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Interpretation of resistivity and magnetic anomalies from the Fox River Sill, Trans Hudson Orogen, Canada

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SUMMARY

The Fox River Belt is a sequence of rocks at the margin of the Proterozoic Trans Hudson Orogen in Canada that have been intruded by the Fox River Sill, a stratiform ultramafic-mafic sill. An earlier 2-D magnetotelluric (MT) study of the sill revealed a conductor that is spatially correlated with a sheared serpentinite unit in the Lower Central Layered Zone of the sill. Re-analysis of the data from 10 MT sites lying on a 1.4 km north-south profile, approximately perpendicular to geological strike, across a 1 km wide portion of the sill produced a resistivity model containing a conductor with an average resistivity of <1 ohm.m.

Using aeromagnetic data from a profile subparallel to the MT profile, a geologically constrained magnetic model of the sill was constructed. Empirical susceptibility-magnetic mineral content relationships were used to estimate the magnetite content of the different geological units from the magnetic model. The results indicated a susceptibility of 0.2 SI for the sheared serpentinite unit, suggesting a magnetite content of ~5% which compares with petrological estimates of up to 10%.

The bulk resistivity of geological units in the resistivity model was interpreted in terms of metallic mineral content using published resistivity relationships and a range of connectivity models. Integration of these results with magnetic and geological analyses suggests the enhanced conductivity in the sheared serpentinite is a result of a higher degree of magnetite interconnectivity due to the shear fabric. The analysis also reveals that although portions of the adjacent Marginal Zone in the sill contain concentrations of magnetite similar to those in the sheared serpentinite, the significantly higher resistivity of the Marginal Zone can be explained by a lower degree of magnetite interconnectivity.

Key words: magnetotelluric anomaly, magnetic anomaly, electrical resistivity, magnetite.

INTRODUCTION

This paper describes geophysical and geological interpretation of magnetotelluric (MT) and magnetic anomalies from the Fox River Sill, Manitoba, Canada. The sill is a 250 km long stratiform ultramafic-mafic complex. It has been explored for nickel, copper, and platinum group element resources.

The Fox River Belt forms part of the northern margin of the Proterozoic Trans Hudson Orogen (Figure 1). It is a supracrustal sequence intruded by coeval ultramafic and mafic sills and dykes, the largest of which is the 1.88 Ga Fox River Sill (Scoates, 1990; Heaman et al., 1986). Geological studies, drilling results and gravity modelling indicate that sill now has a near-vertical orientation (e.g., Gibb, 1968).

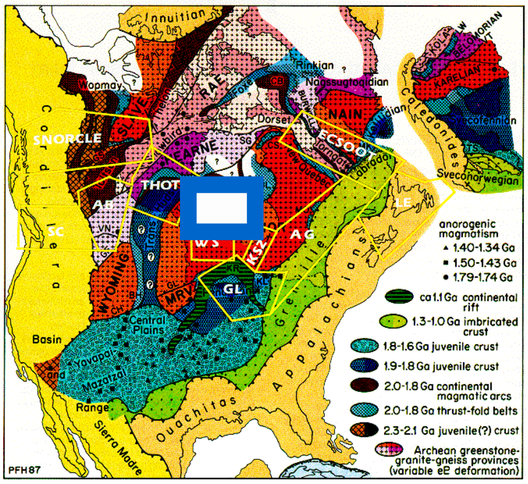

Figure 1. Study location. Labels show the location of LITHOPROBE Project transects and the blue box shows the general location of the current study.

The Fox River Sill is divided into four zones: the Marginal Zone (MZ), Lower Central Layered Zone (LCLZ), Upper Central layered Zone (UCLZ), and Hybrid Roof Zone (HRZ) (Figure 2).

