AN ANOMALOUS ELECTRICAL RESISTIVITY ZONE NEAR STE-MATHILDE, QUEBEC

(Contribution of the Earth Physics Branch No. 922)

R. D. KURTZ[1], E. R. NIBLETT[1], M. CHOUTEAU[2], W. J. SCOTT[3] and L. R. NEWITT[1]

ABSTRACT

A limited region of very low electrical resistivity at shallow depths in the earth's crust has been located near the village of Ste-Mathilde, Québec. Estimates of the depth and areal extent of the anomalous zone have been made, mainly by means of magnetotelluric (MT), audio-magnetotelluric (AMT) and Schlumberger DC resistivity observations. EM31 and EM34 surveys were conducted as well in the same area. One-dimensional modelling techniques indicate that the anomaly lies at depths varying between 250 m and 1000 m. Results of tensor analysis of the data reveal a northwest-southeast trending structure that dips to greater depths to the northwest. While more-detailed surveys are required to delineate and document this unusual feature properly, our limited data indicate that it represents one of the most conductive anomalies ever detected by MT methods.

INTRODUCTION

In June 1977 a magnetotelluric (MT) recording station (SMt-1) was established near the village of Ste-Mathilde, about 6 km northeast of La Malbaie and less than 2 km from the north shore of the St. Lawrence River (Fig. 1). The data from this station revealed strongly suppressed electric fields and indicated very low resistivity at some depth within the earth's crust.

The station was placed just east of the edge of a zone of Paleozoic limestones and shales that overlie the Grenville rocks in the immediate vicinity of La Malbaie. The station was located on a granite body which is more than 2 km long and 0.6 km wide (Rondot, 1966). It is medium-grained, pale pink, heterogeneous rock composed of orbicular plagioclase held in biotite and quartz. It is surrounded by a wide migmatite zone which is injected by many bodies of pegmatite. The pegmatites are apparently related to the granite body and are weakly radioactive. Zones of paragneiss lie to the northwest of SMt-3. The overburden is thin in the survey area and outcrops of Precambrian rock are frequently encountered. The station is within a few kilometres of Logan's Line, a major thrust fault beneath the St. Lawrence which separates the Grenville Province from the Appalachian regime to the south; it also lies just outside the eastern rim of a large Paleozoic impact crater known as the Charlevoix Crater (Robertson, 1968, 1975; Rondot, 1968). Ste-Mathilde is near the northeast end of an active microearthquake zone which is approximately 70 km long, 40 km wide and coincides with the St. Lawrence River. Larger earthquakes have occurred near the ends of the microearthquake zone (Stevens, 1980).

In June 1978 preliminary electrical surveys at the site with EM31 and EM34 instruments (Geonics Ltd.) provided no evidence for highly conductive material within 50 m of the surface. Telluric soundings made in a single direction at four sites within a 4.5 km radius of the original station (SMt-1, Fig. 1) implied that the region of electric field suppression is probably quite restricted in size, extending perhaps 1 km or so in the northwest-southeast direction and at the most a few kilometres in the northeast-southwest direction. Following this preliminary reconnaissance, the area was surveyed in greater detail with Schlumberger DC resistivity measurements and with audio MT. These

[1]Division of Geomagnetism, Earth Physics Branch, Dept. of Energy, Mines and Resources, Ottawa K1A 0Y3, Canada.
[2]Ecole Polytechnique, Montréal, Québec.
[3]Hardy Associates (1978) Ltd., Calgary, Alberta.

We would like to thank Dr. Michel David, managing director of the Mineral Exploration Research Institute, for his interest in this project and for making available the AMT profiling and sounding equipment.

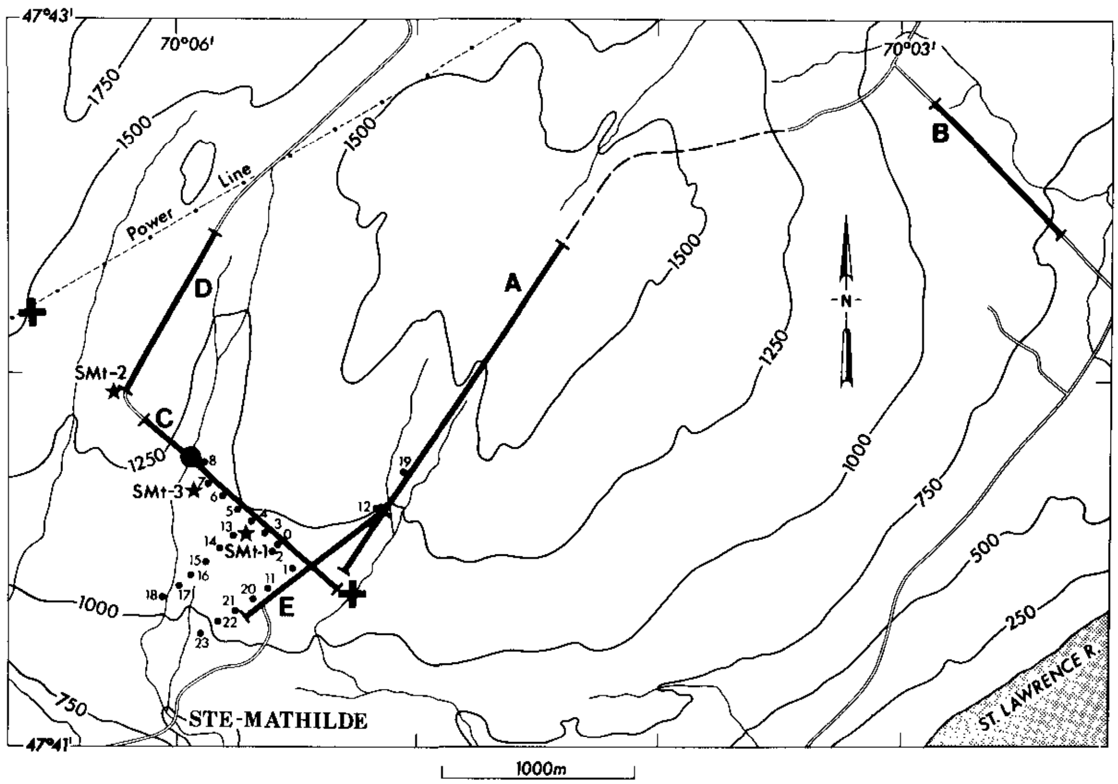

Fig. 1. Location map of the three AMT sounding stations (SMt-1, SMt-2, SMt-3), the AMT profiling stations (0-23) and the Schlumberger current electrodes (A-E). The crosses indicate the locations of the current electrodes for the Schlumberger profiling. The large circle locates the origin of Figure 3.

observations have been summarized by Scott (1981) and by Kurtz *et al.* (1979).

