Aeromagnetic Data Interpretation for the McDougal Lakes Area, Duluth Complex Lake County, Minnesota

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For The Minnesota Dept. of Natural Resources

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Objective

In this study, aeromagnetic and to a lesser degree, gravity data are analyzed for a four-township sized area in the block T59-61N, R9-11W, Lake County, Minnesota (Fig. 1). Techniques utilized include: Werner deconvolution-based inverse modeling, Talwani-based forward modeling and frequency-domain filtering. The objective of this study is to define geologic structures and lithologic units within the Duluth Complex, based on information provided by these techniques.

Data

Digital aeromagnetic and gravity data were taken from magnetic tapes owned by the Minnesota Geological Survey.

Aeromagnetic Data

The high-resolution aeromagnetic survey used in this study was flown in 1979-80, and consists of flight lines oriented south-north, spaced 400 m apart, and sampled at a 50 m interval. Tie lines are oriented west-east, spaced 2000 m apart and sampled every 50 m. Both flight and tie lines were flown at a mean terrain clearance of 150 m.

Aeromagnetic anomalies in the study area have amplitudes ranging from < -2000 to > 1000 gammas. The anomaly expression is complicated by strong remanent magnetization, having an average declination and inclination of (290^0, 40^0) (Halls and Pesonen, 1982). Induced magnetization is assumed to be aligned along the main geomagnetic field which has an approximate declination and inclination of (3^0, 75^0). The Koenigsberger (Q) ratio, or ratio of remanent to induced magnetization generally ranges between 1 and 10 throughout the study area (Holst and others, 1986).

The strong remanent magnetization described above results in magnetic anomalies that are significantly asymmetrical. For a west-east (south-north) profile, and a vertical prism