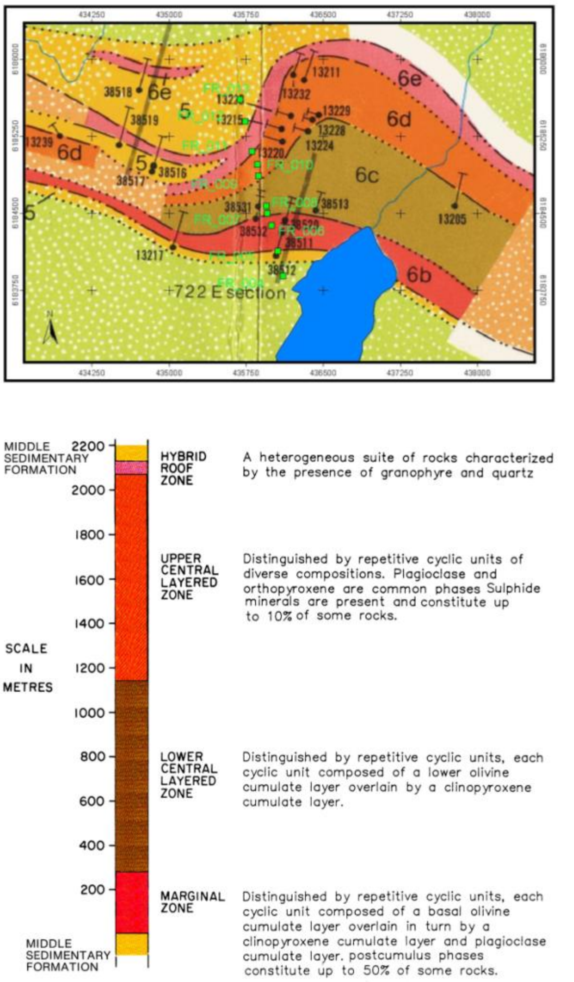

Figure 2. Geology of the Fox River Sill in the study area (modified from Scoates 1990). Upper panel shows the geological map adjacent to the Pinch and Swell structure. Green crosses show MT sites. Lower panel shows the geological section including the Middle Sedimentary Formation (Unit 5), MZ (labelled 6b), LCLZ (6c), UCLZ (6d), and HRZ (6e).

An MT survey of the Fox River Sill was conducted as part of the Canadian LITHOPROBE Western Superior (WS) Transect in 2000 (Ferguson et al. 2005). The survey included 10 audiofrequency MT (AMT) sites and 2 broad-band MT sites on a profile crossing the sill (Figure 2). It was conducted by Geosystems Canada using Metronix equipment. The region is inaccessible by road and was accessed by float-plane.

An earlier study by Orellana (2006) determined a southeast geoelectric strike azimuth, using the observed regional trend of the sill to resolve the 90° ambiguity in the strike azimuth. Subsequent 2-D inversions using this strike azimuth revealed a conductor associated with a black-coloured, foliated, magnetite-rich serpentinite unit in the LCLZ (Figure 3). In the present study (Epp 2014), the strike analysis was redone using a depth-based MT tensor decomposition, 2-D inversion was redone using a revised strike angle, and magnetic modelling was added to complement the MT analysis. The Fox River Sill has a 4000 nT magnetic anomaly (Figure 4) that can be used to constrain the location of lithological boundaries and to and to constrain magnetic mineral content.

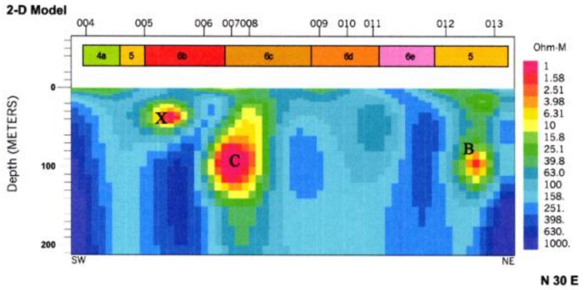

Figure 3. 2-D electrical resistivity model obtained by Orellana (2000) using a strike angle of E30^{o}S.

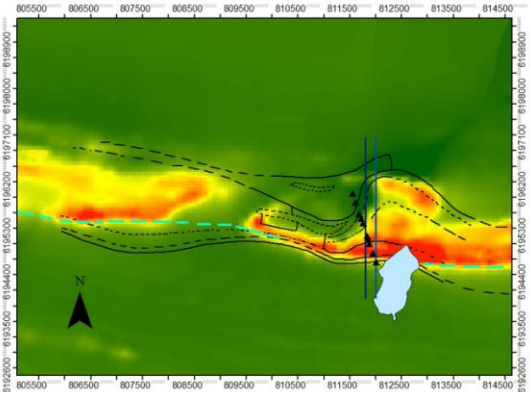

Figure 4. Total magnetic field response over the Fox River Sill near the Pinch and Swell structure. Solid and dashed lines show interpreted geological units. Magnetic data are from Aerodat Limited (1987). Triangles show MT sites and grey lines show the location of the aeromagnetic flight-lines used for detailed magnetic modelling.

MAGNETIC MODELLING

Magnetic modelling was done with POTENT using polygonal prisms with geometry constrained by borehole results (Scoates, 1990). The anomalies are all positive and are correlated spatially with the geological units, which with the high magnetic inclination of 80°, suggests dominantly induced magnetization. Results (Figure 5) indicate that the strongest magnetization occurs within the MZ with additional significant magnetization in the adjacent LCLZ, corresponding to the sheared serpentinite unit. The models include a susceptibility of 0.3 SI in the MZ and 0.2 SI in the lower part of the LCLZ.