The DC Resistivity Results

A DC Schlumberger sounding is carried out by measuring the voltage between two receiver electrodes caused by current flowing between two transmitter electrodes. All four electrodes are collinear, with the transmitter electrodes straddling the receiver electrodes. Increased penetration is achieved by increasing the transmitter electrode spacings while holding receiver electrodes fixed. For each spacing an apparent resistivity is calculated from the measured values of voltage, current and spacing (Telford *et al.*, 1976, p. 656).

Five Schlumberger soundings were carried out at the locations shown in Figure 1. The results were interpreted with the aid of an interactive computer program.

In order to determine the approximate lateral limits of the low-resistivity feature, a profile was surveyed along the line of sounding C. A modified Schlumberger array was used, in which the current electrodes were fixed (as shown in Fig. 1) and the receiver electrodes were moved to obtain apparent resistivity values as a function of position.

The interpreted models for the soundings are shown in Figure 2. Soundings A and B give no indication of the presence of low-resistivity material within the top 300 m. There is some scatter in the data that is felt to be the result of lateral variation in resistivity, caused probably by changes in overburden thickness.

Soundings C and D give a clear indication of the presence of a low-resistivity zone. The data do not provide a very good estimate of the actual resistivity, however, because of insufficient spacing between the transmitter electrodes. This is demonstrated in sounding D,

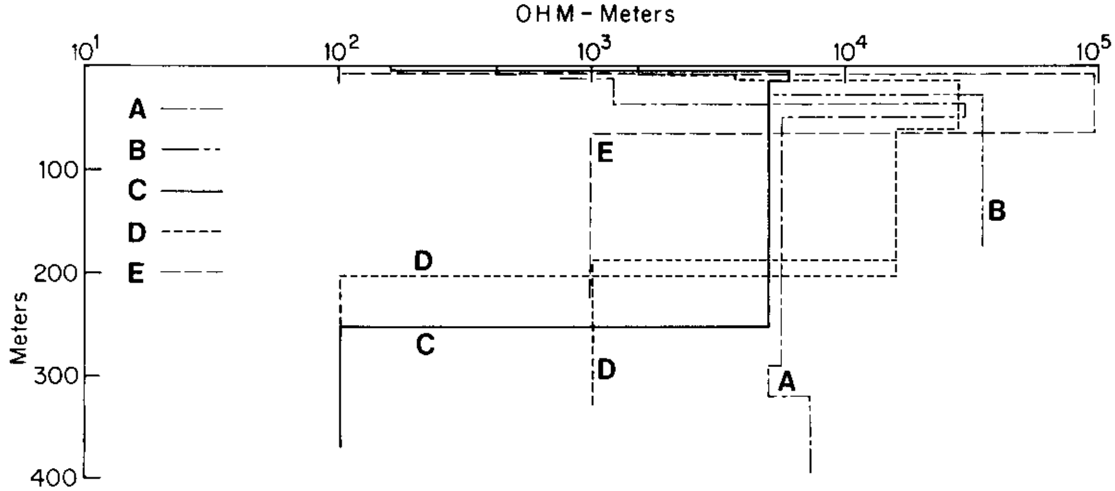

Fig. 2. Computed models to fit the Schlumberger sounding data.

where two alternative interpretations are presented. The depth to the top of the zone, however, appears to be well determined.

The slope of the field sounding curve at E was considerably greater than the theoretical maximum obtainable for uniform horizontal layering, and it is probable that strong lateral variations of resistivity altered the shape of the sounding curve. It is likely that there is a low-resistivity region below site E, but neither its depth nor its resistivity can be determined with any reliability.

Figure 3 shows the apparent resistivity profile measured on sounding line C. The fixed-current electrodes at the ends of the line were separated by 2.2 km, and the receiver electrode spacing was 50 m. It is obvious that there is a wide variation in resistivity with position along the line. Apparent resistivities drop as low as 35 Ωm on the least resistive part of the profile, which indicates that the true resistivity of the anomalous region is probably less. These results provided confirmation of a highly conductive near-surface zone and demonstrated the need for further geophysical work.

Audio Magnetotelluric (AMT) Surveys at Ste-Mathilde

In October 1978 the Mineral Exploration Research Institute (MERI) of Ecole Polytechnique de Montréal and the Earth Physics Branch (EPB) conducted a series of AMT profiles and soundings over the Ste-Mathilde anomaly to obtain more information about its areal extent, depth and physical character. The instruments were provided by MERI under contract to the Department of Energy, Mines and Resources.

The MERI tensor sounding equipment has been described by Pham Van Ngoc (1977). In regions where there is minimal man-made electric noise, it can measure MT fields in the frequency range from about 0.01 Hz to 1000 Hz. However, at Ste-Mathilde a major power transmission line lying only about 1.5 km from the survey area created a noisy environment, and a satisfactory response could not be obtained at frequencies above 30 Hz. The horizontal telluric components E_x and E_y and the horizontal magnetic components H_x and H_y are measured simultaneously to permit tensor analysis of the data.

The profiling equipment is light and highly portable, but provides only scalar values of apparent resistivity along a direction parallel to the orientation of the telluric electrode pair. Telluric and magnetic fields are measured at a number of discrete frequencies: 1, 3, 5, 8, 21, 34, 100, 250, 400, 700, 1200 and 2000 Hz. The system is called TELMAG 2 and is described by Pham Van Ngoc (1977). In the surveys at Ste-Mathilde an electrode spacing of 20 m was used at all profiling stations. Signal-to-noise ratios were too low for data acquisition at 1, 3, 5 and 2000 Hz, but useful scalar data were obtained at the remaining frequencies.

