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Combined 3-D Interpretation of Airborne, Surface, and Borehole Vector Magnetics at the McConnell Nickel Deposit

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ABSTRACT

The McConnell nickel deposit is an elliptical amphibolite-biotite quartz diorite pod within the Sudbury Metabreccia that surrounds the main mass of the Sudbury Igneous Complex. The geometry of the deposit is tabular with a strike length of approximately 152 m and depth of 610 m. Various magnetic surveys were conducted in this study area. A regional aeromagnetic survey was conducted by the Ontario Geological Survey. A more detailed ground magnetics survey and borehole magnetic survey are used in the interpretation of the character of the causative body. Five boreholes which intersect the deposit at 40 m, 105 m, 135 m, 210 m, and 250 m provide good lithological control of the deposit with depth. Eight other boreholes used in this study did not have logged lithology, but all 13 holes were logged with gamma ray, density, spectral gamma-gamma, IP, resistivity, SP, magnetic susceptibility, temperature, and three-component magnetic field probes. Only the measurements of magnetic susceptibility and three-component magnetic field measurements and their interpretation will be discussed in this paper. Three-component magnetic vector surveys show different signatures for boreholes that pass through a magnetic source body, and for holes that are adjacent to the source body. Using inverse models of the surface magnetic data, values of magnetic susceptibility and magnetic remanence direction and intensity for the various lithological units are estimated. Modelling of the subsurface data reveals fine structure within the ore body and may be used to estimate the direction and distance to the magnetic bodies.

INTRODUCTION

Aeromagnetic and ground magnetic surveys have long been used in the interpretation of the locality and geometry of ore bodies. However, "surface" methods can often not distinguish fine structure and detail of the source body. Such detail can be resolved by the use of borehole susceptibility and vector magnetic measurements.

What is vector magnetics?

Vector, or 3-component magnetics, examines the three orthogonal elements of the magnetic field, that is, $\mathbf{F} = \mathbf{l}Mx + \mathbf{m}My + \mathbf{n}Mz$, where **l**, **m**, and **n** are unit vectors. The magnetic field has a vector nature, however, most geophysical interpretation methods treat the field as a scalar (i.e., total magnetic field) and/or examine the vertical component or gradient. The choice of total or vertical component has been dictated by the type of instrument used to collect data. With the increased use of three-component fluxgate magnetometers it is now possible to derive the full vector orientation of the magnetic field.

The presence of a magnetically enhanced (or depleted) body within a region of uniform magnetic field produces a magnetic signal in the surrounding medium. The causative body acts as a local source of magnetic fields. The localised enhanced magnetic field may originate from induced magnetic fields created by concentrated regions of high magnetic susceptibility of ferromagnetic minerals such as magnetite and pyrrhotite. Alternatively, the locally anomalous field maybe associated with a divergent remanence signature. Also, possible, are any combination of the two end members of remanence and induced magnetic fields. Particular lithologies have a magnetic signature defined by the composition, grain size, and concentration of magnetic minerals. Lithologies such as basic flows and diabase dikes have higher concentrations of magnetic minerals and so can be easily detected by their increase in magnetic susceptibility (Killeen *et al.*, 1995). In addition, anomalously low

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magnetic susceptibilities within a lithological unit are often indicative of hydrothermal alteration in which minerals such as magnetite are chemically altered to less magnetic phases by oxygen rich percolating fluids (Morris *et al.*, 1984). Magnetic remanence also contributes to the direction and intensity of the total magnetic vector. The remanence field is a magnetic field that is locked within the rock as it passes through its blocking temperature (TRM) or blocking volume (CRM). Conventionally, the remanence field is assumed to be weak. The remanence component of the total magnetic field in this situation is generally ignored. However, physical property measurements indicate the remanence field can often rival or exceed the induced component (Mueller *et al.*, 1996).

Borehole total magnetic intensity

Measurements of the magnetic vector and scalar field with depth can further constrain models of the geometry of a causative body. Using standard surface magnetic surveys, the least constrained parameters of the geophysical model are the depths to the top and bottom surfaces of the source. Figure 1 shows the calculated surface and borehole total magnetic fields due to a prism model that extends from 300 m to 500 m below the surface along with a depth unlimited model where the top surface is at a depth of 300 m. The surface profiles in both cases are similar in shape, but differ in amplitude. This difference could be attributed to susceptibility variations rather than the geometry of the source body. However, the total magnetic field signature in an *offbody* borehole is distinctly different due to the dipole nature of the depth limited body. An offbody borehole is a borehole that does not pass through the source body. Correspondingly, an *onbody* borehole does pass through the source body.

