Cherty, Lower Slaty and Lower Cherty), together with the mineable magnetic taconite intervals. Mineable magnetic taconite occurs only in the Lower Cherty at some taconite mines and largely in the Upper Cherty at other taconite mines; some taconite mines have mineable magnetic taconite in three of the four members of the Biwabik Iron Formation. The Dunka Mine contains the highest grade magnetic taconite on the Mesabi range, resulting from metamorphism and recrystallization of the Biwabik Iron Formation by the intrusion of the Duluth Complex. West of the Butler Taconite area (Nashwauk), the taconite is largely oxidized (nonmagnetic) with small, isolated deposits of magnetic taconite.

The following pages contain descriptions of each of the eight magnetic taconite operations on the Mesabi range from west to east. The geology and other pertinent information presented for the taconite operations was prepared by the geologists who have worked in these taconite mines.

BUTLER TACONITE

Louis A. Mattson

The Butler Taconite operation, managed by the Hanna Mining Company, was located between Nashwauk and Calumet, Minnesota. Concentrator operations began in January 1967, and the first pellets were produced in March 1967 at an initial design capacity of 2 million long tons per year. The operation was closed in June 1985 prior to exhaustion of ore reserves. Average production was 2.65 million long tons per year during the period of operation. All mining, concentrating, and pelletizing facilities have been removed from the site and the pits are now filling with water.

The Butler magnetic taconite ore bodies are located in the western portion of the Mesabi range, near the western end of known commercial quantities of magnetic taconite (near locality 3 on fig. 6).

The taconite mining operations deepened and expanded previous open pit areas that had produced hematite-goethite direct shipping ores and concentrates. Magnetic taconite was mined exclusively from the Lower Cherty member. The mineable interval, about 200 feet thick, in the central portion of the Lower Cherty is subdivided into eight stratigraphic units based on differences in mineralogy, texture, and layering. The iron-formation in this interval contains an average of about 30 percent magnetite along with quartz, minnesotaite, stilpnomelane, and talc, plus sideritic and ankeritic carbonates. Minor to trace minerals include primary hematite, pyrite, greenalite, chlorite, and apatite.

In the Butler area, a complex pattern of faults, fracture zones, and folds has locally destroyed the magnetic properties of the iron-formation and separated the ore body into several taconite pit areas, with oxidized nonmagnetic taconite between the ore bodies. A steeply dipping reverse fault system has been traced from the Snowball Lake area, near Calumet, northeastward through the LaRue Mine east of Nashwauk. Offset on this fault system varies from about 20 feet on the west end to about 100 feet near Nashwauk. A series of northwest-trending fracture zones cross the fault system. Measurable displacement has not been observed in these fracture zones. However, the location and alignment suggest that the zones are related to pre-iron-formation fault zones in the basement rocks. Two major north-south trending monoclinical folds are also present in the Butler pit area; each displaces the iron-formation downward to the east a maximum of 75-100 feet. Maximum dips on limbs of the two folds are 45° and 70° to the east.

Significant resources of magnetic taconite remain in the Butler area. The ore has a magnetite content and above-average liberation characteristics compared to other Mesabi range taconite operations.

NATIONAL STEEL PELLET COMPANY

James E. Hanttula

The National Steel Pellet Company plant is located approximately one mile northeast of Keewatin, Minnesota (near locality 4 on Foig. 6). The ore body is another 0.5 miles to the north and strikes northeastward. The dip is between 6° and 9° to the SE. As at other taconite operations, the pit is an expansion of older natural ore pits. Current expansion is largely to the southwest.

The taconite being mined is approximately 120 feet thick and is from the central portion of the Lower Cherty. During 1992, the ore body averaged 27.8 percent weight recovery and 18.8 percent magnetic iron at 80 percent -325 mesh. The upper quarter of the mined taconite interval is variably oxidized. Mineral assemblage includes chert, magnetite, siderite, ankerite, minnesotaite, stilpnomelane, greenalite, hematite, and minor pyrite. Faulting and other structures have not been significant in mine development. The bottom of the mine zone is defined by the top of a fairly uniform slaty layer some five feet thick. Due to variations in the ore body characteristics, principally the magnetic iron liberation and oxidation, blending of the "ores" is necessary.

In 1992, 18.5 million tons of ore were mined and 5 million tons of pellets were produced. Total pellet production from June 1967 through December 1992 was 85.9 million tons.

HIBBING TACONITE COMPANY

Henry Djerlev

The Hibbing Taconite Company plant is located approximately four miles northwest of Hibbing, Minnesota (near locality 5 on fig. 6), just north of the Laurentian Divide. The initial pit was developed in Section 36, T.58N, R.21W, starting in 1975. Since inception, this pit has expanded east, west, and south along the northern crest of the historic Hull-Rust Mahoning natural ore mine. In 1990, a second pit was begun approximately three miles to the southwest. Erosion has removed the Upper Slaty and most of the Upper Cherty members. Where present, the Lower Slaty member

and the upper 30 feet of the Lower Cherty member are stripped as rock waste. Approximately 150 feet of cherty and slaty taconite is mined from the central portion of the Lower Cherty. The formation strikes northeast and dips 6°-8° to the southeast. The Pokegama Quartzite forms the footwall of the iron-formation and outcrops to the north, along the south edge of the divide. The dip of the formation and the slope of the erosion surface have required from 1-4 mining benches, each averaging 45 feet in height. The only significant structural features are common, but minor, northwest-trending normal faults. Numerous natural ore mines were located along these oxidized structures.

The Hull-Rust Mahoning Mine, actually a combination of 30 separate mines, was developed along an east-trending structure and operated from 1895 to 1979. Material movement from this "largest open pit iron mine in the world" totaled more than 1.1 billion tons.

The taconite mined by Hibbing Taconite Company averages 20 percent magnetic iron with the general mineralogy consisting of quartz, magnetite, siderite, ankerite, minnesotaite, stilpnomelane and hematite. Of the mineable units in the Lower Cherty, the upper three (120 feet thick) are predominantly "cherty" taconite with 6- to 12-inch-thick massive silicate-chert zones separated by 1/8- to 2-inch-thick slaty bands. The lower two units (30 feet thick) are predominantly "slaty" taconite with interbedded argillite, magnetite, and minor hematite forming slaty bands from 2-10 inches in thickness separated by 2- to 4-inch massive cherty zones.

Glacial overburden, waste rock, lean oxidized taconite, and old stockpiles are the materials requiring stripping, they vary widely in thickness from area to area. Standard rotary drilling, blasting, electric shovel loading, and 240-ton truck haulage are the mining methods utilized. The processing flowsheet differs significantly from the standard Mesabi range taconite plant in the area of crushing and grinding. A single stage of gyratory crushing in one of two 60-inch crushers reduces the crude to 10 inches. This is followed by autogenous grinding in one of nine 36-foot-diameter mills. Water is added and as the ore tumbles, it reduces itself to powder fineness.

The annual production capacity of Hibbing Taconite Company is 8.27 million tons of taconite pellets, operating 24 hours per day year-round, employing 950 people.

MINNTAC

Frank Pezzutto

Minntac is a taconite mining and pelletizing operation located along the central Mesabi range (near locality 6 on Fig. 6), approximately 70 miles north of Duluth, Minnesota. Minntac, which is totally owned by the USS division of the USX Corporation, began pellet production in 1967. Mining operations, which cover an area approximately 8 miles long by 1 1/2 miles wide, consist of the West Pit and the smaller East Pit. The ore is mined using 14-cubic-yard electric shovels in 15-40 foot banks. The relatively shallow dipping and expansive deposits with constant strike and dip allow for rail haulage to the primary crusher. Minntac blasts approximately 60 million tons of material annually (Eloranta, 1993; personal communication).

Natural Ore

The discovery of hematite-goethite ores in 1890 near the town of Mountain Iron ushered in the first commercial development of the iron resources on the Mesabi range. The Mountain Iron Mine, which began operations in 1892, sits between the Minntac East and West Pits. In plan view, numerous old natural iron ore pits and workings such as the Prindle, Wheeling, Snively, and Atkins occur along a lineament that parallels the general strike of the iron-formation in the Mountain Iron area. Their derivation from weathering and their stratigraphic and spatial relation to structural elements such as faults and folds is clear.

Structural Geology of the Minntac Area

The gross structure of the iron-formation in the Minntac area is a gently dipping homocline that strikes ENE and dips 6°-15° to the southeast. From mine sections, the homocline appears as a prominent flexure along the basal Pokegama Quartzite; it can be traced from the Prindle Pit westward along the Wheeling and Snively workings and becomes vague south of the Minntac West Pit. Numerous ENE-striking flexures are also visible from the mine sections and likely represent weak faults subparallel to the homocline. As a whole, the iron-formation in the Minntac area is consistently shallow-dipping.

Oxidized zones are readily traceable from magnetic probe results and field observations. These linear and generally vertical oxidized zones probably represent late faults. A right-lateral fault with several hundred feet of horizontal displacement is inferred from magnetic probe results and field observations in the East Pit. In several locations, thin horizontal oxidized zones mark horizontal bedding faults. The bedding faults are related to anisotropic properties of different lithologic units during mild deformation.

Previous unpublished work by W. L. Plummer (longtime mine geologist with USX) on joints in both pits concludes that major joint sets are parallel to the strike of the iron-formation in the area (azimuth-062°). Minor sets are somewhat random. More work is needed to identify joint patterns in order to increase production blast efficiency.

Stratigraphy

The iron-formation in the Minntac area is generally several hundred feet thick except along the northern edge of the pits, where it thins along the contact with the Pokegama Quartzite. There are two types of iron-formation exposed in the area: cherty and slaty. All four members of the iron-formation are present in the Minntac area. At present, only the Lower Cherty and Lower Slaty Division are being mined and stratigraphic descriptions will be restricted to them. During the last six years, production trends have been relatively constant, with 70 percent of production coming from the Lower Cherty Division. Twenty percent of production originates from the "high silica" Lower Slaty Division. The remaining crude is mined from the Interbedded Chert (IBC) unit, which occurs locally in the Lower Slaty Division. The author believes that the irregularly distributed IBC unit represents intertidal channels formed on ancient mud flats during a dominantly transgressive period.

Stratigraphic intervals are based upon field observations, drill logs, and descriptive work by W. L. Plummer.

Lower Cherty Division

The Lower Cherty Division has been subdivided from bottom to top into the following subunits: LC1, LC2, LC3, LC4, LC5A, and LC5B. Lower subunits are generally massive and fragmental, whereas upper subunits are bedded. X-ray diffraction work by the author has identified the following minerals: magnetite, hematite, maghemite (?), minnesotaite, iron-carbonates, stilpnomelane, and quartz (chert). A thick basal sandstone sits between the Pokegama Quartzite and the LC1 subunit. The gray to reddish sandstone is locally conglomeratic. In some areas, algal chert interbeds may be present and are either gray and flinty or reddish and jaspery.

- LC1 Subunit: Massive- to vaguely-bedded and locally fragmental. Generally grayish in color with magnetite, chert, hematite, and light brown ankerite.
- LC2 Subunit: Fine-grained, dark, vaguely bedded magnetite, with purplish jasper layers and local iron-carbonate blotches.
- LC3 Subunit: Thin green to gray wispy-bedded magnetite with or without iron- carbonate mottling. Distinct coarse-grained cherty and green iron-silicate bands. Local pyrite.
- LC4 Subunit: Greenish, mottled to well-bedded magnetite and cherty bands; grades into a massive greenish iron-silicate and cherty subunit with local patches of magnetite and iron-carbonates.
- LC5A Subunit: Massive, very lean (uneconomic), grayish, and cherty. Local interformational conglomerate.
- LC5B Subunit: Grayish, irregular to wavy-bedded magnetite and iron- carbonates in an iron-silicate and chert matrix.

Lower Slaty Division (LSD)

The Lower Slaty Division is characterized by a series of fine-grained and interbedded argillaceous and cherty members. X-ray diffraction and field observations have identified the following minerals: magnetite, hematite, quartz (chert), jasper, minnesotaite, stilpnomelane, graphite, pyrite and locally chlorite in quartz-carbonate veins. The lower-most member of the Lower Slaty Division is a buff to black, extremely fissile and finely laminated lean slate. Locally, the subunit is soft, well-oxidized to a brick-red color, and almost clay-like in texture. This unit grades into a well-bedded, and nodular "graywacke," generally with economic magnetite values. Green silicate nodules are common as are thin red beds of jasper. Locally interbedded with the LSD is a package of massive to thick-bedded and lensoid chert, magnetite, iron-silicate and carbonate bands. The interbedded chert contains scattered jasper layers. The IBC is capped by a series of thick, dark gray to black well-laminated and nodular chert, and iron-silicate beds. Mottled magnetite and hematite occur throughout this subunit. The overlying subunit consists of conglomerate with thick-bedded chert-iron- silicate and magnetite-hematite bands. The topmost subunit of the LSD is a very finely laminated slate with local chert nodules and lenses.

The Upper Cherty Division and Upper Slaty Division are not exposed in the Minntac pits.

EVELETH MINES

Robert J. Waidler

Local Geologic Setting

The Thunderbird North open pit mine is located just north of the city of Eveleth and one mile south of the city of Virginia (near locality 7 on Fig. 6). The mine lies on the northwest limb of the Eveleth Anticline, one of the pair of folds that define the Virginia Horn (Fig. 12). Although no Pokegama Quartzite is exposed in the mine area, there is an exposure of Pokegama in a shallow roadcut on the east side of U.S. Highway 53 just north of the Minnesota Highway 37 intersection (Field trip stop PQ-3). Several deep diamond drill holes have pierced the top of the quartzite, but nowhere in the immediate mine area is the total thickness of the quartzite known. Diamond drill hole cores show a white to light gray quartzite with the framework grains mostly fine sand-sized quartz with minor microcline and plagioclase. The grains are cemented with silica. The contact between the Pokegama Quartzite and the overlying Biwabik Iron Formation, as indicated by diamond drill holes, appears to be conformable, and apparently represents an abrupt change from dominantly clastic sedimentation to dominantly chemical precipitation. The source of the Pokegama Quartzite is thought to be the Giants Range batholith, based on heavy mineral studies.

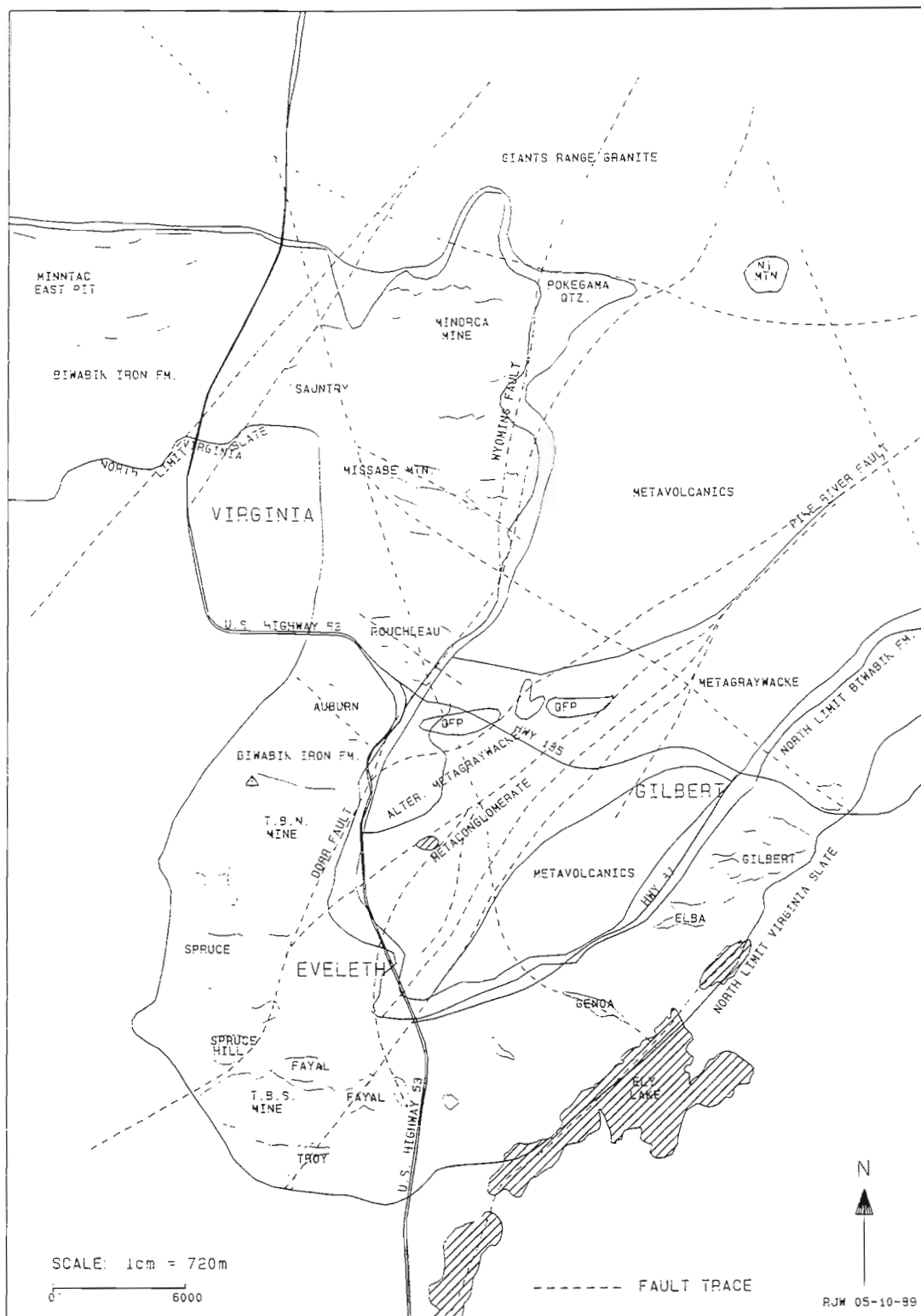


Figure 12 Geology of the Virginia Horn area (Compiled by R.J. Waidler).

In the Thunderbird North Mine area, the Biwabik Iron Formation is a mineralogically complex rock that is essentially a ferruginous chert averaging approximately 30 percent total iron. Where unoxidized, the formation is called magnetic taconite. The principal mineral components of taconite are chert (micro-crystalline quartz); iron silicates (minnesotaite, stilpnomelane and greenalite); iron oxides (magnetite—the ore mineral, hematite and goethite); carbonates (siderite, calcite and ankerite-dolomite); and sulfides (minor pyrite and very minor traces of other sulfides) (Table 3). The taconite can be classified on the basis of textures observable in hand-specimens or thin sections as "granular" or cherty; and fine-grained or "slaty." Beds or groups of beds having cherty and slaty textures are interbedded on all scales in the iron formation. In the mine area, the Biwabik is divided into several major units based on magnetic iron content. From bottom to top they are: The Footwall Zone (conformable above Pokegama Quartzite), the Lower Cherty (divided into Bottom Lower Cherty and Top Lower Cherty ore horizons), Lower Slaty (waste), Upper Cherty (consists of a Lower Upper Cherty ore horizon, an Upper Cherty waste zone, a Middle Upper Cherty ore horizon, another Upper Cherty waste zone, and an Upper Upper Cherty ore zone), and Upper Slaty. Except for the Lower Cherty-Lower Slaty contact, which is fairly sharp, the contacts between adjacent members, especially the Lower Slaty-Lower Upper Cherty contact, are gradational (Fig. 13 and Table 3).

In the unoxidized cherty members, the minerals are commonly aggregated into spherical or ellipsoidal "granules" that average 0.5 to 2.0 mm in diameter. The granules are internally structureless.

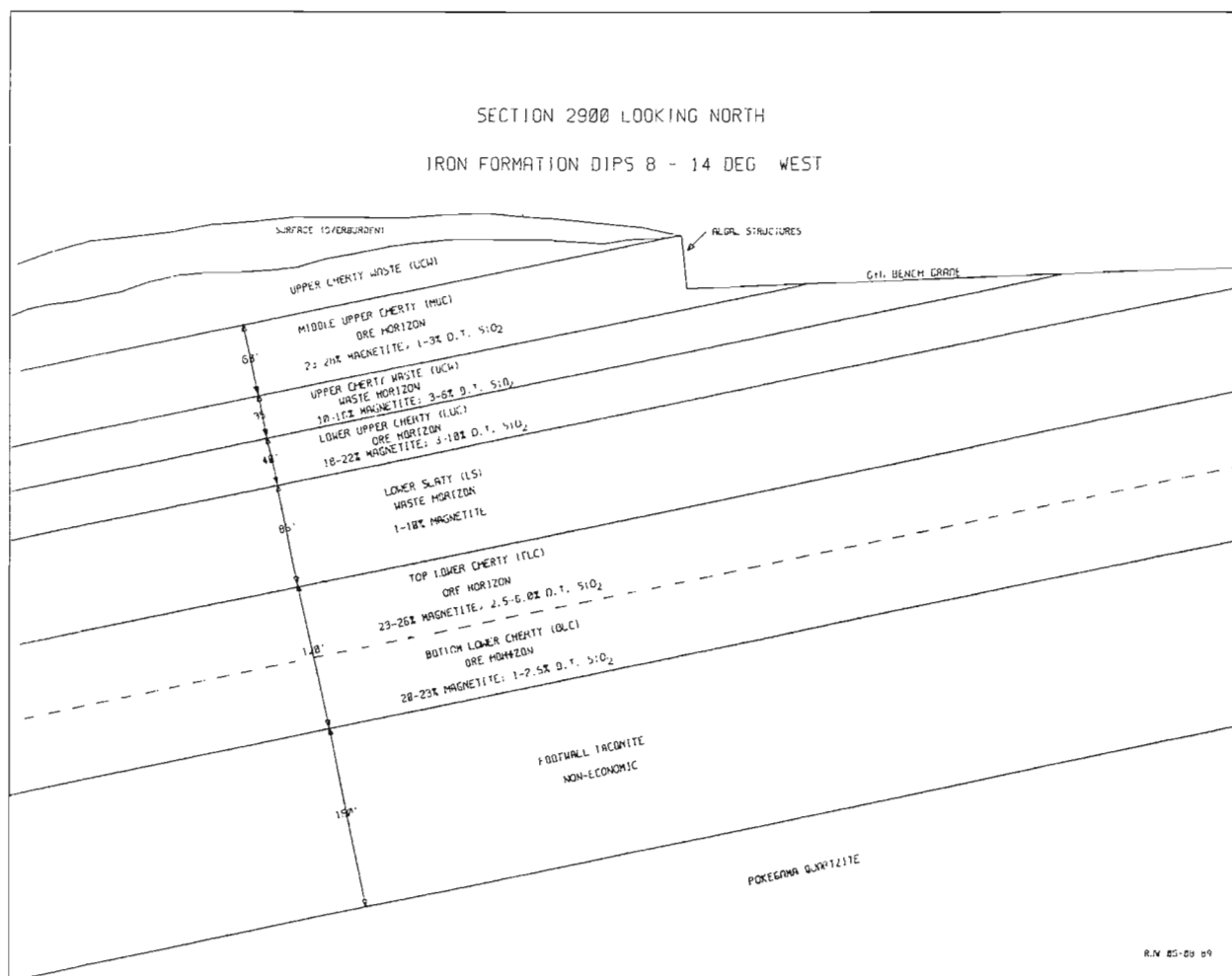


Figure 13 Generalized cross-section of Thunderbird North Mine.

The dominant mineral is micro-crystalline quartz (chert), which rarely is pink to red (jasper) in color due to inclusions of finely divided hematite (Table 4). Quartz also occurs locally in thin (typically <1/4-inch thick) vertical to near vertical veins, and as 1/2- to 2-inch-thick layers mixed with siderite and conformable with bedding in the lean ore Footwall Zone at the bottom of the Bottom Lower Cherty ore zone.

The ore mineral magnetite (Table 4) forms tiny octahedra that are rarely more than 0.1 mm in diameter. Commonly, individual octahedra are clustered together in regular- to extremely irregular-banded beds, or patchy or mottled aggregates. On close inspection, magnetite can be seen to be replacing silicate minerals, and in turn, being replaced by hematite in and near zones of oxidation.

Iron silicate minerals (Table 4) occur commonly in combination as intimate mixtures in matted or radiating aggregates. Individually, they are very difficult to distinguish because of intermixing and fine grain size. Because of the intimate mixtures with magnetite (magnetite replacements), some iron silicates are invariably recovered in the magnetic concentrate and are represented in Davis Tube Silica numbers.

Carbonate minerals (Table 4) occur as (1) coarsely crystalline with milky quartz in 1/2- to 2-inch-thick beds in the top of the Footwall Zone, (2) indistinct 1-2 inch beds and mottles with granule texture near the top of the Lower Cherty ore zone, (3) flattened to perfectly spherical nodules ranging in size from 1.4 to 6 inches in diameter in the Middle Upper Cherty ore zone, and (4) disseminated individual small rhombs or irregularly-rounded grains.

In the unoxidized slaty members, the minerals are very fine grained and finely laminated, and are composed mostly of iron silicates and iron carbonates. The slaty members also contain more magnesium and alumina than do the cherty members (7 percent Al_2O_3 vs 1 percent Al_2O_3).

Algal structures are present at the top of the Middle Upper Cherty ore zone; they occur in their original configurations (visible in drill core) or as intraformational fragments exposed in the northwest corner of the Thunderbird North Mine.

The top of the Biwabik Iron Formation is not exposed or encountered by drill holes in the mine area. The highest ore horizon exposed is the Middle Upper Cherty ore horizon of the Upper Cherty member.

The overall continuity of the Lower Cherty ore member in the Thunderbird North Mine is very good, averaging about 117 feet thick. There is a lean zone near the bottom of the Lower Cherty member that gradually thickens from north to south and results in a step-up in the economic footwall surface of the mine.

The ore horizon that shows the greatest variability is the Lower Upper Cherty horizon of the Upper Cherty member. The thickness varies considerably, based on magnetic iron content, ranging from 17 feet to 110 feet, and changing as rapidly as 1 foot of thickness for every 10.2 feet of distance downdip. In addition to magnetic iron variability, the Lower Upper Cherty also has the greatest variation in the amount of Davis Tube Silica present in liberation data results.

The highest absolute value for magnetic iron content occurs in the Middle Upper Cherty ore zone in the northwest corner of the mine (one 8 foot interval @ 40.28 percent). Overall, mineral inventories for the mine indicate that the Lower Cherty ores (Bottom Lower Cherty and Top Lower Cherty) have an approximate magnetic iron content of 24.3 percent, while the Upper Cherty ores (Lower Upper Cherty and Middle Upper Cherty; Upper Upper Cherty not exposed) have an approximate magnetic iron content of 22.4 percent.

Statistical studies show that the level of Davis Tube Silica in the top part of the Lower Cherty member (TLC) gradually increases from south to north through the mine area.

MINING HORIZON	GEOLOGIC HORIZON	THICKNESS		DESCRIPTION
		AVG.	RANGE	
Middle Upper Cherty (MUC)	UC-4 (Upper) UC-3 (Lower)	76'	46'-95' (Gradually thickening to the north)	Cherty Taconite: Upper part has massive beds of chert w/confetti-like angular chert fragments w/disseminated magnetite; occasional lenses and nodules of siderite. Lower part is massive chert w/irregular beds, mottles, and disseminations of magnetite. Chert has large to medium granule texture. Occasional irregular beds and nodules of siderite and chert fragments w/magnetite rims. Magnetic to very magnetic.
Upper Cherty Waste (UCW)	UC-2	60'	10'-92' (Pinching & swelling)	Cherty Silicate Taconite: Mixed thick and thin beds of chert with disseminated magnetite and iron silicates. Thick zones of thinly laminated iron silicates in lower portion. Occasional jasper and hematite beds. Occasional vertical fractures w/secondary pyrite and quartz. Slightly magnetic.
Lower Upper Cherty (LUC)	UC-1	61'	17'-110' (Pinching & swelling)	Cherty Silicate Taconite: Thin chert layers and lenses w/distinct beds and wavy concentrations of magnetite grains. Disseminated hematite and jasper in upper portion. Disseminated carbonates and iron silicates; green silicates gradually increasing in abundance toward Lower Slaty below and rock becoming finer grained. Magnetic. Gradational contact with Lower Slaty below.
Lower Slaty (LS)	LS-3 (Top) LS-2 (Middle) LS-1 (Lower)	82'	55'-130'	Fine-grained, thinly laminated green iron silicates. Minor disseminated magnetite in upper portion but decreasing w/depth. Indistinct bedding in upper portion. Occasional fine thin chert and carbonate beds. Occasional steeply dipping secondary quartz veinlets. In middle portion, distinct beds of dark and light iron silicates. In lower portion dark silicates w/numerous partings usually soft and crumbly. Occasional veins of calcite or green iron silicates. Nonmagnetic.
Lower Slaty (LS)	LC-6	(Included in the above LS)		Cherty Silicate Taconite: Thick beds of large granule-textured chert containing iron silicates as disseminations and in irregular beds. Occasional irregular beds of goethite and hematite. Minor magnetite w/iron silicate beds in lower portion. Nonmagnetic.
Top Lower Cherty (TLC)	LC-5	63'	45'-81'	Cherty Taconite: Massive beds of medium granule-textured chert containing irregular beds of magnetite w/disseminated granules of iron silicates. Near the top a distinctive zone approx. 2' thick of very hard, brittle, light pink jasper w/irregular mottles of magnetite. Occasional mottles and 1/4" to 1" thick beds of carbonates. Some chert fragments w/magnetite rims. If any oxidation is present, it invariably affects the hard, brittle, light pink jasper zone. Magnetic to very magnetic.
Bottom Lower Cherty (BLC)	LC-4	54'	40'-68'	Cherty Taconite: Distinct wavy beds of magnetite in medium granule textured chert. Magnetite/hematite beds range from 1/4" to 2" thick and gradually become more regular w/depth. Occasional chert fragments w/magnetite rims. In the lower portion, "salt and pepper" disseminations of magnetite important. Occasional thin crenulated beds of magnetite. Occasional partings w/thin talc coatings. Magnetic to very magnetic.
Footwall Zone ↓	LC-3 LC-2 LC-1	150'	125'-175'	Cherty Silicate Taconite: Top Portion: Regular beds of green iron silicates w/numerous graphitic partings interbedded w/thin beds of fine granule-textured chert containing disseminated iron silicates. Occasional beds of quartz and carbonate. Very minor magnetite. This zone is 1' to 2' thick just south of the Auburn Mine but gradually thickens southward to approx. 20' thick at the south end of the mine. Nonmagnetic. Middle Portion: Coarse-grained magnetite as disseminations and thin beds in medium granule-textured chert. Jasper granules in beds increasing w/depth. Magnetite gradually decreasing in abundance w/depth. Included w/BLC in north part of mine; usually 12' to 15' thick. Magnetic. Lower Portion: Mixed thin beds of hematite, chert and green iron silicates. Some jasper beds. Magnetite decreasing w/depth. Ferruginous sandstone in lower portion w/hematite beds.
Pokegama Quartzite				Massive fine-grained gray quartzite.

Table 3 Generalized stratigraphic column of Thunderbird North Mine.

Origin of the Biwabik Iron Formation

The Biwabik Iron Formation is generally accepted to be a mostly chemical sediment. Field evidence in the Thunderbird North Mine supporting this view includes: (1) the presence of spherical carbonate nodules; a minor number of carbonate nodules contain euhedral arsenopyrite crystals; these were located in the top part of the Middle Upper Cherty ore zone in the northwest corner of the mine; (2) the presence of local fine-grained, radiating nodules of pyrite in the Middle Upper Cherty ore zone; and (3) the "granule" texture of the cherty ore horizons.

Other field evidence suggests that the sediments were deposited in a shallow- water, agitated environment: (1) the presence of algal conglomerates; (2) the presence of angular chert fragments in the cherty ore horizons; and (3) faint, relic cross-bedding visible in the Middle Upper Cherty ore horizon.

There is some question concerning the origin of the various minerals and whether or not the Biwabik Iron Formation in the mine areas has been subjected to low-grade metamorphism or merely to diagenesis. According to French (1973), chert, siderite, hematite, greenalite, graphite, pyrite, possibly some magnetite, and chlorite are regarded as primary, while magnetite (replacing earlier minerals), minnesotaite, stilpnomelane, and some carbonates are secondary. Both minnesotaite and stilpnomelane replace greenalite and partly obscure pre-existing granule structures.

It is interesting to note that approximately contemporaneous with the Biwabik Iron Formation in northeastern Minnesota, other iron-formations in Brazil, Africa, India, Australia, and North America were deposited. This suggests that worldwide atmospheric conditions in Early Proterozoic time (2000 to 1800 million years ago) may have been favorable for the deposition of large amounts of iron minerals, and that large amounts of iron were available for deposition.

Structure

The strike and dip of the Biwabik Iron Formation within the mine area varies some due to the configuration of the Eveleth Anticline. In the south part of the mine area, the strike is N13.7°E with a dip of 8.5°NW; in the center section of the mine, the strike is N10°W with a dip of 7.5°SW; and in the north part of the mine, the strike is N38.1°E with a dip of 10.1°NW. Small gentle folds that are normal to strike occur locally.

The mine area contains numerous structures, both major and minor in scale. To the east of the mine is the major Dorr Fault that forms an escarpment that can be seen on the west side of U.S. Highway 53 (Figure 12). This fault continues along the western edge of Eveleth and passes through the Fault Mine (a natural ore mine), which is now filled with waste material. To the south and southwest, several structures controlled the oxidation of the taconite and the formation of soft hematite "natural" ore in the Spruce and Virginia pit area. To the north of the mine, a structure striking approximately N40°W controlled the oxidation of the taconite in the Auburn "natural" ore mine. Within the mine, a local structure produced an oxidation zone along an east-west axis approximately 100 feet wide (Section 7500 North). Most structures have displacements of less than 100 feet and are high-angle faults or joints of Precambrian age.

Oxidation

It has been calculated that approximately 27 percent of the outcrop area of the Biwabik Iron Formation contains natural ore mines, giving some idea as to the extent of oxidation present. Locally, as around the Thunderbird North Mine, oxidized areas can be related to either high-angle faults trending N75°W, N20°W and north, or to steep joint and fracture sets trending N10°E, N40°W and east. These structures were important in localizing the distribution and extent of oxidation.

Of the cherty ore horizons, the top of the Lower Cherty ore zone (Top Lower Cherty) seems to be one of the most likely members to experience oxidation, probably due to the extreme brittleness of the massive cherty beds. In the south part of the mine, from Section 10200 south (see guidebook stop EM-1), the top part of the Top Lower Cherty ore zone is oxidized for at least 1800 feet downdip.

Some iron-formation outcrops in the mine area show slight to partial oxidation, although this surface oxidation is usually minor in extent or depth (usually less than 10 feet in depth).

Economics

Today virtually all of the material mined on the Mesabi range consists of magnetic taconite. Marsden (1978) estimated the total Mesabi range taconite ore reserves as:

- 25.0 billion metric tons of good taconite (magnetic)
- 10.5 billion metric tons of oxidized "semi-taconite" (nonmagnetic)
- 3.9 billion metric tons of high-silica taconite (magnetic)
- 3.6 billion metric tons of lean taconite (magnetic)

It is also estimated that there are 145 million metric tons of high-grade "natural" iron ore reserves remaining.

In the Thunderbird North Mine, the current economic cutoff for magnetic iron is 17.0 percent, with an upper limit for Davis Tube Silica of 10.0 percent. Current mining plans estimate a target grade of approximately 23.0 percent magnetic iron with a Davis Tube Silica of 3.8-4.2 percent.

Mineral inventory studies for the Thunderbird North Mine indicate reserves of approximately 305 million metric tons at a magnetic iron content of 23.5 percent (includes the area between the Thunderbird North Mine and the Auburn natural ore mine), with a stripping ratio of 0.65 (1 ton of ore for every 0.65 ton of waste).

The taconite is mined using conventional mining techniques (drilling, blasting, loading, hauling, and crushing through various stages). Because the ore mineral is magnetite, it can be separated from most of the other minerals by strong magnets after the ore is ground to a fine powder (about 0.044 mm in diameter). Magnetic concentrates are dewatered to about 10.5 percent water content and balled with various binding agents into "green" pellets that are then indurated in a traveling grate kiln operating at temperatures of approximately 2550°F. The process of firing the pellets is an exothermic reaction that causes the magnetite to be converted to hematite. It takes approximately 3.3 tons of crude ore to make one ton of fired pellets.

The typical chemistry of Eveleth Mines pellets is:

Total Iron	Fe	65.3%
Ferrous	FeFe++	0.8%
Total Silica	SiO ₂	5.28%
Phosphorus	P	0.017%
Manganese	Mn	0.10%
Alumina	Al ₂ O ₃	0.26%
Lime	CaO	0.25%
Magnesia	MgO	0.32%
	K ₂ O	0.015%
	Na ₂ O	0.02%
	TiO ₂	0.03%
Sulfur	S	0.002%
Ignition Loss	LOI	0.10%

Future Investigations and Concerns

A number of different subjects are available for future study; some of which may have future economic impact.

- 1) Hydrologic and Environmental Studies: Because of the nature of the location (near the continental drainage divide) and the dip of the iron-formation, water quality and movement will be of increasing concern. Contaminants, both human-made and naturally-occurring, will need to be identified and studied for impact and possible mitigation.
- 2) Geologic Studies: Numerous geologic questions remain, such as the source of Precambrian iron and other elements, condition of the Precambrian atmospheres over time, the thickness of the Pokegama Quartzite and the nature of the rocks beneath, and the quality and extent of the Biwabik Iron Formation downdip.
- 3) Mining and Technology Studies: Many avenues exist for improving the economics of iron-ore mining and processing, such as improved drilling and blasting, in-pit crushing and conveying, dry cobbing of crude ore to upgrade crude ore quality, improved crushing and grinding, slurry pipelines for ore transportation, methods for reducing the silica level of the ore and concentrate, self-fluxing, direct reduction concentrates, and cost reductions for all phases of mining, milling, and processing.

INLAND STEEL MINING COMPANY MINORCA & LAURENTIAN MINES

John L. Arola

The Minorca Mine and plant are located approximately 2.5 miles northeast of Virginia, Minnesota. The Minorca pit is located on the north end of the Virginia Horn, east of the Alpena Monocline. Upper layers of the Biwabik Iron Formation have been eroded, leaving Lower Cherty strata exposed directly below the glacial drift (Figure 14). Because of its location on the north end of the Virginia Horn, the Minorca pit taconite has been broken and fractured and is slightly to moderately oxidized from top to bottom. The strike of the iron-formation is northeast-southwest, and it dips to the southeast at an angle of 4°-11°.

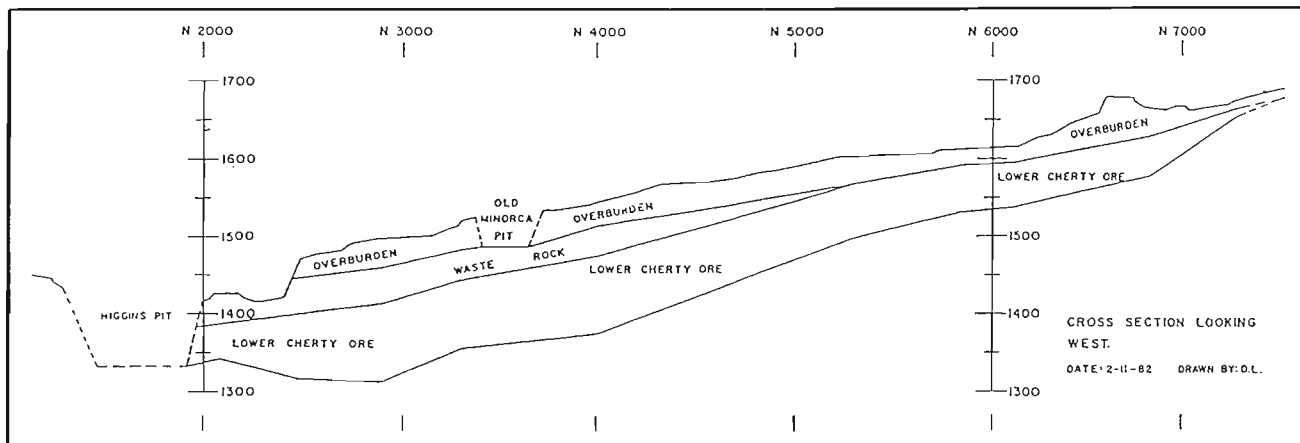


Figure 14 Generalized cross-section of Minorca Mine (Inland Steel Mining Company).

The weathered taconite is characterized as a weakly to moderately magnetic, coarse liberating ore. The magnetite liberates at a grind of 78 percent -325 mesh, and the average magnetic iron content for the Minorca ore is 21 percent. Mining in the Minorca pit began in 1977, and the pit was depleted in January 1993.

The Laurentian pit, currently being mined, is located 0.5 miles northeast of Gilbert, Minnesota. This ore body is characterized as a strongly magnetic, unoxidized taconite. The magnetite liberates at 90 percent -325 mesh, and the average magnetic iron content is 24 percent. Iron-formation crops out as a knob near the northwest corner of the pit and is extremely fine grained and hard. Upper Cherty, Lower Slaty, and Lower Cherty units of the iron-formation are mined in this pit (Fig. 15). The two cherty horizons are the ore horizons, and the slaty unit is barren of magnetite in this pit. The strike of the iron-formation in this area is northeast-southwest, and it dips to the southeast.

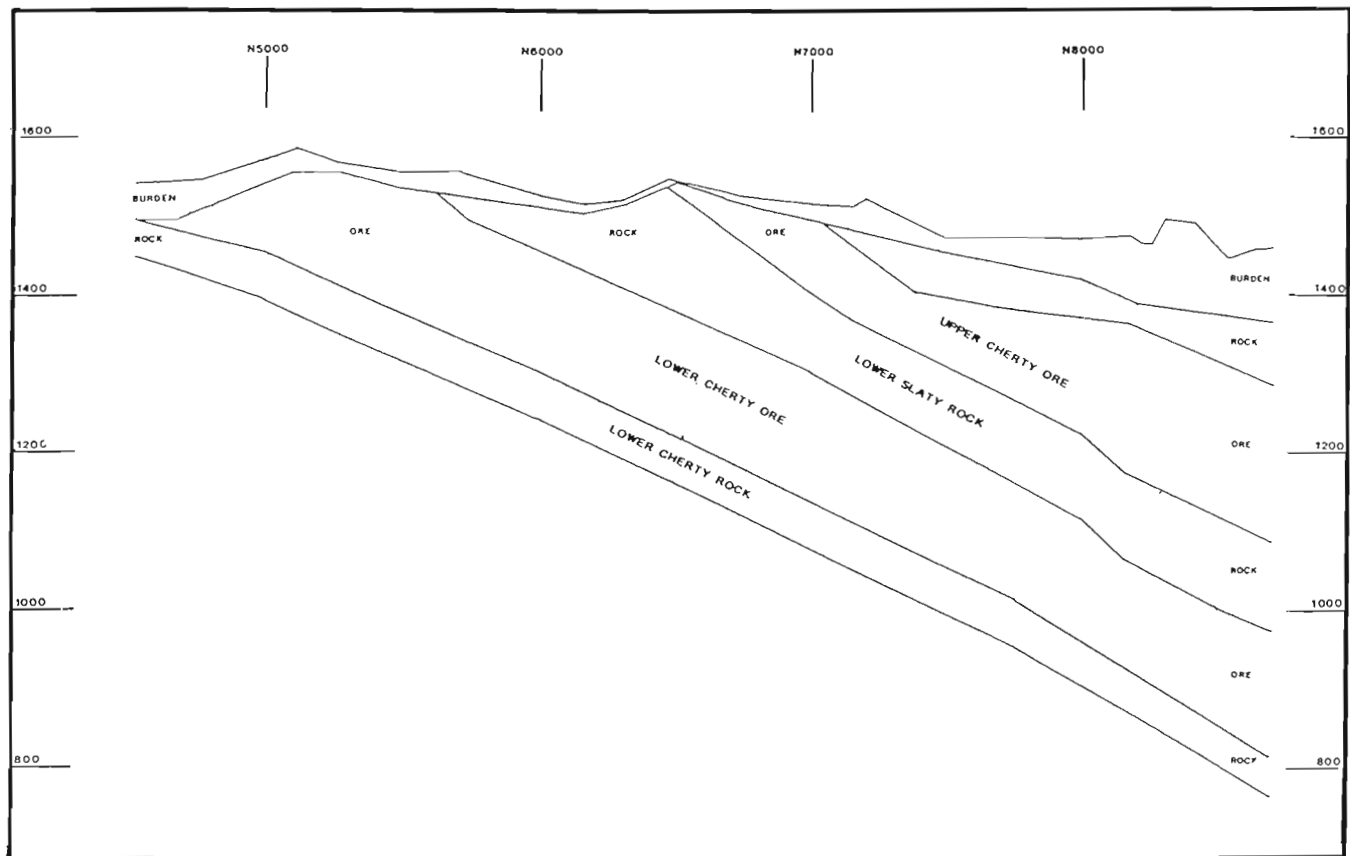


Figure 15 Generalized cross-section of Laurentian Mine (Inland Steel Mining Company).

Other magnetite reserves in this area are the Ordean (Fig. 16), East Rouchleau, and two unnamed reserves near McKinley, Minnesota. The Ordean is located on the west edge of the Alpena Monocline. Ore horizons include the Upper and Lower Cherty and the Lower Slaty members. The iron-formation in this area has an east-west strike and dips to the south.

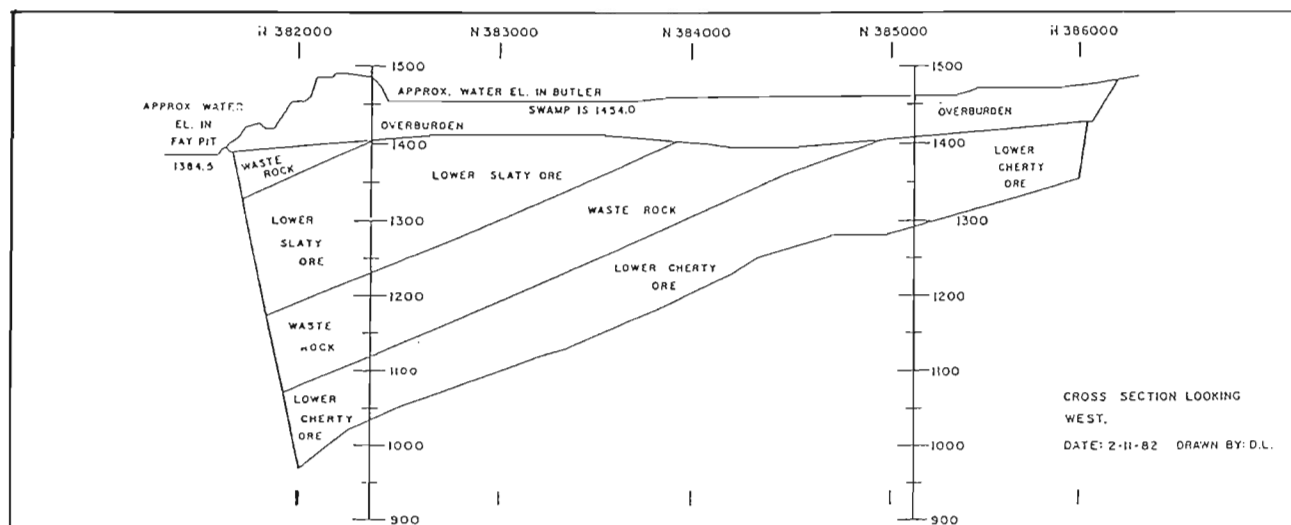


Figure 16 Generalized cross-section of Ordean Reserve (Inland Steel Mining Company).

To the south of the Minorca pit is the East Rouchleau reserve. Ore horizons are the Lower Slaty and Lower Cherty units of the Biwabik Iron Formation. The iron-formation in this area has a north-south strike and dips to the west toward the city of Virginia.

LTV STEEL MINING COMPANY Ronald G. Graber

The subcrop of the Biwabik Iron Formation occupied by LTV Steel Mining Company's taconite operation has a variety of unique geological features, including significant changes in stratigraphic thicknesses, structural styles and mineralogy.

A total of 12 separate mining areas, including the satellite Dunka Mine situated over 20 miles from the plant site, have been developed at LTV Steel Mining Company over its 36-year existence. The large number of mining areas is a reflection of the multiple stratigraphic ore layers mined and the structural complexity of the eastern Mesabi range.

Geologic Subdivision	Geologic Subunit	Typical Thickness (Feet)	Column	Remarks	Field Stop		
					LT-2	LT-3	LT-4
Upper Slaty	A B C	35-55	— — — — —	Conglomeratic Limestone			
	D E	25-55	•••••	Apatite Rich Ore			
	F	35-50	— — — — —	Moderate Magnetite Poor Liberation			
Upper Cherty	G H I J	40-75	••••• ~ ~ ~ ~ ~ •••••	Upper Ore Layer Algal Stromatolite Horizon	*	*	
	K K'	15-40	— — — — —	Low To Moderate Magnetite Poor Liberation	*	*	
	L M	40-80	•••••	Lower Ore Layer			
	O	20-35	~ ~ ~ ~ ~	Algal Stromatolite Horizon High Magnetite, Poor Liberation			
	P	85-130	— — — — —	Low Magnetite			
	Q	10-20	— — — — —	Intermediate Slate			
Lower Cherty	R	10-20	— — — — —	Low Magnetite			
	S T U	45-95	•••••	Lower Cherty Ore Layer			*
	V W	25-45	— — — — — ~ ~ ~ ~ ~	Low To Moderate Magnetite Poor Liberation Algal Stromatolite Horizon			*

Total Biwabik 430-650 Feet
Iron Formation
Thickness

☐ Ore Zones
Waste Zones

Figure 17 Generalized stratigraphy of iron-formation at the LTV Steel Mining Company mines (excluding the Dunka Mine area). Positions of field trip stops are shown.

The stratigraphic column in Figure 17 shows the stratigraphic diversity of the ore layers mined at LTV Steel Mining Company. Ore is derived not only from the Lower Cherty member, which provides the bulk of the crude ore to taconite operations on the central Mesabi range, but also from the Upper Slaty and Upper Cherty members. The stratigraphic thickness of the Biwabik Iron Formation decreases gradually from 650 feet in the western portion of the LTV property near the Aurora townsite, to 560 feet near the Siphon structure (see Geologic Map of Mesabi Iron Range in back pocket of this Guidebook). A very abrupt decrease in iron-formation thickness to as little as 435 feet, occurs directly to the east of this structure.