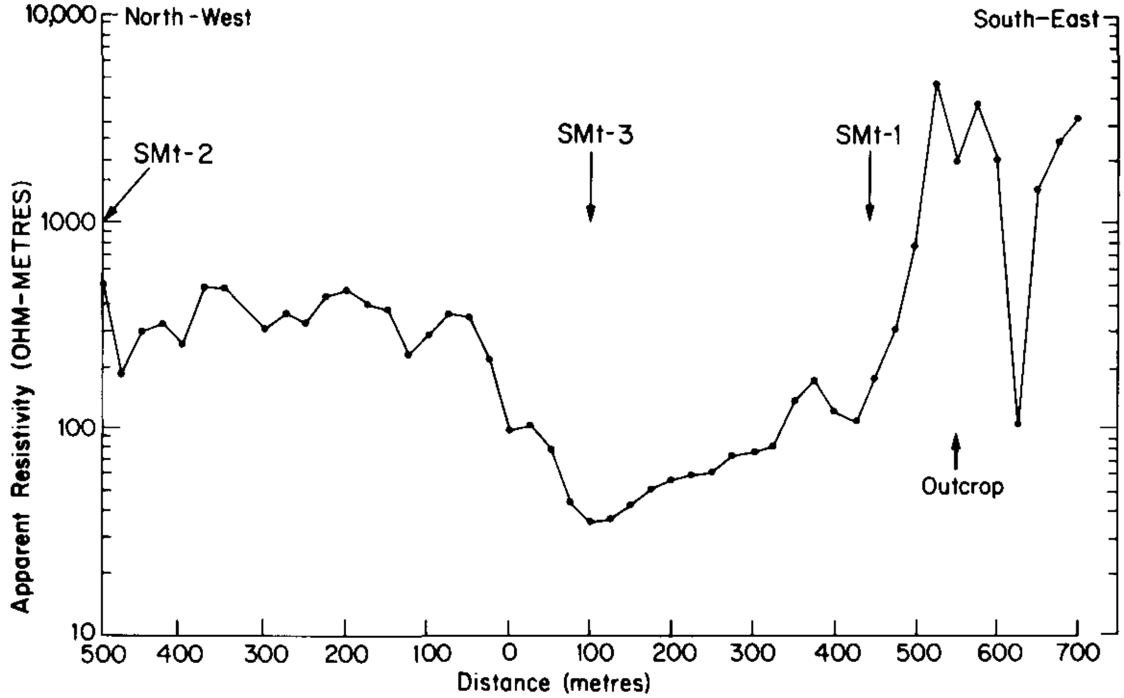

Fig. 3. Schlumberger apparent-resistivity profile for current electrodes represented by crosses in Figure 1. The approximate centres of the telluric lines for the AMT sounding stations are indicated.

AMT soundings were obtained at three locations marked SMt-1, SMt-2 and SMt-3 in Figure 1. SMt-1 is the site of the original MT station established earlier by EPB. Here the MERI audio MT system was connected to the telluric lines and electrodes already in place.

From the impedance estimates derived by spectral analysis, the apparent resistivities (ρ_a) were calculated along the direction of the major and minor axes of anisotropy (Pham Van Ngoc, 1977; Kurtz and Niblett, 1978). For SMt-1 the apparent resistivities corresponding to both principal directions of the impedance tensor are plotted against period in Figure 4. These two sets of ρ_a data extend from 0.03 s to just over 100 s. At periods between 100 and 10,000 s, the ρ_a values were derived from the long-period EPB recordings made on the same electrodes. Because of the severe attenuation of the electric field at these periods, signal-to-noise level was low and only ρ_a values along the major axis of the impedance tensor could be calculated with acceptable precision. At the high-frequency end of the graph, ρ_a values were derived from the scalar AMT data acquired at profiling stations in the vicinity of SMt-1. The error bars for these data represent the total range of ρ_a values for the five scalar stations near the sounding site. Scalar data from profiling station 5 (Fig. 1) closely overlapped the tensor sounding data whereas curves for 3, 4, 13 and 14 were somewhat higher, perhaps because of near-surface lateral changes in resistivity, and short electrode spacing.

Figure 4 also shows a plot of the skew (Swift, 1967) derived from the impedance tensor elements. Values of skew less than 0.2 indicate that the distribution of MT fields should be compatible with a one-dimensional or a two-dimensional earth structure. Substantially larger values indicate that a three-dimensional body would be required for interpretation of the ρ_a-vs-period plots, or that the signal-to-noise ratio was small.

Figures 5a and 5b show apparent resistivity values and skew acquired at stations SMt-2 and SMt-3 with the MERI AMT sounding apparatus.