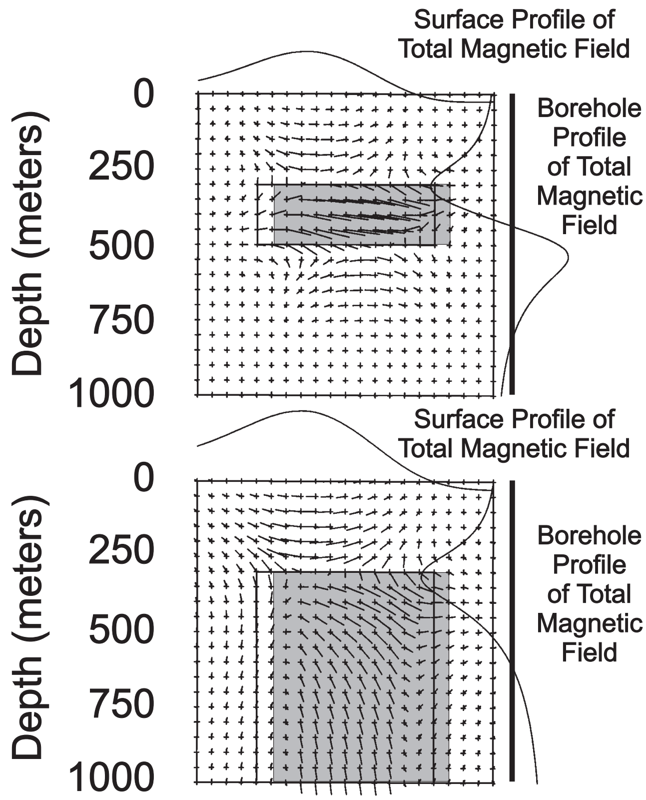


Figure 1: *Surface and borehole total magnetic field responses of a depth limited and depth unlimited causative body. Crosses within and outside of the modelled sources indicate direction and amplitude of the magnetic vector.*

Borehole magnetic vector

The arrows within Figure 1 indicate the direction and intensity of the magnetic vector within and outside of the magnetic body. Note that the direction of the vector changes by 180° from the outside to the inside of the body. Such a rapid and intense change is indicative of a borehole passing through a magnetic body, an onbody borehole. As well, the contact or boundary of the magnetic body is at the point of the magnetic vector reversal. With offbody boreholes, the amplitude and orientation of the magnetic vector has the property of a dipole response. That is, the vectors converge and diverge with respect to the poles of the source body (Figure 2); the poles of the source body are controlled by source body geometry and the effective orientation of the magnetic vector (induced plus remanence). Multiple boreholes can be used to triangulate the location and geometry of the source body. With multiple sources the observed vector is the vectorial sum of all source contributions. Different sources in close proximity may give rise to opposing vector components resulting in a sum vector of lesser magnitude than predicted at distances close to an individually magnetised body, i.e., there is a masking effect (Hattula, 1986). By subtracting the theoretical magnetic fields of some known sources, hidden sources may then be revealed. As well, the effect of remanence may be resolved. An example of this type of survey using three-components was used to determine the geometry of a vanadium-bearing ilmenite-magnetite body at the Otanmaki mine in Rautaruukki Oy, Finland (Hattula, 1986).

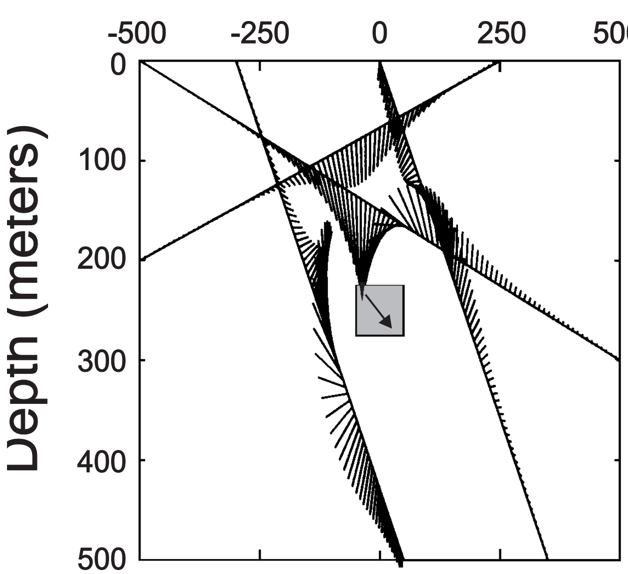


Figure 2: *Magnetic vector response of four offbody boreholes. The arrow within the source body indicates the magnetisation direction. The magnetic vectors converge and diverge at the poles of the source body.*

In a borehole survey, it is necessary to establish a reference frame for relative deviations. Magnetic north provides the local reference point. For navigation purposes, it is assumed that the local magnetic vector is invariant. However, in the vicinity of varying lithological magnetisations, deviations of the local magnetic field vector will be present. This can result in misleading X, Y, and Z positions of the borehole probe. The use of a continuous recording probe containing a three-component fluxgate magnetometer and two orthogonal tiltmeters provides redundant information about the orientation of the probe. In the presence of no off-body sources, probe rotations defined by the two sensor sets will be comparable. An anomalous source will produce a divergence between the two estimates of probe rotation. Differences in orientation can be attributed to a magnetic body and be used to determine the borehole geometry as well as the presence and location of offbody magnetic sources (Morris *et al.*, 1995 and Bosum *et al.*, 1988). The actual geometry of the observed anomalous vector field is a function of the geometry of the source body, the position of the sensor relative to the source body, and the ratio of remanent and induced magnetic fields in the source. For example, if a reversely magnetised remanent component dominated the magnetisation of a source body, it would produce a different vector situation than one in which the magnetisation was purely induced.

THE MCCONNELL DEPOSIT

Regional geology

The McConnell deposit is located in Garson township in Ontario, Canada (Figure 3) southeast of the Sudbury Structure. The outer ring of the Sudbury Structure is defined by a sequence of intrusive rocks (norite and granophyre) referred to as the Sudbury Igneous Complex. Structural, radiometric, and paleomagnetic evidence indicates that the Sudbury Igneous Complex was intruded as a series of magmatic pulses starting with the norite at 1850±3 Ma (Krogh *et al.*, 1984). The sublayer is located at the contact between the norite and the Sudbury Breccia in the form of lenses and flat sheets (Dressler, 1984). Compositionally, the sublayer is a gabbroic to quartz-dioritic rock that includes most of the nickel-copper ore bodies.