The structural complexity of the area is displayed by the geologic map shown in Figure 18. LTV Steel Mining Company's mineral lands occupy a transition zone where structures apparently related to the intrusion of the Duluth Complex exist along with a variety of older structures such as the Siphon structure. The magnitude of the structures is sufficient to disrupt the continuity of the iron-formation, which results in a large number of isolated ore bodies. Additionally, a number of dikes and sills further complicates the structure. The Aurora Sill is the largest of these intrusions, having a known strike length of more than 3 miles and exceeding 100 feet in maximum thickness. This Na-rich syenitic intrusion produces a distinct steepening of the iron-formation's dip along its outcrop length. The sill is of uncertain age and origin.

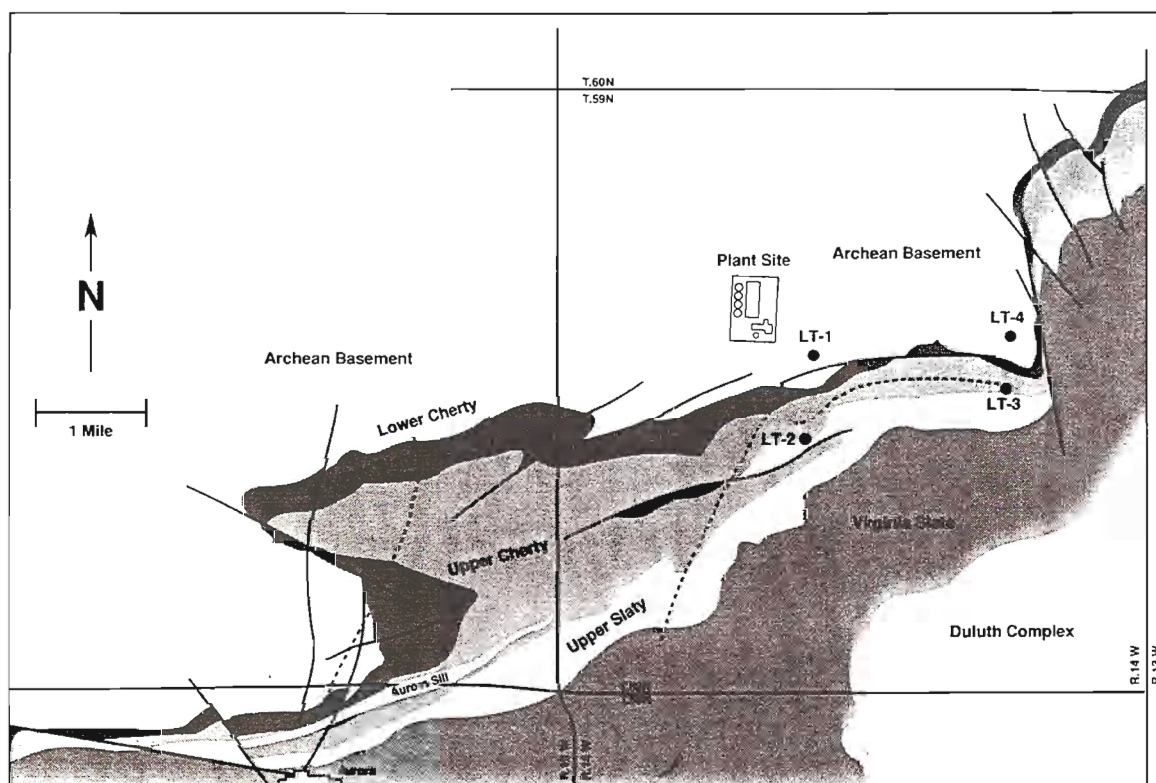


Figure 18 Geologic map of a portion of LTV Steel Mining Company's taconite operations. Locations of field trip stops LT-1 through LT-4 are shown.

The most unusual geologic feature at LTV Steel Mining Company is the abrupt mineralogical changes accompanying the thermal contact metamorphism of the iron-formation by the Duluth Complex. The metamorphism produced sequential zones of varied mineral assemblages as the Duluth Complex is approached. Figure 19 shows this metamorphic zonation. The crude ore quality changes dramatically with changing mineral assemblages, both with regard to magnetite abundance and liberation characteristics.

The mining method at LTV Steel Mining Company consists of a shovel to truck to train crude ore delivery system. Due to the relatively thin ore layers, mining benches are designed to follow the dip of the iron-formation. Magnetite-separation in the processing plant consists of crushing and grinding, followed by magnetic-separation to generate an initial concentrate. Further upgrading of this concentrate is accomplished via silica flotation. The flotation concentrate is then pelletized for shipment to LTV's steel mills. LTV Steel Mining Company operates its own railroad line and harbor facility on Lake Superior (Taconite Harbor) for pellet transportation.

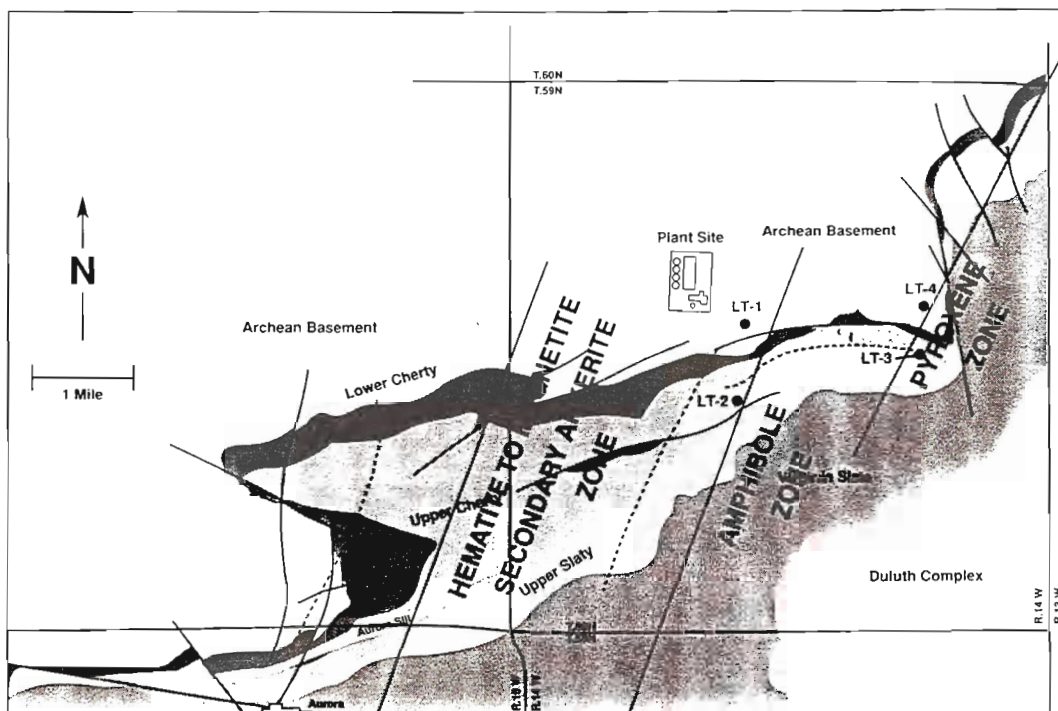


Figure 19 Map of the major metamorphic zones in the broad contact aureole of the Duluth Complex at LTV Steel Mining Company. Locations of field trip stops LT-1 through LT-4 are shown.

CYPRUS NORTHSORE MINING CORPORATION PETER MITCHELL MINE

Mark J. Severson

Introduction

The Peter Mitchell Mine is located approximately three miles south of Babbitt, Minnesota, just south of the Laurentian Divide. The taconite mine was initially developed by Reserve Mining Company in 1955. Large-scale mining operations eventually resulted in a practically continuous pit that spanned some eight miles along the trend of the Mesabi range. Cyprus Northshore Mining acquired the property in 1989 and is currently mining in Sections 16, 17, 19, and 20, T.60N, R.12W. Where present, the upper 60-100 feet of the Upper Slaty (submembers A through E or F,

Fig. 20) are stripped as rock waste. Approximately 120-200 feet of taconite is mined from the Upper Slaty (submembers F and/or G) and the Upper Cherty (submembers H through M, and/or N and O). The taconite mined at the eastern portion of the Peter Mitchell Mine currently averages 26 percent magnetic iron. Annual production capacity is 4 million tons of taconite pellets; the pit operates 12 hours per day and employs 115 people.

Geology

The Biwabik Iron Formation is divided into four main members that have been further divided into several submembers. A generalized listing of the submembers of the Biwabik Iron Formation, including the lowermost portion of the overlying Virginia Formation, appears in Figure 22. Throughout the western two-thirds of the pit area, the Biwabik Iron Formation exhibits shallow dips of 2-10° to the southeast. However, in the eastern third of the pit area where the Biwabik Iron Formation is in close proximity to the Duluth Complex (Middle Proterozoic), the Biwabik Iron Formation beds exhibit steeper dips of 8-30° (locally up to 45°). The intensity of metamorphism also increases to pyroxene hornfels facies near the contact of the complex. A brief description of the submembers of the Biwabik Iron Formation and their thickness ranges are included in Figure 20. Submembers that deserve special mention include:

BDD PO submember of the Virginia Formation: consists of cordierite- plagioclase- orthopyroxene+graphite metasediment with regularly-spaced (1-20 mm) pyrrhotite laminae (0.5-3.0 mm thick). The Bedded Pyrrhotite member (BDD PO) is locally present within the bottom 110-50 feet of the Virginia Formation. Where it has been assimilated by the Duluth Complex, the BDD PO is an excellent local source of sulfur for basal massive sulfide mineralization (e.g., Serpentine and Dunka Pit Cu-Ni Deposits).

SILL(S) within the Virginia Formation: fine-grained sills within the Virginia Formation (Fig. 20) exhibit a granoblastic texture with fine- to medium-grained subhedral to euhedral brown hornblende. Major constituents of the sills, in decreasing order, are: brown hornblende, plagioclase, orthopyroxene, olivine, biotite, and clinopyroxene with minor ilmenite and sulfides. Two sills are present within the Virginia Formation immediately south of the Peter Mitchell Mine (outcrops are more resistant to erosion than the Virginia Formation) and in the footwall rocks of the Babbitt Cu-Ni Prospect. Both the sills and the Virginia Formation are dark gray and fine grained, and thus difficult to distinguish in hand sample. The effects of metamorphism (granoblastic texture) within the sills is obvious in thin section. Because both sills and the Virginia Formation have been metamorphosed by the Duluth Complex, the age of the sills is inferred to be pre- to early Duluth Complex emplacement (Logan sill age?).

SILL within the Biwabik Iron Formation: a 2-18 foot thick sill is present within the C submember of the Biwabik Iron Formation in the Peter Mitchell and LTV Dunka Mines. In the footwall rocks at the Serpentine Cu-Ni Prospect, the sill is bifurcated into the A and B submembers adjacent to a major north-south fault zone. Mineralogy of the sill is similar to that of the Virginia Formation and probably is of the same ore. The sill in the Biwabik differs in that both a granoblastic plagioclase- hornblende variety and a diabasic plagioclase-pyroxene variety are present (overall distribution of the two varieties is unknown at present). Apatite (as much as 1 percent) is also a minor constituent of the sill in the Biwabik Iron Formation.

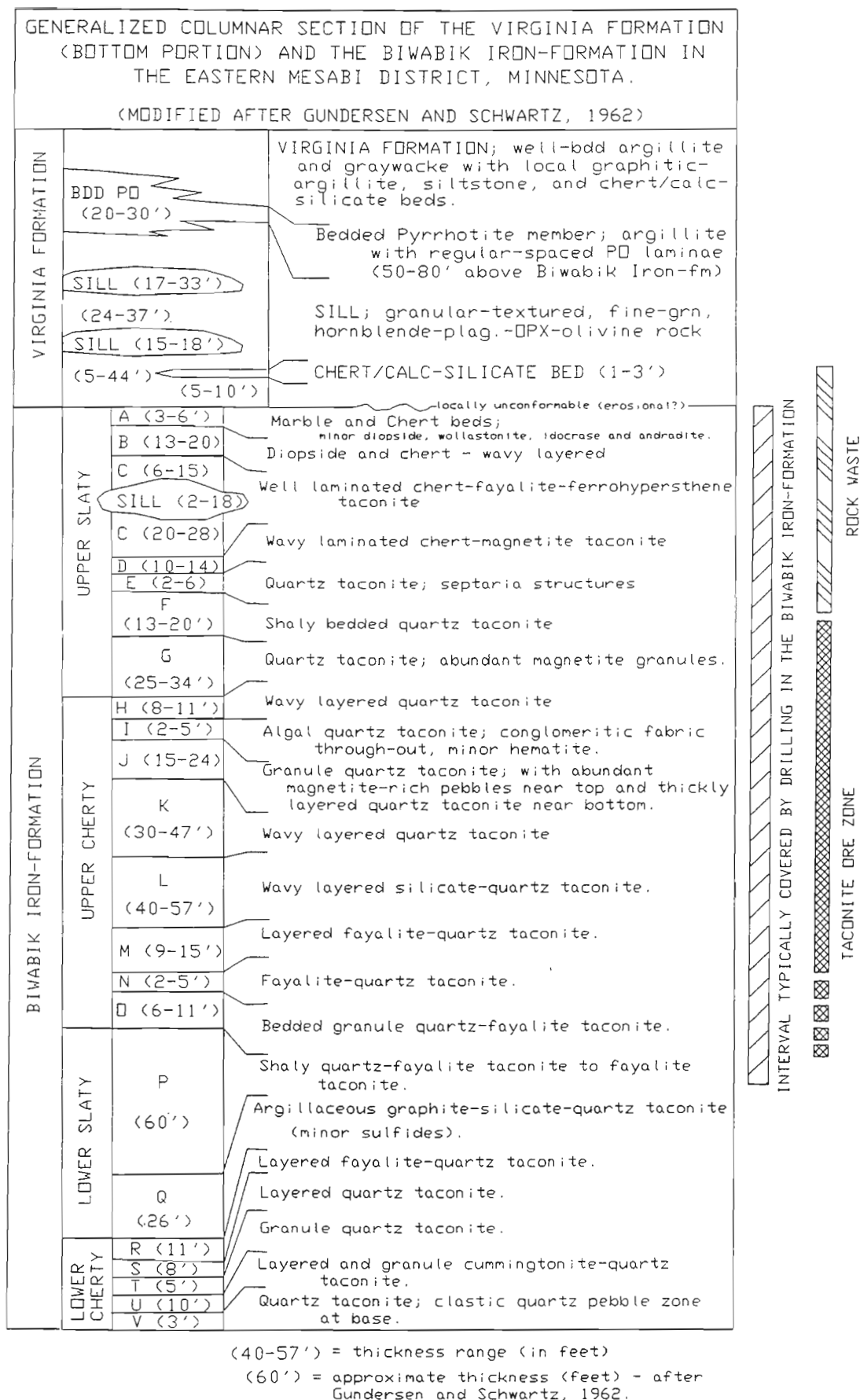


Figure 20 Generalized stratigraphic column of the eastern Mesabi Range, based on the Peter Mitchell Mine of Cyprus Northshore Mining Corporation, LTV Steel Mining Company, including Dunka Pit, and the Babbitt Cu-Ni Deposit (modified from Gundersen and Schwartz, 1962).

Structure

Several large- and small-scale folds are present within the eastern half of the Peter Mitchell Mine. The axial trace of the folds shows two dominant trends: 30° and 110° . Local drag folding is also locally present along some faults. Folding of the Biwabik Iron Formation is inferred to have taken place during emplacement of the Duluth Complex.

At least 17 faults have been located within the Peter Mitchell Mine. One of the faults trends northwest; the remainder trend north to north-northeast (see Geologic Map of Mesabi Iron Range in back pocket of this Guidebook). The faults are near-vertical with offsets ranging from more than 50 feet to less than 5 feet. Almost all of the faults display a "scissors-type" offset in that the relative displacement along the fault is the most pronounced at one end of the fault and relatively minor at the other. Most of the faults exhibit substantial offset at their southern end, where the Biwabik Iron Formation is overlain by the Duluth Complex, but only minor motion is evident at the northern end of the same fault, where the Biwabik Iron Formation overlies the Giants Range batholith (Archean). However, the reverse situation is true of some of the other faults within the pit area. The faults (1 to 10 feet wide) are characterized by limonite-stained angular pieces of Biwabik Iron Formation within a heavily limonite-stained matrix. Typically, coarse-grained to pegmatitic calcite is present within the fault zones as either breccia matrix or pinch-and-swell veins ranging from < 1 inch to 5 feet wide. Sulfides (pyrite) are also locally present within the fault zone. At some localities (1000-foot-wide zone in the center of Section 17), pyrite cubes (up to 1 cm) and cubic pyrite aggregates (up to 1 inch) are present along vertical joint planes and along adjacent subhorizontal bedding planes (replacement).

Dikes

Five extremely fine grained, black, basaltic dikes are present within the Peter Mitchell Mine. Several trends are present: 85° , 100° , and 140° (three dikes). The dikes generally average about 5-10 feet wide, but locally are as wide as 40 feet. At two separate localities, individual dikes bifurcate into two parallel dikes. At another location, a dike exhibits a gradual pinch-out from 5 feet wide to less than 1 foot wide over a distance of about 1200 feet. No apparent offset of the Biwabik Iron Formation is associated with the dikes, with one exception. A northwest-trending dike (Sections 19 and 30, T.60N, R.12W) is located adjacent to a major fault. This same dike was intercepted in several drill holes to the southeast within the Babbitt Cu-Ni Prospect, where it cuts trocolitic rocks of the Duluth Complex. In these holes, the trocolitic rocks are typically brecciated, and the dike exhibits chilled margins. A late- or post-Duluth Complex age for the dikes is indicated.

FIELD TRIP GUIDEBOOK

POKEGAMA QUARTZITE Richard W. Ojakangas

Mileage for this portion of the field trip starts at the intersection of the access road to the Holiday Inn and U.S. Highway 53. The four stops are shown on Figures 10 and 21.

NOTE: On the east side of U.S. Highway 53 about 0.9 mi (1.4 km) north of the above intersection (near the Kordel Furniture store) are two small roadcuts of vertical Archean graywacke, the basement for the Pokegama in this area. They will not be visited during this field trip.

About 1.4 mi (2.2 km) north of the Holiday Inn access road, turn right at Spur station onto frontage road that parallels U.S. Highway 53. Proceed another 0.25 mi (0.4 km) to Stop PQ-1.

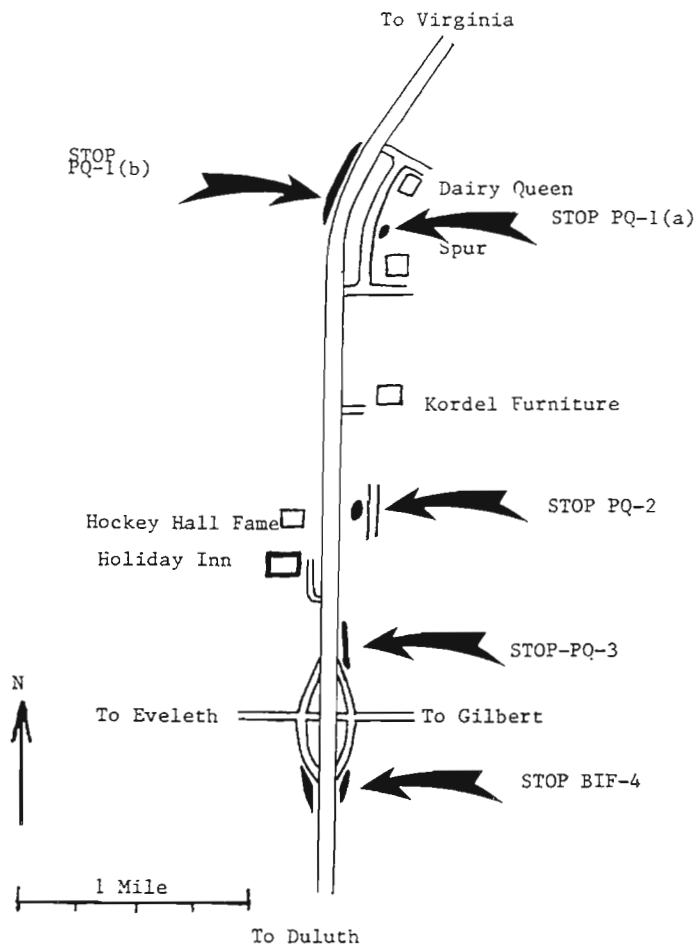


Figure 21 Locations of field trip stops PQ-1, PQ-2, PQ-3, and BIF-4.

STOP PQ-1

This stop consists of two substops: PQ-1(a) Archean basement with a basal Pokegama conglomerate and PQ-2(b) the argillaceous lower member of the Pokegama Quartzite.

PQ-1(a) By a windfall in the bushes to the right (east) of the frontage road is a small outcrop of Archean basement rock. This rock, a conglomerate with a subvertical foliation, is capped by a thin smear of basal conglomerate with a few flat subhorizontal clasts that have a foliation parallel to the long dimensions of the clasts (i.e., subhorizontal). A better exposure of the basal conglomerate, with large clasts of vein quartz, can be found on the flanks of a small knob of Archean basement rock some distance behind the Kordel Furniture store.

Walk across U.S. Highway 53 to PQ-1(b).

PQ-1(b) Argillaceous lower member, Pokegama Quartzite. On the west side of U.S. Highway 53 is a roadcut about 500 feet long and 5-10 feet high in the lower argillaceous member of the Pokegama Quartzite. This is the only exposure of this member. The roadcut consists largely of shale and siltstone with minor sandstones, and has been interpreted (Ojakangas, 1983) as having been deposited in a low-energy upper tidal flat environment in a sea that peneplaned Archean surface (Fig. 11). Minor channeling is common at the bases of the thicker sandstone beds, and at one spot, 0.5 m of section has been eroded. Small-scale cross-bedding occurs in some siltstone beds. Concretions as large as 15 cm in diameter are present. Soft-sediment deformation of the beds is common. Hemming et al (1991) illustrated the soft-sediment deformation and interpreted it as evidence that the Animikian basin was tectonically active during deposition of the Pokegama and the Biwabik Iron Formation. Alternatively, it could be interpreted as soft-sediment slumping into tidal channels.

Proceed northward on the frontage road for a distance of about 0.15 mi (0.24 km) to a stop sign. Continue another 0.2 mi (0.32 km) to the Dairy Queen. Turn left and cross over to the southbound lane of U.S. Highway 53. Proceed south for 1.5 mi (2.4 km) and stop just before the U.S. Hockey Hall of Fame. Walk across both lanes of U.S. Highway 53 to a low graded area just south of a low hill.

STOP PQ-2: Sandy-Silty-Argillaceous Middle Member, Pokegama Quartzite

This low rubbly exposure is (was?) the only accessible "outcrop" of the middle member. Recently it has been greatly modified by human activity. Note the well-laminated nature of most pieces of rock. Note also that various scour marks, low angle (hummocky?) cross-bedding, flaser bedding, parting lineation, and ripple marks can be observed on the loose rock slabs. This member was interpreted by Ojakangas (1983) as having been deposited in a middle tidal flat environment of alternating low and high energy (Fig. 11).

Proceed south on U.S. Highway 53 for another 0.65 miles and stop opposite a 20- foot-high roadcut of quartzite.

STOP PQ-3: Sandy Upper Member, Pokegama Quartzite

Note the coarser grain size (sand and grit), massive beds as thick as 1.5 m, and rare syneresis cracks. The massive beds are separated by thin beds of shale or siltstone. Silica cementation likely has obscured some original cross-bedding. This member was interpreted by Ojakangas (1983) as having been deposited in a high-energy, lower tidal or subtidal environment (Fig. 11).

Proceed south for 0.6 mi (0.96 km) on U.S. Highway 53, (passing over an overpass and driving past a long roadcut of iron-formation) to a crossover to the northbound lane. Cross over and proceed north about 0.2 mi (0.32 km) to the roadcut on the east side of the highway.

STOP BIF-4: Lower Cherty Member, Biwabik Iron Formation

Note that this member overlies the sandy member of the Pokegama Quartzite of the last stop, and that both units dip gently southeastward. Observe the thick wavy bedding, the trough cross-bedding, and the sandy texture. The cross-beds are best observed at this eastern roadcut, but are also present at both ends of the western roadcut. Cross-bedding measurements made to date (Fig. 22), although not definitive, are suggestive of a tidally-influenced marine environment. This, coupled with Walther's law of succession of facies (i.e., facies observed vertically are also similarly related laterally), places the deposition of the iron-formation seaward of the Pokegama Quartzite (Fig. 11). Sedimentological studies are continuing in the taconite pits.

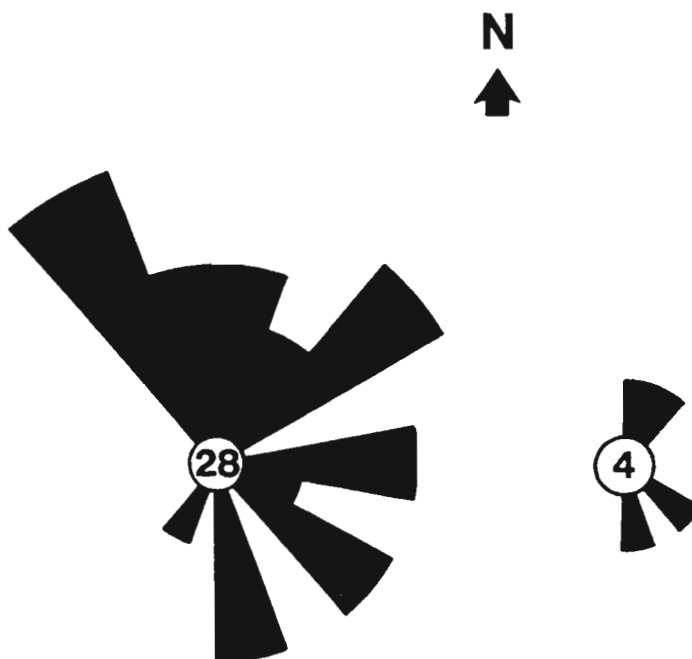


Figure 22 Plots of cross-bed measurements in high-energy Lower Cherty member of the Biwabik Iron Formation at two localities. Most of the readings on the larger rose diagram are from the roadcuts at field trip stop BIF-4; the smaller rose is from an outcrop northeast of Virginia (from Ojakangas, 1983).

IMPORTANT NOTE: SAFETY FIRST! EXERCISE EXTREME CAUTION NEAR
HIGHWALL—DO NOT CLIMB OR SCALE!

STOP EM-1: Lower Cherty Ore Horizon Exposure (Highwall)

The footwall slope here strikes N38°E and dips approximately 14°NW. The total thickness of the Lower Cherty ore zone at this point is 155 feet.

Starting an examination of the Lower Cherty at the footwall surface, note that the Bottom Lower Cherty (BLC) (Fig. 13 and 23) consists of wavy beds of magnetite and hematite interbedded with granule textured chert. Notice "salt and pepper" disseminations of magnetite in the lower portion, along with local chert fragments surrounded by haloes of magnetite. In this area, there is a lean zone included with the ore, which consists of numerous regular beds of green iron silicates associated with minor magnetite. Numerous parting surfaces are coated with graphite.

Moving up the stratigraphic section, we encounter the Top Lower Cherty (TLC) (Fig. 13). This consists of massive bedded chert containing very irregular beds and mottles of magnetite with very minor hematite. Fine-grained green iron silicates are intimately associated with the magnetite, giving higher Davis Tube Silica numbers. Near the top of the TLC ore zone is a marker bed of jasper. The contact with the Lower Slaty above is quite sharp, with the bottom part of what is locally termed Lower Slaty, actually a silicate taconite with very minor magnetite. The Lower Slaty at this location is 90 feet thick with an average magnetic content of 5.5 percent.

LIBERATION DATA FROM NEAREST DRILL HOLE

	Footage	Magnetic Fe	D.T. SiO ₂
Bottom Lower Cherty	13'	24.56%	1.2%
	9'	15.41%	2.7%
	53'	26.06%	1.4%
Top Lower Cherty	80'	27.43%	5.7%
Total Lower Cherty	155'	260%	3.8%

STOP EM-2: Transition Between Lower Slaty and Lower Upper Cherty Ore Zone

The strike of the formation here is N38°E and dips approximately 12°NW.

This exposure shows the gradational change in lithology from Lower Slaty with very fine grained, thinly laminated green iron silicates to the Lower Upper Cherty ore zone with increasing mineral grain size, more abundant chert, and gradually-increasing amounts of magnetite (Fig. 23). This contact gives the most problems with crude ore blending due to fine grain size of the magnetite and the accompanying green iron silicates. It is not uncommon to find quartz veins with carbonates in the Lower Slaty and "slickensided" green iron silicate surfaces conformable with the bedding planes.

LIBERATION DATA FROM NEAREST D.D.H.

	Footage	Magnetic Fe	D.T. SiO ₂
Lower Upper Cherty	17.5'	18.96%	6.4%
Lower Slaty	17.5'	16.84%	12.8%
Total 35' Bench	35'	17.90%	9.5%

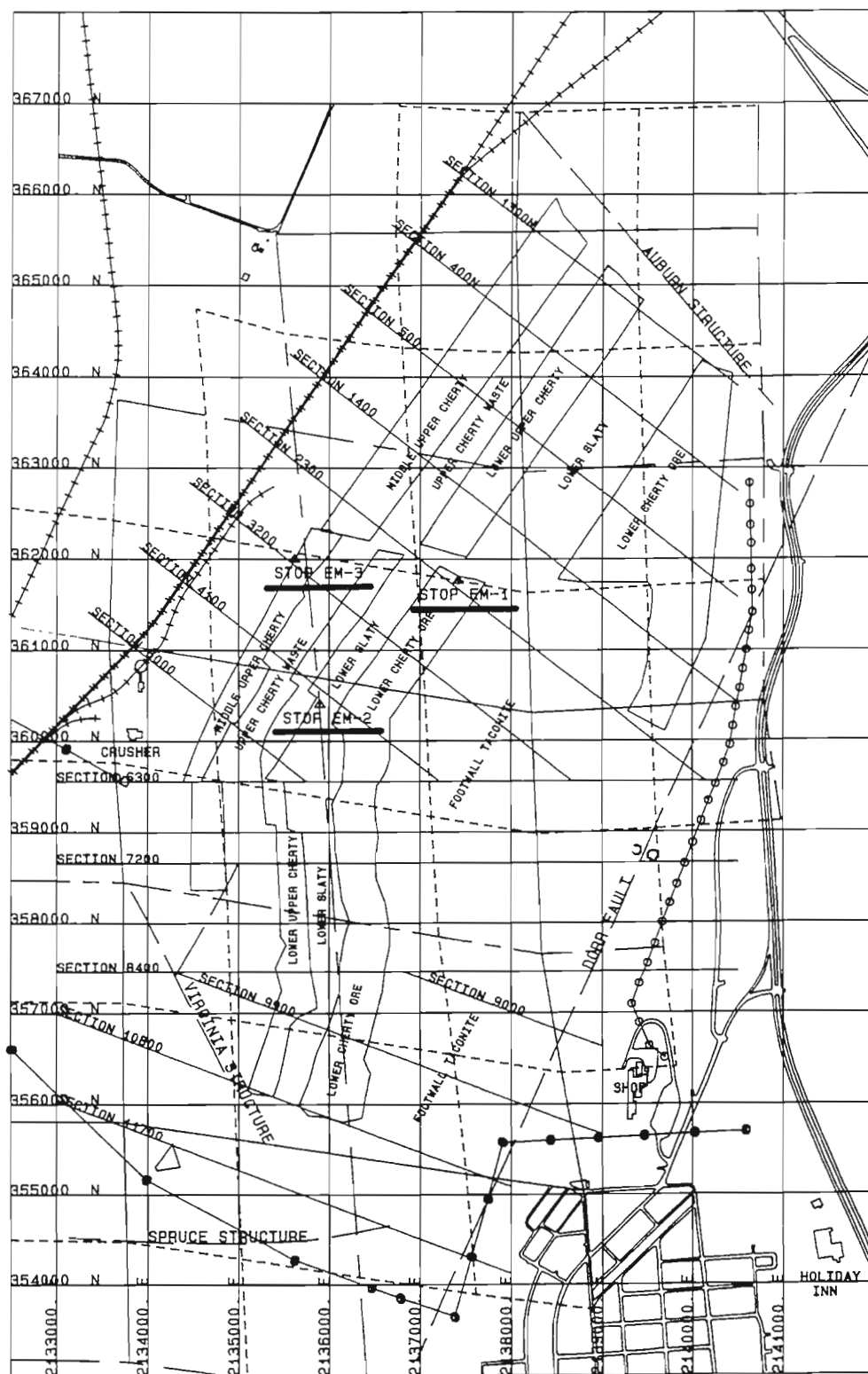


Figure 23 Geology of Thunderbird North Mine. Locations of field trip stops EM-1, EM-2, and EM-3 are shown.

STOP EM-3: Top of Middle Upper Cherty Ore Zone

The footwall slope here strikes N38°E and dips approximately 14°NW. The total thickness of the Middle Upper Cherty ore zone at this point is 98 feet (Fig. 23).

This exposure at the top of the Middle Upper Cherty ore zone displays a conglomeratic "hash" of algal stromatolites with minor associated pyrobitumens. Immediately below the jasperoid stromatolites are massive beds of chert containing strong disseminations of magnetite with occasional carbonate lenses and concretions. Note traces of oxidation due to the proximity to the surface. Also note that the carbonate lenses and nodules in the lower part of the Middle Upper Cherty are the first to be oxidized.

LIBERATION DATA FROM NEAREST D.D.H.

	Footage	Magnetic Fe	D.T. SiO ₂
Top of Middle Upper Cherty	28'	2014%	3.5%
Next Bench of Middle Upper Cherty	35'	28.41%	3.4%
Total Middle Upper Cherty	98'	26.37%	3.5%

LTV STEEL MINING COMPANY
Ronald G. Graber

STOP LT-1: Mine Overview. LOCATION: Surface stockpile centrally located within LTV Steel Mining Company's mining operations (NW1/4-SE1/4, Section 16, T.59N, R.14W)

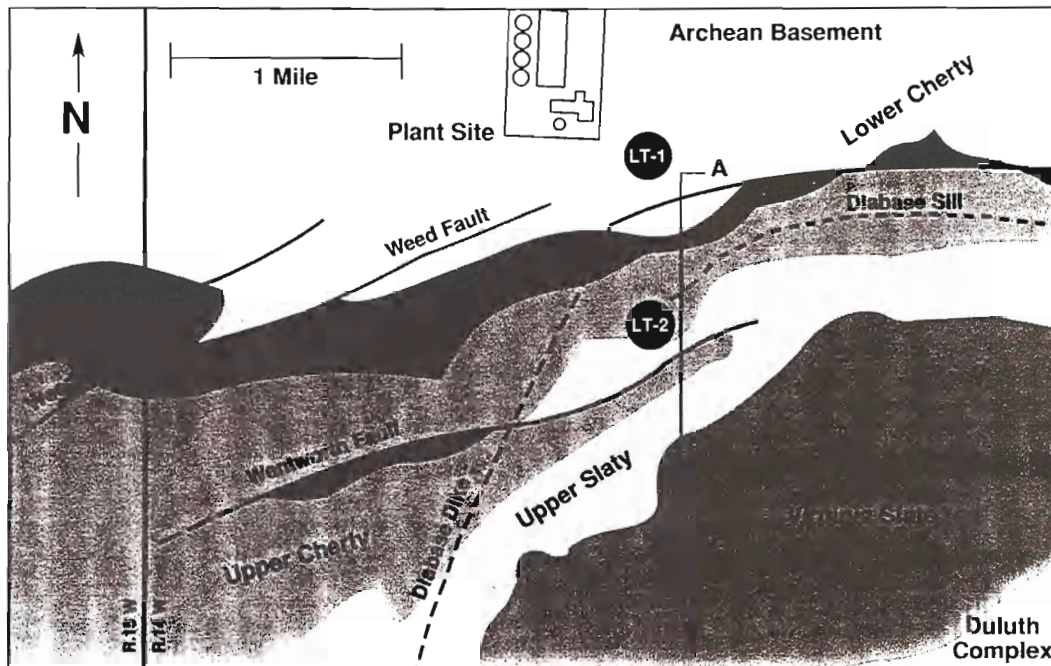


Figure 24 Geologic map of the central portion of LTV Steel Mining Company's taconite operation. Locations of field trip stops LT-1 and LT-2 are shown, along with the location of cross-section A-A' from Figure 27.

From this vantage point (shown on Fig. 24), the central portion of LTV Steel Mining Company's taconite operation can be viewed in relation to the geology of the eastern Mesabi range. The next three stops within the mine pits can be seen from this overview, providing an excellent opportunity to put these stops in the context of the mine's structural and metamorphic geology.

To the north of the overview, the taconite processing plant and tailings basin area resides on Archean bedrock consisting of the Giant's Range batholith intruding metagraywacke and slate. To the south of the overview, the Early Proterozoic Biwabik Iron Formation subcrops. The present visible mining activity is concentrated within the Upper Slaty and Upper Cherty members of the iron-formation. The set of three visible mine pits, stretching on the panorama from east to west, are separated only because of physical obstructions (i.e., not due to ore grade).

The structural geology of this central portion of LTV Steel Mining Company's operations is dominated by a series of east-west trending faults and monoclines. The inactive pit directly south of the overview occupies a downfaulted block of Biwabik Iron Formation produced by a north-side-up fault directly below (south of) the overview, and the Wentworth structure to the south, which is a faulted monocline with the south side up (Fig. 25). A significant portion of the subcrop of the Lower Cherty member has been faulted out between the overview and the inactive pit, which explains the absence of a pit in the Lower Cherty in this area.

The series of low hills beyond the stockpiles to the south of the pits is underlain by the Duluth Complex. The location of the metamorphic effects of the Duluth Complex on iron-formation are within sight of this overview. The amphibole and pyroxene isograds occur between the railroad line, running adjacent to the stockpile, and the eastern extent of the visible pit development.

Stop LT-2 will provide an opportunity to inspect the mineralogy of the iron-formation just outside the amphibole isograd, while Stop LT-3 will straddle the pyroxene isograd (Fig. 19).

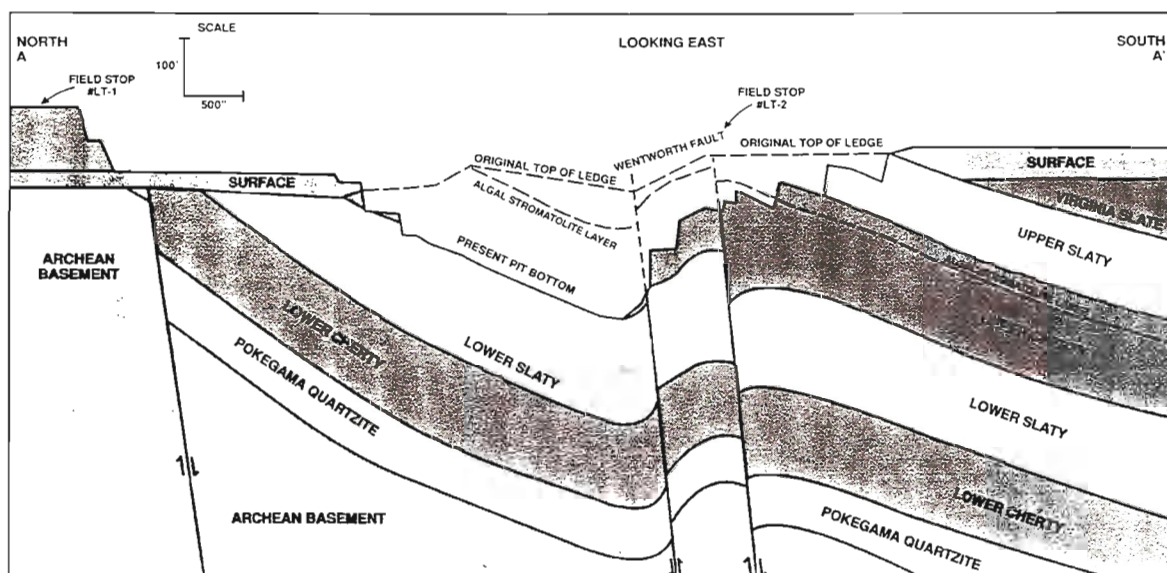


Figure 25 Generalized cross-section A-A' (Figure 26) of LTV Steel Mining Company's Area 2 West pit, showing locations of field trip stops LT-1 and LT-2.

STOP LT-2: Mining Area 2W. LOCATION: Along the truck haulage ramp on the east wall of the Area 2W pit. (W1/4-NE of Section 21, T.59N, R.14W)

At this stop we will view a cross-section of the Upper Cherty and Upper Slaty members exposed in the east pit wall (Fig. 25). Several features at this stop are of interest:

- 1) A thin, 2- to 4-foot-thick, mafic sill is present within the K subunit of the Upper Cherty member. It can easily be identified in the pit wall by its uniform vertical jointing.
- 2) The Wentworth structure, a faulted monocline with its south side up, is exposed in cross-section in the east pit wall where the haulage road turns to the west. Alteration and oxidation of the primary minerals of the iron-formation result in a reddish-brown tinge to the rocks in the immediate vicinity of the structure. This is a classic example of the structural control on the genesis of the natural iron ore bodies (hematite-goethite ores) of the Mesabi range. The Wentworth natural iron ore mine, which was active from 1953 to 1956, was centered on this east-west trending structure.
- 3) An algal stromatolite unit (I subunit) can easily be identified in the pit wall by its massive nature, producing a 4- to 8-foot-thick layer lacking visible bedding. The massive nature of this algal stromatolite unit is retained even in the zone of alteration and oxidation associated with the Wentworth structure.

Note the mineralogy of the Upper Cherty member here prior to proceeding to Stop LT-3. Here at Stop LT-2, we are just outside the amphibole isograd. As such, the mineralogy is still largely typical of the central part of the Mesabi range, with the carbonate minerals, siderite, and ankerite still stable, and hematite only partly converted to magnetite. The stable silicate minerals are the hydrous phyllosilicates, mainly minnesotaite and stilpnomelane.

STOP LT-3: Mining Area 2E. LOCATION: Along an old railroad grade in Mining Area 2E (N1/4-NW of Section 23, T.59N, R.14W)

At Stop LT-3 (Fig. 18 and 19), we will have an opportunity to view two unique exposures. The first is a classic exposure of the algal stromatolite unit (I subunit). On the south side of the railroad cut, a dip slope has been revealed by the stripping off of a thin veneer of surficial materials. Individual stromatolite mounds protrude up through a thin covering of the overlying finely laminated beds of the H subunit (Fig. 26). When viewing this outcrop, it is not difficult to envision what the ancient shoreline would have looked like.

The second feature that will be observed at this stop is the progressive metamorphism of the Biwabik Iron Formation. At the algal stromatolite exposure, we are within the pyroxene grade of metamorphism. As we progress west along the railroad cut, we will leave the pyroxene grade and enter the lower grade amphibole zone. The metamorphic changes are best displayed in the originally carbonate-rich subunits, such as the J and K subunits. Compared to the same stratigraphic section observed at Stop LT-2, the iron-formation at the higher grades of metamorphism possesses a more drab appearance largely due to the conversion of primary hematite (jasper) and carbonate minerals to magnetite and silicates.



Figure 26 Field trip stop LT-3. Upper: individual algal stromatolite mounds protruding from the glaciated outcrop. Lower: the intricate details of the internal structure of an algal mound. This cross-section of an algal mound, created by blasting, is one of the large blocks in the background of the upper photo.

STOP LT-4: Mining Area 3. LOCATION: Pit exposures at the east end of Mining Area 3. (Center of Section 14, T.59N, R.14W)

Stop LT-4 will allow inspection of the Lower Cherty member at the pyroxene grade of metamorphism. Of special interest is the presence of numerous thin pyrrhotite-bearing vertical fissure veins cutting the iron-formation. Locally, the iron-formation adjacent to these veins also contains significant amounts of pyrrhotite.

The genesis of this pyrrhotite veining and replacement has not been studied in any detail. The orientation of the veins (NNW-SSE) mimics the overall trend of the nearby Siphon structure, a rather unusual structure for the Mesabi range (Fig. 27). The Siphon structure, just to the east of the eastern terminus of this pit, displaces the Biwabik Iron Formation subcrop belt to the north by nearly a mile, and a significant decrease in stratigraphic thickness occurs abruptly across the structure. This abrupt change has been presented in evidence that the structure was active during, as well as after, deposition of the iron-formation.

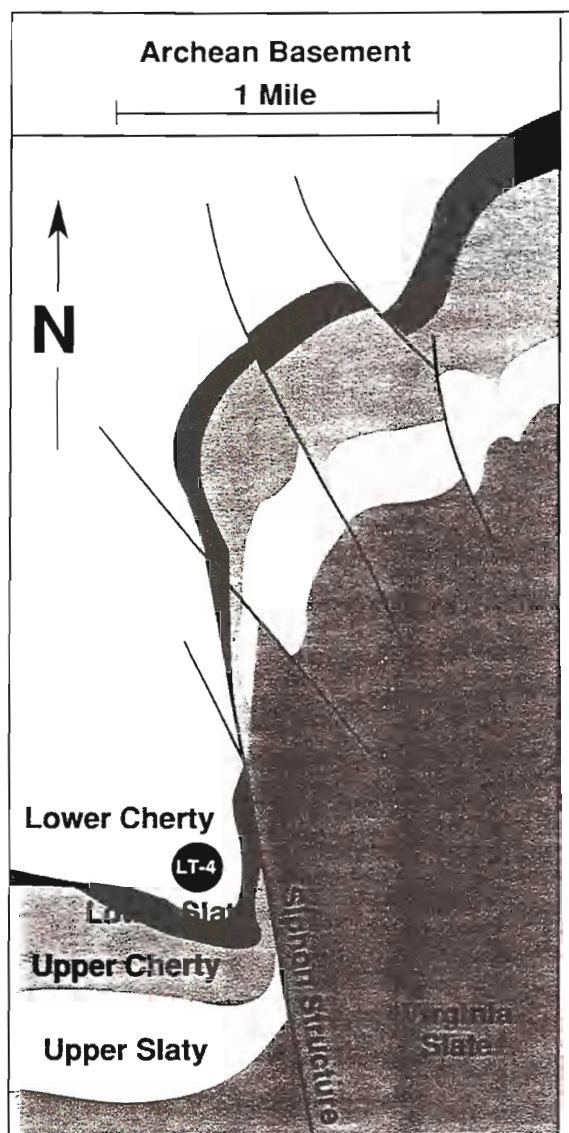


Figure 27 Geologic map detailing the structural complexity associated with the Siphon Structure. Field trip stop LT-4 is just west of the structure.

Additionally, mapping of the pyroxene isograd at LTV Steel Mining Company has failed to reveal any apparent offset across the Siphon structure. As such, this structure predates the intrusion of the Duluth Complex and may have provided the structural conduits for the emplacement of the pyrrhotite veins.

The overlying Lower Slaty member contains a pyrite-rich subunit at its base that could have been a source of sulfur within the Duluth Complex's metamorphic aureole through the stabilization of pyrrhotite at the expense of pyrite:



The pyrrhotite replacement of the iron-formation in this area displays a preference for the originally carbonate-rich portions of the Lower Cherty member. Limited analyses of pyrrhotite-rich samples have not detected any significant base or precious metal values.

From Stop LT-4, we will travel east on the mine's private road, approximately 20 mi (32 km), to LTV Steel Mining Company's Dunka Pit.

STOP LT-5: Dunka Mine/North Pit Overlook. LOCATION: An overlook perched on the footwall of the Dunka Pit (SE1/4-SE1/4 of Section 34, T.61N, R.12W).

A review of the geology of the Dunka Mine will be conducted from this overlook prior before we descend into the pit (Fig. 28). The Dunka Mine has been in continuous operation since 1965. The mine has largely been depleted with the only remaining economic reserves occurring directly below the overlook. This tour group will likely be the last group to have the opportunity to visit the Dunka Mine prior to flooding of the pits in 1994.

The Dunka Mine provides an opportunity to view high-grade metamorphism of the Biwabik Iron Formation. Although the stable silicate mineralogy is not significantly different from that observed at Stops LT-3 and LT-4, as shown in Figure 29, recrystallization has produced a noticeable increase in grain size. Despite the extensive recrystallization, the bedding features characteristic of the individual subunits are still discernible.

