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RELATIONSHIP OF STRUCTURAL GEOLOGY OF THE DULUTH COMPLEX TO ECONOMIC MINERALIZATION

A Final Report to the Minnesota Department of Natural Resources
and the Natural Resources Research Institute
of the University of Minnesota Duluth

by

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INTRODUCTION

A series of mafic igneous rocks (both intrusive and extrusive), known from outcrop or inferred from geophysical data, forms an arc that runs from Kansas, through Iowa and Minnesota, through Lake Superior, and south through Michigan, perhaps into Ohio. This middle Proterozoic feature is known as the Midcontinent Rift system. In northeastern Minnesota, Keweenawan extrusive and intrusive igneous rocks, as well as sedimentary rocks, are a result of the abortive rifting episode which caused the development of the Midcontinent Rift System. The dominantly-mafic extrusive rocks of the North Shore Volcanic Group are intruded by the rocks of the Duluth Complex, and are overlain by clastic sedimentary rocks.

The Duluth Complex is a large body of dominantly mafic intrusive igneous rock that occurs in an arcuate pattern from Duluth, Minnesota to very near the United States-Canada border, and nearly to the Lake Superior shore to the east. It consists of a series of intrusions of diverse composition, but can be divided generally into an early series of anorthosites and gabbroic anorthosites, and a later troctolitic series. Many studies have been done on various aspects of the geology of the Keweenawan igneous rocks in Minnesota, and recent papers by Weiblen and Morey (1980), Weiblen (1982), and Green (1982, 1983) provide useful summaries and syntheses of the geology of Keweenawan igneous rocks.

Many of the large intrusive igneous bodies of the world contain economic mineralization, and there has been interest in the economic potential of the Duluth Complex for some time (Sims, 1967; Craddock, 1972;

Weiblen, 1982; Ryan and Weiblen, 1984). There is commonly some control of mineralization by geologic structure in a wide variety of ore deposit types, but little detail is known concerning structural relationships within the Duluth Complex, or possible relationships of mineralization to structure. In fact, within the Duluth Complex, "definition of individual intrusive units, correlation of stratigraphic sequences within presumed intrusive units, and pre- and post-emplacement structural control on stratigraphic relations of the intrusive igneous rocks are vague and uncertain" (Weiblen, 1982, p.57).

The Hoyt Lakes-Kawishiwi area, which includes the basal contact of the Duluth Complex, has been the primary focus of attention for Cu/Ni resources for some time since several large though subeconomic discoveries have been made there (e.g. Watowich, 1978; Klein, et al., 1975).

The overall structural geometry of the Duluth Complex has been inferred to be that of an extensive half-graben system by Weiblen and Morey (1980). They interpret the individual intrusions in the Hoyt Lakes-Kawishwi area to have a half-graben geometry, with steep, southeast-dipping, northeast-trending normal faults underlying the Complex on the northwest, and a conduit from the magma chamber existing at depth to the southeast. A half-graben geometry has also been suggested for other layered intrusions such as the Skaergaard (McBirney, 1975) and the Samail Ophiolite (Pallister and Hopson, 1981), and Weiblen and Morey (1980) suggest that the pattern they find in the Hoyt Lakes-Kawishwi area is characteristic of the complex as a whole. In their interpretive cross section, a series of steep normal faults at the northwest boundary of the Complex pass with progressively further foundering of footwall material to the southeast into the conduit to the magma chamber. In map view, they suggest that these steeply southeast-dipping, northeast-trending normal faults may be offset by a series of northwest-trending near-vertical strike-slip faults (Weiblen and Morey, 1980, Figure 13, p. 123). They envision this pattern to be a rift-transform type of geometry, consistent with the idea that the Midcontinent Rift represents the early stages of an abortive plate separation (Chase and Gilmer, 1973).

This type of geometry could have important consequences for localization of potential mineralization in the Duluth Complex. The steep northeast-trending normal faults and northwest-trending strike-slip faults would be excellent sites for the concentration of late-stage magmatic or hydrothermal fluids. Weiblen has pointed out (personal communication) that the principal sites of development of copper-nickel potential in the Duluth Complex are localized in what he infers to be zones of high-density "rift-transform" offsets. He suggests that these areas are zones of intense fracturing of country rock, and were favorable sites for the country rock-magma interaction necessary to form copper-nickel deposits in the troctolitic-gabbroic rocks of the Hoyt Lakes-Kawishiwi area.

Green (1980, 1983) has pointed out a number of problems with the half-graben model, as applied to the Complex and the Keweenawan as a whole, and suggests an alternative model of subsiding sequences of plateau lavas, which does not imply the high degree of faulting as does the half-graben model of Weiblen and Morey. Little direct evidence for the faulting postulated by Weiblen and Morey for the troctolitic rocks has been found, and it is conspicuously absent in the North Shore Volcanic Group lava sequences to the southeast (Green, 1980, 1983). Cooper and others (1981) have suggested the presence of a series of northeast-trending steep (presumed normal?) faults and a less well-developed set of northwest-trending (presumed "transform") faults along the base of the Complex in the Hoyt Lakes-Kawishwi area. Although no direct evidence for these faults is found in the field, they were postulated on the basis of topographic lineaments, aeromagnetic anomalies, and joint density data gathered from outcrops in the region. Weiblen (personal communication) has pointed out that the record of faulting in the troctolitic rocks themselves could easily be obscured, as the rocks were a crystal mush during much if not all of the post-emplacement movement along the faults, and some (or much) of the faulting would have taken place prior to actual magma emplacement. A record of the nature of postulated faulting associated with the emplacement of the Duluth Complex should, however, be present in the country rocks.

The country rocks (sometimes referred to as the footwall rocks) beneath the Duluth Complex in the Hoyt Lakes-Kawishwi area are those of the Archean Giants Range Granitic Complex and the early Proterozoic Animikie Group (Sims and Morey, 1972). The Animikie Group of the Mesabi Range, which unconformably overlies the Giants Range Granite, consists of the Pokegama Quartzite, the Biwabik Iron Formation, and the Virginia Formation (basically an argillite) in ascending stratigraphic order. The rocks of the Animikie Group for the most part dip gently south-southeast in this region. The stratigraphy of these rocks is much better known than for the rocks of the Giants Range Granite in this area, and they are simpler structurally. They are also much better exposed, because of the open pit mines developed to exploit the taconite and natural iron ores of the Biwabik Iron Formation.

In addition to the mine-pit exposures, thousands of holes have been drilled in the area of the footwall rock-Duluth Complex contact in this region on both sides of the contact. These holes were drilled to ascertain the potential of down-dip iron mining in the Biwabik Iron Formation, and in some cases to ascertain the extent of copper-nickel mineralization in the Duluth Complex.

This intensive mineral exploration and development provides a unique opportunity to determine the actual three-dimensional characteristics of the rock structures at the base of the Duluth Complex, and thus to constrain models of intrusive history and development.

This study, combining field work, structural analysis, compilation of existing data, geophysics, and drill core analysis, was undertaken in an attempt to understand the structural features present in the Duluth Complex and the country rock below the Complex in the Hoyt Lakes-Dunka River area, where the structural information is best, in the belief that an understanding of these features would be an invaluable tool in assessing the potential mineral resources of the area. This study led to the observation, compilation, integration, and discussion of many structures in the Biwabik Iron Formation at some distance from the contact with the Duluth Complex which had not heretofore been done.

Using existing mining company data, and by field inspection of natural outcrop, and mine pit exposure, a map of the geology of the northeast Mesabi Range (Plate I) and the Dunka River Area (Plate VI) have been compiled. These maps are described and further discussed later in this report.

The extreme eastern end of the Mesabi range, where the Animikie Group rocks are in contact with and are ultimately cut out by the Duluth Complex, occurs at the site of the Dunka Pit of Erie Mining Company. Mine pit exposures were examined in some detail, and the structural features found were analyzed. In addition, drill hole data were compiled, and a structure contour map of the top of the Lower Slaty unit of the Biwabik Iron Formation was produced, as well as a structure contour map of the base of the Duluth Complex in this region. These features are further discussed later in this report.

Data from approximately 6000 drill holes from a number of different exploration and mining companies and located from the Dunka River area to Hoyt Lakes were compiled and stored on the computer at the University of Minnesota Computer Center. These data have been used to generate (by computer) a structure contour map of the base of the Duluth Complex for this entire area (Plate IV). The enormous quantity of data now available for the Minnamax area was compiled, plotted by hand, and corrected for drill hole trend. These data were used to produce a detailed structure contour map of the base of the Duluth Complex for the Minnamax region (Plate III). Drill hole data on the base of the Duluth Complex in the Dunka River area are also plentiful, and a detailed, hand-drawn structure contour map for this area has also been produced (Plate V). These maps are described and further discussed later in this report.

Several weeks were spent searching for previously-unknown outcrop within the Duluth Complex. Maps showing the locations of the newly-discovered outcrops, and brief descriptions of their lithologies occur later in this report.

Geophysical studies undertaken for this project included both magnetic and gravity techniques. A plate of the aeromagnetic data (Chandler, 1984) at the same scale as the map of the northeast Mesabi Range (Plate I) has been produced, and the aeromagnetic signature of the structural features investigated. Gravity and magnetic models for the Minnamax area have been produced, and computer processing (including second derivative and poisson technique) has been done for a new gravity and magnetic grid over the central Duluth Complex.

The cooperation of the following mining and exploration companies is gratefully acknowledged: Erie Mining Company, Pickands-Mather Company, Reserve Mining Company, LTV Steel Corporation, U. S. Steel Corporation, and Bear Creek Mining Company.

In particular, discussions with Neil Walker of Pickands-Mather Company, and with Ron Graber of Erie Mining Company were invaluable in the completion of this work. Helpful discussions with Ralph Marsden, Leon Gladen, Jim Emanuelson, Cedric Iverson and Jim Miller are also gratefully acknowledged.

STRUCTURAL ANALYSIS OF THE NORTHEAST MESABI RANGE

The geologic map of the northeast Mesabi Range (Plate I) exhibits a number of interesting structural features. These are described below in a general west-to-east fashion. Individual structural features are numbered on Plate I for reference. Some faults have been given names by mining company personnel, or have names that already exist in the literature. When this is the case, both the name and number are used to refer to the fault.

Faults

B-1

The Dark Lake/Biwabik fault has been described by White (1954). He estimated 150 feet of vertical offset along this fault, down to the southwest, in the Embarass Mine west of Aurora. The fault is shown here to extend to the southeast into the Duluth Complex east of Hoyt Lakes. The trend of the fault in the Biwabik Iron Formation is approximately N 75 W.

B-2

The Hudson Fault occurs in the Hudson Mine in sec. 4, T. 58 N., R. 15 W. The fault is intruded here by a (diabase?) dike (Walker, personal communication). The vertical offset estimated from drill hole data is about 50 feet. The trend is N 35 W with the southwest side down. White

(1954) suggests that the fault may strike more nearly north and account for some of the downdropping shown in the supposed structural basin in secs. 29 and 32, T. 59 N., R. 15 W. The intersection relationship between the Hudson Fault and the Dark Lake/Biwabik Fault are unknown at present.

B-3

The Donora Fault is exposed in the pit wall at the west end of Mine area #1, sec. 28, T. 59 N. operated by Erie Mining Company. The exposure is characterized by Pokegama Quartzite outcropping along the west wall of the pit. Associated with the fault, folding in the banded iron-formation (Figure II-1) is also present. The actual attitude of the fault plane cannot be determined here, but the fault can be traced to the southeast where it disappears into an oxidized natural ore zone of the pit wall. The trend of the fault here, estimated from drill hole data, is N 50-70 W. Drill hole data indicate a vertical offset of about 125 ft. with the northeast side down. The attitude of layering in the quartzite is N 40 W/45°NE on the northeast side of the fault, compared to the gentle regional dip, indicating disturbance.

The fault enters the northwest end of the Donora Mine in a 50 ft. wide oxidation zone (Figure II-2). Strata of the Lower Cherty Member are asymmetrically folded on the south side of the oxidation zone (Figure II-3) which is in the upthrown block of the fault. The trend of the asymmetric fold is N 50-55 W. The dip of the axial plane is nearly vertical at the crest, but begins to decrease to the north where it disappears under debris. The trend of fracturing parallel to the oxidized fault zone is N 60-70 W/75-80°NE. The fault is interpreted to change dip direction at least four times, as it traverses the Donora Mine mining

Figure II-1: Folding in the Lower Cherty Member of the Biwabik Iron Formation along the Denora Fault at the west end of the Erie Mining Company Area #1. View is looking southwest.

Figure II-2: Oxidation along the Denora Fault at the northwest end of the Denora Mine. The figure in the left-central portion of the photo is standing next to a bench face of Pokegama Quartzite (Pq). The dotted area outlines the area shown in Figure 3A. View here is to the northwest.

A

B

Figure II-3: A: Probable drag folding in the Lower Cherty Member along the Denora Fault on the upthrown block. View is to the northwest.
B: Close-up view of A.

company cross-sections. The Donora Fault is intersected by two other faults, the Mesabi Lake Fault and the E-W Fault as it passes through the Donora Mine. The vertical offset of the Donora Fault decreases to 40 feet southeast of the three-fault intersection. The character of the Donora Fault changes to become a fracture zone on the hinge of a monocline in the Erie Mine Area #6 (Figure II-4). The attitude of the fracture zone is N 55 W/vertical. The attitude of bedding west of the fracture zone is N 40 W/5 NE. East of the fracture zone, the attitude of bedding is N 70 W/33°NE at its steepest point. This structure was inferred to extend into the Duluth Complex (Morey and Cooper, 1978), producing a fault offset in sec. 4, T. 58 N., R. 14 W. Drilling in this area of the Complex is sparse, but does indicate the presence of a depression in the base of the Complex. Since the vertical displacement along the Donora Fault decreases to the southeast and becomes zero in area #6, we have chosen to extend it as a monocline that enters the Duluth Complex as a synformal trough.

B-4

This fault occurs in the trough of a syncline trending E-W through Erie Mine Area #9 and the Donora Mine. The syncline is inferred to intersect the long syncline east of the Donora Mine. The E-W Fault can be traced through several pit wall outcrops in Erie Mining area #9 and the Donora Mine in sec. 8, T. 59 N., R. 15 W. The fault intersects the west wall of the Donora Mine in the Lower Cherty Member as a vertical to steeply dipping (85°N) fracture zone with an estimated trend of N 80 E (Figure II-5). The vertical offset determined from drill hole data is about 40 ft. with the south side down, at this location.

Figure II-4A: The Denora Fault is seen in Erie Mine Area #6 to be a fracture zone with no vertical offset, on the hinge of a monocline. The dark layer in the photo is the "intermediate slate" or "Q" layer. View to northwest.

Figure II-4B: View to the southeast of a monocline in the Biwabik Iron Formation. Folding is shown in the black layer (intermediate slate) in the center of the photo.

A B

Figure II-5: A: View to the west of fault B-4 in the west wall of the Denora Mine. B: Close-up of A.

The E-W Fault is exposed 500 feet to the west in the east pit wall of Erie Mine Area #9. Here it is a normal fault with a 20 foot-wide fracture zone, attitude N 80 E/77°S (Figure II-6). A minor fold occurs on the north side of the fault.

Faulting can be observed again in Area #9 another 2000 feet to the west. The attitude of the fault here is N 75 E/60°SE. The plane of the fault is slightly convex upward to the south (Figure II-7). Bedding in the Upper Cherty Member is also dipping to the south about 60°. This does not seem to be the actual trace of the E-W Fault. The trace of the E-W fault plane is probably within 50 feet to the north. The vertical offset estimated from drill hole data has decreased to about 15-20 feet, down to the south.

The plane of the E-W Fault outcrops in the pit wall about another 200 feet west in a road cut. The fault plane is concave upward, dipping to the south (Figure II-8). The attitude of the fault plane in the pit wall across the road to the west is about N 50 E/50°S (Figure II-9A). Here the Lower Cherty Member is cut by a number of high-angle fractures (Figure II-9B). Note the chevron geometry associated with the southernmost fracture. This may correlate with the N 75 E/60°SE fault described earlier. The E-W Fault can be traced for another 100 feet to the west beyond the road cut along an E-W trending bench face. Here the vertical offset, estimated from drill hole data, is reversed, bringing the south side up about 10 feet. The fault appears to die out before it reaches the limit of the pit, 1800 feet further to the west, although it may be associated with an oxidized zone in the west pit wall.

A

B

Figure II-6: A: Exposure of fault B-4 in the east pit wall of Erie Mine Area #9. B: Close-up of II-6A. Note minor folding on the left side of the fault.

C

Figure II-6C: Close-up of Figure II-6B.

A

B

Figure II-7: A: Faulting in the Lower Cherty Member related to the East-West Fault. View to the west. Dotted line shows approximate area of II-7B. B: Close-up of II-7A.

C

Figure II-7C: Close-up of fault zone of Figures II-7A and II-7B showing the presence of rock powder and fracturing.

Figure II-8: Probable exposure of the East-West Fault in Area #9. This eastward view is about 200 feet west of the exposure shown in Figure II-7.

A

B

Figure II-9: A: View west on opposite side of road from Figure II-8. Note fracturing and faulting. Dashed line is probable trace of the East-West Fault. B: Close-up of chevron fold visible in upper left corner of II-9A.

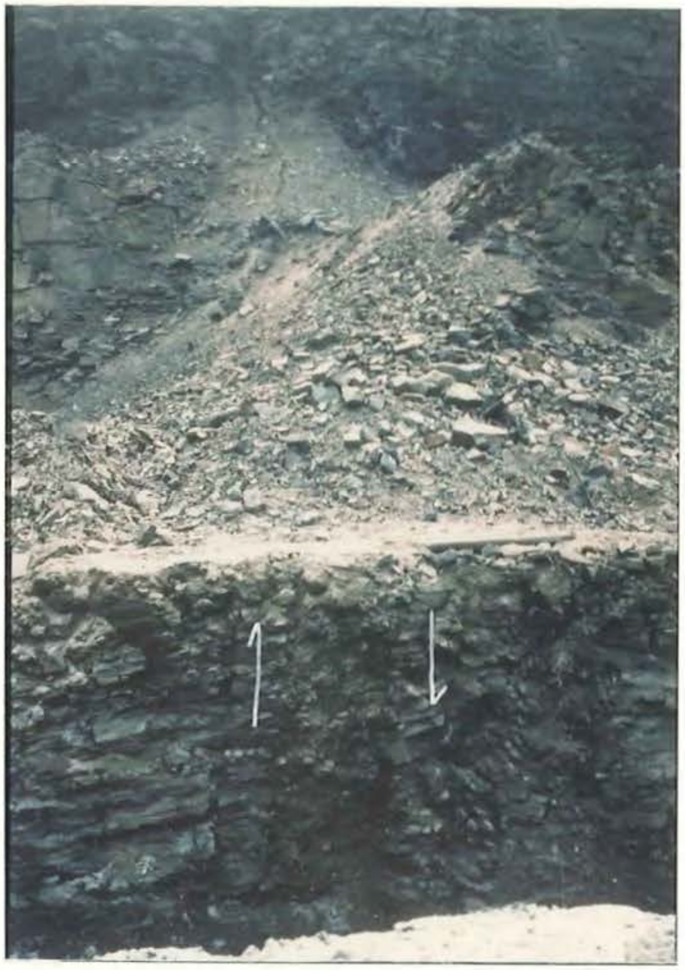
B-5

The Mesabi Lake Fault is a roughly N-NE trending fault that passes from north to south through Erie Mine Area #1, the Donora Mine, Erie Mine Area #9S and probably the St. James Mine. The fault was recently exposed by mining company operations in area #1 in a freshly-cut trough. Here it is characterized by a 5-foot wide breccia zone with folding on the west side of the breccia zone (Figure II-10). The fault plane is identified in the south pit wall by a weathered-out rubbly zone. The attitude of the fault here is N 10 E/80°E. The vertical offset estimated from drill hole data is 30-40 feet (Evers, personal communication) with the west side down, making this a high-angle reverse fault at this location. The Mesabi Lake Fault is traced south by drill hole data through the Donora Mine where it intersects the E-W Fault and the Donora Fault. The trend becomes nearly N-S and continues south through Area #9S where it is concealed by water. It is inferred to pass through the west end of the St. James Mine and into the town of Aurora. The vertical offset along the fault decreases to less than 10 feet in Area #9S.

B-6

A reverse fault crops out in the northwest corner of Area #9S. Folding associated with the fault occurs in the north pit wall (Figure II-11). The fault plane is characterized by a 1.5-foot wide zone of gouge. The attitude of the fault is N 55 E/60°NW with a vertical offset, estimated from drill hole data, of 20 feet or less. The relationship between this fault and the Mesabi Lake Fault to the northwest is not known.

A



B

Figure II-10: A: View south of the Mesabi Lake Fault in Erie Mine Area #3. B: Close-up of II-10A. Note folding in the iron formation on the right (west) side of the breccia zone.

A

B

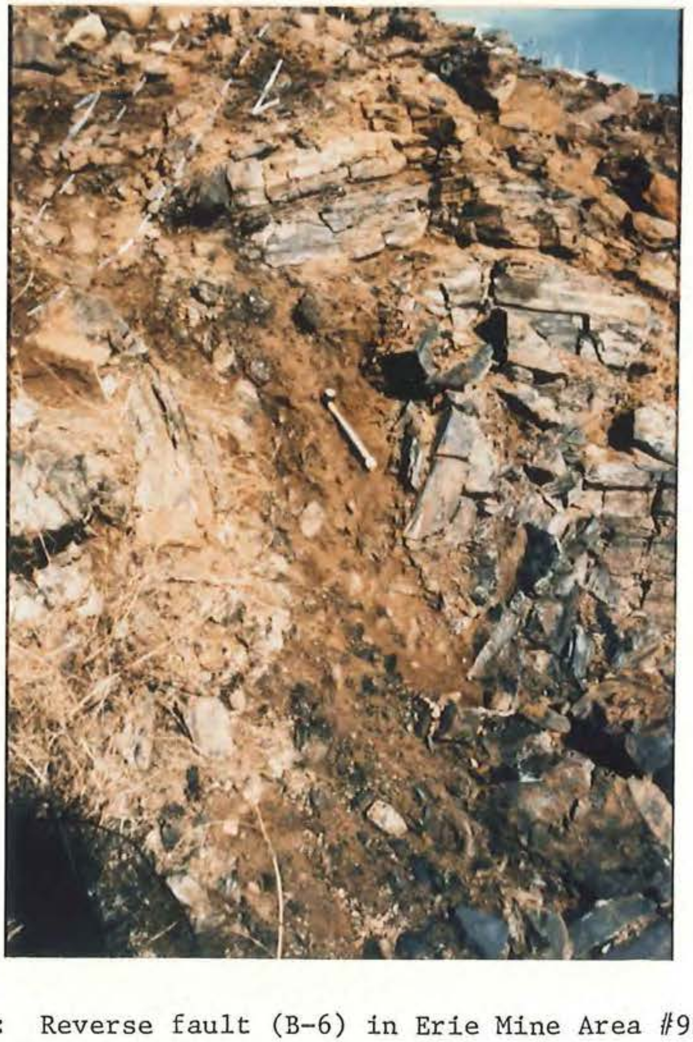


Figure II-11: A: Reverse fault (B-6) in Erie Mine Area #9S. The fault zone is shown dashed where exposed, dotted where covered. Note folding on downthrown side. View to northeast. B: Close-up of II-11A.

B-7

A normal fault, the Fowler Fault occurs about 1/2 mile to the east of the Mesabi Lake Fault. It is observed south of the Donora Fault and coincides with a N-S trending road which bisects Erie Mine Area #6 in sec. 34, T. 59 N., R. 15 W. The fault is known to dip to the west (N. Walker, personal communication) The fault changes strike to the southwest and passes through the Fowler Mine and continues on a N-S strike to the St. James Mine in sec. 3, T. 58 N., R. 15 W. The offset estimated from drill hole data increases from about 20 feet near the Donora Fault to the north, to about 50 feet (N. Walker, personal communication) at the Fowler Mine with the east side down. This is opposite to the sense of motion shown on Erie Mining Company maps in the St. James-Fowler area. A breccia zone probably associated with the Fowler Fault is exposed in the west pit of area #6 (Figure II-12). The breccia zone strikes obliquely to the wall of the pit which is parallel to the north-south road believed to coincide with the Fowler Fault.

B-8

A fault is inferred to exist in secs. 21, 22, and 27, T. 59 N., R. 15 W. from structure contour maps of Erie Mining Company open pit Area #1. The estimated trend is about N 50 W with the southwest side down. The estimated offset is 8 to 10 feet. This fault has not been observed in the field. It may be a minor fold in the iron-formation. Its existence is open to question.

B-9

A normal fault is exposed in sec. 22, T. 59 N., R. 15 W. The fault

A

B

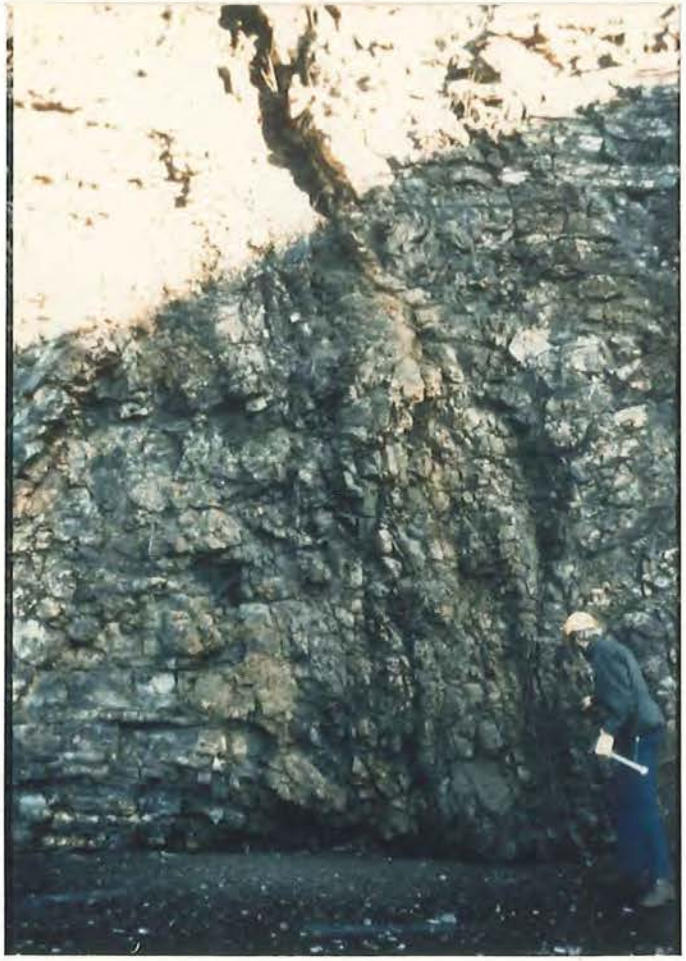


Figure II-12: A: Eastward view of a breccia zone, sub-parallel to the north-south road that coincides with the Fowler Fault. B: Close-up of II-12A.

outcrops in Erie Area #1 with an attitude of N 45 W/75 W. Drag folding occurs on the southeast side of the fault (Figure II-13). The vertical offset estimated from drill hole data is about 30 feet. The offset may decrease to the south.

B-10

Fault B-10 occurs in sec. 19, T. 59 N., R. 14 W. near the east end of Erie mine Area #1. It intersects the Lower Slaty Fault to the south, and the intersection relationship is not presently known. The estimated trend is N 30 W and vertical offset about 70 feet. Toward the north, the trend changes to about N 45 W and the vertical offset decreases to about 30-40 feet.

B-11

Fault B-11 occurs in secs. 13, 18, 19, 20, 27, and 28, T. 59 N., R. 14 W. The fault is indicated on Minnesota Geological Survey State Map Series, S-13. This fault coincides with a feature indicated by Erie Mining Company structure contour maps in the Knox, Vivian and Wentworth mine areas. Structure contouring indicates a feature with a trend of about N 50 W with 40 to 50 feet of vertical offset, down to the northeast. It cannot be determined from the structure contour maps whether the structural feature is a fault or a monocline. Information is not sufficient to justify extending the feature into the Duluth Complex.

B-12

The Lower Slaty Fault (B-12) is shown here to extend for about six miles to the west from the Stephens Mine (through the Weed Shaft and

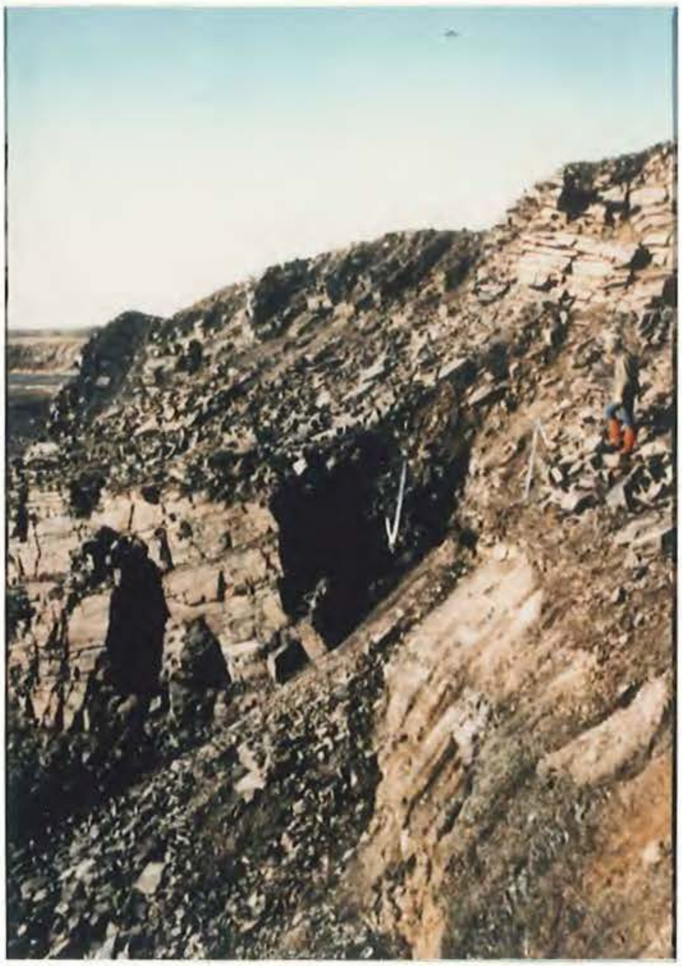


Figure II-13: Fault B-9 is a normal fault which occurs in the Erie Mine Area #1. This northwest view shows drag folding in the iron formation on the downthrown block.

continuing east) into Erie Mine Area #2, where it dies out. The fault is known to exist from drill hole data (N. Walker, personal communication). The fault trends N 65 E for about 3.5 miles and continues on an east-west trend for about another 2.5 miles. The fault has a vertical offset of about 100 feet (down to the south) near Fault B-10 which decreases to zero in Erie Mine area #3 to the east.

B-13

Fault B-13 has an estimated extent of about 3.5 miles. The fault is identified from drill hole data. It begins south of Erie Mining Area #2 West Extension (2WX) and continues to the northeast through the Vivian Mine and may pass into metagraywacke and slate of the Archean basement. Ron Graber (personal communication) observed that the fault is intruded by a diabase dike in area 2WX. The fault/dike has also been encountered by drilling. The fault trends about N 20 E from the south into area 2WX and continues from here on a N 40 E trend into the Archean basement. The fault drops down to the southeast and has a vertical offset of about 20 feet.

B-14

The Siphon Fault (B-14) is shown here to extend for about 3 miles from northwest of the Spring Mine to southeast of Erie Mine area #2. Evidence is not sufficient to continue this major fault into the Duluth Complex. The fault coincides roughly with a basement lithologic boundary between Giants Range Granite and metagraywacke and slate. The estimated trend of the fault is N 10 W from the Spring Mine for about 2 miles south and changes to N 40 W as it passes through the iron-formation into the

Virginia Formation. A decrease in stratigraphic thickness in the iron formation occurs from west to east across the Siphon Fault. West of the fault the Lower Slaty Member averages about 145 feet thick and the Lower Cherty Member averages about 143 feet thick. East of the fault in Erie Mine Area #5 the average thickness of the Lower Slaty Member decreases to about 99 feet and the average thickness of the Lower Cherty Member decreases to about 58 feet. The fault is downthrown to the east with an estimated vertical offset in excess of 400 feet. The Siphon Fault marks a change in the strike of the iron-formation to a more northeasterly trend. Neil Walker (personal communication) believes that the structure is a fault because the outcrop width across the structure is not sufficient to contain the entire stratigraphic thickness of the iron-formation. Evers (personal communication) reports the presence of fracturing and breccia in drill core and the existence of dips in the iron-formation bedding of up to 70°.

B-15

Fault B-15 is shown here extending about 0.3 mile in Erie Mine Area #5. The fault was observed in the pit by an Erie Mining Company engineer. He observed that the iron-formation was offset, bringing the Lower Cherty Member in fault contact with Pokegama Quartzite. The trend of N 15 W and vertical offset of 7 to 10 feet down to the east are estimated from drill hole data. The exposure of the fault has been destroyed by subsequent blasting, although some fractures containing calcite and pyrite crystals occur in the southeast pit wall on strike with the fault. There did not appear to be any vertical offset in that area, indicating that the fault may die out to the south.

B-16

Fault B-16 is shown here to extend for about one mile in Erie Mine Area #5. Neil Walker (personal communication) infers this questionable fault from structure contour maps. Examination of the pit in the vicinity of this feature revealed only a small shallow syncline in the southeast pit wall. The estimated trend and vertical offset are N 15 W and 10 feet down to the west.

B-17

Fault B-17 is a reverse fault exposed in Erie Mine area #5 and is inferred to extend for about two miles. The actual fault plane is very narrow, characterized by a rock powder zone less than one half foot wide (Figure II-14). Drag folding is present in the iron-formation on the east side of the fault. The attitude of the fault at this exposure is N 60 W/76°NE while the trend estimated from structure contouring is about N 45 W. The vertical offset estimated from drill hole data is about 100 feet down to the southwest.

B-18

Fault B-18 is inferred to extend for about 1.3 miles in Erie Mine Area #5. Neil Walker (personal communication) suggests that the existence of this fault is questionable since it is inferred from structure contouring. The trend of the fault is estimated to be about N 45 W with the southwest side dropped down abut 5 to 10 feet. The "intermediate slate" (or Q layer of the Biwabik Iron Formation) shows a high degree of deformation where exposed in Area #5. The unit is about 6 feet thick here as opposed to 25 to 30 feet thick in areas near Aurora to the west. The

B

A

Figure II-14: A: Reverse fault B-17 exposed in Erie Mine Area #5. Note folding in the iron formation on the downthrown side. View to the southeast. B: Close-up of the fault in II-14A. C: (next page) Close-up of the fault plane.

C

unit is highly broken, and slickensides occur at diverse orientations. Thin sulfide layers are present and have the appearance of foil wrapped around the slate blocks (Figure II-15). The deformation in this unit indicates that some movement occurred along this horizon.