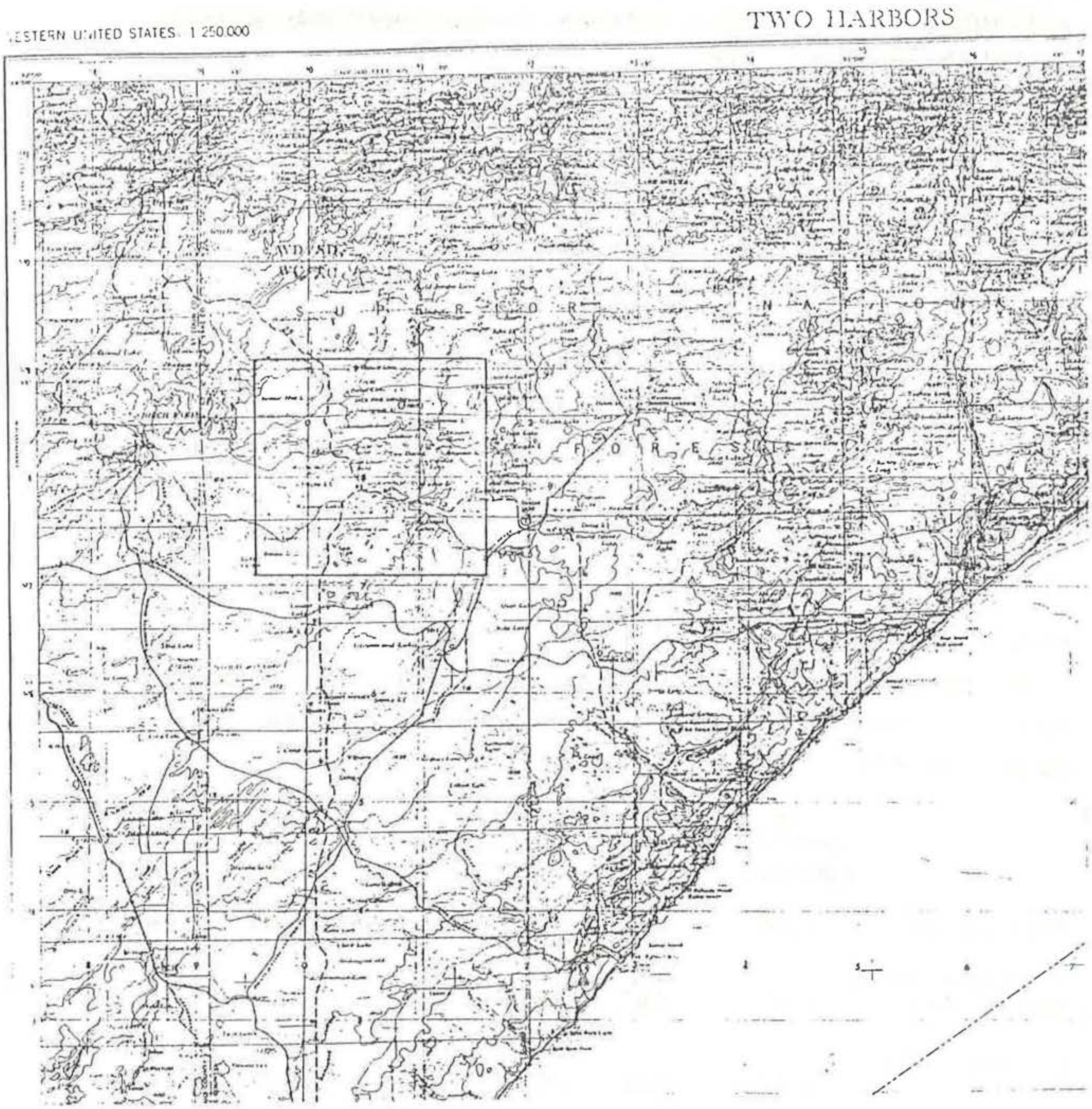


Figure 1. Location map.

anomaly source, an anomaly minimum occurs near the western (northern) contact and a maximum occurs near the eastern (southern) contact (Fig. 2).

Gravity Data

Gravity coverage over the study area is poor, as measurements have been taken at less than one hundred stations. Bouguer gravity anomaly data indicate a strong near-linear gradient, with anomaly values increasing from northwest to southeast. This regional anomaly is interpreted to be related to eastward thickening of the Duluth Complex (Ferderer, 1982). Superimposed on the regional anomaly are shorter-wavelength anomalies that are more indicative of the near-surface geology in the study area. The strongest of these anomalies has an amplitude of about 20 milligals.

Rock Property Data

Rock property data pertinent to this study are summarized in Table 1. NRM is the intensity of natural remanent magnetization.

	Avg. Density (gm/cc)	Avg. Susc. (cgs)	Avg. NRM (cgs)	Avg. Q (cgs)	Avg. NRM decl.	Avg. NRM incl.
Ferrogabbro	3.18*	.0050*	.0058*	1.9*	304*	32*
B. Eagle Ring Troctolite	2.97	.0007	.0012	2.8	303	55
B. Eagle Core Gabbro	2.98	.0003	.0038	21.0	291	30
Anorthositic Rocks	2.80	.0010*	.0006*	1.0*	296*	37*
Basal Troctolites	2.91	.0013	.0033	4.2	284	44

Table 1. Rock property information for Duluth Complex rocks. Taken from Holst and others (1986), and V.W. Chandler (personal communication). Asterisks denote values based on less than 5 measurements.