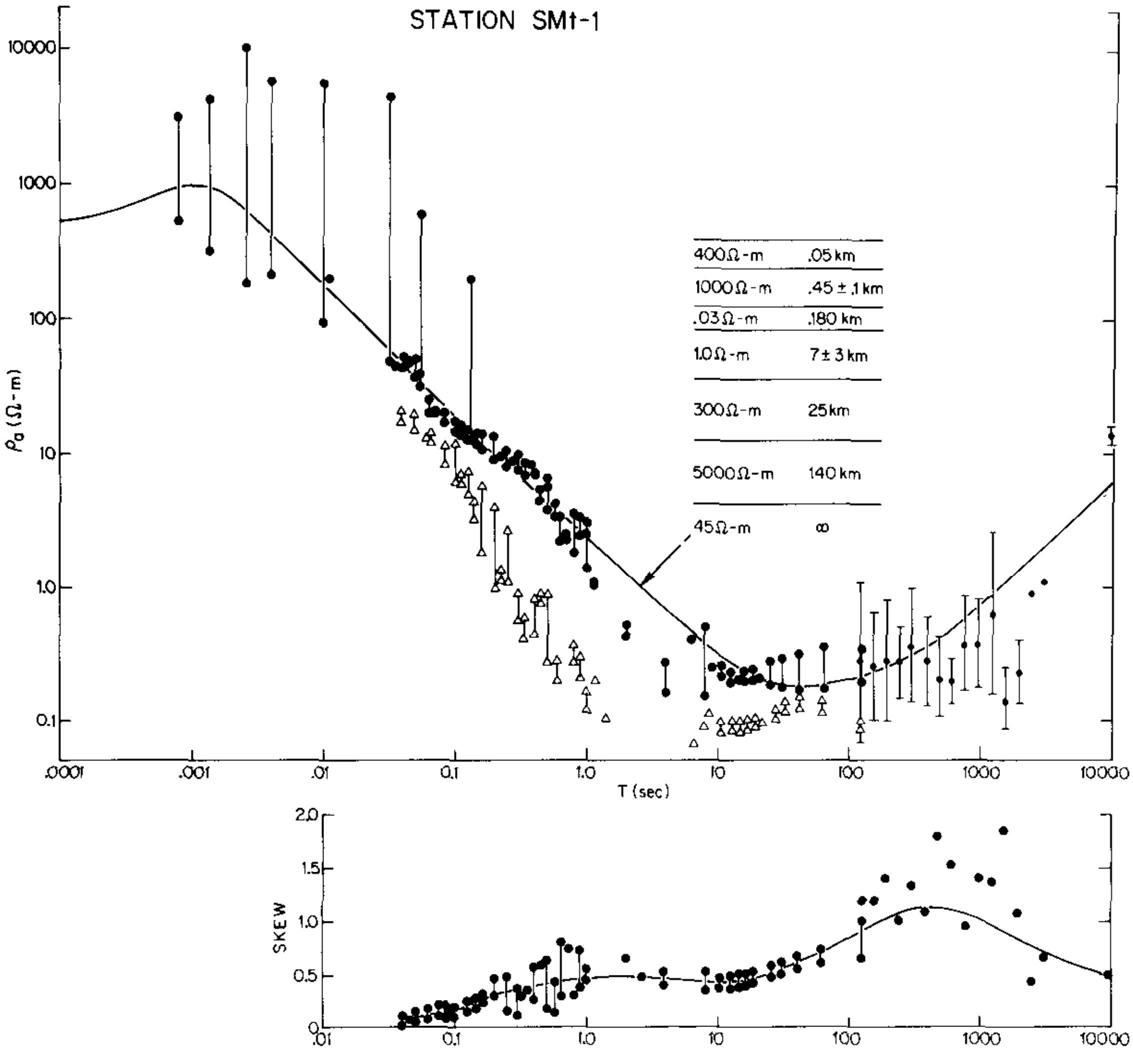

Fig. 4. Apparent-resistivity curves for SMt-1. Tensor data in the principal axes of anisotropy from .03 s to 10,000 s. Scalar data from .0008 s to .13 s. Error bars from .0008 s to 100 s represent maximum scatter in the resistivity. Bars from 100 s to 10,000 s represent two standard deviations. Solid curve is for the one-dimensional model shown. *In the upper diagram, dots are the apparent-resistivity values for the major axis of anisotropy;* triangles are values in the minor axis of anisotropy.

Scalar AMT data were obtained at a total of 22 profiling stations as shown in Figure 1. These stations form three lines or profiles, profile 1 extending in a northwest-southeast direction along an access road, and profiles 2 and 3 running in a northeast-southwest direction parallel to the main road through Ste-Mathilde. Profile 1 lies along line C of the Schlumberger resisitivity measurements and profile 2 is parallel to line E. The data are shown in the form of pseudo-sections in Figures 6, 7 and 8. In each pseudo-section the ρ_a contour interval is logarithmic ($\Delta \log \rho_a = 0.33$.) All ρ_a values were measured in the northwest-southeast direction.

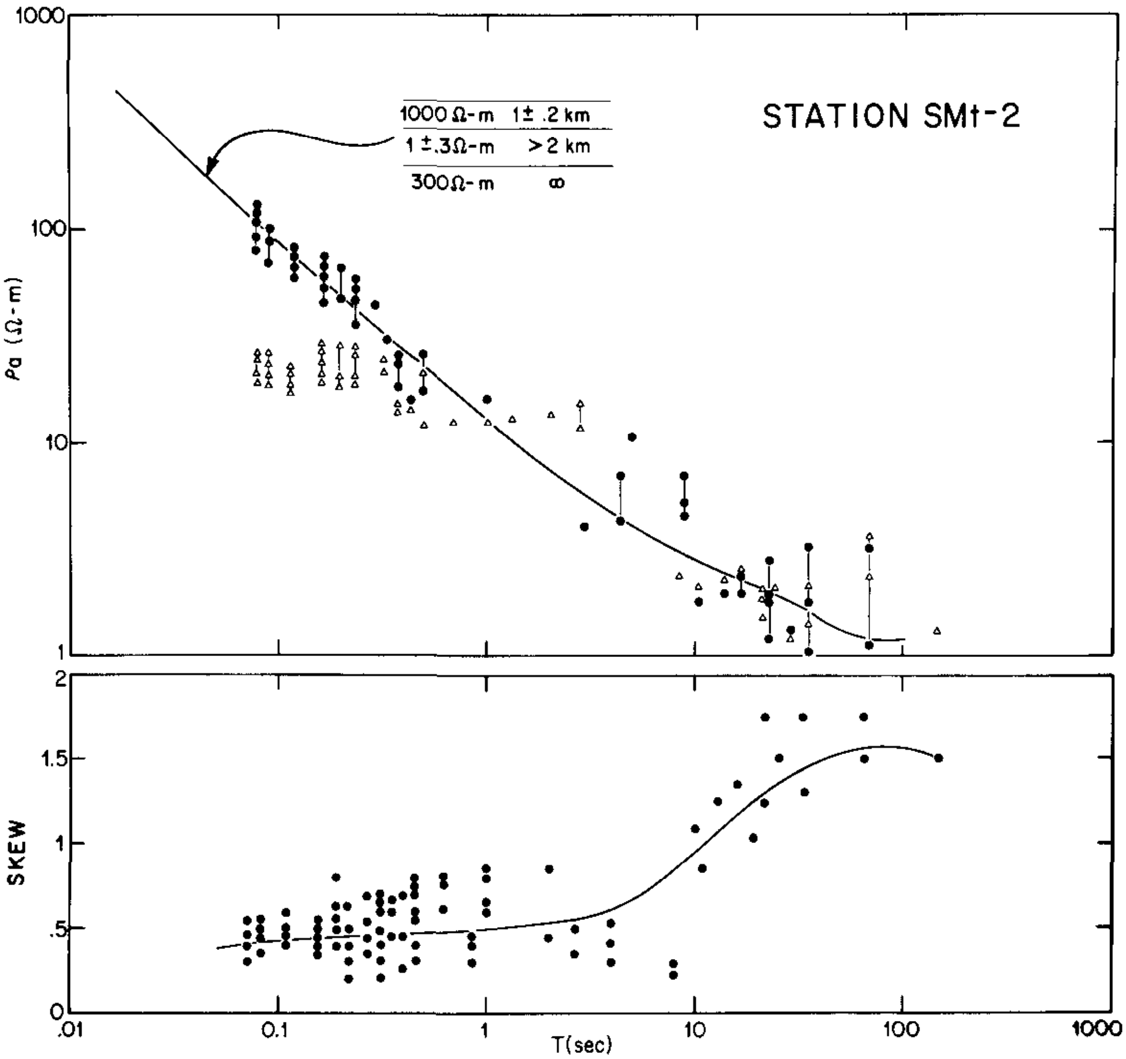

Fig. 5a. Tensor apparent resistivity in principal axes of anisotropy at SMt-2. Solid curve is for the one-dimensional model shown.