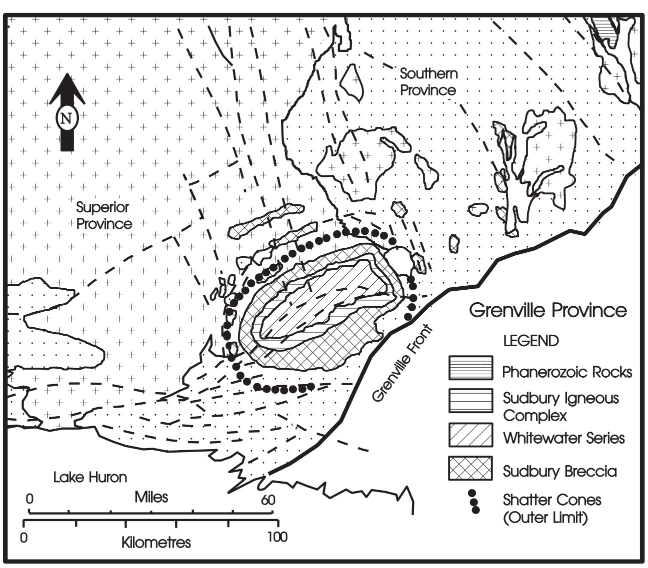


Figure 3: *Regional geology of the Sudbury Structure of Central Ontario, Canada.*

Local geology

The McConnell deposit occurs in a nickel bearing offset dike that extends from the Kirkwood mine and continues southeast as a series of elliptical pods for approximately 1200 m (Figure 4). The particular deposit of interest in this study (Figure 5) is an elliptical amphibolite-biotite quartz diorite pod within the Sudbury Breccia (Grant and Bite, 1984). This breccia locally consists of metasedimentary and metavolcanic fragments. The sulphides (pentlandite, pyrrhotite, and chalcopyrite) occur as 1 to 2 cm blebs within the quartz diorite, but mainly as disseminated sulphides in the surrounding breccia. The McConnell deposit, located upon INCO Ltd. property, is representative of the nickel deposits of the Sudbury area (Killeen *et al.*, 1996).

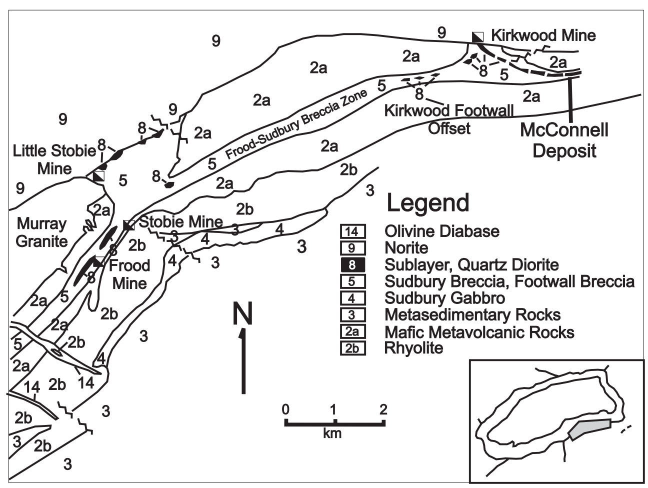


Figure 4: *Local geology of the southeast section of the Sudbury Structure. The McConnell deposit is one of a number of offset dikes (Frood-Stobie, Kirkwood, and McConnell) in the area (Grant and Bite, 1984).*

Borehole investigations

The Geological Survey of Canada (GSC) has measured the borehole geophysical signatures of a variety of ore deposits. This project is jointly funded by the federal and provincial governments in the Northern Ontario Development Agreement (NODA) (Killeen *et al.*, 1996).

Borehole intersection and surface mapping imply a deposit geometry that is tabular with a strike length of approximately 152 m and a depth extent of 610 m (Killeen *et al.*, 1996). A fence of five boreholes intersects the deposit (Figure 6) at 40 m, 105 m, 135 m, 210 m, and 250 m which gives a lithological control of the deposit with depth and indicate that the massive sulphide portion of the deposit is steeply dipping. Eight other boreholes used in this study did not have logged