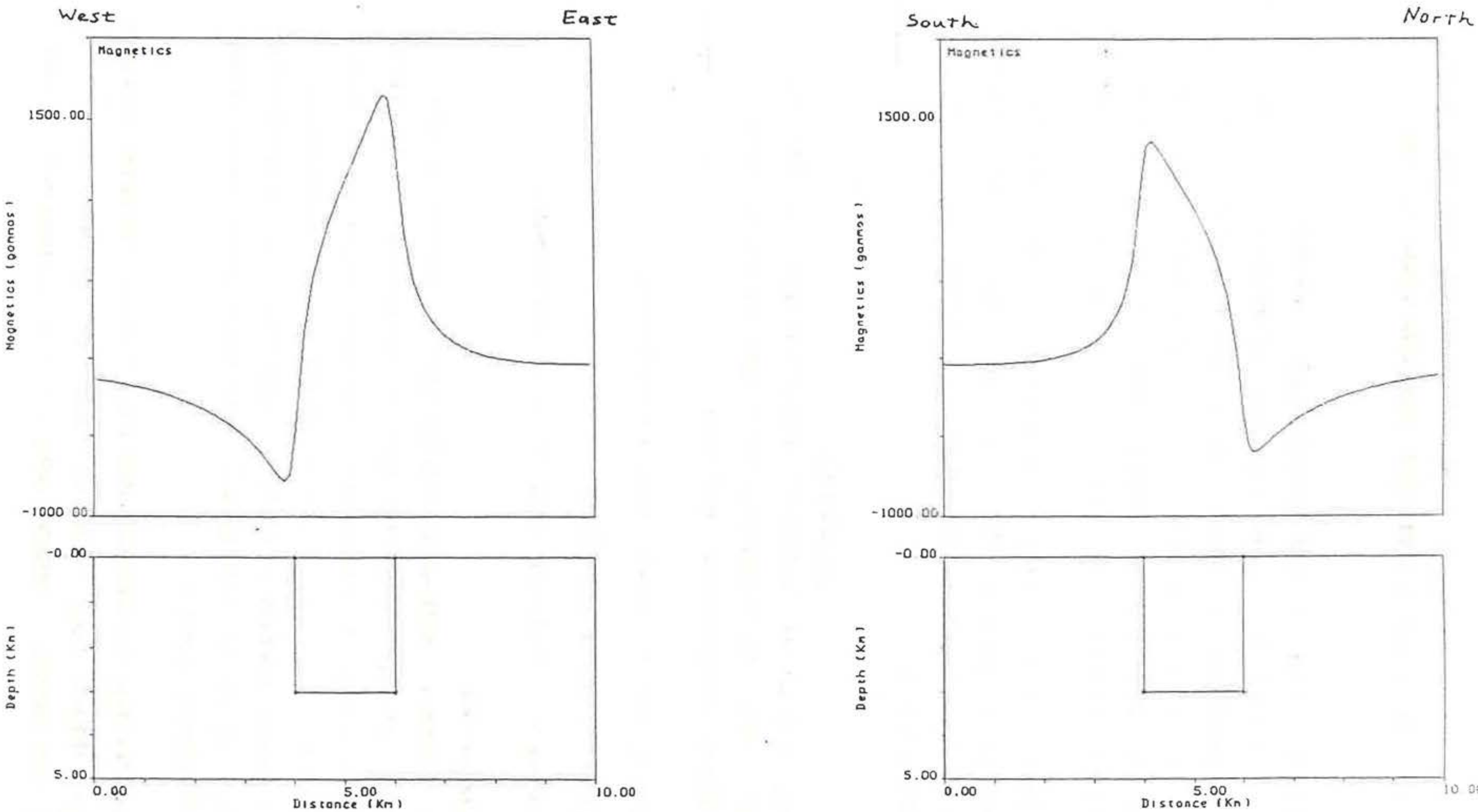


Figure 2. Magnetic anomalies along (a) west-east and (b) south-north profiles, over a vertical prism that has a strong remanent magnetization (inc.,dec. = $40^0,290^0$).

The majority of the Bald Eagle ring troctolite samples used for Table 1 were obtained along the eastern side of the intrusion.

Weakly magnetized rocks in the study area include anorthositic, troctolitic, gabbroic and granophyric rocks. The magnetic properties of these rocks are not generally distinctive. If outcrop or drill hole information exists, rock types may be assigned to weakly magnetized zones that have been defined through modeling, filtering and imaging.

Rock magnetization measurements indicate that many of the stronger magnetic anomalies observed over the Duluth Complex are produced by troctolitic and gabbroic rocks that are enriched in magnetite.