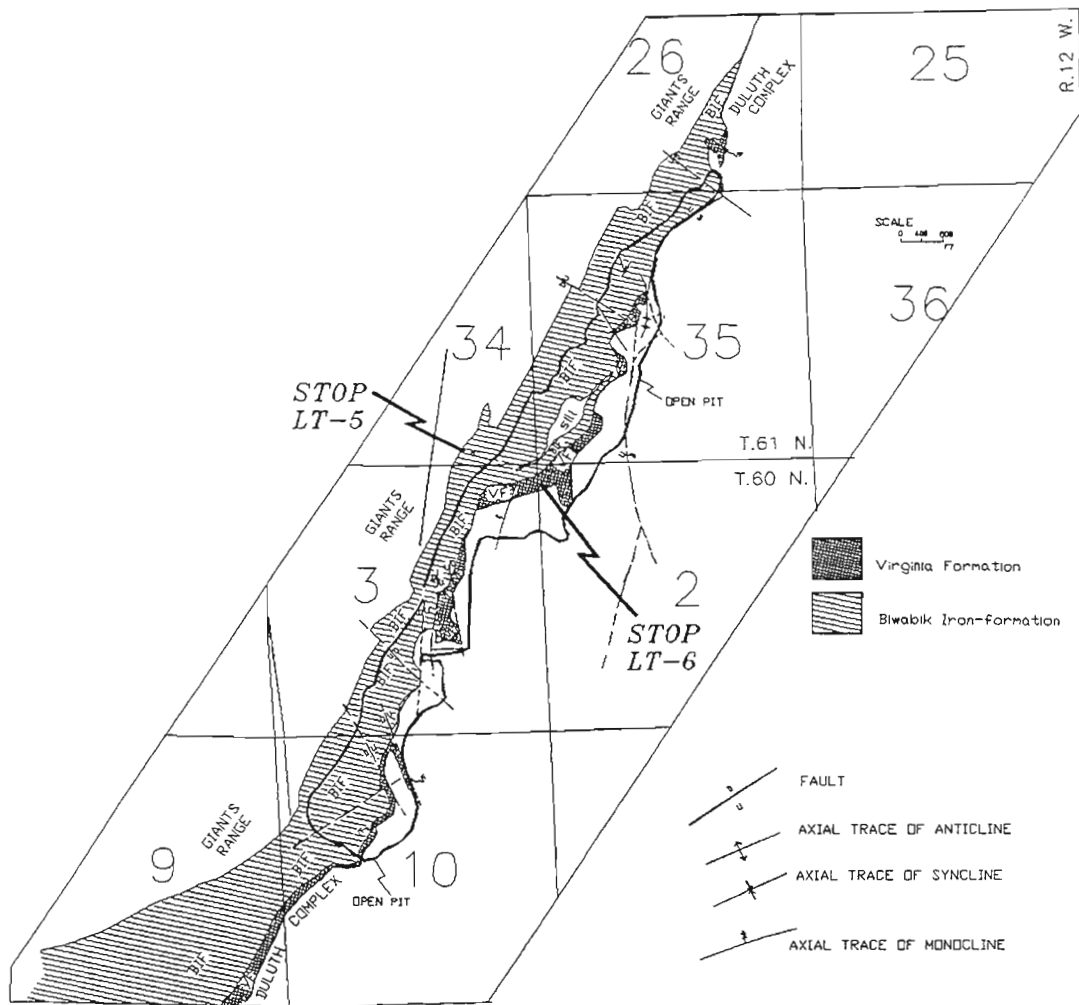


Figure 28 Geology of Dunka Pit area, LTV Steel Mining Company (geology shown is based on pre-pit drilling compiled by Severson after Bonnichsen, 1968; Holst and others, 1986; and Severson, in preparation). Locations of field trip stops LT-5 and LT-6 are shown.

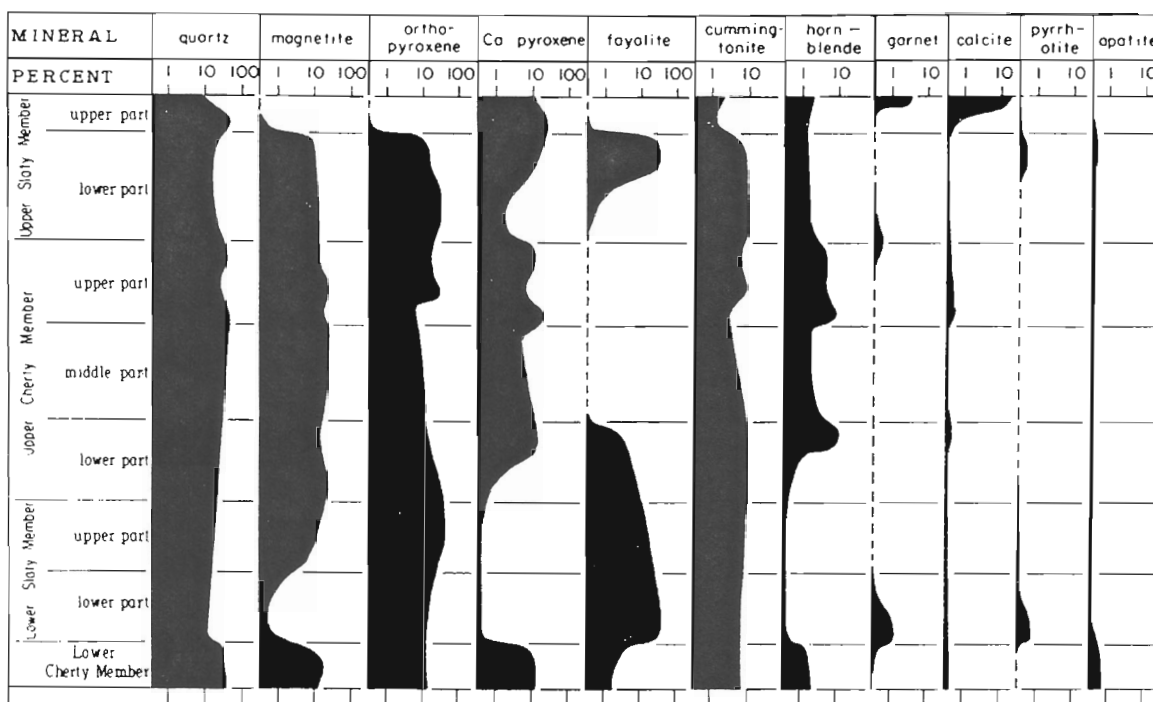


Figure 29 Mineralogical distributions in the Biwabik Iron Formation at the Dunka Mine (from Bonnichsen, 1968). Field trip stop LT-6 will allow inspection of the middle part of the Upper Cherty for comparison with the mineralogy at field trip stops LT-2 and LT-3.

The Dunka Mine derives ore from the basal part of the Upper Slaty and all of the Upper Cherty members. The overlook resides on the footwall of the deposit that is the Lower Slaty. Behind the overlook, the wooded hills are underlain by rocks of the Giants Range batholith (Archean). Across the pit, the hanging wall is made up of Duluth Complex, Virginia Formation hornfels, and the uneconomic portions of the Upper Slaty. Structurally, the iron-formation dips at an average 35° to the east, but in detail the structure of the deposit is quite complicated. The northeastern limit of the Mesabi range can be seen from this overlook. A northwest-trending fault zone marks the end of the contiguous suboutcrop of the Mesabi range, beyond which only sporadic "rafts" of Biwabik Iron Formation inclusions exist "swimming" in Duluth Complex.

STOP LT-6: Dunka Mine/North Pit. LOCATION: Pit exposures of the Upper Cherty member. (NE1/4-NE1/4 of Section 3, T.60N, R.12W)

The exact exposures that will be visited in the pit will be predicated on accessibility at the time of the visit. We hope that access to the middle portion of the Upper Cherty member (H, I, J and K subunits) will be possible, to allow comparisons with the stratigraphic sections observed at Stops LT-2 and LT-3. The most dramatic mineralogical change, from an economic viewpoint, is the generation of abundant coarse-grained magnetite in the K subunit. At Stop LT-2, this subunit consists mainly of quartz-siderite-stilpnomelane with only a trace of magnetite. At Stop LT-3, within the pyroxene isograd, the magnetite content of the K subunit increases to nearly 20 percent. Here at the Dunka Mine, the magnetite content averages 45 percent in this subunit. The distinctive thin banding of this subunit, though, is retained throughout the various metamorphic zones.

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REFERENCES

- Anderson, R.R., and Black, R.A., 1983, Early Proterozoic development of the southern Archean boundary of the Superior Province in the Lake Superior region [abs.]: Geological Society of America Abstracts with Programs, v. 15, no. 6, p. 515.
- Barovich, K.M., Patchett, P.J., Peterman, Z.E., and Sims, P.K., 1989, Nd isotopes and the origin of 1.9-1.7 Ga Penokeyan continental crust of the Lake Superior region: Geological Society of America Bulletin, v. 101, pp. 333-338.
- Bonnichsen, Bill, 1968, General Geology and Petrology of the Metamorphosed Biwabik Iron Formation, Dunka River Area, Minnesota: Unpublished Ph.D. Dissertation, University of Minnesota, Minneapolis.

- Djerlev, Henry, 1993, personal communication.
- Dolence, J.D., 1961, The Pokegama Quartzite in the Mesabi Range [Unpublished M.S. thesis]: Twin Cities, University of Minnesota, 72 p.
- Ewers, W.E., and Morris, R.C., 1981, Studies of the Dales Gorge Member of the Brockman Iron Formation, Western Australia: *Economic Geology*, v. 67, pp. 1929-1953.
- French, B.M., 1973, "Mineral Assemblages in Diagenetic and Low-Grade Metamorphic Iron-Formation": *Economic Geology* v. 68, pp. 1063-1074.
- Goldich, S.S., Nier, A.O.C., Baadsgaard, Halfdan, Hoffman, J.H., and Krueger, H. W., 1961, The Precambrian Geology and Geochronology of Minnesota: Minnesota Geological Survey Bulletin 41, 193 p.
- Goodwin, A.M., 1956, Facies relations in the Gunflint iron formation: *Economic Geology*, v. 51, no. 6, pp. 565-595.
- Grout, F.F., and Broderick, T.M., 1919, The magnetite deposits of the eastern Mesabi Range, Minnesota: Minnesota Geological Survey Bulletin, v. 17, 58 p.
- Grout, F.F., 1933, Contact metamorphism of the slates of Minnesota by granite and by gabbro magmas: *Geological Society of America Bulletin*, v. 44, pp. 989-1040.
- Gruner, J.W., 1926, The Soudan formation and a new suggestion as to the origin of the Vermilion iron ores: *Economic Geology*, v. 21, pp. 629-644.
- _____, 1930, Hydrothermal oxidation and leaching experiments; their bearing on the origin of the Lake Superior hematite-limonite ores: *Economic Geology*, v. 25, no. 7, pp. 697-719; no. 8, pp. 837-867.
- _____, 1937, Hydrothermal leaching of iron ores of the Lake Superior type; a modified theory: *Economic Geology*, v. 32, pp. 121-130.
- _____, 1946, The mineralogy and geology of the taconites and iron ores of the Mesabi Range, Minnesota: Office of Commissioner Iron Range Resources and Rehabilitation, St. Paul, in cooperation with Minnesota Geological Survey, 127 p.
- _____, 1956, The Mesabi Range, *in* Schwartz, G.M., and others, eds., Precambrian of northeastern Minnesota: Geological Society of America, Annual Meeting, 1956, Guidebook for field trip no. 1, pp. 182-215.
- Gundersen, J.N., and Schwartz, G.M., 1962, The Geology of the Metamorphosed Biwabik Iron Formation, eastern Mesabi district, Minnesota: Minnesota Geological Survey Bulletin 43, 139 p.
- Han, T.M., 1978, Microstructures of magnetite as guides to its origin in some Precambrian iron-formations: *Fortschritte der Mineralogie*, v. 56, no. 1, pp. 105-142.
- _____, 1982, Iron formations of Precambrian age: Hematite-magnetite relationships in some Proterozoic iron deposits—a microscopic observations, *in* G.C. Amstutz and others, eds., *Ore Genesis: The State of the Art*: New York, Springer-Verlag, pp. 451-459.

- Hemming, S., Hanson, G.N., McLennan, S.M., and Sharp, W.D., 1991, Isoclinal slump-folds in the lower Pokegama Quartzite: Evidence for seismicity and slope instability during deposition of the Animikie Group [abs.]: Abstracts & Proceedings, 37th Institute on Lake Superior Geology, Eau Claire, WI, pp. 56-58.
- Hoffman, P.F., 1987, Early Proterozoic foredeeps, foredeep magmatism and Superior-type iron-formations of the Canadian shield, *in* A. Kroner, ed., Proterozoic lithospheric evolution: American Geophysical Union Geodynamics Series, v. 17, pp. 85-98.
- Holst, T.B., 1984, Evidence for nappe development during the Early Proterozoic Penokean orogeny, Minnesota: *Geology*, v. 12, pp. 135-138.
- _____, 1991, The Penokean orogeny in Minnesota and Upper Michigan: A comparison of structural geology: *in* Sims, P.K. and Carter, L.M.H., eds., Contributions to Precambrian geology of the Lake Superior region: U.S. Geological Survey Bulletin 1904-D, 10 p.
- Holst, T.B., Mullenmeister, E.E., Chandler, V.W., Green, J.C., and Weiblen, P.W., 1986, Relationship of Structural Geology of the Duluth Complex to Economic Mineralization: Minnesota Department of Natural Resources, Division of Minerals, Report 241-2.
- Irving, R.D., 1886, Origin of the ferruginous schists and iron ores of the Lake Superior region: *American Journal of Science*, v. 32, pp. 255-272.
- James, H.L., 1954, Sedimentary facies of iron-formations: *Economic Geology*, v. 49, pp. 235-293.
- Klasner, J.S., and Sims, P.K., 1993, Thick-skinned, south-verging back thrusting in the Felch and Calumet troughs area of the Penokean orogen, northern Michigan, *in* P.K. Sims and L.M.H. Carter, eds., Contributions to Precambrian geology of Lake Superior region: U.S. Geological Survey Bulletin 1904-L, in press.
- Leith, C.K., 1903, The Mesabi iron-bearing district of Minnesota: U.S. Geological Survey Monograph 43, 316 p.
- Lepp, H., 1966, Chemical composition of Biwabik Iron Formation, Minnesota: *Economic Geology*, v. 61, no. 2, pp. 243-250.
- Lucente, M.E., and Morey, G.B., 1983, Stratigraphy and sedimentology of the Lower Proterozoic/Virginia Formation, northern Minnesota: Minnesota Geological Survey Report of Investigations 28, 28 p.
- Marsden, R.W., 1972a, Cuyuna district, *in* P.K. Sims and G.B. Morey, eds., *Geology of Minnesota: A Centennial Volume*: Minnesota Geological Survey, pp. 227-239.
- _____, 1972b, General geology of the central Mesabi Range, parts 1 and 2 of Field trip no. 1: General geology of the Mesabi Range, in Precambrian Iron-Formation Symposium, Duluth, Minnesota, 1972, Abstracts and field guides: Society of Economic Geologists, University of Minnesota, Duluth, variously paged.
- _____, 1978, Iron ore reserves of the Mesabi Range, Minnesota: a minerals availability system report, *in* Productivity in Lake Superior district mining: Mining Symposium, 39th Annual, and American Institute of Mining and Metallurgical Engineers, Minnesota Section,

- 51st Annual Meeting, Duluth, 1978, Proceedings: Minneapolis, University of Minnesota, Department of Conferences, Continuing Education and Extension, paper 23, 57 p.
- Marsden, R.W., Emanuelson, J.W., Owens, J.S., Walker, N.E., and Werner, R.F., 1968, The Mesabi Range, Minnesota; *in* John D. Ridge, ed., Ore Deposits of the United States 1933-1967: The American Institute of Mining, Metallurgical and Petroleum Engineers, pp. 535-537.
- Morey, G.B., 1972, Mesabi Range; *in* P.K. Sims and G.B. Morey, eds., Geology of Minnesota: A Centennial Volume, Minnesota Geological Survey, pp. 204-217.
- _____, 1973, Stratigraphic framework of Middle Precambrian rocks in Minnesota: *in* G.M. Young (ed.) Huronian stratigraphy and sedimentation, Geological Association of Canada, Special Paper 12, pp. 211-249
- _____, 1978, Lower and Middle Precambrian stratigraphic nomenclature for east-central Minnesota: Minnesota Geological Survey Report of Investigations 21, 52 p.
- _____, 1979, Stratigraphic and tectonic history of east-central Minnesota: *in* Field trip guidebook for stratigraphy, structure, and mineral resources of east-central Minnesota: Minnesota Geological Survey Guidebook Series No. 9, pp. 13-28.
- _____, 1983, Lower Proterozoic stratified rocks and the Penokean orogeny in east-central Minnesota, *in* L.G. Medaris, Jr., ed., Early Proterozoic geology of the Lake Superior region: Geological Society of America Memoir 160, pp. 97-122.
- _____, 1983, Animikie basin, Lake Superior region, U.S.A., *in* A.F. Trendall and R.C. Morris, eds., Iron-formation facts and problems: Amsterdam, Elsevier, pp. 13-67.
- _____, 1992, Chemical composition of the eastern Biwabik Iron Formation (Early Proterozoic), Mesabi Range, Minnesota: Economic Geology, v. 87, pp. 1649-1658.
- Morey, G.B., Southwick, D.L., and Schottler, S.P., 1991, Manganiferous zones in Early Proterozoic iron-formation in the Emily district, Cuyuna Range, east-central Minnesota: Minnesota Geological Survey Report of Investigations 39, 42 p.
- Morey, G.B., and Van Schmus, W.R., 1988, Correlation chart of Precambrian rocks in the Lake Superior region: U.S. Geological Survey Professional Paper 1241-F, 30 p., 1 plate.
- Muhich, T.G., 1993, Diffusion of Ti across the Duluth Complex-Biwabik Iron Formation contact at Dunka pit, Mesabi Iron Range, Northeastern Minnesota [abs.]: Geological Society of America, Abstracts with Program, v. 25, no. 3, p. 69.
- Ojakangas, R.W., 1983, Tidal deposits in the early Proterozoic basin of the Lake Superior region "The Palms and the Pokegama Formations; Evidence for subtidal-shelf deposition of Superior-type banded iron-formation: *in* L.G. Medaris, Jr., ed., Early Proterozoic Geology of the Lake Superior Region: Geological Society of America Memoir 160, pp. 49-66.
- _____, 1993, Sedimentology and provenance of the Early Proterozoic Michigamme Formation and Goodrich Quartzite, northern Michigan "Regional stratigraphic implications and suggested correlations: *in* P.K. Sims and L.M.H. Carter, eds., Contributions to Precambrian geology of the Lake Superior region: U.S. Geological Survey Bulletin 1904-R, in press.
- Ojakangas, R.W. and Matsch, C.L., 1982, Minnesota's Geology, University of Minnesota Press, Minneapolis.

- Perry, E.C., Jr., Tan, F.C., and Morey, G.B., 1973, Geology and stable isotope geochemistry of the Biwabik Iron Formation, northern Minnesota, in *Precambrian iron-formations of the world: Economic Geology*, v. 68, no. 7, pp. 1110-1125.
- Pfleider, E.P., Morey, G.B., and Bleifuss, R.L., 1968, Mesabi deep drilling project: Progress report no. 1, *in* Mining Symposium, 29th Annual, and American Institute of Mining and Metallurgical Engineers, Minnesota Section, 41st Annual Meeting, Duluth, 1968 [Proceedings]: Minneapolis, University of Minnesota, pp. 52-92.
- Robinson, D.J., 1984, Silicate facies iron-formation and stratabound alteration: Tuffaceous exhalites derived by mixing"evidence from Mn garnet-stilpnomelane rocks at Redstone, Timmons, Ontario: *Economic Geology*, v. 53, pp. 708-721.
- Schmidt, R.G., 1958, Titaniferous sedimentary rocks in the Cuyuna district, central Minnesota: *Economic Geology*, v. 53, no. 6, pp. 708-721.
- _____, 1963, Geology and ore deposits of Cuyuna North Range, Minnesota: U.S. Geological Survey Professional Paper 407, 96 p.
- Schulz, K.J., 1991, Tectonic evolution of the Early Proterozoic Penokean orogen [abs.]: Minnesota Geological Survey Information Circular 34, pp. 29-31.
- Severson, M. J., in preparation, Igneous stratigraphy of the South Kawishiwi Intrusion, Duluth Complex, northeastern Minnesota: Natural Resources Research Institute, University of Minnesota, Duluth, Technical Report.
- Sims, P.K., Van Schmus, W.R., Schulz, K.J., and Peterman, Z.E., 1989, Tectonostratigraphic evolution of the Early Proterozoic Wisconsin magmatic terranes of the Penokean orogen: *Canadian Journal of Earth Sciences*, v. 26, pp. 2145-2158.
- Southwick, D.L., and Morey, G.B., 1991, Tectonic imbrication and foredeep development in the Penokean orogen, east-central Minnesota"An interpretation based on regional geophysics and the results of test drilling: U.S. Geological Survey Bulletin 1904-C, 17 p.
- Southwick, D.L., Morey, G.B., and McSwiggen, P.L., 1988, Geologic map (scale 1:250,000) of the Penokean orogen, central and eastern Minnesota, and accompanying text: Minnesota Geological Survey Report of Investigations 37, 25 p., 1 pl.
- Van Hise, C.R., and Bayley, W.S., 1897, The Marquette iron-bearing district of Michigan: U.S. Geological Survey Monograph 28, 608 p.
- Van Hise, C.R., and Leith, C.K., 1911, The geology of the Lake Superior region: U.S. Geological Survey Monograph, v. 57, 641 p.
- White, D.A., 1954, The stratigraphy and structure of the Mesabi Range, Minnesota: Minnesota Geological Survey Bulletin 38, 92 p.
- Winchell, N.H., 1893, Twentieth annual report for the year 1891: Minnesota Geological Natural History Survey, 344 p.

Wolff, J.F., 1915, The ore bodies of the Mesabi Range: Engineering and Mining Journal, v. 100, Nos. 3, 4, 5, 6, pp. 89-94, 135-139, 178-185, 219-224.

— 1917, Recent geologic developments on the Mesabi Iron Range, Minnesota: American Institute of Mining and Metallurgical Engineers, Transactions, v. 56, pp. 229-257.

FIELD TRIP 2

DNR CORE LIBRARY OPEN HOUSE AND CORE DISPLAY

The cores on display depict three separate topics:

A. BIWABIK IRON FORMATION

Leader: G.B. Morey, Minnesota Geological Survey

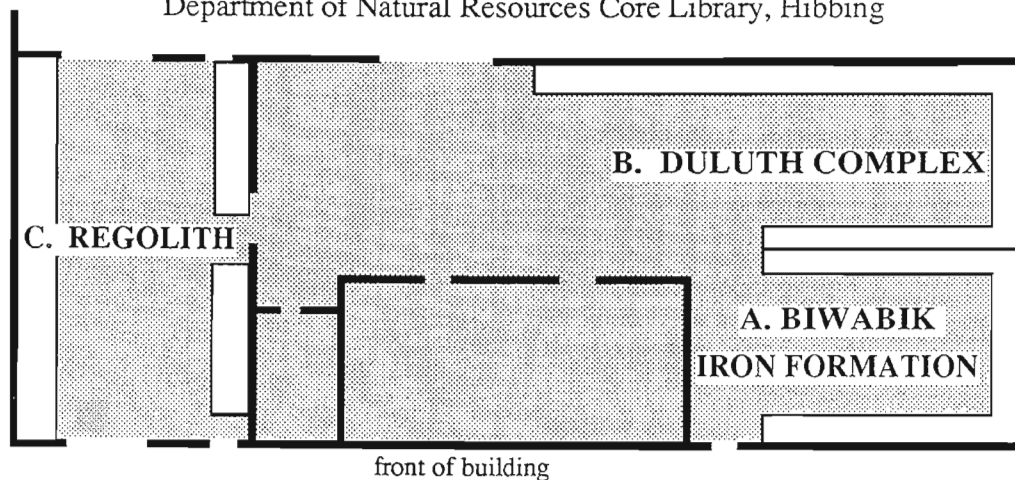
**B. IGNEOUS STRATIGRAPHY OF THE PARTRIDGE RIVER AND
SOUTH KAWISHIWI INTRUSIONS-DULUTH COMPLEX**

Leader: Mark J. Severson, Minnesota Natural Resources
Research Institute, University of Minnesota, Duluth

**C. STRATIGRAPHIC AND COMPOSITIONAL VARIATIONS IN REGOLITH
DEDUCED FROM ROTASONIC CORES IN NORTHERN MINNESOTA**

Leaders: Dennis P. Martin and Dale F. Cartwright, Minnesota
Department of Natural Resources, and
Gary N. Meyer, Minnesota Geological Survey

Location of core displays within building #3,
Department of Natural Resources Core Library, Hibbing



Field Trip 2A

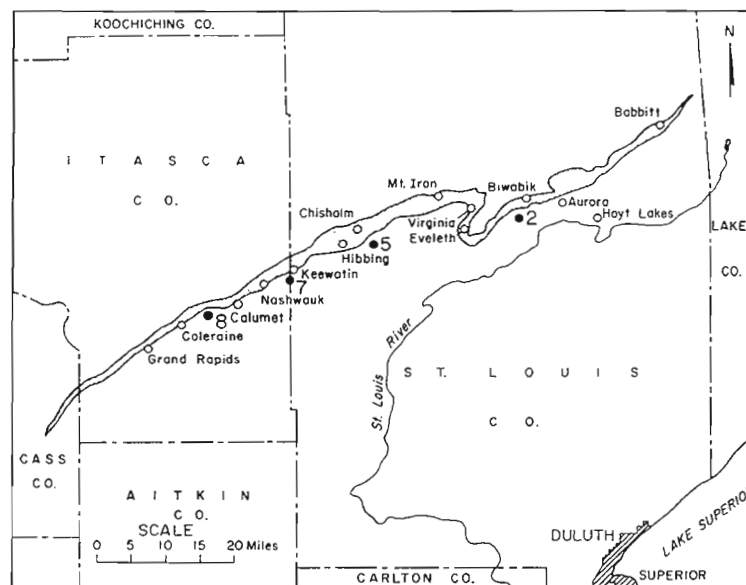
BIWABIK IRON FORMATION CORE

G.B. Morey
Minnesota Geological Survey

INTRODUCTION

The Mesabi Range field trip provided an opportunity to examine parts of the Early Proterozoic Biwabik Iron Formation at the eastern end of the range, from near Eveleth to the vicinity of the Dunka River, Minnesota. That part of the iron-formation is characterized by thick intervals of magnetite-bearing strata capable of supporting several taconite production facilities. Not all of the Biwabik contains magnetite as an important mineral phase, however; therefore, today's mini-field trip will examine drill core from near Buhl and near Calumet, where the Biwabik consists dominantly of either silicate iron-formation or carbonate iron-formation, respectively. The cores that we will examine were acquired by the School of Mines and Metallurgy, University of Minnesota, in 1966 and 1967 as part of an appraisal of the potential for underground mining of taconite from buried iron-formation along the south side of the Mesabi range (Fig. 1). Information regarding these sites, including a discussion of stratigraphic and metallurgical relationships, is summarized in Pfeider and others (1968). The cores have provided materials for a variety of studies, including whole rock and minor element chemistry (Morey and Morey, 1990; Morey, 1992), the carbon isotopes (Perry and Tan, 1973) and oxygen isotopes (Perry and others, 1973), the rare earth elements studies (Morey and Boerboom, 1992), and sedimentological studies of the Virginia Formation (Lucente and Morey, 1983).

Figure 1 Index map of the Mesabi Range, showing localities discussed in the text. Stipple represents generalized subcrop distribution of the Biwabik Iron Formation.



Buhl Site (Hole 5)

The Buhl site was selected by Pfeider and others (1968) partly because a positive magnetic anomaly, thought to be related to a magnetite-bearing interval in the Lower Cherty member, extends from the vicinity of the Shenango mine (Meineke and others, 1993) southeastward across the southeast corner of T. 58 N., R. 20 W. In all, 216 m of iron-

formation were cored with approximately 98 percent recovery. The base of the iron-formation is easily recognized by an abrupt transition from quartz arenite to oxide iron-formation, characterized by stromatolitic intervals composed of admixed hematite and chert (jasper) intercalated with thin intervals of laminated hematite and jasper. In contrast, the top of the iron-formation is a transitional interval of approximately 12 m consisting of interbedded mudstone or shale, limestone or dolomite, and chert; the Virginia-Biwabik contact is arbitrarily placed at the top of the uppermost chert bed. Therefore the Biwabik Iron Formation contains appreciable epiclastic material at this locality.

Of particular interest at this site is a small breccia zone at a depth of 163 m that produced considerable artesian flow. It was subsequently established that the site was located on the southeastward projection of a structurally disturbed (breccia) zone exposed along the south side of the Sherman Mine (Meineke and others, 1993). It is likely that the breccia zone penetrated at the Buhl site is the down-dip extension of this brecciated area.

On display are the lower part of the Lower Slaty member and the upper part of the Lower Cherty member. The contact at the top of the Lower Cherty member is placed at the top of a nonmagnetic unit of granular iron-formation characterized by large silicate granules set in a matrix of chert and disseminated carbonate. Throughout much of the range, the basal part of the Lower Slaty member is characterized by a thin-bedded to laminated, carbon-rich ashfall tuff called the Intermediate slate. However, at the Buhl site the lowermost Lower Slaty member contains beds of granular iron-formation with abundant disseminated silicates. These beds are interlayered with intervals of laminated iron-formation characterized by very thin beds of red, green, and black silicates. The laminated iron-formation passes transitionally upward into typical Intermediate slate. Although evidence from one drill core is inconclusive, it may be that the granular and laminated strata beneath the Intermediate slate are a fining-upward sequence deposited in a channel cut into uppermost Lower Cherty strata.

The Lower Cherty member is approximately 77 m thick. Except for approximately 6 m of oxide iron-formation at the base, most of the member consists of interlayered silicate-rich granular and laminated iron-formation. The laminated parts are composed of very thin beds and laminae of red and green silicates, both with and without disseminated magnetite, whereas the granular parts are composed of disseminated magnetite set in a matrix dominated by silicates. Granular iron-formation is more abundant in the upper part of the member, where silicates occur as disseminated grains, granules, mottles, and patches. Magnetite occurs around and within granules, as disseminated grains, and as irregular and diffuse beds several millimeters thick.

There is no active taconite production facility in the Buhl-Chisholm segment of the range. However, taconite is produced from the Lower Cherty member both at Mountain Iron to the east and at Hibbing to the west. I have no specific data from either mining operation, but parts of the Lower Cherty member east of Mountain Iron at Biwabik have an average magnetic iron content of approximately 26 percent (drill core no. 2, Fig. 2). Similarly, parts of the Lower Cherty member west of Hibbing at Keewatin have an average magnetic iron content of 24 percent (Pfleider and others, 1968). In contrast, the same stratigraphic interval at the Buhl site (drill core no. 5, Fig. 2) has an average magnetic iron content of only 19 percent. The data in Figure 2 from core no. 5 at Buhl confirm that the lower cherty member contains less magnetite in the eastern half of the range than in the western. Nonetheless, the bulk chemical composition, especially total iron as elemental Fe, differs little across the range (Fig. 2).

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The iron-formation at the site, however, does contain more Al_2O_3 , TiO_2 , and Na_2O , and these differences are consistent with the petrographic conclusion that much of the iron at the Buhl site is tied up in iron silicates rather than magnetite. The Buhl site also contains on the average more Li, V, Co, Cu, Zn, Y, Zr, Ba, and Pb. Morey and Morey (1990) showed that these constituents are generally somewhat more abundant in silicate-rich, laminated parts of the Biwabik Iron Formation. Robinson (1984) concluded that the elemental association Fe-Mn-Mg-Ca-Co in a silicate iron-formation in Canada was chemically precipitated, whereas the elemental association Al-Ti-Zr-V-P-Nb had a volcanoclastic origin. If so, it is likely that silicate-rich strata in the Biwabik Iron Formation are a composite entity composed of materials derived from a mixture of chemical, volcanic, and possibly epiclastic sources. This mixed provenance suggests that the individual silicate minerals, like magnetite, are diagenetic products formed from some unknown precursor. Juneau (1979) described silicate iron-formation from the Keewatin area and suggested that the silicate assemblage there may have formed and been stabilized because the precursor had an above-average magnesium composition. The data in Fig. 2 show that that does not seem to be the case in the Buhl area.

Calumet Site Hole 8

The geology of the Biwabik Iron Formation west of Nashwauk (Fig. 1) differs considerably from that of the remainder of the range. There is a mineralogical change within the iron-formation in which silicates and carbonates gradually replace magnetite as one proceeds westward from Nashwauk. Consequently, much of the iron-formation there is locally oxidized and partly decomposed, attributes unmistakable in the core from drill hole 8 at the Calumet site. This core, however, represents the only complete record of the western Biwabik Iron Formation in the public domain. Interestingly, however, the overlying Virginia Formation is little altered or decomposed.

There also are several large-scale stratigraphic changes as the iron-formation is followed to the west. For example, the Intermediate slate pinches out toward the west, and the Lower Slaty member thins appreciably from more than 35 m near Keewatin to little more than 6 m at the Calumet site. It is difficult to define the contact between the Biwabik and overlying Virginia Formation. Much of the Upper Slaty member, which is 60 m thick at the Calumet site, consists of black iron-formation intercalated with black shale and mudstone, which can be distinguished from the iron-formation in hand-specimen only by the difference in specific gravity. In addition, thin to thick intervals of irregularly laminated carbonate iron-formation and white cryptocrystalline chert are intercalated. Thin beds of green, waxy shale of volcanogenic origin occur throughout the Biwabik-Virginia transition, as well as in the lower 30 m of the overlying Virginia Formation. As defined, the Biwabik is 210 m thick at the Calumet site. A second unit of iron-formation, in the Virginia Formation some 60 m above uppermost Biwabik strata, also was penetrated there. This unit, 20 m thick, consists of irregularly laminated carbonate iron-formation intercalated with thick intervals of black, carbonaceous shale. Lenses and angular fragments of light-bluish-gray and white, cryptocrystalline chert are common in the iron-rich strata.

The Calumet site was selected by Pfeider and others (1968) for investigation of one of several large positive magnetic anomalies in the area, which implied the possible presence of magnetite-rich intervals in the iron-formation subcrop south of the range. That possibility was never confirmed. Among other things, the hole penetrated a thick shear zone in the Upper Slaty member where the rocks are brecciated and considerably deformed. The brecciated interval seems to be part of a pronounced magnetic gradient that corresponds to a steeply dipping northeast-trending fault at the east end of the Hill-Annex mine (Meineke and others, 1993). It is likely that fluid flow along this structural channelway

was at least partly responsible for decomposition and leaching of the iron-formation at the Calumet site. Therefore any magnetite originally present would have been transformed into martite or other secondary minerals.

On display are the Lower Slaty member and parts of the overlying Upper Cherty and underlying Lower Cherty members. The Lower Slaty member consists of thin goethite-rich intervals intercalated with beds of granular iron-formation composed mainly of chert and disseminated carbonates. Much of the Upper Cherty member consists of granular iron-formation characterized by disseminated grains, mottles, and patches of carbonate. The granular units are interlayered with thin to thick intervals having various proportions of laminated hematite and chert, green and black silicates, and black carbonaceous and argillaceous iron-formation.

The Lower Cherty member is about 110 m thick. As elsewhere on the range, the lower 10 m is oxide iron-formation characterized by beds of jasper, both with and without stromatolitic structures, intercalated with thin intervals of laminated hematite-rich strata and beds of cryptocrystalline chert. The oxide iron-formation is overlain by 25 m of granular iron-formation characterized by disseminated grains, patches, and mottles of magnetite, set in a chert-rich groundmass. Martite pseudomorphically replaces much of the magnetite. The overlying 75 m of the member consists of granular carbonate iron-formation, characterized by disseminated grains and granules of carbonate. They are intercalated with thin to thick, irregularly to regularly shaped beds of goethite, as well as thin intervals of silicate iron-formation marked by disseminated grains and granules of minnesotaite. Goethite pseudomorphically replaces much of the carbonate.

Because of the generally decomposed nature of the iron-formation, no metallurgical or chemical data were acquired from core obtained from the Calumet site.

REFERENCES CITED

- Juneau, P.J., 1979, Origin and petrology of iron silicate-rich bodies in the Biwabik Iron Formation, Minnesota: Unpublished M.S. thesis, University of Minnesota, Duluth.
- Lucente, M.E., and Morey, G.B., 1983, Stratigraphy and sedimentology of the lower Proterozoic Virginia Formation, northern Minnesota: Minnesota Geological Survey Report of Investigations 28, 28 p.
- Meineke, D.G., and others, 1993, Geologic map of the Mesabi range, Minnesota: Hibbing, Mesabi Range Geological Society, scale 1:62,500.
- Morey, G.B., 1992, Chemical composition of the eastern Biwabik Iron Formation (Early Proterozoic), Mesabi Range, Minnesota: *Economic Geology*, v. 87, p. 1649-1658.
- Morey, G.B., and Boerboom, T.J., 1992, Rare earth element distribution patterns in Early Proterozoic iron-formations of the Penokean orogen, East-central Minnesota: *Institute on Lake Superior Geology*, 38th Annual, Hurley, Wisconsin, Proceedings, part 1, p. 68-69.
- Morey, G.B., and Morey, P.R., 1990, Major and minor element chemistry of the Biwabik Iron Formation and associated rocks, Minnesota, *in* AIME, Minnesota Section, 63rd Annual Meeting, and Mining Symposium, 51st, 1990, Minnesota, Proceedings: University of Minnesota, Duluth, Continuing Education and Extension, Center for Professional Development, p. 259-287.

- Perry, E.C., Jr., and Tan, F.C., 1973, Significance of carbon isotope variations in carbonates from the Biwabik Iron Formation, Minnesota, *in* Genesis of Precambrian iron and manganese deposits: Unesco Earth Science Series 9, p. 299-305.
- Perry, E.C., Jr., Tan, F.C., and Morey, G.B., 1973, Geology and stable isotope geochemistry of the Biwabik Iron Formation, northern Minnesota, *in* Precambrian iron-formations of the world: Economic Geology, v. 68, no. 7, p. 1110-1125.
- Pfleider, E.P., Morey, G.B., and Bleifuss, R.L., 1968, Mesabi deep drilling project: Progress report no. 1, *in* Mining Symposium, 29th Annual, and American Institute of Mining and Metallurgical Engineers, Minnesota Section, 41st Annual Meeting, Duluth, 1968 [Proceedings]: Minneapolis, University of Minnesota, p. 52-92.
- Robinson, D.J., 1984, Silicate facies iron-formation and stratabound alteration: Tuffaceous exhalites derived by mixing—Evidence from Mn garnet-stilpnomelane rocks at Redstone, Timmons, Ontario: Economic Geology, v. 53, p. 708-721.

Field Trip 2B

IGNEOUS STRATIGRAPHY OF THE PARTRIDGE RIVER AND SOUTH KAWISHIWI INTRUSIONS—DULUTH COMPLEX, MINNESOTA

Mark J. Severson
Natural Resources Research Institute, Duluth, MN

INTRODUCTION

The Duluth Complex (Fig. 1, inset map) is a composite series of shallow, east-dipping tholeiitic intrusions of Keweenaw age (1.1 b.y.) that formed with associated basaltic volcanism along a portion of the Midcontinent Rift System. Rocks that are footwall to the complex include the Lower Proterozoic Virginia Formation (argillite and graywacke) and Biwabik Iron Formation (BIF), and Archean granitic rocks of the Giants Range Batholith. Hanging wall rocks typically are basalts of the North Shore Volcanic Group (Middle Proterozoic-Keweenaw), but locally

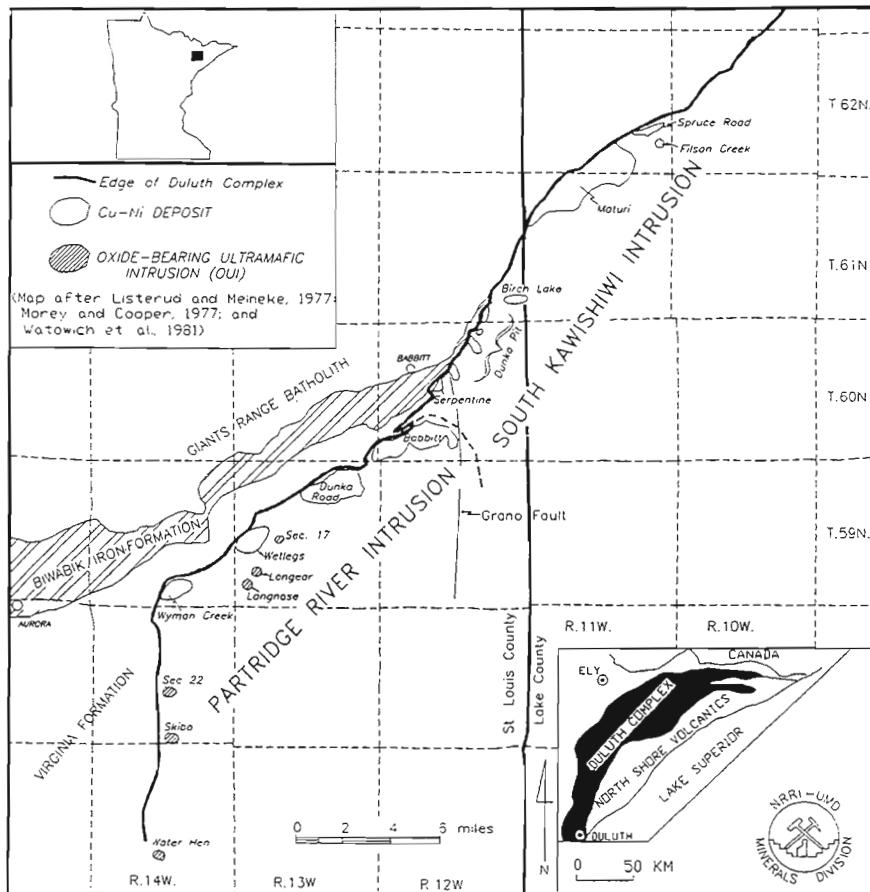


Figure 1. Location map of Cu-Ni and Fe-Ti deposits/prospects within the Partridge River and South Kawishiwi Intrusions of the Duluth Complex in northeastern Minnesota.

quartzite strata and inclusions (of Nopeming Formation?) are present. Emplacement of the complex occurred during an episode of extensional tectonism that produced the Midcontinent Rift System. Weiblen and Morey (1980) have presented a half-graben model for the overall emplacement style. They envision a step-and-riser configuration of the basal contact due to steep, southeast-dipping, northeast-trending normal faults. According to the model, magma was injected into faulted, fault-bounded voids formed during rifting to produce multiple smaller intrusions that collectively make up the complex. Two of these smaller intrusions have been extensively explored for Cu-Ni deposits; they are informally named the Partridge River (PRI) and South Kawishiwi (SKI) intrusions. During the last six years, 550 drill holes (634,000 ft of drill core) from within these two intrusions have been relogged and described by Geerts (1991), Hauck (in prep.), Severson and Hauck (1990), Severson (1991), Severson and Barnes (1991), Severson (in prep.), and Zanko and Severson (in prep.). The stratigraphy of the two intrusions and the potential Cu-Ni deposits they contain are summarized below and shown on Figure 1. Figure 2 is a schematic section showing the regional stratigraphy of the two intrusions relative to their country rocks.

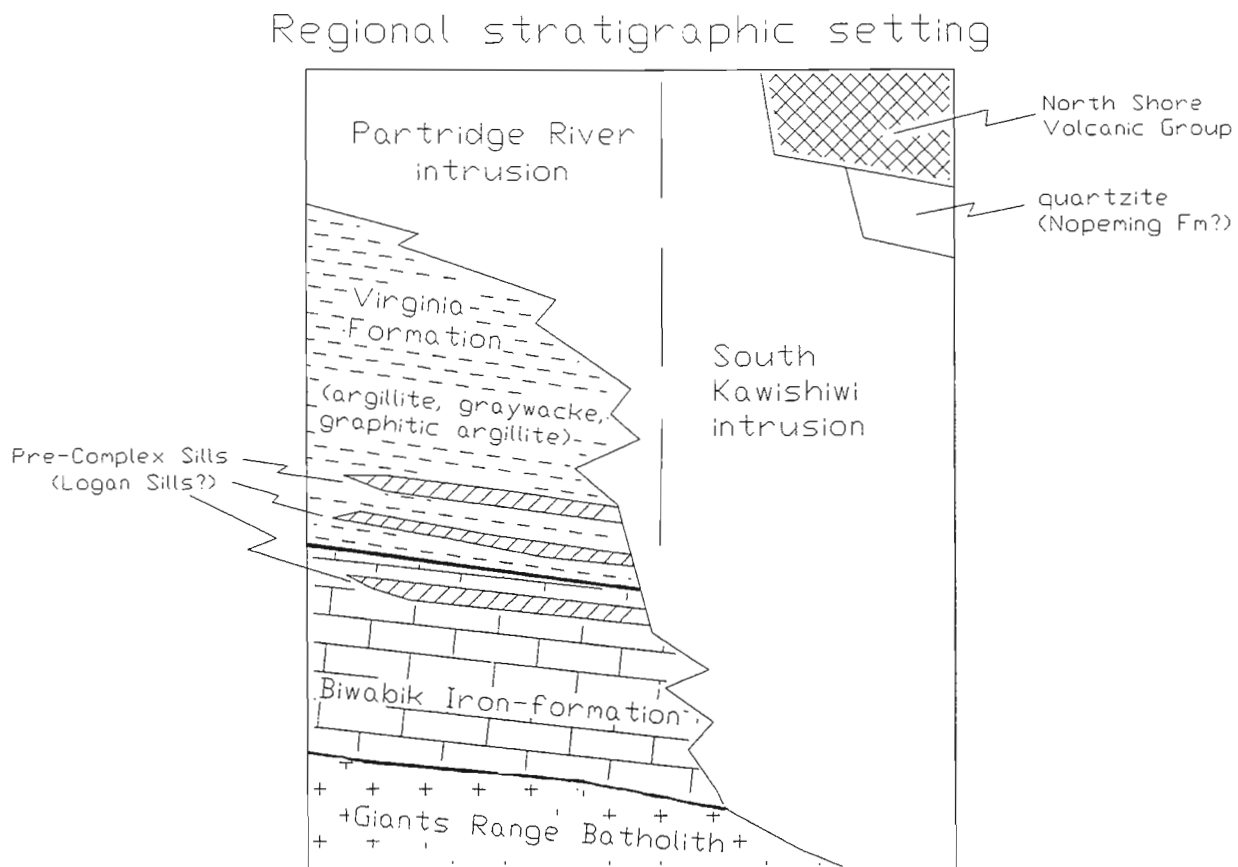


Figure 2. Regional stratigraphic setting of the Partridge River and South Kawishiwi Intrusions relative to the country rocks they intrude.

Partridge River Intrusion (PRI)

The PRI contains the following Cu-Ni prospects/deposits: Wyman Creek, Wetlegs, Dunka Road, and Babbitt/Minnamax (Fig. 1). Within these areas, rocks of the Partridge River Troctolite Series (PRTS) consist of at least seven major igneous units that can be correlated in drill holes along a 15-mile strike length shown schematically and described on Figure 3. These units are described below.

All units have shallow dips of 10-20° southeast toward the axis of the rift. Most of the upper units (III through VII) are floored by ultramafic horizons and may represent single cooling events. By contrast, Units I and II near the footwall are heterogeneous and contain abundant internal members and hornfelsed footwall inclusions. These characteristics indicate continuous magma replenishment and associated contamination from the footwall rocks. Though age relationships are uncertain, Unit I appears to have been intruded earliest along bedding planes of the Virginia Formation (as evidenced by abundant inclusions and heterogeneous nature), in contrast to the more homogeneous Units III through VII, which were emplaced into a progressively developed magma chamber. The laterally continuous ultramafic horizons of the upper units probably represent the inception of episodic magma injection that crystallized more primitive ultramafic layers before mixing with the resident magma.

The units are regularly stacked throughout most of the PRI, and only minor lateral and downdip changes occur; however, local stratigraphic and lithologic irregularities include 1) pinch-out and reappearance of specific marker units; 2) down-strike gradational changes of ultramafic horizons from peridotite to picrite to olivine-rich troctolite; 3) extremely limited areal extent of some ultramafic horizons, for example, the extensive repetition of ultramafic horizons within Unit II at Wetlegs, and the "Bathtub Layered Series" (Hauck, in prep.) at Babbitt; and 4) the gradational changes in troctolitic rocks that occur locally between any two drill holes. In some areas, particular marker horizons "disappear" laterally and are replaced by other marker horizons. Stratigraphic correlation within the PRI cannot be made solely by the use of any one specific marker bed, as it may not persist throughout the intrusion, and even if lost, the marker bed may "reappear" again at the same stratigraphic horizon elsewhere. In spite of these local difficulties, most of the PRTS units (I-VII) can be recognized at all Cu-Ni deposits within the PRI.

Several horizons containing Platinum Group Element (PGE) mineralization have been delineated within the PRTS at the Dunka Road deposit (Geerts, 1991). Three horizons are present within Unit I, and a fourth horizon is locally present in the top of Unit VI (Geerts, 1991). Of these four horizons, the most enriched one lies within the top 10-30 feet of Unit I, where an average of 1200 ppb Pd+Pt is present (Red zone of Geerts, 1991). Elsewhere within the PRTS, PGE values as large as 11 ppm Pd and 8 ppm Pt have been obtained from the massive sulfide ore (Local Boy zone) of the Babbitt deposit (Severson and Barnes, 1991). The majority of anomalous PGE values at Local Boy are spatially associated with an east-trending anticline in the footwall rocks.

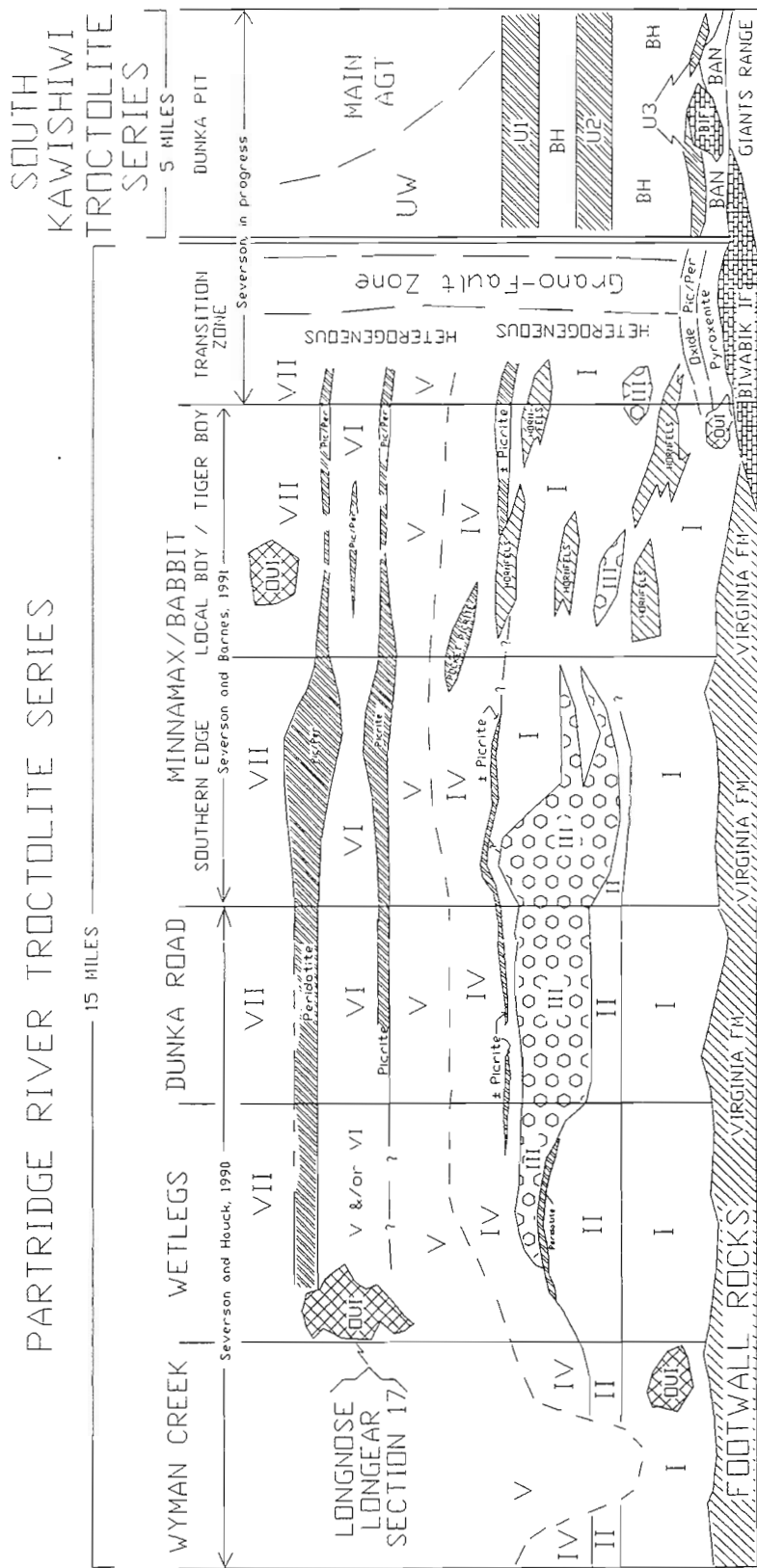


Figure 3. Generalized stratigraphic column of the Partridge River Intrusion and the southwestern end of the South Kawishiwi Intrusion (no scale is implied).

