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High-resolution electromagnetic images of conducting zones in an upthrust crustal block

Alan G. Jones[1], Richard C. Bailey[2] and Marianne Mareschal[3]

Abstract. A high-resolution, controlled-source, electromagnetic survey in the Kapuskasing region, over exposed deep crustal material upthrust along ramp-and-flat geometry faults, reveals a shallow weakly-conductive layer (5,000-10,000 Ω·m) within a resistive host (50,000-100,000 Ω·m). This layer, at ≈1 km depth, correlates spatially with a zone of enhanced reflectivity, and coincident breaks in both conductivity and reflectivity suggest that a high-angle fault zone offsets the layer. The cause(s) of this enhanced conductivity is conjectural until this unit is drilled, but the two probable candidates are: (1) electrolytic conduction in saline-filled porous rocks, or (2) ionic conduction along connected grain-boundary films of graphite. Or both conduction mechanisms may be operating with the graphite interconnectivity provided by the brines.

Introduction

The Kapuskasing Uplift (KU) of the Canadian Shield (inset, Fig. 1) is one of the rare exposed crustal cross-sections that survived exhumation relatively intact from a depth of at least 20 km. Under LITHOPROBE a variety of geophysical, geological and geochemical studies have been carried out over the last decade on the KU including seismic reflection, refraction and electromagnetic (EM) surveys [see the synthesis of KU studies by *Percival and West,* 1994]. The crustal model derived from the regional seismic data, with surficial geological control, is illustrated in Fig. 2. Deep crustal material, originally at depths of 20 to 30 km, was transported ≈100 km to the east and brought to the surface along ramp-and-flat geometry thrust faults. The master decollement thrust is interpreted to be the Ivanhoe Lake Fault Zone (ILFZ, Figs. 1 and 2).

An east-west Vibroseis survey along the Warren-Carty road (Fig. 1) of the Chapleau block (CB, Fig. 1 inset), showed reflections that can be traced to within 0.3 s (1 km) of the surface (Fig. 3, left panel) [*Milkereit et al.,* 1991]. However, this package of lamellar reflectors cannot be correlated directly with surface exposures.

Regional-scale, natural-source EM studies carried out on the KU (see review by *Mareschal et al.* [1994]) showed no evidence of any enhancements of conductivity corresponding to the presently-exposed Archean intermediate to lower crustal rocks. However, controlled-source UTEM surveys along the Warren-Carty road (Fig. 1) were able to detect zones in the upper 5 km in which the resistivity dropped from a host value of >40,000 Ω·m to at least as low as 6,000 Ω·m (see *Mareschal et al.* [1994]) The shallowest zone, at ≈2 km depth, seemed to correlate with a series of shallow reflections. Such weakly conductive zones in a very resistive host are virtually invisible to natural-source EM methods, and are poorly resolved by these UTEM data.

As exposed cross-sections of deep crustal material may possibly be used as windows on lower crustal physical properties, particularly seismic and electromagnetic, it was proposed to drill into the Kapuskasing structure down to a depth of over 1 km at the location shown in Fig. 1 under the auspices of the Canadian Continental Drilling Program (CCDP) [*Percival et al.,* 1991]. This drillhole would penetrate the package of lamellar reflections and possibly also the faint conductor, thereby, hopefully, addressing fundamental questions regarding the cause(s) of the frequently-observed lower-crustal high-reflectivity [e.g., *Mathews,* 1986] and high conductivity [e.g., *Jones,* 1992].

To aid optimal location of the drillhole for penetration of this target, very high resolution seismic [*Milkereit et al.,* 1991] and UTEM surveys were undertaken in the restricted area shown in Fig. 1. This paper presents the results of the UTEM survey, and discuss their correlation with those of the seismic survey.

High resolution seismic experiments

Figure 3 shows a fence diagram of part of the seismic sections from the Warren-Carty road Vibroseis survey (left panel) and the high-resolution north-south dynamite survey (right panel) at the proposed CCDP drillhole location (asterisk in Fig. 1). A prominent package of gently dipping reflections at shallow depth (<1 km) is evident on both sections. These reflectors can be traced seismically to 20 km depth approximately 70 km west of the Warren-Carty road, and represent the base of the shallow-dipping detachment zone shown in Fig. 2.