Many vertical calcite veins cut the southeast pit wall, west of the reverse fault in Area #5. They range in thickness from one inch up to about 1 foot. Some are vuggy and contain quartz and sulfide crystals while others contain pebble-sized iron-formation fragments in a solid calcite matrix. Spacing of the fractures ranges from several inches up to 10 or more feet. The veins have trends in the range N 50-65 W, N 35-40 W, and N 5-10 E.

B-19

Fault B-19 is shown here to extend for less than one mile in the Peter Mitchell Mine operated by Reserve Mining Company. Jim Emanuelson (personal communication) observed an exposure of the fault in the mine. The estimated trend and vertical offset are N 25 W and 7 feet, down to the northeast.

B-20

Fault B-20 is shown to extend for about three quarters of a mile in the Peter Mitchell Mine. Jim Emanuelson (personal communication) observed the fault in the mine and stated that the fault was intruded by a diabase dike. The estimated trend and offset of the fault are N 45 W and 30 feet, down to the southwest.

Figure II-15: Two views of deformation in the "intermediate slate" (Q layer) in the Erie Mine Area #5.

Folding

Folding in the Biwabik Iron Formation (BIF) occurs north and east of Aurora, Minnesota. Here the Biwabik Iron Formation overlies Archean metasediments which were more easily deformed than the massive crystalline Giants Range Granite to the east, as suggested earlier by White (1954). A syncline roughly parallels the Donora Fault at its northwestern extent in Erie Mine Area #1. The syncline parallels the fault to the southeast for about a mile and then it changes to a more easterly trend. It passes to the south of the Stephens Mine where it is joined by several southerly trending converging folds which merge with the syncline. The syncline then makes an arcuate swing to the north where it is joined by another syncline trending east from the Knox Mine. The synclines merge and continue through the Graham-Wentworth Mine areas and to the east where it can no longer be traced.

The East-West Fault occurs in the trough of a syncline. The syncline trends roughly east-west for about 2 miles from the Archean-Biwabik Iron Formation contact to the east where it is projected through the Donora Mine to merge with the syncline previously described.

The attendant anticline begins about one half mile south of the East-West Fault. It continues on an east-west trend for about 2 miles until it crosses the Donora Fault/Monocline where it turns north to parallel the syncline and continues east of the Wentworth Mine. White (1954) describes two folds located on outcrop maps by Grout and Broderick (1919b). The folds, are a few hundred feet wide; one occurs nearly south of Iron Lake the the other passes between Iron Lake and Argo Lake. This fold probably continues to the south as an antiform in the base of the Duluth Complex and is associated with an embayment of Virginia Formation in the basal contact.

STRUCTURAL ANALYSIS OF THE DUNKA RIVER AREA

Faults

Faults B-21 through B-30 located on Plate II and VI were first described by Bonnichsen (1968). Direct field evidence is presented here for some of these faults although field evidence for the others may have been obscured by mining operations or overlooked. Unequivocal field evidence exists for Faults B-21 and B-29 with indirect evidence existing for B-25 and/or B-26.

Fault B-21 is a thrust fault shown here to extend for about 3400 feet in Erie Mine Area #8 (Dunka Mine). The fault is exposed in the southeast wall of the south pit. A diabase sill known to occur in the C layer of the Biwabik Iron Formation is folded in this area. (Nomenclature designating layers within the Biwabik Iron Formation by capital letter follows the system of Erie Mining Company. The "A" layer is uppermost Biwabik, and layers progress alphabetically down the stratigraphic section.) The A, B, and part of the C layer beneath the metamorphosed diabase sill in the Biwabik Iron Formation have been faulted out (Figure III-1). Biotite, generally less than one mm in diameter, has developed along joint faces in a two to three inch thick zone within the Virginia Formation and C layer at the contact. The surface trace of the fault trends about N 55 E with an apparent dip of 20°SE, calculated from drill-hole cross sections. Faults B-22 through B-28 were described by Bonnichsen (1968).

The Boundary Fault (B-29) can be traced in outcrop, geophysical, and

A

B

Figure III-1: A: Thrust fault in the south pit of Erie Mine Area #8. Granite is intruded along the fault plane in the upper part of the photo. View to the east. gr = granite; VF = Virginia Formation; B = diabase sill; b,c = layers of banded iron formation. B: Close-up of III-1A.

drill hole information for about one mile. The fault occurs at the northeast end of Area #8 and has a somewhat sinuous trend. The fault plane itself is exposed for about 900 feet in the southeast pit wall between diamond drill hole lines 16,200 N and 17,100 N (see Plates I and V). A veneer of iron-formation a few feet thick is attached to the fault plane along parts of the exposure. The iron-formation veneer contains abundant slickensides, which plunge steeply to the northwest and southeast. A three-foot wide zone of fault gouge and highly altered gabbro with fibrous quartz veins probably defines the fault plane (Figure III-2). The plagioclase of the gabbro is altered to a dull green color and the interstitial minerals are completely decomposed to a dull black powder. The gabbro along the fault plane is highly magnetic. Magnetite occurs in 0.5 to 1.0 inch bands and is also disseminated within the gabbro (Figure III-3). Neil Walker (personal communication) notes the presence of high titanium values in the banded iron-formation adjacent to the fault and believes the source was the magma. This rock is known as "gabbroized iron formation" to Erie geologists.

The attitude of the fault at this outcrop is about N 15 E/80°NW indicating a reverse sense of movement here. Ron Graber (personal communication) has determined from drill hole logs that the sense of movement becomes normal with the dip changing to 65°SE along the fault to the southwest. He has also been able to determine the location of the fault using ground magnetic methods within the pit. An outcrop of Biwabik Iron Formation occurs about 100 feet south of drill hole line 15,600 N. Here the Biwabik Iron Formation is in sharp contact with gabbro on the northwest side (Figure III-4). The contact is irregular with no evidence of faulting. The gabbro adjacent to the iron-formation is magnetic. The

Figure III-2: Alteration and gouge along the Boundary Fault. View to the northeast. Dunka Mine, north end.

Figure III-3: Magnetite banding in troctolite intruded along the Boundary Fault.

A

B

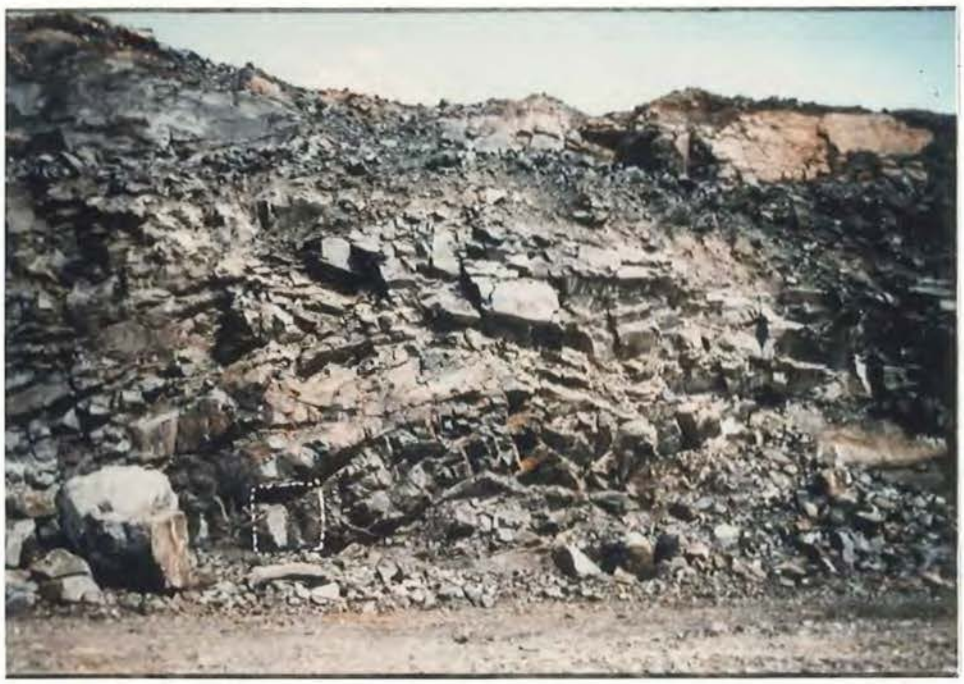


Figure III-4: A: Iron formation (BIF) in contact with gabbro (DC). The contact appears to be intrusive. View to the southeast, north end of Dunka Mine. B: Large view of the area of Figure III-4C (dotted line).

C

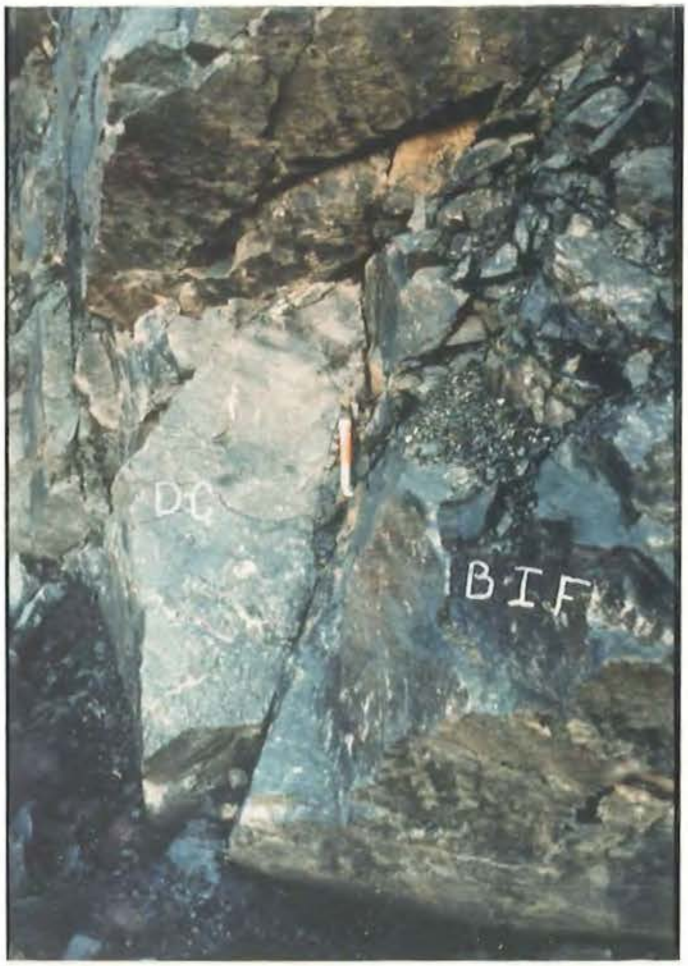


Figure III-4C: Intrusive contact between the Duluth Complex (DC), and the Biwabik Iron Formation (BIF).

attitude of the Biwabik Iron Formation here is N 10 W/54° NE and is probably the limb of a drag fold adjacent to the southeast-dipping plane of the Boundary Fault. Offset along the Boundary Fault is estimated from drill hole data to be in excess of 150 feet, down to the southeast.

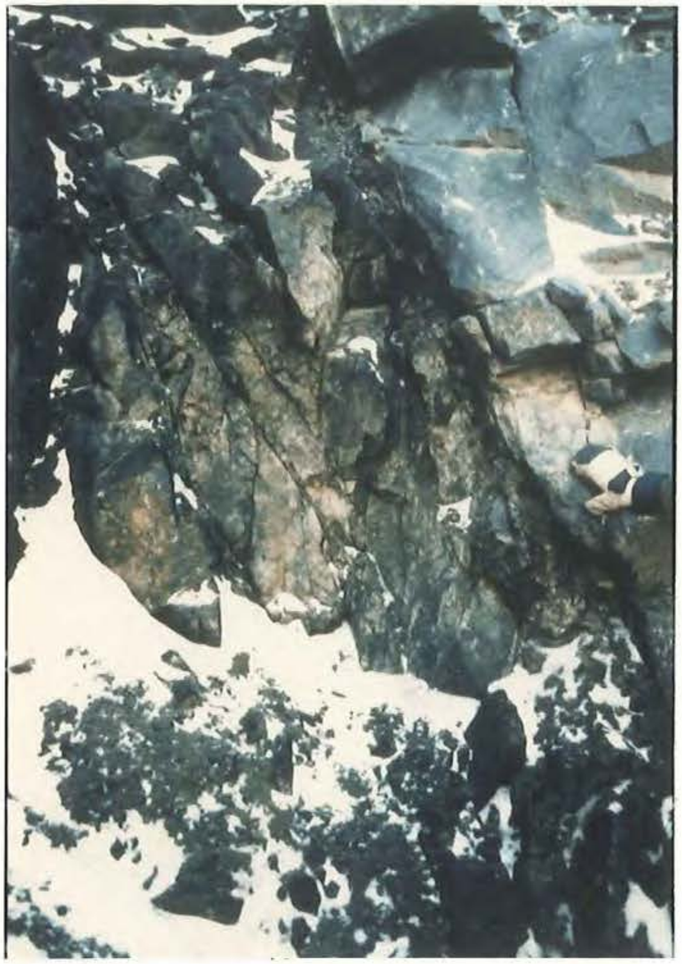
The following discussion is modified from Bonnichsen (1968) with information acquired during this study.

The iron-formation is cut by two sets of faults which evidently are part of the regional fracture system, and by additional fractures that probably are related to the intrusion of the Duluth Complex. Small monoclinal and drag folds are associated with north-south faults; other folds apparently are not related to faulting.

A zone of steeply-dipping faults that strike approximately north-south transects the iron-formation between drill lines 8,000 N and 9,000 N. Two faults, B-25 and B-26 in this zone seem to be continuous for a few hundred feet and are shown on Plates I and V. One or both of these faults may coincide with two breccia zones observed in the pit during the 1984 field season. The breccia zones occur near drill lines 6,900 N and 7,500 N (Figure III-5) and have attitudes of N 10 E/73°NW and N 20 E/60°NW respectively.

The faults that cut the iron-formation between drill lines 8,000 N and 9,000 N are aligned with a conspicuous northward-trending topographic notch in the hill underlain by granite in sections 3 and 34 (Plate I). The notch is interpreted by Bonnichsen (1968) to reflect differential erosion along the same fault zone.

A second set of steeply-dipping faults that strike northwestward, approximately at right angles to the strike of the Animikie rocks are widely spaced along the outcrop belt. The most prominent faults of this



A B

Figure III-5: A: Breccia zone in the Duluth Complex probably associated with faults B-25 and B-26. B: Close-up of III-5A. See text for location.

set that transect the iron-formation are B-22 at 5,600 N, B-24 at 7,200 N,B-28 at 15,200 N and B-30 at 18,400 N (Plate I and Figure III-4). Except for the fault at 7,200 N, they have the same relative movement, the northeast side having moved upward with respect to the southwest side. The displacements are small but are sufficient to shift the strata on opposite sides several tens of feet because of the generally gentle dips.

In the area between drill lines 8,400 N and 9,000 N, Fault B-23 strikes approximately N 25 W and has the west side raised with respect to the east side, based on inference from drill hole information.

A northwest-trending fault, closely paralleled by a tight southeast-plunging syncline in the iron-formation, are the main structural features at the north end of the mine area, where the Upper Cherty and Upper Slaty Members are cross-cut by the Duluth Complex (Figure III-6). At its western end, the axial plane of the syncline dips steeply to the south whereas at its eastern end the axial plane is approximately flat-lying, so the syncline opens to the north. Numerous drag folds, many of which are associated with narrow shear zones, and others which are recumbent, are located on the flanks of the syncline.

Both reverse faults and normal faults were observed in the Dunka Mine during the 1984 field season. One set of normal faults and fractures have alteration zones similar to that of the Boundary Fault. They trend N 20-30 E and dip 55-65°SE and represent an early period of faulting. Offsets along these faults cannot be determined, except at one location near drill line 11,400 N where rocks of the Duluth Complex are in fault contact with Virginia Formation and at least 20 feet of displacement must have occurred. The attitude of the fault here is about N 25 E/71°SE. These southeast-dipping fractures appear to be offset by northwest-dipping

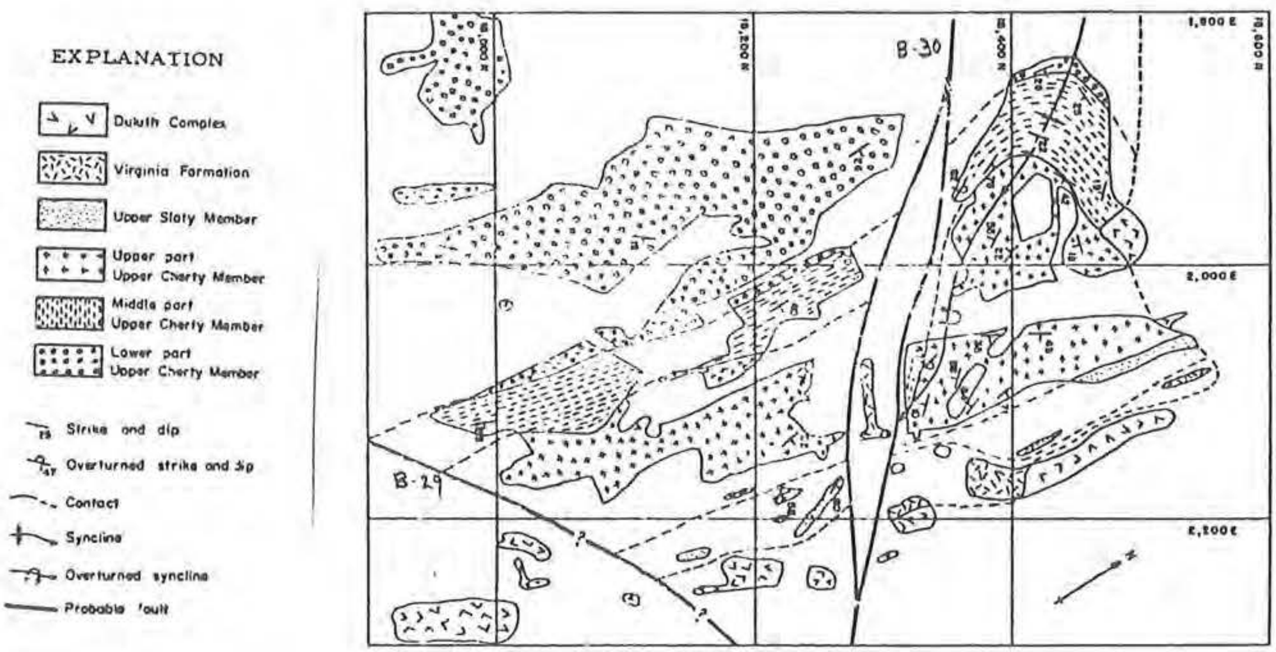


Figure III-6: Geologic map of the north end of the Dunka Pit area, from Bonnichsen, 1968.

reverse faults. The relationship between these two fault sets are exposed along a road cut trending northwest into the pit parallel to drill line 11,100 N. In Figure III-7A a southeast-dipping fracture, attitude N 30 E/62°SE, is offset by a parallel set of two reverse faults, attitude N 20 E/50-60°SE, about 20 feet apart. The southeast-dipping fractures are observed to bend and be offset in the direction of motion of the reverse faults. The reverse fault planes contain abundant slickensides (Figure III-7B) and fibrous quartz veins, but they do not exhibit the severe alteration associated with the southeast-dipping normal faults.

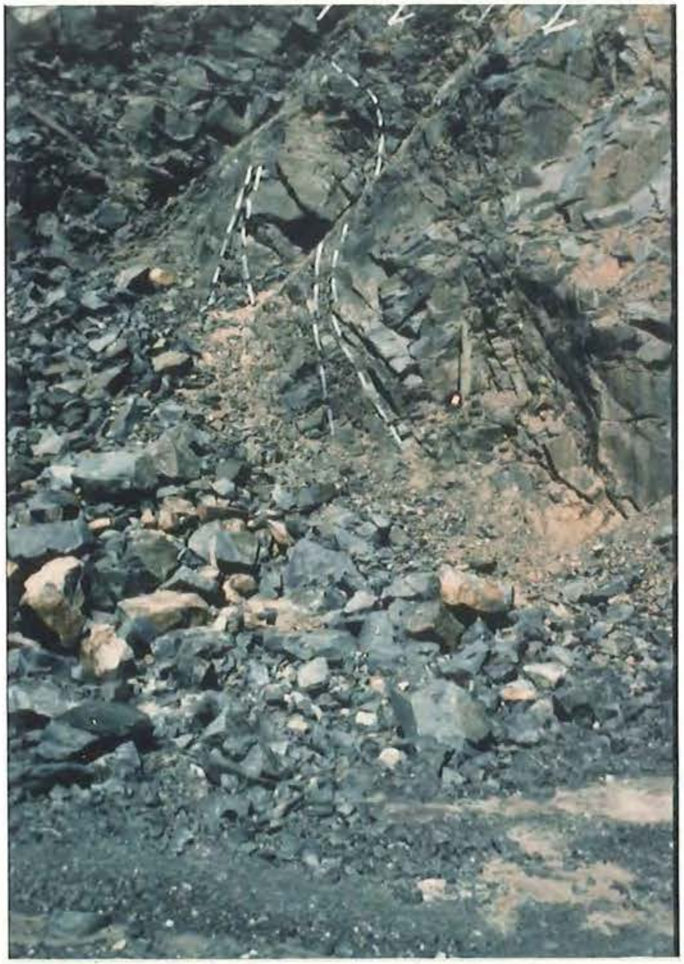
Folds

A number of folds occur in the Dunka River area. The overturned southeasterly plunging syncline that occurs adjacent to Fault B-30 has already been mentioned. Two small synclines, each a few hundred feet long were mapped by Bonnichsen (1968). One occurs in the northwest quarter of section 35, trends roughly N-S and plunges to the south. The other occurs in the northeastern quarter of section 3 again trending roughly N-S and plunges to the south.

Another syncline with a sinuous axial trace was mapped by Bonnichsen (1968) in the northwest quarter of section 35. The syncline had an overall trend and plunge to the southeast where it was terminated at the Boundary Fault. Subsequent structure contour maps and field observations indicate that the syncline may turn to the south and parallel the Boundary Fault up to Fault B-28 which either terminates or offsets the syncline (Plates II and VI).

A monocline or asymmetric anticline is illustrated in Figure III-8.

A



B

Figure III-7: A: Northeast view of offset of a fracture zone along reverse faults, Dunka Mine. B: Slickensides on reverse fault surface.

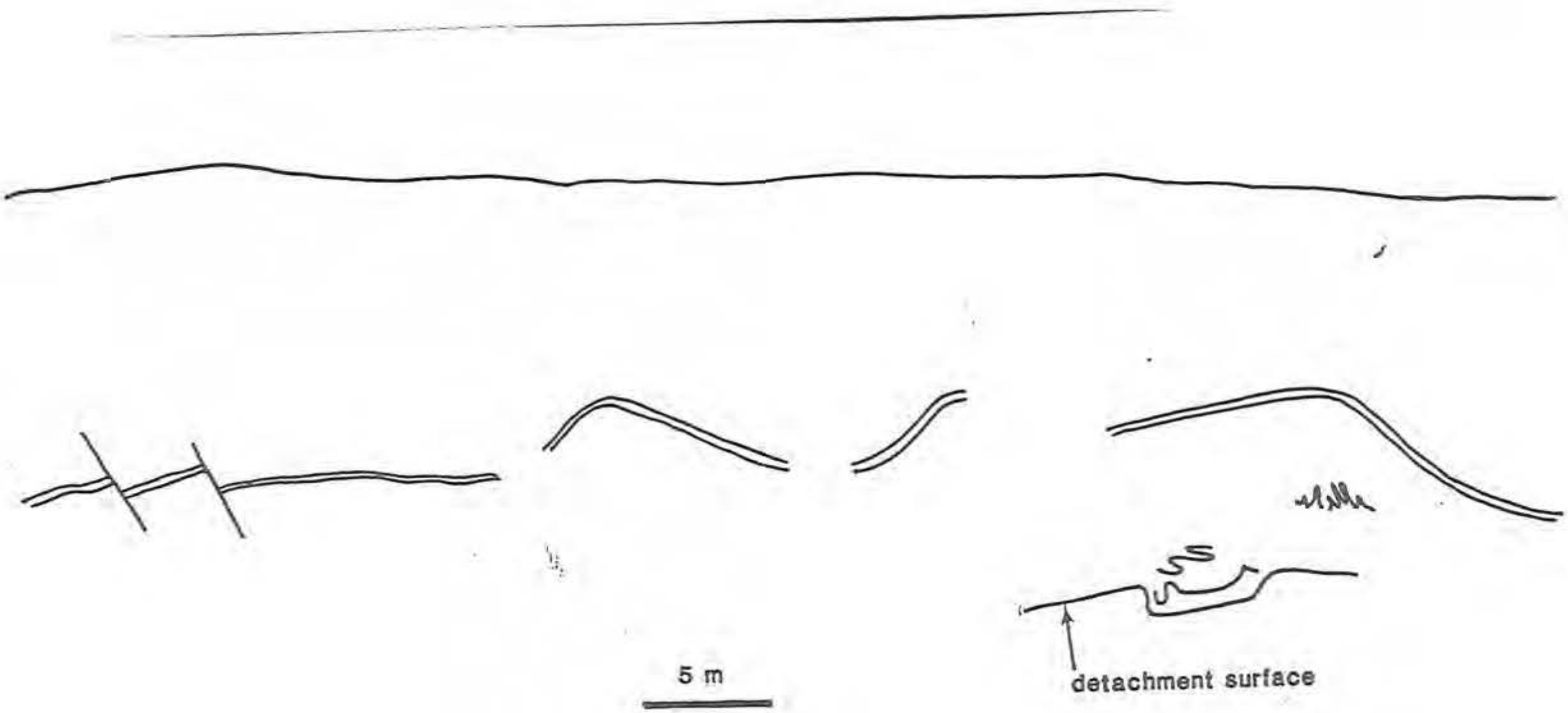


Figure III-8: View of a wall in the Dunka Pit (SE side) showing several types of structural features. The marked bed is a thin carbonate bed within the Virginia Formation. The detachment feature shown is DS-5.

Folding in the Virginia Formation is clearly illustrated by a thin, light-colored carbonate layer. The monocline, which has small-scale disharmonic folding in the core occurs in the northeast quarter of section 3. The fold axis trend and plunge of 5^{o} to S 15 W was estimated from cross sections constructed from drill hole data.

Other folds exist in the pit, but are too small to be delineated by the 200 feet x 300 feet drill hole spacing.

The only large-scale fold is a broad anticline in section 2 and 3 of Plate VI, best defined by structure contouring in the base of the gabbro (Plate V), and less prominent in Plate II. The anticline has a sinuous trend to the southeast. Ron Graber (personal communication) states that the highest grade of Cu-Ni mineralization in the overlying Duluth Complex occurs in the vicinity of this structural high.

Small-Scale Folds and Detachment Structures

In addition to the structural features described above and in the previous section, there are structures found in Animikie Group rocks in the Dunka Pit in close proximity to the Duluth Complex that are found nowhere else in the northeast Mesabi Range. These features include tight to isoclinal small-scale folds (amplitudes and wavelengths a meter or less), and some unusual undulatory sub-horizontal faults, here termed detachment features.

The small-scale folds in some cases occur in the core of a larger-scale fold (e.g. Figure III-8) with amplitudes on the order of ten meters. These larger folds are those discussed above. The tight, small-scale folds also occur associated with the detachment features, in the upper plate of rocks, above the detachment fault (e.g., Figure III-8,9). The vergence, attitude, and geometry of these small folds is quite variable and they are always disharmonic. These folds always occur within the uppermost Biwabik Iron Formation (the "A" layer of the Erie Mining Company terminology) or in the lowermost portion of the overlying Virginia Formation.

Sawed sections of examples of these folds (Figure III-10) or photomicrographs (Figure III-11) clearly show that a foliation, axial-planar to the folds, has developed in the calcite matrix. The crystals in the matrix have a well-developed shape fabric and have been strongly twinned.

The detachment features are well-defined faults (Figure III-9) which have variable dips (usually shallow) and can be traced for up to tens of meters across the pit wall. Eight of these structures were identified during the 1984 field season (Plate I).

Structures DS-4 and DS-5 occur in the trough of the monocline previously mentioned (Figure III-12). Detachment structure DS-5 is about 25 feet wide and has placed the Virginia Formation in fault contact with the B layer of the Biwabik Iron Formation on its east and west borders (Figure III-13). The basal contact is obscured by debris. Folding in the Virginia Formation and/or the A layer of the Biwabik Iron-Formation occurs within and above the structure (Figure III-14). The axial plane of the folds dip to the west. The trend and plunge of the axis of the large fold within the structures is 13° to S 25 W. The attitude of the contact on the west side is estimated to be N 55 E ($\pm$ 20°)/85°SE.

Detachment structure DS-4 is exposed about 120 feet west of DS-5. It is about 34 feet wide with recumbent folding of the Virginia Formation

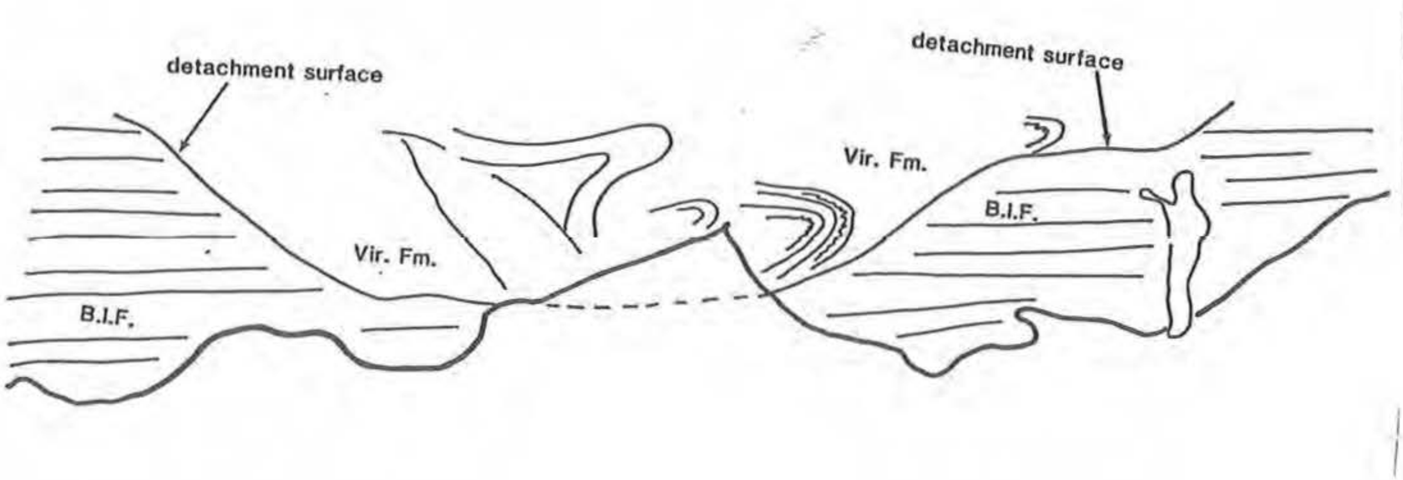


Figure III-9: Detachment structure DS-4 in the Dunka Pit.

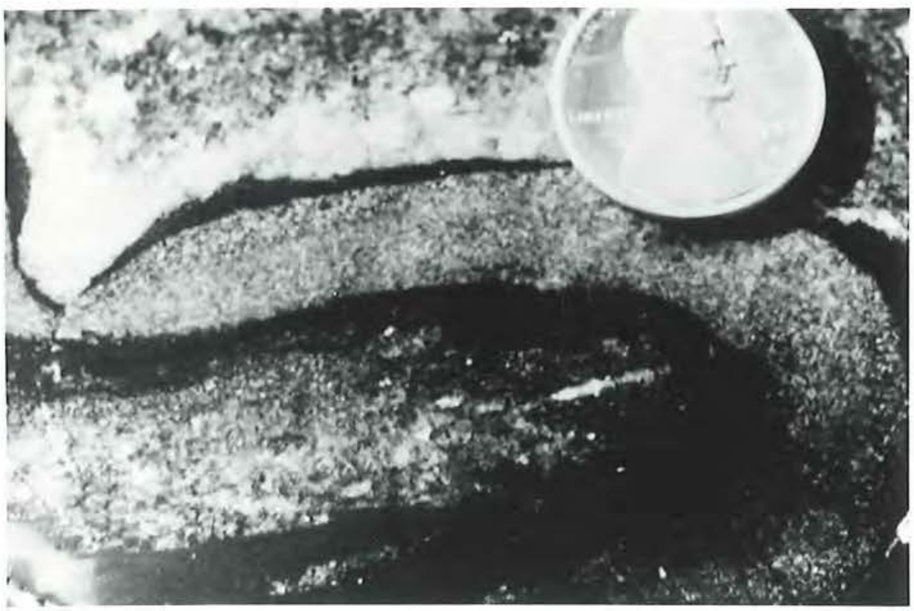


Figure III-10: Cut slab of a small-scale fold from the Dunka Pit. The axial-planar fabric is clearly seen in the core of the fold.

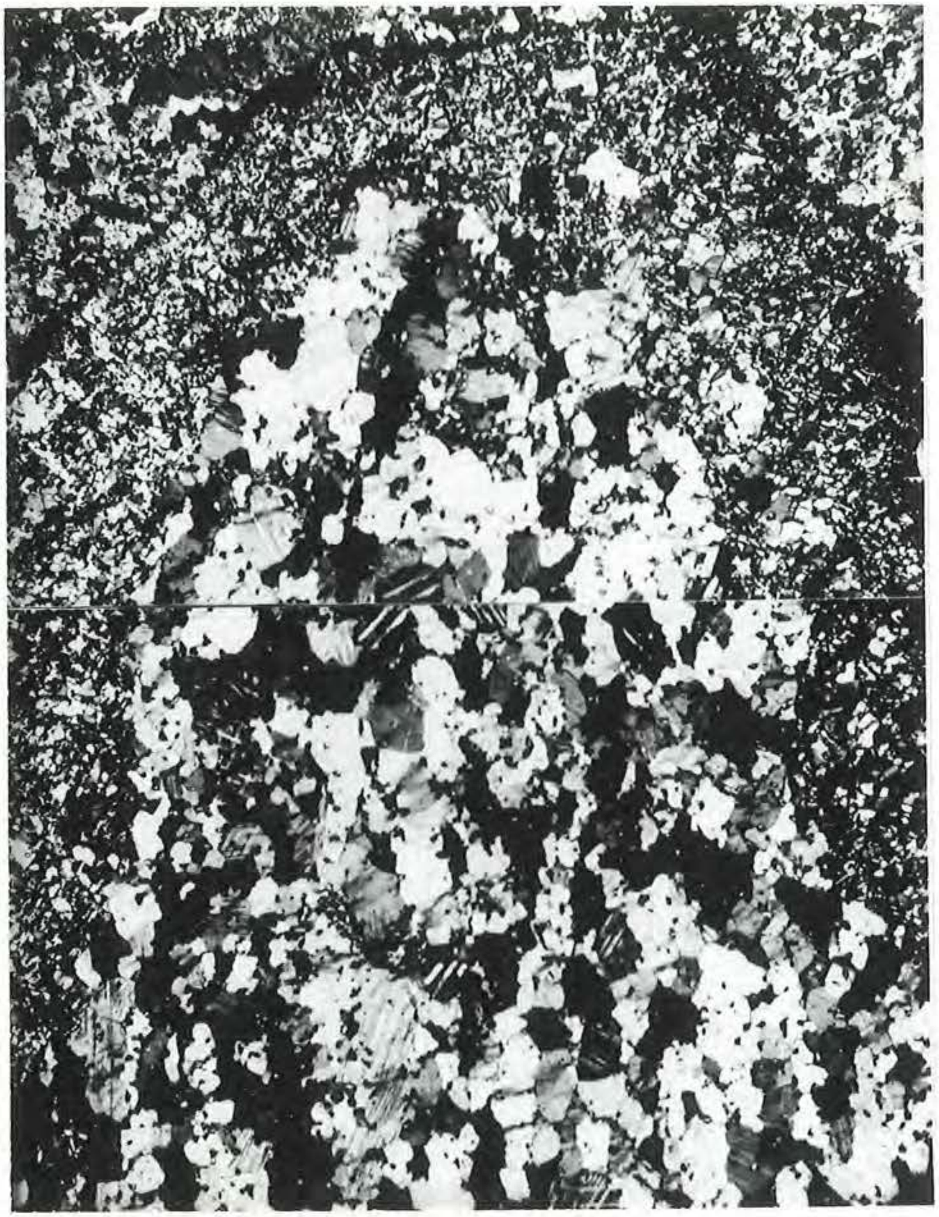


Figure III-11: Photomicrograph of the fold shown in Figure III-10. Note the shape, fabric and the abundant twinning of the calcite. Crossed polars.