Base of PRI

- Unit I Sulfide-bearing heterogeneous mixture of augite troctolite and troctolite containing minor discontinuous ultramafic horizons. Unit I is the major sulfide-bearing horizon in all the Cu-Ni deposits.
- Unit II Homogeneous-textured troctolite and abundant ultramafic horizons in the Wetlegs area. Minor sulfide-bearing horizons are scattered throughout Unit II.
- Unit III Mottled-textured, fine grained, anorthositic troctolite exhibiting a very irregular distribution of olivine oikocrysts that are unique to this unit and make it a major "marker horizon."
- Unit IV Augite troctolite (homogeneous) with a moderately continuous basal ultramafic horizon that is termed "picrite" in the Babbitt area.
- Unit V Coarse grained, homogeneous anorthositic troctolite that grades downward into Unit IV (contact is shown on Fig. 3 by a dashed line).
- Units VI and VII Homogeneous troctolite to anorthositic troctolite. Each unit is marked by a continuous ultramafic base.

Top of PRI

Oxide-bearing Ultramafic Intrusions (OUI) Within the PRTS

The PRTS is cut by later plugs and vertical bodies of Oxide-bearing Ultramafic Intrusions (OUIs). The OUIs are characterized by coarse-grained to pegmatitic pyroxenite, peridotite, and dunite, most of which contain thick lenses of massive oxide. Some of the bodies exhibit a crude zonation consisting of an olivine-rich core and a pyroxenite rim (e.g., Longnose and Section 17 Fe-Ti deposits). Locally, pegmatitic hybrid hornblendite and granophyre also cuts the PRTS and is commonly associated with the OUI bodies (especially in the eastern Babbitt area). In almost all cases the OUIs occur along vertically dipping planar zones that correspond to known structural discontinuities at the basal contact of the complex, implying that faulting was important to OUI formation. In addition, some of the OUIs (Longnose, Longear, and Section 17 OUIs) are associated with localized areas where the Virginia Formation is absent from the basal contact and the Biwabik Iron Formation is in direct contact with the Duluth Complex. This implies a genetic link of OUI formation to areas of massive iron-formation assimilation by the complex.

In the deep holes of the eastern Babbitt area, iron-formation is again present at the basal contact. At this locality, the iron-formation grades upward into pyroxenite, which in turn grades upward into picrite-peridotite containing massive oxide zones. Both the "basal" peridotite and pyroxenite of eastern Babbitt (Fig. 3) are megascopically similar to the Longnose-Longear OUI bodies, supporting the genetic link between iron-formation assimilation and OUI formation.

Several near-vertical pyroxenite-hornblendite-granophyric veins intrude the troctolitic rocks of the PRI along the eastern margin of the Babbitt deposit. These late veins occur in drill holes that lie along a north-south boundary zone between the Partridge River and South Kawishiwi intrusions; however, the veins occur only in the PRI. This same zone corresponds to a major north-trending normal fault that is down-dropped on the east and is named the Grano-Fault (Fig. 1) for its association with granophyric veins.

South Kawishiwi Intrusion (SKI)—in progress

An entirely different igneous package is present within the South Kawishiwi Troctolite Series (SKTS). Specific layers of the SKTS can be correlated in drill cores from each of the Cu-Ni deposits (Serpentine, Dunka Pit, Birch Lake, Maturi, Spruce Road, and Filson Creek—Fig. 1); however, the correlative stratigraphic package differs at each deposit. Typically, only alternating portions of the entire stratigraphic package are present at any one locality. Additional complexities include gradational, lateral, and down-dip changes in rock type and thickness variations. A generalized section of correlative igneous units of the SKTS that occur along a 19-mile strike length is shown in Figure 4. Units of the SKTS are described below.

Base of SKTS

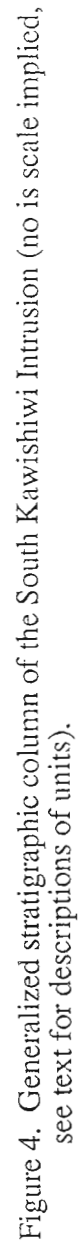
- BAN** Bottom Augite troctolite and Norite zone: Heterogeneous mixture of augite troctolite and norite (both are sulfide-bearing), containing local inclusions of BIF and Giants Range granite (GRAN). Norite is most common at the basal contact due to contamination of the magma from melting of the footwall rocks.
- BH** Basal Heterogeneous zone: Mixture of troctolite and anorthositic troctolite. The BH unit is the main sulfide-bearing ore zone in each of the Cu-Ni deposits. This unit shows extreme thickness changes (thins abruptly down-dip). It grades both upwards and laterally into the AT-T unit (homogeneous-textured sulfide-free troctolites). The term "Spruce Breccia" used by INCO geologists appears to be synonymous with extremely heterogeneous fine- to coarse-grained zones.
- U3** Ultramafic 3: A package of alternating layers of ultramafic and troctolitic rocks. U3 typically contains massive oxide horizons and/or BIF inclusions and is generally sulfide-bearing. It marks the top of the mineralized ore zones in the Birch Lake and Maturi deposits. Rust-

colored, liquid drops of iron chlorides (Cl drops) commonly coat drill core of the U3 unit and appear to have formed by deliquescence (hydration). Other iron, manganese, and magnesium chlorides locally coat drill core in zones that exhibit the Cl-drops.

- PEG Pegmatitic unit of Foose (1984): A poorly defined unit in which pegmatoids and gradational pegmatite zones are sporadically present. The PEG unit also commonly has local heterogeneous zones that contrast with the overlying thick sequences of homogeneous-textured rock. The PEG unit is not present in the Dunka Pit and Spruce- Road deposits.
- U2 Ultramafic 2: A package of alternating layers of ultramafic and troctolitic rocks; massive oxide layers are only rarely present and Cl-drop-coated core is common. U2 is absent at Maturi and only locally present at Birch Lake and Deep Maturi.
- AT-T Anorthositic Troctolite to Troctolite zone: Homogeneous package of both rock types that are gradational into each other. The AT-T unit is weakly mineralized (Cu-Ni) in the Dunka Pit area and grades into heterogeneous sulfide-bearing rocks of the BH unit. The BH and AT-T units may be synchronous; the main distinctions between the two are variations in homogeneity and sulfide content.
- U1 Ultramafic 1: Package of alternating layers of ultramafic and troctolitic rocks; Cl-drop coated core is common and massive oxides are totally lacking. The U1 unit is absent at Maturi and locally present at Birch Lake and Deep Maturi.
- UW Updip Wedge: Package of heterogeneous sulfide-bearing troctolite that occurs in the western portion of the Dunka Pit area and extends southwestward to the Serpentine deposit. The UW unit commonly contains xenoliths of the Virginia Formation and occurs only where the Virginia Formation is present at the basal contact (Fig. 4).
- MAIN AGT: Delineated by a zone where augite troctolite (AGT) is the dominant rock type. The Main AGT occurs as a thick package of homogeneous-textured augite-rich rocks that either thin or become augite-poor down-dip. The "contact" between the Main AGT and UW unit is nearly vertical in the Dunka Pit area. The LOW AGT is another zone where AGT is dominant.
- AT & T: Thick, monotonous zone of anorthositic troctolite and troctolite with minor augite troctolite and troctolitic anorthosite. Both sharp and gradational contacts between the rock types occur. Local thin anorthosite and gabbroic anorthosite beds are also present. The AT & T unit also contains two ultramafic horizons tentatively called the High Picrite #1 and #2.
- AT (T): Thick, monotonous zone of anorthositic troctolite to troctolitic anorthosite containing minor troctolite and rare augite troctolite zones.
- Highway One Corridor Rocks: A thick igneous stratigraphic sequence has been delineated in 5 deep drill holes (each 4000-5200 feet deep) in the "Highway One Corridor" area (Fig. 4). The most definitive rock types of the sequence are the AN-G GROUP (intermixed anorthositic and gabbroic rocks) and the "Incl" unit, which is a fine-grained, granular inclusion of what may be magnetite-rich basalt. The age relationship of this sequence of rocks to the rest of the SKI is unknown. It is impossible to determine if the AN-G GROUP rocks are correlative with the Anorthositic Series of the Duluth Complex.

Top of SKTS

19 MILES
(Severson, in progress)



Unlike units of the Partridge River intrusion, units of the South Kawishiwi intrusion do not represent individual "cooling events." Rather, the SKI units are zones in which one particular rock type or a package of rock types is predominant (e.g., augite troctolite is the dominant rock type in the MAIN AGT). Changes from one unit to another typically are gradational, and the thickness of individual units varies abruptly. Although these units are not single cooling events, they do indicate that changes occurred in the magma chamber which may reflect: 1) that crystallization occurred during periods of repeated magma injection to produce alternating ultramafic and troctolitic rocks (e.g., the U1, U2, and U3 units); 2) that the magma underwent a more complete crystallization history (e.g., the augite troctolite zones); or 3) that the magma was contaminated due to variable assimilation of the footwall rocks (e.g., BAN and U3 units).

Only a few of the units described above are present throughout *all* of the SKI (see Fig. 4). Because the specific units occur sporadically throughout the SKTS, determination of the age of one unit relative to another is severely hampered. This is also complicated by the overall stratigraphic pattern, which indicates that the SKI is not only "layered" vertically but is also "compartmentalized" horizontally along its strike length. In other words, the SKI is itself a multiple intrusion in which each of the individual units exhibits a finite spatial extent, and the units overlap each other in a myriad of patterns, producing the stratigraphic section shown in Figure 4.

PGE-enrichment is associated with the U3 unit in the Birch Lake area (e.g., drill hole Du-15). Drill core analysis by the Minnesota Department of Natural Resources and analysis of core drilled by E.K. Lehmann and Associates indicate that up to 4.6 ppm Pt, 5.4 ppm Pd, and 10% Cr₂O₃ are associated with some massive oxide horizons and with sulfide-bearing ultramafic and troctolitic rocks of unit U3.

DRILL CORE DISPLAY

Core segments representing an abbreviated version of igneous units in the Partridge River and South Kawishiwi intrusions have been set up in Building #3 of the Minnesota Department of Natural Resources, Hibbing, Minnesota. Several drill cores were selected from four Cu-Ni deposits to illustrate various "type sections" and types of mineralization. The arrangement of this core is shown in Figure 5. Additional posters and explanations are above the drill core display where pertinent.

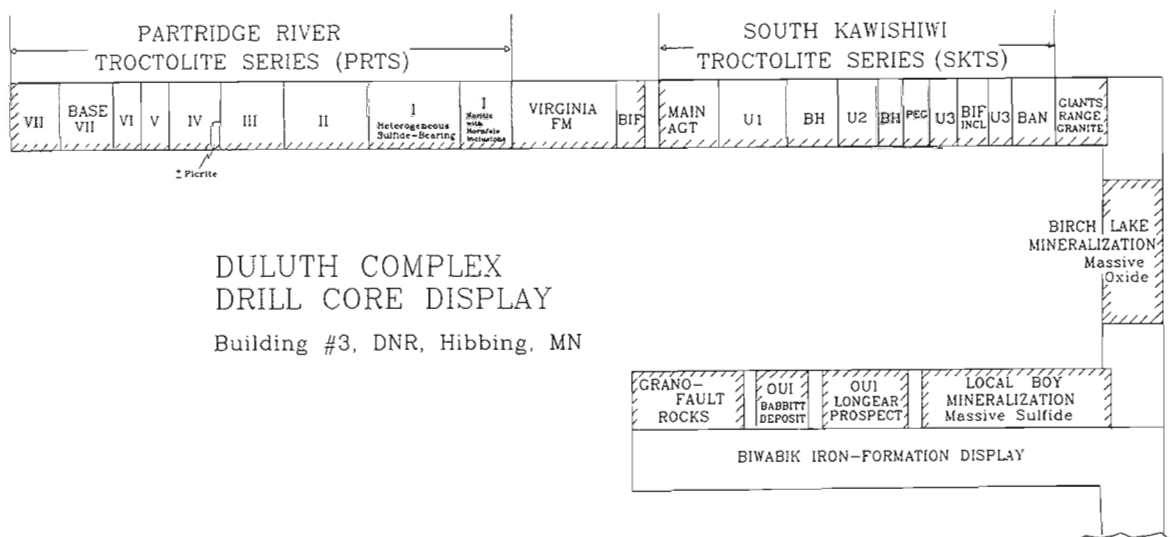


Figure 5. Arrangement of drill cores at the DNR Core Library display area.

ACKNOWLEDGMENTS

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REFERENCES

- Foose, M.P., 1984, Logs and correlation of drill holes within the South Kawishiwi intrusion, Duluth Complex, northeastern Minnesota: U.S. Geol. Survey, Open-file Rept. 84-14.
- Geerts, S.D., 1991, Geology, stratigraphy, and mineralization of the Dunka Road Cu-Ni prospect, northeastern Minnesota: Nat. Res. Research Inst., Univ. Minn., Duluth, Tech. Rept., NRRI/TR-91/14, 59 p.
- Hauck, S.A., in prep., Geology and mineralization of the Bathtub Cu-Ni area, Minnamax Cu-Ni deposit: Nat. Res. Research Inst., Univ. Minn., Duluth, Tech. Rept.
- Severson, M.J., and Hauck, S.A., 1990, Geology, geochemistry and stratigraphy of a portion of the Partridge River intrusion: Nat. Res. Research Inst., Univ. Minn., Duluth, Tech. Rept., NRRI/GMIN-TR-89-11, 235 p.
- Severson, M.J., 1991, Geology, mineralization, and geostatistics of the Minnamax/Babbitt Cu-Ni deposit (Local Boy area), Minnesota, Part I: Geology: Nat. Res. Research Inst., Univ. Minn., Duluth, Tech. Rept. NRRI/TR-91-13a, 96 p.
- Severson, M.J., and Barnes, R.J., 1991, Geology, mineralization, and geostatistics of the Minnamax/Babbitt Cu-Ni deposit (Local Boy area), Minnesota, Part II: Mineralization and geostatistics: Nat. Res. Research Inst., Univ. Minn., Duluth, Tech. Rept. NRRI/TR-91-13b, 221 p.
- Severson, M.J., in prep., Igneous stratigraphy of the South Kawishiwi intrusion, Duluth Complex, northeastern Minnesota: Nat. Res. Research Inst., Univ. Minn., Duluth, Tech. Rept.

Weiblen, P.W., and Morey, G.B., 1980, A summary of the stratigraphy, petrology and structure of the Duluth Complex: *Am. Jour. Sci.*, v. 280, p. 88-133.

Zanko, L.M., and Severson, M.J., in prep., Geology and mineralization of the Serpentine Cu-Ni area, Minnamax Cu-Ni deposit: Nat. Res. Research Inst., Univ. Minn., Duluth, Tech. Rept.

Field Trip 2C

STRATIGRAPHIC AND COMPOSITIONAL VARIATIONS IN REGOLITH DEDUCED FROM ROTASONIC CORES IN NORTHERN MINNESOTA

Leaders:

Dennis P. Martin, Minnesota Department of Natural Resources, Minerals Division,
Gary N. Meyer, Minnesota Geological Survey, and
Dale F. Cartwright, Minnesota Department of Natural Resources, Minerals Division

INTRODUCTION

The Archean greenstone belts in northern Minnesota have the potential for world-class gold and base-metal deposits, but thick regolith locally hinders development of cost-effective exploration programs. This drill core display presents an interpretation of the stratigraphy of regolith covering the Archean terrane in northern Minnesota, with emphasis on that in the Baudette Area. The term *regolith* is used here for all materials derived from the breakdown of bedrock, including in situ weathered rock (saprolite), and deposits of glacial till and outwash that overlie bedrock. This guide focuses on samples that define the stratigraphy and composition of regolith and the steps used to interpret these materials. A secondary focus is to demonstrate how quantitative methods have been applied to overburden drill core samples for the purposes of stratigraphic correlation and exploration. Because the core samples provide a more limited picture of the regolith than that derived from surficial exposures, the quantitative data are essential. On the last stop, we discuss the application of exploration geochemistry to subsurface regolith samples. Although significant progress has been made toward understanding the regolith stratigraphy and composition, that understanding is still incomplete.

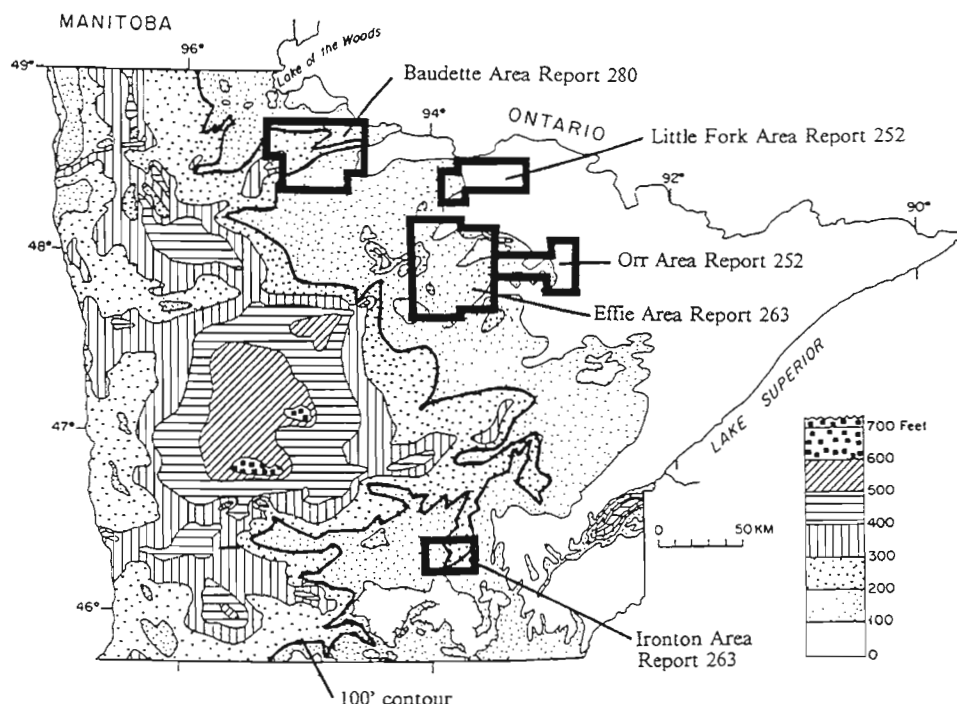


Figure 1. Overburden drilling project areas shown on map of regional glacial drift thickness that is modified from Southwick, 1989. See References for report numbers shown for each area.

The DNR conducted a series of regolith drilling programs from 1985 to 1989. The resulting glacial drift cores, which are displayed in part here, were macroscopically logged by Gary Meyer of the Minnesota Geological Survey. Funding was provided by the Legislative Commission on Minnesota Resources and the Minerals Diversification fund. The drilling took place in the area that extends from St. Louis County in northeastern Minnesota, westward to Lake of the Woods County in the north central part of the state (Fig. 1). Typically, more than 100 feet of regolith overlies bedrock in the five separate study areas shown on Figure 1, and the surficial drift covering the entire area is from the Koochiching lobe. Koochiching drift is not an effective medium for geochemical sampling for gold exploration; therefore, drilling is required to sample the buried tills that lie beneath it. One Rotasonic core (3.5 inch diameter) was collected from the accessible townships in the study areas, giving a total of 65 drill cores. Those cores define the regolith stratigraphy shown in Figure 2. The Rotasonic cores of buried tills and saprolite were analyzed for mineralogic and geochemical clues to mineralization on the scale of a mining camp. In the Baudette Area, Rotasonic drilling was combined with geophysical and geologic studies to better define the mineral potential for land management purposes and to encourage minerals exploration. The complete results of these studies are presented in three reports: Martin and others, 1988; Martin and others, 1989; and Martin and others, 1991. The cores are available for further study at the Department of Natural Resources Core Library in Hibbing, MN.

A.

LAKE OF THE WOODS AREA		AGE
West	East	
Post-glacial		HOLOCENE
bedded sediment		LATE WISCONSINAN
Koochiching lobe		
Koochiching lobe		
Koochiching lobe		
Rainy lobe		
Winnipeg lobe		PRE-LATE WISCONSINAN
Old Rainy lobe		
Winnipeg lobe		
Winnipeg lobe		
Old Rainy lobe		
Old Rainy lobe		

B.

Name	Continental Provenance
Koochiching lobe deposits	Keewatin
Rainy lobe deposits	Labradorean
Winnipeg lobe deposits	Keewatin
Old Rainy lobe deposits	Labradorean

Figure 2. Stratigraphic and compositional variation in glacial drift units of northern Minnesota: A) Time-distance diagram of relative timing and extent of glacial events in the Baudette area. B) Continental provenance of glacial units shown in A.

GLACIAL STRATIGRAPHY

Koochiching Lobe

The clasts and matrix of the Koochiching lobe deposits are rich in Paleozoic limestone, dolostone, chert, and Cretaceous Pierre Shale derived from southeastern Manitoba and northwestern North Dakota. The matrix becomes progressively more silty and clayey to the east, as the till overrode its own proglacial lake sediment. The Koochiching lobe deposits have a complex internal stratigraphy. All three phases of the lobe were fronted by a large glacial lake during both advance and retreat. Sediment deposited in the western part of the glacial lake is generally coarser than that to the east, where clay dominates the lacustrine sections. Likewise, subglacial Koochiching till, where composed largely of reworked lake sediment in the Lake of the Woods area, is rich in silt and fine sand, in contrast to the very clayey tills found to the east in Koochiching County. Incorporation of underlying till and lake sediment accounts for the large textural variation of the Koochiching tills, particularly till of the more deeply buried first phase, which incorporated both lake clay and sandy till of the Rainy lobe.

Rainy Lobe

Rainy lobe deposits are very different from those of the Koochiching lobe in terms of their distribution, flow path directions, physical character, variation in composition across the region, and bedded sediment features. The Rainy lobe drift contains abundant Precambrian rock clasts that were incorporated during the lobes' advance across the Canadian Shield. Variations in direction from almost due south to S 70° W may be due to local variations in the sub-ice topography, or may represent different phases of the ice advance. The variation in Rainy lobe till composition displays both regional and property-scale trends due to differences in the character of the underlying material as well as to variations in bedrock topography. The regional trend is best displayed by increased carbonate content in the western part, where the Rainy lobe advanced over Winnipeg lobe deposits.

Winnipeg Lobe

Winnipeg lobe deposits are similar to the Koochiching in terms of Keewatin (Precambrian) continental provenance, but are older. The high clay content of Winnipeg lobe till is thought to be the result of incorporation of Cretaceous marine and nonmarine sediment (reworked saprolite) as the ice moved across southeastern Manitoba. Winnipeg lobe till is typically gray to dark gray, in contrast to the greenish-gray color of Rainy lobe till, and contains abundant Paleozoic carbonate pebbles. The matrix has much more clay than the Rainy or Old Rainy, and has very high matrix solubility due to carbonate content. The weight of heavy minerals extracted from matrix is significantly less than that in the Rainy or Old Rainy lobe deposits. Limonite pisoliths are more common in the heavy mineral fraction of these tills. The matrix chemistry, such as the significantly greater median values for Hg, B, As, Ni, Zn, and Pb, and the large matrix solubility define a background composition for the Winnipeg till that is distinctive from tills of Labradorean provenance.

Old Rainy Lobe

The Old Rainy tills contain more saprolite than those of the Rainy lobe, an abundance of Precambrian rock clasts, and a variable Paleozoic carbonate content. Where the Old Rainy deposits are rich in carbonate, they can be distinguished from Winnipeg lobe till by a sandier texture, greenish color, and low clay mineral content. Where Rainy lobe till rests on Old Rainy till without an intervening oxidized zone, the contrast of greater compactness, slightly higher clay content, and higher matrix carbonate content distinguishes the older till. The content of Hg, K, Ti, and Na in the matrix and the matrix solubility define a well-constrained compositional field on X-Y graphs. The Old Rainy tills also contain more siderite in the matrix heavy mineral fraction than overlying tills. Based on gross composition, the provenance of the Old Rainy lobe is similar to that of the Rainy lobe. The main difference between the two is the larger matrix carbonate content in the Old Rainy deposits, which may be the result of incorporation of older Keewatin-source tills, or of incorporation of carbonate from the Hudson Bay lowland.

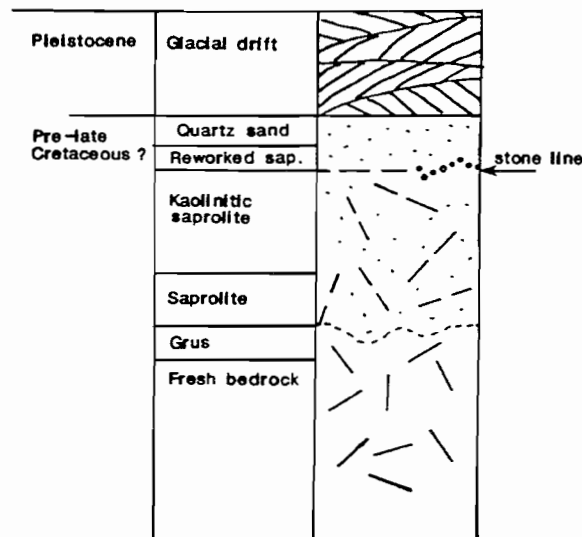
CORE DISPLAY

DISPLAY PANEL 1: TYPICAL CORE SAMPLES

Core samples and tabular compositional data illustrate the three steps used to interpret the glacial stratigraphy in these cores (Fig. 2): *descriptive logging*, *quantitative analysis*, and *final interpretation* using a model that assumes incorporation of underlying detritus by subsequent ice advances. Such a model has been the basis of till prospecting for decades, but we have applied it to buried tills on a regional scale through the use of quantitative data.

The first step was the descriptive logging and preliminary classification of till. Typical buried tills from different drift types are described below in Table 1 and shown at this display. Because the composition of any one drift type varies across the state, examples are given from each area. The samples are further described in the Appendix.

Figure 3. Generalized stratigraphy of saprolite in the Baudette area.



(modified from Smith, 1987)

The saprolite stratigraphy (Fig. 3) is important because its composition, particularly of trace elements, varies dramatically. Typical samples are displayed here and described in Table 2.

Table 1. Examples of typical till composition for each till type in each area. Samples are inferred to represent the average regional background composition. Each drift type varies from west to east across northern Minnesota. See also the detailed core descriptions in the Appendix.

Sample Type	Baudette Area - Western Portion	Baudette Area - Eastern Portion	Effie Area	Orr Area	Observed Variations Within One Drift Type, Between or Within Areas
Koochiching Till [1]	OB-520 11'-20'	OB-503 73'-80'	OB-318 23'-33'	OB-204 11'-25'	Matrix sand/silt/clay content varies significantly
Rainy Till	OB-521 74.5'-80' (sa.521-01)	OB-508 140'-150' (sa.508-02)	OB-315 130'-140'	OB-204 80'-90'	Matrix carbonate and saprolite content varies
Winnipeg Till [2]	OB-517 103'-121' (sa.517-08)	ABSENT	OB-306 84'-100'	ABSENT	Carbonate clasts & matrix carbonate content varies.
Old Rainy Till [3]	OB-520 112'-178' (sa.520-08)	OB-507 197'-204' (sa.520-08)	OB-327 154'-184'	ABSENT	Carbonate clasts & matrix carbonate content varies significantly. Matrix sand/silt/clay content varies.

- [1] The Koochiching lobe deposits have a complex internal stratigraphy. Evidence for three distinct phases of the Koochiching lobe are present across the northern portion of the Baudette Area.
- [2] Glacial sediment from three separate advances of the Winnipeg lobe are recognized in the Baudette Area. Correlation of those between drill holes is uncertain. Hence, in quantitative graphs all Winnipeg tills are lumped as one population.
- [3] Correlation of Old Rainy drift between drill holes is uncertain. Hence, in quantitative graphs all Old Rainy tills are lumped as one population.

Table 2. Examples of saprolite and fresh Archean bedrock. Saprolite can be subdivided into residual vs. reworked, and the residual further subdivided into kaolinitic, saprolite, or grus. Chloritic saprolite is commonly developed on greenstone (metavolcanic) rocks, whereas grus is confined to the coarse-grained granitoid lithologies.

Sample Type	Sample Location
Reworked Saprolite	OB-503 (174-211)
Kaolinitic Saprolite	OB-503 (211-226)
Chloritic Saprolite	OB-503 (226-234)
Weathered Rock	OB-503 (240-260)
Grus	OB-519 (165-185)
Bedrock - Mylonite	OB-503 (260-267)
Bedrock - Massive Sulfide	OB-513 (107-115)
Bedrock - Sericite Schist	OB-326 (251-275)
Bedrock - Altered Tonalite	OB-314 (109-115)

DISPLAY PANEL 2: ANALYSIS

The second step was the quantitative analyses of various size fractions of till samples (Fig. 4). X-Y plots of various components reveal population clusters for each stratigraphic designation; the best examples are presented in Figure 5. Such population clusters reinforced the drift type interpretations based on macroscopic characteristics (Step 1) for 91% of the samples analyzed in the Baudette area.

The quantitative analyses demonstrate a direct link between the incorporation of saprolite in till, and both the siderite content in the heavy mineral fraction of the till and composition of till matrix. This verifies the model that infers incorporation of underlying material into a till, and underscores the deviation in till composition from the norm. A good example is the lowermost till unit in OB-519, 139 to 152 feet, where the till has incorporated a high siderite content from the saprolite.

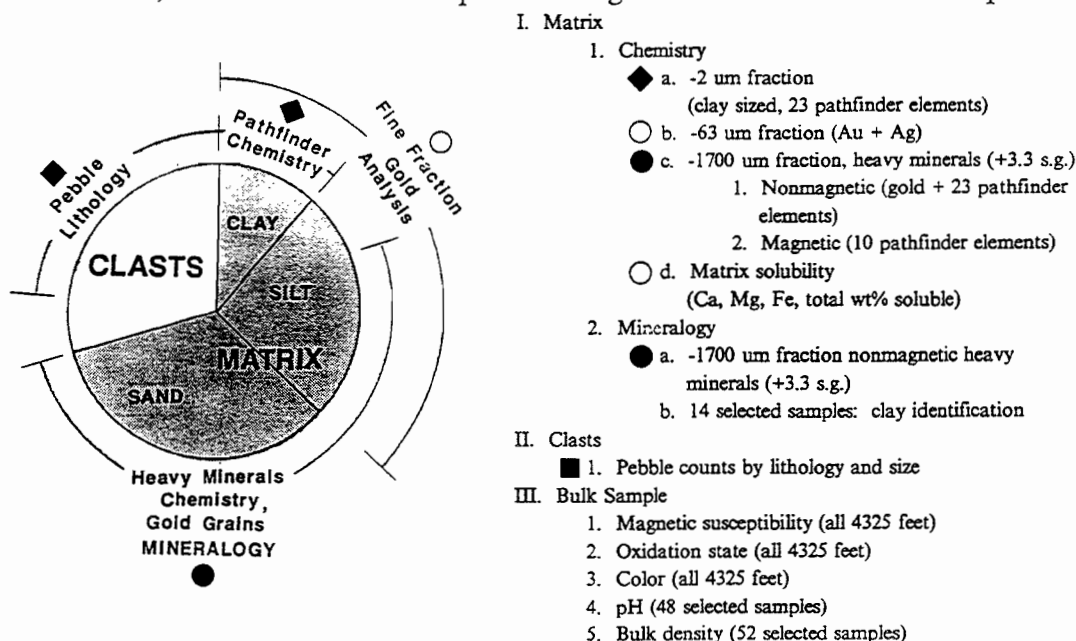


Figure 4. A) Pie diagram of the sample-size fractions analyzed. The total composition was subdivided into two major parts, matrix versus clasts, for quantitative analyses. B) Compositional attributes that were measured.

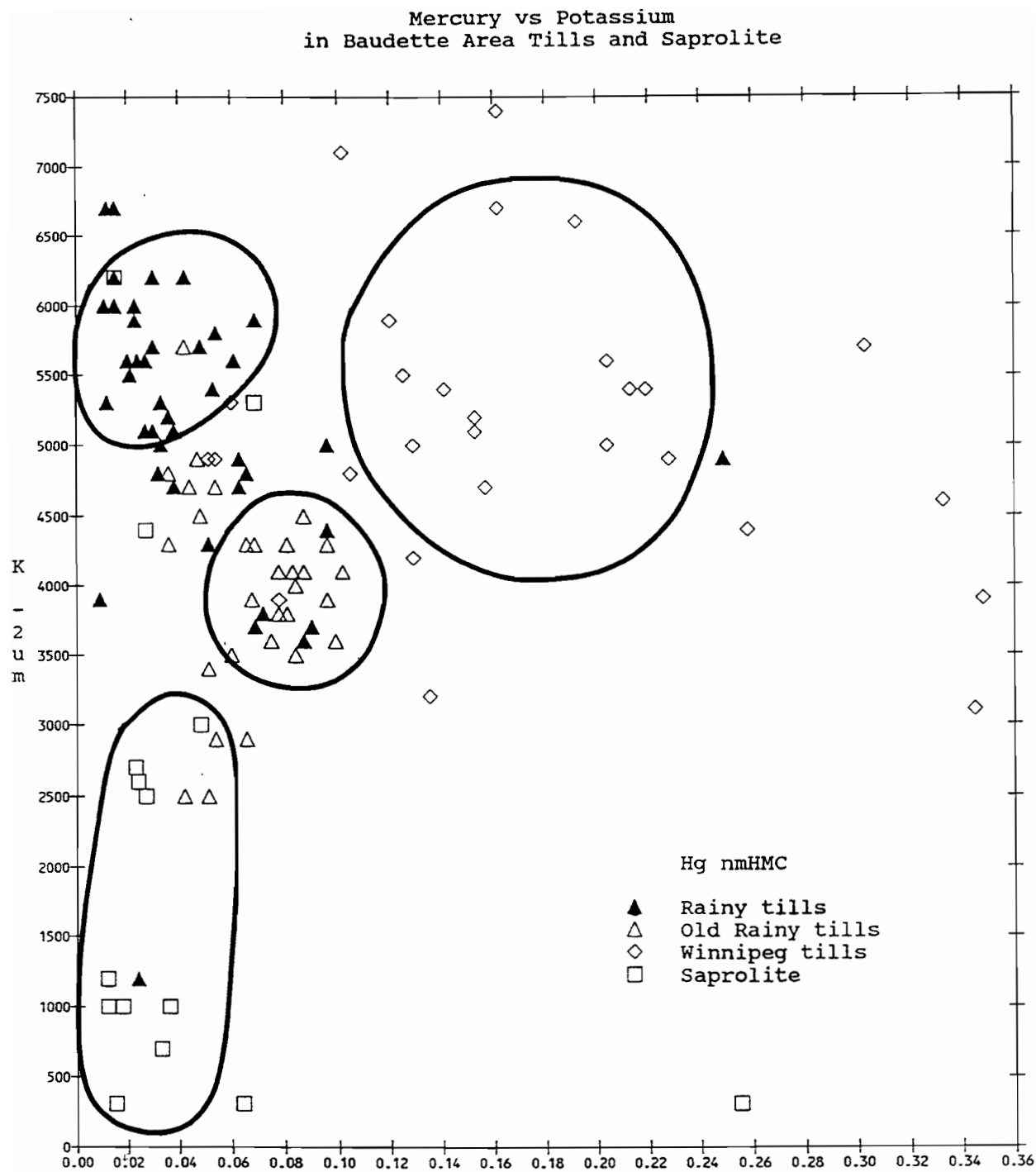


Figure 5. Plot of mercury in the nonmagnetic heavy mineral fraction versus potassium in the 2 micron fine fraction from samples of tills and saprolite in the Baudette area. Population clusters are circled.

DISPLAY PANEL 3: SYNTHESIS AND INTERPRETATION

For the third step, the final interpretation for each stratigraphic unit, the descriptive logs and composition were reviewed. The model of underlying material incorporation was applied to 15 specific cases shown on Table 3 on the basis of observed combinations of stratigraphic units. In about 10% of the till samples analyzed, there is so much incorporation of underlying material (older drift or saprolite) that the till composition is *significantly* different from the typical population cluster. Moreover, in many other till samples that have minor changes in composition, the model permits a quick interpretation of what components were incorporated. This set of case examples is especially useful to help interpret samples from localities where the underlying materials were completely removed by erosion.

Table 3. Fifteen general case examples of tills incorporating different underlying materials. KT = any one till of multiple advances of the Late-Wisconsinan Koochiching Lobe; RT = till from advance of the Late-Wisconsinan Rainy Lobe; WT = any one till of multiple advances of the pre-Late Wisconsinan Winnipeg Lobe (correlation in these older tills between drill holes is uncertain); OT = any one till from multiple advances of the pre-Late Wisconsinan Old Rainy Lobe. [PC = Archean Precambrian rocks; SAP = saprolite]

Case Example	Boreholes and Footage
Case 1: KT overrides RT → more PC in KT	517 (23-38')
Case 2: KT overrides WT → minor changes?	? 512 (63-84.5')
Case 3: KT overrides OT → more SAP and less carb. in KT	No observed example
Case 4: KT overrides SAP → more SAP in KT	No observed example
Case 5: KT overrides PC → more PC in KT	516 (37-47')
Case 6: RT overrides WT → more carb. in RT	517 (38-55')
Case 7: RT overrides OT → intermed. SAP + carb. in RT	507 (148-164')
Case 8: RT overrides SAP → more SAP in RT	501 (131.5-135')
Case 9: RT overrides PC → more PC in RT	509 (83-92')
Case 10: WT overrides SAP → more SAP in WT	511 (133.5-143')
Case 11: WT overrides OT → less carb in WT	517 (55-129')
Case 12: WT overrides PC → more PC in WT	513 (75-93')
Case 13: OT overrides WT → more carb. in OT	No observed example
Case 14: OT overrides PC → more PC in OT	515 (176-212.5')
Case 15: OT overrides SAP → more SAP in OT	505 (224.5-234')

DISPLAY PANEL 4

Several aspects of the data collected in the Baudette Area can be applied to exploration. The bottom line in prospecting is the ability to find a buried geochemical anomaly and trace it to a bedrock source. This can be done, even in this complex landscape, and we present in this display and in Martin and others (1991) the "tools" and methods by which drill samples of buried tills can be used to accomplish that goal. Examples of distinctive tracers that could lead to specific sources in the bedrock are presented in Table 4. Difficulties in interpreting the drift type and the continental transport direction (provenance) are not as important to explorationists as the ability to identify tracers and backtrack them to their specific sources.

The presence of multiple tills that have different transport directions can be useful in two ways: 1) multiple tills may disperse tracers over a larger area, and 2) the backtrack path may be narrowed where the tracers occur in some tills, but not others.

Table 4. Compositional attributes that may be used locally as distinctive tracers to specific bedrock sources in the Baudette area (i.e., those components that contrast with relatively small background values)

A. Matrix		B. Clasts	C. Whole Core
Mineralogy	Chemistry		
1. scheelite 2. gahnite 3. corundum 4. limonite pisolith 5. native copper 6. galena 7. native gold 8. molybdenite 9. kyanite 10. Ag & Pb bearing magnetite 11. siderite	1. Au 2. Hg 3. Ba 4. Zn 5. Pb 6. Ni 7. W	1. tourmalinites 2. magnetic tonalites 3. magnetic coarse grained mafic intrusives 4. komatiites (?)	1. high magnetic susceptibility of till unit

REFERENCES CITED

- Martin, D.P., Dahl, D.A., Cartwright, D.F., Meyer, G.N., 1991, Regional survey of buried glacial drift, saprolite and Precambrian bedrock in Lake of the Woods County, Minnesota: Report 280, 202 pages, 2 plates.
- Martin, D.P., Meyer, G., Cartwright D.F., Lawler, T.L., Pastika, T., Jirsa, M.A., Boerboom, T.J., and Streitz, A.R., 1989, Regional geochemical survey of glacial drift drill samples over Archean granite-greenstone terrane in the Effie area, northern Minnesota: Report 263, Minnesota Department of Natural Resources, Division of Minerals.
- Martin, D.P., Meyer, G., Lawler, T.L., Chandler, V.W., and Malmquist, K.L., 1988, Regional survey of buried glacial drift geochemistry over Archean terrane in northern Minnesota: Legislative Commission on Minnesota Resources Project, Report 252, Minnesota Department of Natural Resources, Division of Minerals.
- Smith, R.E., 1987, Some conceptual models for geochemistry in areas of preglacial deep weathering: *Geochemical Exploration*, p. 337-352.
- Southwick, D.L., 1989, An introduction to Minnesota's geologic framework and its implications for mineral exploration, *in* Morey, G.B., ed., Workshop on the applicability of gold and platinum-group-element models in Minnesota: Saint Paul, University of Minnesota, Minnesota Geological Survey, Information Circular 30, p. 5, figure 2.

APPENDIX

Descriptions of samples listed in Tables 1, 2, and 3.

Part 1. From Table 1

Sample Location	Description
OB-520 (3 1/2-20') (112-178')	LOAM TILL; OXIDIZED; unox below 11 ft; firm; calc; abundant carb, fairly common sh; 6-6 1/2 ft silt; lens of sandy till at 19 1/2 ft. SANDY LOAM TILL; UNOXIDIZED; greenish gray; compact; calc; carb fairly common; fairly pebbly but not many large pebs; large cob near top; 113-114 1/2 ft silty cgr sand w/till ball at 114 ft; coarse loamy texture 126-133 ft, another zone below 145 ft; texture is variable, ranging to sandy clay loam in lower part; v compact below 130 ft; cob at 128 1/2, 130 1/2, 137, 139, 144, 159 1/2, 165 1/2 & 169 ft; boulder 164-165 ft.
OB-503 (73-76 1/2') (76 1/2 -80')	SILTY CLAY LOAM TILL; UNOXIDIZED; grades to silt w/thin clay loam till lam 75-76 1/2 ft; abrupt lower contact. CLAY LOAM TILL; UNOXIDIZED; compact; silt bed at 77 1/2 ft, silt lam below 87 1/2 ft, gradational lower contact.
OB-318 (7 1/2-33')	CLAY LOAM - LOAM TILL; UNOXIDIZED; calc; not many large pebs; 19-20 ft clay loam till w/clay & silt beds; 20-20 1/2 silty, pebbly sand w/till lenses (could be sluff); carb & sh pebs; large cobs at 27 1/2, 18 1/2, 32 1/2.
OB-204 (11-27 1/2') (80-95')	CLAYEY TILL, sand and a few small pebbles also present, dolomite, jointed, pebble content increases below 25'. SANDY LOAM TILL to coarse cobbly loamy sand till, pebbles include: dark ig.(?) gneissic, dark schist, phyllitic, sulfides.
OB-521 (74 1/2-80 1/2')	SANDY LOAM TILL; UNOXIDIZED; greenish gray; firm; calc; fairly common carb; sand bed at 76 ft, v sandy till below w/sand beds; cob at 76 1/2 & 79 ft; bed or inclusion of loam till at 79 1/2 ft; loam till w/carb pebs in last 1/2 ft.
OB-508 (140-153')	SANDY LOAM TILL; UNOXIDIZED; greenish gray; firm, compact below 143 ft; mod calc; cob near top but not real rocky; more large pebs 146-150 ft; rare carb, common dark Precambrian pebs; some evidence of mixing w/saprolite below 150 ft; 152-153 ft reworked saprolite w/large peb at base.
OB-315 (133 1/2-152 1/2')	SANDY LOAM TILL; UNOXIDIZED; loamy sand till in upper two ft; sl calc; occ cobs; harder and grner w/depth; darker, clayey calc till lam at 141 (older till); mod calc by 141; more silty w/depth; sm carb cob at 146 1/2, interbedded sand and sandy till to 148; little carb but mostly Precambrian; loam till by 150; 151-152 1/2 mgr sand, silty w/sand pebbles in lower part.
OB-517 (103-121')	LOAM TILL; UNOXIDIZED; olive gray; firm; v calc; common carb; coarse side of loam texture, less so & compact below 107 ft; couple sm cobs at 116 1/2 ft; v compact below 115 ft; clay loam till, dark gray, & less compact below 117 ft; large carb peb at base, fairly abrupt contact.
OB-306 (84-100 1/2')	CLAY TILL; UNOXIDIZED; highly calc; ox spot at 92 ft; harder w/depth; apar more clasts from 93; clay loam till by 96; sandy gvl lenses at 96, 96 1/2.
OB-507 (197-204') (204-207')	LOAMY SAND TILL; UNOXIDIZED; sl calc; mostly pebbly sand in upper foot; 200-201 ft silty pebbly cgr sand, mod sorted, could be sluff; 202-203 ft compact, sl calc-calc silt to v silty till w/sm carb pebs; 203-204 ft boulder. GRAVELLY SAND; silty, cobbly, cgr; mod-poorly sorted; rare carb; grades to till below.
OB-327 (153 1/2-178 1/2')	LOAM TILL, UNOXIDIZED; calc; compact; pebbly cgr sand lens at 159 ft; mod calc by 160; fairly cobbly to 168, calc & less rocky below; cob & large pebs at base.

Part 2. From Table 2

Sample Location	Description
OB-503 (174-211')	SAPROLITE; REWORKED; very light gray fine to very fine-grained sand. Grains angular to subrounded and coated with clay minerals. Siderite nodules change to a reddish brown color. Similar to 158-164 ft. except much finer-grained. Small flakes of mica. Sandy, clayey silt from 193-194 ft. Boulder at 185 ft. Slightly calcareous to noncalcareous.
OB-503 (211-226')	SAPROLITE; KAOLINITIC; light greenish gray. Powdery, soft and massive. Oxidation occurs around some of the nodules. Abundant 0.1 mm - 3 cm siderite nodules. Line of 4 cm subrounded quartz pebbles 6 inches from contact with reworked saprolite. Noncalcareous.

OB-503 (226-234')	SAPROLITE; CHLORITIC; greenish gray. Preserved mylonitic texture less weathered and harder than above. Relict veining and sparse hairline oxidized quartz veins from 230-234 ft. Siderite nodules are fewer and smaller. More chlorite-rich than above. Noncalcareous.
OB-503 (240-260')	WEATHERED BEDROCK; mylonite.
OB-519 (165-185')	GRUS; light olive-gray. Resembles sand when crushed. Majority of minerals are recognizable; quartz, feldspar, biotite. Feldspars are altered. Boulder at 185 ft. Calcareous.
OB-503 (260-267')	BEDROCK; light yellow-tan, fine-grained rock with very fine-grained biotite-rich augen 1 x 5 mm comprise 5 to 10% of the rock. Augen are not folded but some are rounded. Light green, altered plagioclase(?) clasts (3 mm) show rotation of up to 30°. Two foliations are present with a strongly developed S ₁ parallel to CA and weak S ₂ at 30° to CA. A composite, 0.5-2 cm thick quartz vein composed of light gray translucent quartz with numerous chloritic wall rock inclusions is nearly continuous over the length of the core. White quartz with a well developed fibrous texture is found along the boundaries of the gray, crack-seal quartz veins. Fibers are oriented perpendicular to the vein walls. Iron oxide pseudomorphs after pyrite are present in trace amounts within the veins. Calcite replacement of the wallrock is apparent in the deepest core samples where it has not been removed by weathering. Thin section description available: samples at 250 and 256 feet. Lithology: mylonite (protolith may have been a quartz-bearing plutonic rock). [Description by Terry Klein, USGS]
OB-513 (107-115')	BEDROCK; pyrrhotitic massive sulfide with minor amounts of pyrite. Intercepts of swirling, highly-deformed, banding alternate with intervals of wispy banding. A one foot interval (at 111) feet of a deformed pyrrhotite-cemented breccia with some light gray, chlorite-rich, fragments showing a seriate texture which developed before sulfide replacement of the groundmass. Subhedral to euhedral pyrite crystals are present in aggregates ranging from 0.3 to 1 cm in diameter. Pyrrhotite sometimes fills fractures in crosscutting, highly silicified, medium gray quartz-feldspar porphyry dikes. Blue, waxy, quartz? veins and patches may be related to the silicification of the porphyry dikes. All lithologies show a moderate to strongly developed S ₁ to 10° to CA. [Description by Terry Klein, USGS]
OB-326 (251-275')	White to very light greenish and brownish gray, aphanitic schist. Strongly cleaved at about 75° (S ₁). A second cleavage crenulates S ₁ and dips about 50°. The acute angle between S ₁ and S ₂ is about 55°. This likely is a weathered "fault rock." Protholith may have been argillite or tuff; however, the extent of deformation precludes positive interpretation. Thin section Description: OB-326, 254 ft. Strongly foliated, crenulated quartz-sericite-chlorite schist. Estimated mode (volume %): Quartz 49%; Chlorite (Mg) 39%; Sericite 10%; Rutile 1-2; Apatite Tr. Crenulation cleavage (S ₂), at 40° to foliation (S ₁), is defined by bending of S ₁ - parallel sericite and chlorite, and neocrystallization of muscovite parallel to S ₂ crenulation. Abundant fine-grained subhedral, equant to slightly prismatic crystals of rutile follow the S ₁ fabric; also clusters of anhedral broken apatite are common, and tend to be strung out along the S ₁ foliation direction. The protolith of this rock is probably a highly sheared and/or hydrothermally altered volcanic. X-ray diffraction indicated that chlorite is a magnesium variety, and that sericite and rutile are present. [Description by T.J. Boerboom and M. Jirsa, MGS]
OB-314 (109-115')	Altered tonalite. Rock is equigranular and coarse grained (2-3mm). Color varies from white in freshest parts to red in oxidized zones adjacent to ubiquitous veins. No obvious modal banding, except at 109-11' where a pegmatoid zone occurs. This zone contains 2.0 cm salmon-colored feldspar and minor interstitial quartz and aegirine. Pegmatoid zone has irregular borders that dip about 55°. Veining is complex and pervasive: two vein systems exist, described in relative order from earliest to latest below: 1) Vertical, closely spaced veins are main feature of the rock. They are 1.0 mm to 2.0 cm wide and consist of aegirine (based on thin sections) and calcite with minor quartz and pyrite. Host rock is altered in 0.5 - 1.0 cm wide bands adjacent to veins. This alteration is manifested in red color; petrography indicates color due to oxidized adularia in alteration zones along with calcite, apatite and aegirine. Thin section is from this alteration zone. 2) Two very thin veins of green mineral (aegirine?) dip about 30°. No obvious adjacent wall-rock alteration exists. Magnetic Susc. 0.01 - 0.03 x 10 ⁻³ CGS. [Description by T.J. Boerboom and M. Jirsa, MGS]

Part 3. From Table 3.