Physical property studies on rocks from the KU [*Milkereit et al.,* 1991] indicate that layered sequences of mafic and tonalitic gneiss, with velocity and density contrasts of 0.7 km/s and 0.25 g/cm^3 respectively, give reflection coefficients as high as 0.1. Accordingly, *Milk-*

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[1] Geological Survey of Canada, Ottawa

[2] University of Toronto

[3] Ecole Polytechnique, Montreal

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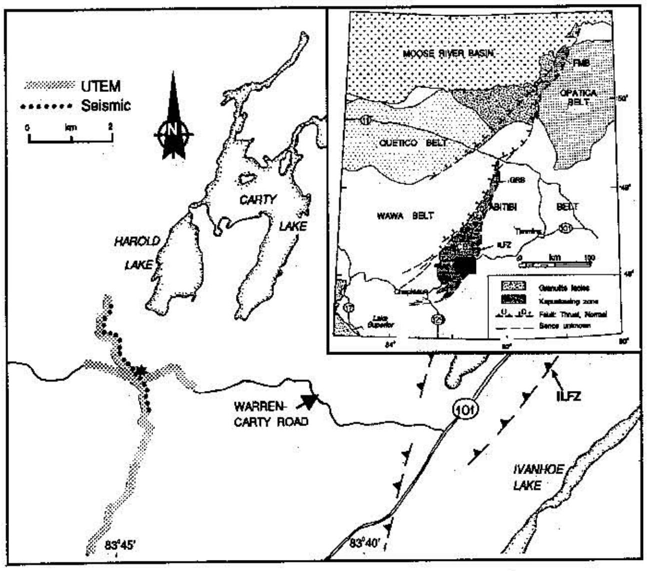

Figure 1. Location map of the seismic reflection and EM surveys along the Warren-Carty road and the high-resolution CCDP studies. The star indicates the proposed drillhole location. ILFZ: Ivanhoe Lake Fault Zone. The location of the map to the Kapuskasing Uplift is indicated by the rectangle in the inset. In Inset: Blocks of the Kapuskasing Uplift are: CB: Chapleau Block; GRB: Groundhog River Block; FMB: Fraserdale-Moosonee Block.

ereit et al. [1991] interpreted the package of lamellar reflections in the uppermost kilometer of the KU in terms of such sequences. They suggested that lower crustal reflectivity is due to interlayered mafic and felsic rocks.

High resolution UTEM results

Aditional UTEM data, using higher resolution parameters (Table 1) than the regional scale surveys, were collected in 1990 along the two profiles shown in Figs. 1 and 4. The two primary objectives of the survey were:
(1): To determine if there is a zone of enhanced electrical conductivity associated with the package of reflectors, and,
(2): To determine what happens to the zone further to the south of the dynamite survey.

If the reflective zone can also be imaged electrically, then one can trace it further to the south to determine whether it shallows, therefore providing a target with lower drilling costs, or whether it changes dip.

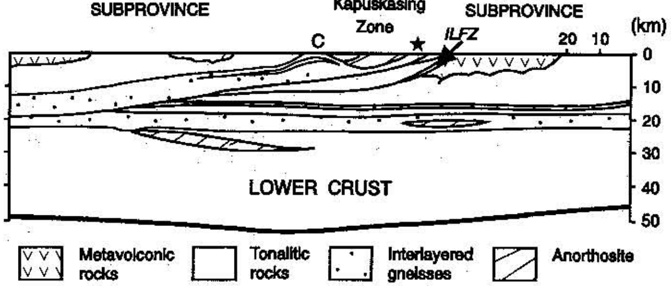

Figure 2. Geological cross section across the Kapuskasing Uplift from the Wawa Belt to the Abitibi Belt (vertical exaggeration 1:1). ILFZ = Ivanhoe Lake Fault Zone; C = mid-crustal (Conrad) discontinuity;

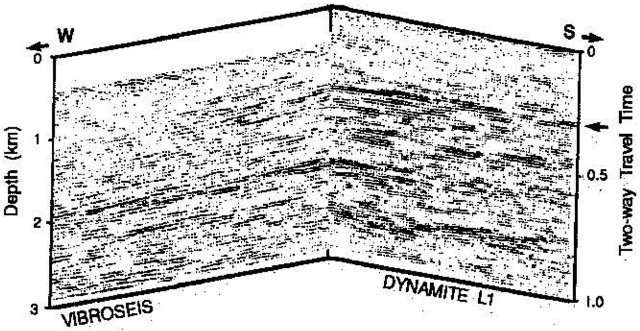

Figure 3. Fence diagram of the high resolution Vibroseis and dynamite profiles from the center point (asterisk on Fig. 1; (500,500) on Fig. 4) to the south (dynamite) and west (Vibroseis). The right ordinate gives the two-way travel time, whereas the left ordinate gives depth. The position of the shallow seismic reflector is indicated by the arrow (taken from Milkereit et al., 1991).