Interpretation of MT Sounding Data

The sounding data from stations SMt-1, SMt-2 and SMt-3, particularly the extended-range data of station SMt-1 (Fig. 4), clearly indicate the presence of a region of extremely low resistivity within the earth's upper crust. The data from stations SMt-1 and SMt-2 are not strongly anisotropic, because apparent resistivities along the two principal directions do not differ greatly, except perhaps for data near periods of one second at SMt-1. At station SMt-3 the data are clearly anisotropic. At all three locations the skews are generally between 0.2 and 1.0, though values larger than unity are obtained at long periods at stations SMt-1 and SMt-2. All three stations have the smallest skews at the shortest periods. This indicates that at small penetration depths of the magnetotelluric field the structure is more nearly one- or two-dimensional. At longer periods the penetration depths should become comparable with the lateral extent of the anomaly, and the MT fields therefore sense a more strongly three-dimensional structure.

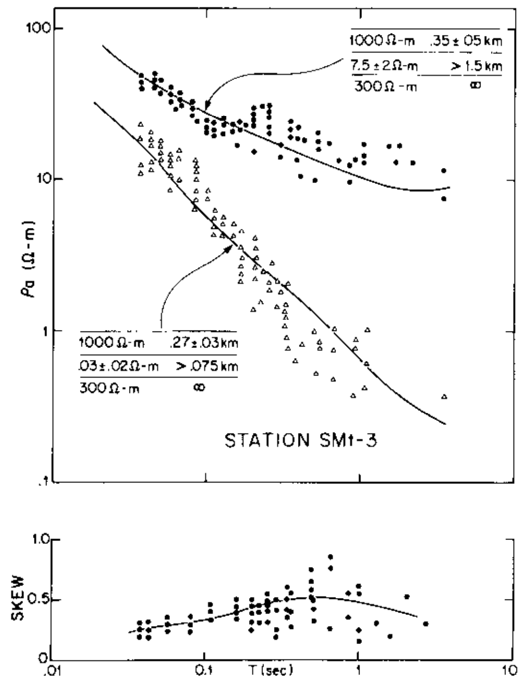

Fig. 5b. Same as Figure 5a for SMt-3.

One-dimensional models are not difficult to calculate and are commonly used to obtain a first estimate of the depth and conductivity when matched to the apparent resistivity data. A one-dimensional layered model which provides a reasonable fit to SMt-1 data is shown in Figure 4. The resistivity of the top layer was estimated from the EM31 measurements and that of the second layer from EM34. The AMT profiles (Figs. 6-8) indicate that the resistivity is quite variable, at least in the top 500 m, which probably reflects changes in water content related to overburden thickness and the presence of fractures, dykes or other structural irregularities. For the layers representing the lower crust and upper mantle, the thicknesses and resistivities are based on the estimates of Kurtz and Garland (1976). However, the sounding data for station SMt-1 do not resolve these layers. The only real constraint is that the resisitivity must increase by several orders of magnitude beneath the anomaly.

For a one-dimensional interpretation the top of the conductor is located at 500 ± 100 m at SMt-1. Its thickness is between 4 and 7 km, and is not well determined because of the poor signal-to-noise ratio in the long-period data. The thin 0.03 Ωm layer is necessary to model the steep slope (minus one) of the apparent resistivity curve. The thick 1 Ωm layer is required to fit the data between 10 s and 1,000 s. The model shown in Figure 4 gives the best fit of 19 that were tried. The orientation of the major axis of anisotropy (Fig. 9) varies from 65° to 18° east of magnetic north, the average being about 45°.

SMt-2 lies close to the power line, and satisfactory MT data were not obtained at frequencies above 14 Hz (0.07 s). The major axis of anisotropy (Fig. 9) is not well defined except at the shortest periods. The apparent resistivity curve (Fig. 5a) along the major axis of anisotropy is nearly parallel to the curve drawn through the ρ_a data from SMt-1. The corresponding layered model gives a conductor (1 Ωm) at least 2 km thick, beginning at a depth of about 1 km.

At SMt-3 the ρ_a curve (Fig. 5b) for the minor axis of anisotropy is parallel to the major axis curves at SMt-1 and SMt-2, but is displaced downward toward lower resistivity values. A layered model for this curve puts the top of the conductor at a depth of only 270 m. On the other hand, a similar one-dimensional interpretation for the major ρ_a curve puts the top of the conductor at approximately 350 m.

The structural direction of a two-dimensional body or an elongated three-dimensional body may be estimated from the axes of anisotropy and the tipper direction. The tipper amplitude (Vozoff, 1972) is defined as

$$T = \{|A|^2 + |B|^2\}^{1/2}$$

if A and B are derivable, at a given period or frequency, from an observed linear relationship between the magnetic field components; *i.e.*, $H_z = AH_x = BH_y$. In general, A and B are frequency-dependent and complex. For a strictly two-dimensional structure, A and B will have the same phase and the tipper direction, which is the direction of the horizontal magnetic field that best correlates with the vertical field, is given by

$$\Theta = \tan^{-1} B/A$$

More general definitions can be made when A and B have different phases (Vozoff, 1972). The tipper amplitudes at SMt-1, SMt-2 and SMt-3 are plotted in Figure 10. For SMt-1, T shows an appreciable change between periods of 0.04 and

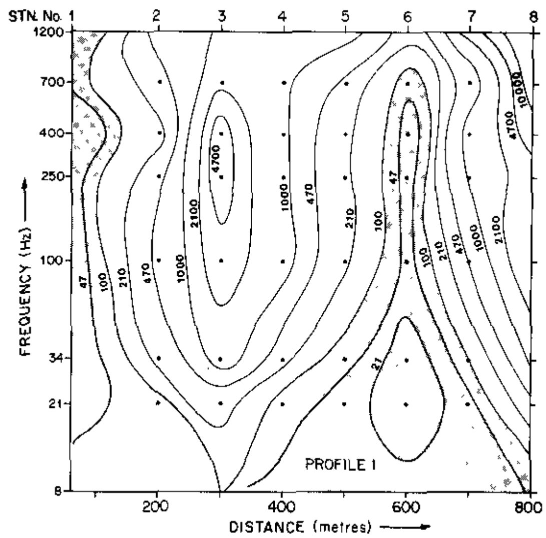

Fig. 6. Profile 1 pseudo-section.