Sample Location	Description
517 (23-38')	CLAY-CLAY LOAM TILL; UNOXIDIZED; firm compact; calc; fairly common carb; apar has partings, could be flow till; softer & lighter gray below 28 ft, loam till below 29 ft; sandy till zones below 32 ft; thin fgr sand bed at 37 1/2 ft.

7512 (63-84.5')	SANDY LOAM TILL; UNOXIDIZED; compact, mod calc-calc; dark pebs out number carb; sand lam 64-65 ft; calc below 65 ft; more clayey 65-66 ft; fair amount of large pebs; texture ranges to sandy clay loam; probably mixed w/Rainy lobe till; no sh noted; boulder 76 1/2-77 1/2 ft; wood chip at 83 ft, more clayey, little more carb below.
No Observed Sample	N/A
No Observed Sample	N/A
516 (37-47')	SANDY LOAM TILL; UNOXIDIZED; compact; calc, common carb; no sh noted; occ large pebs; sm cob at 42 ft.
517 (38-55')	SANDY LOAM TILL; UNOXIDIZED; loose-firm; calc; fairly common carb, but Precambrian pebs dominant; loamy sand texture above 42 ft; cobs at 41, 51, 54 ft; fairly abrupt lower contact.
507 (148-155')	SANDY LOAM TILL; UNOXIDIZED; firm to loose; sl-mod calc; rare carb; cob & large peb at top, cob at 152 1/2 ft. (155'-164') CLAY LOAM TILL; UNOXIDIZED; firm; calc; uncommon carb; not many pebs; crudely stratified in places w/silt; only mod calc, more sandy in places; greenish gray below 156 ft; much interbedded silt below 162 ft; believe till mixed w/saprolite and/or lake sed.
501 (131 1/2-135')	LOAM TILL; UNOXIDIZED; light greenish gray; compact; sl calc-noncalc; only rare, mostly sm pebs; much incorporated saprolite; sandy zone at 134 ft, cob & large peb at 134 1/2 ft; abrupt basal contact.
509 (83-82')	SANDY LOAM TILL; UNOXIDIZED; greenish gray; firm; sl calc; large pebs fairly common; uncommon carb.
511 (133 1/2-138)	LOAM TILL; UNOXIDIZED; compact; calc; abundant carb; almost all pebs sm; gradational lower contact.
(138 1/2-143)	SANDY LOAM TILL; UNOXIDIZED; firm to compact; varies from mod calc to calc; most clasts derived from underlying sandy saprolite; some carb pebs; intact chunks of punky rock saprolite towards base.
517 (55-74 1/2')	CLAY LOAM TILL; UNOXIDIZED; compact; calc; common-abundant carb; loam texture above 59 ft, v compact below 59 ft; somewhat less compact below 73 ft; sm cob at base.
(74 1/2'-98')	CLAY LOAM TILL; OXIDIZED; dark grayish brown; compact; v calc; carb common but not dominant; greenish gray color to 79 ft; silt 80-81 ft; 87-88 ft pebbly, loamy texture w/sand inclusions; short gradational zone at base.
(98-103')	CLAYEY SILT; OXIDIZED; grayish brown, laminated w/dark gray clay below 99 ft; v fgr sandy silt in lower foot or so.
(103-121')	LOAM TILL; UNOXIDIZED; olive gray; firm; v calc; common carb; coarse side of loam texture, less so & compact below 107 ft; couple sm cobs at 116 1/2 ft; v compact below 115 ft; clay loam till, dark gray, & less compact below 117 ft; large carb peb at base, fairly abrupt contact.
(121-129')	CLAY LOAM TILL; UNOXIDIZED; soft; calc; common carb; v compact below 125 ft, & dark gray; silt inclusion at 126 ft; silt lam towards base, grades to lake sed in last few inches.
513 (75-79 1/2')	CLAY LOAM TILL; OXIDIZED; grayish brown; v compact; v calc, abundant carb; unox, less compact below 76 ft; mostly sm pebs; grayish brown inclusion at 77 1/2 ft; clay bed at 79 ft; gradational lower contact.
(79 1/2-93')	CLAY LOAM TILL; OXIDIZED; grayish brown; v calc but less carb than above, more greenish pebs, probably contains fair amount of local rock & saprolite; cob at 92 ft.
515 (176-191')	SANDY LOAM TILL; UNOXIDIZED; firm-compact; calc; fairly common carb; iron stains below 181 ft; more compact w/depth; large pebs fairly common.
(191-212 1/2')	SANDY LOAM TILL; UNOXIDIZED; greenish gray; compact; calc, fairly common carb; somewhat gradational upper contact; sand content of matrix varies somewhat w/depth; fgr sand lam at 197, 197 1/2, 200 1/2 ft; cob at 205 1/2 ft; sand inclusion at 206 ft; loamy bed near base.
505 (224 1/2-234')	LOAM TILL; UNOXIDIZED; greenish gray; loose; sl calc; 225-228 ft many rounded to subangular cobs & large pebs, v large cob at base; no pebs or cobs 228-232 ft, more a v poorly sorted sandy silt; 232-234 ft v poorly sorted sandy clay w/few pebs incl 2 large pebs at top, also large saprolite inclusion different from saprolite below; peb lines at base in reworked saprolite.



GEOLOGY OF ARCHEAN GREENSTONE-GRANITE TERRANE IN THE COOK TO SIDE LAKE AREA

Leaders:

Mark Jirsa, Terry Boerboom and Peter McSwiggen
Minnesota Geological Survey

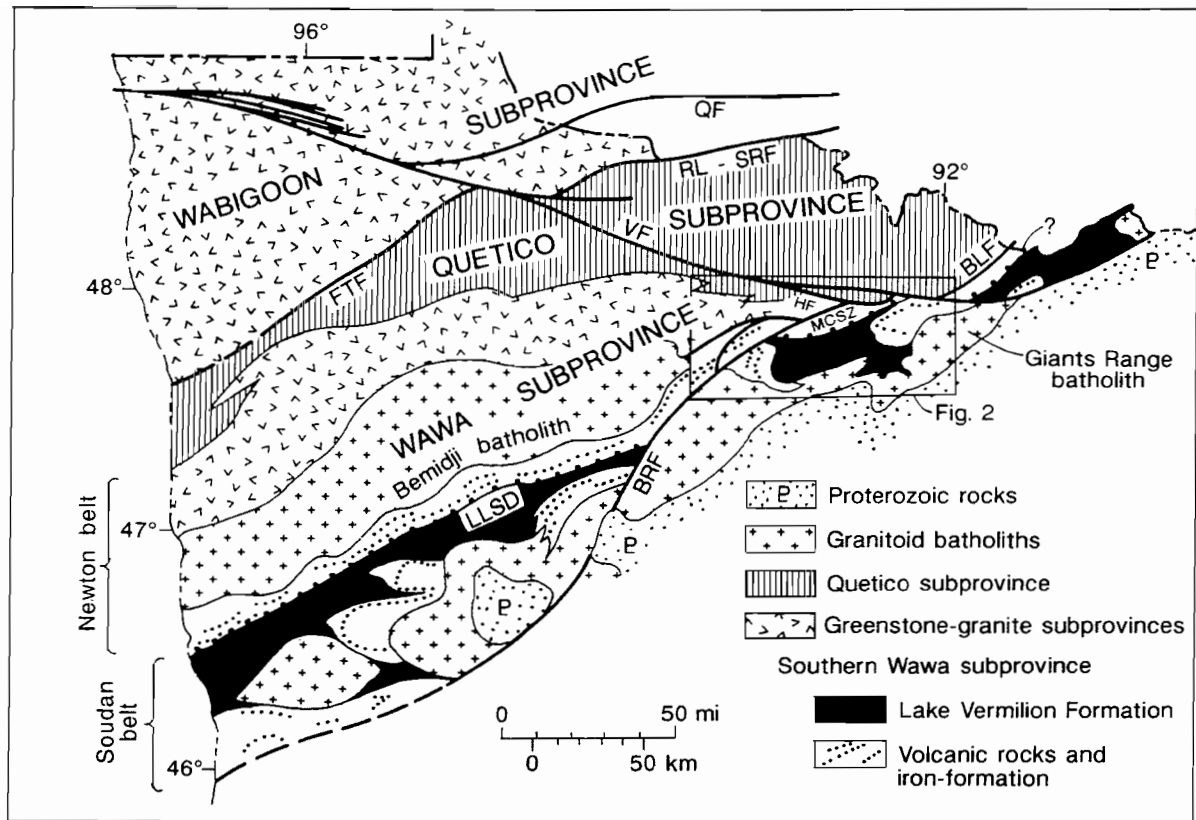


Figure 1. Generalized geologic map of northern Minnesota showing key structural and lithologic elements of the western Wawa subprovince. Labeled faults within the location box for figure 2 are named on that figure. Other regional faults are the Fourtown (FTF), Quetico (QF), and Rainy Lake-Seine River (RL-SRF). Proterozoic dikes are omitted.

Field Trip 3

GEOLOGY OF ARCHEAN GREENSTONE-GRANITE TERRANE IN THE COOK TO SIDE LAKE AREA

Mark Jirsa, Terry Boerboom, and Peter McSwiggen
Minnesota Geological Survey

INTRODUCTION

The Cook to Side Lake area lies within the westernmost exposed portion of the Archean Wawa subprovince and includes a small part of the adjacent Quetico subprovince (Fig. 1 on title page). The Wawa belt in Minnesota includes the classic and relatively well-exposed rocks of the Vermilion mining district (east of longitude $92^{\circ} 30'$). West of the Cook area the bedrock is obscured by glacial cover; it can be mapped solely on the basis of geophysical data and scattered drill holes. The geologic map of the Cook to Side Lake area, shown on Figure 2, is based on outcrop observations (Jirsa, 1988; Jirsa, 1990; Jirsa and Boerboom, 1990; Jirsa and others, 1991; and Southwick, in press), test drilling (Boerboom and others, 1989; Meints and others, 1993), and stratigraphic and structural correlations with the adjacent Vermilion district (for example, Sims and Southwick, 1985) and with the unexposed western extension of the subprovince. The supracrustal successions in the Vermilion district are narrowly confined between migmatite of the Vermilion Granitic Complex (Quetico subprovince) on the north and the Giants Range batholith on the south. The belt widens to the west, and in the Cook to Side Lake area is divisible into two distinct structural panels. These panels differ markedly in structural style, and are separated by the Mud Creek shear zone (MCSZ) and the Bear River fault (BRF). The southern panel, referred to as the *Soudan Belt*, is characterized by arcuate folds and curvilinear structural trends. The northern panel (north of the MCSZ), known as the *Newton belt*, contains the Joy Lake syncline, which separates north-younging strata to the south from south-younging rocks to the north. Its axis is nearly vertical, trends parallel to map units, and is obliquely dissected by the Bear River fault.

This field trip focuses on the stratigraphy, polyphase deformation, and pluton emplacement in the Soudan belt and adjacent terranes in light of recent geochronologic study that provides a regional, temporal framework for the western Wawa subprovince.

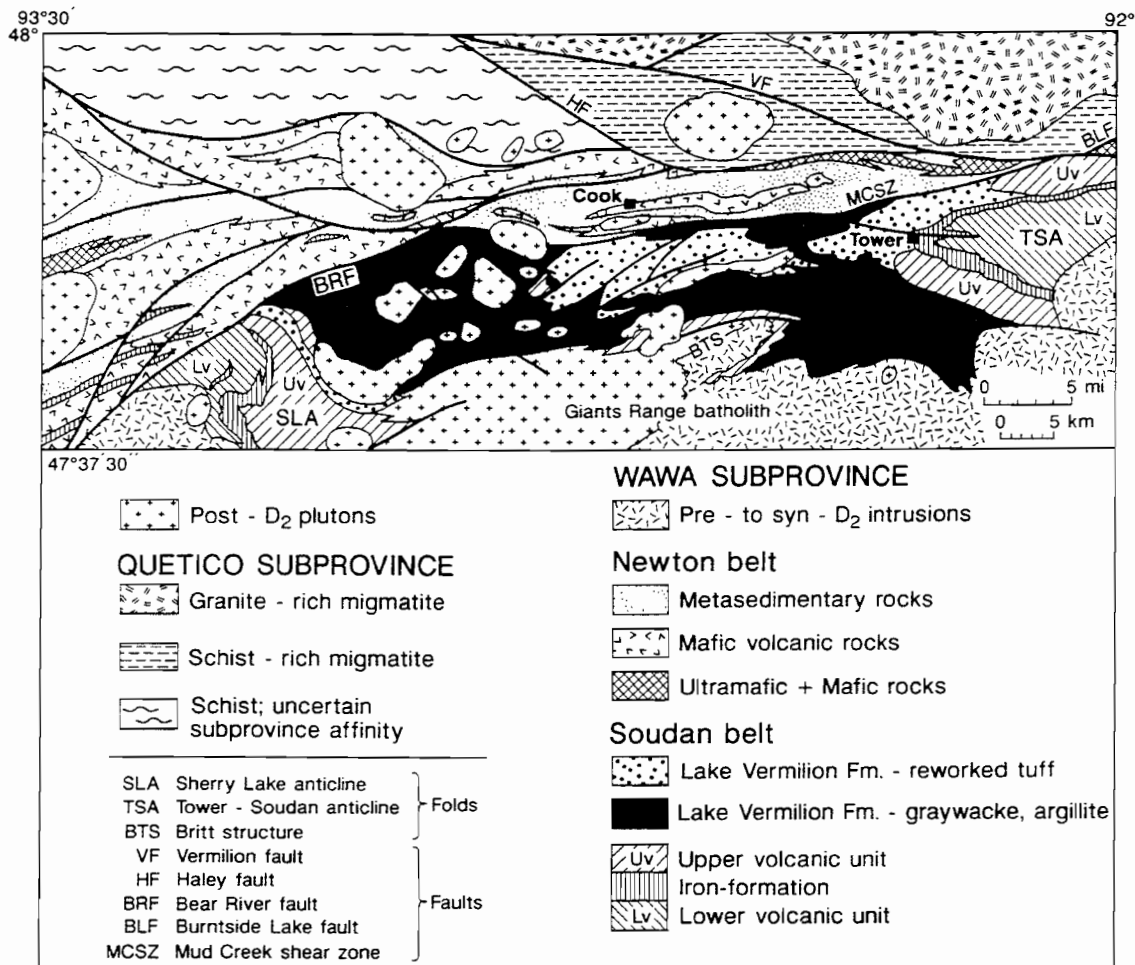


Figure 2 Generalized geologic map of Archean rocks in the Cook to Side Lake area.

STRATIGRAPHY

Soudan Belt

The Soudan belt is characterized by large, west-trending folds which lie along its southern edge adjacent to the Giants Range batholith. The folds are best delineated by antiformal cores composed of mafic volcanic rocks and iron-formation. The recognition that similar lithostratigraphic units are involved in two of the large folds, the Sherry Lake Anticline (SLA) and the Tower Soudan Anticline (TSA), has been a key to deciphering the tectonic history of the belt. The stratigraphic sequence in each major fold is typified by a lower volcanic unit (Lv) of tholeiitic to calc-alkaline composition that is overlain conformably by basaltic to dacitic fragmental rocks containing interbedded thin lenses of cherty magnetite-hematite iron-formation. These units are unconformably overlain by a monotonously uniform tholeiitic volcanic sequence (Uv) containing features indicating deposition in relatively deep water ("Sherry Lake basalts" of the SLA). These strata are overlain by the Lake Vermilion Formation, which contains thick sequences of dacitic volcanoclastic rocks, graywacke, and rare, thin basaltic flows. The Lake Vermilion Formation can be crudely subdivided into two facies (Fig. 3): a lower one composed of reworked dacitic tuff, dacitic graywacke, and schist of pelitic protolith; and an upper graywacke-rich facies containing clasts derived from a diverse source region that included basaltic flows. The transitional boundary zone between the facies assemblages is sporadically marked by the appearance of conglomerate and thin, discontinuous tholeiitic flows. The distribution of these strata outlines a major syncline that is inferred to be a component of an F₁ nappe.

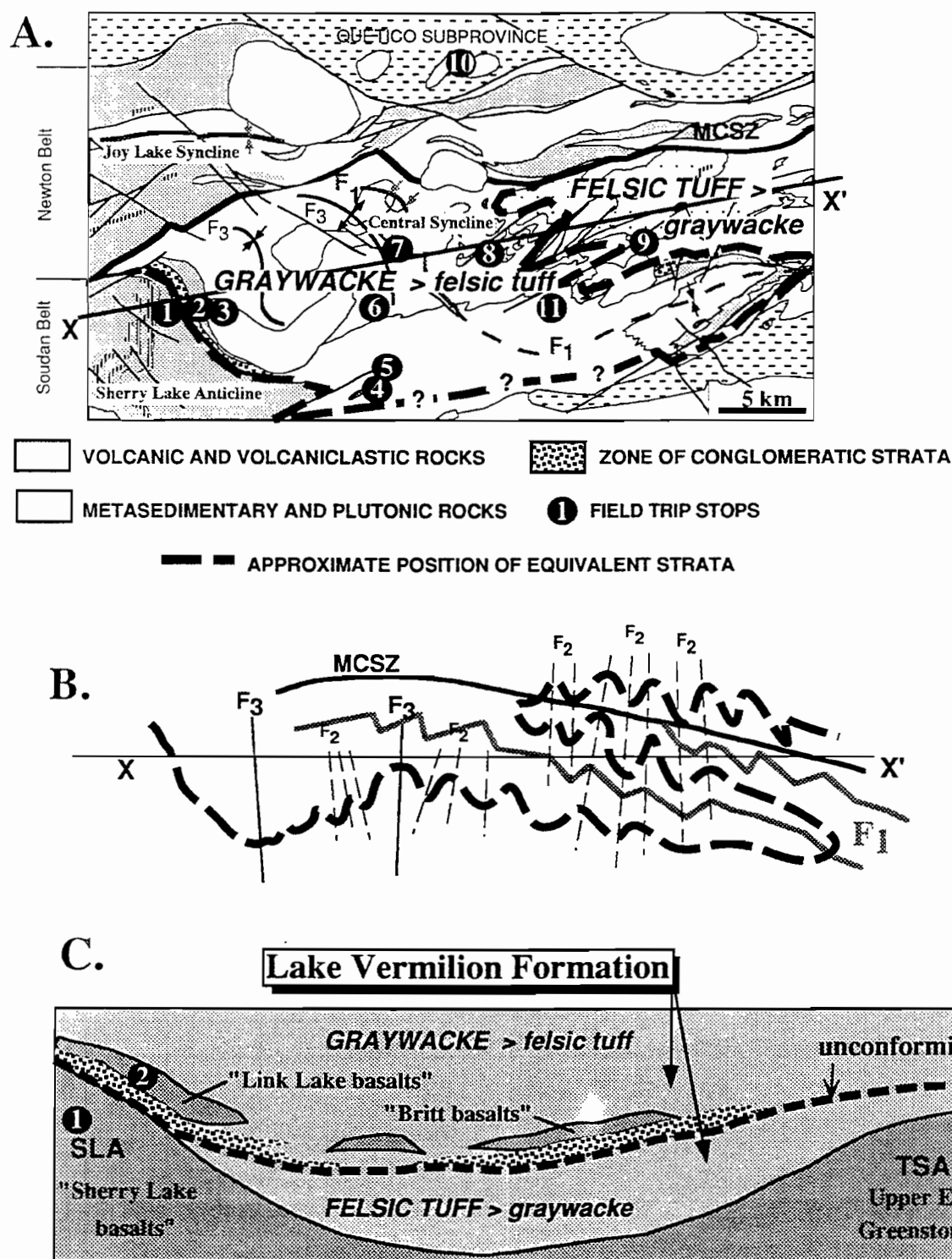


Figure 3 Internal correlation of stratigraphic units of the Lake Vermilion Formation: A) simplified map of the Cook to Side Lake area showing lithologic subdivision of the Lake Vermilion Formation (MCSZ=Mud Creek shear zone, B) model of large F₁ nappe folds, refolded by D₂ and D₃ deformation, and C) schematic palinspastic reconstruction.

Newton Belt

The eastern part of the Newton belt exposed in the Vermilion district contains north-younging volcanic rocks and thick ultramafic sills of the Newton Lake Formation. This sequence can be broadly correlated to the west (Fig. 2) across several complex fault structures, with komatiitic and tholeiitic volcanic rocks intruded by pyroxenite, peridotite, and gabbro of the Deer Lake Complex (Ripley and others, 1982). Field and chemical evidence indicate that sills of both sequences are largely the hypabyssal equivalents of the intercalated volcanic rocks. These volcanic and intrusive rocks are conformably (as best we can determine) overlain by a sequence of latite, dacite, graywacke, and argillite similar to the Lake Vermilion Formation. The Joy Lake syncline is inferred to be an early structure whose axis lies within those sedimentary rocks.

Western Extension of Belts

Although relatively little is known in detail about the stratigraphy associated with fold structures in central and western Minnesota that are covered by glacial drift, the same tripartite subdivision of strata appears to be present. Geophysical and drill-hole data from the covered westward extension of the Soudan belt indicate that the large folds contain volcanic rocks and iron-formation in their interiors and various kinds of clastic rocks in their outer parts (Fig. 1). By analogy with major folds in the Cook to Side Lake area, the folds are inferred to be anticlines that close to the west. Companion synclines are not prominent geophysically and presumably occur within thick sedimentary sections that lack geophysical definition, similar to the large syncline in the central part of the Cook to Side Lake area. Geophysical data show that mafic metavolcanic rocks continuous with the Newton belt occur north of the Leech Lake structural discontinuity (LLSD, Fig. 1). The LLSD is a major structural break inferred to be an early, south-verging thrust fault and is the westward continuation of the MCSZ (Jirsa and others, 1992).

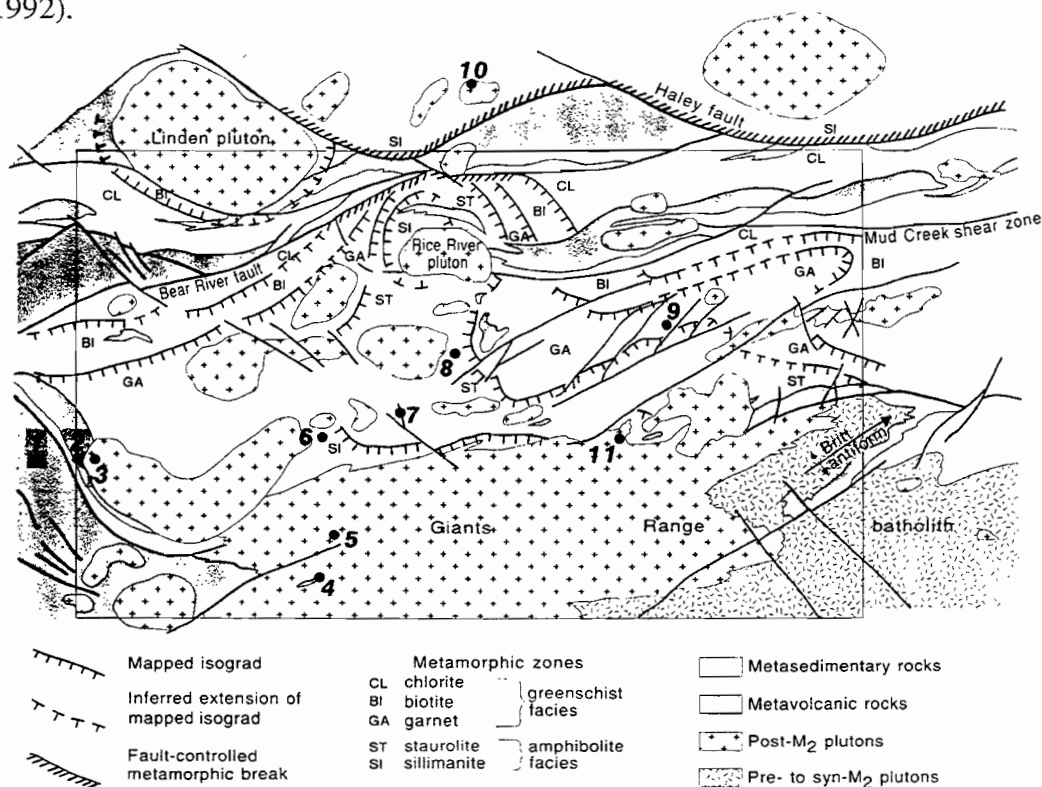


Figure 4 Simplified geologic map of the Cook to Side Lake area showing metamorphic zones. Locations of field trip stops 1-11 are also shown.

METAMORPHISM

The metamorphic grade of rocks in the Cook to Side Lake area ranges from greenschist to amphibolite facies. Metamorphic zones shown in Figure 4 are delineated on the basis of the first appearance of biotite, garnet, staurolite, and sillimanite in the pelitic protoliths. In addition to the mapping of the first appearance of indicator minerals, metamorphic temperatures and pressures were calculated using the garnet-biotite geothermometer (calibrated by Hodges and Spear, 1982), the garnet-plagioclase-biotite-muscovite geobarometer (calibrated by Hodges and Crowley, 1985), and the computer software of Spear and Peacock (1990). These geothermobarometry calculations suggest that this area underwent a moderate pressure (4-6 kbars) Barrovian-type metamorphism. Also, the calculations show a strong correlation between the metamorphic temperatures and pressures (Fig. 5), suggesting that this was largely a regional metamorphic event and not just a thermal event related to the emplacement of plutonic rocks to the south. Such a contact-related thermal event would have produced metamorphic temperatures largely independent of the depth of burial and therefore pressure. If the observed linear relationship between the temperatures and pressures shown in Figure 5 represents the Archean geothermal gradient of the area, it would correspond to a gradient of 20-25° C/km depth.

The main metamorphism, M₂, is so designated because metamorphic minerals define the prominent S₂ cleavage that is axial planar to D₂ folds. Although narrow metamorphic aureoles locally enclose post-metamorphic plutons, most metamorphic effects are the result of regional prograde metamorphism, and thus most structural and plutonic elements in the region can be described and classified on the basis of their apparent relationship to M₂. The metamorphic zones define the three main geologic subdivisions of the area: rocks of the Quetico subprovince lie within the sillimanite zone; the Newton belt is metamorphosed to the chlorite and biotite grades of greenschist facies; and the Soudan belt contains metamorphic zones ranging from chlorite grade in the north, to sillimanite grade in the south. Field evidence indicates that bounding faults between these contrasting belts are complex structures that have experienced repeated movements at different times. Significant post-metamorphic displacements on the boundary structures include uplift of this part of the Quetico relative to the Wawa subprovince. Both the mapped isograds and the geothermobarometry indicate that the metamorphic grade of rocks in the Soudan belt increases southwards. The calculated pressures demonstrate that the supracrustal rocks that are closest to the Giants Range were metamorphosed at pressures of 5-6 kbars in the sillimanite zone, whereas 3 km to the north the pressures are as low as 4 kbars in rocks metamorphosed to the garnet zone. This decrease in pressure is equivalent to at least a 3 km decrease in depth during metamorphism over a horizontal distance of only 3 km. Such an abrupt change in depth may indicate that a major structural break exists between the two metamorphic zones. An alternative explanation is that the Soudan belt was tilted (down to the north); however, post M₂ tilting should produce a fanning of S₂ dips that is not observed. The Soudan belt also contains an enigmatic, north-trending area of high metamorphic grade. Although this high occurs in a zone of multiple plutons, the plutons postdate metamorphism, and geobarometry indicates that schist in the zone was metamorphosed under moderately high pressures. The zone is therefore inferred to be a post-metamorphic dome.

Cook Geothermobarometry

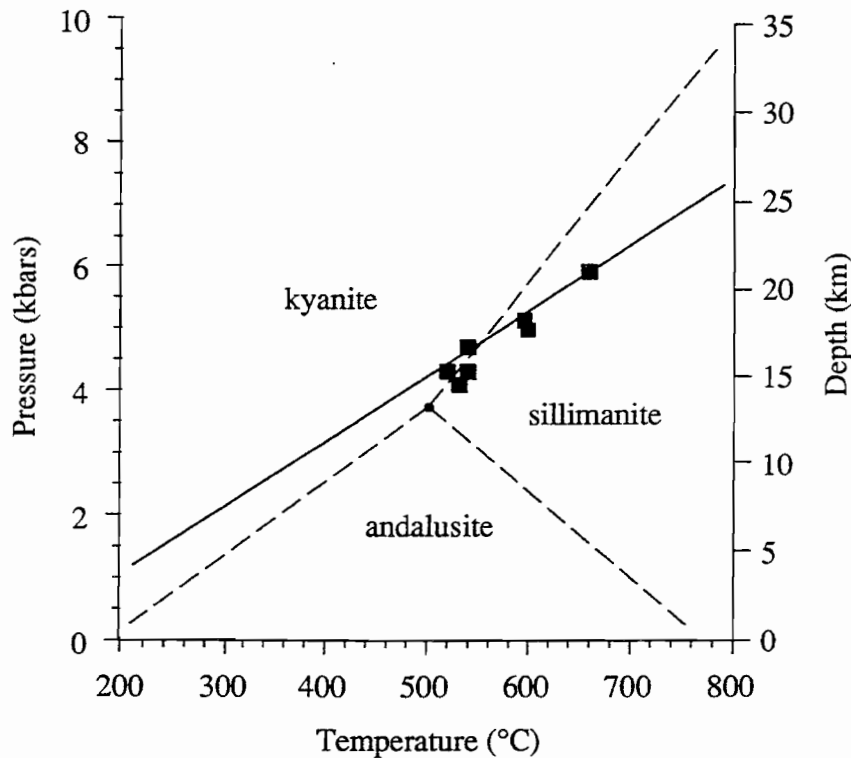


Figure 5 Calculated metamorphic temperatures and pressures from samples within the Soudan belt of the Cook-Side Lake area. Also shown is the Al_2SiO_5 phase diagram of Holdaway (1971) and an estimated Archean geothermal gradient for the area based on the metamorphic pressure and temperature conditions.

STRUCTURE

The three main phases of deformation recognized in the Cook to Side Lake area, designated D₁, D₂, and D₃, are schematically depicted in Figures 3 and 6. The most prominent *outcrop-scale* structures, which include folds, and metamorphic foliation and lineation, are the result of regional north-south-directed transpression assigned to D₂. Folds of this generation are upright and marked by an axial planar cleavage that trends east-northeast. Significant structural contrasts exist between the Newton and Soudan belts. The Newton belt contains steeply dipping strata and steep D₂ lineations. The Soudan belt is structurally diverse and characterized by fold axes, mineral, clast, and cleavage-bedding intersection lineations that plunge shallowly eastward in most of the Lake Vermilion Formation, and more steeply near volcanic rocks. Structural contrasts between the belts are inferred to be the result of differences in the gross orientation of rock units before regional F₂ folding and fabric development. These pre-F₂ orientations were established early in the area's tectonic evolution, probably during D₁ thrust- and nappe-style folding.

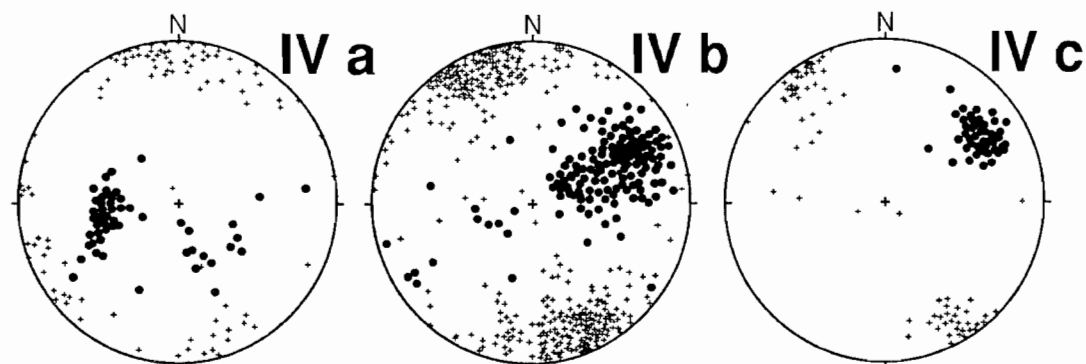
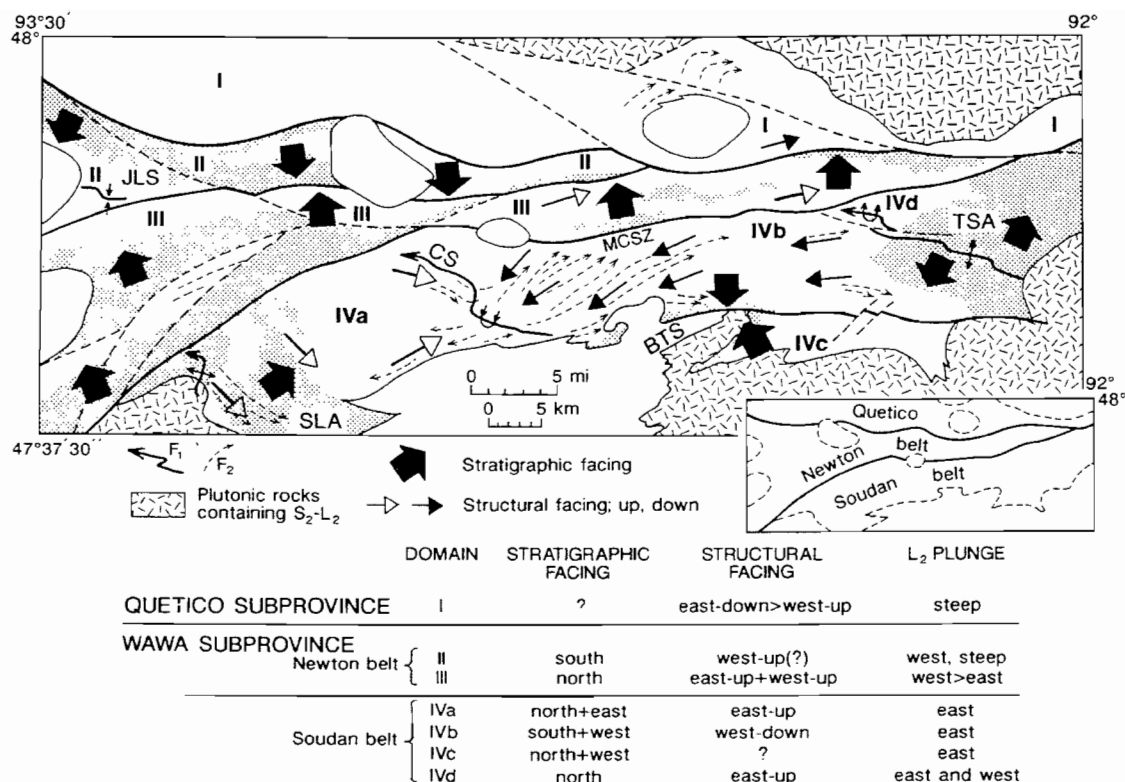


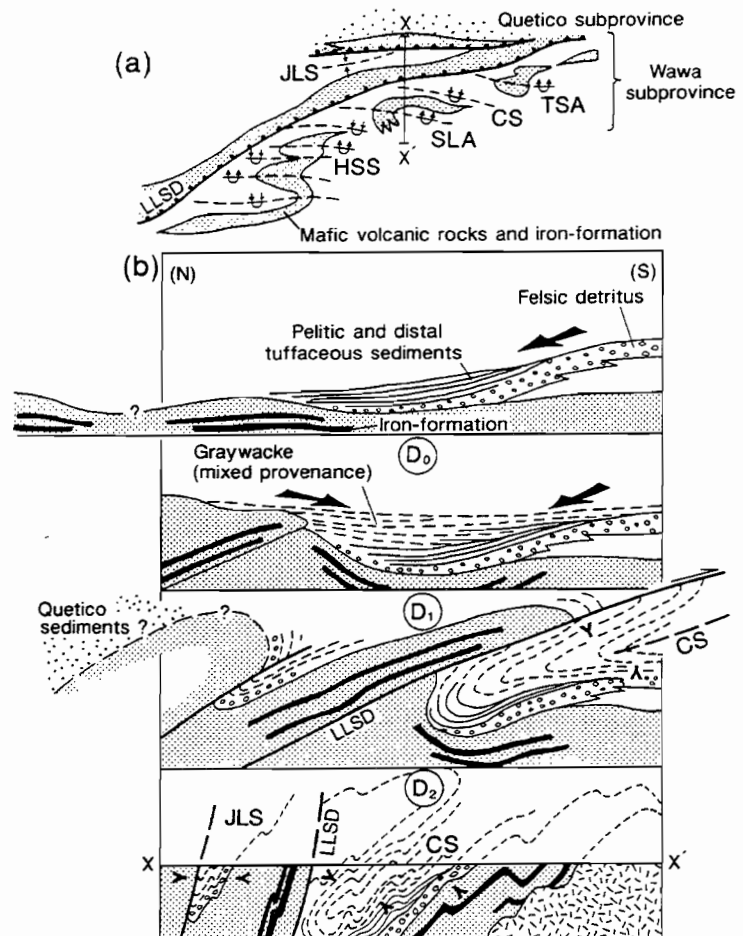
Figure 6 Map of structural and stratigraphic facing directions in the Cook to Side Lake area.

The character of D₁ folds and faults is obscured by D₂ structures and by a lack of S₁ cleavage. The F₁ folds can be inferred from the map distribution of major rock units (such as the TSA, SLA, and other folds inferred from drilling and geophysical data to the west), from rare interference folds, and from structural facing directions taken from the hinge zones of F₂ folds (Fig. 6). The structural facing in the Lake Vermilion Formation between the TSA and the SLA is predominantly downward and westward, implying large-scale inversion of the stratigraphic sequence prior to development of F₂ folds. This in turn implies that the F₁ folding event produced regional-scale recumbent folds whose overturned limbs are preserved at the present level of exposure. Our studies and those farther east (Hooper and Ojakangas, 1971; Hudleston, 1976; Hudleston and others, 1988; and Lundy, 1985) indicate that D₁ folds lack an associated cleavage and are locally disharmonic and sheathlike. This fold style, and the conclusion of Hudleston (1976) that nearly all observable strain can be attributed to D₂, strongly suggest that D₁ deformation was initiated prior to the complete lithification of the sedimentary rocks. From the morphology of the major F₁ folds (JLS, TSA, CS, SLA) and

from the distribution of structural facing, an early thrust-and-nappe sequence such as that shown in Figure 7 can be drawn. Palinspastic reconstruction was required for this figure to restore map units to their inferred positions prior to strike-slip displacement along major faults. Implications of this model include the following:

- 1) D₁ may be the continuation of basin and uplift development during deposition, wherein depositional basins were deformed into synclines, and paleotopographic highlands are now represented by anticlines, metamorphic highs, and early intrusive complexes.
- 2) Detachment surfaces are likely to have developed at an early stage of D₁ deformation. The most probable location for them to have formed was at or near the contacts between ductile clastic successions and relatively rigid volcanic sequences. Bedding-parallel imbrication is likely, but difficult to quantify given the intense subsequent deformation (D₂), paucity of marker units, and sparse outcrop. Early-formed detachment and thrust faults such as the LLSD and MCSZ were steepened and reactivated in D₂ (and later deformations) as zones of strike-slip and dip-slip displacement.
- 3) The gross distribution of major lithologic units was established in D₁. The subsequent modification by D₂ flattening and fault development, though significant at the outcrop scale, affected relatively localized intrastratal areas.
- 4) The correlation between cross-section morphology and map distribution of large F₁ folds in the Soudan belt (section A-A' on Fig. 3) implies northward tilting of the belt. We infer that much of the tilting occurred during D₁ as the Newton belt was thrust southward over the Soudan belt.

Figure 7 Palinspastic reconstruction of the Vermilion greenstone belt showing large D₁ nappes (A.) and schematic vertical section illustrating the inferred sequential deformation of the western Wawa subprovince.



Most structural elements generated after the main metamorphic event are assigned to D₃ and are synchronous with or postdate emplacement of the late plutonic suite described below. Structures assigned to D₃ are dominantly brittle and include local crenulation folds; a weak, northeast-trending fabric in some of the latest plutonic rocks; and those northeast and northwest-trending faults that offset metamorphic zones. The fabric observed in late plutons involves magmatic, rather than metamorphic minerals, indicating that weak tectonism occurred during magma cooling. Most of these structures are consistent with the interpretation of Bauer (1985) that D₃ is the result of continued north-south compression during the waning stages of the same deformation that produced D₂ structures. However, in contrast to the ductile deformation of D₂, the response to D₃ was typically more localized in intensity and more diverse in orientation due to the existence of large plutonic masses, and it typically was more brittle.

PLUTONIC ROCKS

The plutonic rocks in the Cook area are classified on the basis of bulk composition shown on Figure 8, and the temporal relationships between emplacement and D₂ deformation shown on Figure 4. The majority of these intrusions are part of the Giants Range batholith, which was first characterized by Spurr (1894) and later by Allison (1925). No further work was done in the area until Viswanathan (1971) and Sims and Viswanathan (1972) subdivided the batholith into a number of subunits. On the basis of our recent work (Jirsa and others, 1991), the plutonic rocks are now divided into a much simpler, three-component series that consists of: 1) an early monzodioritic to tonalitic suite that was emplaced synchronous with or predated D₂, 2) a tectonically late (post-D₂) alkalic suite, and 3) a granitic suite of similarly late timing.

The Britt granodiorite constitutes the earliest phase of the Giants Range batholith in the Cook area and is best exposed in the core of the Britt antiform (Fig. 2 and 4). Outcrops near the north and south edges of the granodiorite body display a strong northeast-plunging metamorphic lineation (L₂) that is parallel to the stretching lineation in adjacent D₂-deformed pillow basalts (Fig. 6). A contact-parallel mylonite occurs along the boundaries of the intrusion. The Britt granodiorite exhibits complex intrusive relationships near its borders among rock types that range from pink, leucocratic, hornblende-quartz monzodiorite to dark green amphibolitic lamprophyre. In contrast, the granodiorite near the center of the antiform is only weakly foliated and lineated, and shows gradual transitions from mesocratic to leucocratic phases (Fig. 8). Cm-scale, ovoid inclusions of fine-grained, dark gray amphibolitic monzodiorite are common in all phases of the Britt granodiorite. Schistose, feldspar-phyric quartz monzodiorite dikes, and lamprophyre (amphibolite) sills and dikes, inferred to be related to the granodiorite, cut the adjacent basaltic rocks. These dikes and sills locally cross F₂ folds in basaltic interflow clastic rocks, but are themselves deformed by D₂ structures. Dikes of weakly foliated pegmatitic granite from the Shannon Lake granite cross D₂ fabric in the Britt granodiorite and in the adjacent basaltic rocks. Other early plutonic units lie along the southeastern edge of the Cook area but are poorly exposed, and their distribution and character are inferred from geophysical and drilling data.

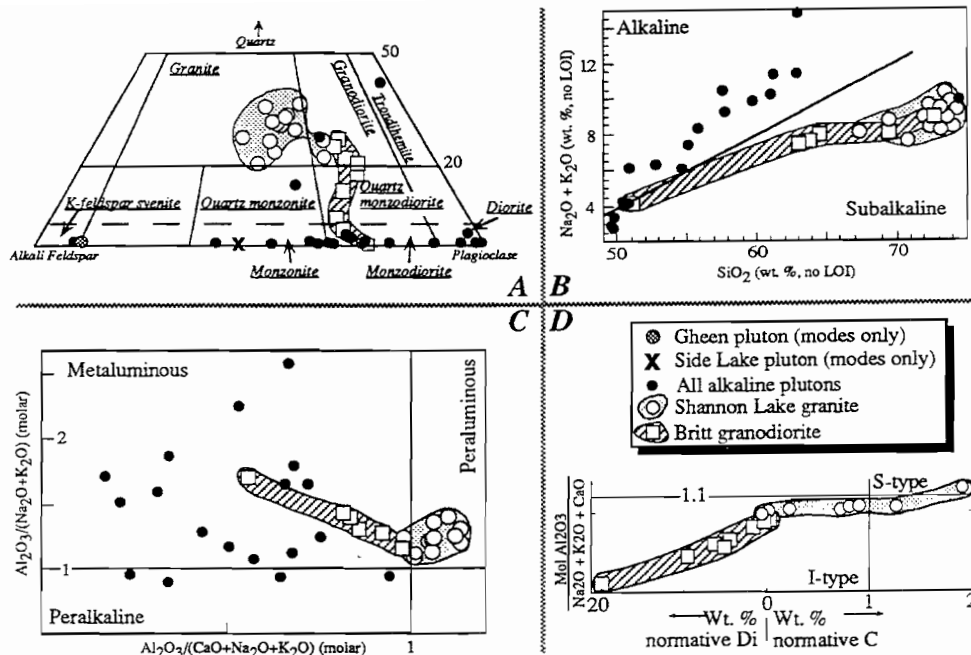


Figure 8 Modal and chemical classifications of plutonic rocks from the Cook area: A) modal classification (modified from Streckeisen, 1973), B) standard alkaline vs. subalkaline discrimination diagram (modified from Irving and Baragar, 1971), C) peraluminous, etc. classification diagram, and D) I- and S-type classification diagram for granitic rocks (modified from Chappell and White, 1974). Symbols shown in D pertain to diagrams A-D.

Intrusive rocks inferred to have been emplaced during the waning stages of D₂ are divided into a suite of metaluminous to peralkaline alkalic rocks and a suite of peraluminous granitic rocks (Fig. 8). The alkalic rocks tend to form relatively small, discrete ovoid plutons that are extremely diverse in mineralogy, geochemistry, and geophysical expression. They vary from syenite to monzodiorite. Magmatically related dikes, both internal and external to the plutons, contain a weak tectonic fabric that indicates post-kinematic timing relative to D₂. Alkaline intrusions in the central part of the area are distributed in an en-echelon pattern elongate to the east-northeast; they may be the product of tension-gash style of tectonic control by pre-existing anisotropic weaknesses in the country rocks. The predominant mineralogy of the intrusions consists of perthitic to antiperthitic feldspar, zoned aegirine-augite, and locally abundant hornblende and biotite. Sphene is a prominent accessory mineral that occurs together with minor amounts of apatite, epidote, and allanite. The intrusions are typified by high Na₂O>K₂O and low SiO₂, except for the Gheen and Linden plutons, where K₂O>Na₂O reflects their more syenitic (versus monzodioritic) composition. The alkalic rocks are enriched in Ba and Sr, as is typical of this type of intrusion.

The largest granitic intrusion in the area is the Shannon Lake granite (southern-most, + patterned on Fig. 4). The granite contains a weak fabric defined by elongate quartz with weak shadowy extinction, tabular feldspar, and aligned micas. Thin-section petrography and field observations suggest that the fabric is the result of magma crystallization under anisotropic stress, rather than a metamorphic recrystallization. Macroscopic evidence of this includes straight-walled pegmatite dikes within the granite that contain acicular megacrysts of microcline, biotite, or rarely tourmaline that are oriented at an oblique angle to the dike walls, parallel to the regional fabric. The alignment of these megacrysts with the regional fabric instead of perpendicular to dike walls implies crystallization under regional stress. Thin granite dikes that cut the surrounding host rock vary from straight to tightly folded. The granite contains locally abundant angular inclusions of metasedimentary rocks and granodiorite that were metamorphosed and folded during D₂ deformation, prior to incorporation in the granite. The

inclusion shapes typically are elongate parallel to their internal fabric which, because of magmatic flow, is also parallel to fabric of the enclosing granite. Arth and Hanson (1975) petrogenetically modeled the unit that is here termed the Shannon Lake granite and concluded that it was derived from partial melting of a short-lived graywacke at crustal depths. Using the criteria of Chappell and White (1974), our geochemical study shown on Figure 8 classifies the Shannon Lake granite as I-type (derived from a partial melt of igneous rocks).

GEOCHRONOLOGY

Recent geochronologic work on intrusions of the Giants Range batholith (Boerboom and Zartman, in prep; summarized by Boerboom and Jirsa, 1992), bracket the D₂ deformation and M₂ metamorphism between 2674 Ma (≈post-D₂ Shannon Lake granite) and 2685 Ma (≈pre-D₂ Britt granodiorite). This time interval for the end of D₂ deformation agrees moderately well with that from adjacent areas along strike including the Michipicoten belt (≈2671 Ma: Turek, and others, 1992), the Hemlo district (≈ 2678 Ma: Pan and Fleet, 1991), and the Batchawana greenstone belt (≈2677 Ma, Corfu and Grunsky, 1987), but differs somewhat from the Shebandowan belt (≈2684-2696 Ma: Corfu and Stott, 1986). Collectively, these data imply that D₂ is a narrowly restricted tectonic event that can be correlated across a broad area of the Superior Province, and that the regional metamorphic fabric (M₂) is a relatively finite structural datum.