The 4 km-long east-west profile, of twelve transmitter loops, was equispaced about the proposed drillhole site (Fig. 4). The north-south profile, of twenty-two transmitter loops, was with 2.25 km to the north of the Warren-Carty road and 4.5 km to the south (Fig. 4), which is almost 4 km further south in extent than the reflection data profile. On the previous UTEM surveys only the vertical magnetic field component, H_z, had been measured at the receiver station. However, to increase resolution, and also to determine whether one-dimensional (1D) interpretation of the data is valid, the two horizontal magnetic components, H_i and H_a (in-line and across-line, respectively), were also recorded.

The data from both profiles, after two-component DIP processing (the approximate 1D inverse scheme of *Macnae and Lamontagne* [1987]), are illustrated in Fig. 5. The shallowest depth of investigation, determined by the earliest-time response, is about 200 - 300 m. The total conductance of the material to that depth, mainly conducting overburden clays of about 40 m thickness with a conductance of, on average. 0.1 S, is distributed uniformly over that distance. Features

Table 1. Comparison of regional vs. high-resolution parameters for the seismic and UTEM surveys

	Regional	High-resolution
Seismics		
vibrators	4	2
shot spacing	100 m	20 m
receiver spacing	50 m	20 m
sweep frequencies	12-52 Hz	20-130 Hz
sampling	4 ms	2 ms
UTEM		
source size	2-6 km^2	0.1 km^2
source spacing	1 km	300 m
receiver spacing	100 m	20 m
base frequency	31 Hz	45.27 Hz
components	H_z	H_i, H_a, H_z

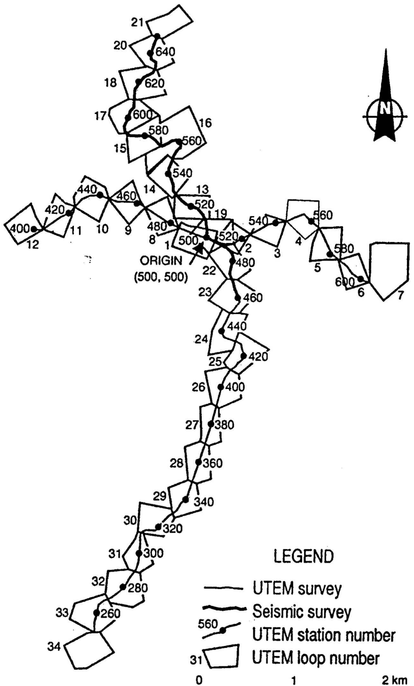

Figure 4. Loop location map for the high-resolution CCDP UTEM survey. The loop numbers are given, whereas the station numbers are listed along the two profiles. Note that the southernmost point of the seismic survey is at UTEM receiver location 460.

deeper than about 2 km are not meaningful due to loss of signal penetration.

Beneath the overburden (yellow/green in Fig. 5) the upper crust is generally highly resistive (blue). Within this resistive host, zones of moderately-enhanced conductivity (reduced resistivity) trending subhorizontally, with occasional interruptions, are seen on both profiles (yellow/green streaks). Although the total conductance in these zones is less than half the total overburden conductance, sensitivity studies show that two-component processing is both essential and validates interpretation of the gross features of the electrical fabric. This fabric for the southern half of the NS line (Fig. 5) mimics the seismic fabric by dipping down to the north at 5 to 10 degrees, which suggests that electrical fabric and seismic fabric (Fig. 3) are controlled by the same structures. The fabric in the EW profile dips down to the west, giving an overall electrical dip of down to the northwest.

The NS section is disturbed in the middle to northern part. Notably, this is not seen on the EW profile, suggesting that it arises from a geological feature (probably faults) crossed by the NS line but not the EW line. Similar features mark the northward termination of the reflecting package on the NS seismic line (see below).