Figure III-12: Detachment structures DS-5 and DS-4 in the trough of a monocline in section 3, Plate 6, Dunka Mine. View to the southeast. Monocline and DS-5 are also shown in sketch in Figure III-8.

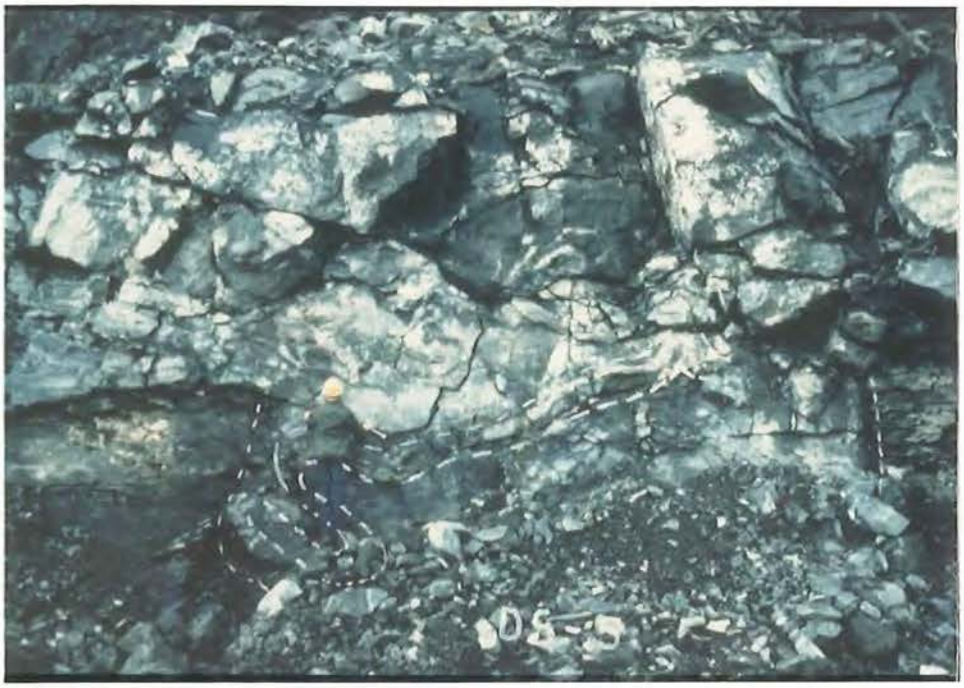


Figure III-13: Detachment structure DS-5 (see Figure III-12). Dashed lines outline fold in the upper plate of the feature. View to southeast. Detail of folds occurring higher in the upper plate than the one outlined here is shown in Figure III-14.

Figure III-14: Two views of detail in folded rocks of the upper plate of detachment structure DS-5.

within the upper plate (Figure III-9). The A, B, and part of the C layer of the Biwabik Iron-Formation are not present and the Virginia Formation is in fault contact with the Biwabik Iron-Formation. About 15 to 20 feet of stratigraphy is therefore missing. The attitude of the contact is N 15 E/67°NW on the east side, N 5 W/84°W on the west side and N 20 E/43°SE at the base of the structure. A thin (0.5 to 1.0 inch) continuous fine-grained black band occurs at the Virginia-Biwabik contact. On the east side, a 1.5 inch wide, dark green band, possibly diopside, occurs next to the black band along the contact.

Detachment structures DS-6, 7 and 8 occur between drill lines 11,400 N and 12,000 N. Two of the structures DS-6 and DS-7 can be traced laterally for about 100 to 150 feet with some certainty by outcrops on the face and roof of the bench. Outcrop is less abundant for structure DS-8, but probably also has a lateral extension. These detachment structures seem to form a set of parallel troughs about 50 to 140 feet apart (Figure III-15) trending about N 25-30 E, parallel or sub-parallel to the trend of the contact of the Duluth Complex . Folding in the C layer of the Biwabik Iron Formation occurs with faulted anticlines developing beneath the detachment structures. This relationship exists beneath structures DS-6, 7 and 8 (Figure III-15). The faults have developed an imbricate fracture pattern with the east side thrust up with respect to the west side. Structure DS-8 has a recumbent fold occurring in the upper plate (Virginia Formation) within the trough. The other two detachment structures are too disrupted to determine if the rocks of the Virginia Formation are folded within the upper plate of the structure.

The remaining three detachment features outcrop in the south pit of Area #8. Two of these, DS-2 and DS-3, occur between drill lines 6,300 N

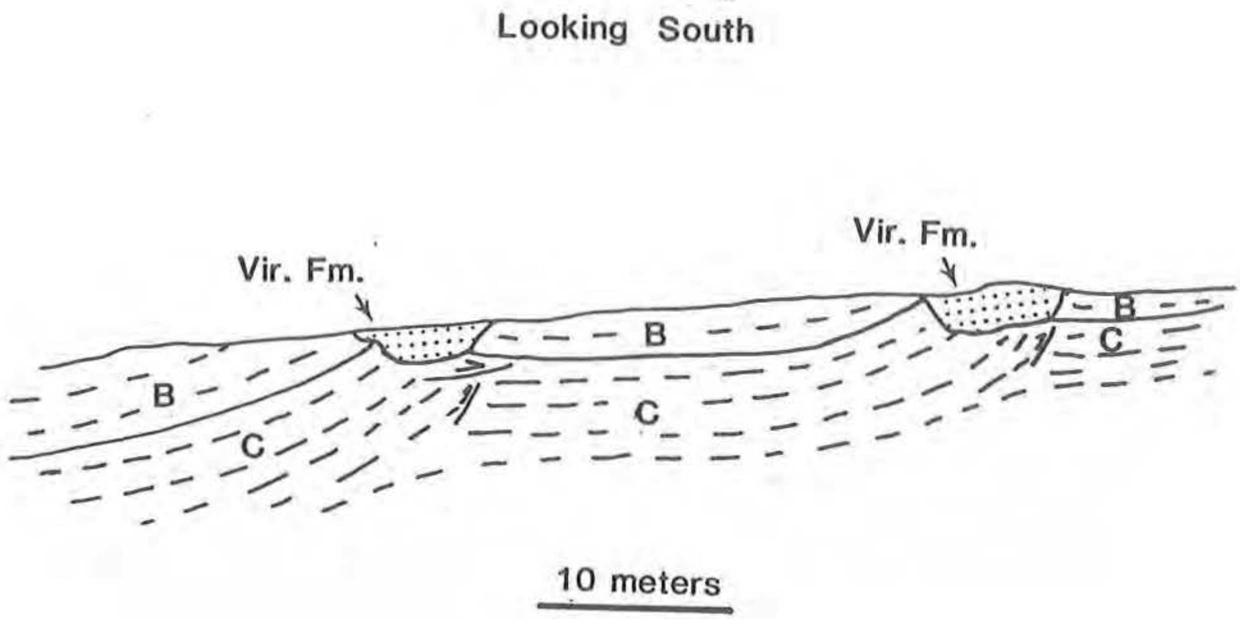


Figure III-15: Detachment structures DS-7, and DS-8 in the Dunka Pit. Letters refer to units in upper part of Biwabik Iron Formation.

and 6,600 N. Detachment structure DS-2, trending N 20 E, is exposed along strike in the face of the southeast pit wall for about 60 feet. Again,the A and B layers are missing and the Virginia Formation is in fault contact with the C layer of the Biwabik Iron Formation (Figure III-16). Two folds occur in the upper plate; one fold axis has a measured trend of N 40-50 E and crops out to the east of the exposure. The other is exposed to the west in the pit wall about 15 feet above the pit floor.

Detachment structure DS-3 occurs near drill line 6,600 N to the northwest of DS-2. This detachment structure cuts out all but about one foot of the B layer. A fracture cleavage trending about N 30 E has developed in the B layer beneath the trough. The trough is estimated to be 15 to 20 feet wide. There is no disruption in the C layer beneath this detachment structure.

Detachment structure DS-1 is exposed in the southeast pit wall along drill line 4,500 N. The structure is about 25 feet wide at the top tapering to about 15 feet at the bottom where the Virginia Formation is in fault contact with the C layer; again the A and B layers are missing (Figure III-17). There appears to be folding in the Biwabik Iron-Formation with a broad anticline flexure occurring beneath the detachment structure. A large recumbent fold occurs in the upper plate on the southwest side of the detachment structure. Granitic material occurs along the Virginia-Biwabik Iron Formation contact on the southwest side of the structure. In places, the granite is mixed with the Virginia Formation.

Certain characteristics are common to a number of the detachment features. These include: 1. In all the structures stratigraphy is removed or missing, placing younger strata on older strata; 2. The

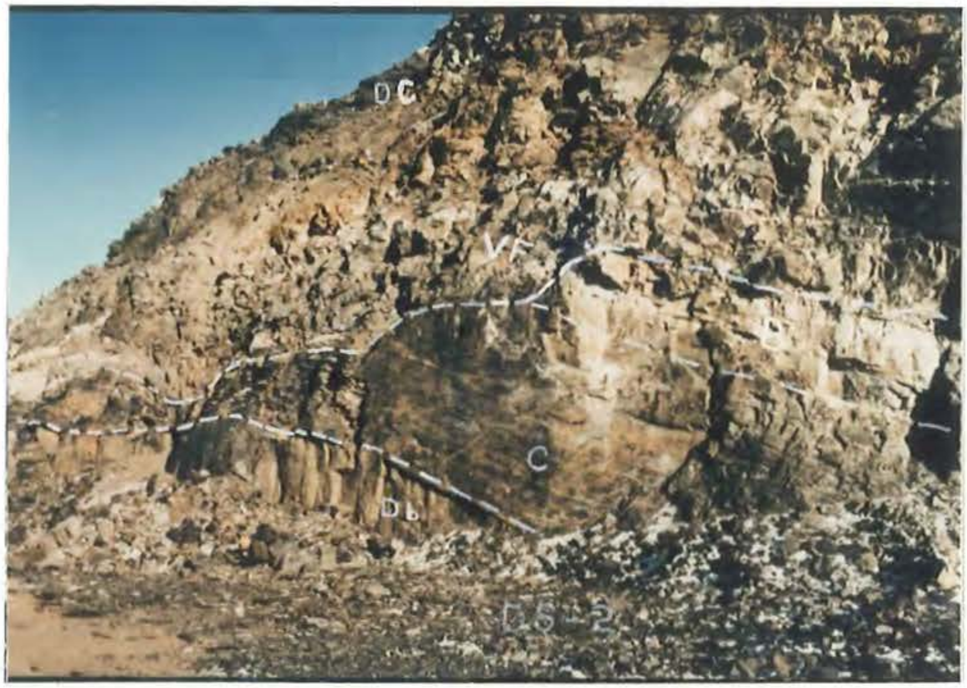


Figure III-16: Detachment structure DS-2 is exposed for about 80 feet along the southeast wall of the south pit, Dunka Mine.

Figure III-17: Southward view of detachment structure DS-1 in the south pit, Dunka Mine.

structures never penetrate below the first few feet of the C layer of the Biwabik Iron Formation; 3. The A and B layers are entirely removed or missing in all but one of the structures (DS-3), where about one foot of B layer remains; 4. The upper plate of the detachment structures contains rocks of the Virginia Formation, which are most often strongly deformed; 5. Where exposure is good, the structures form troughs which can be traced laterally in the pit wall and floor for up to 150 feet along the trough axis (These include DS-2,6,7 and 8.); 6. The troughs range from 20 to 30 feet across their widest extent; 7. All (except for one which was not measured) of the trough axes trend N 20-30 E; and 8. Structures DS-6, 7 and 8 occur at the crests of faulted anticlines.

FORM OF THE BASE OF THE DULUTH COMPLEX

General

The general form of the base of the Duluth Complex in the northeastern Mesabi Range is shown on Plate III, with detail of the Minnamax and Dunka River areas on Plates IV and V respectively. Plates III and V were hand drafted, while Plate IV was computer generated, using the Surface II contouring package of the University of Minnesota Computer Center and data from the mining company drill holes.

The shape of the basal contact is quite variable along its length but there are some generalizations that can be made, and some general trends that are seen. The general slope of the contact is from northwest to southeast, with an average dip of about 30 degrees over the region. There are places where this slope is a fairly constant gradient, and a few places where the geometry of the contact is somewhat similar to the "step and riser" shape suggested by Weiblen and Morey (1980). There are also several areas of complex geometry, involving domes and basins, such as the Minnamax area.

There appear to be several northwest-trending escarpments on the contact, which may be interpreted as steeply-dipping faults, at nearly right angles to the trend of the edge of the Duluth Complex in this region.

With one or two exceptions, there do not seem to be many areas of close spacing of structure contours showing a steep gradient down to the southeast, which could be interpreted as northeast-trending normal faults.

There is, in fact, one area on Plate III where there is a steep gradient with a northeast trend, but the gradient is against the general southeast dip of the contact, and if it represents a fault, it must be a reverse fault (as interpreted on Plate III). It is also possible that this steep gradient is not a fault, but just represents a structural or stratigraphic irregularity in the pre-intrusion country rock.

Data from structure contour maps from several horizons within the Biwabik Iron Formation in the Minnamax area show that many of the features which are expressed on the form of the base of the Duluth Complex are also present in the footwall rock. Thus the domes and basins, ridges and valleys on the basal contact are quite likely related to folds in the country rock, showing a good structural control on the shape of the intrusion in this local region; that is, that intrusion proceeded more or less along bedding planes in the banded iron formation.

Dunka River Area

A number of faults and undulatory structures exist in the Dunka River Area. Many of these have already been discussed previously and will be mentioned only briefly here. A possible "rift-transform" offset relationship (Weiblen and Morey, 1980) may exist at the northeast end of the Dunka pit mine (Plates II, V and VI); at least, a northwest-trending fault is implied here. The existence of the southeast-side-up Boundary Fault is well documented by field observation and drill hole data. The existence of faults B-30 and B-31 is less definite. Fault B-30 was described by Bonnichsen (1968) and is shown to extend for about 600 feet on his base map. We have extended this fault based on structure contour maps developed for this study (Plates II and V). Fault B-31 is inferred from indirect evidence gathered from drill hole information. The other major structure in the base of the Duluth Complex in this area is the broad anticline with a southeasterly trend and plunge in sections two and three of Plate VI which coincides with an anticline observed in outcrop of the Biwabik Iron Formation in the Dunka Mine.

Minnamax Project Area

The major structural features in the Minnamax Project Area include two inferred faults, and a large synform and antiform which diverge to the east to form depressions and lenticular shaped domes with attendant valleys (Plate III). Truncation of the Biwabik Iron Formation in the footwall beneath the Duluth Complex is indicated at the southeast end of the prospect where drill holes pass directly from the Duluth Complex into Archean granite.

Fault DC-3 is inferred here to trend roughly north-south from the north half of section 29, through section 20 into section 17. The offset across this fault is estimated to be between 500 and 1000 feet, down to the east. A synformal structure, probably caused by drag, occurs on the east (downthrown) side of the fault. The fault is inferred to offset the basal contact of the Duluth Complex to the north on the east side. There does not appear to be any evidence for this fault in the Biwabik Iron Formation to the north.

Fault DC-2 is inferred to have a sinuous trend to the northeast for about a mile and a half from the southeast quarter of section 30 to the northeast quarter of section 29. The vertical offset is 200 to 300 feet, down to the northwest. The synform that borders the northwest side of the fault may be a dragfold along this fault. An alternative interpretation of this structure is that of a fold or an irregular surface feature that developed in the Virginia Formation as the magma of the Duluth Complex was emplaced. The Virginia Formation is 300 feet to 400 feet thick on the southeast side of the fault and to the southwest along the Virginia Formation-Duluth Complex contact. In the trough of the synform northwest of the fault the Virginia Formation is missing and the Duluth Complex directly overlies the Biwabik Iron Formation. The Virginia Formation begins to thicken again to the northwest toward the basal contact, where it measures 200 feet thick in drill hole.

A large antiform with an attendant parallel synform to the northwest traverses the Minnamax prospect from southwest to northeast. The antiform may be a continuation of a south-trending anticline occuring in the Biwabik Iron Formation north of the prospect. The anticline probably causes the embayment in the basal contact in section 36, which is indicated by drilling. A drill hole in section 36 penetrates 758 feet of Virginia Formation before reaching the Virginia-Biwabik contact. At this point the anticline changes from a south trend to an east-northeast trend and continues for about two miles to the southeast end of the prospect where the structure becomes complex (Plate III). Here the anticline diverges to form an irregular surface resembling basins and lens-shaped domes and valleys. It is in the vicinity of this irregular topography that the highest grade of mineralization occurs.

Examination of structure contour maps for the top of the Biwabik Iron Formation from company files indicate that this folding also occurs in the iron-formation below. The folds occurring in the base of the Duluth

Complex at the Minnamax Project are probably controlled by the structures in the footwall rocks. These structures are similar to those found throughout the northeast Mesabi Range and are most likely pre-Keweenawan in age.

U. S. Steel Copper-Nickel Prospect

The U. S. Steel prospect extends for about 3 miles to the southwest from the west end of the Minnamax prospect. The anticline that causes the indentation in the basal contact separates the two properties. Iverson (personal communication) describes the general form of the basal contact as that of a monocline (Plate IV). He also mentions the existence of Virginia Formation inclusions in the Duluth Complex, high above the basal contact. He suggests that these inclusions may indicate that the Complex was intruded here as a sill-like body within the Virginia Formation. Hornfels inclusions are also in the Minnamax prospect.

Hoyt Lakes Area

Fault DC-1 is the only fault actually observed in the Duluth Complex during the 1984 field season. It occurs in the Partridge River troctolite in an 8 feet high ledge on the southwest side of the Duluth, Mesabi, and Iron Range railroad track in sec. 14, T. 58 N., R. 14 W. (Plate I). The fault plane is defined by a one-half-foot wide gouge zone (Figure IV-1) with an attitude of N. 53 W/81°NE. The sense of offset is not apparent. This outcrop occurs along the projected strike of the Dark Lake/Biwabik Fault (B-1) to the west. The trend of this fault (D-1) is

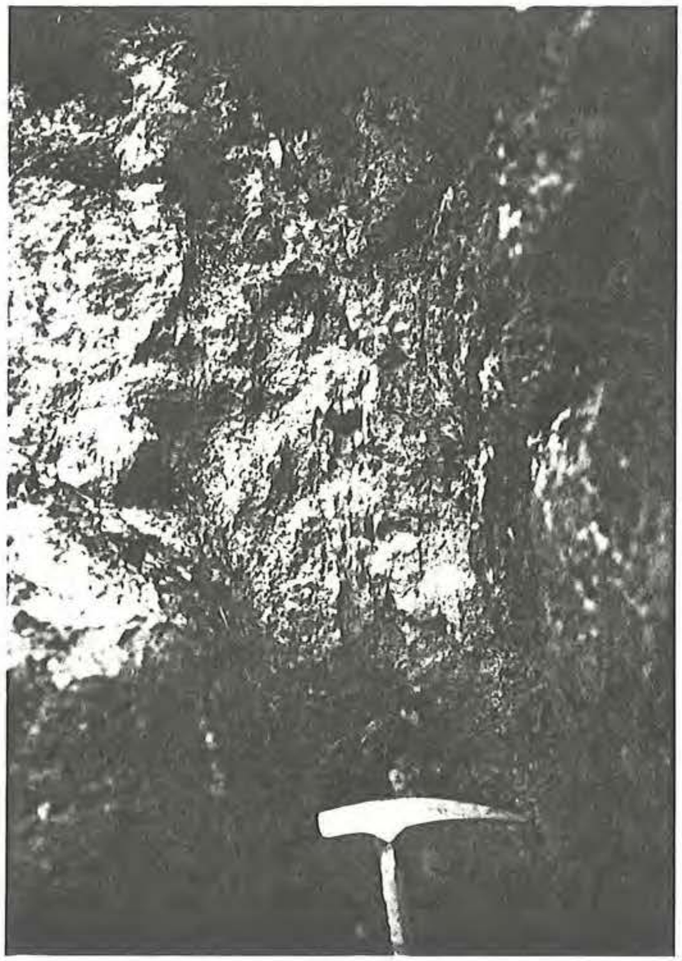


Figure IV-1: Fault gouge zone in outcrop of troctolite in the Duluth Complex along DM & IR railroad track, sec. 14, T. 58 N., R. 14 W. View to the southeast.

more northerly than the Dark Lake/Biwabik Fault (B-1) and may be a reflection of subsequent motion along the fault zone.

The last structure that bears mentioning here is the depression located at the northwest corner of Plate III near coordinator 6000 on the vertical scale and 2000 on the horizontal scale. This feature is tentatively shown as a synform associated with the Denora Fault/Monocline. The depression is based on one drill hole which intersects the contact at about 500 feet below sea level. Drilling is sparse in this area and the nearest holes that intersect the contact are about one mile north and one half mile south. The elevation of the basal contact on both sides of the depression is about 1200 feet above sea level. This depression may be a feeder or conduit to overlying magma chambers.

V

FIELD MAPPING

The geologic mapping was carried out by Eugene E. Mullenmeister during the 1984 season from April to November. Part or all of 47 days were spent examining exposures in the mines, especially those of Erie and Reserve Mining Companies, with the guidance and assistance of company geologists Ron Graber and Joel Evers (Erie), Jack Malcolm (Kennecott) and Jim Emanuelson (Reserve). The results of this intensive work are integrated with studies of company drillcore and logs in the detailed structure and structure-contour maps that are a major product of this study (see chapters II, III, IV).

Twelve days toward the end of the field season (August, October, November) were devoted to searching for, examining, and sampling outcrops in the Duluth Complex in the area east of Hoyt Lakes in the Allen, Bird Lake, and Babbitt SW quadrangles, assisted by Wade Carlson. These field maps are attached to this report; traverses are indicated in blue pencil on these maps. A list of samples collected is given in Table V-1 and a cross-listing of sites described by date is given as Table V-II.

This search showed the existence of much heretofore apparently unexamined outcrop in the area east of Hoyt Lakes, all in the Partridge River Troctolite of Bonnichsen (1974). Most outcrops were described as augite troctolite, with some augite-oxide troctolite, oxide gabbro, and hornfels. A large, conformable (NE-trending) band of troctolitic anorthosite was found southeast of the Partridge River in Sections 6 and 7, T.58N., R.13W. The area of hornfels previously known at Moose Mountain was extended to the northeast to Section 2, T.58N., R.14W. A hilly area in Sec. 31, T.59N, R.12W. and Sec. 1, T.58N., R.13W. is underlain by magnetite-rich troctolite. Other areas of outcrop examined and sampled are in Sec. 25 of T.59N, R.14W.; Sec's 11 and 14 of T.58N., R.14W; Sec's 5-9, 19 and 24-26 of T.58N., R.13W., and Sec's 17-19 of T.59N., R.12W. No evidence was found of the large N-S fault shown on Morey and Cooper's compilation map in Sec's 12-35 of T.59N., R.13W.

Structural data gleaned from this mapping include igneous foliation in the Duluth Complex troctolites, joints measured in both the taconite mines and Duluth Complex outcrops, and diabase dikes.

Foliation was measured in eight outcrops (Fig. V-1), all in the northwestern part of T.58N., R.13W. in an area of abundant outcrop. All but one show an orientation generally conformable with the base of the Partridge River troctolite (ENE, gentle SE dip) as anticipated from other regional observations, but one inexplicably dips to the NW.

The joints, for which only strikes were measured in most cases (they are generally subvertical), were plotted on two rose diagrams, one for those found in the Biwabik Iron Formation in the mines and one for those found in the Duluth Complex outcrops (Figs. V-2,3). They show strikingly different patterns. The 305 joints measured in the BIF show two major concentrations, nearly at right angles, at N. 15°E. and N.70°W. These directions are roughly parallel and perpendicular to the contact with the base of the Duluth Complex in the Dunka Pit, where many of the readings were taken. Two contrasting inferences could be made: did the jointing in the BIF control the intrusion mechanics of the Duluth Complex magma, or did the intrusion and subsequent warping result in brittle deformation (jointing) of the nearby BIF in directions related to the basal intrusive contact? There still do not seem to be enough or appropriate observational data to resolve this question.

The joints in the Duluth Complex (Fig. V-3) show a markedly different strike pattern from those in the BIF. A great variety of directions was found, but with maxima to the NW at N.25°W. and N.45°W., roughly transverse to the general trend of the basal contact. These seem clearly to have been induced by a stress field different from that which produced the jointing in the BIF, and this might be expected since most of the measurements were made several miles from the basal contact in an environment where the rock probably did not become brittle until long after the basal chilled contact was formed.

Five diabase (microgabbro) dikes were found, two cutting the Biwabik Iron Formation in Erie's Area 6, the other three cutting the Duluth Complex. Figure V-4 is a stereogram showing their orientations. The dikes in the BIF strike N.15°E., parallel to one of the major joint sets in this unit, implying the presence of the joints prior to dike intrusion. Similarly, the dikes which cut the Duluth Complex are also parallel to the major jointing in the DC and not very different from the average trend

(N55W) of 16 dikes shown cutting the Duluth Complex in this general region on Morey and Cooper's compilation. These again clearly were intruded along a fracture set or tension direction younger than the actual intrusion of the Partridge River Troctolite. However, the country rocks were evidently either still hot or became reheated after dike intrusion, as shown by the somewhat granoblastic, annealed texture of the dikes.

In summary, the reconnaissance mapping carried out in the Duluth Complex for this project shows that a) there is considerably more outcrop remaining to be studied east of Hoyt Lakes; b) no evidence of faulting was found in the DC in this area, though more field work needs to be done; and c) the joints (and dikes following them) have markedly different orientations in the Biwabik Iron Formation and the Duluth Complex, and probably formed under completely different stress fields.

TABLE V-1

Samples collected in mapping program by E. E. Mullenmeister (Sample Numbers are keyed to localities)

Sample No.	Date	Rock	Location
004	19/4/84	Diabase sill in I.F.	nr. Siphon Structure
005 H	11/5/84	hornfels, just below contact	Dunka Pit
005 G	"	gray, med.-gr. gabbro, 1' above contact	"
010	15/5/84	diopsidic(?) hornfels	"
011	"	slickensided I.F. B-layer hornfels	"
)13A	"	calcite+(?) in fault zone	"
013B	"	altered gabbro at fracture	"
026	23/5/84	granite pegmatite dike in gabbro	"
027	"	" " " "	"
M005A	14/6/84	diabase sill drill core	"
R005	"	gabbro w/sulfides above monocline crest	"
M004	"	diabase sill drill core	Wentworth Mine
030H	20/6/84	hornfels at contact	Dunka Pit
030C	"	C-layer, BIF	"
031	"	granite dike/sill at IF-gabbro contact	"
036	"	hornfels w/sulfide veins	"
R005GC	27/6/84	gabbro 3 ft. above contact	"
R005S	"	Schistose Virginia Fm. hornfels	"
043	28/6/84	Gabbro/w mt. bands; "gabbroized IF"	"
051	3/7/84	alteration on slickensided IF (?)	"
054	"	White granitic dike cutting gabbro	"
054F	"	altered gabbro(?) in fault zone	"

054D	"	pink, granitic dike	"
062	4/7/84	I.F. with gabbro or C-Layer sill	
DC-02FG	23/8/84	"Ferrogabbro" (foliated cummulate gabbro)	Greenwood L.W. quad
DC-020A	"	"Olivine anorthosite" (maybe erratic)	"
#7906	31/8/84	Aurora sill, drill core, 72 ft. down	
E8-073Gb	6/9/84	Gabbro in syncline	Dunka Pit
D-tt1	"	"disseminated troctolite"	Hwy 1 4.3 mi. N of Co.424
P-tt2	"	poikilitic troct.	"
D-tt3	"	disseminated "	"
P-tt4	"	poikilitic "	"
R-075Db	7/9/84	diabase dike in contact w/IF	Reserve Pit
R-075-A	"	diabase sill - center	"
R-075-B	"	" " - contact	"
R-077-A	"	" " fine-gr. chill?	"
R-077-B	"	" " coarser nr. center	"
R-078-A	"	" " fine gr.	"
R-078-B	"	" " coarser, nr. center	"
R-079	"	" "	
E8-055	14/9/84	"gabbroized IF"	Dunka Pit
DC-135	25/10/84	med.-gr. poikil. gabbro	Sec. 7, 58N/13W
DC-136	"	" , foliated	"
DC-137	"	"	"
DC-137A	"	anorthosite w/oxides	"
DC-137B	"	troctolite	"
DC-137C	"	foliated gabbro w/plag. phenos	"
DC-138	26/10/84	poikil. ol. anorthosite	"

Table V-1 cont'd.

DC-139	"	foliated troctolite	"
DC-141	"	anorthositic ol-hbd gabbro	"
DC-142	"	poikil. ol. anorthosite	"
E8-144A	29/10/84	gabbro, S. side of fault zone	Dunka Pit
" B	"	altered rock	"
" C	"	hornfels, N. side of fault	"
DC-153	2/11/84	diabase sill	Erie Area 6
DC-154A	"	diabase dike, fine-gr.	"
DC-154B	"	" " coarser	"
DC-154C	"	"igneous looking rock"	"
DC-155A	5/11/84	Augite troctolite	Sec. 25, 59N/14W
DC-155B	"	altered zone in above	"
DC-156	"	pegmatitic zone in gabbro (?)	"
E5-157A	6/11/84	Diabase sill	Erie Area 5
E5-157B	"	poss. diabase bounded by qtz.	"
E2-160A	7/11/84	diabase sill. 1 ft. fr. contact	Erie Area 2
E2-160B	"	" chilled border	"
SS-165	"	KL metasediments	Sec. 11
SS-173	14/11/84	Iron Fm.	nr. Siphon Structure
E8-167A	16/11/84	fold in hornfels	Dunka Pit
E8-167B	"	" "	"
E8-167C	"	contact zone	"
E8-177A	"	breccia zone in gabbro	"
E8-178	"	"	"
E8-180	19/11/84	diabase dike w/plag pheno's	"
E8-182	20/11/84	granitic dike nr contact	"

TABLE V-II

List of outcrop sites described, by date

(exclusive of mines)

Date	Station No.	Area
30/6/84	Bardons Peak	Duluth
21/8/84	GP-01	Grand Portage area
22/8	GP-02 to 08	" " "
23/8	DC-01 to 03	Greenwood Lake West quad
6/9	(described but not numbered)	
	(Rest in Allen, Bird Lake, Babbit SW, Skibo quads)	
10/10	DC-081 to 088	T59N, R12-13W
11/10	DC-089 to 100	most in Sec. 11,14, T59N, R13W: Sec. 1, T58N, R13W
12/10	DC-101 to 104	Sec. 8, T58N, R12W
15/10	DC-103 to 109	Sec. 8,9, T58N, R13W
16/10	DC-110 to 116	Sec. 5,7,8, T58N, R13W
17/10	DC-117 to 120	Sec. 31, 59N/12W: Sec. 25, 59N/13W
18/10	DC-116(?), 121 to 124	Sec. 8, 58N, 13W; Sec. 25, 59N/13W
19/10	DC-125 to 128	Sec. 24, 59N/13W: Sec. 19, 59N/12W
22/10	DC-129, 130	Sec. 8,7, 59N/13W
25/10	DC-101-104, 108, 134 to 137	Sec. 7, 58N/13W
26/10	DC-138 to 142	Sec. 7, 58N/13W
5/11	DC-155, 156	Sec. 25, 59N/14W

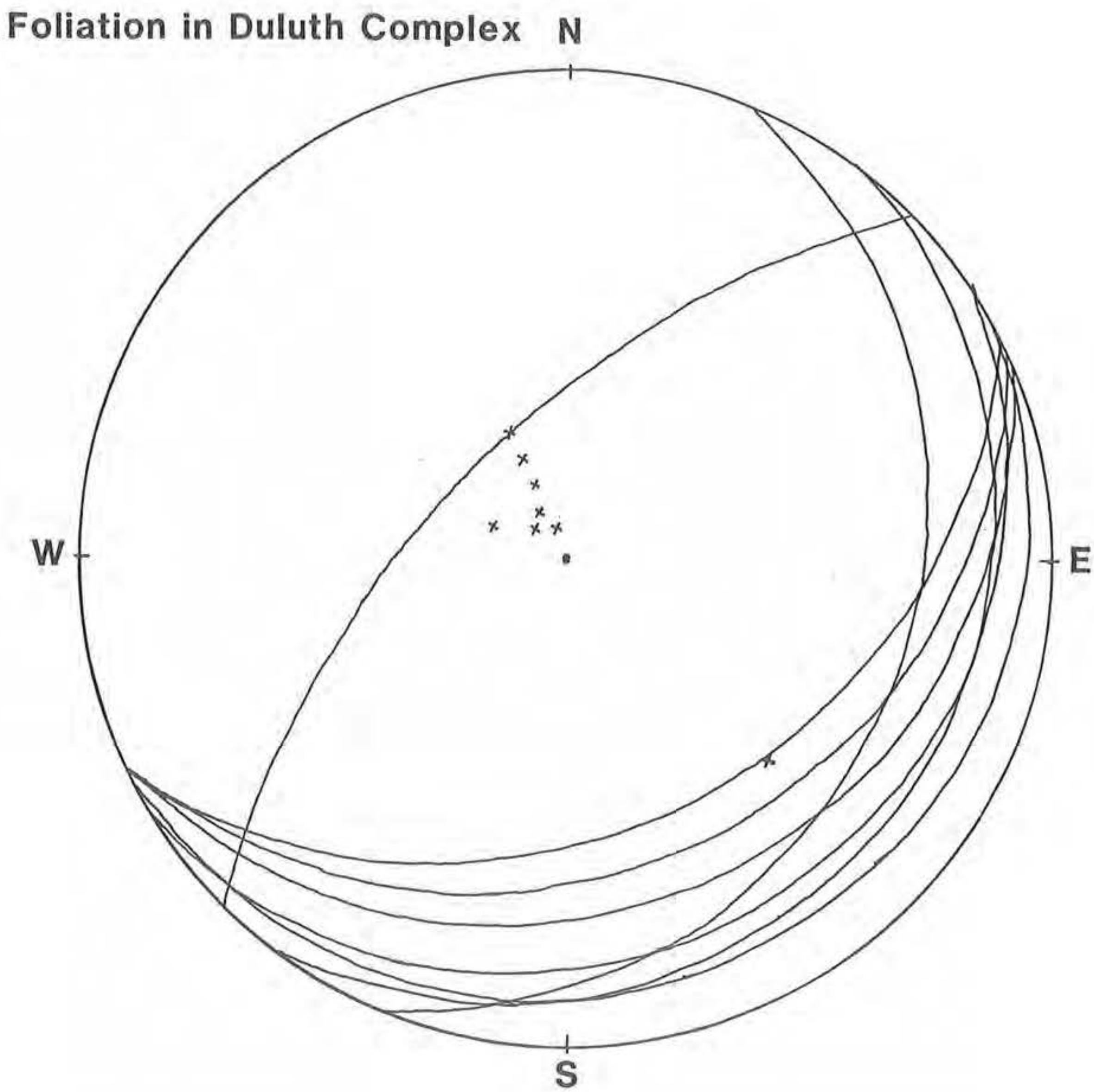


Figure V-1.
Foliations measured in the Partridge River Troctolite, northwestern part of T.58N., R.13W., plotted on a stereogram (lower hemisphere). Poles to foliation represented by "x".