The older of the dates reported by Boerboom and Zartman (≈ 2685 Ma) is from the strongly D₂-foliated Britt granodiorite. This body was emplaced into a stratigraphically inverted volcanic and clastic sequence that forms the Britt (synclinal) antiform. The granodiorite therefore postdates recumbent folding during D₁, and the intrusive age of 2685 Ma is considered a minimum for the end of D₁ in this area. This D₁ termination date is consistent with geochronologic studies in adjacent districts in the Wawa, Quetico, and Wabigoon subprovinces; for example, in the Shebandowan (2689-2696 Ma, Corfu and Stott, 1986), the Quetico (<2687 Ma, Percival and Sullivan, 1988), Michipicoten (<2682 Ma, Corfu and Sage, 1992), Abitibi (>2690 Ma, Card, 1990), and Wabigoon (2682-2696 Ma, Davis and others, 1989).

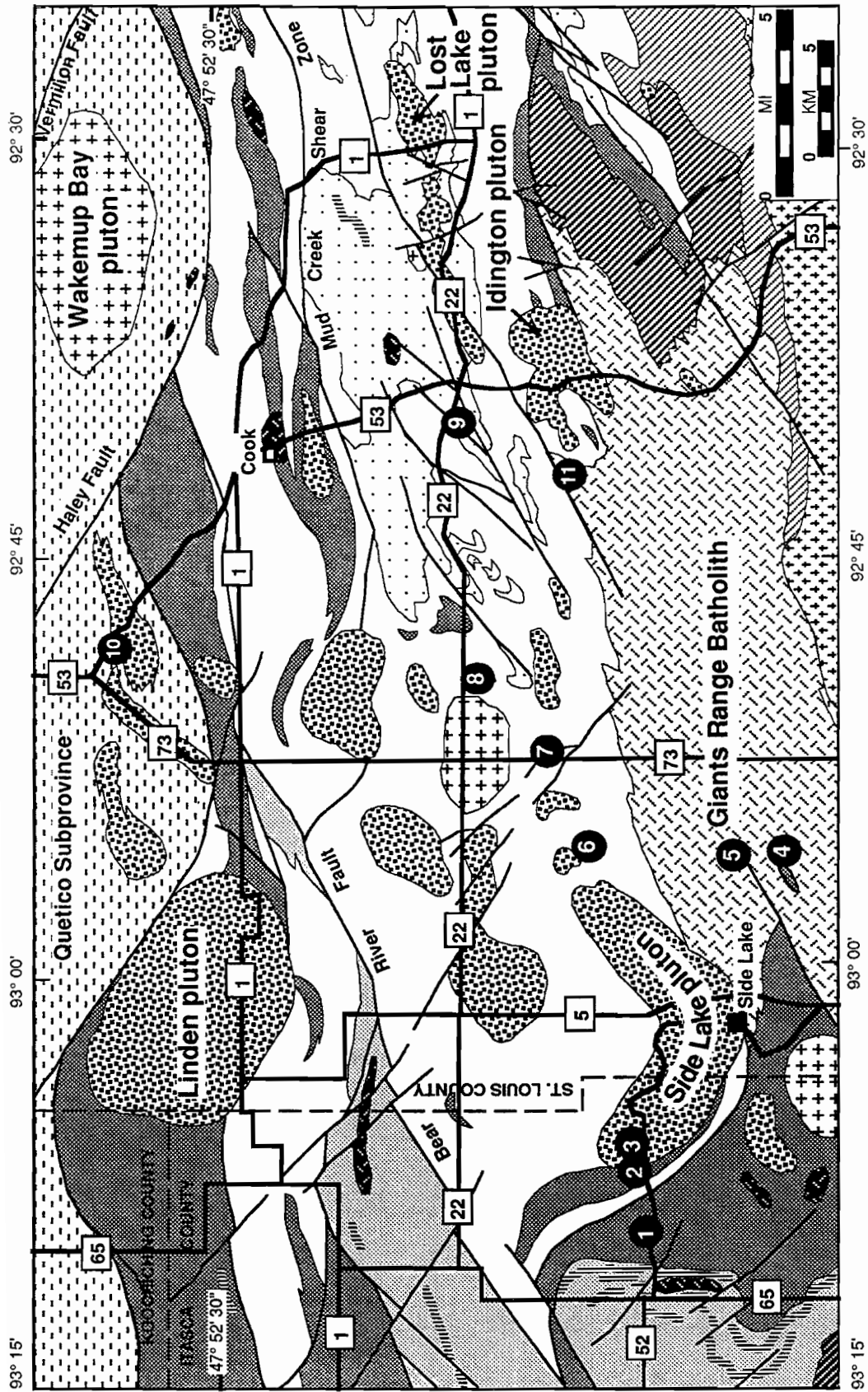
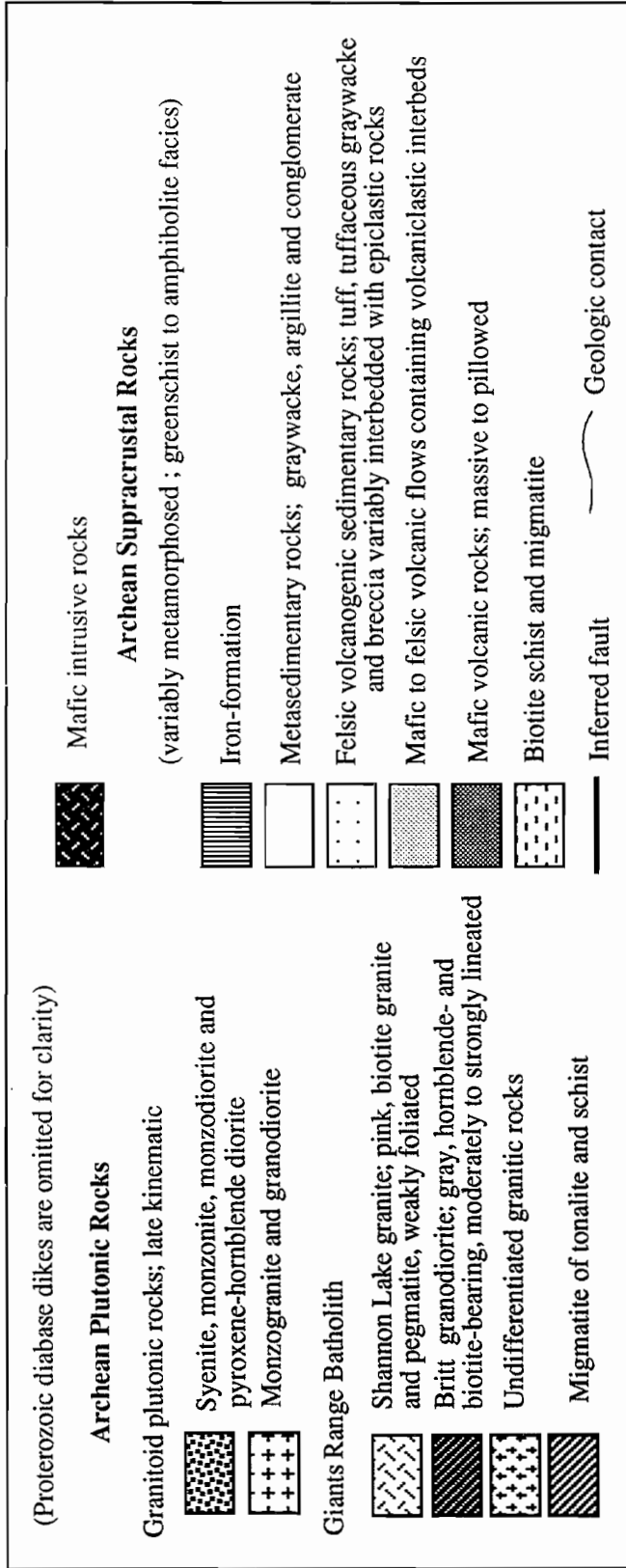


Figure 9. Generalized bedrock geologic map of the Cook-Side Lake area (simplified from Jirsa and others, 1991) showing the location of field trip stops. See summary of stops and explanation of map units on facing page.



SUMMARY LIST OF STOPS (see map on facing page)

- 1 PILLOWED METABASALT FLOWS TYPICAL OF THE "SHERRY LAKE BASALTS"
- 2 PILLOWED BASALT, PILLOW FRAGMENT BRECCIA AND CONGLOMERATE
 - 2A. flattened pillows
 - 2B. multi-lithic conglomerate, pillow breccia, intruded by sill
- 3 SIDE LAKE PLUTON
- 4 METABASALT INTRUDED BY SHANNON LAKE GRANITE
- 5 INCLUSION-RICH ZONE OF SHANNON LAKE GRANITE
- 6 SILLIMANITE-STAUROLITE-BIOTITE SCHIST
 - 6A. xenoliths in Side Lake pluton
 - 6B. folds and high grade schists
- 7 STURGEON RIVER SHEAR ZONE (D₃)
- 8 BIOTITE-STAUROLITE SCHIST AND FELDSPATHIC TUFF
- 9 M-FOLDS (F₂) IN BIOTITE-GRADE GRAYWACKE / SLATE
- 10 GHEEN PLUTON
 - 10A. porphyritic syenite with melanocratic inclusions
 - 10B. Lamproid with schist inclusions
- 11 S-T-R-E-T-C-H-E-D CONGLOMERATE

FIELD TRIP 3 STOP DESCRIPTIONS

Because the trip is organized to minimize travel distances, the itinerary does not follow an orderly progression through the various topics. The following table relates the stops to five main themes.

Topic	Stop Numbers
1) Stratigraphic correlation in the Soudan belt and evidence for earliest (D ₀ -D ₁) structural framework, including D ₁ nappes	1, 5, 6, 7, 8, and 9
2) Style and scope of D ₂ deformation and associated M ₂ metamorphism	all; especially 6, 8, and 9
3) Lithology and fabric of post- and pre-D ₂ phases of the Giants Range batholith relative to temporal implications of the geochronologic data	4, 5, and 11
4) Characteristics of the post-D ₂ alkalic plutons	2B, 3, 7, and 10
5) Post-metamorphic deformation (D ₃)	1, 2, 4, 5, 7, and 10

The field trip begins about 8 mi (13 km) east of the town of Side Lake along the Link Lake Forest trail. Most stops are within the area of recently published bedrock geologic maps. Stop 1 is on MGS Miscellaneous Map M-68 (Jirsa, 1990); most of stops 2 through 11 are within MGS Miscellaneous Map M-75 (Jirsa and others, 1990), with the exception of stop 10, which lies about 7 mi (11 km) northwest of the city of Cook along U.S. Highway #53 in an area where mapping is not yet completed.

STOP 1 PILLOWED FLOWS TYPICAL OF THE "SHERRY LAKE BASALTS"

Location: Glacially polished outcrops along Stony Brook about 80 m south-southwest from the parking lot for the Pelloquin Wildlife Management Area on the Link Lake Forest Trail: T.60 N., R.22 W., sec 9, NW.

Portions of two north-striking flow units are exposed at this locality. The upper part of the western flow contains medium-sized pillows that grade upward to the northeast to isolated pillows and pillow-fragment breccia (via autobrecciation). The overlying flow unit contains large, oblate pillow structures locally exhibiting budding and reentrant structures. Pillow rinds are thin (<1cm), hyaloclastite in the interpillow is relatively minor, and evidence for vesiculation is lacking. Taken together, these attributes indicate deposition in relatively deep water during a period of nearly constant supply of basaltic magma. Notice that pillow shapes are bulbous and show little evidence for flattening. These characteristics are typical of other outcrops in this thick sequence of tholeiitic flows and interdigitated hypabyssal sills informally named the Sherry Lake basalts (unit Uv on Fig. 2), though more schistose fabrics occur locally. The consistent eastward stratigraphic younging in this group defines the upward-facing limb of the D₁ central syncline (CS) shown on Fig. 5.

Directions: Continue eastward along Link Lake Forest Trail 1 mi (1.6 km) to stop 2A.

STOP 2 PILLOWED BASALT, PILLOW-FRAGMENT BRECCIA, AND CONGLOMERATE

Location: Outcrops lie along south side of Link Lake Forest Trail approximately 1 mi (1.6 km) east of stop 1. T. 60 N., R. 22 W., sec. 10 NE NW

STOP 2A

The western exposures show relatively small pillows and pillow-fragment breccia. This is part of a thin (<1 km) sequence of metavolcanic rocks, known informally as the Link Lake basalts, that is composed of thin, graded flow units containing amygdaloidal basalt and numerous zones of biotitic interflow sedimentary rocks and autobrecciated flowtops. A 500 m thick sequence of dacitic tuff and polymictic conglomerate separates this sequence from the Sherry Lake basalts seen at Stop 1. The boundary between the two is not exposed. The Link Lake basalts and the dacite and conglomerate just to the west are the basal part of the Lake Vermilion Formation (LVF).

Clasts and pillows of the Link Lake basalts are composed of green, amphibolitic basalt that have thin black rinds and contain deformed amygdules of quartz, epidote, and calcite. Interpillow matrix is brown, biotite-plagioclase schist of pelitic origin containing garnets as large as 1 cm and local metamorphically coarsened amphibolite clots. This matrix is petrographically similar to graywacke of the Lake Vermilion Formation that occurs in the subsurface a few miles to the east of here. This contrasts with the amphibolitic interpillow material of the Sherry Lake basalts to the west, inferred to be hyaloclastic (intraformational) in origin. The metavolcanic rocks here are variably flattened, and matrices display a strong D2 cleavage that trends north-northwestward and dips steeply to the east. Pillow morphology indicates asymmetrical flattening, possibly in the manner depicted in Figure 10.

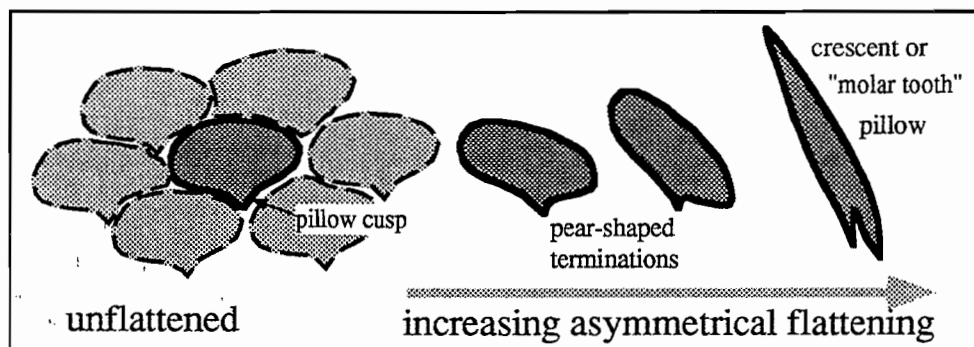


Figure 10 Schematic sequence of progressively deformed simple, single-cusp pillows (modified from Borradaile, 1982).

STOP 2B

The eastern outcrops are composed of polymictic conglomerate and mafic agglomerate intruded by a thin sill of weakly deformed pyroxenite inferred to be related to the Side Lake Pluton. Although intensely deformed and metamorphosed to amphibolite grade, most units in this group lack significant grading and lamination, indicating a debris flow origin. Fragments vary from angular to rounded, and most are not zoned (i.e., not pyroclastic). As with the previous outcrop, fabric here trends north-northwestward and dips steeply to the east. A strong lineation defined by elongate clasts trends S15°E-40°.

The north-trending S₂ fabric at Stop 2 is somewhat anomalous, and its cause enigmatic. Its orientation contrasts with the east-northeastward trend of D₂ structures (fold axis, lineations, S₂ cleavage) in most of the Soudan and Newton belts. The difference in trend may be a product of D₂ shearing along the boundary between the thick basaltic sequence to the west and the more ductile clastic succession (Lake Vermilion Formation) to the east. Alternatively, S₂ may have been rotated during D₃ deformation. S₂ is cut by a pyroxenitic dike mineralogically similar to the Side Lake pluton a short distance to the east. That pluton contains irregularly distributed phases and cognate inclusions of identical composition. The pyroxenite dike contains a well-developed primary magmatic flow banding and numerous late shear discontinuities.

Discussion

Exposures are rare immediately east of here. Drilling and geophysical data imply that the Side Lake pluton lies along the boundary between strongly flattened volcanic rocks and biotitic schist of the Lake Vermilion Formation. The presence of interflow sedimentary rocks of biotitic graywacke and the evidence for upper or distal flow position of these basalts indicates that the LVF conformably overlies the Link Lake basalts. Mixed source (basaltic and dacitic) conglomerate occurs sporadically between here and the Britt antiform, where it lies in a similar stratigraphic position beneath a thin sequence of basaltic flows and separates strata dominated by reworked felsic tuff from that containing only a small percentage of fine-grained felsic tuff in graywacke (Fig. 3). That stratigraphic "horizon" is cut locally by the Shannon Lake granite, which contains xenolithic blocks of conglomerate of largely dacitic composition. Thus, in a general way this stratigraphy outlines a broadly correlative sequence that can be traced intermittently across the central syncline (CV on Fig. 6). The outline of this fold is consistent with the structural facing data.

Directions: Continue eastward along Link Lake Forest Trail to Stop 3.

STOP 3 SIDE LAKE PLUTON

Location: Outcrops lie along a low ridge trending northward from the Link Lake Forest Trail approximately 0.3 mi (0.5 km) east of stop 2B: T. 60 N., R. 22 W., sec. 3, SE SE

This is one of many tectonically late (post-D₂), alkalic plutons that occur sporadically throughout the Cook and adjacent areas. The Side Lake pluton is a crescent-shaped body emplaced into the boundary between basaltic rocks to the southwest and biotite schist of the LVF to the northeast. The crescent shape follows the bend in adjacent volcanic rocks from primarily a northward to an eastward trend that parallels the regional D₂ fabric. It shares the characteristic of most of the alkalic suite of being strongly, though irregularly, magnetic. Exposures here represent only one or two of the multitude of phases that characterize plutons of this type. As a group, they vary from pyroxenite to pyroxene diorite, monzonite, or syenite, and rarely to trondjemite. The dominant phase shown here is a two-pyroxene, "chicken track" biotite inokersantite, in lamproid terminology; it is more appropriately classified as pyroxene-biotite monzodiorite. A thin section

taken from this locality contains 27% plagioclase, 34% microperthitic K-feldspar, 17% augite, 14% hypersthene, 7% biotite, and accessory sphene, apatite, quartz, and opaque oxides. The monzodiorite is medium grained, dark green and pinkish-white, and salt-and-pepper textured. It contains a weak, vertical, primary trachytic fabric trending to the northwest, more or less parallel to the long axis of the pluton. Pyroxenes are subhedral to euhedral, rectangular, and dark greenish gray. Brown biotite occurs as randomly oriented, poikilitic plates as large as 2 cm ("chicken track" texture). The monzodiorite also contains small, cognate inclusions of pyroxenite and pyroxene diorite that are identical to irregularly distributed internal phases of the pluton and to dikes that cut metamorphic fabric in the country rocks (as at Stop 2B).

Directions: Follow the Link Lake Forest Trail eastward into the town of Side Lake. Turn right (south) on County Highway #5, then go about 0.25 mi (0.4 km) to St. Louis County road (CR) #7156. Turn left (east) and proceed to "T" junction of CR#766 and #931. Turn right (south) on CR# 766 and continue 1.2 mi (1.9 km) to stop 4.

STOP 4 LARGE XENOLITH OF METABASALT WITHIN SHANNON LAKE GRANITE

Location: Roadside outcrop west of St. Louis County Road (CR) # 766, 1.2mi (1.9 km) south of its junction with CR# 931: T. 60 N., R. 21 W., sec. 36 NE NE.

This outcrop shows strongly flattened pillowed metabasalt (hornblende-plagioclase schist) intruded by numerous sills and dikes of the Shannon Lake granite (SLG), a late unit (or intrusive phase) of the Giants Range batholith. Field relations indicate that the basalts are part of a large xenolithic block in the SLG, presumably detached from the Sherry Lake basalts, exposed several kilometers to the west, during emplacement of the granite.

The SLG is a biotite granite that can be divided along its strike length into a western, medium-grained, gray phase and an eastern, pegmatitic, pink to white phase that also occurs in dikes adjacent to the pluton which invade country rocks (as seen here). The pink phase occurs as dikes and segregations within the gray phase and increases in abundance to the east, where it is predominant and contains inclusions of the gray phase. The gray phase is inferred from field relations to have been emplaced slightly earlier than the pink phase, though geochronologic data (Boerboom and Zartman, in prep) give a similar age of about 2674 Ma for each.

Notice that the strike of S_2 and the long axes direction of pillows in metabasalt trend about $N65^\circ E$. This is more typical of the structural fabric throughout the region, and contrasts with the northwestward trend at Stops 1 and 2. Kinematic indicators show that the basaltic pillows were asymmetrically flattened prior to granite emplacement. Yet thin granite dikes were mildly deformed more or less symmetrically after intrusion, and this deformation is attributed to D_3 . The degree to which dikes are folded depends in part on the relative competence of the rock type through which the dikes pass. This is illustrated schematically in Fig. 11.

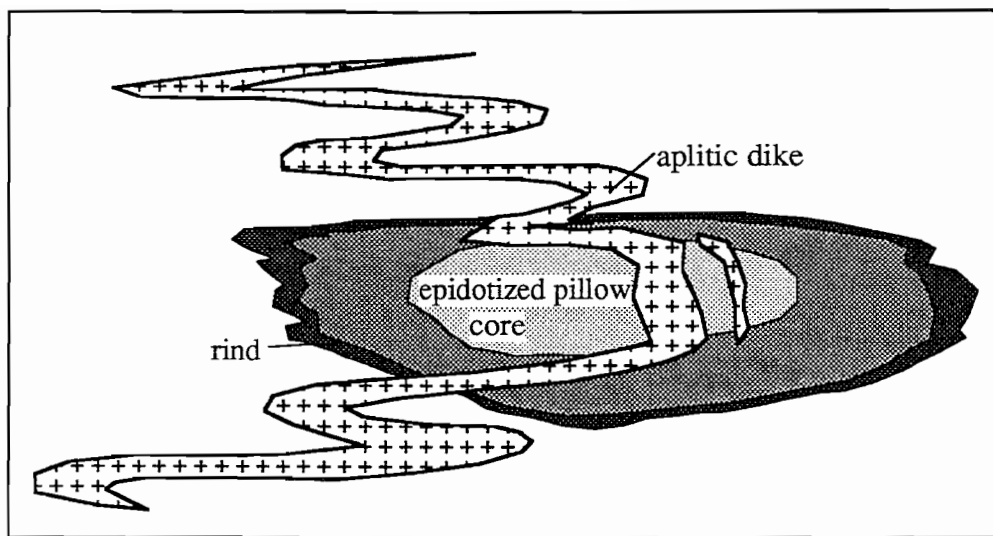


Figure 11 Sketch showing the effects of late, differential compression (strain partitioning) on dike of Shannon Lake granite that cuts metabasalt pillow. The northerly dike orientation preserved in the brittle, epidotized, and silicified core of the pillow may approximate the principal axis of compression during D3.

Typically, pegmatitic dikes of the Shannon Lake granite that are external to the pluton and cross the regional east-northeast fabric are variably but only moderately folded. In contrast, those internal to the granite are straight-walled, with only a hackly cross-cleavage that parallels the regional fabric.

Directions: Turn around (bus can turn around about 0.25 mi to south) and travel north on CR# 766, continuing onto CR# 931, approximately 0.2 mi (0.3 km) past the "T" junction to Stop 5.

STOP 5 SHANNON LAKE GRANITE CONTAINING D₂ DEFORMED XENOLITHS

Location: Large clear-cut area of scattered exposures on gentle rise, either side of CR# 931 approximately 0.2 mi (0.3 km) north of its junction with CR# 766: T. 60 N., R. 20 W., sec. 19 SE SE.

Exposures show the diversity of textural attributes of the Shannon Lake granite. Medium-grained, gray-phase biotite granite representative of the western portion of the Shannon Lake granite is cut by a coarse-grained pink phase, and both are cut by thin pink pegmatite dikes. The two pink phases commonly contain garnet and tourmaline, which is typical of the eastern phase of the Shannon Lake granite. All three phases of the granite have a weak northeast-oriented foliation. Petrographic evidence indicates that the granite foliation is primary, inferred to be the result of cooling under north-south-oriented stress related to D₃ deformation. The granite contains xenoliths ranging from a few centimeters to greater than one meter, most commonly composed of schistose metamorphosed graywacke, felsic tuff, and a fine-grained hornblende-bearing banded rock of possible andesitic tuff composition. Most of the schist xenoliths contain a well-developed cleavage assigned to D₂, as no earlier (S₁) cleavage has been identified in schists adjacent to the intrusion. The S₂ cleavage is folded in some inclusions; others contain parts of F₂ folds with axial planar S₂ cleavage. Typically, the D₂ fabric in inclusions is randomly oriented relative to the weak, primary, east-trending foliation in the enclosing granite. However, there is a tendency for the long axes of inclusions to parallel the regional strike of the intrusion.

Discussion

Farther east, the Shannon Lake granite contains blocky inclusions of foliated rock similar to the Britt granodiorite, which is inferred from field relationships to be the earliest plutonic rock in the region, predating D₂ deformation. The Britt granodiorite was dated at 2685 ma (Boerboom and Zartman, in prep), approximately 10 Ma older than the SLG that was emplaced after D₂. The SLG also intruded the Idington pluton, one of the late alkalic intrusions similar to the Side Lake (Stops 2 and 3) and Gheen (Stop 10) plutons. Most field relationships indicate that the SLG and the alkalic suite are approximately contemporaneous relative to regional D₂ and localized D₃ structures.

Directions: Return to "T" junction and turn right (west). Proceed 2 mi (3.2 km) to north-trending State Forest Trail. Follow the trail north for 1 mi (1.6 km) to where it joins with a road from the west. Continue north and east along this road, now called CR# 652, for 2 mi (3.2 km), after which the road will bend east and north through several turns (stay on main road). Once the road straightens to an easterly trend, follow it 0.75 mi (1.2 km) east to Stop 6.

STOP 6 SILLIMANITE-STAUROLITE-BIOTITE SCHIST

Location: Outcrop **6A** is in the north road ditch of CR# 652 at the junction of a logging trail to the north; **6B** is a low outcrop approximately 250 feet (80 m) to the north-northeast on the same logging trail: T. 61 N., R. 20 W., sec. 32 SW SW.

These outcrops of intensely folded and metamorphosed schist of the Lake Vermilion Formation lie within an irregular border zone of the Side Lake pluton. In contrast with the sharp contacts of the other alkalic intrusions, this boundary zone is characterized by a multitude of leucocratic monzonite sills and dikes that may represent the roof zone of the Side Lake pluton. The border zone forms a regional, eastward-striking, en-echelon array of small plutons separated by multiply intruded schist like that at this locality. The strike of individual plutons in this array is more northeasterly than the (eastward) strike of the group, implying tectonic control of emplacement. The apophosial intrusions at this locality were emplaced subparallel to the pre-existing metamorphic (M₂) foliation and locally contain a large percentage of cognate (magmatic) and schistose (country rock) xenoliths shown at **STOP 6A**. The monzonite is white, equigranular, and coarse grained. As in the previous stop in the Shannon Lake granite, the presence of M₂ fabric in the inclusions supports the interpretation that the alkalic pluton and its dikes were emplaced after D₂.

The schist contains sillimanite, staurolite, and biotite in units of pelitic protolith, and garnet in units inferred to be feldspathic tuff. Collectively, they indicate metamorphism to the sillimanite grade of amphibolite facies. Though obscured by metamorphism and cleavage, bedding and local relict sedimentary grading ("reversed" due to metamorphic coarsening in pelitic units) can be elucidated. Muscovite has locally replaced sillimanite and possibly andalusite during a retrogressive event presumably related to intrusion of the Side Lake pluton. All of the prograde metamorphic features trend N65°E, parallel to the vertical axes of pronounced M-shaped F₂ folds seen at **STOP 6B**.

Directions: Follow CR# 652 eastward about 3 mi (4.8 km) to State Highway #73. Turn left (north) and travel 1.25 mi (1.9 km), pull off in trail access to the right (about 0.25 mi past the bridge over the Sturgeon River, at crest of hill).

STOP 7 STURGEON SHEAR ZONE

Location: Main outcrop is on the east side of State Highway #73, 0.2 mi (0.3 km) north of its crossing of the Sturgeon River: T. 61 N., R. 20 W., sec. 26 SW.

Outcrop of biotitic and feldspathic schist of the Lake Vermilion Formation cut by many thin sills of white, medium- to coarse-grained leuco-monzonite similar to that at the previous stop. Here the attitude of S₂ foliation in country rocks is nearly horizontal, and monzonite sills form flat sheets. This shallow fabric is attributed to D₃ deformation because D₃ affected the D₂ cleavage. The weak fabric in monzonitic sills implies that rotation of D₂ foliation occurred before (or during?) their emplacement.

In exposures nearest the road, both rock types are cut by a north-northwest-trending, brittle fault zone inferred to be a product of D₃ deformation. Local brecciation occurs along the fault; however, no ductile shear is evident. Many of the fault segments and breccia matrices contain chlorite and actinolite. Offset direction is equivocal, but its sense is probably strike-slip, as no significant metamorphic contrast exists between this and the other side of the fault (west side of the road). Many such faults occur in the district, and both right-lateral and left-lateral senses of displacement are recorded. Locally, they form conjugate sets that indicate north-south compression during D₃. The faults typically lack significant mineralization, and although beds are displaced several meters at the outcrop scale, offset of major map units is minimal.

Graywacke beds exposed about 500 ft (151.5 m) east of the shear zone (which probably will not be visited) locally contain statically crystallized metamorphic porphyroblasts of K-feldspar and muscovite, implying that local potassic alteration may have accompanied emplacement of the monzonite. Also at this locality are exposures of white monzonite with numerous small cognate xenoliths of mesocratic to melanocratic monzodiorite that typify phases of the Side Lake pluton, which occur in small plugs exposed both east and west of this locality. The white phase of monzonite here contains 56% blocky, strongly zoned plagioclase with rims that grade from plagioclase to antiperthite to perthite; 26% anhedral-interstitial to poikilitic perthite; 11% hornblende; 3% biotite; 3% chlorite; 0.5% each of epidote, sphene, and apatite; and trace amounts of allanite, zircon, and quartz.

Directions: Follow State Highway #73 northward approximately 3 mi (4.8 km) to County Highway #22 in the burg of Sturgeon. Turn right (east) on #22 and travel 2 mi (3.2 km) to CR# 481. Turn right (south) on CR# 481 and travel 0.5 mi (0.8 km) to an east-trending trail into woods. Follow trail eastward for about 350 ft (110 m) to stop 8.

STOP 8 DOWN-FACING FOLDS OF BIOTITE-STAUROLITE SCHIST AND FELDSPATHIC TUFF

Location: Outcrops are on private property approximately 350 ft (110 m) east of CR# 481: T. 61 N., R 19 W., sec. 18 SW NW

This outcrop of the Lake Vermilion Formation illustrates many characteristics of the overprint of D₂ deformation on D₁ structures, including downward-younging strata. Folds are developed in two rock types: dark gray-brown staurolite-biotite schist of pelitic protolith, and white, garnet-bearing feldspathic schist of tuffaceous origin. The rocks lie within an irregular stratigraphic transition zone between strata dominated by reworked dacitic tuff and dacitic graywacke to the east, and strata containing mostly graywacke to the west (Fig. 3). The western graywacke differs from those to the east in that it contains clasts derived from a mixed-provenance region that included both mafic and dacitic volcanic rocks. The boundary between the two successions is marked by thin, lenticular units of tholeiitic volcanic rocks underlain locally by conglomeratic strata. Collectively, these attributes imply that the boundary zone represents a depositional unconformity.

This exposure further illustrates the contrasts in the response to D₂ deformation between rocks of different competency. The competent felsic rock behaved in a more blocky fashion, producing broad, open folds. By contrast, pelitic schists contain strong metamorphic fabric and isoclinal

folds. The tuff beds are locally disjointed and irregularly distributed in a manner that does not conform to the orientation of D₂ structures, and thus may be the product of D₁ or soft-sediment deformation.

This style of F₂ folding is typical of a large outcrop area. Folds plunge N50°E at about 35° and have an axial planar cleavage that dips steeply. Stratigraphic younging deduced from grading and bed contacts is downward and westward. Analysis of surrounding outcrops indicates that these folds are small parasitic structures on the limb of a much larger F₂ fold (see Fig. 12, below).

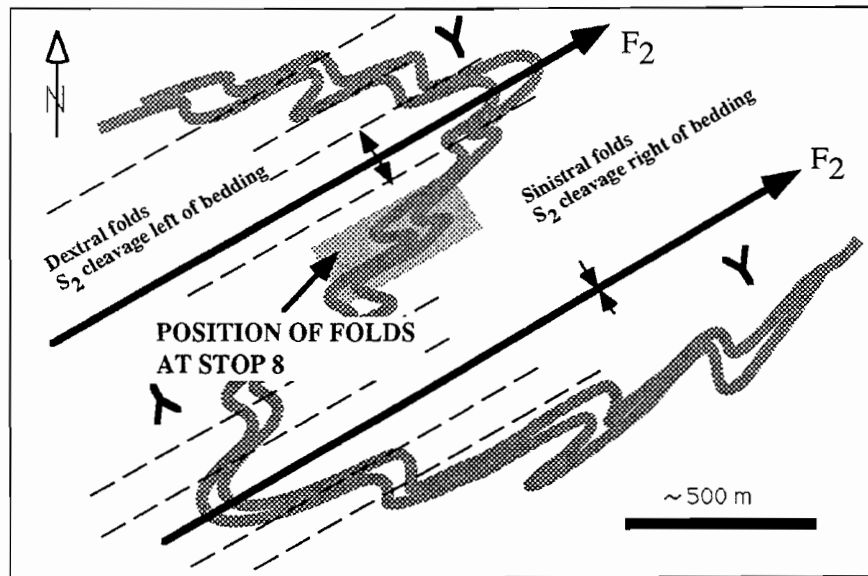


Figure 12 Position of folds at Stop 8 within large F₂ antiform-synform pair. Scale is approximate. Stratigraphic younging direction, shown by Y-shape, defines the folds as antiformal synclines and synformal anticline.

Directions: Drive north on CR#481 to County Highway #22. Turn right on #22 and continue for about 7.3 mi (11.7 km) to trail that trends southward from highway. Walk in about 500 ft (151.5 m) to scattered outcrops in woods on the west side of old landfill.

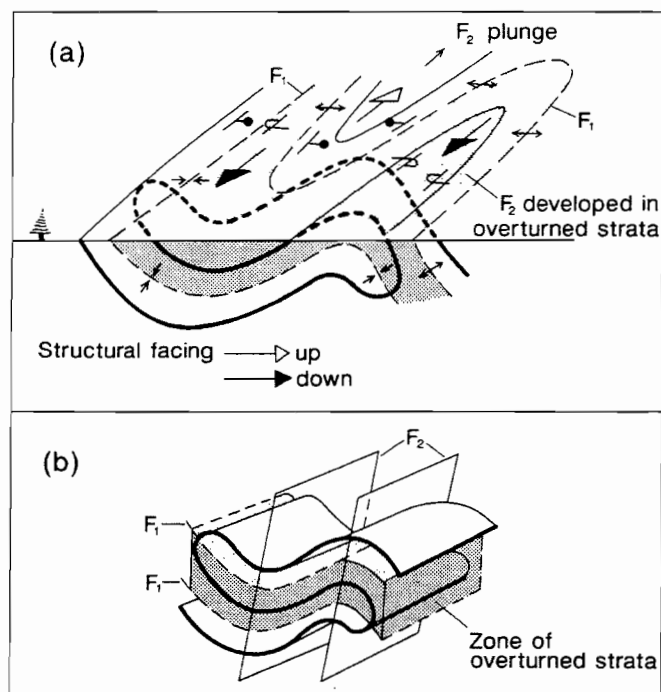
STOP 9 M-FOLDS (F_2) IN BIOTITE-GRADE GRAYWACKE AND SLATE

Location: Outcrops lie 0.8 mi (1.3 km) west of US Highway #53 and 500 ft (151.5 m) south of County Highway #22 near site of abandoned landfill: T. 61 N., R. 18 W., sec. 8 SW NW.

Several outcrops show rock types and structural attributes that are characteristic of much of the central Lake Vermilion Formation. These strata lie within the thinly bedded transitional facies between felsic tuff to the east and graywacke to the west. The majority here are thinly interbedded biotite schist of pelitic protolith and fine-grained feldspathic schist of tuffaceous graywacke origin.

The S_2 foliation and the axial surfaces of the F_2 folds trend $N70^\circ E$ and dip $\approx 75^\circ S$ to nearly vertically. Fold hinges and cleavage/bedding intersections define a consistent shallow eastward ($15-35^\circ$) plunge. Strata young westward and downward. Figure 13 shows the schematic position of this area of down-facing in the regional fold pattern and the inferred position on the large F_1 nappe. The folds are east-plunging antiformal synclines and synformal anticlines; these outcrops lie within a large area of down-facing strata inferred to be the lower limb of a regional scale F_1 nappe fold.

Figure 13 Schematic drawing of fold elements in the central Lake Vermilion Formation. F_2 folds are upright and plunge eastward; they deform both normal and inverted limbs of the southwest-verging F_1 recumbent folds. Stop 9 lies within the down- and west-younging (inverted) limb of the large F_1 fold.



Directions: Follow County Highway #22 for 0.8 mi (1.3 km) east to junction with US highway #53. Turn left (north) on Highway #53 and drive northward through the city of Cook. From the main street of Cook, continue northwestward on Highway #53 for 6.3 mi (10.1 km) to roadcut on the right (northeast) side of highway.

STOP 10 GHEEN PLUTON

Location:: Stop **10A** is a small roadcut on northeast side of US highway 53, 6.3 mi (10.1 km) northwest of the main street of Cook: T. 63 N., R. 19 W., sec 29 SE SW.

Stop **10B** is a pair of prominent roadcuts on either side of the highway about 0.5 mi (0.8 km) northwest of 10A. We may visit both outcrops if time permits; however, the one on the northeast side of the road is most telling: T. 63 N., R. 19 W., sec 29 NW SW and adjacent section.

The Gheen pluton is one of the heterolithic, alkalic intrusions emplaced temporally late (post-M₂ and S₂). At this locality, several discrete intrusive phases and a multitude of sills and dikes intrude sillimanite-biotite-plagioclase schist of the Quetico subprovince. The two dominant, exposed phases of the pluton are biotite-hornblende-pyroxene lamprophyre (pyroxenite) and porphyritic syenite. The contact relationships between comagmatic phases of the intrusion, and between the pluton and schistose country rocks, are well displayed. The Gheen pluton is one of the only intrusions of the alkalic suite that contains significant amounts of sulfide minerals (calcopyrite, pyrite) and yields a small but anomalous content of Au (16 ppb). It also differs slightly from most of the others in that it is a true syenite and contains normal augite instead of aegerine.

STOP 10A

This exposure consists of very coarse grained, mesocratic, porphyritic syenite with perthite phenocrysts, and pyroxene-biotite-hornblende monzodiorite containing inclusions of fine- to coarse-grained melanocratic rock and aplitic dikes. In contrast to many of the other alkaline intrusions, the intrusive sequence deduced from contact and xenolith relationships shows a direct correlation between mafic content and the timing of emplacement, wherein the more mafic phases are earliest and aplitic dikes are latest. The mafic component (biotite-hornblende-pyroxene diorite to pyroxenite) is mineralogically identical to that at Stop 10B.

Leucocratic phases are moderately magnetic and dominated by perthitic feldspar and fibrous amphibole, which is pseudomorphous after pyroxene. Minor amounts of sphene, apatite, opaque minerals, calcite, epidote, and quartz occur.

STOP 10B

Biotite-hornblende-pyroxene monzodiorite (lamprophyre) containing a multitude of cognate inclusions and schistose xenoliths intrudes biotite schist of the Quetico subprovince. The diorite is melanocratic, coarse grained, and massive to crudely lineated. Mode is diverse, but typically pyroxene, biotite, and hornblende make up 45% to 65% of the rock. Pyroxene crystals as large as 2-4 mm are rimmed by magmatic to deuteric hornblende and contain scraps of brown biotite. Plagioclase is nearly twice as abundant as microcline and varies from blocky and subhedral to anhedral-interstitial grains. Microperthite is anhedral and interstitial, and accessory minerals are sphene, apatite, and opaque oxides. Minor alteration products include chlorite after biotite, and sericite after plagioclase. Xenoliths of metasedimentary country rocks display a well-developed S₂ cleavage, and some contain post-S₂ quartz veins that were emplaced prior to incorporation into the diorite. The intrusive contact between diorite and schist is regionally discordant, but nearly concordant here, trending N65°W; dipping 45°SW.

A pink felsic unit of the pluton exposed in the next outcrop to the northwest (on the west side of the road) is similar to phases at Stop 10A and displays the biotite "chicken track" texture observed in the Side Lake pluton (Stop 3). In addition, it contains mirolitic cavities and chaotic fabrics that imply a relatively high level of emplacement. *The face of that outcrop is metastable, at best, and will not be visited by this group.*

Discussion

The boundary between the Wawa subprovince and the Quetico subprovince occurs about 1.5 mi (2.4 km) to the south. Although it is not exposed along the road, outcrops a short distance to the east and west indicate that the boundary is a metamorphic discontinuity known as the Flint Creek fault. It separates volcanic and clastic rocks metamorphosed to the chlorite zone (greenschist facies) to the south, from sillimanite zone (amphibolite facies) metagraywacke to the north. No exposures are known to exist within the fault zone; however, adjacent outcrops indicate that the fault is a relatively narrow, brittle, and temporally late (D3) structure. Younging directions of strata on both sides of the fault are consistently, and somewhat enigmatically, southward.

Directions: Turn around to head southeast on Highway #53, passing through the city of Cook and past County Highway #22. Continue south of #22 about 2.4 mi (3.8 km) to westbound CR# 467. Turn right (west) on CR# 467 and travel 2 mi (3.2 km) to CR# 912. Turn left (south) on #912 and continue for 1.4 mi (2.2 km), stopping at small trail to right (west).

STOP 11 CONGLOMERATE CONTAINING STRONGLY LINEATED CLASTS

Location: Large area of exposure begins about 250 ft (75.8 m) west of CR# 912: T. 61 N., R. 19 W., sec. 36 SE NE. This outcrop was used as a test site for explosives in the 1960s, and the test explosions produced many rubble-filled craters and piles of blocks. *Please watch your step* as some large blocks are loose. From the top of the access trail turn north and proceed to the north end of the large outcrop, to a point where several loose meter-sized blocks are lying about.

At this location, graywacke is interbedded with conglomerate that contains abundant plutonic rock clasts of quartz-hornblende monzodiorite. The graywacke component is macroscopically identical with that of the Lake Vermilion Formation, though contacts between lithologic units in this area are obscured by multiple intrusion of the Shannon Lake granite. In thin section the plutonic clasts in the conglomerate contain lineated metamorphic hornblende in a recrystallized matrix of plagioclase, perthite, quartz, and biotite. These clasts strongly resemble the lineated parts of the Britt Granodiorite, although it is difficult to prove their exact source (see discussion below). The clasts show a strong L2 stretching lineation that plunges 25° to the N 70° E. Bedding and S2 cleavage dip steeply and generally strike N70E, but in places strike nearly north-south due to D3 folding that produced neither cleavage nor metamorphism. The metasedimentary rocks are intruded by an early, slightly discordant set of thin lamprophyric sills that are deformed in D2. Both the metasedimentary rocks and the lamprophyres are cut by gray biotite granodiorite, which is in turn intruded by a white garnet- and tourmaline-bearing granite pegmatite. These granitoid rocks are early and late phases of the Shannon Lake granite, respectively, and are variably affected by D3 deformation. Thin pegmatite dikes emplaced parallel to the S2 schistosity of the host rocks are weakly boudinaged, whereas those emplaced at a high angle to schistosity are weakly to moderately folded. The S2 cleavage of the host schist is folded and crenulated inside folded dikelets of pegmatite, evidence that D3 has produced at least some deformation of the granite (Fig. 14). D3 fold hinges trend northeastward.

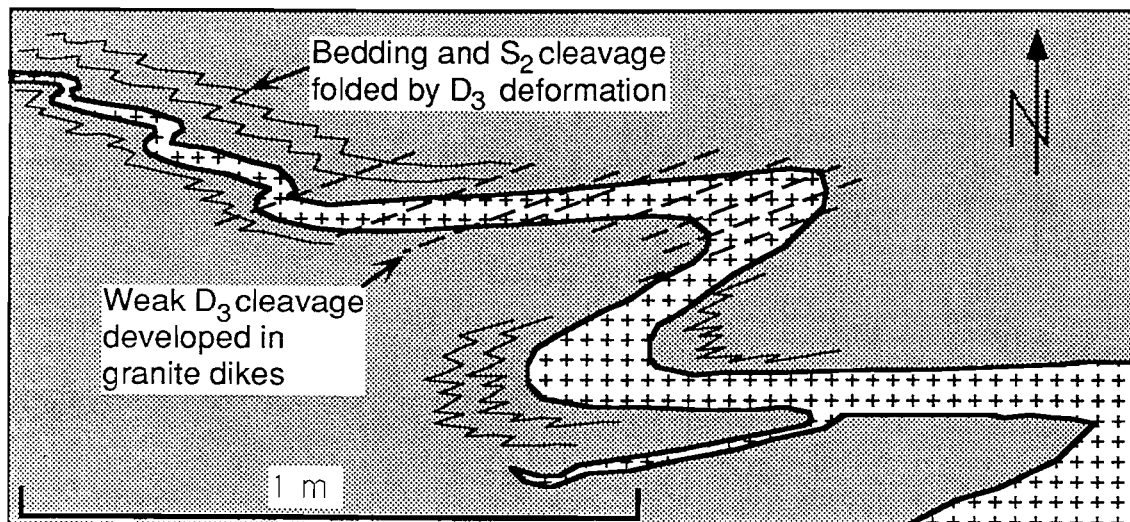


Figure 14 Schematic drawing of S₂ cleavage and bedding in metasedimentary rocks interbedded with conglomerate, along with intrusive dikes of pegmatitic granite, all gently folded by D₃ deformation.

At the northern edge of the bare, east-facing exposure the rock is composed of coarse, lineated, and clast-supported conglomerate. Several dislodged blocks in this vicinity show three-dimensional perspectives of the linear fabric. Near this location, one of the foliation-parallel pegmatite dikes is weakly boudinaged, with quartz-filled brittle tension gashes.

The middle portion of the outcrop (approximately 30m farther south) shows intercalated conglomerate and graywacke, in which both bedding and bedding-parallel S₂ cleavage have been folded by D₃ deformation. Mafic lamprophyric sills are slightly discordant to bedding but deformed by D₂ deformation. S₂ cleavage and bedding in the metawackes are folded along with thin granitic dikelets by D₃ deformation.

Discussion

The source of plutonic clasts in this conglomerate is problematic. The clasts are petrographically and geochemically similar to the Britt Granodiorite (BG). However, BG is inferred to have been emplaced during or prior to D₂ deformation into down-facing strata of the Lake Vermilion Formation, which are interpreted to have been inverted during D₁ deformation. Assuming that this conglomerate lies within the same stratigraphic sequence as the inverted strata of the Lake Vermilion Formation (and the interdigitation with graywacke at most exposures indicate that it is), unroofing of the BG as the provenance for the conglomerate clasts would need to have occurred prior to intense D₂ deformation. If the clasts are truly derived from the BG, it is possible that the conglomeratic succession is not a component of the inverted graywacke sequence, but instead that deposition occurred in a "Timiskaming-like" fault graben or pull-apart basin. In this scenario, the

conglomerate may be associated with a thin sequence of clastic rocks, exposed more or less along strike to the east, that differs in composition from the bulk of the Lake Vermilion Formation. This package of rocks contains exotic fragments that include lamprophyric agglutinate flows, "quartzite" pebbles, vitric tuff, and local trough cross-bedding in buff-colored tuffaceous sandstones. All of these characteristics imply the presence of a major erosional unconformity and a contrasting sedimentological regime, which lends support to the fault graben possibility. Alternatively, the conglomerate clasts may have been derived from an earlier plutonic core of a volcanic highlands (of coincidentally similar composition to the BG) that might have existed in the area now occupied by other intrusions of the Giants Range batholith. A high precision date of the conglomerate clasts is needed to resolve the issue. If the date of clasts matches that of the BG (≈ 2685 ma), it would support the notion that "Timiskaming-like" deposition has occurred, and would be the first such sequence identified within the Wawa subprovince of Minnesota.

Directions to end of trip (Holiday Inn): Continue southward on CR# 912 to eastbound CR# 652. Follow #652 to highway #53. Turn right (south) on #53 and continue into Eveleth, approximately 20 mi (32 km).

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REFERENCES CITED

- Arth, J.G., and Hanson, G.N., 1975, Geochemistry and origin of the early Precambrian crust of northeastern Minnesota: *Geochimica et Cosmochimica Acta*, v. 39: p. 325-362.
- Bauer, R.L., 1985, Correlation of early recumbent and younger upright folding across the boundary between an Archean gneiss belt and greenstone terrane, northeastern Minnesota: *Geology*, v. 13: p. 657-660.
- , 1986, Multiple folding and pluton emplacement in Archean migmatites of the southern Vermilion granitic complex, northeastern Minnesota: *Canadian Journal of Earth Sciences*, v. 23: p. 1753-1764.
- Bauer, R.L., Hudleston, P.J., and Southwick, D.L., 1992, Deformation across the western Quetico subprovince and adjacent boundary regions in Minnesota: *Canadian Journal of Earth Sciences*, v. 29, p. 2087-2103.
- Boerboom, T.J. and Jirsa, M.A., 1992, Geology and tectonic setting of the Archean Giants Range batholith; western Wawa subprovince, Minnesota: (abs) in *Institute on Lake Superior Geology, 38th Annual Meeting, Hurley, Wisconsin, 1992, Proceedings* p. 11.
- Boerboom, T.J., and Zartman, R.E., in prep., Geology, geochemistry, and geochronology of the central Giants Range Batholith, northeastern Minnesota.
- Borradaile, G.J., 1982, Tectonically deformed pillow lava as an indicator of bedding and way-up: *Journal of Structural Geology*, v. 4, p. 469-479.
- Card, K.D., 1990, A review of the Superior Province of the Canadian Shield, a product of Archean accretion: *Precambrian Research*, v. 48, p. 99-156.
- Chappell, B.W., and White, A.J.R., 1974, Two contrasting granite types: *Pacific Geology*, v. 8, 173-174.
- Corfu, F., and Grunsky, E.C., 1987, Igneous and tectonic evolution of the Batchawana greenstone belt, Superior Province: A U-Pb zircon and titanite study: *Journal of Geology*, v. 95, p. 87-105.