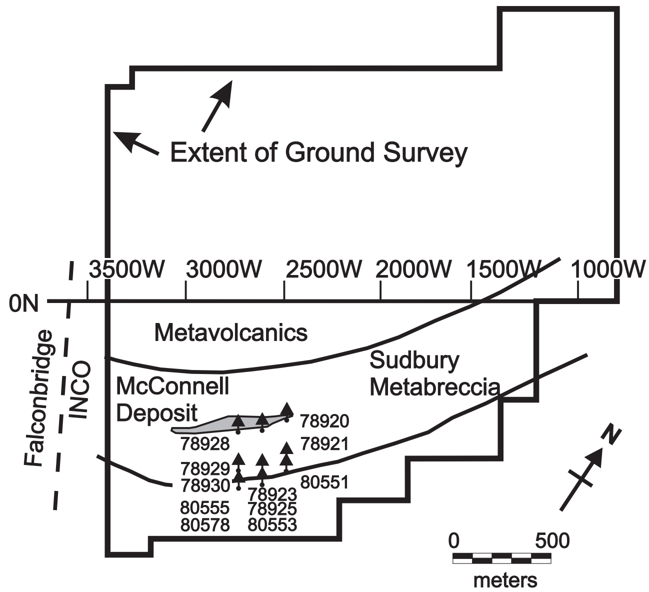
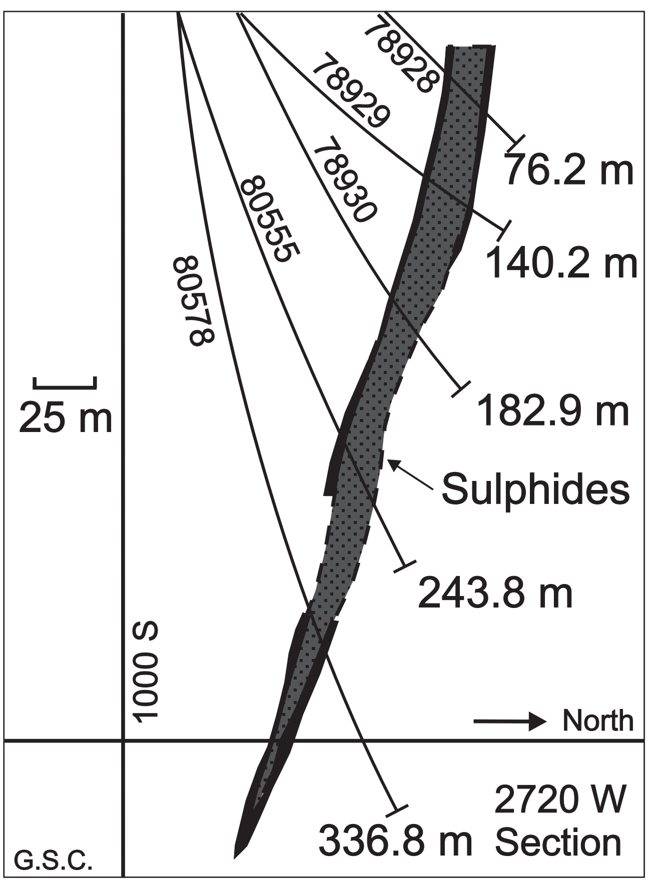


Figure 5: *The McConnell deposit is an elliptical quartz diorite offset dike located within the Sudbury Metabreccia. Thirteen boreholes were logged with a three-component magnetometer of which eleven are shown. The values of 3500W, 3000W, etc. are local INCO mine co-ordinates.*



lithology, but all 13 holes were logged with gamma ray, density, spectral gamma-gamma, IP, resistivity, SP, magnetic susceptibility, temperature, and the three-component magnetic field with an IFG Corp. BMP-4 probe. Only the measurements of magnetic susceptibility and three-component magnetic field measurements and their interpretation for the fence of five boreholes will be discussed in this paper.

Most of the rock units overlying the ore body consist of metasediments and conglomerates. The massive sulphides are bounded, generally at the top, by quartz diorite dikes (the elliptical quartz diorite pods of the McConnell offset dike), but sulphides are found in the surrounding schists, amphibolites, conglomerates, metasediments, Sudbury breccia, and quartz diorite dikes (Pflug *et al.*, 1994).

MEASURED MAGNETIC FIELDS

Airborne magnetics

An aeromagnetic survey conducted by the Ontario Geological Survey (Figure 7) is dominated by highly magnetic features such as the South Range Norite and northwest striking olivine diabase dikes (a.k.a. Sudbury dikes). An examination of the aeromagnetic data over the ground survey (Figure 8) displays no magnetic response of the McConnell deposit. The flight line separation in this area is approximately 800 m. This coupled with the strike length of the deposit being approximately 152 m may account for the fact that its magnetic signal is not apparent. As well, the ground survey area lies on a high magnetic gradient dominated by highly magnetic units of norite and Sudbury dikes to the north so that small magnetic anomalies may not be discernible.

Surface magnetics

Measurements of total magnetic field and the vertical gradient of the total magnetic field were conducted at a 200 m line spacing over the McConnell deposit and surrounding area on INCO Ltd. property. A discrete magnetic high over the McConnell deposit is evident (Figure 9). Magnetic lows on the east and west sides of the deposit are gridding artefacts due to a line spacing effect and the sharpness of this magnetic anomaly. The Sudbury Metabreccia unit tends to be magnetically higher than the surrounding Metavolcanics. The magnetic high east of the McConnell deposit may indicate the presence of another quartz-diorite pod at depth. In the northeast section of the ground survey, evidence of Sudbury dikes is shown.

A profile of total magnetic field over the McConnell deposit can be modelled by a depth limited tabular body. The depth extent of the body was fixed at 610 m while other parameters were allowed to vary. A purely induced model resulted in a near vertical body with a dip of 93° (dipping south) and a very high susceptibility of 0.111 e.m.u. The addition of remanence (inclination = 64° and declination = 189°, similar to other

Figure 6: *The geometry of the sulphide body can be estimated by the intersection of the body with a fence of five boreholes. The ore body is believed to be a steeply dipping body with a strike length of 152 m and a depth extent of about 610 m. These five boreholes were logged with a three-component magnetometer, a magnetic susceptibility meter, and drilled for core (Killeen et al., 1996).*

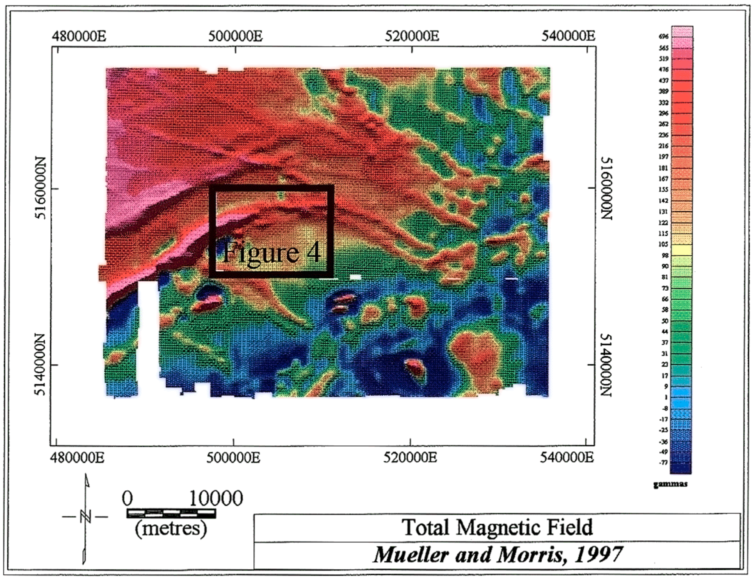


Figure 7: *Aeromagnetic data from the Ontario Geological Survey of the southwestern portion of the Sudbury Structure. IGRF has been removed from the data.*