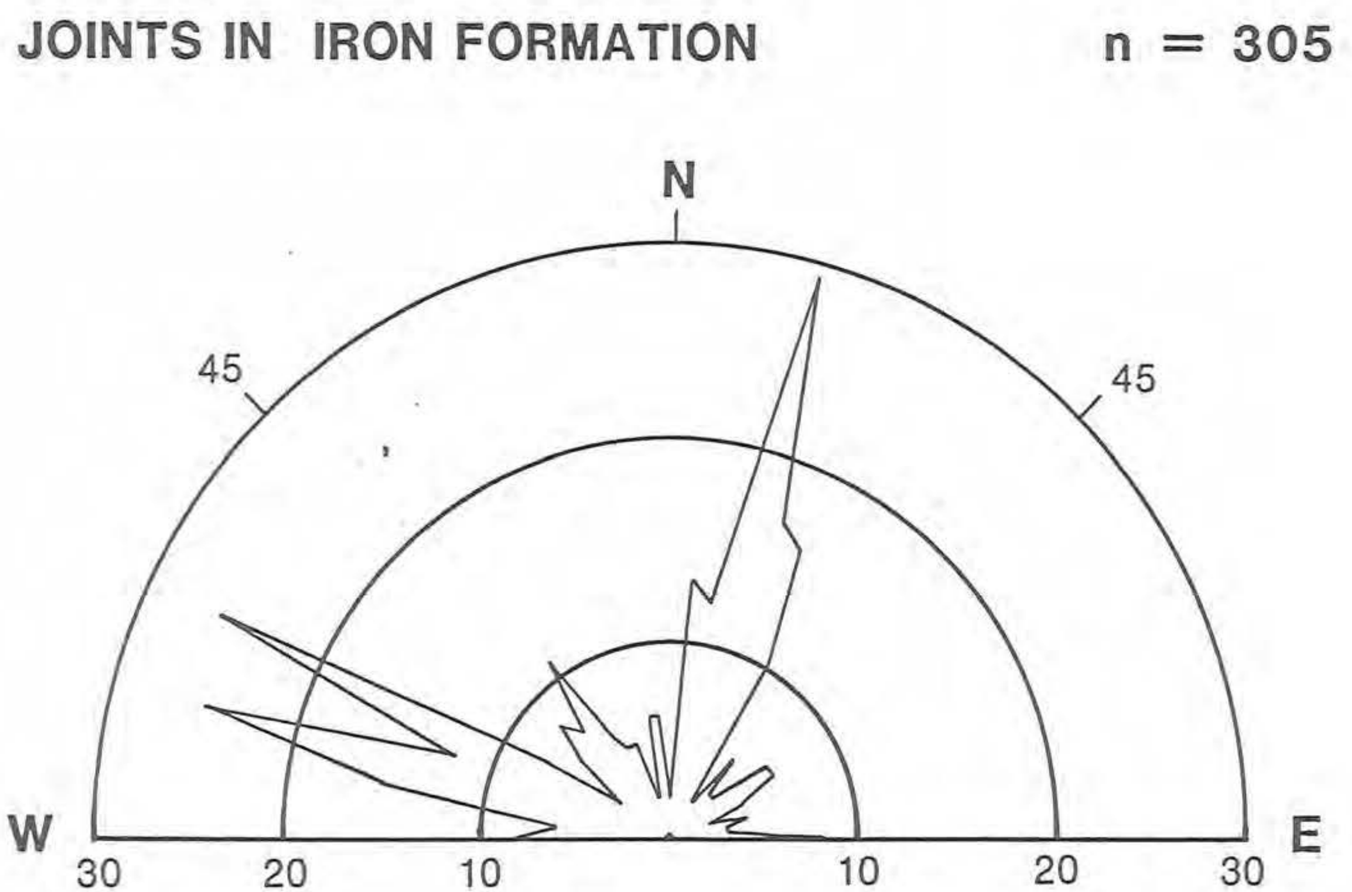


Figure V-2.

Rose diagram of strikes of joints measured in the Biwabik Iron Formation (in the mines).

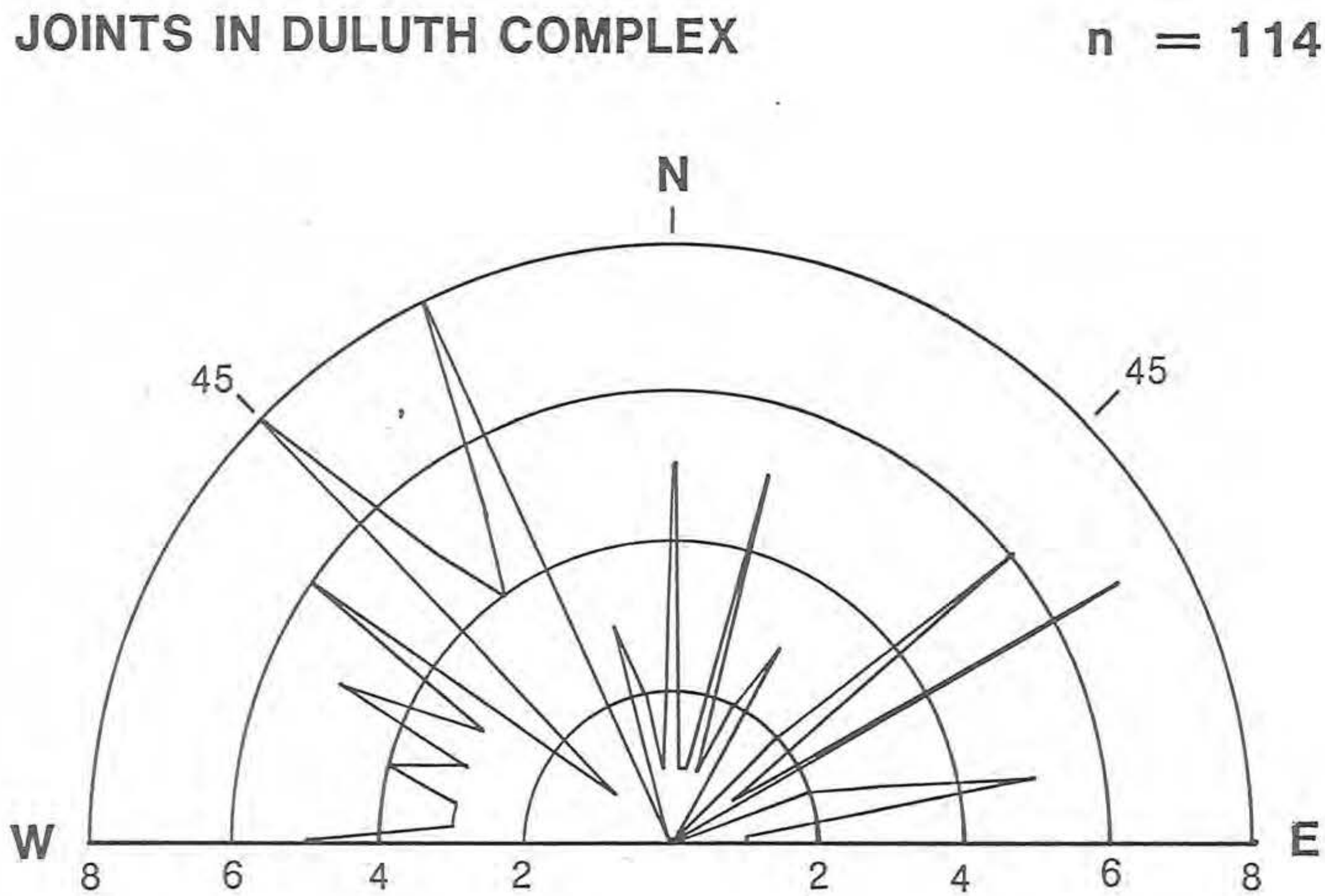


Figure V-3.

Rose diagram of strikes of joints measured in the Duluth Complex.

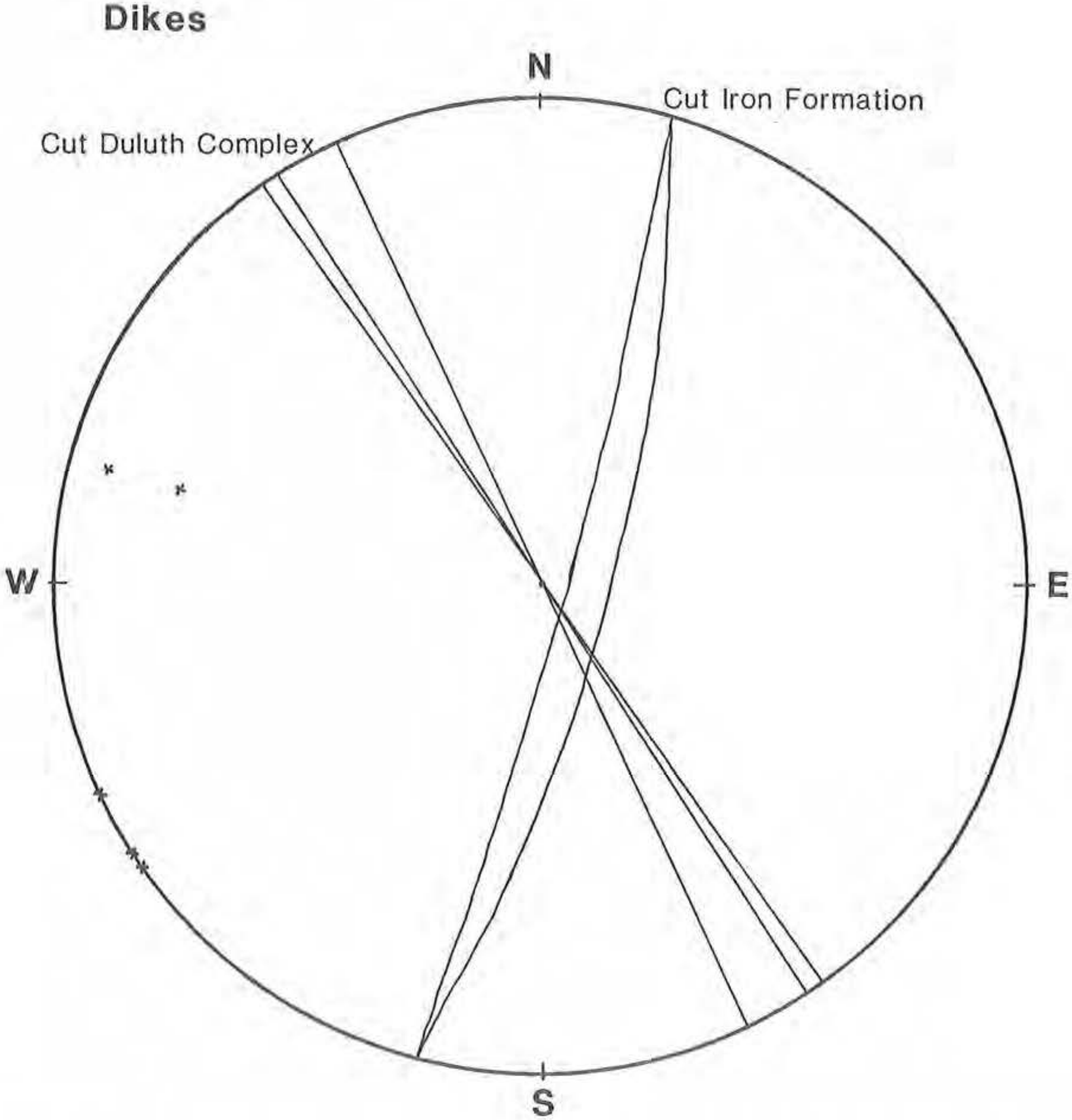


Figure V-4.

Attitudes of dikes found in the mapped area, plotted on the lower hemisphere of a stereogram. Poles represented by "x". The three that cut the Duluth Complex strike northwest; the two that cut the Biwabik Iron Formation strike NNE.

DISCUSSION, INTERPRETATION, AND CONCLUSIONS

As illustrated on Plate I and discussed above, there are a goodly number of structural features in the northeast Mesabi Range. There are several important questions which must be asked about this series of structures, perhaps the most important being their age. Several lines of reasoning suggest that they are pre-Keweenawan. First is the extent of the features. The faults and folds mapped in this study show no sign of decreasing in frequency, size, or displacement with increasing distance from the contact with the Duluth Complex. Features similar to those mapped in this study are known to exist in the entire Mesabi Range to the west of the present study area (Marsden, personal communication). In fact, the displacement on some faults decreases markedly toward the contact with the Duluth Complex. The Denora Fault has a displacement of 125 feet at its northeasternmost exposure, and decreases to effectively zero where it is essentially a joint on the hinge of a monocline just east of the intersection with the Fowler Fault. Further, there does not seem to be a well-developed pattern of the folds and faults, specifically attributable to a Keweenawan rift stress field (such as the postulated half-graben model of Weiblen and Morey, 1980). Rather, the structures exhibit a variety of attitudes, geometries and characteristics. Indeed, some of the faults (the so-called Boundary Fault in the Dunka pit, for example) change their strike and their dip quite rapidly along their extent.

At least one of the structures in the present study area (the Siphon structure) as well as others to the west (the Virginia Horn for example) are known to have exerted stratigraphic control on the Animikie rocks, and must therefore be at least Animikian in age. The combined thickness of the lower slaty and lower cherty members of the Biwabik Iron Formation decreases from 288 feet to 157 feet from west to east across the Siphon structure. This change in thickness is opposite to the sense of post-Animikian (post-Biwabik) displacement.

It is known from recent drilling (Southwick, personal communication) that a penetrative cleavage, well-developed to the south, in rocks equivalent to the Virginia Formation dies out only a few km south of the central Mesabi Range. This foliation is known to be Penokean (1850-1750 Ma) in age. The possibility therefore exists that the structural features in the northeast Mesabi Range are Penokean in age.

Aside from the question of age, the structural features in the northeast Mesabi Range are not easily interpreted as having resulted from a specific compressional or extensional event. The rocks of the Animikie Group are well-layered, and overlie a basement which consists of much more massive rocks of the Giants Range Granitic Complex, and the deformed metasediments and metavolcanics of the Knife Lake Group (Plate I). It is quite possible that the Animikie Group rocks behaved as a highly anisotropic package of brittle or semi-brittle material overlying a strong base, and became fractured and warped in response to fairly low stresses. In such a case, the structural features do not tell us much about the nature of the deformational event. It is nevertheless conceivable that the present distribution of structural features may have resulted from an extensional or a compressional regional stress system. The Archean basement rocks may have behaved in a manner more suitable for recording the nature of the deformational event, but exposure and stratigraphic knowledge of these rocks are both so poor as to preclude the possibility of gathering this information.

Certainly, no evidence was found in the footwall for the types of northeast-trending normal faults suggested by the half-graben model of Weiblen and Morey (1980). This does not preclude their existence, but if they exist, they must be hidden at depth further to the southeast, toward the center of the Duluth Complex.

The small-scale folds and detachment features, unique to the Dunka Pit do seem to be Keweenawan structural features. Although the size and the somewhat chaotic nature of the folds is similar to soft-sediment folds described from many other places, their presence very near to the contact with the Duluth Complex (most often within meters) and absence elsewhere suggests that they developed at the time of the intrusion. The presence of an axial-planar fabric in the small-scale folds confirms a Keweenawan age. The recrystallization event in the Virginia Formation hornfels is undoubtably Keweenawan, and the fold-related fabric is the same age as the recrystallization. The close relationship of the small-scale folds and the detachment features confirms the Keweenawan (syn-intrusion) age of the detachment structures.

The close proximity of the detachment features (both in map and cross-section sense) to the contact with the Duluth Complex, and the somewhat chaotic nature of the small-scale folds associated with these features suggests that they may have formed in a slumping event (or series of such events) at the magma-country rock interface. Slump features are known from other layered intrusions (Wagner and Brown, 1967), however these reported occurrences are wholly within the intrusive rock, and do not involve the country rock at all.

A dynamic analysis of such a slumping mechanism may be readily attempted. The shear stress on a potential slip surface at the bottom of a slump is given by the equation

$$\tau = [\rho_{sm} - \rho_m]\ gh\ \sin\alpha$$

where ρ_m is the density of the magma, ρ_{sm} is the density of the slumping country rock mass, g is the acceleration due to gravity, h is the depth from the country rock-magma interface to the potential slip surface, and α is the slope of the magma-country rock interface. The density of the magma was taken as 2.70 gm/cm^3 (Weiblen, personal communication). The density of the slumping mass was calculated to be 2.83 gm/cm^3 by estimating percentages of Virginia Formation, and the A, B, and C Layers of the Biwabik Iron Formation in the slumping mass (Table VII-1). Using a slope of 30 degrees for the magma-country rock interface, and using 20 m as the depth from the interface to the potential slip surface, we get a value of less than one bar for the driving shear stress. The reason for the low value is the small density difference between the magma and the slumping mass. Even letting h take the value of the maximum depth of burial (2 km) we still only get a driving stress, due to gravity alone, of 22.5 bars.

Tullis (1980) has shown that the shear stress necessary to twin single crystals of calcite is about 100 bars, and is insensitive to temperature. The shear stress necessary to twin polycrystalline calcite aggregates is temperature dependent, ranging from about 300 bars at 800 degress C to 1500 bars at ambient lab temperature (25 degrees C).

Because of the intimate association of the folds with the detachment faults we know they are contemporaneous, and the shear stress within the upper plate must have been more than great enough to twin the calcite in

Virginia Formation		
Plagioclase	50%	
Quartz	20%	$\rho_V = 2.72\ gm/cm^3$
Micas	20%	
Calcite	10%	
Biwabik Formation		
"A" Layer		$\rho_A = 2.71\ gm/cm^3$
Calcite	50%	
Quartz	50%	
"B" Layer		$\rho_B = 3.21\ gm/cm^3$
Diopside	90%	
Wollastonite	10%	
"C" Layer		$\rho_C = 3.53\ gm/cm^3$
Quartz	67%	
Magnetite	33%	

Slump = 70% Virginia; 10% "A" Layer; 15% "B" Layer; 5% "C" Layer

$$\rho_s = 2.83\ gm/cm^3$$

$$\rho_m = 2.70\ gm/cm^3$$

Table VII-1: Summary of density calculations for the dynamic analysis of the gravity-driven slump model for the detachment features found in the Dunka Pit.

the matrix in the folds (Figure III-9) as it resulted in intense twinning, and a dynamic recrystallization. Thus it would appear that gravity alone was not responsible for these detachment features.

It is noteworthy that the folded rocks (basal Virginia Formation, Layers A and B of the Biwabik Iron Formation) are the only rocks in the area containing appreciable carbonate (calcite). A significant weakening of these units may have occurred at the time of intrusion, when the high-temperature contact metamorphism was releasing abundant H_2O and CO_2 and the rock was recrystallizing. However, Tullis (1980) states that the critical shear strees required for twinning in calcite does not appear to be affected by either hydrostatic pressure or by pore fluid pressure. Thus even if there were significant amounts of H_2O and CO_2 in the system, the shear stress necessary to produce the twinning observed in the rocks (Figures III-10, 11) is in the range of 300 bars (according to Tullis, 1980), which the analysis above suggests cannot have been the result of gravity-driven slumping.

The gentle dip of the features with some recumbent folding in the upper plate (Figure III-11) is similar to the style of deformation in some thrust fault terranes. If the detachment surfaces are thrust faults, it would mean a compressional stress regime, and imply some sort of forceful injection of magma during the implacement of the Duluth Complex. In view of the required shear stress for twinning polycrystalline aggregates of calcite (300 bars) this seems most unlikely.

Thrust fault geometries are also importantly different from the detachment features in one aspect: they cut up-section in the direction of tectonic transport (Butler, 1982; Boyer and Elliott, 1982) and thus duplicate stratigraphy (Figure VII-1). The detachment features, where

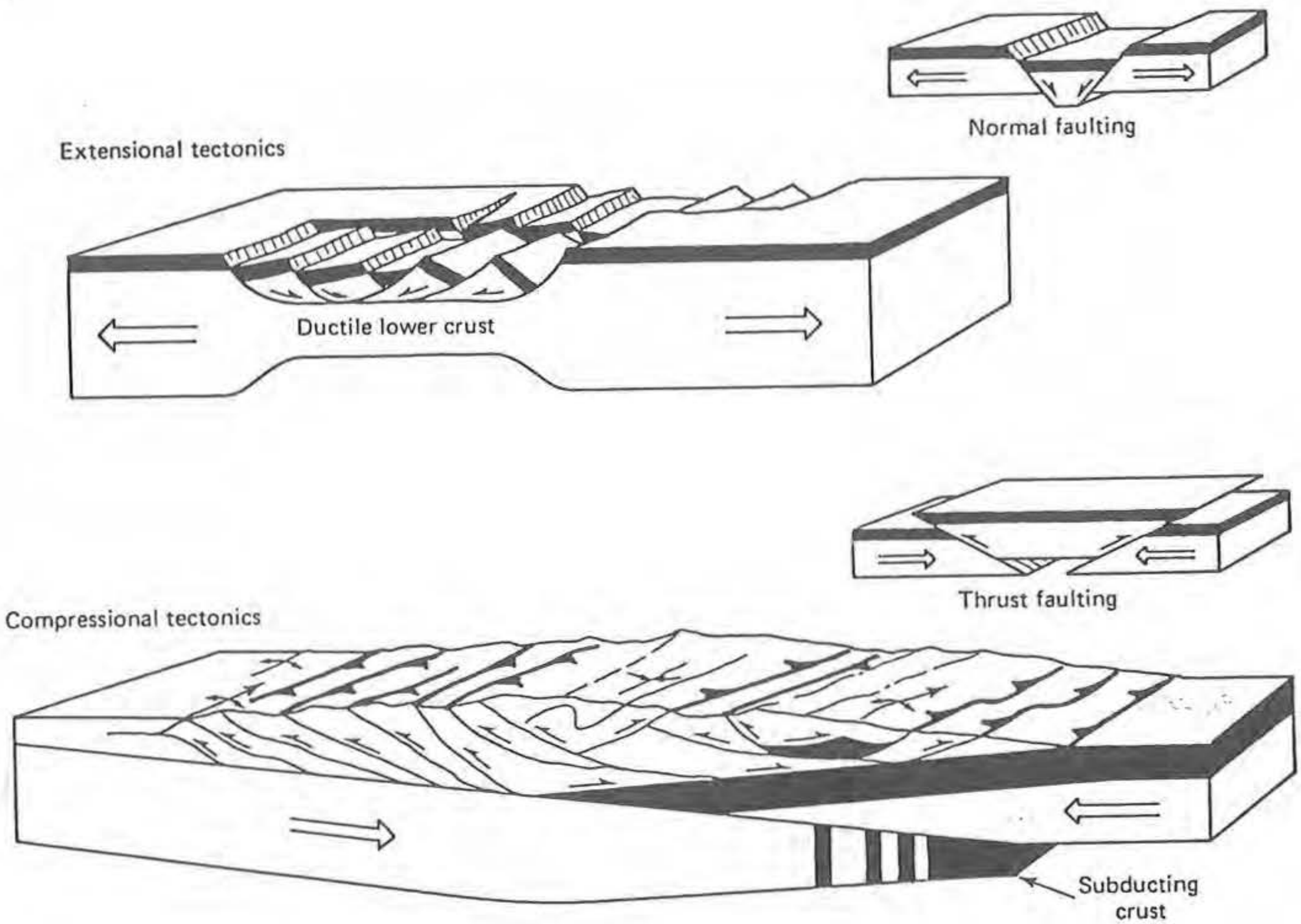


Figure VII-1: Diagram illustrating the differences in low-angle faulting in compressional and extensional regimes. Note the duplication of stratigraphic section in compressional regimes and the "removal" of stratigraphic section in extensional regimes.

they are exposed, without exception eliminate stratigraphy, that is put younger rock on top of older rock, with some intermediate strata removed.

This geometry is similar to that of low-angle detachment faults which are down-dip portions of listric normal faults described from extensional tectonic regimes such as the Basin and Range Province of western North America (Figure VII-1). There are many differences between the features described in the Basin and Range (e.g. Davis and Hardy, 1981; Wernicke and Burchfiel, 1982), and the detachment features in the Dunka Pit, not the least of which is scale. However, the detachment features could possibly be interpreted as having resulted from extensional stresses at the time of emplacement of the Duluth Complex, in broad agreement with the model of Weiblen and Morey (1980). The folding and fabric in the upper plate would then be a result of local compression in the upper plate of the low-angle extensional fault.

While many of the aspects of these detachment features suggest they are slumps, a dynamic analysis shows that body forces alone are not a sufficient cause, although it is possible to argue for compression or extension as the additional driving stress necessary for their formation. Perhaps the most important conclusion from a study of these features is that the emplacement of the Duluth Complex was accompanied by local deformation, as well as contact metamorphism of the country rock.

Because of the sparse nature of the data in some areas interpretations of the form of the base of the Duluth Complex need be general. However the data base is excellent is some areas, and some conclusions may be drawn.

It seems fairly certain that in the Minnamax prospect region at least, the form of the base of the Duluth Complex was controlled to a considerable extent by pre-Keweenawan structures within the footwall rocks. There is little evidence in the data on the form of the base of the Complex (Plates III, IV, and V) to contradict the notion that the shape of the intrusion from Hoyt Lakes to the Dunka River area was controlled by stratigraphic or structural features in the footwall rocks which were pre-intrusion in age. No evidence is seen for the northeast-trending, southeast-dipping normal faults proposed in the half-graben model of Weiblen and Morey (1980), or inferred by Morey and Cooper (1978). The faults of Cooper and Morey were inferred on the basis of geophysics, topographic lineaments, and joint density data. Yet, they are not readily apparent on new gravity or aeromagnetic maps of the region (Chandler, this report) and the topographic lineaments may well be of glacial origin. In addition there is controversy over the use of joint spacing as in a method of locating faults (Shepard, et al., 1982); some suggest joint spacing increases in fault zones (Pohn, 1981) whereas others suggest the spacing decreases in fault zones (Wheeler and Dixon, 1980).

Whereas it seems likely that the postulated northeast-trending normal faults do not exist, there is evidence of steep, northwest-trending faults in the structure contour maps of the base of the Duluth Complex (Plate IV especially). Whether or not these are the "transform faults" suggested in the half-graben model of Weiblen and Morey (1980), and the northeast-trending normal faults are only found further to the southeast, deep beneath the Complex, is impossible to ascertain from present data.

The only faults that clearly cut the Duluth Complex in this area (Boundary Fault, DC-1 fault) and thus are known to be Keweenawan or younger, have southeast side up, and indeterminate displacement, respectively.

FURTHER WORK

Drill core data from the INCO project (in the Kawisihwi River region, northeast of the Dunka area) are now available, and could be added to the computer data base, and the structure contour map on the base of the Duluth Complex could be extended to the northeast. The drill hole density is such that a detailed map of the Inco project region could probably be compiled also, supplementing the detailed maps of the Minnamax and Dunka River areas included in this report.

The data base now on the computer comprises some 6000 drill holes, and most of them contain other stratigraphic information in addition to the depth to the base of the Duluth Complex. For most, if not all, of the distance from Hoyt Lakes to the eastern end of the Mesabi Range at the contact with the Duluth Complex, additional structure contour maps could be generated from the existent data base. These include structure contour maps of the top of the Pokegama Quartzite (base of Biwabik Iron Formation), base of the Virginia Formation (top of Biwabik Iron Formation) and several horizons within the Biwabik Iron Formation.

Mining company data on structural features within the Animikie Group, and data from thousands of drill holes also exist to the west of Aurora-Hoyt Lakes, across the Mesabi Range. This is valuable data and should be compiled to produce a map similar to Plate I for the central and western portions of the Mesabi Range.

The detailed structure contour map on the base of the Duluth Complex in the Minnamax prospect area (Plate III of this report) could be compared with the copper-nickel ore grade data for the region (now the property of Bear Creek Mining Company) to investigate possible structural control of mineralization.

In addition, there are still a number of areas of the Duluth Complex where little or no outcrop is known. If a detailed structural picture of the complex is to be worked out, outcrop in these areas must be searched for, or a drilling program initiated. Some success was achieved in this project in finding previously unknown outcrop. An initial try at searching for outcrop from the air was made during this study. If done in late autumn, before the first snow, this should prove fruitful. From our experience we suggest considering only a fairly small area during each flight, with multiple passes over the area. This will allow better confirmation of possible outcrop sightings, and allow accurate location on maps of the potential outcrop sights, and identification of best field access routes, to facilitate follow-up field work on the outcrops.