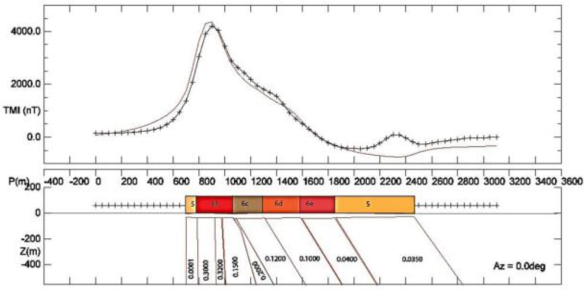

Figure 5. Magnetic model. The model was obtained using a forward modelling approach with a final phase of

inversion of susceptibility values to slightly improve the data fit.

MT STRIKE ANALYSIS AND 2-D INVERSION

The strike azimuth for the MT profile was re-determined using the program STRIKE which implements a pseudodepth-dependent Groom-Bailey tensor decomposition (e.g., Hamilton et al., 2006). The results revealed minimal dependence of strike with depth and strike azimuths that are aligned with local geological boundaries (Figure 6). The uniformity of the results with depth indicates that the resistivity structures associated with the Pinch and Swell structure extend to significant depth.

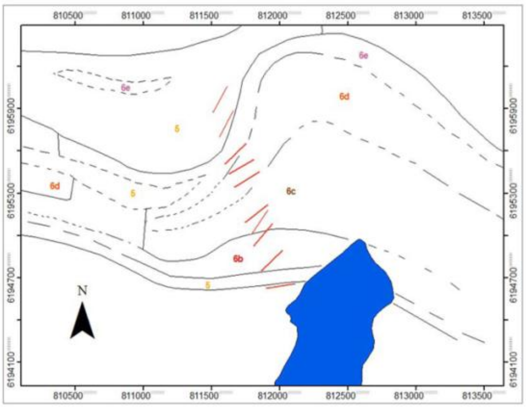

Figure 6. Single-site strike azimuths determined using the STRIKE program correlate with the local geological boundaries.

A least-squares-based average value for strike azimuth of N56°E was used for 2-D MT inversions. The inversions used the non-linear conjugate gradient algorithm of Rodi and Mackie (2001). An optimal regularization factor of Tau=1.75 was determined with an L-curve approach. The final model gives a good fit to the transverse electric (TE) and transverse magnetic (TM) apparent resistivity and phase data (Figure 7). The rms misfit was 2.12 for TE and TM phase and apparent resistivity error floors of 6%, 3%, 24% and 12% respectively.

The final resistivity model (Figure 8) is similar to the earlier result but is considered more reliable. It shows a single conductive anomaly near the margin of the MZ and LCLZ and a weaker anomaly to the north. The reliability of the model was tested by running many inversions with different inversion parameters and starting models. The resolution of individual features was also investigated using constrained inversions, e.g., with resistivity in the vicinity of the features constrained to background values.

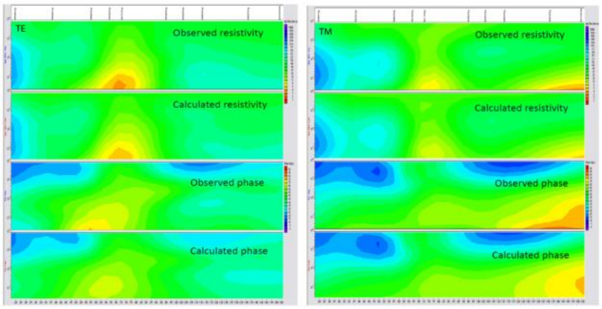

Figure 7. Fit of the final model to the TE (left) and TM (right) apparent resistivity and phase data.

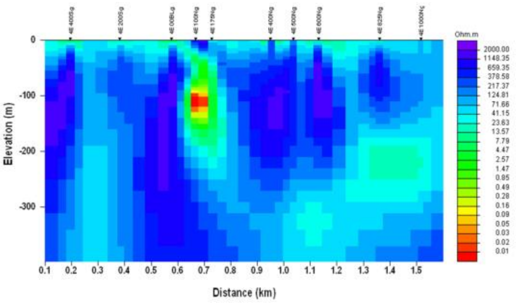

Figure 8. Final 2-D resistivity model.

GEOPHYSICAL AND GEOLOGICAL INTERPRETATION

Comparison of magnetic and resistivity models and geological constraints shows the conductor is spatially correlated with the foliated serpentinite unit in the lower part of LCLZ (unit 6C) (Figure 9) and rocks of susceptibility of 0.2 SI.. Models of susceptibility versus magnetite content (Clark and Emerson 1991) indicate that the conductor corresponds to rocks with a magnetite content of ~5% (Figure 10). In contrast, the MZ (unit 6B) has higher susceptibility, 0.3 SI or ~8% magnetite, but is relatively resistive. The observations raise the question as to whether a single constituent, such as magnetite, can explain enhanced magnetization in both the MZ and LCLZ but enhanced conductivity in only the LCLZ?