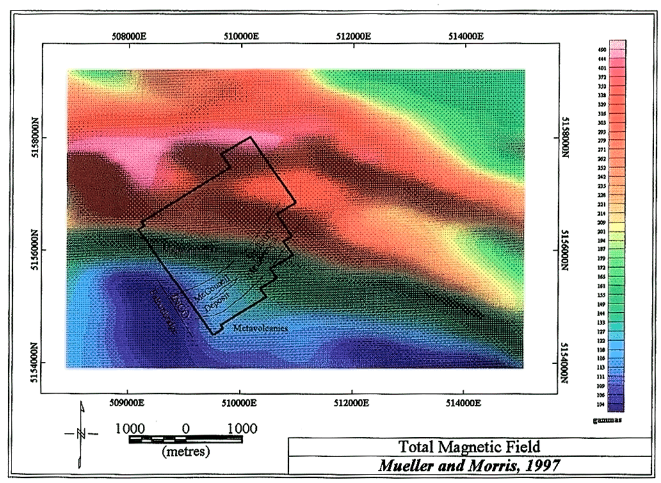


Figure 8: *Aeromagnetic data from the Ontario Geological Survey of the ground survey area.*

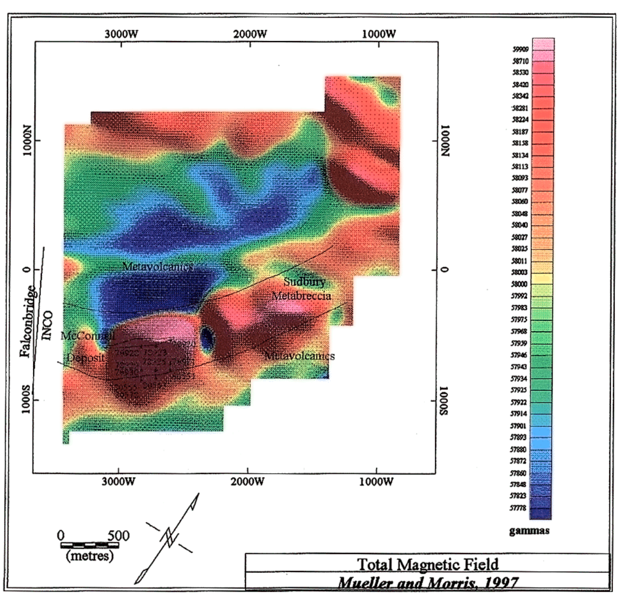


Figure 9: *Measured total magnetic field of the ground survey.*

quartz-diorite bodies in the Sudbury Structure) results in a model with a southerly dip of 122°, a susceptibility of 0.0263 e.m.u., and Koenigsberger ratio (Q, the ratio of intensity of remanent magnetisation to intensity of induced magnetisation) of 3.9. Such a dip closely corresponds to the dip of the deposit as determined by borehole measurements. Thus, modelling of the surface magnetics imply that remanence dominates the magnetic signal. This is reasonable since physical rock property studies also indicate that remanence dominates in the McConnell deposit.

The vertical gradient of the total magnetic field (Figure 10) has the advantage that it can resolve closely spaced magnetic bodies, is more sensitive to near surface sources, and removes the regional gradient and diurnal effects (Keating and Pilkington, 1990). The McConnell deposit is easily visible in the vertical gradient and appears to be a single magnetic source. The singular high in the measured gradient on the Sudbury Metabreccia and Metavolcanic contact east of the McConnell deposit is not visible in a calculated vertical gradient. It may be interpreted as a spurious measurement.

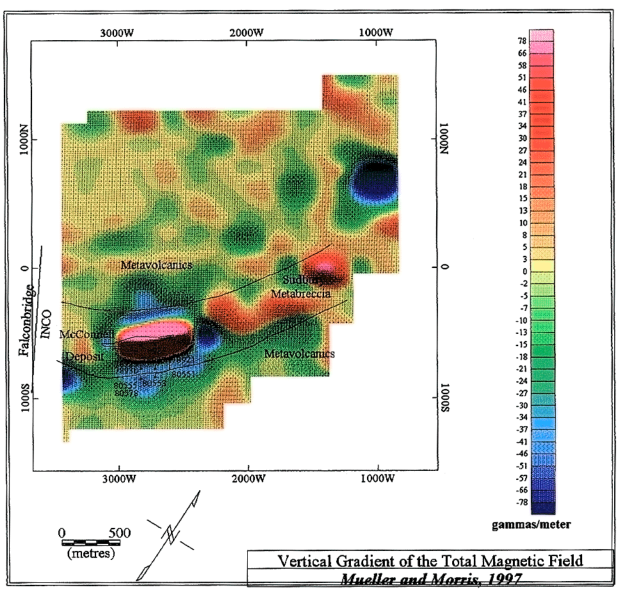


Figure 10: *Measured vertical gradient of the total magnetic field of the ground survey.*

Borehole magnetics

A ground magnetics survey allows one to interpret the McConnell deposit as one tabular depth limited body. However, fine structure within the sulphide body can not be determined due to the coarse between line and along line measurement spacing of the ground survey. Measurements of the magnetic vector and magnetic susceptibility within boreholes that pass through and/or near the body are able to resolve the body in great detail.