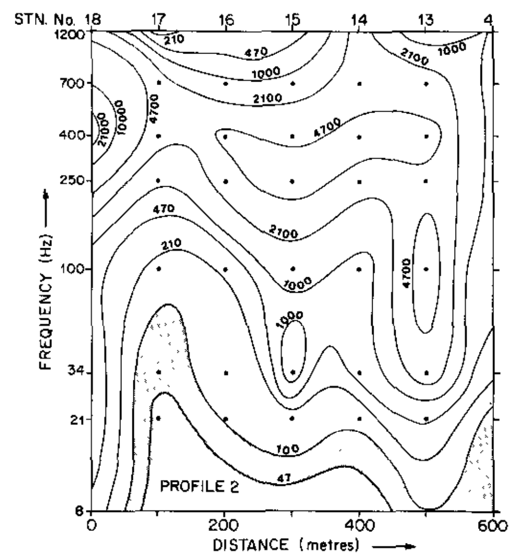

Fig. 7. Profile 2 pseudo-section.

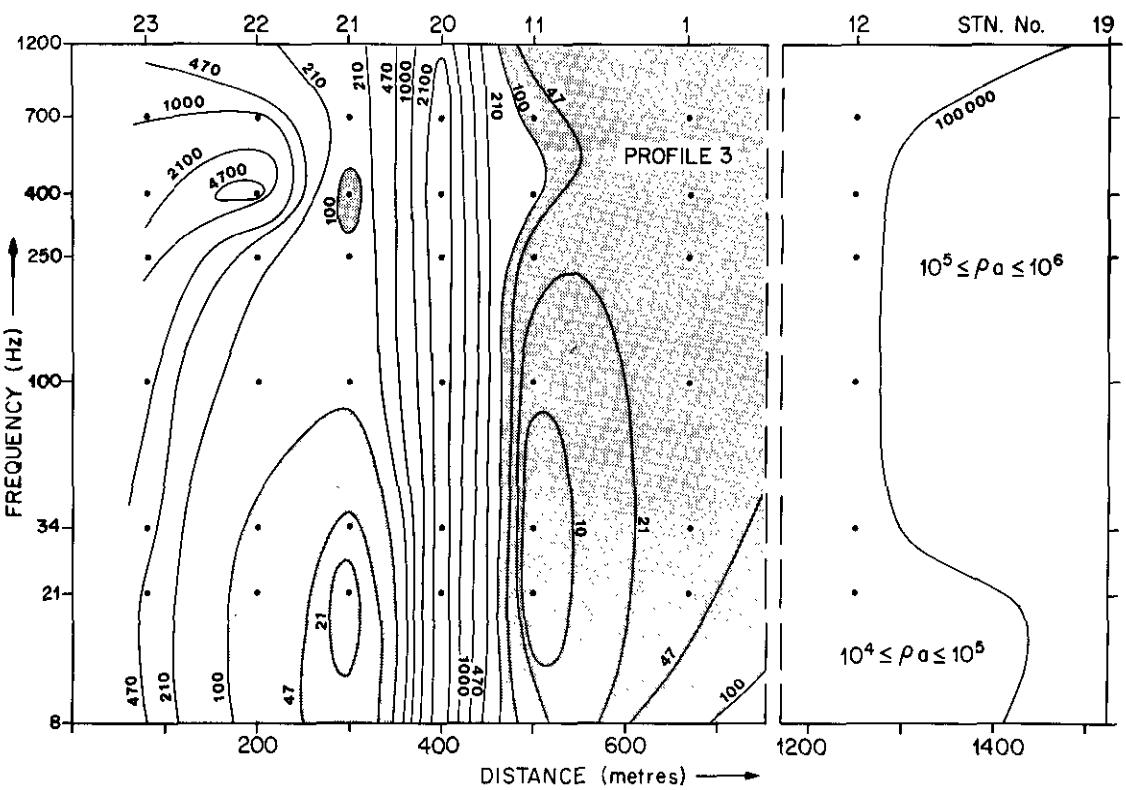

Fig. 8. Profile 3 pseudo-section.

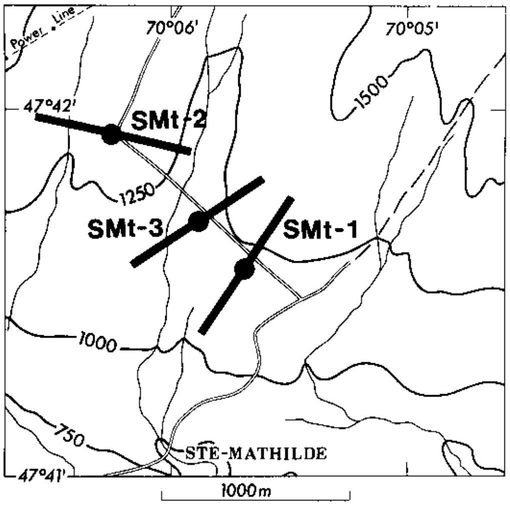

Fig. 9. Major axes of anisotropy at 10 Hz for the three AMT sounding stations.

1 s, with a maximum at about 0.15 s. At these periods, therefore, the magnetic field is displaying a strong inductive response to the local anomaly. The tipper direction (Fig. 11) determines whether the major or minor axis of anisotropy aligns with the strike of the structure. At SMt-1 and SMt-3 the structural directions lie perpendicular to the major axis of anisotropy. At SMt-2 the tipper indicates that the structure strikes parallel to the major axis of anisotropy.

Interpretation of AMT Profiling Data

At frequencies of 100 Hz and higher, Figures 6, 7 and 8 show that ρ_a is usually well above 100 Ωm except at stations 1, 6 and 11, where low values are probably caused by conducting fractures or other kinds of discontinuities near the surface. On all three profiles, the lowest apparent resistivity values are usually found at 8 and 21 Hz, and it seems clear that at these frequencies the MT field is penetrating deep enough to detect the conducting body. Profile 3 (Fig. 8) is particularly interesting because of the enormous resistivity contrast between stations 1 and 11 and stations 12 and 19 at the northeast end of the line. These latter two stations must lie just outside the anomalous zone.