Correlation with seismic results

Figure 6 illustrates a portion of the UTEM data, from receiver stations 455 to 600 on the NS profile, together with the high-resolution seismic data superimposed. The seismic data are plotted on the UTEM depth scale with an assumed velocity of 6 km/s. The bright shallow seismic reflector, indicated by the arrow in Fig. 3,

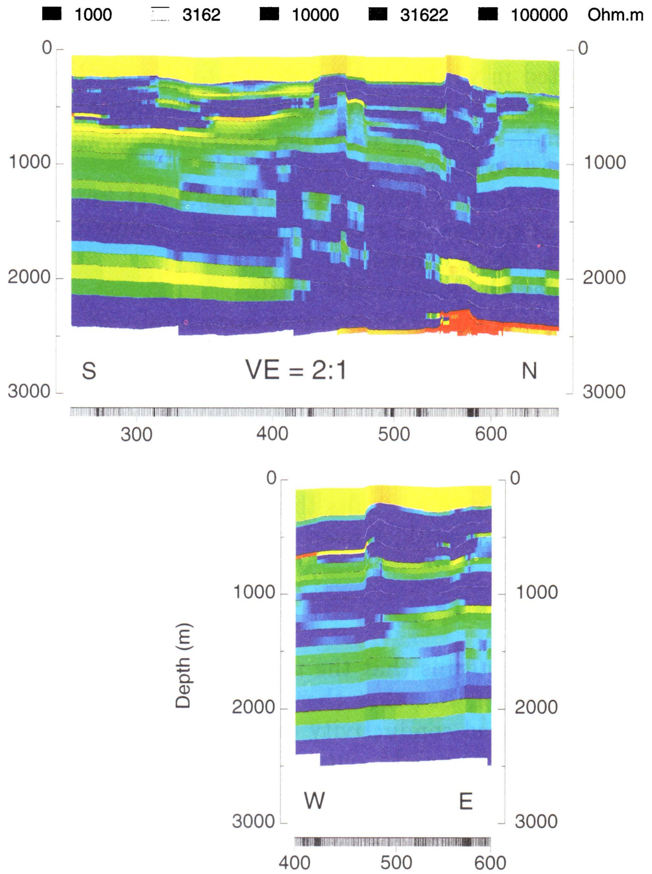

Figure 5. DIP-processed UTEM results for both the north-south (upper) and east-west (lower) profiles (vertical exaggeration of 2:1). The station numbers are shown below the profiles, and station 500 is the same for both profiles. The stations have been projected onto north-south and east-west profiles respectively. The resistivities are color-coded, with reds in the 1,000 - 3,000 Ω·m range, yellows for 3,000 - 10,000 Ω·m range greens for 10,000 - 25,000 Ω·m range, and blues very resistive (>40,000 Ω·m). The black lines denote the various time channels, with the earliest channel (0.0144 ms) giving the shallowest information.

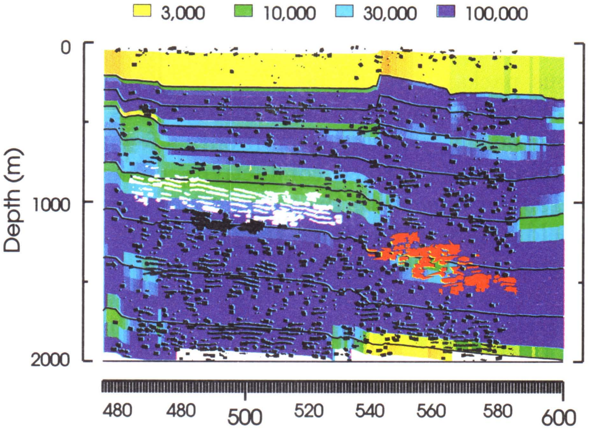

Figure 6. Correlation between the seismic and UTEM results in the proposed location of the CCDP drillhole (UTEM receiver location 500). The UTEM stations are not projected onto a N-S line (as in Fig. 5) but are plotted at 20 m intervals to follow the seismic data. The bright reflectors indicated by the arrow in Fig. 3 have been highlighted in white, and a second band of reflectivity at a depth of around 1300-1500 m highlighted in red.

is highlighted in white, and reflections to the north of UTEM station 540 at approximately 1.5 km depth are shown in red. Note the following correlative features between the two datasets:
1: the bright zone of reflectivity at 0.3-0.4 s (1 km) is at the same depth as the zone of enhanced conductivity (to within a time channel),
2: both zones dip down to the north,
3: both zones appear to terminate horizontally at approximately the same location, to within a few hundred meters, and,
4: there is a possibility that a reflective/conductive region is offset downwards at around UTEM station 540.