Lithology, a projection of the magnetic vector in the My-Mz plane, the Mx-Mz plane, and magnetic susceptibility are shown in Figure 11. The magnetic vector projections have been smoothed by a running average and filtered from the measured data. The susceptibility has been smoothed by a running average. The metasediments and conglomerate units are characterised by low magnetic susceptibility and a small magnetic vector. The quartz diorite dike and massive sulphide units tend to have higher susceptibilities and divergent magnetic vectors, but this is not necessarily true throughout all of the geological sections.

In borehole 78928, the anomalous highs of the magnetic vector and magnetic susceptibility coincide with quartz diorite dike, inclusive massive sulphide, and massive sulphide units at depths of 34 to 51 m. At a lithologically similar unit at 55 to 58 m, there is not a similar magnetic vector and susceptibility response. Such a contrary response may reflect a very different ferromagnetic mineral content in the upper and lower quartz diorite dikes. In the same borehole the magnetic susceptibility and magnetic vector response of the inclusive massive sulphide shift from a high to low value in the middle of the unit at approximately 51 m. This could be interpreted as an effect of remanence or an inhomogeneity in the ferromagnetic mineral content within this unit. Thus, geophysical logging can further subdivide geological units on the basis of their physical properties.

A 30 m section from each borehole in which the magnetic vector is anomalously high and/or changes rapidly in direction is shown in Figure 12. The points of interest in this diagram are the manner in which the magnetic vector *flips* direction, i.e., a sudden or gradual change in the direction of the vector, and the orientation of the vector outside of the source body, i.e., at the top and bottom of the shown sections.

For example, in borehole 78928 it can be seen that the Mx and My components of the magnetic vector changes sign (similar to the magnetic vector within the source bodies in Figure 1) a number of times throughout this 30 m section. Each change in magnetic vector direction is the passage in and out of a magnetised body. From the change in the magnetic vector the source body in borehole 78928 may be subdivided into three major units (35–37 m, 40–42 m, and 45–51 m) and a submeter scale minor stringer at 44 m. Thus, the magnetising body is not one continuous body, but can be resolved as a number of discrete sources and so one can attain fine detail on the structure of the ore body. Data from boreholes 78929, 80555, and 80578 represent a single major source body at approximately 104–111 m, 189–197 m, 241–249 m respectively, with a few minor sources above and below. Borehole 78930 indicates only one magnetic source body at a depth of 131–145 m.

The magnetic vector response of a borehole passing through a dipping dike can be modelled (Figure 13). There is an increase in amplitude of the magnetic vector within the source body as well as a change in direction. The concave variation in the amplitude of the vector (high at the boundaries and less in the centre of the body) can be seen in the unsmoothed and unfiltered data from borehole 78928 at depths between 42 and 44 m and in the model. Since modelling of the surface magnetics implies a high degree of remanence (Q=3.9), the "inducing" magnetic vector was chosen to be at an inclination of 72° and a declination of 192°. That is, a vector summation of the induced magnetic vector and a much larger remanence vector.

The manner in which the magnetic vector changes direction, i.e., sudden or gradual, is illustrated by modelling the borehole response of onbody and offbody magnetic bodies (Figure 14). This figure reproduces the magnetic vector response passing through two dikes of varying thickness and one offbody source. All bodies have an equal susceptibility. When the borehole passes through the magnetising bod-