Approach

The processing and interpretation approach applied in this study utilizes three techniques, each having particular strengths. These techniques include:

- Werner Deconvolution-based inverse modeling.
- Talwani-based forward modeling.
- Frequency-domain filtering and data enhancement.

Werner Deconvolution

This inverse magnetic modeling technique is based on the assumption that anomaly sources may be approximated by thin sheets and interfaces of arbitrary dip and infinite strike and depth extents (Fig. 3). The assumption of polynomial-like anomaly interference allows a wide variety of geologic features (Fig. 4) to be accurately characterized, even when severe interference occurs.

Information provided by Werner deconvolution includes source location (x_0), depth (z_0), dip (d) and susceptibility contrast (k) estimates. These results are presented in map

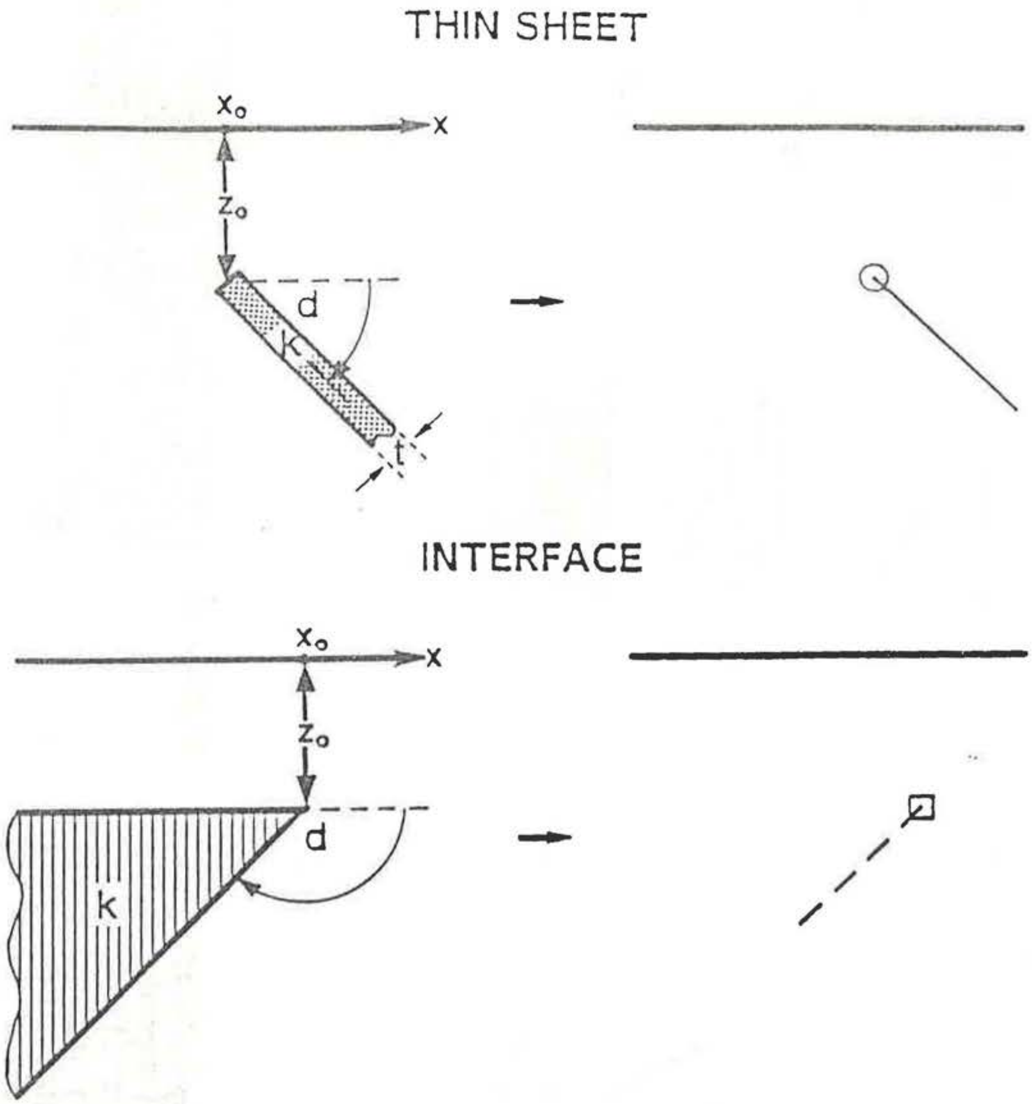
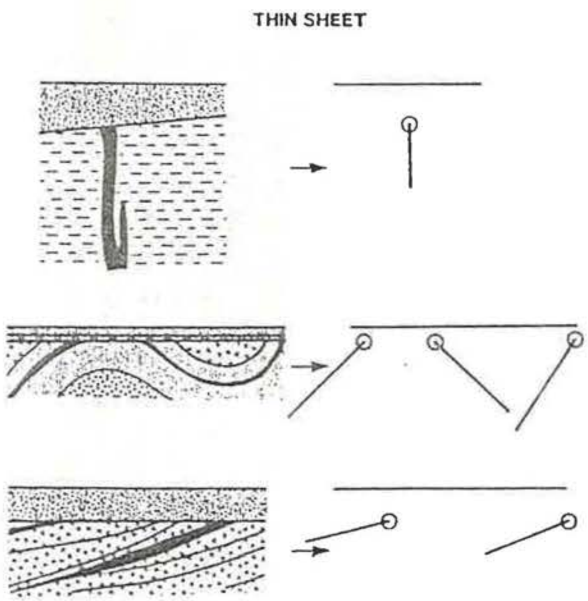
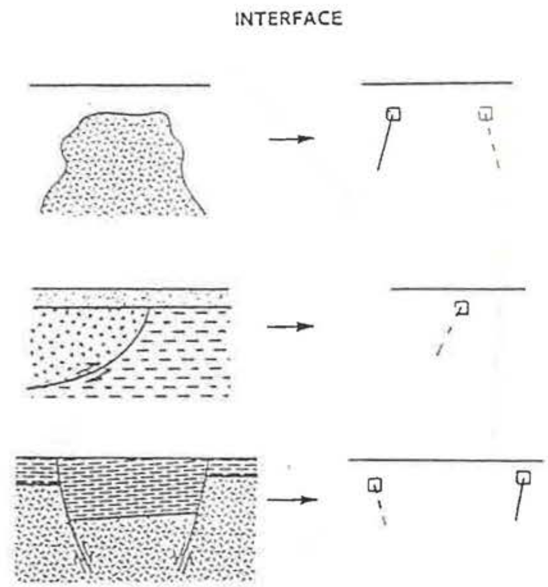