This latter point may be evidence in both datasets for near-vertical normal faults that lie undetected geologically beneath the thick overburden.

Conclusions

This study confirms that the upper crust in the KU is highly resistive, but that there is a shallow (1 km) region of enhanced conductivity dipping moderately to the northwest. Lateral discontinuities are evident, suggesting a high angle fault zone, and a prominent reflecting package is spatially coincident with the zone of reduced resistivity.

Whereas the reflective/conductive zone dips to the north/northwest at around the intersection of the NS and EW profiles (UTEM receiver site 500), to the south the conductive zone flattens and is estimated to come no closer to the surface than 750 m (Fig. 5). Also, there is a marked increase in the conductivity of this zone to the south (receivers 250 - 350) by almost an order of magnitude.

Why the reflecting zone coincides with a zone of enhanced conductivity is an intriguing question. The seismic interpretation of *Milkereit et al.,* [1991] is of interlayered sequences of mafic and tonalitic gneiss, which would not cause enhanced conductivity. Rather, during uplift or tectonically-induced stress such strongly heterogeneous packages would be more likely to undergo internal fracture and shear than homogeneous rock units. The resulting porosity, even if only a few percent, would explain the observed conductivity enhancement [*Jones,* 1992] if filled with the saline water characteristic of shield brines. Alternately, the presence of (disconnected) graphite films at grain-boundaries is consistent with the rock property studies as well as with the measured electrical anomaly [see *Mareschal et al.,* 1994]. In contrast to this either/or scenario, *Duba et al.* [1994] have shown recently that conduction in rocks sampled by the German deep drillhole (KTB) is due to a combination of highly conducting intergranular solid phases (graphite, ilmenite, pyrite and magnetite) electrically connected in distinct subhorizontal zones by saline fluids. Such a combination of conductive mechanisms may be operating in the upper crust of the KU. However, without drillhole sampling the cause of the enhanced conductivity at this location must remain the subject of speculation. Given the lateral discontinuity near the intersection of the NS and EW lines, it would seem appropriate to site a drillhole away from this anomalous region, perhaps near the southern end of the NS line.

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References

Duba, A., S. Heikamp, W. Meurer, G. Nover, and G. Will, Unusual pressure effect on electrical conductivity of saturated rocks from the German deep drillhole, Nature, *367,* 59-61, 1994.

Jones, A.G., Electrical conductivity of the continental lower crust, in *Continental Lower Crust* edited by D.M. Fountain, R.J. Arculus and R.W. Kay, Elsevier, Amsterdam, Chapter 3, 81-143, 1992.

Macnae, J.C., and Y. Lamontagne, Imaging quasi-layered conductive earths by simple processing of TEM data, Geophysics, *52,* 545-554, 1987.

Mareschal, M., R.D. Kurtz, and R.C. Bailey, A review of electromagnetic investigations in the Kapuskasing Uplift and surrounding regions; electrical properties of key rocks, Can. J. Earth Sci., in press.

Mathews, D.H., Seismic reflections from the lower crust around Britain, in *The Nature of the Lower Continental Crust,* editec by J.B. Dawson, D.A. Carswell, J. Hall, and K.K. Wedepohl, Spec. Publ. Geol. Soc. London, 11-22, 1986.

Milkereit, B., J.A. Percival, D. White, A.G. Green, and M.H. Salisbury, Seismic reflections in high-grade metamorphic rocks of the Kapuskasing uplift: Results of preliminary drill site surveys, Geodyn. Ser., American Geophysical Union, *22,* 39-46, 1991.

Percival, J.A., and G.F. West, The Kapuskasing Uplift: A geological and geophysical synthesis, Can. J. Earth Sci., in press.

Percival, J.A. et al., A closer look at deep crustal reflections, EOS, *72,* 337-341, 1991.

R.C. Bailey, Department of Physics, University of Toronto, Toronto, Ontario, Canada, M5S 1A7
A.G. Jones, Geological Survey of Canada, 1 Observatory Crescent, Ottawa, Ontario, Canada, K1A 0Y3
M. Mareschal, Génie Minéral, Ecole Polytechnique, C.P. 6079, Succ. Centre Ville, Montréal, Québec, Canada, H3T 3A7

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