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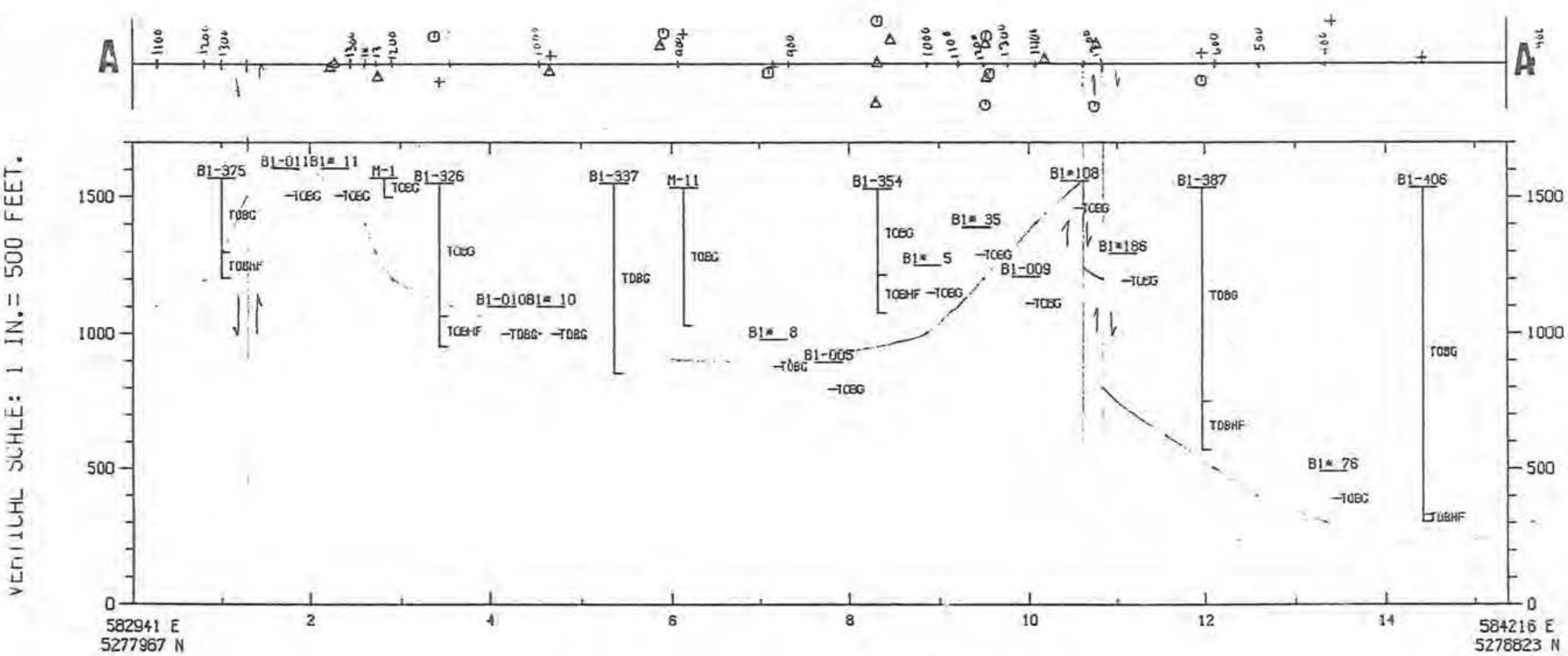

X-AXIS TICKS AT 100. METER INTERVALS.
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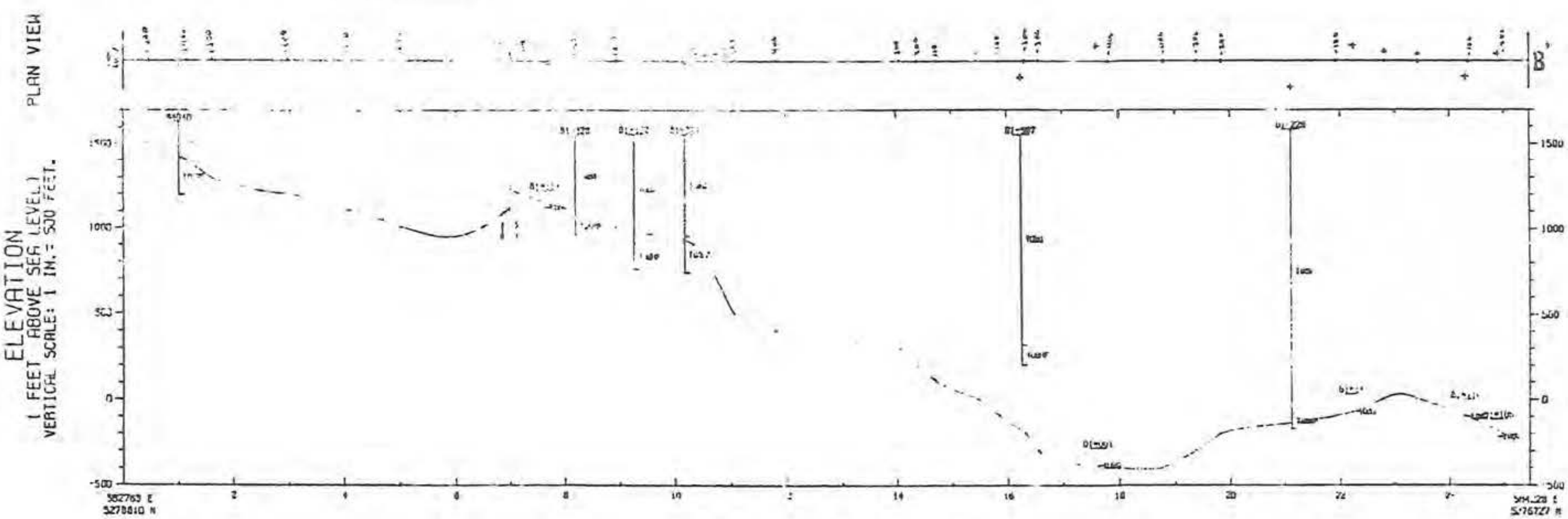

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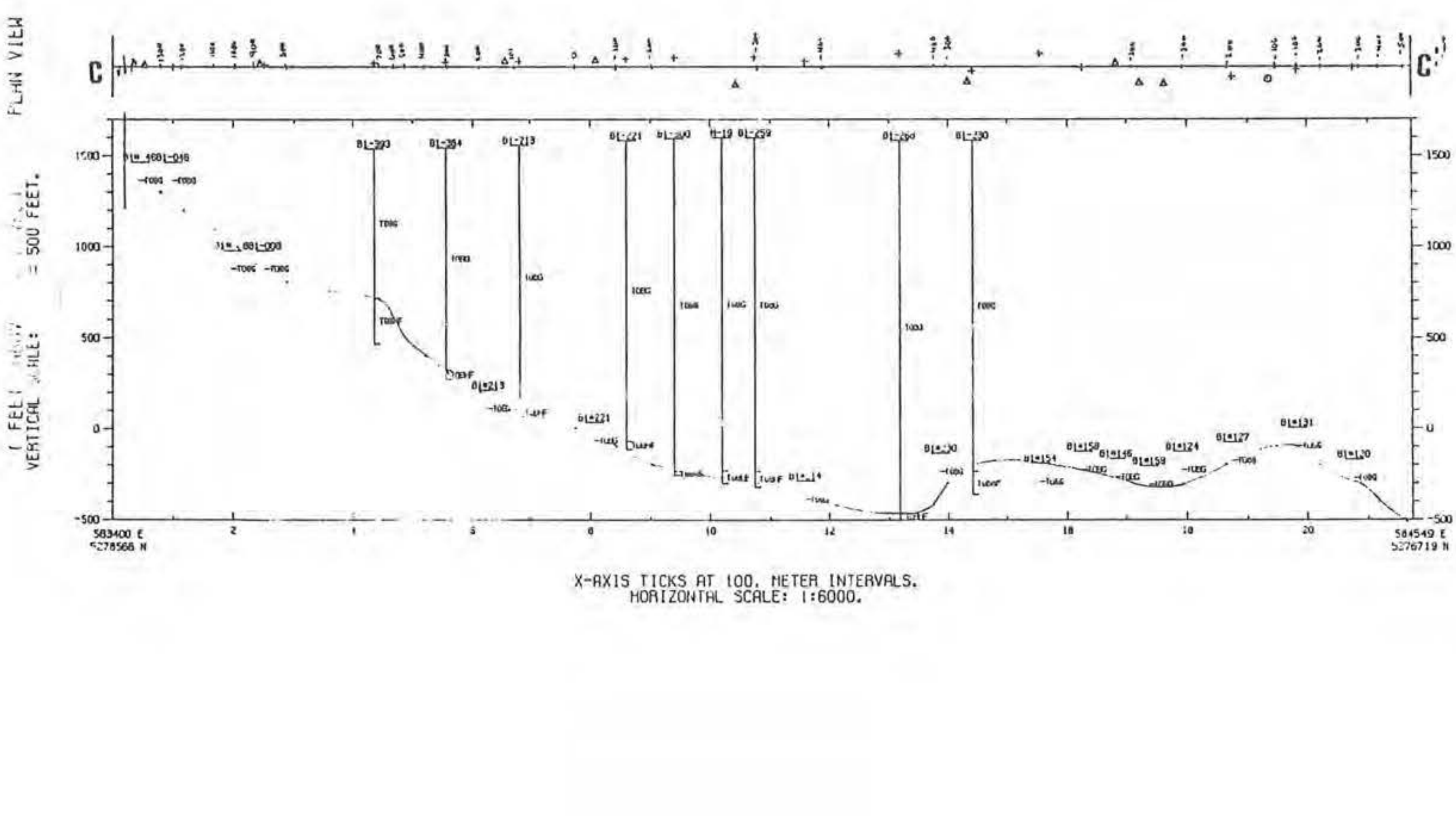

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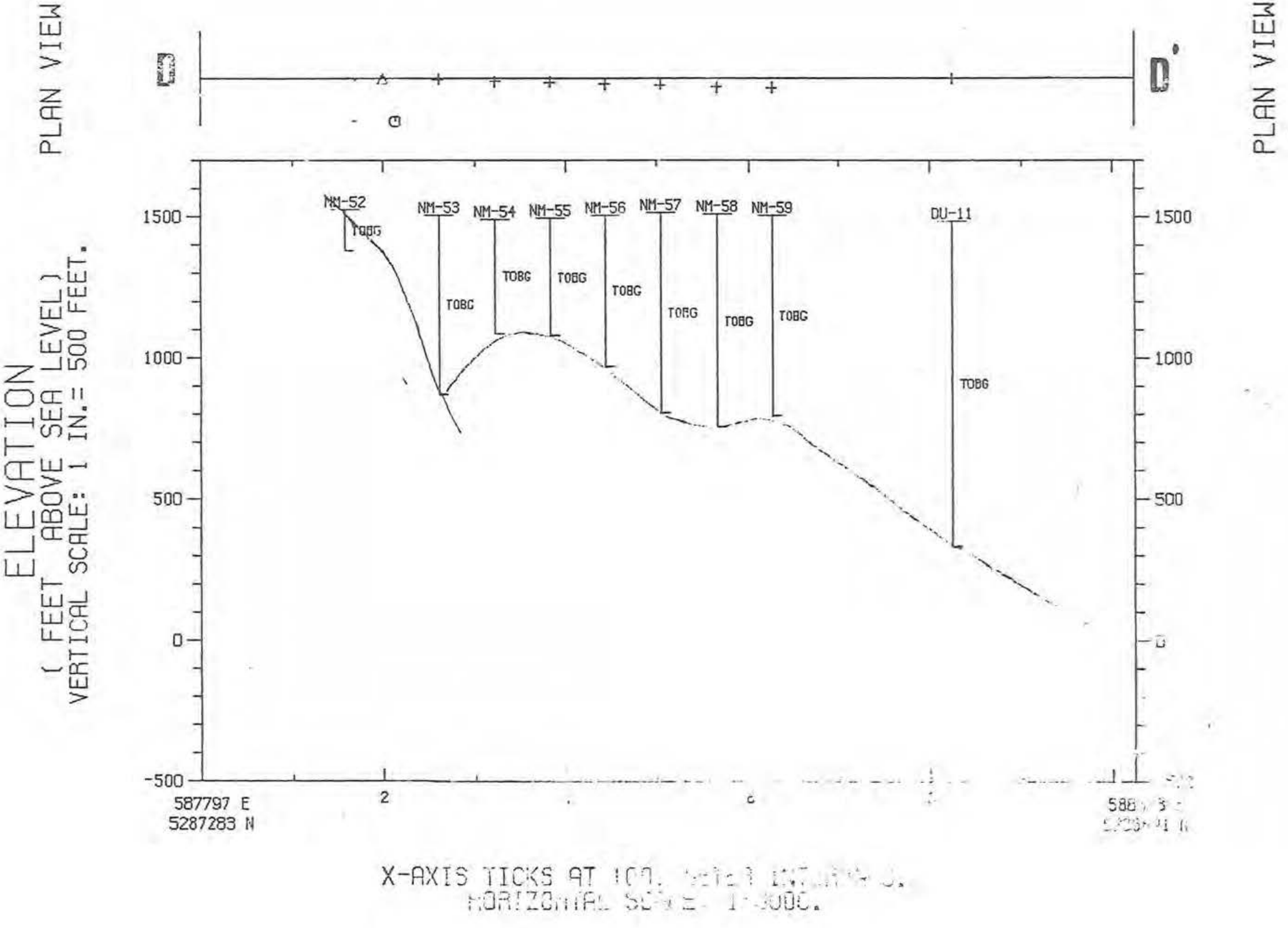

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PLAN VIEW
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GEOPHYSICAL STUDIES: A SECTION OF THE FINAL REPORT OF THE DULUTH COMPLEX STRUCTURAL STUDY

by

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GEOPHYSICAL STUDIES

Introduction

Geologic investigations over most of the Duluth Complex (Figure 1) are severely restricted by a mantle of Pleistocene till (Figure 2). Although exposures are commonly excellent in the mine pits along the basal contact, much of the complex east and southeast of the pits is very poorly exposed. Thus, it is difficult to assess the relationship between the detailed structures of the basal contact zone and regional geologic structure. Historically geophysical data over the complex have been used only in a broad, qualitative context or in tightly focused exploration for ore deposits. This section investigates structure of the central Duluth Complex, using regional-scale gravity data and high-resolution aeromagnetic data.

The geophysical studies here are carried out with three objectives:

1. To investigate the density and magnetic properties of rocks over the central Duluth Complex. The rock properties over the central Duluth Complex are largely unknown, and such data can provide useful constraints on interpretation.

2. To determine the relationships existing between the detailed magnetic signature and the structures along the basal contact described in the previous section. This objective is carried out by model studies and by correlating detailed aeromagnetic contour maps with structural data from the mine pits.

3. To investigate the regional structure of the central Duluth Complex and to see how it relates to the detailed structures at the basal con-

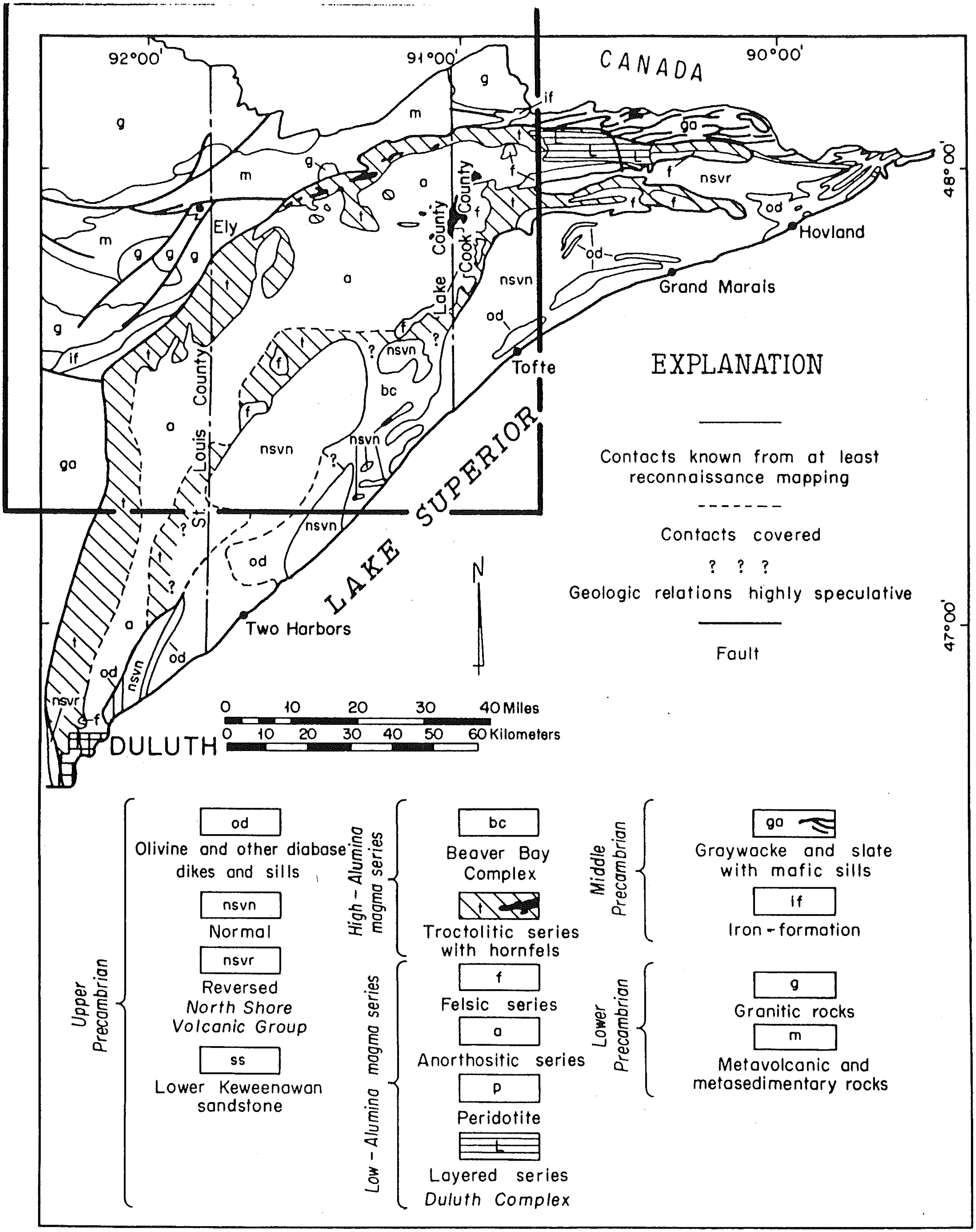

Figure 1. Regional geologic map of the Duluth Complex. The area of the regional gravity and magnetic grids is outlined by the bold square.

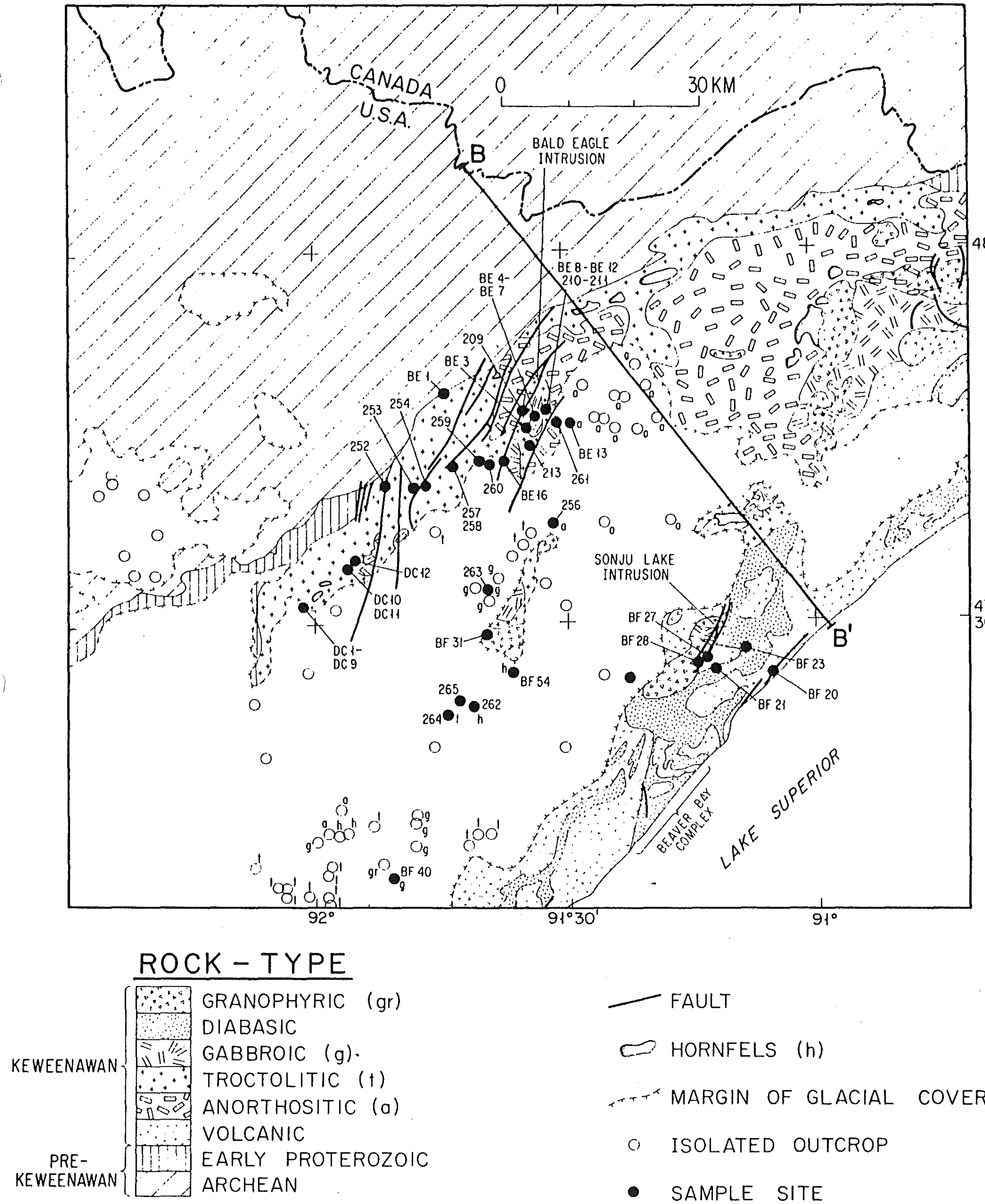

Figure 2. Detailed geologic map of grid study area. Sample sites used in this study are shown as solid circles. Blank parts of the area are covered with Pleistocene glacial till.

tact. This involves analysis of gridded gravity and aeromagnetic data over an area of 135 by 135 km, which includes a large segment of the Duluth Complex and surrounding terranes (Figures 1 and 2). In order to facilitate this task, the data grids are subjected to a variety of processing/enhancement routines, including shaded relief presentation, second derivative enhancement, and estimation of density/magnetization properties through Poisson analysis. In addition to delineating the regional structural framework of the region, the analysis of the gravity and magnetic data grids have targeted areas elsewhere in the complex that warrant future geologic investigations. Complementing the grid analysis are subsurface interpretations, using gravity and magnetic modeling and Werner deconvolution of the magnetic data.

Preparation of Data Sets

Acquisition and Preparation of Rock-Property Data

Sparse rock-property data were previously available over the northwestern and central Duluth Complex. Rock-property studies of Keweenawan intrusive rocks have usually been involved with paleomagnetism and have been restricted to the southernmost Duluth Complex (Jahren, 1965; Beck, 1970), the northeasternmost Duluth Complex (Beck, 1970), or the Beaver Bay Complex (Beck and Lindsley, 1969). In this study, density, magnetic susceptibility, and natural remanent magnetization (NRM) determinations were made at 42 sites traversing the central Duluth Complex (Figure 2). These include some unanalyzed samples collected during a previous Minnesota Department of Natural Resources project (sites 250-265), samples from the Bald Eagle intrusion (sites BE1-BE15), and samples from a study by Ferderer

(1982, sites BF20-BF56). Samples from several additional sites were taken in the area of the detailed structural study (sites DC103-DC135). Samples from sites DC103-DC135 were directly cored from the outcrop, whereas all remaining samples were block sampled and cored in the laboratory. All cores were 2.54 cm in diameter and were cut to a 2.54-cm length. Orientation was by Brunton compass on the DC and BF samples, whereas all remaining samples were oriented using sun compass.

There is some variance in the statistics of the sampling. All BF and most BE sites involve a single-block specimen from which 2 to 5 core specimens were removed. Sites 209-213 and 250-265 were mostly sampled more rigorously by collecting 2 to 5 oriented block samples, and taking 2 to 5 core specimens from each block. Sites DC103-DC135 were sampled by one vertical core, from which 2 to 5 core specimens were derived.

Other data are also used to supplement the rock-property studies. Density and magnetic susceptibility values are averaged for several typical rock types outside of the complex (Table I) and are based on open-file data available at the Minnesota Geological Survey. In addition, previous rock-property studies by Beck and Lindsley (1969), Beck (1970), Books (1972), Sims (1972), and others are considered in the discussion below.

A variety of instruments were used to measure the rock properties. Density determinations were conducted on all core specimens using a Jolly balance. Magnetic susceptibility determinations were made individually on core specimens as well as directly on outcrop, using an _in situ_ coil. All magnetic susceptibility determinations were made using a Bison 3101 magnetic susceptibility bridge. The NRM determinations were made on all core specimens using a Schoenstedt SSM1A spinner magnetometer. All alternating field cleaning was conducted using a Schoenstedt GSD1 sample demagnetizer. All density, magnetic susceptibility, and NRM determinations are presented on a site-average basis in Tables I-V.

Because the in situ rock properties are the most important for interpreting the magnetic anomalies, raw NRM directions were used wherever possible. Many raw determinations yielded directions that clustered around the average Keweenawan normal direction (dec/inc = 290°/40°). Widely scattered NRM directions with extremely high intensities in many specimens, however, suggest the effects of lightning strikes. Subsequently, alternating field (AF) magnetic cleaning was applied to isolate the primary component wherever possible. Because such a procedure may actually destroy some of the primary component, the NRM intensities given for the AF-cleaned samples may be somewhat less than the undisturbed raw NRM intensity. Selected peak levels were based on detailed stepwise AF analysis of several selected core specimens.

Preparation of Gravity Data

A gravity-data grid was generated over an area of 135 by 135 km (Figures 1 and 2), using Bouguer anomaly data of Ikola (1968, 1969) and open-file data from the Minnesota Geological Survey. Station spacing generally ranges from 1 to 5 km, and approximately 4800 stations are used to generate the grid. Over Canada and Lake Superior, gravity values are interpolated at an approximately 10-km interval, using the regional gravity map of O'Hara (1982). The nearest-neighbor approach of Sampson (1975) is used for the gridding with the following parameters: (1) grid spacing =

1.0668 km; (2) grid size = 128 x 128 points; (3) number of nearest neighbors = 8; (4) weighting = constrained distance squared with projection of dips. This gridding procedure results in a generally close agreement with the hand-contured maps of Ikola (1968, 1969). The resulting grid has its southwestern corner at 47°7'30" N. and 92°30' W., and its columns are oriented N.-S. The grid spacing and location were chosen in order to register to a companion aeromagnetic data grid discussed below.

Several processing steps were tested on the gravity-data grid, using frequency-domain programs created at Purdue University (Reed, 1980). By far the most revealing was the application of a second vertical derivative (SVD). This procedure reduces the interference of regional anomaly gradients, which is a serious problem in the grid area, and enhances the contribution of shallow, localized sources. Thus, this operation considerably enhances the geologic mapping utility of the gravity data and facilitates the correlation of the gravity data to the high-resolution aeromagnetic data. Prior to computing the SVD, the gravity data were slightly smoothed by upward continuation to a level of 2 km. This smoothing procedure eliminated the effect of minor errors inherent in the gridding process but left an appropriate amount of anomaly detail. Additional processing was done in order to prepare the gravity grid for Poisson analysis and will be discussed below.

The gravity data were also used in a regional-scale model study along profile B-B' (Figure 2). These profile data were digitized directly from the published 1:250,000-scale gravity maps (Ikola, 1968, 1969) at an interval of 1 km.

Preparation of Aeromagnetic Data

A low-altitude, high-resolution aeromagnetic survey was conducted over the Duluth Complex in 1979 and 1980 by the Minnesota Geological Survey (Chandler, 1983a, 1983b), and these data form the core of all magnetic interpretation in this study. The surveying was conducted at a mean terrain clearance of 150 meters and used a 400-meter line spacing. Sampling along line was 50 or 75 meters. The data were reduced by standard diurnal station removal and tie-leveling techniques and by removal of a regional geomagnetic field as defined by the 1975 American World Charts Model, updated to 1979-80. All survey data are transformed into a grid spaced at 213.36 x 213.36 meters, using minimum curvature interpolation that was proprietary to the airborne contractor (EG&G/Geometrics). The aeromagnetic data grid extracted for this study is denser than the gravity grid, but aligns with it at every fifth point.

All processing for the aeromagnetic data uses the same computer programs as described in the section on processing of the gravity data. The most significant results were obtained by taking the second vertical derivative (SVD) of the raw (unsmoothed) aeromagnetic data grid. As in the analysis of the gravity data, the SVD of the magnetic data is free of the interference of regional anomaly components and enhances the localized and near-surface bedrock sources most important to bedrock mapping. Use of the SVD also minimizes the effect of NRM, which is commonly strong for these Keweenawan igneous rocks. Although this remanence can significantly skew anomalies relative to their sources in unfiltered data (Chandler, 1985), the effect is dependent on wavelength and becomes less for extremely short anomaly wavelengths. Comparison of features in the raw SVD data with a test grid of reduced-to-pole SVD data revealed an offset of only a grid interval or less between the two data sets. Furthermore, the reduced-to-pole SVD data were found to be considerably noisier. Thus, it was decided that the raw SVD data were adequate for 1:250,000-scale mapping.

Preparation of the Gravity and Magnetic Data for Poisson Analysis

A form of Poisson's theorem states that a linear relationship exists between the first vertical derivative of gravity and the magnetic data of vertical polarization with the slope being proportional to the magnetization/density ratio of the anomaly source. This relationship is valid only if the gravity and magnetic sources are coincident, uniform, and isolated from the effect of any other sources. Chandler and others (1981) described a procedure that allowed Poisson's theorem to be applied to multisource data sets by applying the method on a small part of the data at a time, using a small moving window. The derivative gravity and magnetic values within a particular window position are linearly regressed to one another, and the resulting correlation, slope, and intercept coefficients are stored at the central part of the window. The slope values generated by this process are estimates of magnetization to density contrast (dJ/dp) for anomalies in the vicinity of the grid point. The results not only derive a suite of magnetization/density ratio estimates for sources in the area, but also provide a way of quantitatively describing the internal correlations between gravity and magnetic anomalies in an area.

Prior to moving-window Poisson analysis, the gravity and magnetic data grids were regridded to a registered 512 by 512 format with a spacing of 265 meters. The density of original data control is obviously much higher for the area's magnetic data than for the gravity data, so the magnetic data portray greater detail and a much higher loading at the short-wavelength end of the spectrum. Consequently both grids were continued upward to 3 km to enhance the longer wavelengths and make the spectral characteristics of the two data sets more similar. Tests involving several levels of continuation indicated that the 3-km level yielded two data sets with generally similar wavelength characteristics, but left enough detail for analysis of many near-surface features. For Poisson analysis it was also necessary to calculate the first vertical derivative of gravity and the aeromagnetic data reduced to the pole (vertical polarization). The aeromagnetic data were reduced to the pole, assuming a polarization with a declination of 290° and inclination of 40° downward, which lies near the average direction of Keweenawan remanence in the area. To investigate the anomalies in the pre-Keweenawan rocks a second reduced-to-pole magnetic grid was produced, assuming a polarization directed 3° E. and inclined 78° downward. This direction parallels the earth's inducing field, which is assumed to be parallel to the polarization of pre-Keweenawan rocks in the area. In both cases, Poisson analysis was conducted, using a 19 by 19 point window (4.8 by 4.8 km).

Discussion of Rock-Property Data

The rock-property data have been divided into the following five tables: (I) Pre-Keweenawan rocks outside the complex, (II) troctolitic rocks of the lower part of the complex, (III) anorthositic suite rocks, (IV) rocks of the Bald Eagle intrusion, and (V) rocks associated with the roof of the complex. Wherever possible, raw NRM values are used, but wherever magnetic cleaning was necssary, the peak AF field value used is given. Data have been deleted for those samples that failed to achieve a stable NRM direction after AF cleaning.

Pre-Keweenawan Rocks

The density and magnetic susceptibility of some typical Pre-Keewanawan rocks are given in Table I. No NRM measurements were conducted for these rocks, but other studies indicate that NRM values for these rocks are usually weak and have directions that are widely scattered or subparallel to the present earth's field (Symons, 1967; Sims, 1972). Archean granitic rocks have density and magnetic-susceptibility values averaging around 2.70 gm/cc and 800 x 10^{-6} c.g.s., respectively, with the latter property ranging from near 0 to over 5000 x 10^{-6} c.g.s. Archean metavolcanic and metasedimentary rocks have densities averaging around 2.94 and 2.74 gm/cc, respectively, and both rock types are predominantly nonmagnetic. Localized layers of iron-formation within these rocks, however, can be extremely magnetic (>10,000 x 10^{-6}). Early Proterozoic slate and graywacke have densities averaging around 2.75 and are largely nonmagnetic. The Biwabik Iron Formation near the base of the Animikie sequence, however, can be locally dense (>3.00 gm/cc) and highly magnetic (>10,000 x 10^{-6} c.g.s.).

The density values given in Table I, combined with the general spatial distribution of rock types in the region (Sims and others, 1970; Green, 1982), indicate that the Duluth Complex was intruded into an upper crust with an average density probably around 2.75, which agrees with the crustal density estimate derived by Ferderer (1982), using long-range seismic refraction data (Greenhalgh, 1979, 1981). It is also apparent from Table I that most of the pre-Keweenawan upper crust is generally nonmagnetic to moderately magnetic (<1000 x 10^{-6} c.g.s.).

Troctolitic Rocks in the Lower Duluth Complex

Table II gives density, magnetic susceptibility, and NRM values for troctolitic rocks in the lower part of the Duluth Complex. Densities range in value from 2.76 to 3.11 gm/cc and average around 2.91 gm/cc. Magnetic susceptibilities range in value from 212 x 10^{-6} c.g.s. to 4052 x 10^{-6} and average around 1200 x 10^{-6} c.g.s. Thus the magnetic susceptibility values in the troctolitic rocks are not greatly different from values in some of the pre-Keweenawan rocks. However, the troctolitic rocks have strong NRM intensities that are directed along the Keweenawan normal direction (average dec/inc = 290°/40°) with Koenigsberger ratio (Q) values commonly greater than 3. The magnetic properties agree generally with studies of troctolitic rocks in the Duluth area (Jahren, 1965; Beck, 1970), and the results confirm the idea that Keweenawan normal remanence is the primary factor in the magnetic anomaly expression this part of the complex.

Anorthositic Suite Rocks

The results in Table III suggest that, excluding the anomalous samples at site DC12, the anorthositic suite rocks may be slightly less dense (average = 2.81) and have about the same magnetic-susceptibility values (average around 1800 x 10^{-6} c.g.s.) as the underlying troctolitic rocks. Raw NRM parameters for anorothositic rocks tended to have extreme values (>10,000 x 10^{-6} c.g.s.) and were randomly scattered. After extensive AF cleaning, a few samples implied a normal direction, and one sample from site 256 yielded a reversed direction. These results contrast with Jahren's (1965) and Beck's (1970) measurements of anorthositic suite rocks in the Duluth area, which indicated fairly stable NRM directions along Keweenawan normal directions with Q values generally ranging from 1 to 5.

Why the raw NRM of the anorthositic rocks behaved so erratically is unknown. Perhaps, because these rocks are thought to be an early phase of the complex, the subsequent reheating and intrusions may have complicated the paleomagnetism. On the other hand, the high-intensity values and scattered NRM directions would be consistent with lightning strikes. Many of the anorthositic rocks sampled in this study were from very poorly exposed regions, and the few outcrops emerging through the till may have been lightning-prone hilltops in preglacial times.

Rocks of the Bald Eagle Intrusion

Although the Bald Eagle intrusion is generally grouped with the same magmatic event as the troctolitic rocks in the lower part of the complex (Weiblen and Morey, 1980), it differs somewhat in density and magnetization (Table IV), and is discussed separately here. In addition, the rocks of the Bald Eagle intrusion are associated with a distinct mineral layering, and therefore they provide an opportunity here to examine the relationship of igneous layering to magnetic anisotrophy and paleomagnetic structural correction. Some uncertainty still exists as to whether the layering in Duluth Complex rocks should be used for a structural correction, although the most comprehensive discussion to date by Halls and Pesonen (1982) suggests that structural correction is usually not necessary. Beck and Lindsley (1969) indicated that magnetic anisotrophy related to subhorizontal layering in some Beaver Bay Complex rocks deflected the average NRM inclination 8.5° toward the horizontal.

Relative to the troctolites in the lower part of the Duluth Complex, the ring troctolite of the Bald Eagle intrusion has somewhat higher density (average = 2.97), lower magnetic susceptibility (average = 705 x 10^{-6} c.g.s.), and Q values that are generally similar (approx. 2.0). The NRM properties show a fairly tight clustering along the Keweenawan normal direction. Relative to the ring troctolite, the core gabbro of the Bald Eagle intrusion has a similar high density (average = 2.98) and a slightly lower magnetic susceptibily (average 297 x 10^{-6} c.g.s.), but differs dramatically by having extremely large Q values (commonly >20). The direction of this strong and very stable NRM lies approximately along the Keweenawan normal direction but has a significantly shallower inclination (average around 28°) than observed for the ring troctolite (average around 55°).

There appears to be no strong relationship between the NRM direction and layering orientation in Table IV. The igneous layering is vertical at many of the ring troctolite sites, and observed NRM inclinations range from the steepest (69°) to among the shallowest (33°) for the unit. In addition, the moderately dipping (50° SE) layering at site BE3 is associated with an NRM inclination that is quite similar to inclinations observed at sites with vertical layering. Similarly, the vertical layering observed at core gabbro site BE7 is associated with virtually the same NRM inclination values as observed at core gabbro sites with much more shallowly dipping layering. Structural corrections based on layering would cause the NRM directions at all sites to diverge widely from the Keweenawan normal direction.

If the layering can be assumed not to affect the observed NRM directions, the differing inclination values observed in the ring troctolite and core gabbro may reflect a genuine paleogeomagnetic effect. This argues that the two units achieved their principal magnetization at different times between which the geomagnetic field changed either due to marked secular variation or to long-term polar wander.

Rocks Associated with the Roof of the Duluth Complex

Table V gives properties for a few diverse rock types that occur near the roof of the complex. The mafic intrusive rocks vary widely in density (2.80 to 3.18 gm/cc), magnetic susceptibility (289 x 10^{-6} to 4934 x 10^{-6} c.g.s.), and Q values (1.9 to 11.2). These values fall within the general range reported (Jahren, 1965; Beck and Lindsley, 1969; Beck, 1970) for the Beaver Bay Complex and other mafic intrusions into the volcanic roof. Granophyric rocks are low in density and low to moderate in magnetic susceptibility. More extensive work with granophyric rocks by Jahren (1965) and Sims (1972) show Keweenawan normal NRM directions with Q values $\geq$ 5. The results for the few sites over Keweenawan volcanic rocks agree generally with the rock properties from more extensive studies (Mooney and Bleifuss, 1953; Sims, 1972; Books, 1972), which indicate an NRM essentially along the Keweenawan normal direction, regardless of whether the NRM represents a primary component from cooling of the lavas or reflects a resetting by later intrusive events.