Figure 3. Ideal thin sheet and interface sources. The position, depth and dip of the stick symbols shown on the right-hand side correspond directly to those features of the actual sources. Thin sheets are indicated by circles, and interfaces by squares. Stick length is proportional to the reciprocal logarithm of the magnitude of k and is not related to the depth extent of the sheet. Negative k values are designated by a dashed stick and, for the case of an interface, indicate a susceptibility decrease in the positive x-direction.



a



b

Figure 4a. Geological features that can be approximated by thin sheets: (top) dike, (center) magnetic unit (i.e. iron-formation, etc.) contained in the limbs of a truncated fold, (bottom) magnetic lens (i.e. magnetic lava flow, pyrrhotite body, etc.) surrounded by non-magnetic rock. Corresponding stick symbols are shown on the right hand side.

Figure 4b. Geological features that can be approximated by dipping interfaces: (top) edges of a plutonic body, (center) leading edge of a thrust fault, (bottom) normal faults. Corresponding stick symbols are shown on the right hand side.

form so that they may be overlain on aeromagnetic maps. For more detailed information and references, see Ferderer (1988).

Because geologic strike varies considerably in the study area, the aeromagnetic data were gridded prior to deconvolution. The resulting 100 m grid, was broken into south-north and west-east oriented profiles which were upward continued and deconvolved. When data are gridded, smoothing occurs. As a result, gridding prior to deconvolution may result in slight parameter estimate errors. Upward continuation is used to minimize the effects of noise.