At the southwestern end of profiles 2 and 3 (Figs. 7, 8) the anomaly either dips steeply to greater depths or vanishes. Along profile 1 (Fig. 6), running northwest toward the power line, the top of the anomaly is probably showing at frequencies of 8 and 21 Hz, though it appears to dip to greater depths beyond station 6. The sounding results from station SMt-2 tend to support this conclusion. Some of these features are shown in Figure 12, which is a contour plot of the scalar resistivities at 21 Hz. Here the structural complexities at depth are clearly demonstrated and the approximate location of the conductive zone is outlined. The figure also shows the predominantly northwest-southeast structural trend and the highly resistive rocks to the northeast. Note that data for station 20 are not included on the contour map because its anomalously high resistivity is not supported by adjacent stations.

Conclusions

The results presented in this paper illustrate the diagnostic value of the tensor AMT method which permits the calculation of axes of anisotropy, skews, and tipper amplitudes and directions. The scalar AMT technique lends itself to rapid reconnaissance and fills in the gaps between MT sounding stations. The Geonics EM31 and EM34 survey showed no evidence for conducting material within 50 m of the surface. However, the DC Schlumberger soundings penetrated to the upper part of the conductive region and confirmed the implications of the MT data.

The MT anomaly near Ste-Mathilde is characterized by extremely severe attenuation of the telluric field at periods longer that 1s over a limited region. The data indicate that a rather large body of unusually high electrical conductivity must exist at fairly shallow depths in the crust. One-dimensional analysis of the measured apparent resistivities suggests the top of the conductor lies at depths varying between about 250 m and 1,000 m at SMt-1, SMt-2 and SMt-3.

The structural directions from the three sounding stations indicate a northwest-southeast trending structure dipping to greater depths toward the northwest. SMt-1 and SMt-3 are probably near the northeastern flank of the conducting body, as their major axes of anisotropy lie perpendicular to the structural direction. These stations also have large tipper values, indicating that neither is directly over the most conductive part of the anomaly.

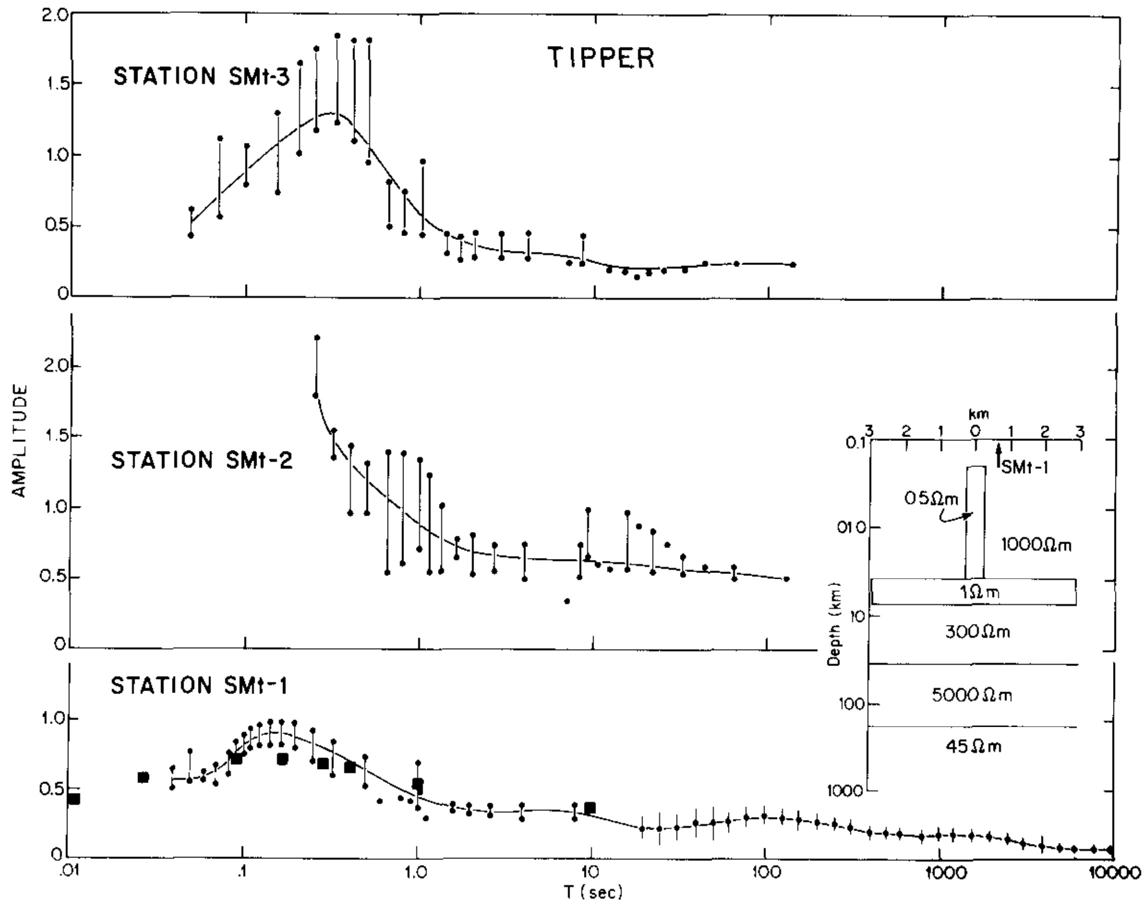

Fig. 10. Tipper amplitude as a function of period at the three AMT sounding stations. Tipper amplitudes for the two-dimensional model are shown as squares for station SMt-1.

The two-dimensional modelling programs of Pascoe and Jones (1972) were utilized to determine the magnetic response of the model shown in Figure 10. The tipper of the model compares well with that for SMt-1, although the amplitude of the experimental results has a sharper peak. This is probably caused by the three-dimensional character of the anomaly, which could result in channelled currents and end effects. However, the apparent resistivities computed for this model are more than an order of magnitude larger than the experimental MT curves for SMt-1, although the model and experimental curves are parallel. A model was constructed for which the resistivity curves agreed, but the tipper amplitude then had the wrong frequency response. It was decided to fit the tipper data, because the telluric fields are strongly influenced by very local lateral changes in conductivity, whereas the tipper responds to the integrated effect of all currents in the area.