Detailed Aeromagnetic Anomaly Expression in the Northeastern Mesabi Range and Adjacent Duluth Complex

General Description of the Aeromagnetic Data

The aeromagnetic data over the northeastern Mesabi range and adjacent Duluth Complex show a wide variety of relationships to the local geology (Plate 7). The Archean granitic rocks northeast of the Mesabi range are associated with a somewhat complex anomaly pattern, although amplitudes are generally moderate (100 to 500 gammas). A broad 1000-gamma maximum in the northeastern part of T. 59 N., R. 15 W. probably arises from a magnetite-rich phase of the Giants Range Granite. The Archean metasedimentary rocks along the rim of the Mesabi range northwest of Aurora (Plates 1 and 7) correspond to a subdued magnetic anomaly expression, as does the area covered by the Early Proterozoic Virginia Formation in the extreme south-western part of the study area.

The most prominent feature in Plate 7 is the northeast-striking belt of maxima and minima of 1000 to 15,000 gammas in amplitude that is associated with the Biwabik Iron Formation along the basal contact of the Duluth Complex. The anomaly amplitudes along this segment of the iron-formation are much greater than observed elsewhere along the Mesabi range, and they primarily reflect a strong remanent magnetic overprint related to emplacement of the Duluth Complex (Bath, 1962). The model studies by Bath indicate that the remanent overprint was directed westward at a subhorizontal angle along the layers of the iron-formation. The remanent direction of the Duluth Complex rocks is actually to the west and down about 40° (Beck, 1970; Halls and Pesonen, 1982; this study), but banded iron-formations typically have a high degree of magnetic anisotrophy (Bath, 1962; Jahren, 1963) which could divert the remanent vector toward the plane of layering. Because of this remanence, prominent minima (-1000 to -8000 gammas in amplitude) lie over much of the low-dipping iron-formation, and maxima tend to lie along the southwestern (uppermost) contact. The abrupt termination of the intense magnetic maxima 1 to 2 km southeast of the exposed upper contact of the iron-formation was interpreted by Bath (1962) to represent the subsurface truncation of the iron-formation by the intrusive rocks of the Duluth Complex. Unlike the central and western Mesabi iron range, highly oxidized natural ore is relatively rare in this area.

In contrast to the sublinear truncation of anomaly maxima to the southeast, the northwestern margin of the iron-formation anomalies is highly irregular, consisting of numerous north- to northwest-striking maxima and minima. Bath (1962) investigated one of these prominent maxima along the east-central margin of T. 60 N., R. 13 W. and concluded that its extreme amplitude (>10,000 gammas) was due to a large buried sill, which locally gave a much stronger magnetic overprint than the more regional effect of the Duluth Complex. This idea is supported by the presence of numerous dikes and sills in the vicinity of the maxima (Plate 7). A similar explanation may apply elsewhere along the northeast Mesabi range, and the numerous maxima that extend tonguelike to the north and northwest may approximately outline buried hypabyssal intrusions extending into the iron-formation from the Duluth Complex.

Magnetic Anomaly Expression of Faults

The correspondence of anomalies to faults is generally poor in the southwestern part of Plate 7, although a few exceptions occur. Fault B-1 (the Dark Lake-Biwabik fault) is associated with a marked decrease in the outcrop width and the magnetic anomaly expression of the Biwabik Iron Formation. In detail, this fault is slightly oblique to and apparently slightly offsets the narrow maximum associated with the iron-formation. Fault B-3 is associated with a break in the anomaly expression along the northern rim of the iron-formation and with a pronounced northwest-striking magnetic gradient near the intersection with faults B-4 and B-5. Faults B-5 and B-7 show little correspondence with any magnetic anomalies over the northern and central parts of the iron-formation, but they appear to bracket a minimum saddle along the southern margin of the iron-formation maximum. Fault B-12 (the Lower Slaty fault) is subparallel to a strong, southward-decreasing anomaly gradient.

A fairly strong correlation of faults and magnetic anomaly signature exists over the central part of Plate 7. Fault B-14 (the Siphon fault) corresponds closely with an extremely strong (-6000 to -8000 gammas in amplitude), north-striking minimum that transects the entire positive anomaly expression associated with the iron-formation. This anomaly probably reflects the western truncation of the westward polarized iron-formation across this offsetting structure. Faults B-15 and B-16 strike north-northwest and align with prominent anomaly gradients. Northwest-striking faults B-17 and B-19 closely parallel the anomaly gradients and appear to bracket a northwest-striking minimum that nearly breaches the positive anomaly expression of the iron-formation. Fault B-17 aligns with a prominent northwest-striking minimum 8 km to the southeast, implying a major extension of the fault into the complex. Similarly, fault B-20 lies along the northeast flank of a strong maximum and approximately aligns with a strong linear gradient inside the complex 7 km to the southeast. Fault DC-3 corresponds to the northeastward narrowing of the iron-formation maxima.

The numerous minor faults in the Dunka River area in the northeastern part of Plate 7 correspond weakly with the anomaly expression. The concentration of northwest-striking faults B-23 through B-27 corresponds to a break in the maximum associated with the Biwabik Iron Formation. Northwest-striking faults B-28 and B-30 are subparallel to some anomaly gradients in the vicinity.

Magnetic Anomaly Expression of Folds

In general, there is not a strong correspondence between the observed magnetic anomaly expression and the folds in the Biwabik Iron Formation. The broad subclinal trough in the iron-formation north of Aurora (Plate 1) corresponds to a widening of the anomalous belt (Plate 7) where maxima along the rim grossly outline the main fold, but very little correlation can be found with the minor folds in this trough. A broad anticlinal flexure in the iron-formation along the eastern margin of T. 60 N., R. 130 W. lies along the flank of a strongly positive magnetic anomaly which, as noted previously, may reflect a buried sill. Such a configuration would suggest that the proposed sill was preferentially emplaced along a synclinal trough flanking the broad anticline.

There appears to be some correlation between the magnetic anomaly expression and the apparent folds in the iron-formation beneath the MINNAMAX prospect area (southeast of faults B-20 and DC-2 in Plate 7). The folding is inferred largely from a trough and ridge structure in the base of the Duluth Complex, which is generally thought to be conformable with folding in the underlying iron-formation (Gene Mullenmeister, personal communication). The apparent syncline and adjacent anticline in the MINNAMAX prospect area lie along a linear negative magnetic anomaly. This negative anomaly lies between the main belt of maxima associated with the metamorphosed iron-formation and an east-striking linear maximum that projects in a spurlike fashion from the main anomalous belt. The intricate fold patterns at the east end of the prospect, which are associated with the highest grades of sulfide mineralization in the area (see previous chapter), occur near the eastern truncation of the linear negative anomaly and spurlike positive anomaly. Two smaller spurlike positive anomalies that resemble the MINNAMAX expression lie in the southwestern part of T. 59 N., R. 13 W.

Detailed Model Studies

The magnetic anomaly expression over the MINNAMAX prospect area was further investigated by modeling along profile A-A' (Plate 7). The modeling assumes two-dimensional (strike infinite) sources. This profile was selected to avoid the tounguelike maxima in hopes that localized sill-like bodies could be avoided, and a simple planar surface could be assumed for the basal contact. Because of possible interference from flanking maxima, two dimensionality may still not be assumable over most of the exposed iron-formation, although the minimum-maximum amplitudes observed along this profile (Figures 3 and 4) are similar to those commonly observed elsewhere along this part of the iron-formation (see region around B-19 on Plate 7). In any case, the area southeast of the intrusion is the region of key interest here, and it has anomalies that are compatible with a two-dimensional assumption. The magnetic profiles are hand digitized from the maps using a 0.1-km interval.

Modeling was done on profile A-A' with several geological and geophysical constraints. The surface contacts and dips of the iron-formation and

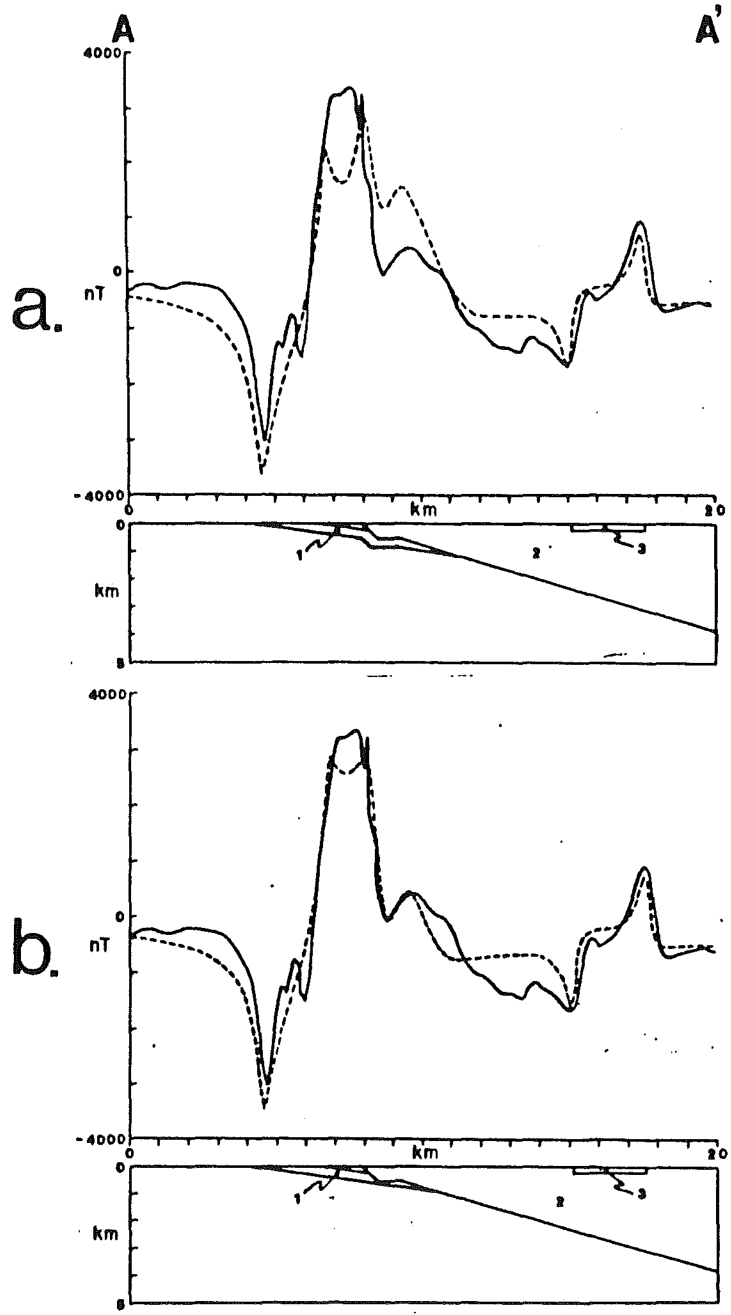

Figure 3. Magnetic model study of the MINNAMAX area. See Plate 7 for location of profile. (a) Model assuming structure of basal contact is conformable with iron-formation (model 1). (b) Model assuming structure of basal contact is unconformable with iron-formation (model 2). Body 1 represents Biwabik Iron Formation (magnetic susceptibility = 0.04 c.g.s., Jr = 0.02); body 2 represents Duluth Complex (magnetic susceptibility = 0.002 c.g.s., Jr = 0.001 c.g.s.); body 3 represents a magnetic member of Duluth Complex (magnetic susceptibility = 0.0025, Jr = 0.01). Induced field is directed 5° east - 75° down with an intensity of 60,000 gammas. All remanent magnetizations (Jr) directed 290° - 40° down. Solid curve represents observed anomaly, and dashed line represents calculated anomaly.

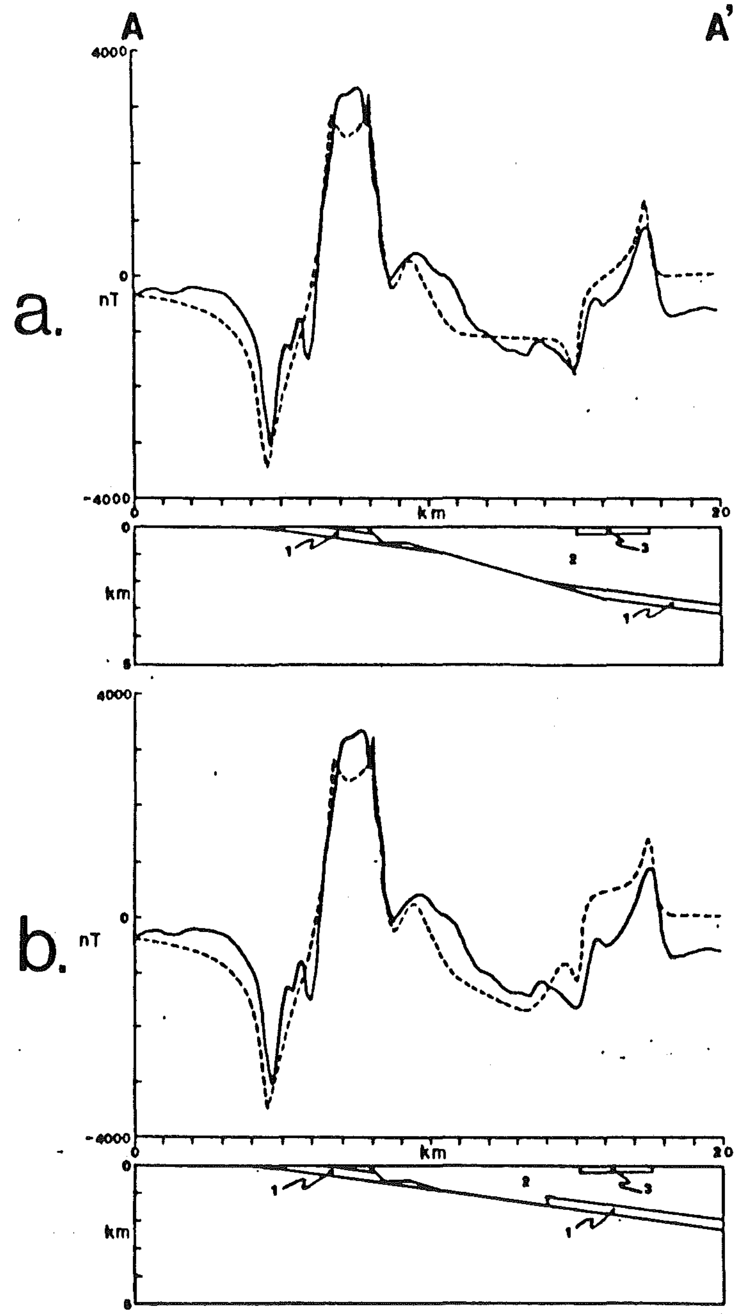

Figure 4. Magnetic model study of the MINNAMAX area. See Plate 7 for location of profile. (a) Model assuming that the Biwabik Iron Formation continues down dip beneath the complex with minor offset. (b) Model assuming that the Biwabik Iron Formation continues down dip beneath the complex without offset. Source parameters are the same as in Figure 3. Solid curve represents observed anomaly and dashed line represents calculated anomaly.

basal contact were accurately known from outcrop and drill-hole data (see previous chapter), as was the subsurface configuration of the base of the complex. An average magnetic susceptibility of 0.04 c.g.s. is assumed for the iron-formation, which was derived by Bath (1962) after accounting for the demagnetization effects. The intrusive rocks of the Duluth Complex were assigned magnetic susceptibility and NRM intensity values of 0.002 c.g.s. and 0.001 c.g.s., respectively, which were based on rock-property data in the area (Tables II-IV). The NRM direction for the intrusive rocks was assumed to lie along the average Keweenawan normal direction (dec/inc = 290°/40° down). An earth's field intensity of 60,200 gammas was assumed with a declination of 5° E. and inclination of 75° down.

Preliminary modeling along A-A' indicated that the iron-formation might be polarized somewhat steeper than the shallow "along the layers" direction proposed for the eastern end of the Mesabi range by Bath (1962). Bath based his conclusion principally on modeling the iron-formation in the vicinity of faults B-17 and B-18, where the minimum over the iron-formation is much larger than the adjoining maximum to the southeast, consistent with a slightly upward to-the-west polarization for a sheetlike source. However, anomaly data in the vicinity of profile A-A' (Figures 3 and 4 and Plate 7) show a minimum over the iron-formation that is somewhat smaller in amplitude than the positive anomaly to the southeast. This configuration is consistent with a polarization down to the west at some moderate angle, and fits reasonably well with the observed data, assuming an NRM of 0.020 c.g.s. for the iron-formation and using the Keweenawan normal declination of 290° and inclination of 40° down.

The first model over the MINNAMAX area (Figure 3a) assumes that the iron-formation is folded concordantly with the trough and rise along the basal contact of the intrusive rocks. A rough fit was achieved although locally the amplitudes directly over the fold structure were over 1000 gammas too high. Consistent with drill-hole data, the iron-formation was also interpreted to be truncated by intrusive rocks down dip, south of which the complex rests directly on Archean basement.

In gross form, the magnetic anomaly expression over the MINNAMAX prospect approximates that of two truncated and slightly offset sheets of iron-formation. The first sheet has its northwestern edge along the iron-formation outcrop and continues down dip for about 3 km, where it is effectively truncated by the downward flexure in the iron-formation. This configuration gives rise to the large-amplitude minimum-maximum anomaly couplet along the basal contact zone. The second sheet effectively has its northwestern edge at the downward flexure in the iron-formation at 8.5 km (Figure 3a) and its southeastern edge at the intrusive truncation near 11 km. The edges of this second sheet give rise to the minor minimum (trough)--maximum couplet over the MINNAMAX area.

Body 3 was incorporated to fit a local positive anomaly, using a magnetic susceptibility of 0.0025 c.g.s. and an NRM intensity of 0.010 c.g.s. Like the basal rocks of the Duluth Complex, the NRM in body 3 was assumed to be directed along the declination of 290° and inclination of 40° down. On Plate 7 body 3 would correspond to a very irregular and high-amplitude anomaly terrane, which, according to Bonnichsen (1974) and Cooper (1978) corresponds to a troctolite mass (the so-called "Railroad troctolite") that locally includes oxide-rich members and also contains a variety of hornfelsic inclusions, including those of metasedimentary origin. The significance of this zone is discussed further in the analysis of the regional data sets.

Model 2 (Figure 3b) assumed that the iron-formation was not structurally concordant with the base of the complex and was instead a uniformly dipping body, across which the intrusive rocks cut. A significantly better fit directly over the structure implies that the basal contact may indeed be discordant to the iron-formation. Drill-hole data, however, imply that the iron-formation is folded concordantly with the basal contact (Gene Mullenmeister, personal communication). Abrupt stratigraphic thickness variations in the iron-formation across the structure might reconcile these two differing conclusions, but further investigation incorporating drill-hole data and more comprehensive model studies are needed.

The observed data between 12 and 15 km in Figure 3b are almost 1000 gammas lower than the model data, making this the area of the poorest fit along model 2. Further modeling, using near-surface sources, did not improve the fit. However, incorporation of a deep source--a buried segment of iron-formation down dip along the base of the complex--did yield the improved results shown on model 3 (Figure 4a). If the iron-formation was at one time continuous down dip, the missing iron-formation between 10 and 15 km was either assimilated by the magma or incorporated into what was then the roof of the intrusion. Perhaps body 3, which may be enriched in magnetic hornfels, represents the remnants of such a roof.

Model 3 implies a slight vertical offset between the two segments of iron-formation, whereas Model 4 (Figure 4b) assumes no offset. Although the differences are not great, the data seem slightly more consistent with an offset (southeast side down) between the two proposed segments of iron-formation.

Regional Gravity and Magnetic Anomly Characteristics over the Central Duluth Complex

Discussion of the Gravity Anomaly Data

Several significant gravity anomaly signatures are evident west of the complex in pre-Keweenawan rocks (Figure 5). Strongly negative Bouguer anomaly amplitudes over Animikie basin rocks southwest of 47°30'N.-92°W. probably reflect Archean granitic basement beneath the Early proterozoic sequence. Similar gravity lows over the west-central, northwestern and northeastern parts of the area correlate with exposed Archean granitic rocks (Giants Range Granite, Vermilion Granitic Complex and the Saganaga Tonalite respectively). The beltlike 20-milligal positive anomaly that strikes easterward immediately south of 48° in the north-central part of the area correlates with Archean metavolcanic rocks of the Ely Greenstone and the Newton Lake Formation (Sims and others, 1970; Green, 1982). Similarly a positive anomaly 15 to 20 milligals in amplitude that strikes to the east immediately northwest of 47°30'N.-92° W. correlates largely with Archean metavolcanic rocks (Sims and others, 1970).

The gravity anomaly expression over the central Duluth Complex is dominated by broad positive anomalies that increase in magnitude to 150 milligals above the regional background (Figure 5). This positive expression reflects the high-density nature of the complex as a whole, although localized variations in the anomaly pattern appear to reflect individual geologic bodies. Along the southeastern margin of the complex, positive anomaly expression resembles a dumbbell in that two subcircular maxima southeast of 47°30' N. and 91°30' W. and southeast of 48° N. and 91° W. are joined by a northeast-striking linear maximum about 25 km inland from the Lake Superior shore. From southwest to northeast, this zone is discussed as three separate bodies: the Cloquet Lake body, the Wilson Lake body (the handle of the dumbbell), and the Brule Lake body.

Existing geologic evidence implies that all three anomalous bodies are related to dense, highly magnetic intrusions. Exposure is generally poor over all three, although significant correlations with intrusive rocks occur in several areas. The eastern edge of the Cloquet Lake body overlaps with granophyric and diabasic rocks of the Beaver Bay Complex (Grout and Schwartz, 1939) and layered mafic intrusive rocks of the Sonju Lake intrusion (see Figure 2) (Stevenson, 1974). Part of the Wilson Lake body overlaps with diabasic rocks (Green, 1982) and layered mafic rocks (Lehman, 1980). The northwestern part of the Brule Lake body corresponds with felsic rocks and olivine gabbro (Davidson, 1977). A gravity model study by Ferderer (1982) across the Cloquet Lake body indicated a thick body with steep contacts, consistent with an intrusive mass. The presence of granophyric and volcanic rocks over parts of the three anomalous bodies indicates that the proposed intrusive rocks may still be partially covered by their original roof.

Several other local anomaly variations over the central Duluth Complex also appear to reflect individual geologic features. A narrow 10- to 25-milligal positive anomaly extends north-northeast for about 20 km from near 47°30' N. 91°30' W. and may reflect a feeder for the Bald Eagle intrusion. The gradients and overall anomaly amplitudes are noticeably less over the northwestern part of the complex (the region southeast of 48° N. and 91°30' in Figure 5), relative to the southern and eastern parts of the complex, and such an anomaly expression might reflect thinning of the complex in this area, a decrease in density contrast between the complex and country rocks, or both.

Discussion of the Aeromagnetic Anomaly Data

Several correlations occur between the magnetic anomaly data and geologic features outside the complex (Figures 6, 7, and 8). The subdued magnetic anomaly in the southwestern corner of the area corresponds to the thick, nonmagnetic slate-graywacke sequence of the Early Proterozoic Animikie basin. Northwest-striking linear features extending from the Duluth Complex and across the Animikie rocks (Figure 7) most likely reflect Keweenawan dikes. The narrow belt of positive anomalies along the northern rim of the Animikie basin corresponds to the Biwibik Iron Formation. Archean metasedimentary and metavolcanic rocks just to the north of the Biwibik Iron Formation correspond to a narrow belt of subdued anomaly expression, which is bounded on the north by an east-striking, 10-km-wide belt of positive anomalies reflecting Archean granitic rocks (Giants Range Granite). A 15- to 20-km-wide belt of subdued anomaly expression northwest of 47°37'30" N.-92° W. corresponds in general with Archean metasedimentary rocks (Lake Vermilion Formation). The tightly curved belt of high-amplitude (>1000 gammas) positive anomalies west of 47°45' N.-92° W. corresponds to Soudan Iron Formation within a belt of Archean metavolcanic rocks assigned to the Ely Greenstone. The maxima associated with this belt are truncated abruptly to the north along east-striking lineaments associated with the Vermilion fault. East-striking belts of positive and negative anomalies in the northwestern corner of the area are associated with the Vermilion Granitic Complex.

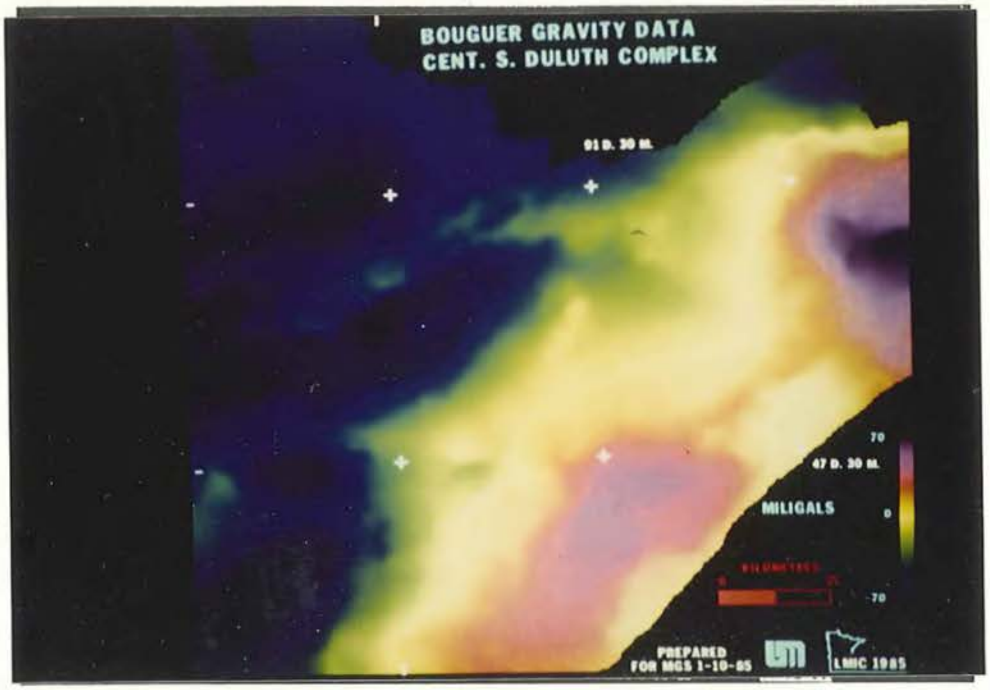

Figure 5. Bouguer gravity anomaly over the central Duluth Complex.

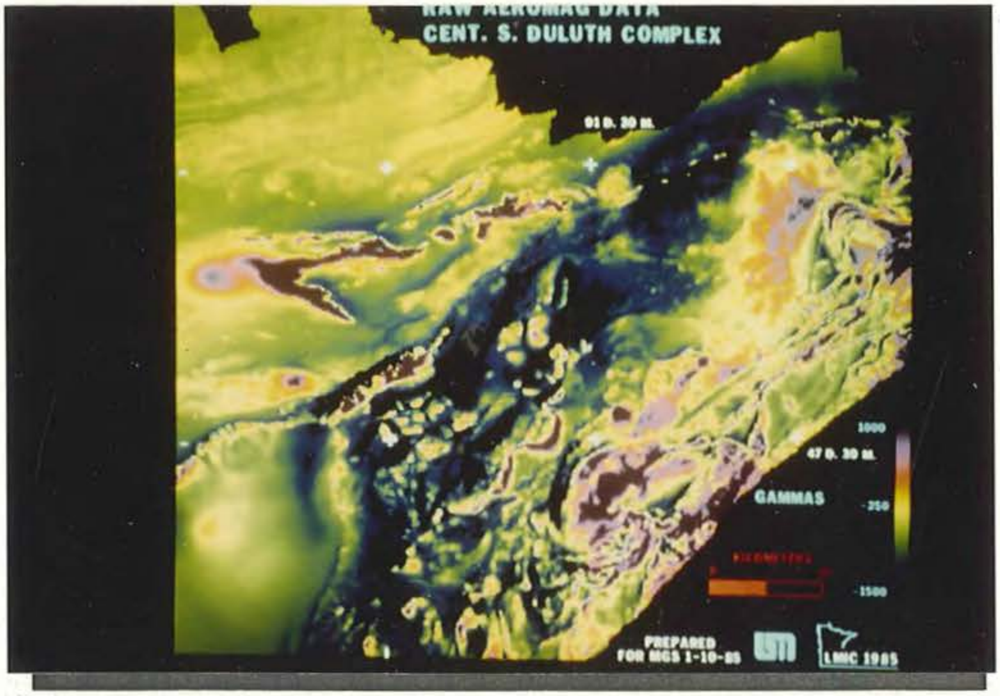

Figure 6. Total magnetic intensity anomaly over the central Duluth Complex.

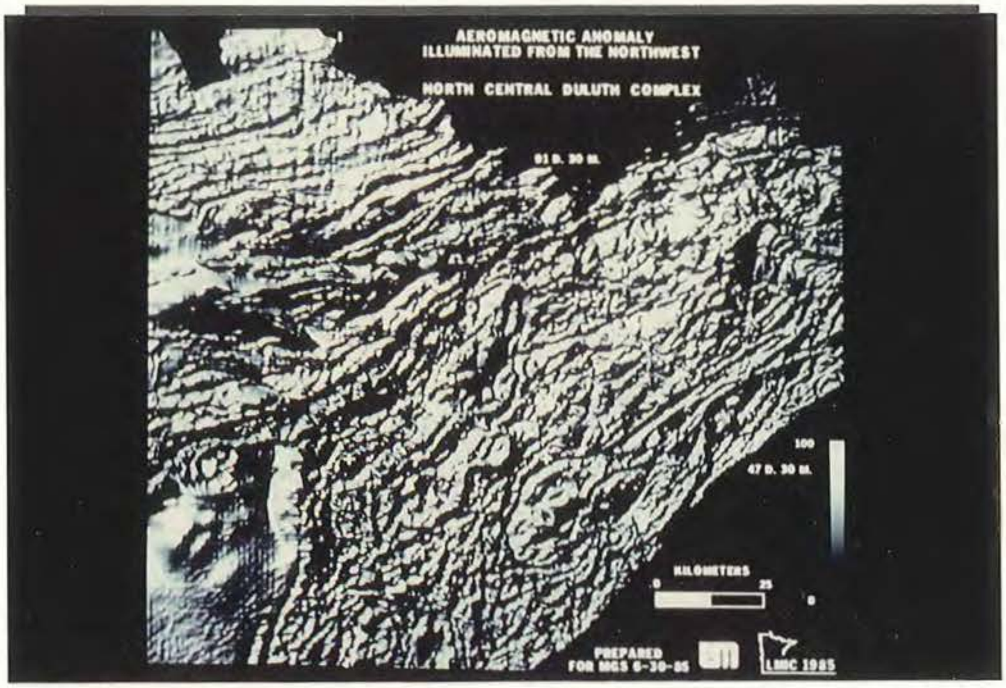

Figure 7. Total magnetic intensity anomaly over the central Duluth Complex. Shaded relief format illuminated from the northwest at 45° inclination.

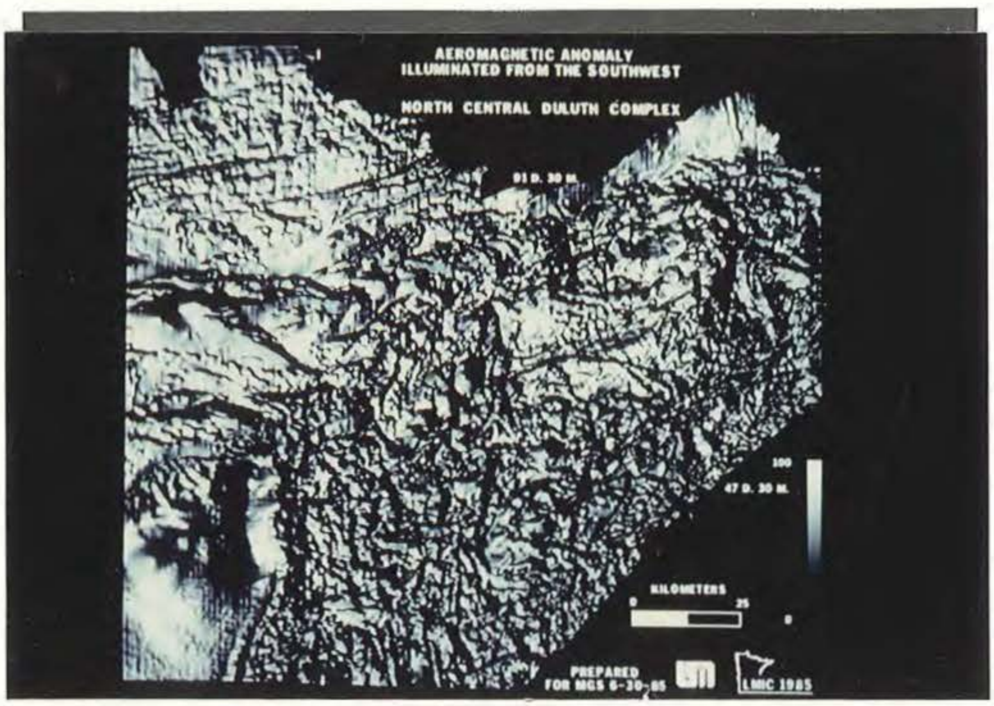

Figure 8. Total magnetic intensity anomaly over the central Duluth Complex. Shaded relief format illuminated from the southwest at 45° inclination.

The magnetic anomaly expression over the Duluth Complex is characterized by a complex and high-amplitude expression (Figures 6, 7, and 8). Probable causes include (1) a complex and multiphase intrusive history; (2) a variable distribution and composition of magmatic oxides, reflecting changing physiochemical conditions during cooling of the magmas; and (3) a widely varying and commonly strong NRM which also is a complex function of physiochemical conditions during cooling of the magma.

Several areas within the complex are characterized by a strongly positive magnetic anomaly expression (>1000 gammas) which correlates closely with the positive gravity anomalies over the Cloquet Lake body, Wilson Lake, and Brule Lake bodies. The strongly positive, serpentine anomaly about 10 km west of the Cloquet Lake body corresponds to an oxide-rich, sulfide-bearing troctolite and gabbro known from drill-hole data (Vadis and others, 1981). A ringlike negative surrounding an axial positive anomaly northwest of 47°45' N.-91°30' W. corresponds to the ring troctolite and gabbro core, respectively, of the Bald Eagle intrusion (Weiblen, 1965). A square zone of localized, strongly positive anomalies just to the east of 47°30' N.-92° W. corresponds to the "Railroad troctolite" of Bonnichsen (1974) which contains oxide-rich zones and large inclusions of wall rock. A broad minimum of 1500 to 2000 gammas in amplitude dominates the western and northwestern margins of the complex and is somewhat suggestive of reversed polarity. This, however, is not confirmed by measurement of NRM in the area (Table I), and model studies (Ferderer, 1982; this report) indicate that the negative expression could be accounted for by an eastward-dipping basal contact, combined with a regional-scale effect of normally polarized rocks (dec/inc = 290°/40°).