Information was obtained for anomaly sources having a wide variety of strike directions. The effects of geologic strike on depth estimates were accounted for during across-profile correlation of results.

Remanent magnetization was accounted for during deconvolution.

Forward Modeling

Forward modeling was performed along four south-north, and six west-east oriented grid lines. This technique assumes uniformly magnetized, two-dimensional, polygonal-shaped bodies, and is based on the technique of Talwani and Heirtzler (1965), Remanent magnetization was accounted for during modeling.

Forward modeling was also applied to one northwest-southeast oriented Bouguer gravity profile.

Frequency Domain Filtering

Four frequency domain filtering techniques were applied to the above mentioned 100 m grid. These techniques include:

- **Reduction to the pole:** The total magnetization vector, comprised of induced and remanent magnetization components, was reduced.

- **Upward continuation:** Data were calculated at levels of 350 m, 500 m and 1000 m. Werner deconvolution was applied to test profiles for each of these three levels, and the 500 m level was chosen for production processing.

- **Second vertical derivative filter.**

- **Bandpass filters:** Wavelengths less than or equal to 2, 5, 10 and 15 km were passed. The 15 km bandpass filter was found to be quite useful for isolating shorter-wavelength gravity anomalies. This technique was not heavily relied on for magnetic interpretation.

Filtering operations were performed in the following sequences:

1) Red. to pole
2) Red. to pole > upward contin. > 2nd vert. deriv.
3) Red. to pole > upward contin. > bandpass filter
4) Upward contin. > Werner deconvolution

Color and shaded relief maps were used to present the raw and filtered data.

Interpretation

Results obtained using each of the three processing techniques described above were plotted at a scale of 1:62,500.

The derived aeromagnetic interpretation is given on Plate 1.

Where Werner deconvolution solutions are strong, contacts were drawn based on these results. In areas of weak or no solutions, results of forward modeling and second vertical derivative data were used to extrapolate contact positions.

Parameter estimates indicated on Plate 1 are average values, obtained from groups of clustered Werner deconvolution solutions. A small number of these estimates are based on the results of forward modeling.

In most cases, interpreted faults are based on evidence provided by Werner deconvolution. This technique is especially useful for locating strike-slip faults, based on sharp offsets in source position estimates. Normal faults are often indicated by offsets in depth estimates.

Depth estimates represent the depth to a magnetic source. This is not necessarily the depth to bedrock. In some cases, deep estimates may represent moderately or strongly magnetized intrusive rocks which lie below more weakly magnetized rocks. Depth estimates are rounded to the nearest 25 m for depths less than 100 m, and to the nearest 50 m for depths greater than 100 m.

In most cases, depth and dip estimates are assigned to mapped contacts and layering. In a few instances, isolated sets of parameter estimates which represent unmapped structures, are given.

Discussion

The study area is located in the west-central portion of the 1.1 Ga Duluth Complex.

Bedrock throughout most of this area is poorly exposed, and with the exception of the northwest corner and the northern margin, mapping has only been performed at a regional scale (1:250,000) (Green, 1982).

The South Kawishiwi Intrusion (SKI) occurs in the northwest corner of the study area. The SKI is relatively well exposed and has been studied by Foose and Cooper (1981), and Foose and Weiblen (1986). On average, the dominantly troctolitic rocks (**ts**) of the SKI strike N40-50^0 E and dip between 5 and 20^0 SE.

Rocks of the SKI are weakly magnetized and have little aeromagnetic expression. Measurements taken from these rocks were included with those of the basal troctolite group of Table 1.

A number of faults have been mapped in the SKI, only one of which appears to be strongly reflected in the aeromagnetic data. Four additional northwest trending faults that intersect the SKI are mapped based on the results of this study.