It is interesting to note that the directions of the tipper and of the major axis of anisotropy are not inconsistent with those that would be observed with a conducting prism, as shown in Figure 11 (Reddy *et al.,* 1977). However, the anomaly is likely to be more complex than this, and further surveys are required.

The sounding data have been interpreted by means of one-dimensional or two-dimensional assumptions and models, and such simplified concepts are obviously inadequate for a rigorous treatment. Nonetheless they do provide crude estimates of the depths where the anoma-

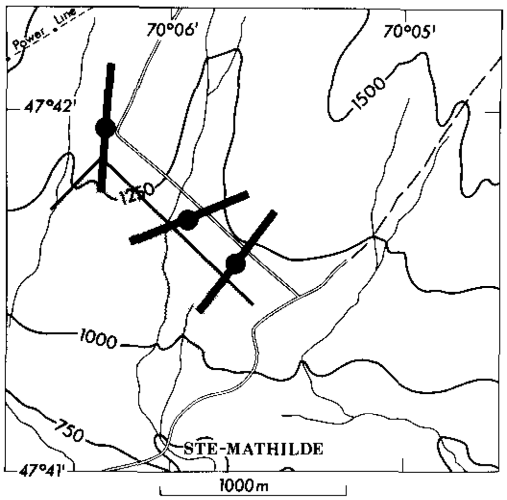

Fig. 11. Tipper directions at 10 Hz for the three AMT sounding stations. The shaded area indicates the approximate position of the buried conductive body.

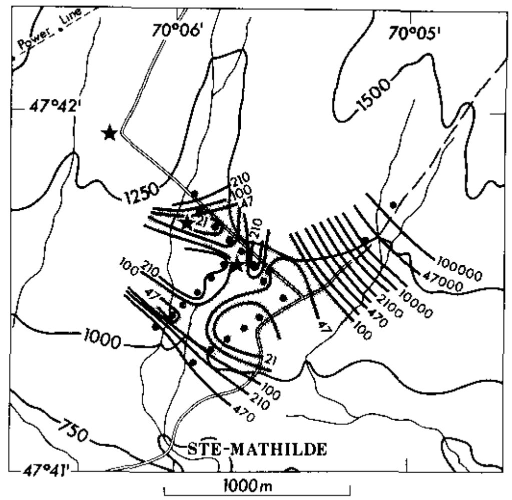

Fig. 12. Countours of constant apparent resistivity (ohm-metres) at 21 Hz at the AMT profiling stations. The shaded areas have apparent resistivity less than 100 ohm-m.

lous feature is expected to lie, and much more sophisticated and expensive analytical techniques would be required to improve the results. It is clear, from the strong suppression of the telluric field and the apparent resistivity data plotted in Figure 4, that the anomaly must be of sufficient size to extend over a few km in depth. The resistivities shown in the layered interpretations could be considerably in error (100% or more). We believe that values as low as 0.03 Ωm may reflect the inadequacies of simple analytical models and are probably not realistic in a physical sense.

The cause of the unusually high electrical conductivities is unknown. It may be that a large volume of broken and fractured rock has become inundated with highly conductive aqueous solutions; it is possible that graphitic, sulphide, or ferrous mineralization is a contributing factor. The aeromagnetic map (Geological Survey of Canada, MAP 1965G) for the region shows that the anomalous zone is situated on the southeast flank of a small magnetic high that strikes northeast-southwest. However, the high is similar to many others on the map sheet and there appears to be nothing unique in its appearance. The zone lies between two flight lines (approximately 800 m apart), and it is possible a small anomalous zone would not have been detected.

The presence of a granite body surrounded by migmatites that contain pegmatites suggests conditions could have been favourable for hydrothermal deposition of metallic ores. It is interesting to note that several areas of copper mineralization have been recognized in the area. One, about 4 km to the south of SMt-1, consists of pyrite and chalcopyrite disseminated in the gneiss (Rondot, 1966).

References

Kurtz, R. D. and Garland, G. D., 1976, Magnetotelluric measurements in eastern Canada: Geophys. J. R. astr. Soc., v. 45, p. 321-347.

_____ and Niblett, E. R., 1978. Time-dependence of magnetotelluric fields in a tectonically active region in eastern Canada: J. Geomag. Geolectr., v. 30, p. 561-577.

_____, Niblett, E. R., Chouteau, M. and Newitt, L.R., 1979, An electrical resistivity anomaly near La Malbaie, Quebec: Open file report of the Earth Physics Branch, 79-4.

Pascoe, L. J. and Jones, F. W., 1972, Boundary conditions and calculation of surface values for the general two-dimensional electromagnetic induction problem: Geophys. J. R. astr. Soc., v. 27, p. 179-193.

Pham Van Ngoc, 1977, Magnetotelluric reconnaissance survey of the Lillooet Valley, British Columbia: Open file report of the Earth Physics Branch, 77-20.

Reddy, I. K., Rankin, D. and Phillips, R. J., 1977, Three-dimensional modelling in magnetotelluric and magnetic variational sounding: Geophys. J. R. astr. Soc., v. 51, p. 313-326.

Robertson, P. B., 1968, La Malbaie structure, Quebec — a Palaeozoic meteorite impact site: Meteoritics, v. 4, p. 1-24.

———, 1975, Zones of shock metamorphism at the Charlevoix impact structure, Quebec: Geol. Soc. America Bull., v. 86, p. 1630-1638.

Rondot, J., 1968, Nouvel impact meteoritique fossile? La structure semicirculaire de Charlevoix: Can. J. Earth Sci., v. 5, p. 1305-1317.

———, 1966, Geology of La Malbaie area, Charlevoix County: Dept. of Natural Resources, Québec, Prelim. Rept. 544.

Scott, W. J., 1981, Resistivity soundings near La Malbaie, Quebec: Geol. Surv. Canada, Current Research (*in press*).

Stevens, A. E., 1980, Re-examination of some larger La Malbaie, Quebec, earthquakes (1924-1978): Bull. Seismological Soc. America, v. 70, p. 529-557.

Swift, C. M., 1967, A magnetotelluric investigation of an electrical conductivity anomaly in the southwestern United States: Ph.D. Thesis, M.I.T.

Telford, W. M., Geldart, L. P., Sheriff, R. E. and Keys, D. A., 1976, Applied Geophysics: Cambridge, the Cambridge University Press.

Vozoff, K., 1972, The magnetotelluric method in the exploration of sedimentary basins: Geophysics, v. 37, p. 98-141.