Regional-Scale Model Study

The regional-scale gravity and magnetic anomaly expression in the study area was further investigated by a model study along profile B-B', which traverses the central part of the Duluth Complex ((Figures 2, 9, and 10). The profile was selected to be nearly perpendicular to the major structures in the area, and gravity and magnetic data were hand digitized from contour maps at a 0.5-km interval. The profile was extended about 30 km into Lake Superior, by tying in anomaly values given by O'Hara (1982). Two-dimensional modeling programs as modified by Ferderer (1982) were used, and existing rock-property data provided general constraints. Ferderer's (1982) seismically determined upper crustal density of 2.76 gm/cc was used for the pre-Keweenawan crust, and wherever possible, geologic control was incorporated. It was assumed that all NRM within the complex was along the Keweenawan normal direction (dec/inc = 290°/40°). Where dips of sources were uncertain, a 45° dip was assumed.

The final gravity model (Figure 9) fits the observed data with geologically reasonable sources. At the northwest end of the profile the shallow bodies (extending to 5 km in depth) with densities of 2.70 and 2.88 gm/cc represent the Archean Vermilion Granitic Complex and Ely Greenstone, respectively. For the basal contact of the complex, the gravity model estimates an average dip of about 15° southeastward down to a maximum thickness of 10 km. Between 55 and 62 km, three southeastward-dipping bodies with densities of 3.02, 2.90, and 2.80 correspond approximately to the Wilson Lake body. The block of 2.87-density material between 72 and 84 km correlates spatially with the North Shore Volcanic Group. The 2.92 gm/cc material between 84 and 100 km lies beneath Lake Superior and might

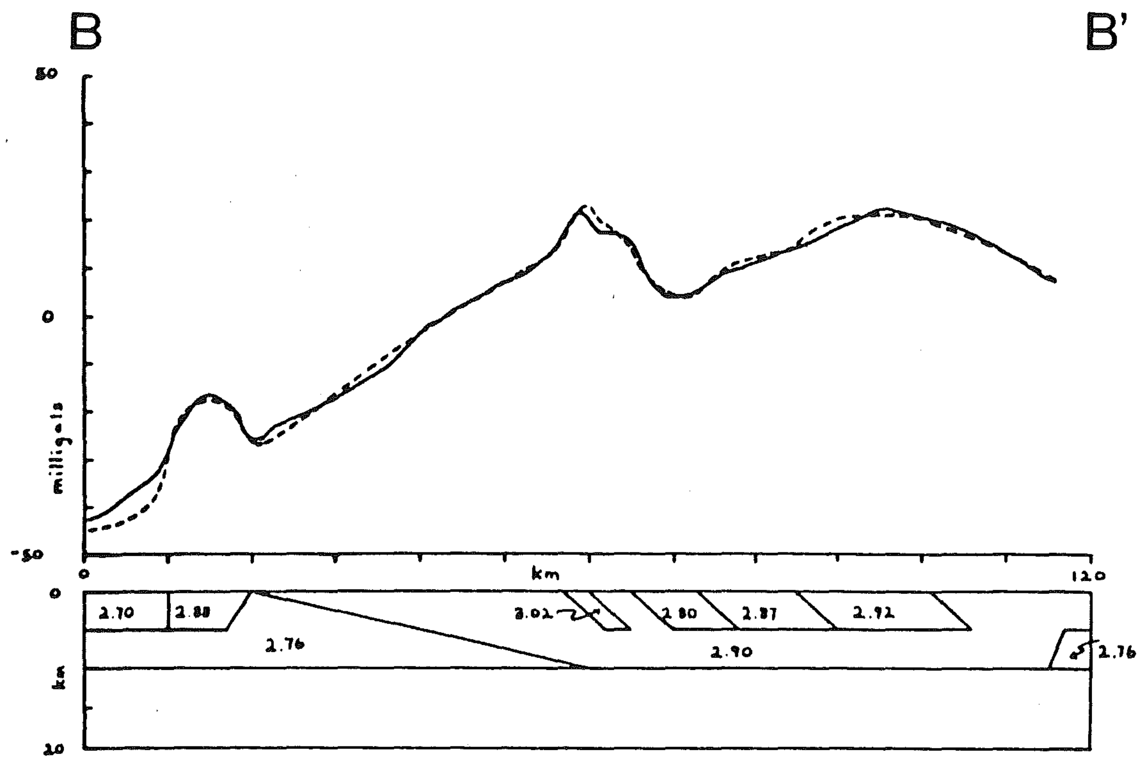

Figure 9. Gravity model of profile B-B'. Density is in gm/cc. Solid line is observed anomaly; dashed line is calculated anomaly.

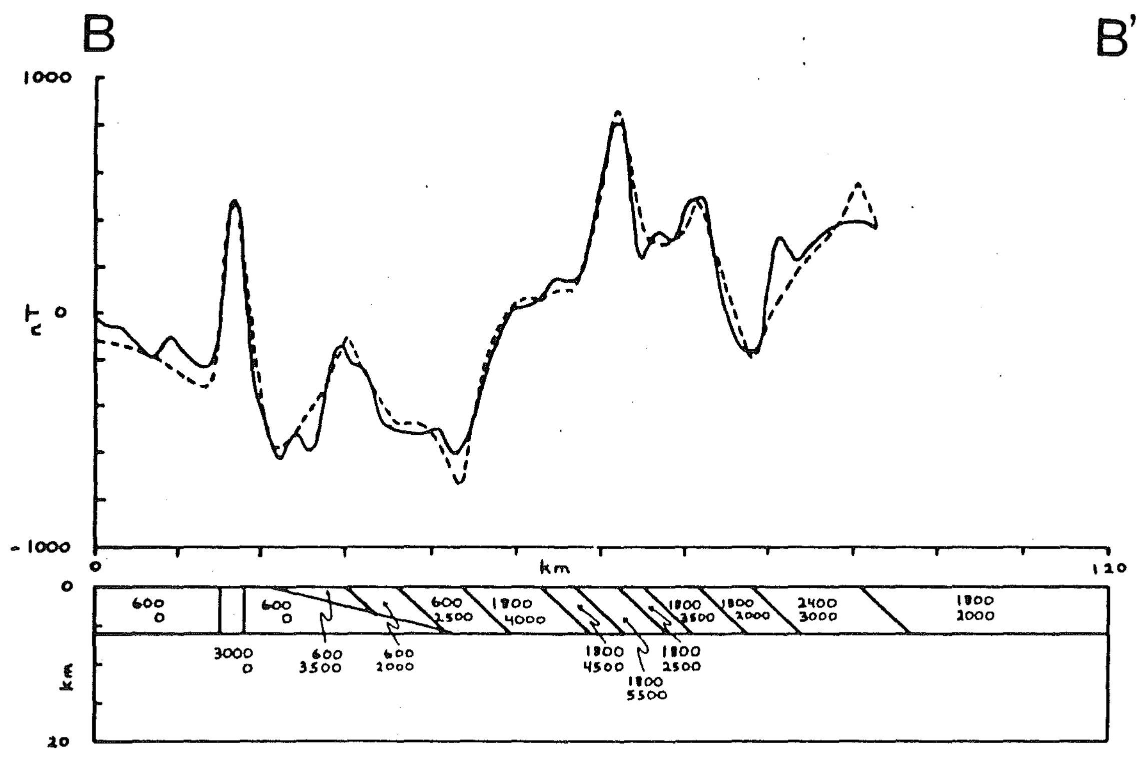

Figure 10. Magnetic model of profile B-B'. Upper number is induced magnetization and lower number is remanent magnetization. Both units are x 10^{-6} c.g.s. Induced magnetization declination and inclination are 5° E. and 75° down, and remanent magnetization declination and inclination are 290° and 40° down. Solid line is observed anomaly; dashed line is calculated anomaly.

represent mafic intrusions, because the gravity high over this area is a southern extension of a much larger anomaly over the northeastern Duluth Complex.

The gravity model in Figure 9 implies that the central Duluth Complex is considerably thinner and has a less steeply dipping basal contact than observed to the south. Model studies by Ferderer (1982) estimated that south of 47°30' N. the complex may be as thick as 20 km and have a basal contact that dips 30° to 60° eastward. Thus, assuming our densities are fairly well constrained, these model studies imply that the central part of the complex may have undergone significantly less development than in areas to the south. This implication is consistent with outcrop data, which reveal a general lack of troctolitic rocks and a widespread sheet of anorthositic rocks over much of the central Duluth Complex (Green, 1982). This part of the complex also corresponds approximately with a northward projection of a broad topographic rise in the pre-Keweenawan basement, which was associated with significant thinning of Keweenawan lavas in western Lake Superior (White, 1966).

A thin Duluth Complex along B-B' is also indicated by the magnetic modeling (Figure 10). In fact, a suitable fit was achieved by extending sources to a depth of only 6 km. However, previous model studies (Ferderer, 1982) indicate that depth extents are generally difficult to estimate with magnetic modeling, and thus the gravity-based thickness of 10 km is probably more reliable. The vertical body outside the complex represents an iron-formation-bearing zone in the Ely Greenstone belt. The body between 20 and 30 km in Figure 10 corresponds to a narrow belt of troctolitic rocks, whereas the bodies between 30 and 52 km correspond largely to anorthositic rocks. The sources between 52 and 72 km correspond generally to the Wilson Lake body, although they do not correlate spatially with the modeled gravity anomaly sources. The bodies between 72 and 90 km correlate with flows of the North Shore Volcanic Group.

Discussion of Second Vertical Derivative (SVD) Anomaly Data.

The use of gravity and magnetic data for geologic mapping in the central Duluth Complex is significantly enhanced by second vertical derivative (SVD) filtering (Figures 11 and 12), and discussion here is in terms of zones defined by patterns in the SVD data. The SVD aeromagnetic anomaly data provided the greatest detail, and most zone boundaries were picked to outline areas of common anomaly character in the SVD magnetic data, paying particular attention to anomaly amplitudes, spacing and strikes. The zones defined by the SVD magnetic data commonly showed a high degree of spatial correlation to features in the SVD gravity data. In several areas where the SVD magnetic anomaly character was ambiguous, the SVD gravity data were used to define zone boundaries. The zones thus defined were compared with existing outcrop and drill-hole information, and control was adequate to assign geologic significance to zones 1 through 10 on Figure 13.

Zone 1 (Figure 13) corresponds to troctolitic units along the base of the complex. This zone is characterized by a distinct belt of subdued (1000 to 2000 gammas/km^2) SVD magnetic anomaly expression (Figure 12) and by low-amplitude ($\pm$ 0.1 milligal/km^2) variations in the SVD gravity data (Figure 11). The SVD magnetic data show a weak banding that roughly parallels the basal contact zone. Based on subtle changes in patterns, zone 1 has been further subdivided into three parts. The northernmost part

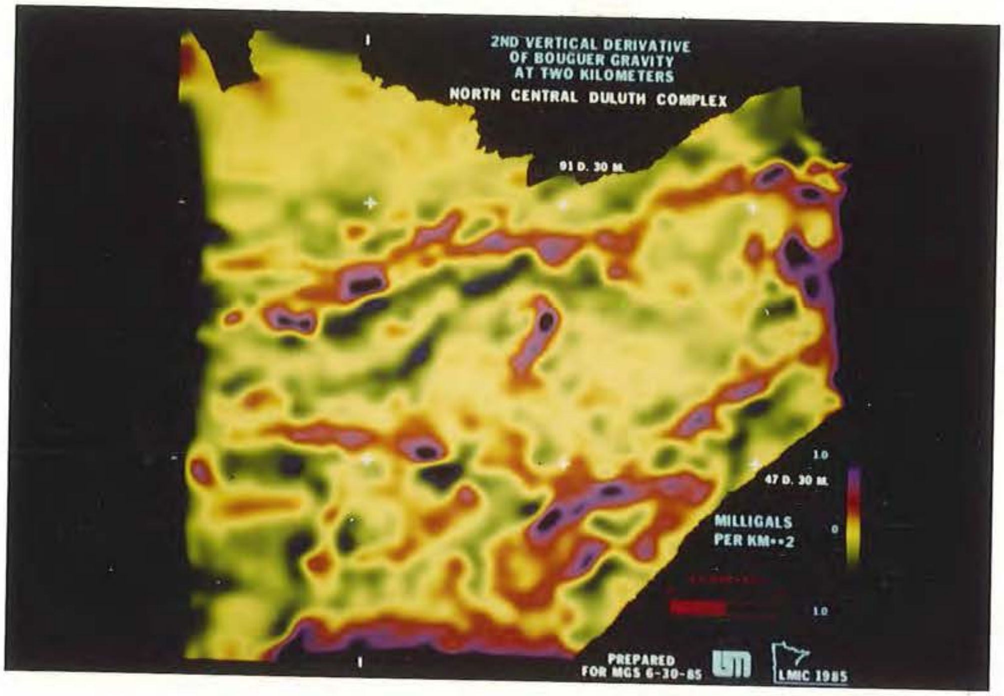

Figure 11. Second vertical derivative (SVD) of Bouguer gravity anomaly over the central Duluth Complex. Gray scale presentation with extreme shades representing +0.15 milligal/km^2 (white) to -0.5 milligal/km^2 (black). Data have been slightly smoothed by upward continuation to 2 km.

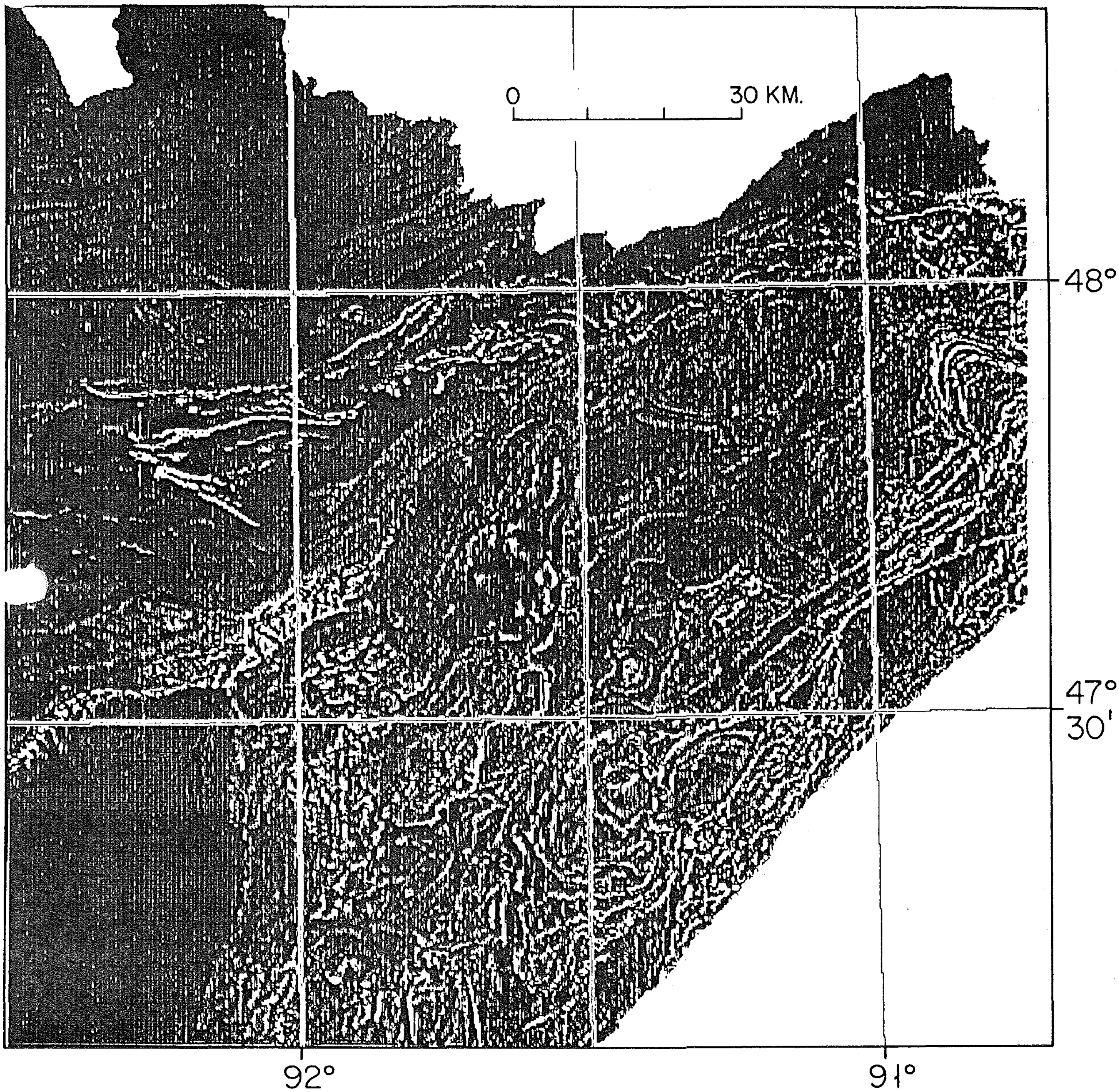

Figure 12. Second vertical derivative (SVD) of total intensity magnetic anomaly data over the central Duluth complex. Gray scale presentation with extreme shades representing +5000 gammas/km^2 (white) to -5000 gammas/km^2 (black).

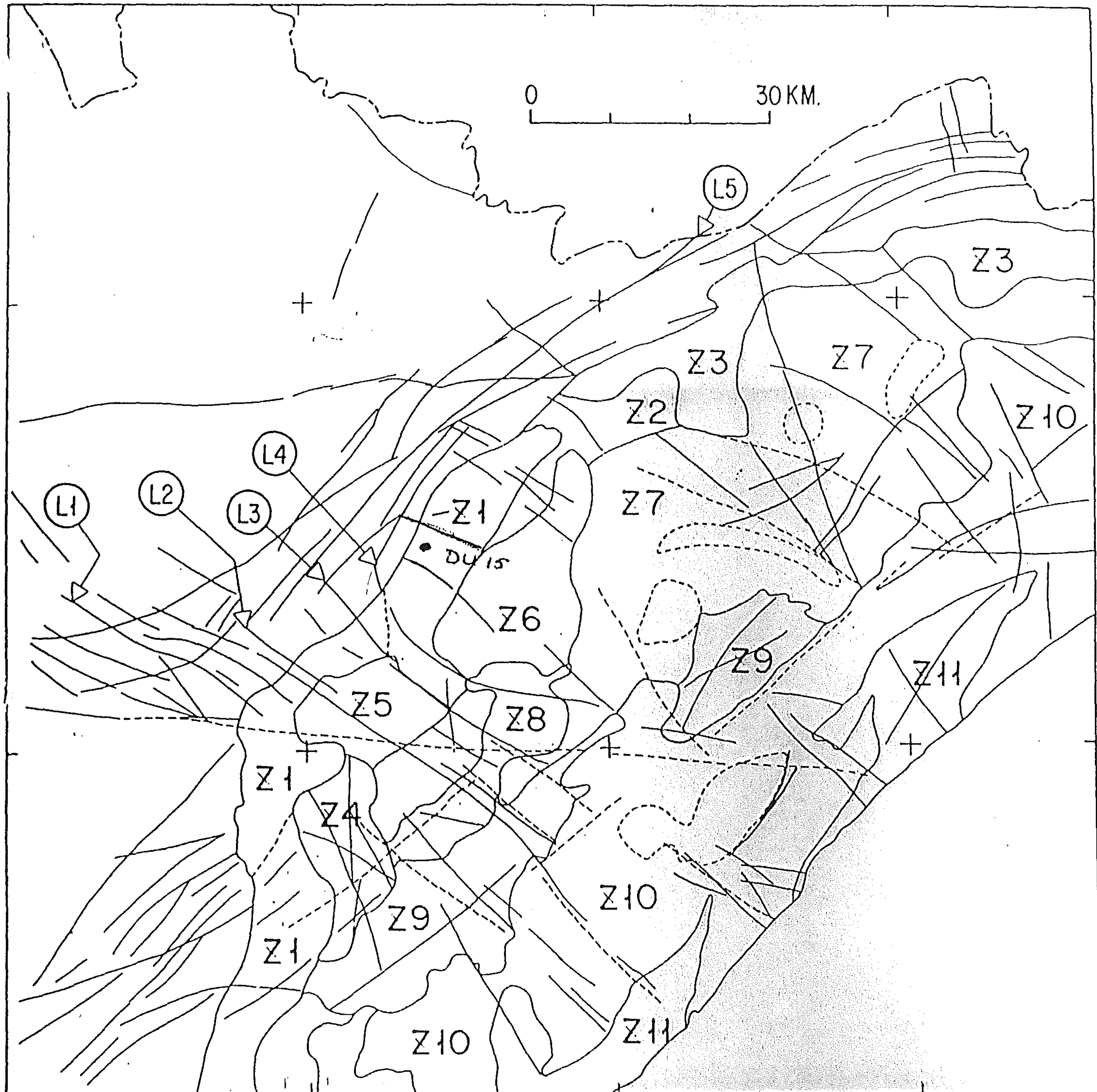

Figure 13. Geologic interpretation of regional-scale gravity and magnetic anomaly data. Gray lines outline zones defined by the second vertical derivative (SVD) gravity and magnetic data. Zones discussed in the text are labeled Z1 through Z11, and dashed lines outline subzones discussed. Thin black lines represent lineaments picked from the aeromagnetic data primarily using the shaded relief and SVD maps. Thin dashed lines are lineaments picked from the SVD of gravity anomaly data.

correlates closely with the South Kawishiwi intrusion (Bonnichsen, 1974; Cooper, 1978). The central part corresponds to the Partridge River troctolite and Powerline gabbro (Bonnichsen, 1974; Cooper, 1978), and the uniformity of expression over this part of the zone implies that both rock types may form integral parts of the same intrusive mass. Although exposure is extremely poor in the southernmost part of zone 1, it probably represents another large intrusion of troctolitic rocks.

Zone 2 (Figure 13) is associated with intermediate-amplitude (2000 to 4000 gammas/km^2) SVD magnetic anomaly variations which crudely form northeast-striking bands (Figure 12). The zone corresponds to weakly negative (-0.1 to -0.2 milligals/km^2) SVD gravity anomaly variations (Figure 11). The zone correlates with exposed anorthositic suite rocks as reported by Green and others (1966), which here extend from along the basal contact zone to the Bald Eagle intrusion, some 10 km to the east.

Zone 3 appears to be related to a belt of troctolitic rocks along the northern rim of the complex (Figure 13). Zone 3 is very similar to zone 1 with regard to the magnetic anomaly expression, but differs by being closely associated with a belt of strongly positive (0.4 to 0.5 milligals/km^2) SVD gravity anomalies (Figures 11 and 12). The positive gravity expression may arise from two possible sources: The troctolitic units themselves, or an Archean metavolcanic Ely Greenstone belt which lies along the footwall and is known to cause a similar high west of the complex. The close correlation of the positive belt with a southward projection of troctolitic rocks in the Wilder Lake area (west of 47°52'30" N.-91°15' W. in Figure 11), however, implies that the SVD gravity high of zone 3 may primarily reflect the troctolitic rocks.

Zone 4 (Figure 13) appears to reflect a block of anorthositic suite rocks. It is characterized by intermediate to large (3000 to 5000 gammas/km^2) variations in the SVD magnetic data and weakly to moderately positive (0.1 to 0.2 milligals/km^2) SVD gravity anomaly values (Figure 11). Outcrop control is extremely poor in the zone, but scattered occurrences of anorthositic rocks and gabbro have been reported (Bonnichsen, 1971; Leon Gladen, personal communication). Thus, zone 4 is tentatively interpeted to be part of the anorthositic suite rocks, although the markedly different SVD magnetic anomaly character implies that the rocks of zone 4 are significantly different from the anorthositic suite rocks of zones 2 and 7.

Zone 5 (Figure 13) appears to define a body of troctolitic rock which contains abundant inclusions of hornfelsic rocks. This zone corresponds to body 3 in the model study of the MINNAMAX area (Figures 3 and 4). The zone is sharply distinct in the SVD-magnetic data, consisting of a square region containing numerous subcircular maxima with high (>5000 gammas/km^2) amplitudes (Figure 12). The zone also correlates closely with a strongly positive (>0.6 milligal/km^2) anomaly in the SVD gravity data (Figure 11). The northeastern part of zone 5 correlates with the Railroad troctolite of Bonnichsen (1974), which contains oxide-rich zones and locally abundant inclusions of hornfelsic country rock and anorthositic suite rocks (Cooper, 1978). The inclusions appear to be of both a metasedimentary and metaigneous origin. A few individual magnetic maxima occur directly over large hornfelsic inclusions. The heterogeneous nature of the rocks in zone 5, combined with its distinct magnetic anomaly signature, make this zone an intriguing feature. The inclusion-rich character implies that the unit was emplaced very near either the floor or roof of the complex, and the sharp boundaries of the zone, as defined by the SVD magnetic anomaly data, are suggestive of fault-related contacts with surrounding rocks. If a significant part of the hornfelsic inclusions are of Animikie origin, zone 5 might be a promising area for mineral exploration. Magmatic interaction with Animikie footwall rocks was an important factor in the formation of copper-nickel sulfide ores at the base of the complex (Weiblen and Morey, 1980).

The northward projection of zone 6 correlates closely with the troctolitic Bald Eagle intrusion (Figures 2 and 13). A ring of very subdued SVD magnetic anomaly expression corresponds to the ring troctolite, whereas a narrow, strongly positive (5000 gammas/km^2) anomaly along the intrusion's axis correlates with a core of olivine gabbro (Figure 12). A strongly positive (>0.5 milligal/km^2) SVD gravity anomaly correlates closely with the Bald Eagle intrusion (Figures 2 and 11) and is consistent with the somewhat higher density of the Bald Eagle rocks relative to surrounding rocks (Tables II-IV). The southern part of zone 6 is outlined by a bulbous extension of the subdued SVD magnetic expression. The positive SVD gravity anomaly over the Bald Eagle intrusion attentuates toward the south end of zone 6, possibly indicating a thinning of these rocks. I tentatively propose that the bulbous southern end of zone 6 represents a shallow, spoonlike extension of the Bald Eagle intrusion, in particular of the ring troctolite. Widely scattered SVD magnetic maxima over this southern extension may reflect isolated equivalents of the olivine gabbro in the core of the Bald Eagle intrusion to the north. The overall anomaly patterns in the SVD data, together with the rock-property data (Table IV), imply that the Bald Eagle intrusion may be lithologically and structurally distinct from both the anorthositic suite rocks and the basal troctolitic rocks.

Over zone 7 the subdued SVD gravity ($\pm$ 0.1 milligal/km^2) and magnetic ($\pm$ 500 gammas/km^2) anomaly expression implies a widespread and fairly uniform composition and structure. A prominent saddle in the positive Bouguer gravity anomaly (Figure 5) and the regional gravity model study (Figure 9) imply that the complex may be somewhat thin in this area. Because outcrop data indicate the abundance of anorthositic suite rocks (Figure 2), zone 7 is tentatively interpreted to reflect an extensive, undisturbed sheet of largely anorthositic suite rocks. Granophyric and volcanic rocks exposed sparingly along the southern and southeastern margins of zone 7 may reflect the roof zone of the anorthositic rocks. Several localized highs in the SVD gravity data correlate with subtle patterns in the SVD magnetic data (Figures 11 and 12) and are indicated on Figure 13 by closed dashed lines. The southernmost of these subzones is associated with a concentric pattern in the SVD magnetic anomaly data that is suggestive of a zoned intrusion.

The high-amplitude SVD gravity (Figure 11) and magnetic (Figure 12) anomalies of zone 8 reflect a poorly exposed terrane of gabbro and ferrogabbro (Figure 12). Weiblen and Morey (1980) found the ferrogabbro in this zone to be texturally similar to the olivine gabbro core of the Bald Eagle intrusion and inferred that the two units may be genetically related. No direct connection can be inferred, however, from the SVD data. The Greenwood Lake or "Snake" magnetic anomaly of Vadis and others (1981) occurs inside the eastern margin of this zone. Drill-hole data indicate that this strongly positive magnetic anomaly is caused by oxide-rich gabbro and troctolite. Because magnetic oxide enrichment is commonly a product of advanced igneous differentiation in the Duluth Complex (Taylor, 1964; Beck, 1970), the Greenwood Lake anomaly is interpreted to represent a late oxide-rich phase in the upper part of the zone 8 intrusive mass. Granophyric rocks that lie immediately to the southeast in zones 7 and 9 may actually be the uppermost part of the inferred intrusive sequence of zone 8.

Zone 9, which is in two parts, is characterized by SVD magnetic anomalies of moderate to high amplitude that form linear to tightly curvilinear patterns and by chiefly negative SVD gravity anomaly values (Figures 11, 12, and 13). Although outcrop control is generally poor, the zone appears to be underlain primarily by volcanic rocks similar to the North Shore Volcanic Group, with lesser amounts of granophyre, gabbro and clastic sedimentary rocks (Figure 2). The volcanic rocks are commonly hornfelsed and have been metamorphosed into the oxide-rich "magnetic basalts" of Bonnichsen (1971). Zone 9 is tentatively interpreted to be a belt of volcanic rocks, which has been significantly disrupted and metamorphosed by younger intrusions, possibly by those of zones 8 and 10.

Complex and strongly positive SVD gravity and magnetic anomalies characterize zone 10 (Figures 11, 12, and 3) and are believed to reflect a mass of poorly exposed intrusive rocks. The large southwestern and northwestern parts of the zone correspond to the Cloquet Lake and Brule Lake bodies, respectively, and the narrow central neck of the zone corresponds to the Wilson Lake body. The Beaver Bay Complex has been merged with the Cloquet Lake part of zone 10, as has a small anomalous terrane north of 47°15' N.-91°45' W. The Sonju Lake intrusion (Figure 2) corresponds to a distinct banded anomaly pattern in the SVD magnetic data (Figure 12) along and south of 47°30' N. and 91°15' W., and the data clearly show that the intrusion extends for at least 10 km to the west-southwest beneath glacial cover. To the east, northwest-striking faults truncate the rocks of the

Sonju lake intrusion against diabasic rocks of the Beaver Bay Complex (Stevenson, 1974), and the SVD magnetic data clearly show this faulting and its extension for at least 15 km to the southwest. A dashed line in Figure 13 outlines a subzone of zone 10, which is defined by a subdued SVD magnetic expression and a moderately negative SVD gravity anomaly. This subzone correlates with numerous exposures of granophyre (Bonnichsen, 1971) and probably represents a large granophyric cap over part of the Cloquet Lake body. In addition to granophyric rocks, it is possible that the intrusions in zone 10 may locally contain large masses of invaded volcanic rocks, such as observed in the Beaver Bay Complex.

Although little can be inferred regarding the detailed nature of the zone 10 intrusive rocks, limited data from around the Beaver Bay Complex suggest a complex instrusive history. Anorthosite inclusions of deep crustal origin (Morrison and others, 1983) are locally abundant in the Beaver Bay Complex and imply proximity to a major open feeder zone. Such a large feeder zone would probably have served as a conduit for numerous magmatic phases at different times. Recent geologic mapping over the northern part of the Beaver Bay Complex indicates that the Beaver Bay diabase cuts and is chilled against a coarse-grained oxide gabbro (James Miller, personal communiciaton).

In zone 11, subdued SVD magnetic anomaly patterns and moderately negative SVD gravity anomaly expression correspond to undisturbed volcanic rocks of the North Shore Volcanic Group. The two parts of zone 11 are separated by Beaver Bay Complex rocks associated with zone 10. Bedrock is extensively exposed here. The near-shore flows in the northeastern segment of zone 11 are the uppermost flows known in the North Shore volcanic sequence (Green, 1972). The rather limited extent of zone 11 implies that relatively undisturbed and unmetamorphosed lavas of the North Shore Volcanic Group are a very minor part of the total Keweenawan sequence in northeastern Minnesota; the volcanic rocks in zones 9 and 10 are highly metamorphosed and disrupted.

Interpretation of Anomaly Lineaments

To further assess the structural framework of the Duluth Complex, lineament data were compiled from the shaded relief maps of the aeromagnetic data (Figures 7 and 8), the SVD gravity data (Figure 11), and the SVD magnetic data (Figure 12). Although the visual selection of lineaments from these data is a subjective process, the overall pattern, as well as a few individual lineaments, appears to be geologically significant (Figure 13). Lineaments both inside and outside the complex appear to favor either northeast or northwest strikes. This pattern generally agrees with the structural model proposed by Weiblen and Morey (1980), although there is little evidence in Figure 13 for most of the north-striking faults (Figure 2) proposed originally by Cooper (1978).

Several of the northwest-striking structures can be related to known dikes or faults. Northwest-striking lineament L1 extends entirely across the Giants Range Granite and cuts the Biwabik Iron Formation along or very near the traces of faults B-10 and B-11 (Plates 1 and 7). Lineament L2 cuts northwest across the Biwabik Iron Formation where it corresponds with fault B-17. Lineament L3 crosses the Biwabik Iron Formation near or along fault B-20, which is known to be intruded by a Keweenawan diabase dike (Plates 1 and 7). Lineament L4 crosses the Biwabik Iron Formation near a cluster of north- to northwest-striking faults (faults B-21 to B-27 on Plates 1 and 7). The structures associated with magnetic lineament L4 may extend into the complex as the boundary between the central and northern parts of zone 1, or they may connect with west- to northwest-striking lineaments that penetrate deep into the complex across the northern end of zone 8 (Figures 7 and 13). Many of the lineaments between and including L1 and L3 appear to penetrate the Duluth Complex and lie along a wide belt of northwest-striking lineaments that extends across the entire complex (Figure 13). This belt intersects the basal contact of the complex where its strike changes from north to northeast. This overall configuration suggests that the northwest-striking lineaments in this region may reflect some fundamental crustal structure that had significant control on the emplacement of the complex.

Northeast-striking lineaments are prominent over the Archean rocks in the north-central part of the area and appear to reflect faults and dikes. Many of the lineaments correlate with strike-slip faults mapped by Sims and others (1970) that formed in late Archean time. Part of lineament L5 corresponds to the Camp Rivard fault, and its left lateral movement is dramatically demonstrated by offset in the positive magnetic anomalies associated with Giants Range Granite east of 47°45' N.-92° W. in Figure 12. Although these northeast-striking faults probably originated in late Archean time, they would have been oriented roughly perpendicular to the regional tensional axis for Keweenawan rifting and could have been reactivated at that time. The base of the Duluth Complex closely parallels many of these northeast-striking structures, and Green (1970) reported Keweenawan diabase dikes in the region which had an average strike of

N. 65° E. Many of the northeast-striking magnetic anomaly lineaments outside the complex in the southwestern corner of the area may reflect Keweenawan dikes similar to those exposed south of the study area (Chandler, 1985).

Poisson Analysis of Data

Description of Anomaly Data

The density and magnetization structure of the central Duluth Complex was investigated, using moving-window Poisson analysis on the data upward continued to 3 km. The upward-continued first vertical derivative of gravity data and the upward-continued reduced-to-pole (Keweenawan remanence) data are shown in Figures 14 and 15, respectively. Before applying the Poisson analysis, the significance of the long-wavelength anomaly characteristics are briefly discussed below.