The Bald Eagle Intrusion (BEI) (Weiblen, 1965; Chandler, 1985) is a second, well studied structure occurring in the study area. The southern end of this intrusion intersects the northern margin of the study area. The BEI is a funnel-shaped intrusion, consisting of a core gabbro surrounded by troctolitic rocks.

Anomaly data suggest that the magnetizations and densities of troctolitic rocks on the western and eastern sides of the intrusion differ significantly. Troctolitic rocks on the western side (**tb1**) are moderately magnetized and have a relatively low density (two samples of this rock have a density 2.73 gm/cc, Holst and others, 1986). Those on the eastern side (**tb2**) are weakly magnetized and quite dense (several samples have an average density of 3.03 gm/cc). The magnetization of the core gabbro (**gb**) is intermediate to those of the western and eastern troctolites, and it is also quite dense.

A magnetic high occurs near the mapped contact (Green and others, 1966) between the core gabbro and the eastern troctolitic rocks. Model studies suggest that this high is related to two factors, a zone of more magnetic gabbro or troctolite (**otg1**), in contact with, or located near the weakly magnetized eastern troctolitic rocks.

Immediately west of the BEI, rocks are weakly to moderately magnetized. Both troctolitic and anorthositic rocks have been mapped in this area by Green and others (1966).

Due to lack of exposure, the geology of the remainder of the study area is much more poorly understood.

A unit denoted **ts1**, interpreted along the southeast margin of the SKI and striking approximately N45^{0}E, is slightly more magnetic than surrounding **ts** and **t** units. This unit may be a reaction zone, produced when younger rocks were intruded to the southeast of the SKI. Rocks of the **t** unit, mapped just south of the SKI, may actually belong to the SKI, in which case the **ts1** unit would likely represent an internal structure of the SKI.

Three large, oblong to circular shaped anomalies occur in the western half of the study area. The units **otg1-3** have been assigned to the magnetic bodies that produce these anomalies, referred to as the northwestern, southwestern and eastern bodies. At least two of these bodies appear to be magnetically zoned, which may reflect further petrologic zoning. The three bodies are separated by rocks of the **t** unit.

The weakly magnetized zone to which the **t** unit has been assigned is widespread throughout the study area and more poorly defined to the southeast. A small number of outcrops indicate that rocks in this zone are troctolitic. Possible relationships between the **t** unit and rocks that produce the three large anomalies include the following:

1) A single, moderately to very strongly magnetized intrusion was forcibly injected by rocks of the t unit, possibly along faults, and its parts were spread apart.

2) Three separate intrusions of moderately to very strongly magnetized rock were emplaced into the weakly magnetized t unit.

3) The three anomalies are produced by large inclusions of the Lower Proterozoic Biwabik Iron Formation, in the **t** unit. This possibility seems least likely based on geometries and magnetizations derived through modeling.

The western and northern contacts of the northwestern body are indicated to dip moderately to steeply to the northwest. This is evidence that this body is discordant with rocks of the SKI.

Modeling indicates that the southwestern body has a deep root which may represent a feeder. It is further implied that this root rises from the east and from depths in excess of 5 km. Large depth estimates obtained along this anomaly suggest that the mapped **otg1** unit is covered by weakly magnetized rocks along the northern and western sides of the anomaly.

Thin ledges of the **otg1** unit, which extend and thin to the south, are interpreted for both the southwestern and eastern bodies. These ledges may have been shaped when the original body or bodies were intruded by rocks of the **t** unit. Alternatively, they may represent an original funnel shape for the magnetic body or bodies.

Offsets in Werner deconvolution solutions indicate that strike-slip faults occur within each of the three bodies.

Gravity and magnetic expressions just east of the eastern body (near UTMs 606,5285) are especially interesting. The anomaly source in this area is weakly magnetized, yet quite dense. Forward modeling was applied to a residual Bouguer gravity anomaly along a northwest-southeast trending profile in this area. The residual anomaly was obtained by subtracting values calculated assuming a linear gradient, from data of Ikola (1970). The model suggests a source rock density of 3.15 gm/cc, and it is implied that the source rock contains weakly-magnetic oxides or considerable olivine. Although these rocks appear to be denser than the relatively dense troctolitic rocks of the eastern BEI to the north, it is likely that the two rocks are related. Accordingly, both of these dense rocks are assigned to the unit **tb2**. Werner deconvolution results suggest that this unit may form the core of the moderately magnetic eastern body at depth.