- Corfu, F., and Sage, R.P., 1992, U-Pb age constraints for deposition of clastic metasedimentary rocks and late-tectonic plutonism, Michipicoten Belt, Superior Province: *Canadian Journal of Earth Sciences*, v. 29, p. 1640-1651.
- Corfu, F., and Stott, G.M., 1986, U-Pb ages regional deformation in the Shebandowan Belt, Superior Province, Canada: *Canadian Journal of Earth Sciences*, v. 23, p. 1075-1082.
- Davis, D.W., Poulsen, K.H., and Kamo S.L., 1989, New insights into Archean crustal development from geochronology in the Rainy Lake area, Superior Province, Canada: *Journal of Geology*, v. 97, p. 379-398.
- Hodges, K.V. and Crowley, P.D., 1985, Error estimation and empirical geothermobarometry for pelitic systems: *American Mineralogists*, v. 70, p. 702-709.
- Hodges, K.V. and Spear, F.S., 1982, Geothermometry, geobarometry, and the Al_2SiO_5 triple point at Mt. Moosilauke, New Hampshire: *American Mineralogists*, v. 67, p. 1118-1134.
- Holdaway, M.J., 1971, Stability of andalusite and the aluminum silicate phase diagram: *American Journal of Science*, v. 271, p. 97-131.
- Hooper, P.R., and Ojakangas, R.W., 1971, Multiple deformation in Archean rocks of the Vermilion district, northeastern Minnesota. *Canadian Journal of Earth Sciences*, 8: 423-434.
- Hudleston, P.J., 1976, Early deformational history of Archean rocks in the Vermilion district, northeastern Minnesota. *Canadian Journal of Earth Sciences*, 13: 579-592.
- Hudleston, P.J., Schultz-Ela, D., and Southwick, D.L., 1988, Transpression in an Archean greenstone belt, northern Minnesota. *Canadian Journal of Earth Sciences*, 25: 1060-1068.
- Irvine, T.N., and Baragar, W.R.A., 1971, A guide to the chemical classification of the common volcanic rocks. *Canadian Journal of Earth Sciences*, v. 8, p. 523 -543.
- Jirsa, M.A., 1988, Bedrock geologic map of the Sherry Lake Quadrangle, northeastern Minnesota, Minnesota Geological Survey, Miscellaneous Map M-64, scale 1:24 000.
- _____, 1990. Bedrock geologic map of northeastern Itasca County, Minnesota. Minnesota Geological Survey, Miscellaneous Map M-68, scale 1:48 000.
- Jirsa, M.A., and Boerboom, T.J., 1990, Bedrock geologic map of parts of Koochiching, Itasca, and Beltrami Counties, north-central Minnesota. Minnesota Geological Survey, Miscellaneous Map M-67, scale 1:250 000.
- Jirsa, M.A., Boerboom, T.J., Chandler, V.W., and McSwiggen, P.L., 1991, Bedrock geologic map of the Cook to Side Lake area, St. Louis and Itasca Counties, Minnesota. Minnesota Geological Survey, Miscellaneous Map M-75, scale 1:48 000.
- Jirsa, M.A., Southwick, D.L., and Boerboom, T.J., 1992, Structural evolution of Archean rocks in the western Wawa subprovince, Minnesota: refolding of precleavage nappes during D2 transpression: *Canadian Journal of Earth Sciences*, v. 29, p. 2146-2155.
- Lundy, J.R., 1985, Clues to structural history in the minor folds of the Soudan iron-formation, northeastern Minnesota. MS. thesis, University of Minnesota, Minneapolis, Minnesota.

- Meints, J.P., Jirsa, M.A., Chandler, V.W., and Miller, J.D., Jr., 1993, Scientific core drilling in parts of Itasca, St. Louis, and Lake Counties, northeastern Minnesota, 1989-1991, Summary of lithologic, geochemical and geophysical results: Minnesota Geological Survey Information Circular 37, 159 p.
- Pan, Y., and Fleet, M.E., 1991, Metamorphic petrology and alteration assemblages of the Hemlo gold District: Ontario Geological Survey Miscellaneous Paper 156, p. 147-169.
- Percival, J.A., and Sullivan, R.W., 1986, Age constraints on the evolution of the Quetico belt, Superior Province, Ontario: in Workshop on the Tectonic Evolution of Greenstone Belts, Lunar Planet. Inst. Contrib., v. 584, p. 91-93.
- Ripley, E.M., Rao, B.V., and Berkley, J.L., 1982, Mineralogical and chemical variations within layered sills of the Deer Lake Complex, Minnesota: Contributions to Mineralogy and Petrology, v. 80, p. 230-239.
- Sims, P.K., 1976, Early Precambrian tectonic-igneous evolution in the Vermilion district, northeastern Minnesota: Geological Society of America Bulletin, 87: 379-389
- Sims, P.K., and Southwick, D.L., 1985, Geologic map of Archean rocks, western Vermilion district, northern Minnesota. U.S. Geological Survey, Miscellaneous Investigations Series, Map I-1527, scale 1:48 000.
- Sims, P.K., and Viswanathan, S., 1972, Giants Range batholith. *In* Geology of Minnesota: A centennial volume. Edited by P.K. Sims and G.B. Morey, Minnesota Geological Survey, St. Paul, Minnesota, U.S.A., p. 120-139.
- Southwick, D. L., 1992, Geologic map of Archean rocks, Soudan-Bigfork area, northern Minnesota. Minnesota Geological Survey, Miscellaneous Map, scale 1:100 000, in press.
- , In press, An alternative map interpretation of the Archean rocks in the western Vermilion district, northeastern Minnesota. Minnesota Geological Survey, Miscellaneous Map, scale 1:48 000.
- Southwick, D.L., Setterholm, D.R., and Boerboom, T.J., 1990, Scientific test drilling in west-central Minnesota. Minnesota Geological Survey, Information Circular 31.
- Spear, F.S. and Peacock, S.M., 1990, Metamorphic P-T-t Paths: Program manual and computer exercises for the calculation of metamorphic phase equilibria, pressure-temperature-time paths and thermal evolution of orogenic belts: Rensselaer Polytechnic Institute, Troy, New York, 188p.
- Streckeisen, A.L., 1973, Plutonic rocks: classification of nomenclature recommended by the IUGS subcommission of the systemation of igneous rocks. *Geotimes*, v. 18, p 26-30.
- Turek, A., Sage, R.P., and Van Schmus, W.R., 1992, Advances in the U-Pb zircon geochronology of the Michipicoten greenstone belt, Superior Province, Ontario: Canadian Journal of Earth Sciences, v.29, p. 1154-1165.
- Viswanathan, S., 1971, A petrological and geochemical study of granitic and metamorphic rocks in and adjacent to the western part of the Giants Range Batholith, northeastern Minnesota. PhD thesis, University of Minnesota, 900 pp.
- Williams, H. R., 1990, Subprovince accretion tectonics in the south-central Superior Province. Canadian Journal of Earth Sciences, 27: 570-581.



THE DULUTH COMPLEX AT DULUTH

Leaders

James D. Miller, Jr.
Minnesota Geological Survey

John C. Green
University of Minnesota-Duluth

Val W. Chandler
Minnesota Geological Survey

FIELD TRIP 4

THE GEOLOGY OF THE DULUTH COMPLEX AT DULUTH

James D. Miller, Jr., John C. Green, and Val W. Chandler

INTRODUCTION

The well-exposed gabbroic rocks forming the escarpment above Duluth have long been recognized as the type locality of the Duluth Complex—the 1.1-Ga multiple intrusive complex that underlies much of northeastern Minnesota. Many early studies, beginning with J.H. Kloos and N.H. Winchell in the 1870s, established the general rock types, structures, and economic potential of the Duluth area. The pioneering studies of Frank Grout stand as a major contribution to petrology. In a series of papers published in 1918 from his Ph.D. dissertation, Grout (1918a-e) recognized the complex to be a multiple intrusive body predominantly composed of early anorthositic gabbros, younger layered gabbros, and felsic differentiates. Moreover, he used examples from the Duluth area to argue for (1) the role of fluids in the creation of gabbroic pegmatite, (2) the role of crystal settling and magma convection in forming igneous lamination (fluxion structure), modal layering, and differentiated rock compositions, and (3) the role of liquid immiscibility in creating granophyre (red rock)—topics that are still debated today. Although recent seismic studies contradict Grout's suggestion that the complex represents the eroded edge of an immense lopolith that thickens beneath Lake Superior, most of his observations and conclusions are still valid and form the basis of our understanding of the Duluth Complex.

Recognizing that Grout's conclusions about the differentiation of the layered gabbros at Duluth resembled those of Wager and Deer in their now classic 1939 treatise on the fractional crystallization of the Skaergaard Intrusion of East Greenland, Richard Taylor set out in the mid-1950s to better characterize the petrology of Duluth Complex at Duluth as part of his Ph.D. dissertation. Although Taylor found many similarities in the two magmatic systems, he observed little cryptic variation in feldspar and mafic mineral compositions in the Duluth layered series, compared to the strong alkali and iron enrichment observed in the Skaergaard, and attributed the difference to periodic magmatic replenishment of the Duluth system. Perhaps Taylor's greatest contribution to Duluth Complex geology was the first large-scale (1:24,000) geologic map (Taylor, 1964), which distinguished intrusive units of anorthositic gabbro, layered series gabbro, ferrogranodiorite, granophyre, and diabase.

Even after 120 years of investigation, many questions remain about the fundamental geology. Although Taylor recognized a definite stratigraphy to the layered series, he did not map in sufficient detail to subdivide the series. Such detail is needed if we are to understand the history of crystallization and intrusion that created the differentiated layered series, and this history in turn has implications for mineralization potential. Other problems yet to be resolved include determining the form of the Duluth Complex at Duluth relative to the enclosing volcanic rocks, because it has implications for the style and mechanism of emplacement. Also, in light of identical U-Pb dates (Paces and Miller, in press), what is the petrogenetic relationship between the anorthositic and layered series rocks? To address these questions, the Minnesota Geologic Survey, in cooperation with the University of Minnesota at Duluth and with funding from the Minnesota State Legislature through the Minerals Coordinating Committee, is remapping the bedrock geology of the Duluth

Complex in the Duluth area in greater detail. Field work was conducted over a five-month period last summer (1992) by Jim Miller and John Green with assistance from Terry Boerboom (MGS) and Thomas Nylen (UMD). Geophysical modeling of aeromagnetic and gravity data by Val Chandler is leading to better understanding of the three-dimensional structure of the complex. This field trip is intended to point out some of the main features of the Duluth Complex found by our study and some problems that still remain. We should emphasize that this summary presents only preliminary results of an ongoing project.

REGIONAL SETTING

The Duluth Complex is a large composite mafic intrusive supersuite emplaced into comagmatic flood basalts associated with the creation of the Middle Proterozoic (Keweenawan) Midcontinent rift system. In the Lake Superior region, where the 2000-km-long arcuate rift is exposed, the Duluth Complex and related hypabyssal intrusions cover more than 5000 km² on the northwest flank of the main rift axis (Fig. 1A). The off-axis position and immense volume of the complex are anomalous relative to the central graben model of the rift interpreted from seismic reflection profiles across most of the length of the rift (Chandler and others, 1989; Cannon, 1989). Two of the largest gravity anomalies associated with the entire rift are situated over the Duluth Complex, and thereby indicate that the complex is itself deeply rooted in the crust.

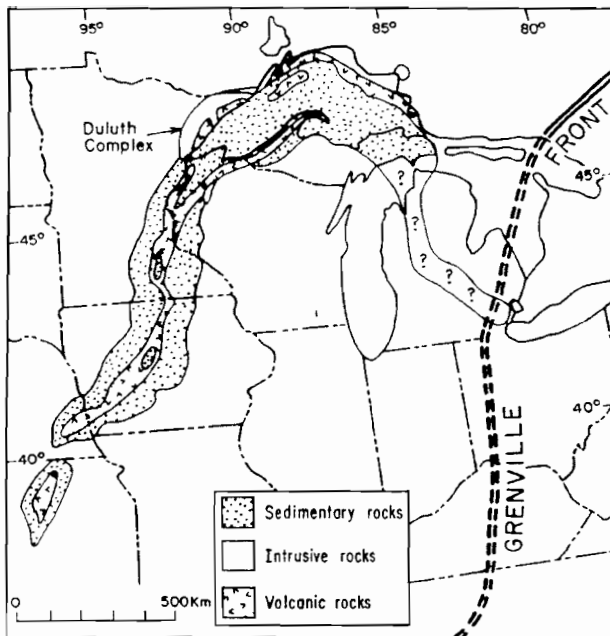
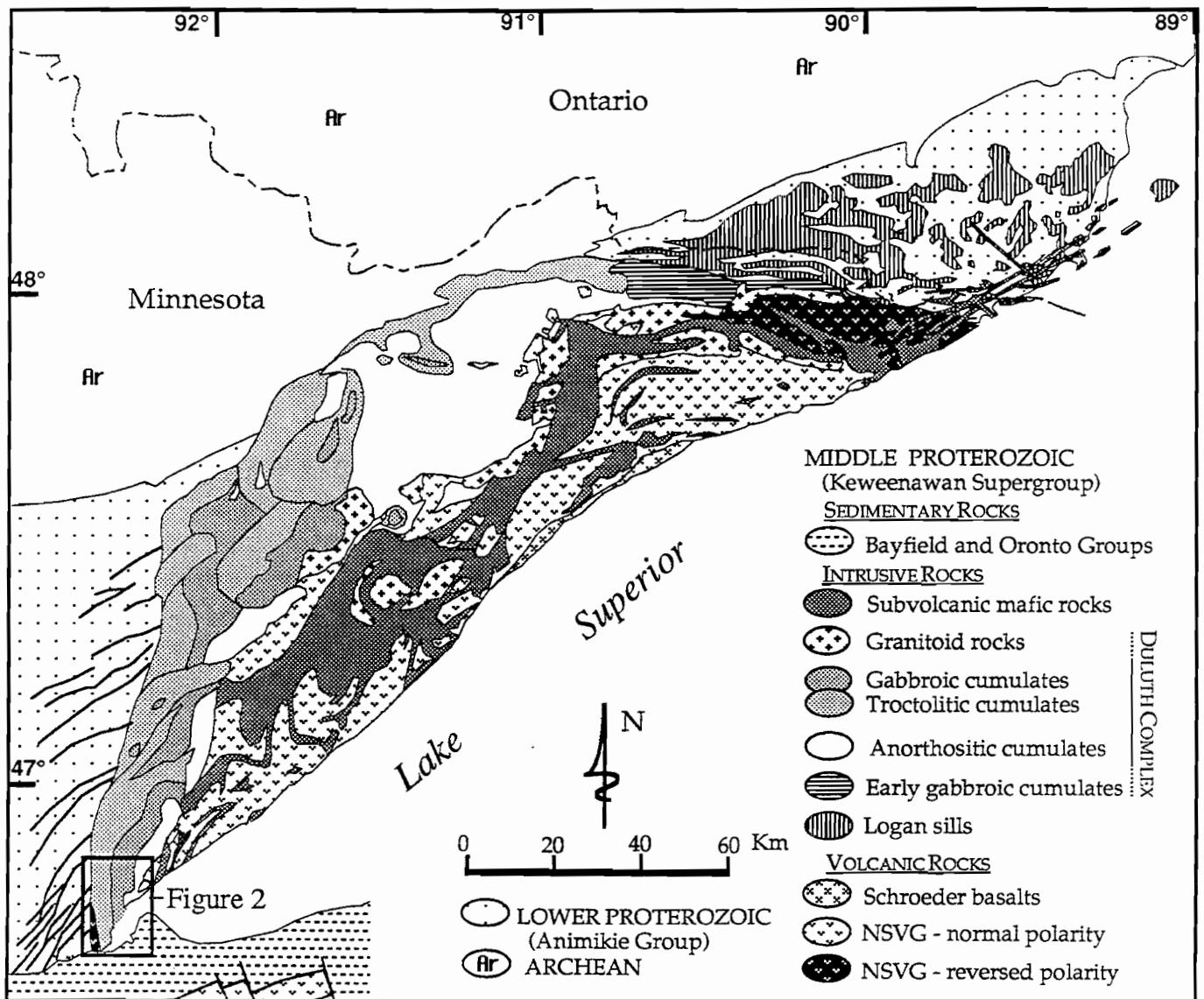


Figure 1 *Left*: Generalized geology of the Midcontinent rift system. *Below*: Middle Proterozoic rocks of northeastern Minnesota and part of Ontario.



Duluth Complex intrusions were emplaced in and near an unconformity between an older penneplained crust of Early Proterozoic (Animikian) graywacke, slate, and iron-formation and Archean granite-greenstone and the plateau lavas and minor clastic sedimentary rocks forming the early rift fill (Fig. 1B). The abundance of volcanic hornfels bodies suggests that magma chambers were formed by effectively delaminating lava flows at the base of the volcanic pile, which was probably less than 7 km thick. Internal structures and geophysical modelling (Chandler and Ferderer, 1989; Chandler, 1990) indicate that some intrusions were emplaced roughly concordant with overlying flows as south to southeast-dipping sheets, whereas others have steeply dipping contacts that are more consistent with emplacement by synmagmatic faulting. Geophysical studies, especially aeromagnetic data, also were integral to geologic mapping of large poorly exposed areas in the southern and central complex.

Recent high-resolution U-Pb zircon dates (Paces and Miller, in press), in conjunction with previously established field relationships, indicate that the earliest intrusive event was the emplacement of layered oxide-rich gabbroic cumulates along the northern tier of the complex (Fig. 1B) at about 1107 ± 0.5 Ma. The bulk of the complex was not emplaced until 1099 ± 1 Ma, at which time the two major rock series, recognized early by Grout—the anorthositic and troctolitic series of Weiblen and Morey (1980)—were formed. For troctolitic series rocks at Duluth, we retain the term layered series of Taylor (1964), because troctolitic rocks compose less than half of the sequence there (Fig. 2).

Anorthositic series rocks occupy the structurally highest levels of the complex (along with felsic rocks) as a multiply intrusive, structurally complicated suite of laminated, but unlayered, plagioclase cumulates that generally show no sign of internal differentiation except for some minor residual felsic material. Their erratic internal structure and distinctive mineralogical and textural features have been interpreted as the result of emplacement as plagioclase crystal mushes (Grout, 1918c; Taylor, 1964; Miller and Weiblen, 1990). By contrast, the layered troctolitic to gabbroic cumulates compose discrete, well-differentiated, layered mafic intrusions, which intrude and include anorthositic series rocks. The stratiform internal structure and cryptic compositional layering of these intrusions are consistent with their formation by crystal fractionation accompanied by periodic recharge or eruption or both. Field relationships indicate that anorthositic series rocks are older than layered series rocks, but the identical U-Pb ages of four rocks from the two series (two each from widely separated areas of the complex), suggest a close temporal and perhaps a genetic relationship.

Other intrusive components of the Duluth Complex include felsic intrusions concentrated along the upper contact of the complex (Fig. 1B) and small oxide-rich ultramafic bodies concentrated along the western basal contact. The felsic bodies, which range in composition from ferromonzodiorite to granophyre, and in size from dikelets to large plutons, appear to span a greater range of ages than associated mafic rocks and to have a variety of origins, including generation by mafic differentiation, partial melting of volcanic rocks, melting of older crust, and as Grout suggested, liquid immiscibility. Small, irregular bodies of oxide-rich mafic to ultramafic bodies that cut layered series rocks along the basal contact (Severson and Hauck, 1990) are common and have been variably interpreted to have a magmatic (Taylor, 1964; Linscheid, 1991) or metasomatic (Ross, 1985) origin.

The youngest suite of intrusions, the Beaver Bay Complex, was emplaced higher in the volcanic sequence at about 1096 Ma (Miller and Paces, in press). It has the same range of magma compositions as the Duluth Complex, but its more hypabyssal environment rarely produced the cumulate rock types common to the more plutonic Duluth Complex intrusions. Between the Beaver Bay Complex and hypabyssal intrusions related to it, and the deeper Duluth Complex, the boundary appears to be a rather abrupt transition from thinner (<1 km) sheetlike intrusions with abundant intervening volcanic rocks to thicker (1-4 km) tabular bodies with only minor, strongly metamorphosed volcanic rocks. Although more age dating is necessary to determine how

magmatism changed spatially and temporally between 1099 and 1096 Ma within the Duluth and Beaver Bay Complexes, this span of intrusive activity corresponds to a period of increased vigor in magmatism throughout the rift (Cannon, 1992).

DULUTH COMPLEX AT DULUTH

Although much more petrographic and geochemical work remains to be done on samples collected in this and previous studies, we describe here the major units of the Duluth Complex distinguished thus far (Fig. 2) based mainly on field observations and some petrography. For a description of the underlying Ely's Peak basalts (and Thomson Formation) see Kilburg (1972) and Kilburg and Morey (1977), and for details of the overlying North Shore Volcanic Group in the Duluth quadrangle see Motamedi (1984) and Green (see abstract volume).

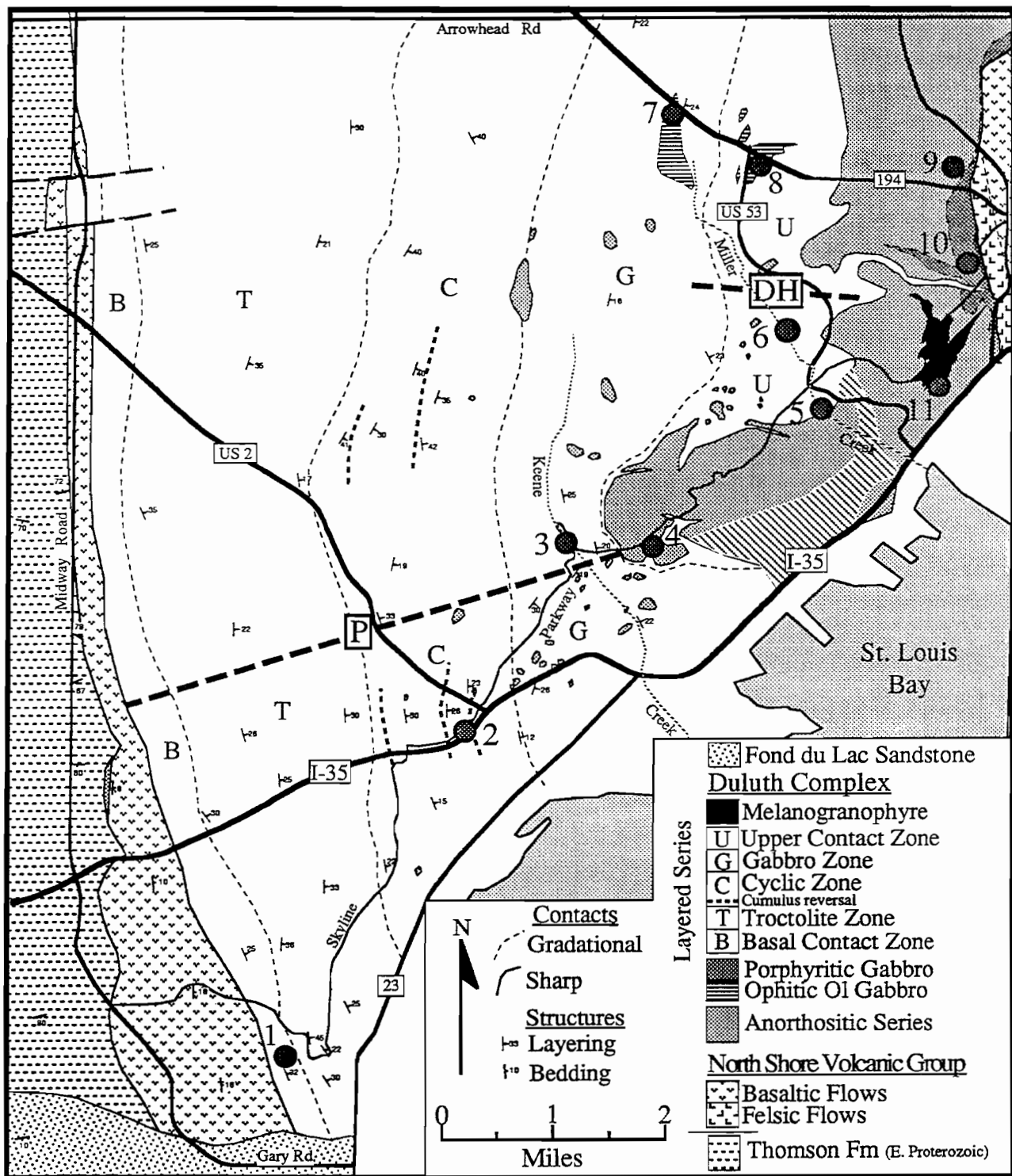


Figure 2 Geology of the Duluth area showing field trip locations. Dashed lines labeled P and DH, profiles in the Proctor and Duluth Heights areas along which samples were collected. The diagonally ruled area east of Stops 4 and 5 represents an area of no outcrop which Taylor (1964) interpreted to be underlain by anorthositic series rocks but which may contain layered series rocks.

Anorthositic Series

The anorthositic series is a structurally complex suite of coarse-grained, plagioclase-rich cumulates that forms a stratigraphic cap to the Duluth Complex (Fig. 2). The average rock type of the anorthositic series is an altered, coarse-grained, moderately laminated (foliated), ophitic olivine leucogabbro, about 80 percent of which is plagioclase. Moderate to nearly complete hydrothermal alteration of olivine, pyroxene, and to a lesser degree, of plagioclase is evident in all anorthositic series rocks. With the exception of some occurrences of granular olivine, subhedral to euhedral plagioclase is the only cumulus phase in these rocks. As can be observed at Stops 4, 5, 9, and 11, the anorthositic series contains a broad range of rock types. Plagioclase mode ranges from 70 to 99 percent; mafic mineral proportions $(Ol)/(Ol+Pyx+Ox)$ from 0 to 1; olivine texture from granular to poikilitic; overall grain size from medium to very coarse; and abundance of granophyric mesostasis to 20 percent. Changes in rock type occur across sharp (but unchilled) to gradational boundaries, and one type of anorthositic rock (typically a more leucocratic composition) is common as discrete inclusions in another. Another complicating factor is that although rarely layered, these rocks typically have some alignment of plagioclase, the attitude of which is remarkably variable on an outcrop-to-outcrop scale.

The lithologic and structural complexity of the anorthositic rocks on a small scale makes it difficult to divide the anorthositic series into subunits. However, some general lithologic variations are noteworthy. The interstitial abundance of granophyric mesostasis, the proportion of pyroxene and Fe-Ti oxide over olivine, and the intensity of hydrothermal alteration of primary phases all gradually increase in the vicinity of the melanogranophyre body (Fig. 2), suggesting a causal relationship (see discussion of melanogranophyre). Another variation near the upper contact with the volcanic rocks is that of a coarsely porphyritic texture and an accentuated plagioclase lamination because the intercumulus matrix is filled almost entirely with altered mafic minerals. This variant can be observed at Stop 9, where the gabbroic anorthosite also contains small "snowball" inclusions of well-laminated anorthosite. Finally, a band of medium-grained intergranular leucotroctolite, 10 to 20 m thick and 1 km long, forms part of the contact northwest of Skyline Parkway. Geochemical and petrographic work is underway to determine whether this band is correlative with the troctolite zone of the layered series or is a phase of the anorthositic series.

We interpret many of the anorthositic rock exposures that Taylor (1964) tied to the main mass to be inclusions in the layered series (Fig. 2). Because anorthositic rocks are so much more resistant to erosion than the gabbroic and dioritic rocks, which underlie and commonly include them, it seems likely that many isolated anorthositic outcrops are erosional remnants of xenoliths. The anorthositic cap itself is cut by many intrusions ranging from diabase to layered gabbro to granophyre (larger bodies shown in Figure 2), most of which probably emanate from the layered series. The projection of continuous anorthositic series exposure to the west at its southern extent (to about Stop 4) may be an oversimplification. The rarity of exposure at the base of the escarpment leaves open the possibility that the contact between the anorthositic and layered series may actually project northeast of Stop 4 (toward Stop 11), rather than to the southeast as shown by Taylor (1964), and perhaps it even pinches out in the poorly exposed area northeast of Miller Creek (Fig. 2, diagonally ruled area). If so, the anorthositic rocks exposed between Stops 4 and 5 may actually be detached from the main mass and therefore would be an inclusion, albeit a very large one. The less evolved composition of layered series rocks in contact with this anorthositic mass, compared to that of layered series rocks adjacent to the main mass (see below), supports this conjecture.

Layered Series

The layered series at Duluth¹ is a sequence of layered gabbroic cumulates 3 to 4.5 km thick, which strike generally north-south and dip an average of 25° to the east, though local variations are common (Fig. 2). The cumulates are bounded by a lower contact zone of olivine gabbro and a complex upper zone of ferrodiorite, ferromonzodiorite, and quartz ferromonzodiorite. One of the primary objectives of our mapping was to delineate the cumulate stratigraphy² of the layered series. The troctolite cumulates forming the lower third of the layered series indicate that the parent magma to the series was initially saturated in olivine and plagioclase. Throughout the middle third of the layered series, the sequence alternates between Pl+Ol cumulates and three- to four-phase cumulates of Pl+Cpx+Ox±Ol. The arrival of cumulus Fe-Ti oxide corresponds very well with an abrupt transition from subdued aeromagnetic anomalies over the troctolitic zone to generally high, patchy anomalies upsection from the cyclic zone (Fig. 3). The upper third of the layered series is composed exclusively of gabbroic cumulates (Pl+Cpx+Ox), which locally contain cumulus olivine and apatite. This succession of cumulate rock types is generally consistent with formation from a fractionally crystallizing tholeiitic basaltic magma which underwent either periodic replenishment or eruption, or both.

-
1. Related rocks in other parts of the Duluth Complex are referred to as the troctolitic series (Weiblen and Morey, 1980). In the Duluth area, however, troctolitic rocks account for less than half of the sequence, and we retain the layered series term of Taylor (1964).
 2. A mineral is considered to be cumulus if it displays an anhedral to subhedral granular habit and is a component of the structural framework of the rock. Minerals having poikilitic or otherwise interstitial habits relative to the cumulus minerals are thought not to have been saturated in the magma at the time of accumulation but to have become saturated with crystallization of the trapped intercumulus melt.

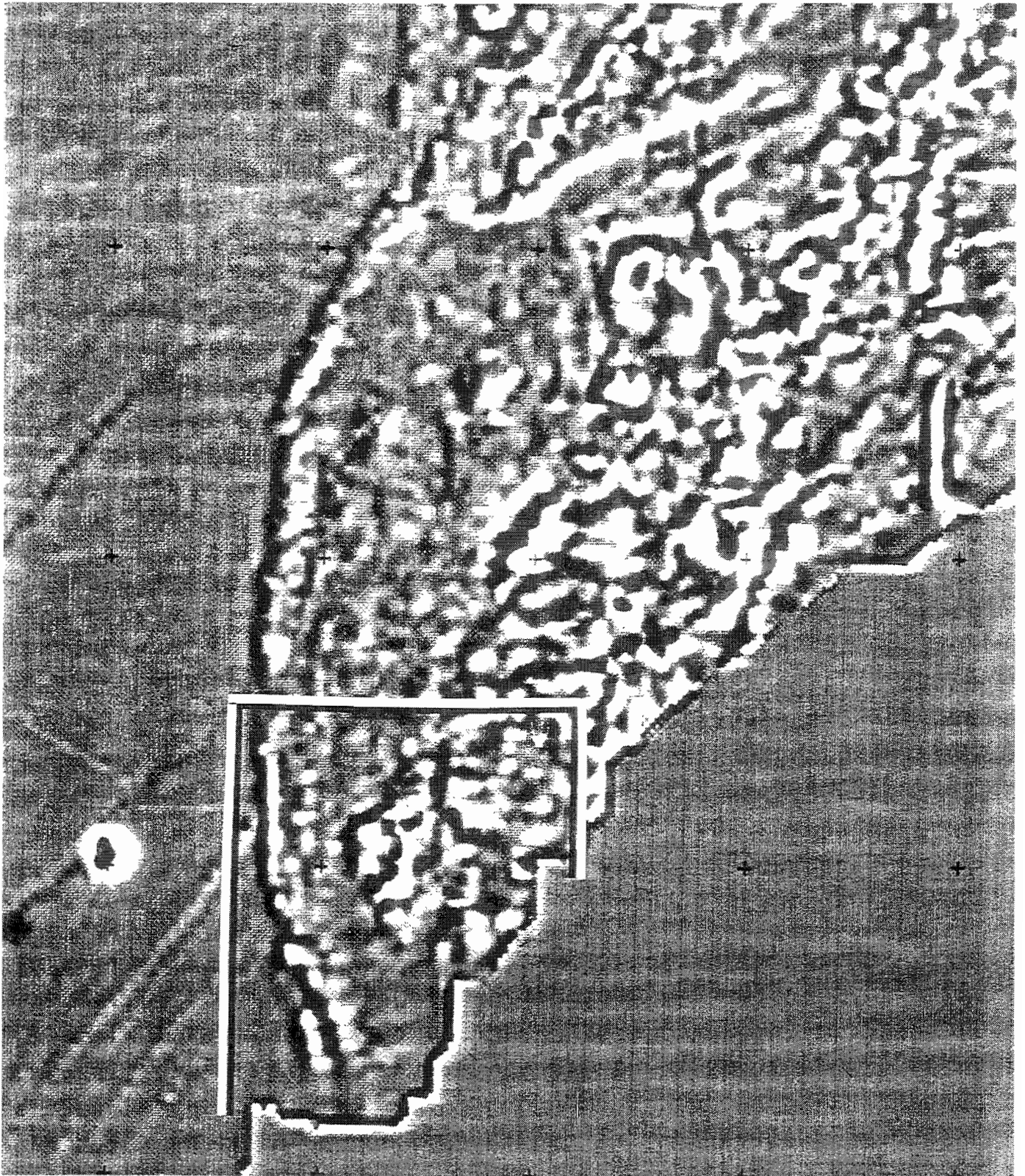


Figure 3 Gray-scale image of the first vertical derivative of high-resolution aeromagnetic data in the Duluth area. Area of Figure 2 is outlined. The anomaly west of the Figure 2 area is a gabbroic stock with a reversed magnetism.

From optical measurements on fewer than 15 samples from the layered series, Taylor (1964) concluded there was little cryptic variation in mineral compositions, and he attributed its absence to periodic addition of more primitive magma into the layered series magma chamber. However, our more than 1200 microprobe analyses of pyroxene and olivine in over 50 samples collected along two profiles through the layered series (Fig. 2) indicate trends of iron enrichment consistent with progressive differentiation owing to fractional crystallization (Fig. 4). Although repeated replenishment probably did occur and may have produced some of the cumulus reversals observed in the cyclic zone, such incursions apparently caused only minor setbacks to the overall differentiation of the layered series. Figure 4 shows that the compositions of pyroxene in monzodioritic rocks, which compose part of the upper contact zone, and in melanogranophyre, which intrudes the anorthositic series, are consistent with these rocks being differentiates of the layered series, as Taylor (1964) speculated, though they do not exclude other origins.

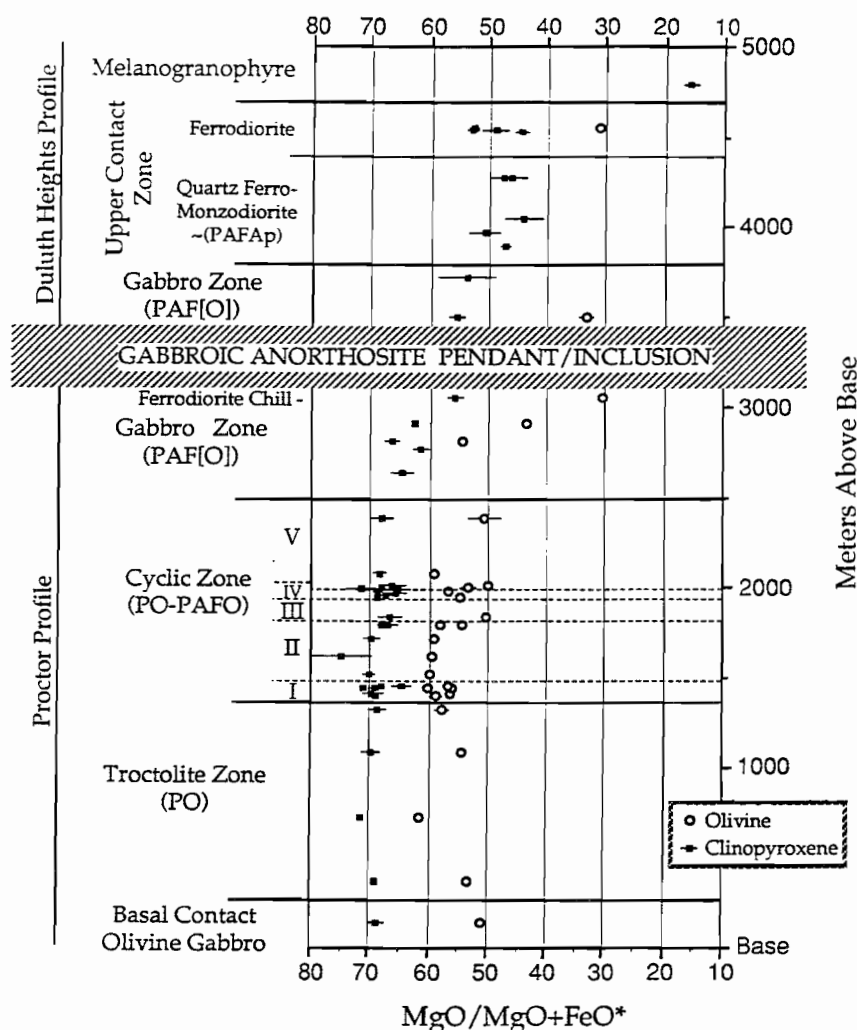


Figure 4 Stratigraphic variations of $\text{MgO}/\text{MgO}+\text{FeO}$ (mole percent) in olivine and clinopyroxene from samples taken along profiles P and DH shown in Figure 2. Horizontal bars through data points indicate standard deviation of multiple analyses. Macrocycles I-V are the same as in Figure 5. The plots of ferrodiorite and melanogranophyre compositions reflect their relative stratigraphic positions. Cumulate rock type abbreviations in parentheses are minerals (Plagioclase, Olivine, Augite, Fe-Ti oxide, Apatite) listed in order of decreasing abundance.

Basal Contact Zone—The lower 200-300 m of the layered series is composed of medium- to coarse-grained, decussate, ophitic olivine gabbro, which is locally interlayered with medium-grained, poorly laminated augite troctolite. The basal contact zone is most completely exposed along the south slope of Bardon Peak (Stop 1). Although the intrusive contact with lower Keweenaw lavas is nowhere directly visible, the gabbroic rocks within 10 m of the contact are very coarse grained, and the basaltic rocks are strongly granoblastic. In the Bardon Peak area, the macrolayers of olivine gabbro and troctolite range in thickness from 50 to 150 m. Contacts from troctolite up through gabbro are gradational, and contacts between gabbro and overlying troctolite are rather sharp (Ross, 1985). The troctolite macrolayers commonly are olivine-rich at their base and have some modal layering. Gabbro macrolayers are rarely internally layered. The rather sharp contacts between some gabbro and troctolite layers led Taylor (1964) to conclude that the gabbro was an intrusive body into the troctolite. However, Ross (1985) was able to trace the macrolayers over a distance of 3 to 5 km and concluded that they are comagmatic. He interpreted the gabbro-troctolite cycles as the result of early relatively rapid cooling of the magma forming the marginal gabbro, and periodic replenishment by more primitive liquid producing the troctolite.

Other features of the basal contact zone in the Bardon Peak area and elsewhere in the complex (Severson and Hauck, 1990) are small, irregular bodies of coarse-grained, biotitic ilmenite peridotite (Ross, 1985). Most are subcircular pipes to dikes that locally cut across layering in enclosing gabbro and troctolite but are nevertheless in gradational contact with these rocks. In one body, layering in troctolite continues through the crosscutting peridotite body. The relationships and the odd chemistry of the mineral phases in the peridotite (Ca-rich plagioclase with Fe-rich mafic minerals) led Ross (1985) to conclude that these are replacement bodies formed by metasomatic fluids generated from devolatilization of the basalt footwall.

Troctolite zone—This lower zone of the cumulate sequence is composed primarily of homogeneous, medium- to coarse-grained, moderately laminated, ophitic augite troctolite and troctolite. Modal layering of cumulus olivine and plagioclase abundance are locally developed but variable in frequency, scale, modal extremes, uniformity, lateral continuity, and orientation. Random enrichment in augite oikocrysts (1-5 cm) and Fe-Ti oxide clots (<2 cm) to as much as 15 percent of the olivine+plagioclase cumulates throughout the zone suggests periodic replenishment or eruption during crystallization. Nonsystematic variation in olivine and pyroxene composition is also evident in the troctolite zone (Fig. 4).

Cyclic zone—The variations in rock type through this zone indicate a transition from dominantly olivine-plagioclase cumulus crystallization to four-phase crystallization including augite and Fe-Ti oxide. Within this 1-km-thick zone, at least five macrocycles are recognized in the Thompson Hill area north of Interstate 35 (Fig. 5). The lower two cycles grade fairly abruptly from medium-grained ophitic augite troctolite to coarse-grained, subophitic olivine gabbro to medium-grained, well-laminated, intergranular oxide-olivine gabbro, which is commonly interlayered with a fine-grained equivalent. The upper three cycles grade from coarse-grained, subophitic olivine gabbro to medium-grained, well-laminated, and intermittently layered, intergranular oxide-olivine gabbro (e.g., Stop 2). All boundaries between the cycles are abruptly gradational to sharp, and the boundary at Stop 2 is marked by a gabbroic anorthosite inclusion. More significantly, these boundaries mark the regression of cumulus paragenesis from $Pl+Cpx+Ox\pm Ol$ back to $Pl+Ol$.

General Rock Types

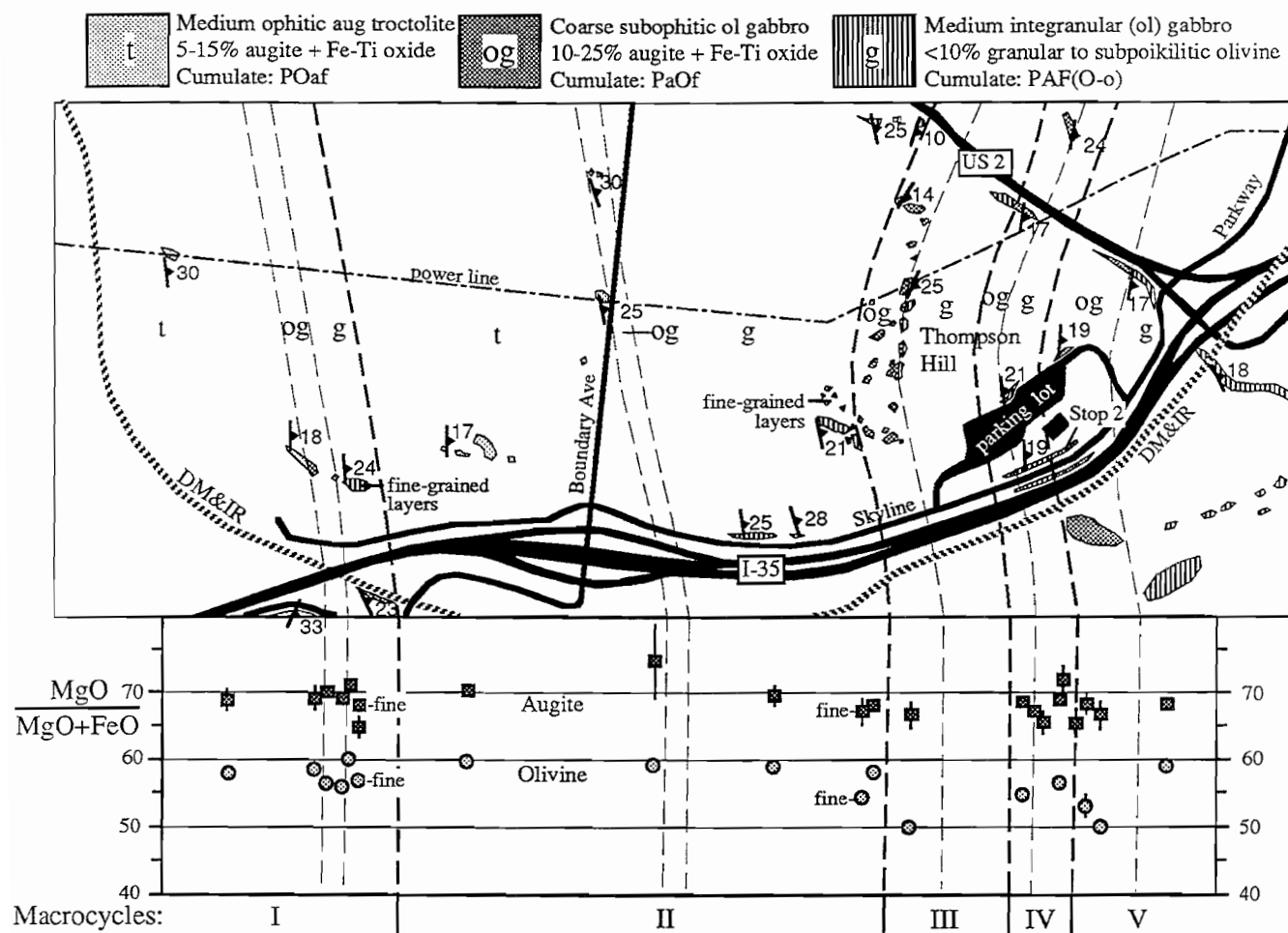


Figure 5 Geology and cryptic variation of olivine and clinopyroxene across the cyclic zone of the layered series in the vicinity of Thompson Hill. Cumulate rock abbreviations as described in Figure 4 (lower case letters for intercumulus phases). Alternations between three general rock types define five macrocycles (I-V) as discussed in the text and in Miller (abstract volume).

The progression of rock types within each macrocycle, as well as the cumulus regressions between them, is probably the result of normal magmatic differentiation interrupted by recharge of a more primitive magma, periodic eruption and concomitant decompression of the magma chamber, or some combination of both processes (see Miller, abstract volume).

Gabbro zone—With the exception of nearly continuous exposure along Keene Creek (Fig. 2), this zone is poorly exposed, with some areas having more outcrops of gabbroic anorthosite inclusions than gabbro. The gabbro is typically medium-grained, poorly to well-laminated, intermittently layered, intergranular (olivine-)oxide gabbro (i.e., a Pl+Cpx+Ox±Ol cumulate). Ilmenite is a ubiquitous phase in these rocks and commonly occurs as aligned blades paralleling plagioclase to create a well-developed igneous lamination. Olivine is not everywhere present and locally is subpoikilitic (intercumulus), though typically it is granular. Gabbro lacking olivine is commonly rich in inverted pigeonite. Many exposures in the upper part of the zone contain up to 3 percent apatite as large prismatic grains, which are considered to be cumulus.

The transitional contact between the gabbro zone and the overlying upper contact zone is defined as the approximate level where obvious lamination in the gabbro is lost (Fig. 2). Although the overall cryptic layering in the gabbro zone varies by as much as 20 percent in Fo and En content of olivine and augite (Fig. 4), the gabbro at the contact exposed along Skyline Parkway is significantly more primitive than the less well exposed transition in the Duluth Heights area (Fig. 2) and supports the suggestion that the anorthositic rocks projecting southwest along the escarpment may actually be a very large inclusion, which broke away from the anorthositic series roof and settled into the layered series cumulates at the time the gabbro zone was accumulating. If so, it would also explain the synformal structure of the layered series whose axial trace projects west of this anorthositic mass (Fig. 2). If the anorthositic cap does prove to be continuous, it implies a very irregular roof to the layered series.

Upper contact zone—This upper unit of the layered series is composed of two distinct rock types that are complexly intermixed and share a common decussate (noncumulate) texture. One rock type is everywhere adjacent to the main contact with the anorthositic series and in many places also occurs some distance away from it. It is very fine to medium-grained, decussate to locally flow-laminated, intergranular, ilmenitic ferrodiorite. Locally, the fine-grained variety of ferrodiorite consists of as much as 10 percent biotite, occurring as 3- to 5-mm subpoikilitic clots, and is locally cut by abundant felsic veins and dikes ranging in composition from leucogranite to quartz monzodiorite (e.g., Stops 5 and 6). Some of the ferrodiorite is so fine grained and equigranular that it can be easily mistaken for a metabasalt. At the westward extension of the anorthositic mass between Miller and Keene Creeks (Fig. 2), the ferrodiorite alone forms the narrow (<50 m) upper contact zone, which grades abruptly into underlying gabbro cumulates. Downsection from the contact in the Duluth Heights and Piedmont Heights area (e.g., Miller Creek between Stops 5 and 6) however, the second rock type—a medium-grained, apatitic, hornblende-pyroxene quartz monzodiorite, which Taylor (1964) called ferrogranodiorite—occurs as irregular bodies intruded into and eventually predominating over the fine-grained ferrodiorite. Although lacking the textural characteristics of a cumulate rock, the monzodiorite in the Duluth Heights area does have progressively more evolved compositions upward through the upper contact zone, which are continuous with compositions observed in the underlying gabbro zone (Fig. 4).