Locally, there is not a great deal of similarity between the two upward-continued data sets (Figures 14 and 15). The first vertical derivative gravity data delineate many features that were previously described for the SVD gravity data, including the maxima over the dense, magnetic intrusions near the roof of the complex. In contrast, the long-wavelength magnetic maxima along the roof of the complex cover a much larger area and roughly define a 50-km wide rectangular zone with a northeast strike (Figure 15). The overall configuration implies some sort of structural control along northwest- and northeast-striking directions. The southwestern terminus of this rectangular zone corresponds with the concentration of northwest-striking lineaments discussed in the previous section (Figure 13). The lack of correlation with the first vertical derivative gravity data implies

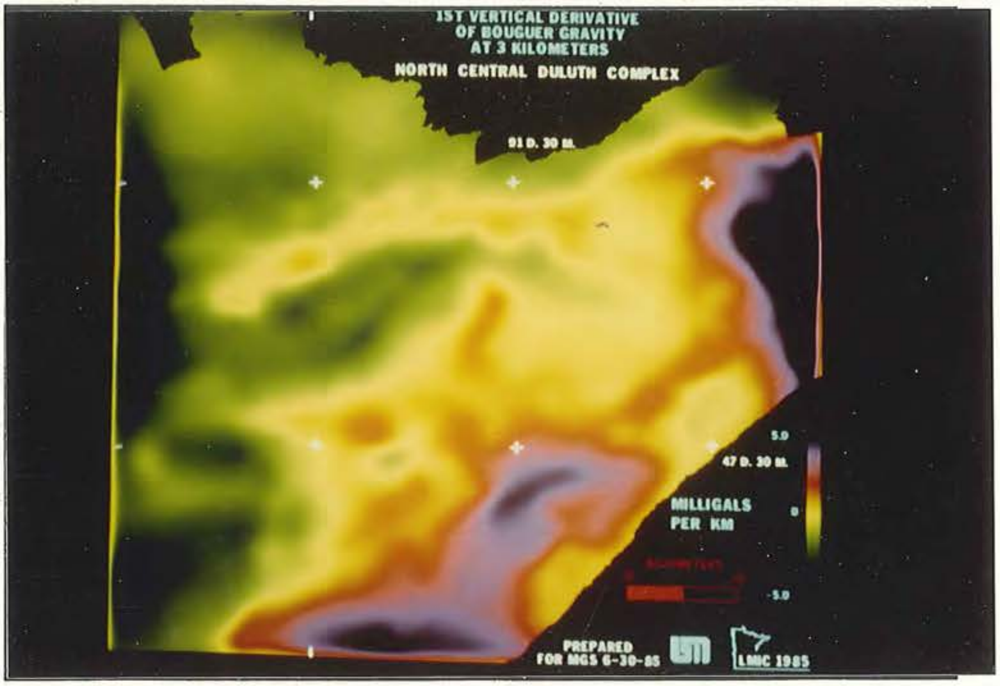

Figure 14. First vertical derivative of gravity data over the central Duluth Complex, upward continued to 3 km.

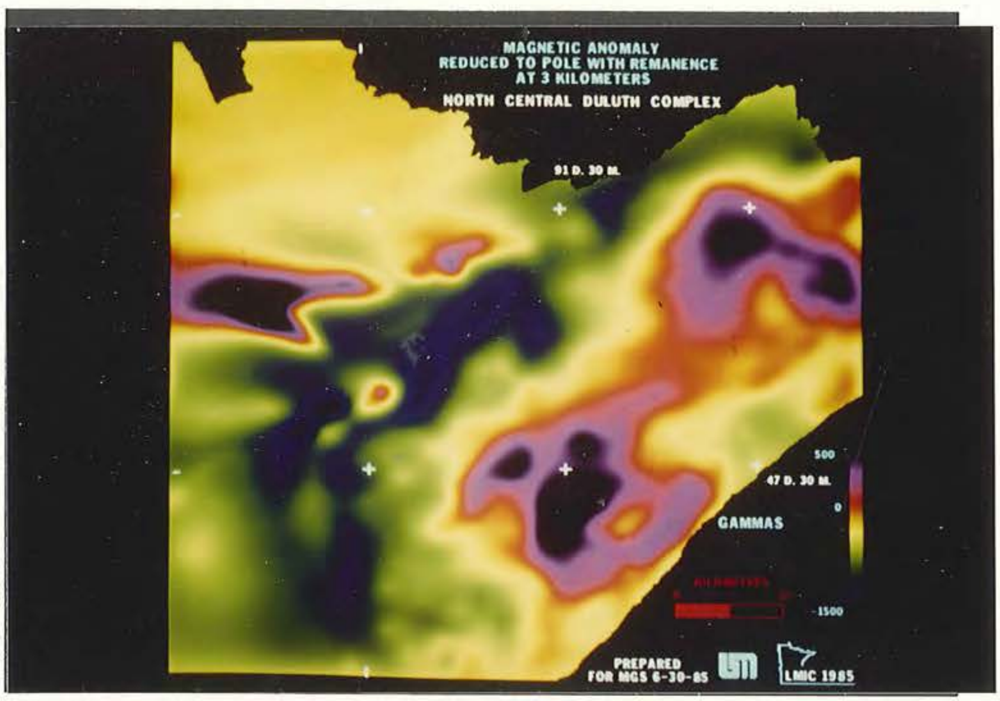

Figure 15. Magnetic anomaly reduced to pole assuming Keweenawan remanence upward continued to 3 km.

that the magnetic sources along the northwestern margin of this anomalous zone do not contrast in density with the enclosing rocks. Furthermore, the broad magnetic maxima along the northwestern margin of this zone show little correlation with near-surface features as delineated by the SVD magnetic data (Figures 11 and 12), suggesting the anomalous magnetic sources here may be buried.

Discussion of Poisson Analysis Remanence Case

Locally there is a correlation between the remanence reduced-to-pole magnetic data and the first vertical derivative of gravity data, and the dJ/dp values resulting from the Poisson analysis are believed to be valid (Figure 16). Along the basal contact, the Poisson analysis yielded several large areas of dJ/dp estimates averaging around 0.02. If a density contrast of 0.1 to 0.25 can be assumed between the wall rock and the complex, the corresponding range of magnetization would be 2000 to 5000 x 10^{-6} for the basal complex. This range compares favorably with the measured NRM intensities of troctolitic rocks, implying that properties observed at the surface may extend to considerable depths along the basal contact zone.

The Cloquet Lake body yields several areas of strong correlation and dJ/dp estimates ranging between 0.01 and 0.05 along its outer contacts. Near the center of the Cloquet Lake body, a suite of dJ/dp values averaging near 0.025 corresponds to secondary gravity and magnetic minima which reflect a large mass of granophyric rocks within the largely mafic terrane. Granophyric rocks in this area typically have low densities and are commonly nonmagnetic. Thus, if a range of 0.20 to 0.35 gm/cc is assumed for the contact between the granophyric rocks and the underlying mafic intrusive rocks, a dJ/dp value of 0.025 would imply magnetization values between 5000 and 8750 x 10^{-6} c.g.s. for the underlying rocks. Southeast of the Cloquet Lake body, the Beaver Bay Complex yields dJ/dp values averaging near 0.02. Along both the southwestern margin of the Wilson Lake body and the west-central margin of the Brule Lake body, dJ/dp values around 0.01 probably represent a contact of intrusive rocks against volcanic rocks. This ratio is somewhat lower than observed over most of the Cloquet Lake body and could reflect either a decrease in the magnetization contrast or an increase in density contrast.

Discussion of Poisson Analysis: Induced Case

On the induced-case Poisson analysis (Figure 17) several features over the Archean rocks appear to have geologic significance. East and southeast of 48° N., 92° W. the contact of the Vermilion Granitic Complex with meta-volcanic rocks of the Newton Lake Formation yields a suite of dJ/dp estimates around 0.010, whereas those areas surrounding the belt of Ely Greenstone yield dJ/dp values averaging between 0.02 to 0.30. Assuming a density contrast range of 0.15 to 0.25 for the Ely Greenstone and the enclosing granitic rocks, a dJ/dp value of 0.25 would imply average magnetization values between 3750 and 6250 x 10^{-6} c.g.s. for the greenstone. Greenstone belts are typically nonmagnetic, but the high incidence of iron-formation throughout the greenstone section drives up the average magnetization. At this level of continuation, the greenstone belt approximates a uniformly magnetized mass.

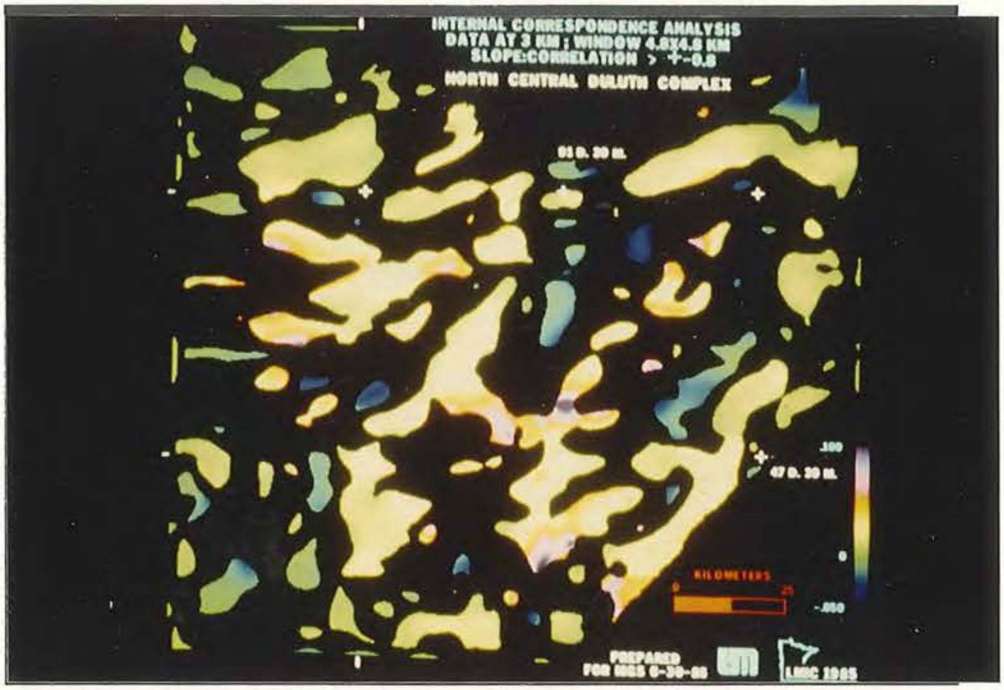

Figure 16. Poisson analysis dJ/dp estimates based on reduction to pole assuming direction of Keweenawan remanence (dec/inc = 290°/40° down). Areas where dJ/dp estimates are associated with low correlation coefficient values (smaller than ± 0.80) are black.

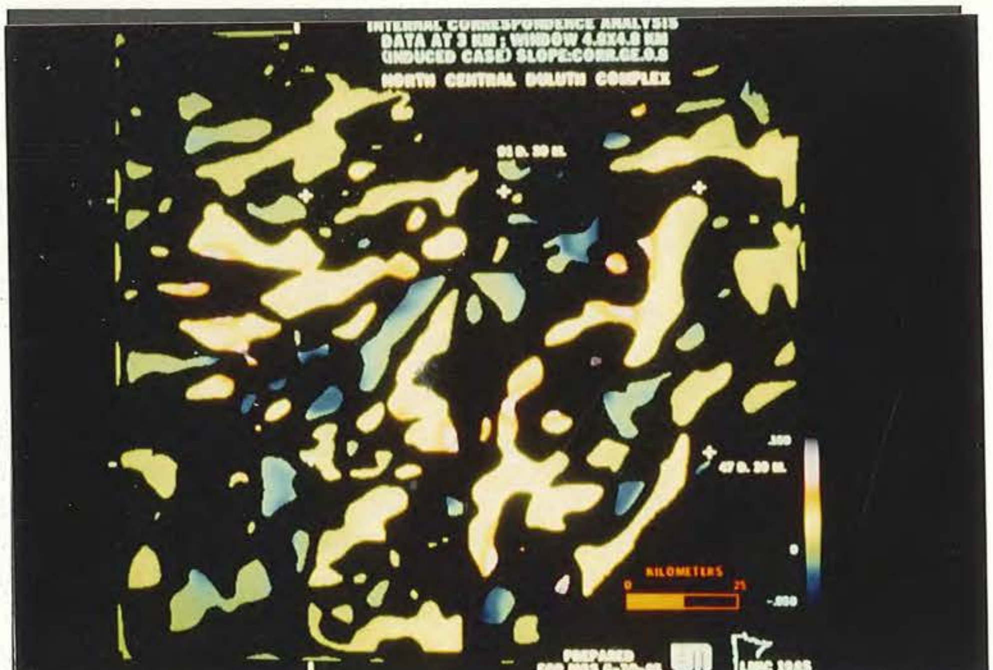

Figure 17. Poisson analysis, dJ/dp estimates based on reduction to pole assuming direction of induced magnetization (dec/inc = 5°/75° down). Areas where dJ/dp estimates are associated with low correlation coefficient values (smaller than ± 0.80) are black.

Werner Deconvolution

The usefulness of a method called Werner deconvolution was briefly investigated in this study. The method, originally developed by Werner (1953) and since improved by others, optimally fits observed anomalies with sheet and/or interface sources. The method uses linear inversion of long-profile magnetic anomaly values to solve for four unknowns--horizontal position, depth, dip, and magnetic susceptibility contrast--that describe the idealized source. Unlike most modeling or inversion routines that are restricted to highly simplified solutions, the Werner deconvolution method allows rapid interpretation of complex, multisource data, like that observed over the Duluth Complex.

The method used here is based on an algorithm described by Ku and Sharp (1983) and several modifications have been made. The program was modified to account for remanence oblique to the inducing field, although an average direction and intensity must be assumed for the whole profile. To achieve solutions, the program observed the profile internally through a seven-point window that moved over the entire data set in increments of one data interval. Wherever a solution was achieved, the source parameters were stored. The profile data were then decimated at a 50-meter interval, and the entire process was repeated. This cycle of decimation and seven-point window analysis were repeated until a final window analysis, using a 500-meter data interval, was completed. Solutions that were repeated for more than one window width were averaged, providing they all agreed to within 0.2 km in horizontal position, 0.2 km in depth, and 20° in dip.

Prior to discussing the results, several cautions are important. The method as currently developed assumes sources that are strike infinite and perpendicular to the profile. Obviously this will not be upheld everywhere. Futhermore, the ambiguity inherent in potential field interpretation is compounded by anomaly interference, which usually precludes identification of the complete anomaly. Therefore, a particular anomaly may yield several significantly different solutions. Finally, because the method is simply a mathematical inversion, it may sometimes propose sources that are geologically unreasonable. Thus, spurious solutions are commonly included among the results, and the user must use caution. In the analysis to follow, we will try to alleviate these problems by (1) selecting a profile where strike-related effects are minimized and (2) directing most attention to general patterns in the solutions instead of emphasizing individual solutions. Further improvements on the Werner deconvolution method are currently being investigated in a separate research project being conducted by Robert Ferderer at the University of Minnesota.

An east-west tie-line from the original survey was subjected to Werner analysis. This profile has its western end at 48°27'22" N., 92°21'23" W., and it extends eastward across the complex approximately 5 km south of 47°30' N. The profile was originally sampled at a 50-meter interval at a mean terrain clearance of 150 meters, and only the diurnal and geomagnetic field effects were removed. The profile was chosen because it is approximately normal to many elongate anomalies in the complex, thereby alleviating strike-related limitations. An average Keweenawan remanence was assumed with a declination of 290°, inclination of 40° down, and Q = 3, which appeared reasonable from the rock-property data (Tables I through V).

The Werner deconvolution results presented a somewhat bewildering array of sources (Figure 18). Nonetheless, a few generalizations can be made.

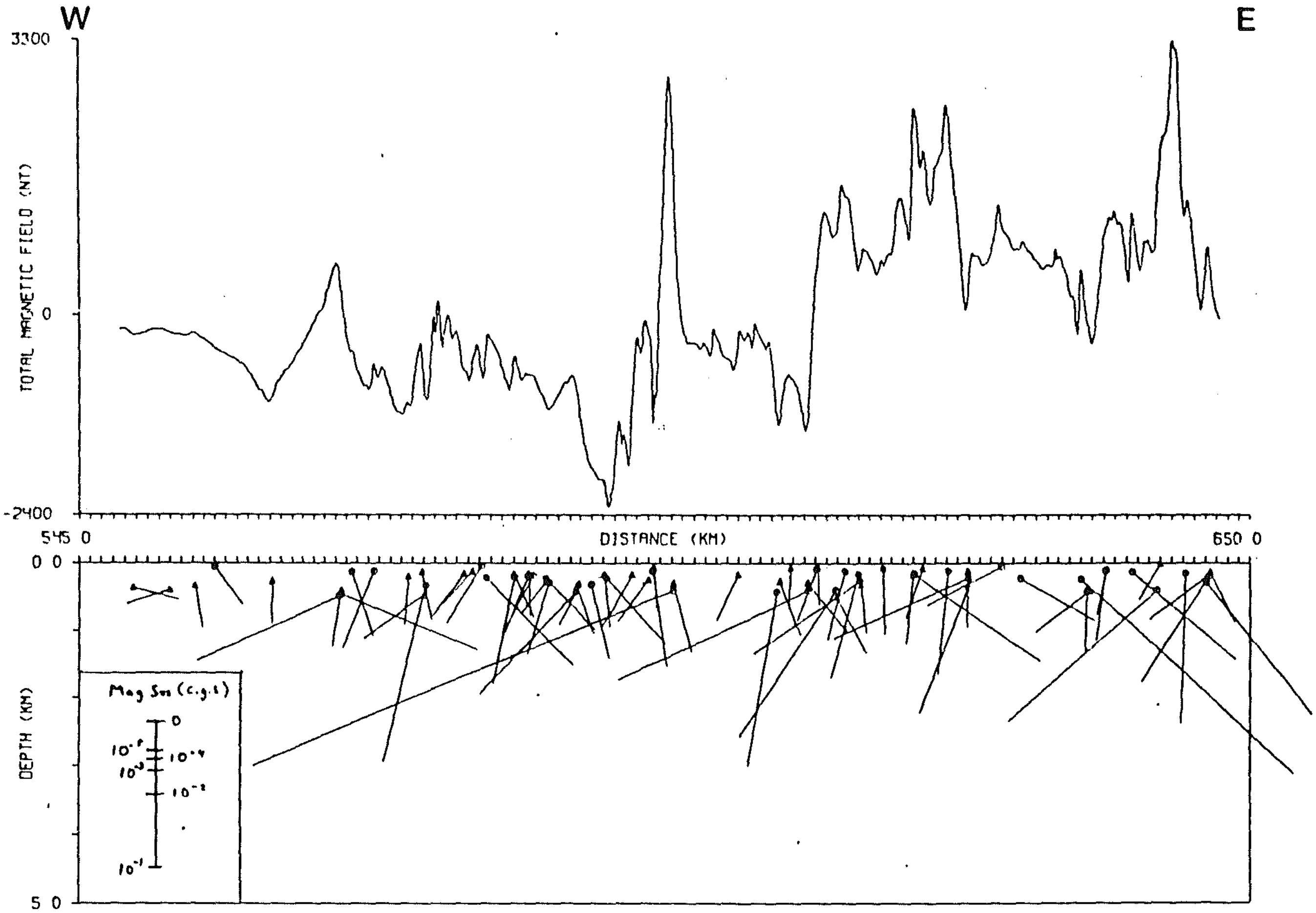

Figure 18. Werner deconvolution analysis along tie-line 1054-0 of the northeastern Minnesota survey. Distances along horizontal line are UTM values in the region. Sources shown as circles represent dike solutions, whereas those shown as triangles represent interface solutions. All sources are interpreted to be vertically infinite; the length of line along dip represents magnetic susceptibility contrast; no discrimination is made for negative versus positive susceptibility contrasts.

The widely varying dips observed in the results imply an extremely complicated internal structure, and there is little evidence for anything that is concordant with the gently dipping volcanic roof. There also seems to be a bias in favor of steeply dipping (>45°) sources. The ambiguity inherent in the method is demonstrated near 568 km where three widely different sources were derived for a prominent maximum along the basal contact zone. Bath (1962) interpreted this high to be the subsurface truncation of the Biwabik Iron Formation by the Duluth Complex. Although the three solutions differ greatly in dip, they do closely agree on a depth of about 0.5 km. No solution appears to have been derived for the moderately dipping basal contact zone itself.

Synthesis and Conclusions

In conclusion, the gravity and magnetic studies described above have extended our knowledge of the Duluth Complex and have yielded several hypotheses that warrant further testing. The wide scope of the problems covered here includes rock-property investigations, the detailed structures of the basal contact, and the regional structure of the complex.

Rock-property investigations over the central Duluth Complex reveal rocks that are dense relative to the pre-Keweenawan crust and have magnetizations that are dominated by Keweenawan normal remanence (dec/inc = 290°/40°). Prior to this study, very little was actually known about the rock properties of the region. Troctolitic suite rocks near the base of the complex have an average density around 2.91 gm/cc, an average magnetic susceptibility around 1200 x 10^{-6} c.g.s., and Q values commonly exceeding 3. Anorthositic suite rocks have a density averaging around 2.81 gm/cc and magnetic susceptibility values averaging around 1800 x 10^{-6}. Many anorthositic suite rocks showed unstable NRM directions with high intensities, suggesting lightning strikes, although alternating-field demagnetization commonly isolated Keweenawan normal directions. The ring troctolite and core gabbro of the Bald Eagle intrusion have magnetic susceptibility values and NRM directions that are generally similar to the anorthositic and troctolitic suite rocks, but differ by having a density averaging around 2.98. In addition, the core gabbro has extremely large Q values. No correlation of NRM direction and layering was observed for the Bald Eagle intrusion, and slightly different pole positions may exist for the core gabbro and ring troctolite. Roof-related intrusive and extrusive rocks show a wide range of properties but appear to be dominated by Keweenawan normal remanence. The complex appears to reside in an upper crust with an average density of around 2.76 gm/cc and a moderate to weak induced magnetization directed along the present earth's field.

High-resolution aeromagnetic anomaly data along the basal contact zone locally correlate with detailed structure. The magnetic anomaly expression of the Biwabik Iron Formation is considerably enhanced along the basal contact by a strong Keweenawan normal overprint. This enhanced anomaly expression continues southeastward to about 1.5 km inside the exposed basal contact where it is abruptly truncated along a strong northeast-striking gradient. This gradient is believed to represent the subsurface truncation of the iron-formation by the complex. In contrast, the magnetic anomaly expression along the northwestern margin of the iron-formation is extremely irregular. It is believed that hypabyssal intrusions into the iron-formation locally enhance the Keweenawan magnetic overprint considerably above the regional effect of the complex. Thus, many of the tonguelike maxima that project northwestward over the Virginia Formation and the Biwabik Iron Formation may reflect the effect of buried sill-like intrusions into the iron-formation. Some of the faulting in the area may have had a causal relationship to the sills because northwest-striking faults commonly flank the high-intensity maxima in the region.

A few north- to northwest-striking faults mapped in the mine pits correlate with anomaly features over the iron-formations. A few of these faults align with anomaly gradients inside and outside the complex. A strong negative anomaly appears to be associated with the Siphon fault, an offsetting structure which truncates the westward-polarized iron-formation.

The magnetic anomaly expression of folds in the MINNAMAX area was investigated in detail. The MINNAMAX structure is reflected by a positive anomaly spur that extends east-southeast from the margin of the iron-formation anomaly. Model studies, constrained by drill-hole data, indicate that most of the anomaly expression can be accounted for by simple folding of the iron-formation and by down-dip truncation of the iron-formation by rocks of the Duluth Complex. The model studies imply that the iron-formation varies in thickness over the structure. Although the iron-formation is truncated down dip about 2.5 km southeast of the exposed basal contact, the model studies imply that more iron-formation could exist about 3 km farther down dip along the basal contact.

The regional gravity and magnetic data, enhanced by second vertical derivative (SVD) filtering, imply that the central Duluth Complex is a patchwork of various rock bodies, and that it departs significantly from the simplified lower troctolite/upper anorthositic cap model. Among the rock bodies outlined by the SVD data are the "Railroad troctolite," the Erie Mining railroad ferrogabbro and the southern extension of the Bald Eagle intrusion. The gravity and magnetic data also indicate that a large belt of dense, highly magnetic intrusions exists near the volcanic roof of the complex. Although exposures are very poor in this region, several intrusive bodies lie along or appear to be connected with the belt, including the Beaver Bay Complex, the Sonju Lake intrusion, and several unnamed gabbroic units. The presence of this large intrusive belt implies that undisturbed volcanic rocks actually comprise only a minor part of the Keweenawan sequence here, and that they are largely restricted to the North Shore of Lake Superior. Metamorphosed volcanic rocks may, however, be locally present within this intrusive belt, as well as along a narrow zone to the northwest.

Analysis of gravity and magnetic anomaly lineaments over the complex and surrounding terranes implies a northeast and northwest structural fabric which may largely be of pre-Keweenawan origin. Northeast- and northwest-striking lineaments are common outside of the complex and some of them correspond to faults that are believed to have been active in pre-Keweenawan time. The regional tensional stresses associated with Keweenawan rifting, however, certainly could have reactivated many of these structures. Some of the northwest-striking magnetic anomaly lineaments outside of the complex are believed to reflect Keweenawan dikes. A diffuse belt of gravity and magnetic anomaly lineaments crosses the entire complex and extends into the Archean rocks north of the Mesabi range. Several of these features correspond to detailed structures mapped in the mine pits, and the belt as a whole crosses where the basal contact of the complex changes from a northward strike to a northeastward strike. Thus, northwest-striking structures, regardless of their origin, appear to have had an important bearing on the emplacement of the complex, although the nature of this structural control must await further geologic investigations.

In contrast to the surrounding terranes, there appear to be relatively few northeast-striking anomaly lineaments inside much of the complex. If northeast-striking normal faults were involved in the emplacement of the complex, as envisioned by Weiblen and Morey (1980), there is little evidence in the anomaly data that these faults significantly disrupted the intrusive rocks, once they were emplaced and solidified. Such faulting, however, could still have occurred in the footwall rocks deep beneath the complex during the initial emplacement of the magmas.

Poisson analysis of gravity and magnetic anomaly data over the central Duluth Complex yielded magnetization/density ratios consistent with rock-property data. Poisson analysis of the basal contact zone yielded magnetization/density values around 0.02. Some magnetization/density estimates over the intrusive rocks along the roof of the complex were large values averaging around 0.02 to 0.035. Considering reasonable density contrasts, this ratio would imply that the intrusive rocks here would contrast 5000 to 8750 x 10^{-6} c.g.s. with the roof rocks.

Investigations of the subsurface structure of the Duluth Complex, using gravity and magnetic anomaly data, indicate a complicated body. Modeling along a profile across the northwestern part of the complex indicates a basal contact dipping 15° to the southeast to a maximum depth of 10 km. This dip and overall thickness are considerably less than those derived from model studies to the south, implying that the northwestern part of the complex may be less developed than observed to the south. The northwestern part of the complex lies along a northward projection of the pre-Keweenawan basement high that corresponds to thinning of volcanic rocks in western Lake Superior (White, 1966). Relatively subdued SVD gravity and magnetic anomalies over the northwestern complex also imply that this region may have a fairly simple geology, perhaps consisting chiefly of anorthositic suite rocks. Although the basal contact may dip gently, model studies and Werner deconvolution analysis imply that contacts within the complex commonly dip steeply (>45°).

Although this study did not attempt to locate specific mineral deposits, several areas were delineated that may warrant further investigation. The "Railroad troctolite" appears to be a well-defined body that is heavily enriched in hornfelsic inclusions. If some of these inclusions are of Animikie origin, they may have provided interaction similar to the wall rock-magma process that helped produce the sulfides in the basal contact zone. The MINNAMAX structure corresponds to a positive magnetic anomaly that projects spurlike into the complex from the iron-formation-related anomalies. Similar but smaller spurlike projections in the southwestern part of T. 59 N., R. 13 W. have recently been investigated by a private company (MGS well records, open file). Finally, the highly dense and magnetic intrusive rocks along the roof warrant further work, because the density and magnetization may reflect ultramafic or oxide-rich zones. Investigation of these intrusive rocks, however, may be hampered by Pleistocene cover, as well as a cover of volcanic and/or granophyric rocks.

ACKNOWLEDGMENTS

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TABLE I

Average density and magnetic susceptibility values for major pre-Keweenawan crustal units outside the Duluth Complex.

Rock Unit	No. Density Meas.	Avg Density (gm/cc)	Range of Density	No. Mag. Sus. Meas.	Avg Mag. Susceptibility ($x10^{-6}$ c.g.s.)	Range Mag. Sus. Meas. ($x10^{-6}$ c.g.s.)
Early Prot. Metased. rock	27	2.78	2.70-3.09	37	55	9-117
Early Prot. iron-fm.	16	3.06	2.67-3.92	30	39,564	29-131,893
Archean granitic rock	22	2.70	2.59-2.86	33	805	30-6332
Archean meta-sed. rock	14	2.74	2.63-2.93	22	68	30-323
Archean iron-fm.	5	2.94	2.67-3.27	10	9916	26-53,426
Archean meta-volcanic rock	7	2.94	2.65-3.14	13	107	55-162

TABLE II

Site-averaged density, magnetic susceptibility, and NRM values for troctolitic rocks of the lower Duluth Complex. Asterisks denote values based on less than three measurements. Data have been deleted where AF cleaning failed to isolate a stable NRM direction.

Site No.	Avg Density (gm/cc)	Avg Mag. Susceptibility ($x10^{-6}$ c.g.s.)	Avg NRM Intensity ($x10^{-6}$ c.g.s.)	Avg Q	Avg NRM Declination	Avg NRM Inclination	AF Peak Field (Oe)
252	3.03	794	1422	2.9	297°	53°	200
253	2.76	206	5081	39.8	295°	36°	0
257	2.79	602	3939	10.6	295°	50°	0
258	2.78	470	3715	12.8	290°	31°	0
259	2.96	2185	5593	4.1	302°	45°	0
260	2.77	477	285	0.9	305°	55°	0
BE1	2.96*	958	2333*	3.9*	297°*	58°*	0
DC1	2.86*	552*	220*	0.7*	198°*	46°*	300
DC2	2.97*	2093*	314*	0.2*	266°*	21°*	300
DC3	2.86	436	-	-	-	-	-
DC4	2.94	712	-	-	-	-	-
DC5	2.98*	378	1318*	5.7*	284°*	42°*	300
DC6	2.81	212	320	2.5	253°	63°	300
DC7	3.03	2497	-	-	-	-	-
DC8	3.11	4052	-	-	-	-	-
DC9	2.93*	858*	-	-	-	-	-
DC10	2.96	1279	-	-	-	-	-
DC11	2.90	3860	209*	0.1*	325°*	33°*	300

TABLE III

Site-averaged density, magnetic susceptibility, and NRM values for anorthositic rocks of the Duluth Complex. Asterisks denote values based on less than three measurements. Data have been deleted where AF cleaning failed to isolate a stable NRM direction.

Site No.	Avg Density (gm/cc)	Avg Mag. Susceptibility ($x10^{-6}$ c.g.s.)	Avg NRM Intensity ($x10^{-6}$ c.g.s.)	Avg Q	Avg NRM Declination	Avg NRM Inclination (-,up)	AF Peak Field (Oe)
254	2.78	418	2038*	7.9*	285°*	27°*	450
256	2.93	5,457	347	0.1	131°	-46°	450
261	2.79	369	107	0.5	290°	20°	750
265	2.82	657	227*	0.6*	294°*	53°*	200
BE13	2.78	575	232	0.7	314°	47°	350
BE49	2.81*	3,200	-	-	-	-	-
DC12	3.14	40,270	-	-	-	-	-

TABLE IV

Site-averaged density, magnetic susceptibility, and NRM values for rocks of the Bald Eagle intrusion. Asterisks denote values based on less than three measurements. Data have been deleted where AF cleaning failed to isolate a stable NRM direction.

Site No.	Avg Density (gm/cc)	Avg Mag. Susceptibility ($x10^{-6}$ c.g.s.)	Avg NRM Intensity ($x10^{-6}$ c.g.s.)	Avg Q	Avg NRM Declination	Avg NRM Inclination	AF Peak Field (Oe)	Igneous Layering Strike/Dip
RING TROCTOLITE								
BE3	2.73*	348	401*	1.9*	295°*	54°*	400	NNE/50°SE
BE8	3.15	466	830	2.9	293°	56°	0	N-NNW/90°
BE9	3.08	582	1037	2.9	309°	51°	0	N-NNW/90°
BE10	3.03*	377	544*	2.3*	314°*	47°*	300	N-NNW/90°
BE11	2.89	1280	434	0.5	282°	50°	500	N-NNW/90°
BE12	3.03	434	279	1.0	307°	69°	0	N-NNW/90°
BE15	2.89	654	878	2.2	301°	33°	300	N-NNW/90°
209	2.73	1872	-	-	-	-	-	NNE/50°SE
210	3.11	594	473	1.3	309°	63°	0	N-NNW/90°
211	3.03	403	251	1.0	309°	69°	300	N-NNW/90°
213	3.03	743	3366	7.3	307°	57°	0	NNE/75°SW
CORE GABBRO								
BE4	3.04*	191	3657*	30.9*	288°*	34°*	0	NNE/30°SE
BE5	2.97	160	4316	43.5	291°	29°	0	NNE/30°SE
BE6	3.07*	202	5238*	16.1*	290°*	27°*	500	NNE/65°SW
BE7	2.97	197	4112	33.7	259°	31°	300	NNW/90°
BE16	2.81*	604	67*	0.2*	310°	40°*	300	-
212	3.03	426	3366	12.7	307°	19°	0	N-NNE/30°SE

TABLE V

Site-averaged density, magnetic susceptibility, and NRM values for rocks associated with the roof of the Duluth Complex. Asterisks denote values based on less than three measurements. Data have been deleted where AF cleaning failed to isolate a stable NRM direction.

Site No.	Rock Type	Avg Density (gm/cc)	Avg Mag. Susceptibility ($x10^{-6}$ c.g.s.)	Avg NRM Intensity ($x10^{-6}$ c.g.s.)	Avg Q	Avg NRM Declination	Avg NRM Inclination	AF Peak Field (Oe)
263	Ferro-gabbro	3.18	4934	5942	1.9	304°	32°	0
264	Troct.	2.80	289	1992	11.2	304°	62°	0
BF23	Gabbro	2.93	2800	16900	9.7	302°	15°	0
BF27	Gabbro	2.88	1100	6800	9.9	249°	64°	0
BF28	Grano-phyre	2.60	0	-	-	-	-	-
BF40	Gabbro	2.98	3100	-	-	-	-	-
BF31	Grano-phyre	2.60	2600	-	-	-	-	-
BF56	Grano-phyre	2.67	2000	-	-	-	-	-
BF54	Mag. basalt	2.95	9000	-	-	-	-	-
BF20	Basalt	2.79	300	500	2.6	281°	43°	0
BF21	Basalt	2.81	6000	8900	2.4	289°	28°	0