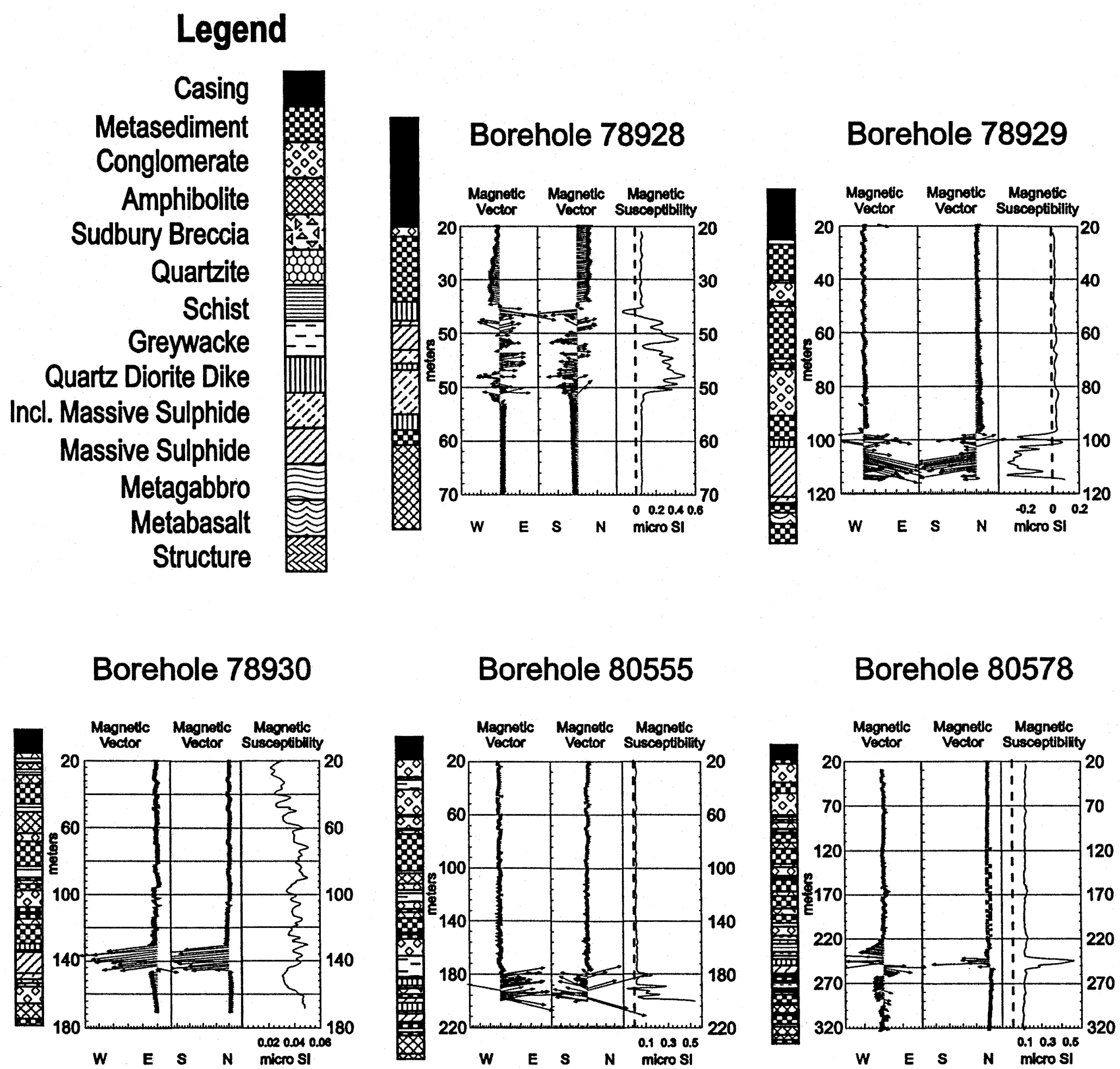


Figure 11: *Lithology, magnetic vector, and magnetic susceptibility of a fence of five boreholes that pass through the McConnell deposit. The magnetic vector is a projection in the My (east-west) and Mz plane and Mx (north-south) and Mz plane. Mz is measured with respect to the borehole, i.e., down is down the borehole, not geographically downwards. The magnetic vectors have been smoothed by a running average and filtered. The susceptibility data has been smoothed by a running average.*

ies, the direction of the magnetic vector changes suddenly. The effect of a magnetising body that is not intersected by the borehole results in a gradual change in direction of the magnetic vector. The presence of off-body anomalies can also be determined by examining the magnetic vector when it is outside of the magnetising body, that is, the nature of the background magnetic vector, i.e., above 34 m and below 52 m in borehole 78928. Above 34 m the magnetic vector is orientated towards the northwest and below 52 m it is orientated towards the southeast. If the borehole passed through a single magnetising body the direction of the magnetic vector would be in the same orientation above and below the magnetising body, i.e., orientated towards north in Figure 13. An off-body source acts as a dipole and that signal is superimposed upon the effect of the onbody sources (Figure 14). Thus the magnetic vector is orientated towards the north above the bodies and towards the south below the bodies. The presence of an offbody source body may account for this characteristic of borehole 78928. Boreholes 78929 and 80555 are not deep enough to measure a sufficient amount of background magnetic vector orientations below the magnetising source bodies. Borehole 78930 is also similar in that the background magnetic vector orientations point north above and south below the onbody source bodies.