A possible interpretation of the two phases of the upper contact zone, which was suggested by Taylor (1964), is that the fine-grained ferrodiorite represents an upper chill of layered series magma against the earlier formed, cold anorthositic series cap and that the monzodiorite phase represents a late differentiate of the layered series, which later intruded this upper chill zone. Although the ferrodiorite is clearly finer grained where it is in contact with anorthositic rocks, two lines of evidence suggest that the anorthositic cap was quite hot when the layered series intruded beneath it. First, given the identical ages³ of samples from both series (1099.2 ± 0.4 Ma), it is very improbable that the anorthositic series could have been cool enough to quench layered series magma. Second, although a whole rock composition of the ferrodiorite has yet to be analyzed, its mineralogy and mineral chemistry (Fig. 4) seems to be too evolved to represent a quench of the layered series parent magma. Rather, the ferrodiorite would more appropriately be equivalent to differentiated magmas that produced rocks of the cyclic and gabbro zones. At this later stage of layered series crystallization, the anorthositic cap would have been heated by the underlying layered series if it were not already hot at the time of initial emplacement.

3. There is some question as to whether the gabbro sample dated from the Duluth area contains inherited zircons from anorthositic series inclusions (see Stop 3 description). However, similar 1099 Ma ages of other samples of the troctolitic and anorthositic series from the northwestern part of the complex support the general conclusion that the two series are nearly contemporaneous in their formation (Paces and Miller, in press).

An alternative explanation for the origin of the ferrodiorite is that it represents a quench resulting from eruption and decompression of the magma chamber at some stage further along in the differentiation of the layered series magma. Repeated magma expulsion through the roof zone is evident from the many and varied compositions of intrusions into the anorthositic series cap (Fig. 2; see description of other rock units below). A problem with a decompression model is accounting for the apparently large volume of this fine-grained "quench zone." For example, if the upper contact is parallel to the uppermost layered series lamination in the gabbro zone (dips of 10-25° to the east; Fig. 2), the thickness of ferrodiorite in the Miller Hill Mall area (Fig. 9), where it predominates over quartz monzodiorite, would be in the range of 350 to 750 m.

Melanogranophyre—An irregular body of predominantly felsic to intermediate rocks cuts the anorthositic series downslope from Enger Park (Fig. 2). Over 90 percent of the body is composed of a salmon-red melanogranophyre (3-10 percent Fe silicate and oxide) grading locally to a medium-grained, intergranular quartz ferromonzodiorite. Other rock types near the margin of the body include a medium-grained, layered olivine ferrogabbro, which is similar to rocks in the gabbro zone, and a coarse-grained, strongly altered, leucocratic hornblende monzogabbro. The textural and mineralogic variability of the monzogabbro and its compositional characteristics led Seifert and Kracher (1992) to conclude that it is a heterogeneous hybrid of the granophyre/monzodiorite and the host gabbroic anorthosite. The gabbroic anorthosite in this area is strongly altered and tends to contain abundant granophyric mesostasis. The range of rock compositions suggests that this body is a composite intrusion formed from magmas derived from the underlying layered series at various stages in its differentiation history. However, it is also possible that some portion of the body may have been derived from expulsion (by filter pressing?) and concentration of intercumulus melt from the surrounding gabbroic anorthosite.

Upper porphyritic gabbro — A medium-grained, sparsely to moderately plagioclase-porphyritic, subophitic to ophitic olivine gabbro containing locally abundant volcanic hornfels and rare gabbroic anorthosite inclusions occurs intermittently along a 200- to 300-m-wide zone sandwiched between metamorphosed volcanic rocks and coarse gabbroic anorthosites at the upper contact of the Duluth Complex (Fig. 2). Where this inclusion-rich unit is well exposed on the Radio Tower hill above downtown Duluth (Stop 10; Fig. 10), Taylor (1964) incorrectly mapped it as part of the base of the volcanic series. The actual contact with the volcanic rocks is marked by a thin (<10 m) selvage of quartz monzonite which irregularly grades into the olivine gabbro. The gabbro generally contains less than 15 percent phenocrysts but locally may contain up to 35 percent. The abundance of phenocrysts generally, but nonsystematically, increases away from the volcanic contact. The contact with the main suite of gabbroic anorthosite is not well exposed, but it seems to be abrupt, and the porphyritic gabbro may actually finger into the anorthositic series as dike-like apophyses.

A possible interpretation of the porphyritic gabbro is that it represents the upper border phase of the anorthositic series that formed by flow differentiation of plagioclase crystals away from the contact with overlying volcanic rocks. Several problems exist with this interpretation, however. For one, this rock type is not everywhere exposed along the contact between the main suite of anorthositic rocks and the volcanic rocks, though it can be inferred along most of it. Second, the gabbro contains anorthositic and basaltic xenoliths that are not flow differentiated from the contact like the plagioclase phenocrysts. Third, although the contact between the gabbro and the anorthositic rocks is not directly exposed, field relations suggest that it is very abrupt. However, such a rapid transition from nonporphyritic margins to porphyritic interiors is common in flow-differentiated dikes. Finally, the map pattern of the gabbro suggests that the gabbro transgresses down into the anorthositic rocks though this is by no means certain.

An alternative explanation is that this body represents a discrete intrusion into the anorthositic series that was emplaced at the anorthositic-volcanic contact. Except for its highly altered state, its primary composition and texture are similar to the basal contact zone of the layered series. That it is intruded by a more evolved gabbro (see Stop 10) is consistent with its being emplaced early in the crystallization history of the layered series. Clearly more study of this unit is necessary to establish the relationships to the adjacent gabbroic anorthosite.

Ophitic olivine diabase— Many outcrops in the Miller Hill Mall area (e.g., Stops 7 and 8) are of a medium-grained, decussate, ophitic olivine diabase/gabbro of obscure origin. Other nearby exposures are ascribed to the gabbro and upper contact zones, but contacts between the diabase and these layered series rocks are poorly exposed. In the southern part of the large western body along Decker Road (Fig. 9), the diabase appears to include fine-grained mafic rocks similar to the ferrodiorite of the upper contact zone, thereby implying an intrusive origin to the diabase. However, at Stop 8, similar fine-grained ferrodiorite underlies ophitic olivine diabase along a sharp, shallow (20°) southeast-dipping contact without any apophyses or xenoliths. Whereas the diabase is relatively unaltered in most exposures, there it has clouding of plagioclase and recrystallization textures near the contact with fine-grained ferrodiorite. Moreover, the ferrodiorite is subtly coarser away from the contact..

If the diabase is a xenolith, its origin is unclear. Although its ophitic texture is similar to that of most anorthositic rock types, the diabase is more uniform in texture, more medium in grain, more cotectic in its plagioclase content, and less flow laminated than typical anorthositic series rocks. Although texturally and mineralogically similar to the porphyritic gabbro at the upper contact, it is significantly less hydrothermally altered, not obviously porphyritic, and contains no inclusions.

PETROGENETIC RELATIONSHIP BETWEEN THE ANORTHOSITIC AND LAYERED SERIES

Given the apparent mafic "chill" of the layered series against the anorthositic series rocks in several locations and the distinct lithologies and structures that characterize both series, it is entirely understandable that the accepted interpretation has been that the anorthositic series is significantly older than the layered series (troctolitic series of Weiblen and Morey, 1980)—an interpretation that has become the main paradigm for the Duluth Complex. However, the U-Pb zircon dates, which indicate virtually identical ages of 1099 Ma for both anorthositic and layered series rocks (Paces and Miller, in press), severely undermine this interpretation (Miller, 1992). Although the ages do not contradict the generally older status of anorthositic rocks, which is unquestionable on the basis of abundant field evidence, they nevertheless imply that the two series were emplaced in rapid succession (within 0.9 Ma of each other at Duluth and within 1.2 Ma in the northwestern part of the complex).

Many geologic features of the two series are consistent with their nearly contemporaneous formation. For example, if the fine-grained ferrodiorite at the anorthositic-layered series contact is in fact a decompression quench rock, rather than a chill of the original layered series parent magma, emplacement of the layered series beneath a hot and perhaps even partially molten anorthositic series cap is not a problem. The possibility that the ferrodiorite formed some time later in the differentiation of the layered series also allows the interpretation that the leucotroctolite mantling part of the lower anorthositic series is comagmatic with some phase of the troctolitic zone. Also, the enrichment of granophyric mesostasis in gabbroic anorthosite in the vicinity of the melanogranophyre body and the presence of hybrid monzogabbros at its margins are consistent with at least part of the anorthositic series being partially molten during the crystallization of the layered series.

FIELD STOP DESCRIPTIONS

STOP 1. BASAL CONTACT ZONE AND LOWER TROCTOLITE ZONE OF THE LAYERED SERIES

Location: Roadcuts along the abandoned Duluth, Winnipeg, and Pacific (upper) Railroad on the south slope of Bardon Peak. Approach is from the south by heading up a footpath beginning where 108th Street. curves from north to west. S1/4 of section line, secs. 33-34, T. 49 N., R. 15 W.

Description: This stop examines the basal contact of the layered series with lower Keweenaw basalts, stratigraphic variations through the 200 to 250-m-thick basal contact zone, and the lower 50 m of the troctolite zone (Fig. 6) along the upper abandoned railroad grade. Within 5 m of the unexposed basal contact, the volcanic footwall rocks of the Ely's Peak basalts (Kilburg and Morey, 1977) are strongly recrystallized to a dense granoblastic hornfels. This hornfels is locally intruded by irregular bodies of coarse-grained to pegmatitic, biotitic, feldspathic to pyroxenitic gabbro. One such gabbro body grades abruptly into a core of melanogranophyre. Preliminary geophysical modeling suggests that the basal contact dips moderately to steeply to the east, a conclusion consistent with the straight trend of the contact down the escarpment and the steeper layering of the troctolite relative to the bedding of the volcanic rocks (Fig. 6).

For 500 m east along the upper grade, generally poor exposures of coarse-grained, decussate olivine gabbro (og) and medium-grained, intermittently layered troctolite (t) are found that Ross (1985) recognized as forming cyclic macrolayers in the basal contact zone (Fig. 6). In several locations, both rock types are cut by small, deeply weathered, irregular bodies of biotitic peridotite to olivine melagabbro (Ross's Type III peridotite). Near the abrupt contact between coarse olivine gabbro and overlying troctolite (forming the base of the troctolite zone), are several larger ilmenitic peridotite bodies. The largest is a deeply weathered, 12-m-long body that is subparallel to the grade and straddles the gabbro-troctolite contact. East of this body is a subvertical dike up to 1 m across, which is in sharp but unchilled contact with layered troctolite and is closely associated with a nearby mafic hornfels inclusion. Layering in the troctolite can be traced through the peridotite mass without any discernable disruption, a feature which Ross (1985) cited as evidence for a metasomatic origin of the peridotite. Between 5 and 50 m above the gabbro-troctolite contact, the troctolite becomes melanocratic, very well laminated, and layered. Types of layering include graded laying, isomodal layering, fine-scale rhythmic layering, and trough layering. Above this zone the troctolite becomes homogeneous with only intermittent olivine layering.

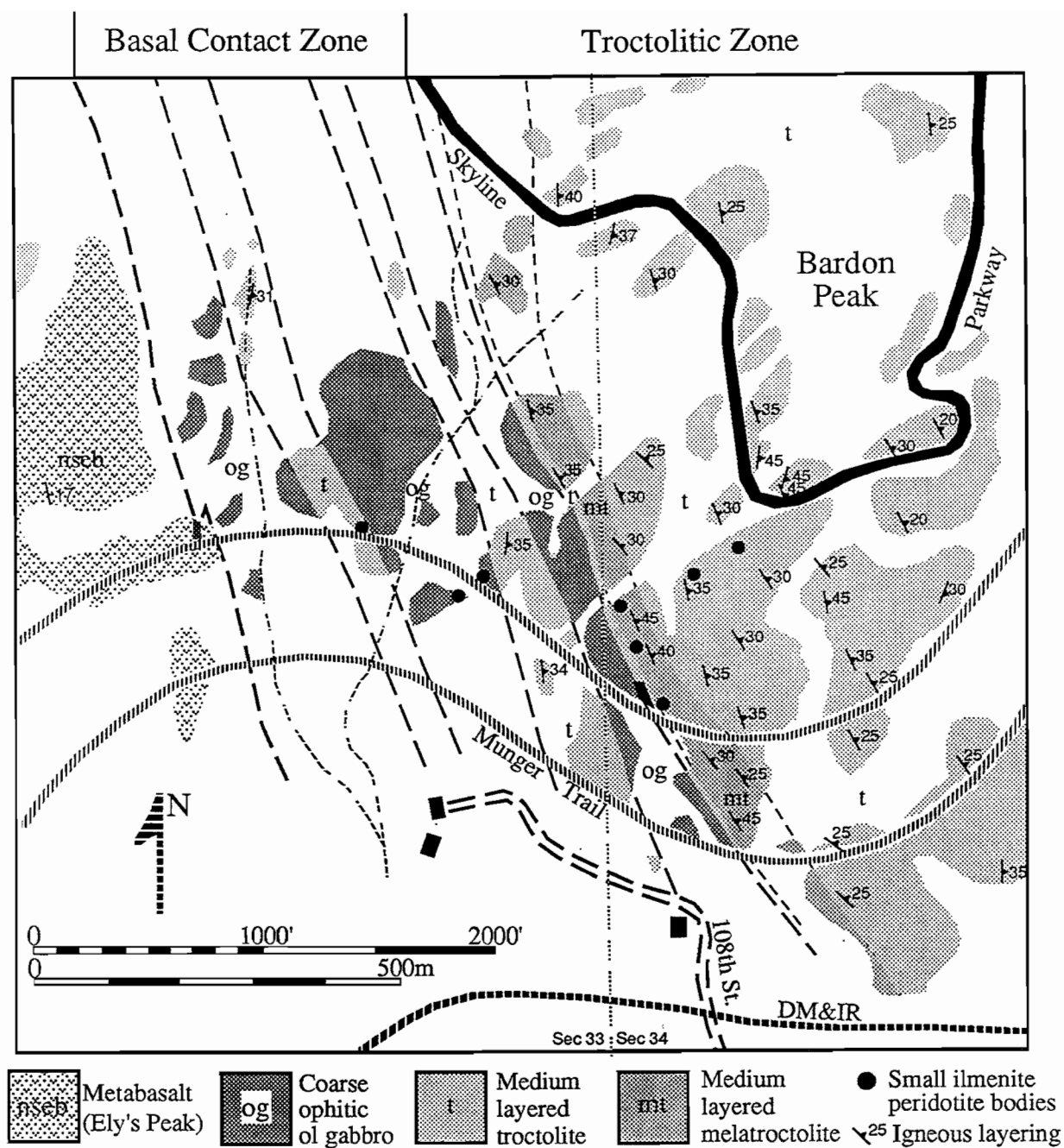


Figure 6 Outcrop geology of the Bardon Peak area (geology after Ross, 1985; structural data from Foster, 1982).

STOP 2. CYCLIC ZONE OF THE LAYERED SERIES

Location: Roadcut on Skyline Parkway below overlook at Thompson Hill rest area. Center sec. 14, T. 49 N., R. 15 W.

Description: The layered sequence of gabbroic rocks along this 200-meter-long roadcut (Fig. 7) exposes a reversal in cumulus paragenesis that is observed at many horizons in the cyclic zone of the layered series (Fig. 2 and 5). The west end of the roadcut begins with a coarse-grained, moderately laminated, subophitic olivine gabbro which locally is intergranular and elsewhere is leucocratic (sample A, Fig. 7). Augite in this rock is marginally cumulus but becomes definitely so a short distance upsection where it consistently displays an anhedral granular to subprismatic habit. This coarse-grained, intermittently layered (locally graded) olivine-poor (<5%) oxide gabbro (sample B) classifies as a Pl+Cpx+Ox+Ol cumulate. Beyond a poorly exposed interval, this gabbro includes a 2-m-thick interval in which minor olivine becomes subpoikilitic and concentrated in layers (sample C). Another 3 m above this, the coarse gabbro passes abruptly into a medium-grained, well-laminated subpoikilitic olivine-bearing oxide gabbro (samples D&D') which displays layering of olivine oikocryst concentration; elsewhere isomodal layering of Fe-Ti oxide+pyroxene abundance occurs. The very strong alignment and subhedral to euhedral habit of cumulus phases (plagioclase, pyroxene, and ilmenite) impart an adcumulate texture to this rock. Across a poorly exposed interval of about 15 m is an altered, coarse-grained, ophitic gabbroic anorthosite (sample E) that is texturally and mineralogically identical to rocks of the anorthositic series. At the beginning of the next well-exposed section of roadcut are several similar gabbroic anorthosite inclusions in a coarse-grained, subophitic to intergranular olivine gabbro (sample F), which gradually grades upward into a more consistently subophitic texture over the remainder of the roadcut (sample G). This rock type closely resembles that at the west end of the roadcut and indicates a downgrading in the cumulus status of pyroxene (and oxide?) and a reemergence of cumulus olivine.

A possible interpretation of this reversal in the cumulus status of the mafic mineral phases is that it represents recharge by magma undersaturated in pyroxene and oxide, which was emplaced and mixed with an evolved resident magma that, prior to recharge, had been saturated in both these phases and undersaturated in olivine. The gabbroic anorthosite inclusions presumably mark the floor of the magma chamber at the time this recharge event occurred. However, the cryptic variation of MgO/MgO+FeO in pyroxene and olivine through this sequence (Fig. 7) is not consistent with such an explanation. The expected decrease in this ratio, albeit observed in samples A, B, and C, actually increases to its greatest value in the most "differentiated" cumulates in samples D&D'. This MgO enrichment may reflect the adcumulate nature (i.e., a low trapped-liquid component) of these medium-grained, well-laminated gabbro samples, or it may reflect a shift in the equilibrium compositions of mafic silicates caused by the cumulus crystallization of Fe-Ti oxide. Regardless, the expected increase in MgO/MgO+FeO above the recharge horizon is not obvious in either the pyroxene or olivine. An alternative explanation is that the textural and compositional variations across this interval reflect decompression of the chamber caused by eruption to the surface (also see Miller, abstract volume). Such an event could produce abrupt textural changes without much compositional variation, as observed here and in other parts of the cyclic zone (Fig. 4). Magma expulsion through the roof of the layered series would also explain the occurrence of gabbroic anorthosite inclusions in this interval and elsewhere throughout the cyclic zone.

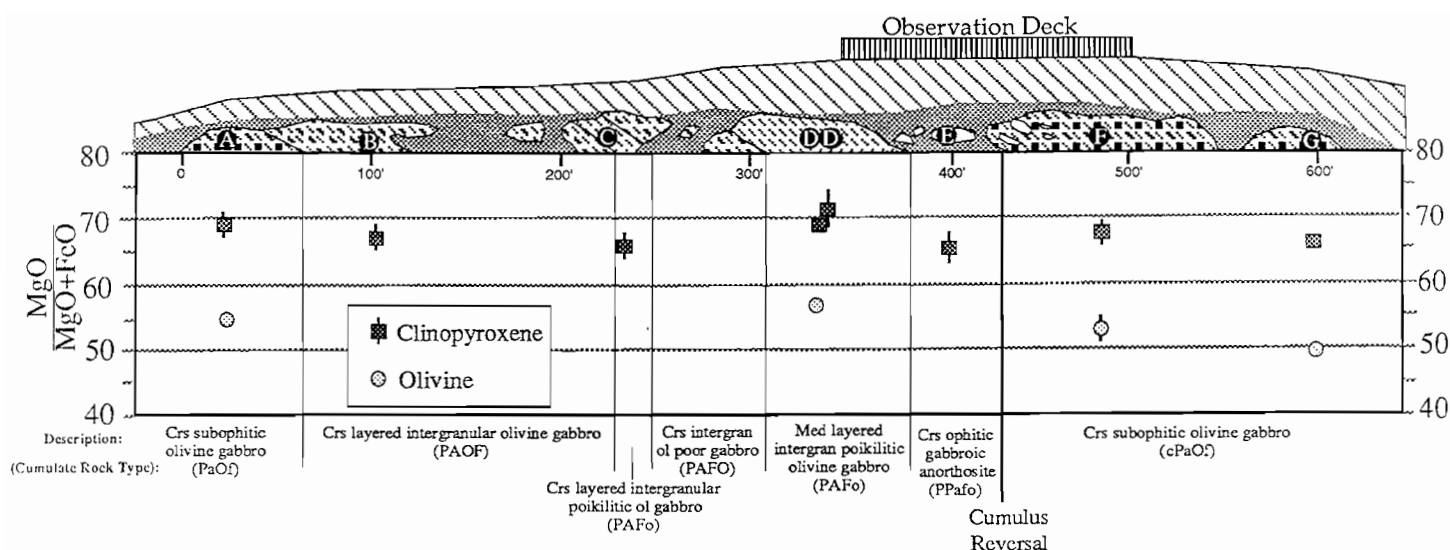


Figure 7 Detail of geology and cryptic variation along Skyline Parkway roadcut near Thompson Hill rest area. View is to the north. Dip of lamination and layering is exaggerated; it averages about 20° to the east. Contacts between units are gradational over thicknesses of 10 cm to 1 m. Cumulate rock type abbreviations as defined in Figure 4.

STOP 3. GABBRO ZONE OF THE LAYERED SERIES

Location: Roadcut on Skyline Parkway on southwest side of Keene Creek and outcrop in streambed; 0.2 mile east and north of intersection with Getchell and Highland Roads. SW1/4 sec. 1, T. 49 N., R. 15 W.

Description: The dominant rock type exposed in the roadcut and streambed exposures along this stretch of Keene Creek is a medium-grained, moderately laminated, locally layered, intergranular olivine gabbro. This rock, with its cumulus mineralogy of plagioclase, augite, Fe-Ti oxide (mostly ilmenite), and variable amounts of olivine, is typical of most of the gabbro zone. Along the main roadcut, the rock is laminated but generally unlayered. In the streambed, its fine-scale, cross-bedded modal layering locally appears disrupted as if by slumping. Elsewhere in the streambed exposure, the medium-grained gabbro is interlayered on a larger scale with a coarser, leucocratic, subophitic gabbro. Another roadcut northwest of a jog in the road shows the medium gabbro in irregular gradations with coarse, decussate, locally leucocratic gabbro. This coarser gabbro may actually be gabbroic anorthosite inclusions, which are in great abundance throughout the gabbro zone in this area. If so their gradational contact relationship with the medium-grained gabbro suggests that they were incorporated while hot and perhaps partially molten.

The abundance of anorthositic xenoliths in the gabbro zone was not appreciated at the time that a sample was taken for zircon dating of similar rocks on the opposite side of the creek valley (Paces and Miller, in press). That sample, a varitextured gabbro that included a coarse subophitic phase, yielded a 1099.3 ± 0.3 Ma age that is identical to a sample taken from the anorthositic series (1099.2 ± 0.4 Ma). However, the zircons derived from this sample show no overgrowths or isotopic compositions that would indicate a complicated history. Unless additional dating proves otherwise, this date should be accepted as the crystallization age of the gabbro zone.

STOP 4. MAFIC APOPHYSIS OF THE LAYERED SERIES & ANORTHOSITIC SERIES

Location: 57th Avenue quarry; access by taking 57th Avenue north across DM&IR Railroad tracks to trail heading west and north. SW1/4 sec. 6, T. 49 N., R. 14 W.

PLEASE DO NOT CLIMB UP THE UNSTABLE STEEP SLOPES!

Description. Many mineralogic and textural varieties of gabbroic anorthositic rocks forming the anorthositic series are represented in the blocks scattered along the base of the quarry face. The most common is a coarse-grained, moderately laminated, ophitic, poikilitic olivine gabbroic anorthosite.

Exposed along the crest of the quarry face is a subhorizontal sheet intrusion, at least 15 m thick in places, of fine-grained mafic rock which upon closer inspection proves to be a composite intrusion. Exposures of the mafic rock in the north corner of the quarry can be reached by a foot trail leading up along the northeast slope. Just before the corner of the quarry, an outcrop at the crest of the face shows a very fine grained microgabbro in sharp contact with gabbroic anorthosite and a more medium-grained olivine gabbro intruding the microgabbro as a near-vertical dike (Fig. 8A). A thin section across the contact of the gabbroic anorthosite and the microgabbro (taken from the contact exposed on the opposite end of the quarry) shows the latter to contain equigranular pyroxene, oxide and minor olivine, but well-aligned laths of plagioclase are parallel to the contact. A thin section of the contact between the medium-grained olivine gabbro and the microgabbro shows the lamination in the microgabbro to be at a right angle to the contact (Fig. 8B). Within a centimeter of the contact, plagioclase in the medium-grained olivine gabbro is aligned parallel to the contact, but then abruptly fans away from it. Farther up from the gabbroic anorthosite-microgabbro contact and the diking relationships, it appears that the microgabbro coarsens and eventually grades into the medium-grained olivine gabbro (Fig. 8A).

Another good, slightly different exposure of this composite mafic intrusion occurs about 40 m southwest of the quarry corner at the lip of the face (BE CAREFUL). Here, a microgabbro is again in sharp contact with the gabbroic anorthosite and can be seen to coarsen slightly away from the contact. However, within a meter of that contact, the microgabbro is cut by a slightly coarser gabbro of similar composition (Fig. 8C). This contact is sharp and contains a gabbroic anorthosite inclusion. Also, the upper gabbro rock is slightly finer grained at the contact with the lower mafic rock.

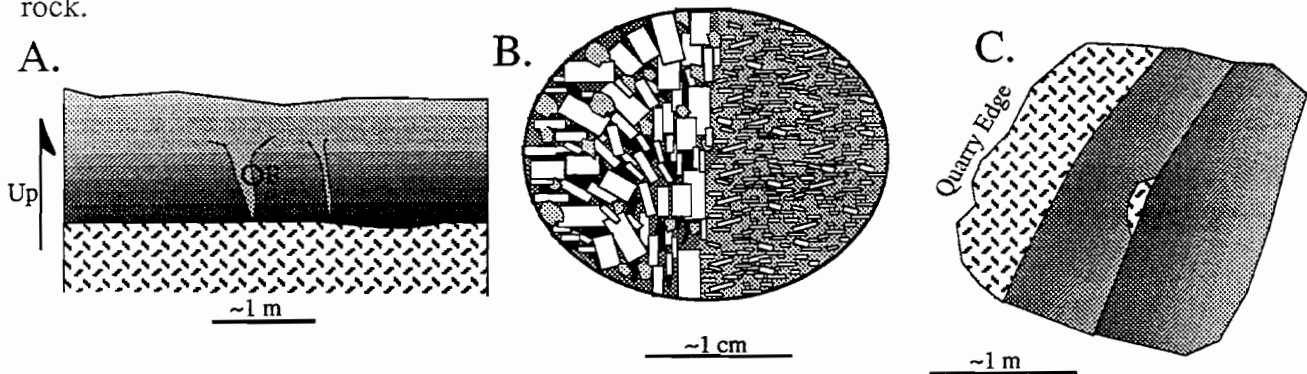


Figure 8 Sketches of contact relationships between gabbroic anorthosite (hatched pattern), microgabbro (darker tone), and olivine gabbro (lighter tone) in the crest of the 57th Avenue quarry. A) Diking relationships of coarser olivine gabbro into fine-grained microgabbro in vertical section. B) Sketch of texture of contact relationships between well-laminated microgabbro (right) and medium-grained olivine gabbro. Phases portrayed are plagioclase (white rectangles), ilmenite (black blades), olivine (lighter grains), and pyroxene (darker areas). C) Composite intrusive relationships of gabbro in subhorizontal outcrop surface at crest of quarry face.

Schwartz (1949) first reported these relationships and concluded that the mafic body is a large hornfels inclusion which was recrystallized and partially melted by the heat of the gabbroic anorthosite. Taylor (1964) recognized that the body was a composite intrusion emanating from the layered series. He concluded that the microgabbro was chilled against the cold gabbroic

anorthosite and then recrystallized to a granoblastic texture by the intrusion of the medium-grained olivine gabbro. Although the mafic and oxide phases in the microgabbro are clearly equigranular, they rarely form 120° triple junctions typical of mafic hornfels. Together with the well-aligned plagioclase laths, this suggests that the texture of this rock does not reflect recrystallization, but rather rapid crystallization during emplacement into the anorthositic rock. Not surprisingly, the microgabbro looks identical to parts of gabbroic intervals in the cyclic zone of the layered series, which may have resulted from decompression quenching. What is clear is that this rock does not represent the parent magma of the layered series. Whole rock analyses of the microgabbro reported by Taylor (1964, Table 3) show it to be a titaniferous ferrogabbro (7% TiO₂, 17% FeOT). Phase equilibrium calculations indicate that this composition would give rise to a Pl+Cpx+Ox(ilm) cumulate. Therefore, the parent magmas to these gabbros most likely were derived from the layered series during crystallization of the cyclic or gabbro zones. Mineral composition data and more whole rock analyses will be acquired to better constrain this relationship.

STOP 5. UPPER CONTACT ZONE OF THE LAYERED SERIES AND ANORTHOSITIC SERIES

Location: Lincoln Park on Miller Creek below the 10th Street Bridge. SW1/4 NE1/4, Sec. 32, T. 50 N., R. 14 W. WATCH YOUR FOOTING, SLIPPERY ROCKS.

Description: Steambed exposures starting just downstream from the 10th Street Bridge and continuing upstream to the culvert beneath the intersection of Skyline Parkway and U.S. 53 show an assemblage of rock types typical of the upper contact zone of the layered series. Outcrops beneath the bridge to about 40 m downstream are predominantly a very fine to fine-grained, ilmenitic ferrodiorite cut by many felsic veins and dikes. Between 25 and 40 m downstream from the bridge are abundant inclusions of gabbroic anorthosite. Typically, these inclusions are mantled by granophyre, suggesting that they may be the source for some of the felsic material. Below 40 m all exposures are of gabbroic anorthosite. The ferrodiorite of the contact zone has a felty texture formed by decussate subprismatic plagioclase, bladed ilmenite, and anhedral pyroxene and amphibole. Typically, subpoikilitic biotite clots compose as much as 5 percent of this rock, but here such clots are rare. The felsic veins and dikes cutting the ferrodiorite are typically medium grained and intergranular but range in mafic mineral content (mostly Fe-pyroxene, amphibole, and iron oxide) from 5 to 30 percent. Upstream from the bridge, the felsic dikes are somewhat less abundant, but otherwise the ferrodiorite remains fine grained and unstructured. However about 250 m upstream from the 10th Street bridge, is a reddish, medium-grained, intergranular quartz ferromonzodiorite, which is composed of, in decreasing order of abundance, altered plagioclase, amphibole (primary and secondary after pyroxene), orthoclase, quartz, ferroaugite, iron oxide, biotite, and apatite. The nature of the transition from ferrodiorite to ferromonzodiorite is not clear here, though at the next stop the ferromonzodiorite is observed to intrude the fine-grained ferrodiorite. Upstream to the culvert, the ferromonzodiorite coarsens slightly and is locally cut by felsic dikes.

STOP 6. UPPER CONTACT ZONE OF THE LAYERED SERIES.

Location: Along Miller Creek, southwest of Duluth Technical College. SW1/4, sec. 29, T. 50 N., R. 14 W.

Description: The most common rock type exposed in the 4-m-high outcrops flanking the creek is a reddish, medium-grained, apatitic quartz ferromonzodiorite. The mafic phase of the rock is predominantly iron-rich hornblende (MgO/MgO+FeO=31.2%), Fe-Ti oxide and minor Fe-augite. This rock is very similar to that in upper Lincoln Park, except that it is much more enriched in apatite (2-3% here). As seen at the last stop, some parts of the exposure (e.g., near the north end of the high cliff on the west bank) contain fine-grained ilmenitic ferrodiorite. Here, however, the

ferrodiorite is clearly intruded by and is volumetrically subordinate to the quartz ferromonzodiorite. The more evolved nature of the monzodiorite compared to the ferrodiorite is evident in their mineralogies as well as their mineral compositions. For example, the $\text{MgO}/(\text{MgO}+\text{FeO})$ (molar) ratio of primary hornblende is 39.6 percent in the ferrodiorite and 31.2 percent in the monzodiorite. Downstream and roughly upsection, the ferrodiorite becomes dominant, with quartz ferromonzodiorite restricted to discrete dikes. Upstream (downsection), the ferrodiorite is rare and the apatitic ferromonzodiorite grades into a more mafic composition with the addition of ferroaugite and loss of quartz, orthoclase, and hornblende, and locally it is poorly laminated and subtly layered. The field relationships here and at Stop 5 suggest that the apatitic quartz ferromonzodiorite (which Taylor called ferrogranodiorite) represents the upper differentiate of the layered series, which has locally reintruded the upper "chill" zone represented by the ferrodiorite.

STOP 7. OPHITIC OLIVINE DIABASE

Location: Whaleback outcrop north of the Target store on the southwest side of Highway 53-194 (Central Entrance), 0.25 mile northwest of intersection with Maple Grove Rd. SW1/4, sec. 18, T. 50 N., R. 14W.

Description: Several apparently separate bodies of massive, medium-grained, ophitic (2- 4-cm oikocrysts) diabase or gabbro are exposed in the Miller Hill Mall area (Fig. 9). Regional field relationships indicate that the diabase is enclosed by both upper gabbro cumulates and upper contact zone rocks of the layered series (Fig. 2). In the outcrop here, north of Target, the ophitic diabase is very massive and fresh looking (unaltered and unmetamorphosed). Across Highway 53, layered olivine ferrogabbro of the gabbro zone can be seen, but a contact between these rocks is not exposed. However at the next stop, it seems clear that a similar diabase is a xenolith.

The diabase is cut by a spectacular set of pink granophyre veins and dikes which have intruded along dilating fractures. The dike margins and thinner veins are generally coarser grained than the interiors of the thicker dikes, which might be explained by decompression quenching or degassing of felsic magma, as noted in some plutonic pegmatite-aplite complexes. The source of the felsic magma is unclear, but it may be residual differentiate from the surrounding gabbro zone cumulates.

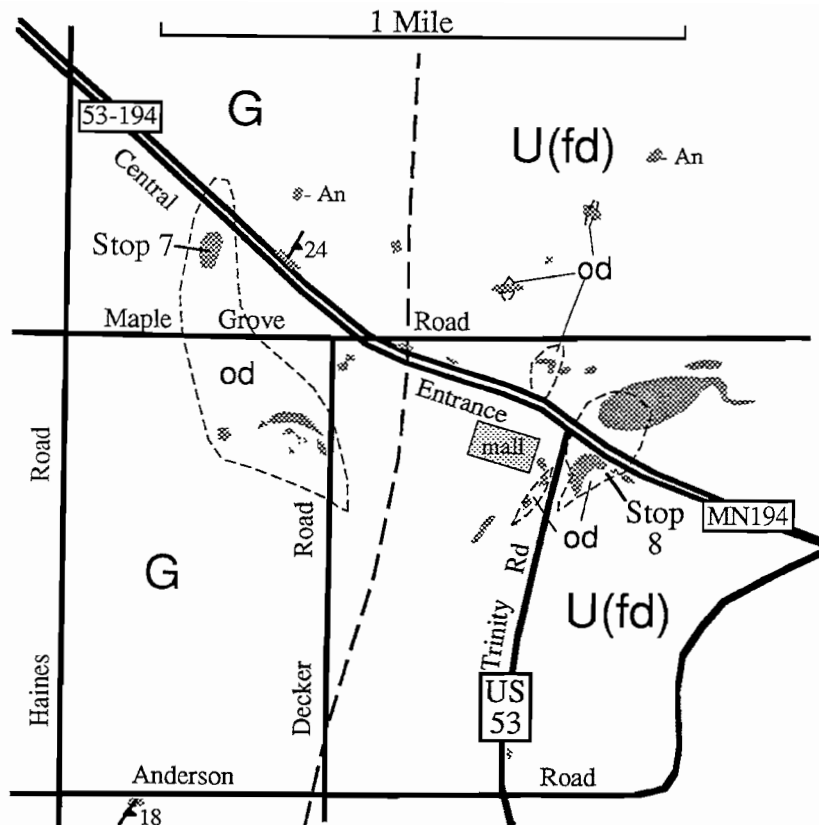


Figure 9 Outcrop geology of the Miller Hill Mall area, showing locations of Stops 7 and 8. G, gabbroic cumulates of the gabbro zone; U (fd), upper contact zone of the layered series, here predominantly composed of fine-grained ferrodiorite; od, ophitic olvine diabase bodies; An, outcrops of gabbroic anorthosite, probably inclusions.

STOP 8. OPHITIC OLIVINE DIABASE AND UPPER CONTACT ZONE OF THE LAYERED SERIES.

Location: South side of Central Entrance (Hwy 194) east of intersection with Trinity Road (Hwy 53). N1/2, secs. 19-20, T. 50 N., R. 14W.

Description: A series of roadcuts and outcrops along the south side of Central Entrance show another large body of massive ophitic olvine diabase in contact with fine-grained ilmenitic ferrodiorite of the upper contact zone. Here, the ophitic diabase underlies the ferrodiorite along a sharp contact dipping 20° south-southeast without any apophyses or xenoliths on either side. The ferrodiorite does appear to be slightly finer grained next to the diabase, whereas the diabase shows no change in texture. However, clouded plagioclase and some recrystallization textures are evident

in thin section in the diabase adjacent to the contact. These features are consistent with the diabase being an inclusion in the ferrodiorite.

Across the highway to the north, the large mall excavation has exposed a large amount of ferrodiorite and to the west, massive ophitic olivine diabase. The ferrodiorite again overlies the diabase along a southeast-dipping contact and grades from fine grained at the contact to more medium grained several meters away.

STOP 9. ANORTHOSITIC SERIES.

Location: Outcrop behind Windwood Townhouses, just west of Pecan Avenue and 0.1 mi north of Hwy 194 (Central Entrance). E-central, sec. 21, T. 50 N., R. 14W.

Description: This glacially scoured outcrop (and another across Pecan Avenue behind the Marshall School) shows some typical textural and structural features of the anorthositic series that give evidence for its multiple intrusive origin from plagioclase crystal mushes (basaltic magma laden with intratelluric plagioclase). Several intrusive cycles of erratically flow-foliated (or laminated) olivine gabbroic anorthosite are evident in this exposure. Intrusive relationships defined by crosscutting plagioclase lamination indicate that more leucocratic compositions are generally older. Also, some gabbroic anorthosites gradually increase plagioclase concentration away from contacts with older anorthositic rocks, perhaps as a result of flow differentiation of the crystal mush. A unique feature here is the occurrence of "snowball" inclusions composed of concentrated plagioclase tablets whose lamination is independent of that in the surrounding gabbroic anorthosite. Overall, the relationships here give the distinct impression of several irregularly shaped, intrusive pulses of gabbroic magma choked with previously crystallized plagioclase and cognate inclusions of varied size.

STOP 10. PORPHYRITIC GABBRO.

Location: Easternmost Radio Tower hill. East of corner on gravel road corresponding to 5th Avenue and 9th Street. NE1/4, sec. 28, T. 50 N., R. 14W.

Description: The entire east slope of this hill is composed of abundant basaltic hornfels inclusions in a varitextured matrix of medium- to fine-grained, plagioclase-porphyritic (5-15%), subophitic to ophitic olivine gabbro. The mafic hornfels inclusions are locally intensely recrystallized and in places are hard to tell from the gabbro, which shows little to only a weak chill around the inclusions. Rarely, an inclusion of gabbroic anorthosite is present in the gabbro. The gabbro typically displays intense hydrothermal alteration resulting in sericitic breakdown of plagioclase and uraltite, chlorite, and oxide replacement of pyroxene and olivine, though its primary subophitic to ophitic texture is typically preserved. To the east, down the slope, the gabbro gradually becomes finer grained and less porphyritic, and at the base of the slope, it abruptly grades into a hornblende quartz monzonite visible in exposures next to Skyline Parkway and the driveway to 415 W. Skyline Parkway (Fig. 10). This quartz monzonite apparently formed against the contact with (and perhaps by partial melting of) strongly recrystallized felsic lavas of the overlying North Shore Volcanic Group. West of the hilltop, the ophitic olivine gabbro generally contains more plagioclase phenocrysts and fewer hornfels inclusions though not in a systematic way.

The contact with the anorthositic series is not evident in this area because of an intervening intrusion of intergranular gabbro (Fig. 10). Heading 170 m southwest on 9th Street from the road corner, a pavement outcrop forming the base of the small radio tower southeast of the road shows the diabase chilled against medium-grained, plagioclase-porphyritic, ophitic olivine gabbro, which here contains a coarse-grained gabbroic anorthosite inclusion but no mafic hornfels. Away from the contact and downhill to the southeast, the intergranular gabbro coarsens to medium grained and develops a subtle modal layering dipping 15° to the northeast. The southwest contact of the gabbro

(exposed on the roadcut on 9th Street) is formed against coarse gabbroic anorthosite. This intergranular gabbro intrusion may be traced along strike to the east, where it cuts volcanic rocks forming the roof zone, and to the west, where it appears to pass into the upper contact zone of the layered series.

This rock type may represent either a flow-differentiated marginal phase of the anorthositic series or a later intrusion emplaced along the contact zone and perhaps derived from the layered series.

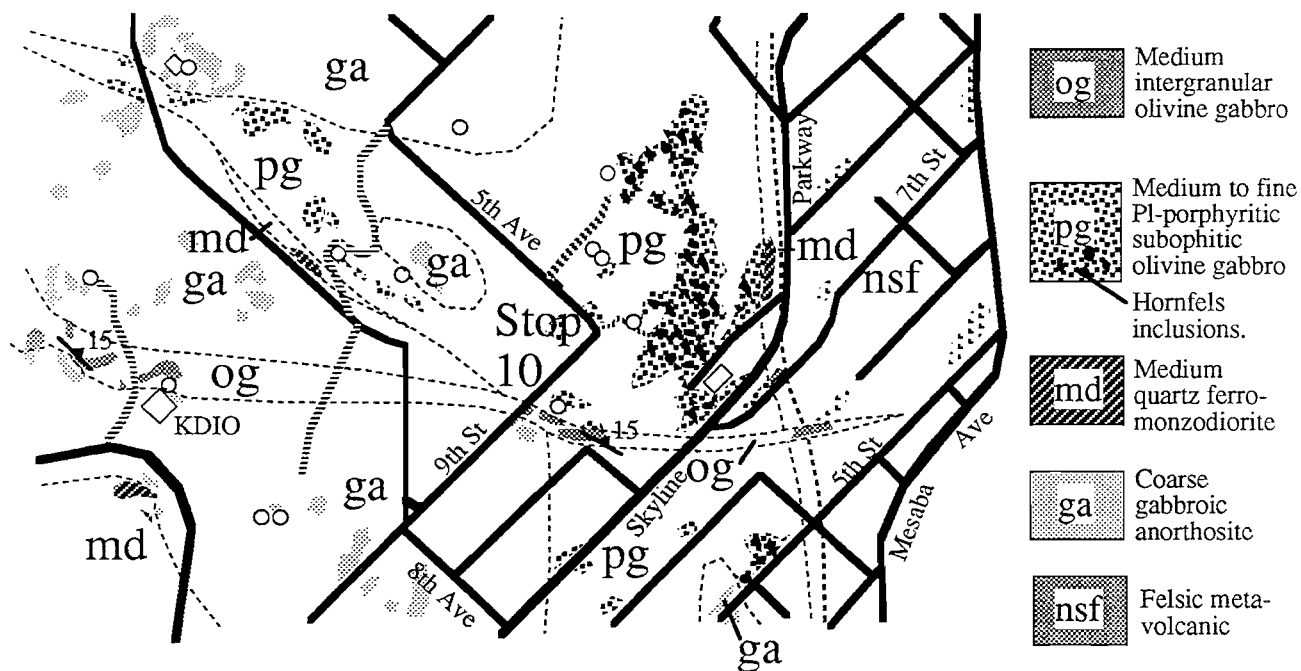


Figure 10 Outcrop geology of the Radio Tower hill area, showing location of Stop 10. Open circles indicate the locations of radio towers.

STOP 11. MELANOGRANOPHYRE

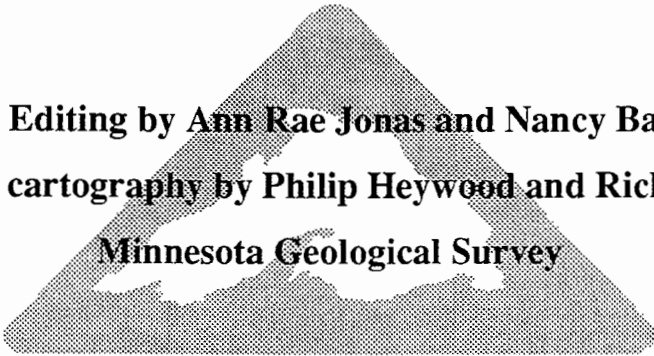
Location: Roadcut on northwest side of West 3rd Street, 0.1 mi. northeast of 17th Ave and beneath a pair of powerlines. NW1/4, sec. 33, T. 50 N., R. 14W.

Description: Roadcut beneath the powerline exposes the two main felsic rock types comprising the southwestern part of an irregularly shaped, multiphase melanogranophyre body that intrudes the anorthositic series (Fig. 2). One rock type is a medium-grained intergranular, olivine-bearing, quartz ferromonzodiorite. Microprobe analyses of a similar rock sampled just up the hill from here indicate that pyroxene in this monzodiorite is the most Fe-rich composition found thus far (Fig. 4). This quartz monzodiorite irregularly grades into and in places seems to be cut by a darker red, melanogranophyre containing up to 10 percent dark-green mafic prisms of amphibole and altered Fe-pyroxene. This mix of felsic rock types continues southwest to a sharp contact with gabbroic anorthosite. Medium-grained quartz ferromonzodiorite forming the felsic side of the contact contains irregularly shaped, strongly altered clots of gabbroic anorthosite. These relationships

REFERENCES CITED

- Cannon, W.F., 1992, The Midcontinent rift in the Lake Superior region with emphasis on its geodynamic evolution: *Tectonophysics*, v. 213, p. 41-48.
- Cannon, W.F., and eleven others, 1989, The North American Midcontinent rift beneath Lake Superior from GLIMPCE seismic reflection profiling: *Tectonics*, v. 8, p. 305-332.
- Chandler, V.W., 1990, Geologic interpretation of gravity and magnetic data over the central part of the Duluth Complex, northeastern Minnesota: *Economic Geology*, v. 85, p. 816-829.
- Chandler, V.W., and Ferderer, R.J., 1989, Copper-nickel mineralization of the Duluth Complex, Minnesota—A gravity and magnetic perspective: *Economic Geology*, v. 84, p. 1690-1696.
- Chandler, V.W., McSwiggen, P.L., Morey, G.B., Hinze, W.J., and Anderson, R.R., 1989, Interpretation of seismic reflection, gravity and magnetic data across middle Proterozoic Midcontinent Rift, northwestern Wisconsin, eastern Minnesota and central Iowa: *American Association of Petroleum Geology Bulletin*, v. 73, p. 261-275.
- Foster, M.E., 1981, Analysis of small-scale structures in the Duluth Complex at Bardon Peak, St. Louis County, Minnesota: Unpublished M.S. thesis, University of Minnesota, 144 p.
- Grout, F.F., 1918a, The pegmatites of the Duluth Gabbro: *Economic Geology*, v. 13, p. 185-197.
- _____, 1918b, The lopolith; an igneous form exemplified by the Duluth Gabbro: *American Journal of Science*, v. 96, p. 516-522.
- _____, 1918c, Internal structures of igneous rocks; their significance and origin with special reference to the Duluth Gabbro: *Journal of Geology*, v. 26, p. 439-458.
- _____, 1918d, Two-phase convection in igneous magmas: *Journal of Geology*, v. 26, p. 481-499.
- _____, 1918e, A type of igneous differentiation: *Journal of Geology*, v. 26, p. 626-658.
- Kilburg, J.A., 1972, Petrology, structure, and correlation of the upper Precambrian Ely's Peak basalts: Unpublished M.S. thesis, University of Minnesota, 97 p.
- Kilburg, J.A., and Morey, G.B., 1977, Reconnaissance geologic map of the Esko quadrangle, St. Louis and Carlton counties, Minnesota: *Minnesota Geological Survey Miscellaneous Map M-25*, scale 1:24,000.
- Linscheid, E.K., 1991, The petrography of the Longnose Peridotite and its relationship to the Duluth Complex: Unpublished M.S. thesis, University of Minnesota—Duluth, 121 p.
- Miller, J.D., Jr., 1992, The need for a new paradigm regarding the petrogenesis of the Duluth Complex: *Institute on Lake Superior Geology*, 38th, Proceedings, p. 65-67.
- Miller, J.D., Jr., and Weiblen, P.W., 1990, Anorthositic rocks of the Duluth Complex: Examples of rocks formed from plagioclase crystal mush: *Journal of Petrology*, v. 31, p. 295-339.

- Motamedi, S., 1984, The Keweenaw lavas in the city of Duluth: Unpublished M.S. thesis, University of Minnesota—Duluth, 140 p.
- Paces, J.B., and Miller, J.D., Jr., in press, Precise U-Pb ages of Duluth Complex and related mafic intrusions, northeastern, Minnesota: New insights for physical, petrogenetic, paleomagnetic and tectono-magmatic processes associated with 1.1 Ga Midcontinent rifting: *Journal of Geophysical Research*.
- Ross, B.A., 1985, A petrologic study of the Bardon Peak peridotite, Duluth Complex: Unpublished M.S. thesis, University of Minnesota, 140 p.
- Schwartz, G.M., 1949, The geology of the Duluth metropolitan area: *Minnesota Geological Survey Bulletin* 33, 136 p.
- Seifert, K.E., and Kracher, A., 1992, Rock-magma mixing in the Duluth Complex, Enger Hill, Duluth: Part 1—Bulk compositions [abs.]: *EOS, Transactions, American Geophysical Union*, v. 73, no. 43, p. 655.
- Severson, M.J., and Hauck, S.A., 1990, Geology, geochemistry, and stratigraphy of a portion of the Partridge River intrusion: University of Minnesota—Duluth, Natural Resources Research Institute Technical Report 89-11, 236 p.
- Taylor, R. B., 1964, Geology of the Duluth Gabbro Complex near Duluth, Minnesota: *Minnesota Geological Survey Bulletin* 44, 63 p.
- Wager, L.R., and Deer, W.A., 1939, Geological investigations in East Greenland, part III: Petrology of the Skaergaard intrusion, Kangerdlugssuaq, East Greenland: *Meddelelser om Gronland*. v. 105, 352 p.
- Weiblen, P.W., and Morey, G.B., 1980, A summary of the stratigraphy, petrology, and structure of the Duluth Complex: *American Journal of Science*, v. 280-A, p. 88-133.



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Minnesota Geological Survey