Outcrops of anorthositic rocks (**a**) occur in the northwest, northeast and southeast portions of the study area. Consistent with rock property data, these rocks appear to be weakly magnetized and have a low density. Their magnetic expression is generally uninformative.

A unit denoted **a1**, located in the northeast portion of the study area is slightly more magnetic than surrounding rocks. Anorthositic rocks outcrop on both sides of this unit near the northern margin of the study area. It is therefore likely that this unit reflects an original structure within the anorthositic rocks.

East of the study area, a major eastward trending aeromagnetic lineament splits into two lineaments which transect the **tau** unit as they enter the northeast portion of the study area, trending about $N70^0E$. Strong Werner deconvolution interface solutions, were obtained along the northern lineament, and the anomaly source is interpreted to be a fault. Magnetization decreases from south to north across this fault, which appears to have been refaulted by strike-slip faults that trend about N45^{0}W.

Thin sheet solutions are strongest along the southern lineament. This lineament is interpreted to correspond to a second fault which has been intruded by moderately magnetic material so that it generates a sheet-like anomaly. Both of these lineaments are truncated by rocks in the west-central portion of the study area, implying that they are older than these rocks, or that they originated with the intrusion of these rocks.

Several strong, elongate and plug shaped anomalies occur in the western and southern parts of the study area. These anomalies are interpreted to be produced by oxide-rich troctolitic and gabbroic rocks, similar to those thought to be responsible for the "Snake" or "Greenwood Lake Anomaly", in the Greenwood Lake area (Vadis and others, 1981). It is likely that the longest of these bodies is a continuation of the source of the Snake Anomaly.

Dip estimates obtained along the contacts of these intrusions indicate that they are wedge-shaped, their contacts dipping outwards at moderate to steep angles. Magnetizations estimated for these rocks are similar to those for the rocks responsible for the three oblong to circular shaped anomalies in western portion of the study area. This does not necessarily imply a genetic relationship.

Rocks occurring in the southeast portion of the study area are magnetically indistinct. Anorthositic rocks are observed at a small number of outcrops, and it is likely that troctolitic rocks are also present in this area. The unit **tau** is used to represent these rocks. It is also likely that granophyric rocks are more widespread than is indicated on Plate 1.

Forward modeling was performed along a south-north oriented profile, near the southeastern corner of the study area. The modeled bodies were all assigned depths greater than 500 m. This implies that more strongly magnetized rocks in the southeast corner of the area are located at depth, beneath less magnetic rocks.

Faulting does not always produce a magnetization contrast, and it is likely that faulting is significantly more widespread than indicated on Plate 1.

Recommendations

Drilling should be performed to test and refine the interpretations that have been made here. Some of the interpreted structures may have implications for mineral exploration. Possible targets include:

- The dense, weakly magnetized **tb2** unit, along the northeastern side of the large anomaly in the north-central portion of the study area (near UTMs 606,5285). It is likely that this unit does not intersect the bedrock surface everywhere it has been mapped. Further geophysical studies may be helpful in this regard.

- The series of intersecting faults interpreted near (611,5284). Ground-geophysical surveys should be used to more precisely locate these faults before drilling is performed.

- The units **ts1** and **a1**, to determine how they differ from surrounding rocks.

- The unit **t**, at different locations, to more specifically define its character.

- Rocks of the units otg1-3, which produce large, oblong to circular shaped anomalies in the western half of the study area, to verify that petrologic zoning occurs in these rocks.

The analysis performed in this study is almost entirely geophysical in nature. The resulting interpretation should therefore be regarded as a first approximation of the geology in the study area, and be used judiciously by geologists working in the area.

Respectfully submitted,

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