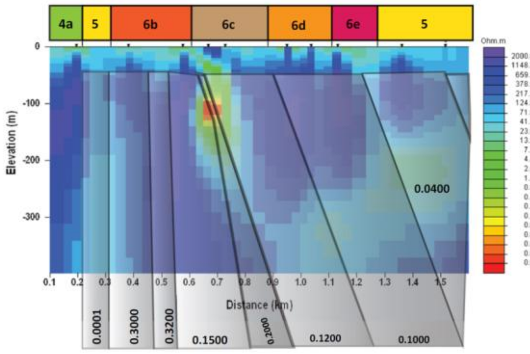

Figure 9. Comparison of magnetic and resistivity models.

Magnetite ore exhibits an extreme range of resistivity with no clear relationship between magnetite content and resistivity. However, results published in Parasnis (1956) are fairly well bracketed by Hashin-Shtrikman bounds for a magnetite resistivity of 0.02 ohm.m and matrix resistivity of 500 ohm.m (Figure 10). The results suggest that the resistivity of the MZ and serpentinite unit in the LCLZ can indeed be explained the magnetite content provided the magnetite in the LCLZ serpentinite is extremely well-connected.

Other studies suggest that the resistivity in the sheared serpentinite unit is lower than expected for ~5% magnetite. In order to determine whether the required connectivity of the magnetite is possible, thin-sections were made from archived core samples (Figure 11). Preliminary examination of the thin-sections shows that the rocks are pervasively strained and magnetite grains are extremely well-connected forming continuous veins and interconnected blobs. Samples from the drill core also exhibit high susceptibility (0.025-0.25 SI) providing confirmation of the magnetic modelling results.

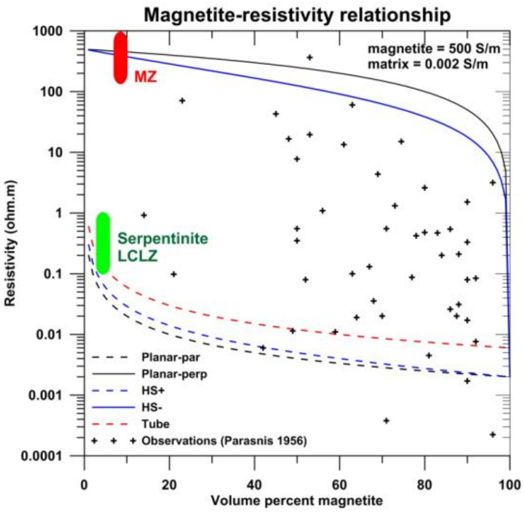

Figure 10. Relationship of electrical resistivity and magnetite content. Crosses represent data from Parasnis (1956) and curves show the theoretical response for different magnetite connectivity. The red and green regions show the magnetite content and resistivity for the MZ and lower LCLZ respectively.

The combined MT, magnetic, and geological results from the Fox River Sill allow the observed resistivity anomaly to be attributed to magnetite. They also suggest the possibility of using surface geophysical measurements to map locations of extreme strain in units containing moderate magnetite content.

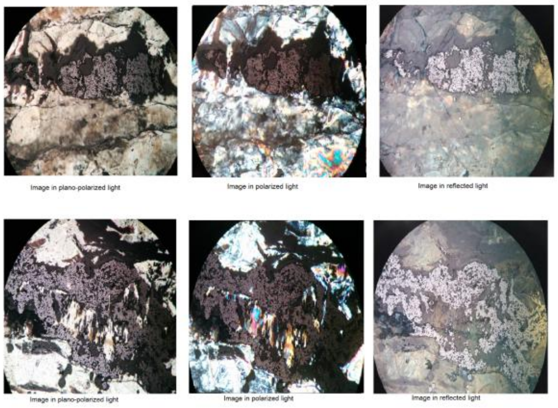

Figure 11. Plain (left), polarized (centre), and reflected (right) light images of samples from the LCLZ of the Fox River Sill. The diameter of each image is ~ 1mm.

CONCLUSIONS

Comparison of MT and magnetic geophysical results and geological constraints shows that a conductor in the Fox River Sill occurs within a basal sheared-serpentinite unit of the LCLZ and is spatially correlated with rocks of susceptibility of 0.2 SI. The corresponding magnetite content of ~5% is able explain the enhanced conductivity because the rocks are strongly strained and magnetite grains exhibit a high degree of interconnection. The adjacent MZ of the sill contains a greater abundance of magnetite but is more resistive than the sheared-unit, indicating lower connectivity of the magnetite.

ACKNOWLEDGMENTS

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