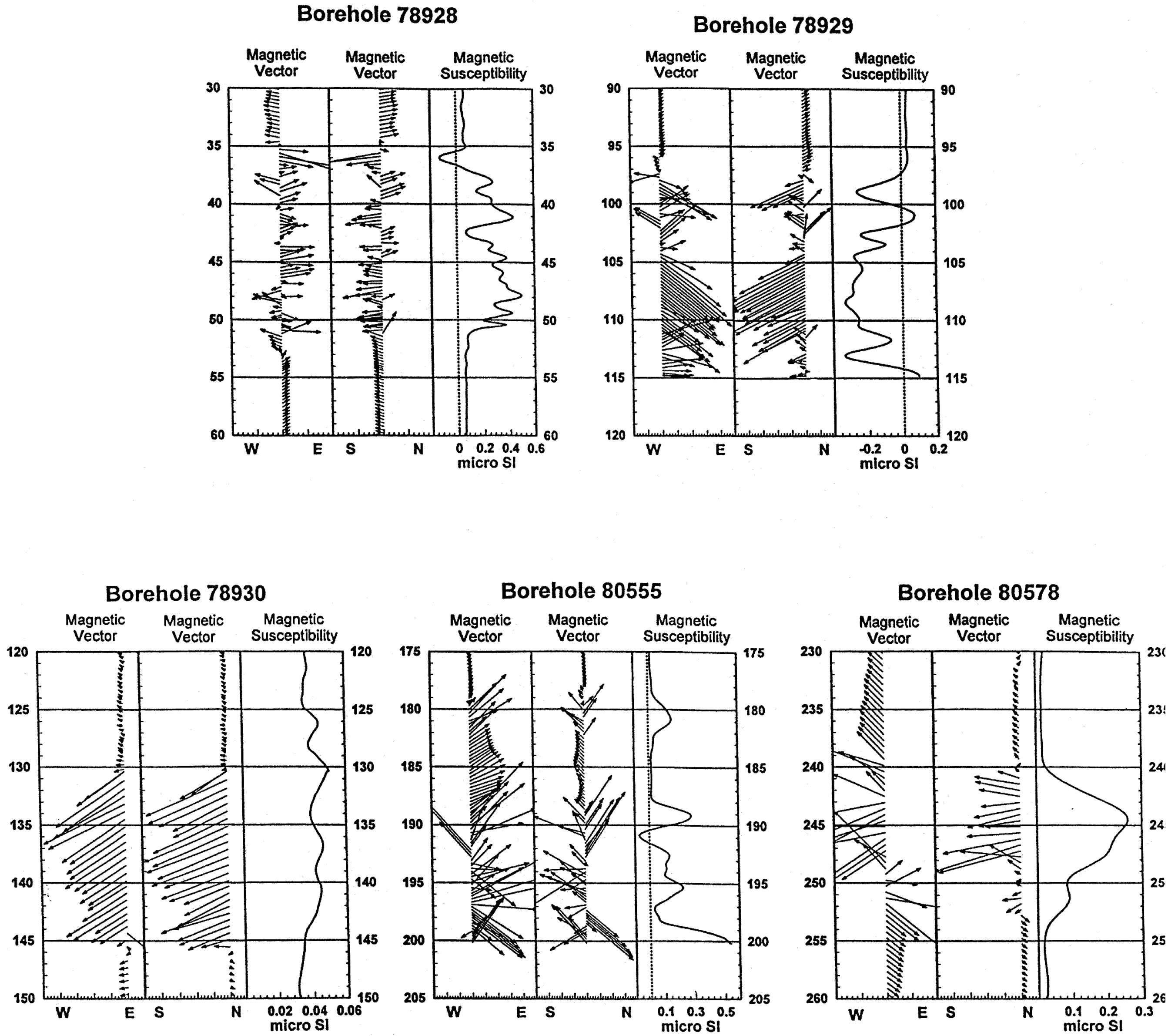


Figure 12: *A closer examination of 30 m sections of the five boreholes shown in Figure 11. These sections correspond to depth range of the sulphide body.*

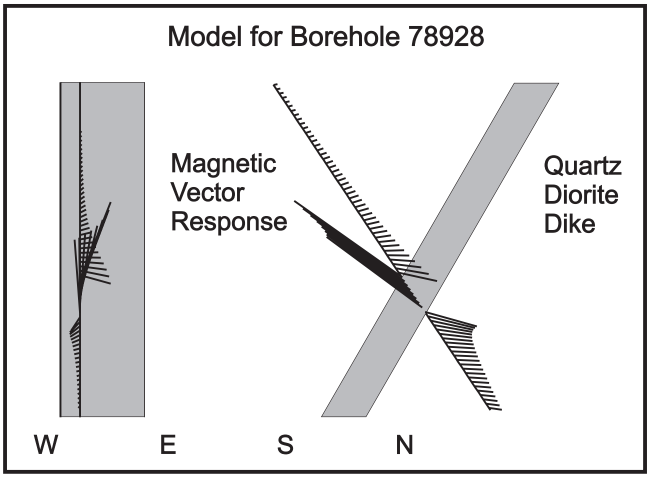


Figure 13: *The borehole magnetic vector response of a model consisting of one dipping dike. Note that the magnetic vector changes direction within the magnetising body.*

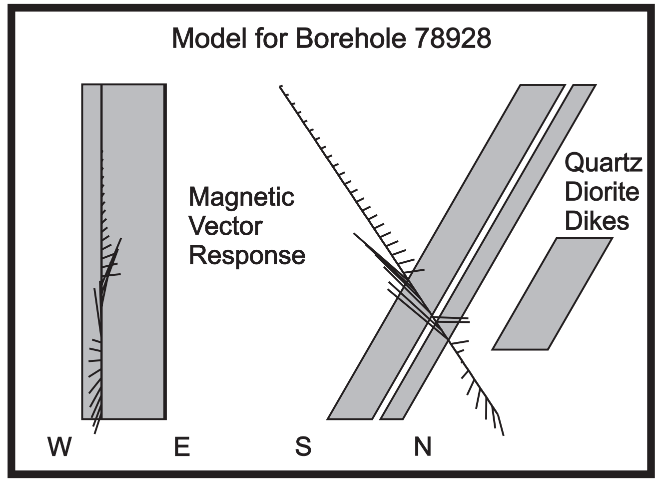


Figure 14: *The borehole magnetic vector response of a model consisting of three units, i.e., two dipping dikes of variable width and an off hole source body. The effect of the off body source causes a change in the sign of the magnetic vector near the top and the bottom of the borehole.*

Borehole 80578 shows contrary results, i.e., the magnetic vectors are orientated to the southwest above the magnetic body and towards the northeast below the body.

CONCLUSIONS

Geophysical logging is sensitive to chemical and physical changes that are not easily discernible and thereby may aid in geological interpretation. A low resolution aeromagnetic survey could not resolve the magnetic signature of the McConnell deposit. A ground magnetic survey of total magnetic field and vertical gradient of the magnetic field can determine a crude geometry of the deposit, i.e., a tabular geometry dipping towards the south with a high remanence component. Finer detail can not be resolved. The three-component magnetic vector signatures within the boreholes show evidence of passage through multiple magnetic source bodies as well as the possible presence of one or more offbody anomalies. The structure of the magnetic source can be determined on a submeter scale varying from one major body to multiple bodies in the form of stringers. Using the estimated values of magnetic susceptibility and magnetic remanence direction and intensity, further modelling it may estimate the direction and distance of the magnetic bodies. As well, vector magnetics permit improved 3-D constraints upon the geometry of the magnetic causative body. This is an enhancement upon conventional interpretations using only the total magnetic field.

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