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ONTARIO GEOLOGICAL SURVEY

Open File Report 5615

Ontario Geoscience Research Grant Program
Grant No. 118
Surface Electromagnetic Mapping in Northern Ontario

by

J.D. Redman and D.W. Strangway

1986

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V.G. Milne

V.G. Milne, Director
Ontario Geological Survey

ONTARIO GEOSCIENCE RESEARCH GRANT PROGAM

Final Research Reports

Preface

This publication is a final report of a research project that was funded under the Ontario Geoscience Research Grant Program. A requirement of the Program is that recipients are to submit final reports within six months after termination of funding.

A final report is defined as a comprehensive summary stating the findings obtained during the tenure of the grant, together with supporting data. It may consist, in part, of reprints or preprints of publications and copies of addresses given at scientific meetings.

It is not the intent of the Ontario Geological Survey to formally publish the final reports for wide distribution but rather to encourage the recipients of grants to seek publication in appropriate scientific journals whenever possible. The Survey, however, also has an obligation to ensure that the results of the research are made available to the public at an early date. Although final reports are the property of the applicants and the sponsoring agencies, they may also be placed on an open file. This report is intended to meet this obligation.

V.G. Milne
Director
Ontario Geological Survey

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Abstract

There are many areas in Northern Ontario in which there are considerable thicknesses of a clay-rich and hence electrically conductive overburden. This conductive overburden is a hindrance to the application of traditional EM exploration methods in areas with high mineral potential. The AMT(Audio frequency magnetotelluric) method with it's greater depth penetration is particularly suited to this problem of mapping the conductivity of the basement rocks beneath thick conductive overburden. AMT surveys were carried out on a regional scale at six sites in the Timmins, Cochrane and Kirkland Lake region. The AMT technique was successful in all of these areas in mapping the basement conductivity. In the Moody township area our data show that the metasediments are highly anisotropic in their conductivity. We attribute this to a preferred direction of fracturing or to the presence of cracks parallel to the fabric of steeply dipping metasediments. A detailed survey at the Night Hawk Lake geophysical test site clearly delineated the conductive graphitic zone and our data suggests that the conductive feature extends further to the west than previously thought. As part of our research, since we thought it was important to understand in some detail the electrical structure of the overburden, we have carried out laboratory and in situ measurements of the conductivity of the sand, silt and clay soil components of the overburden. The clays are the most conductive overburden component with an average resistivity of 23 ohm-m. Complex resistivity measurements on these silts and clays, in the frequency range .01 Hz to 1 MHz, show that they have little frequency dependence in their resistivity. In areas in which the conductivity varies laterally, as well as with depth, tensor AMT measurements can provide important information on the electrical structure that can not be obtained with the scaler AMT method. We have developed a tensor AMT system and carried out preliminary testing.

SURFACE ELECTROMAGNETIC MAPPING IN NORTHERN ONTARIO

by

J.D. Redman

D.W. Strangway

Manuscript approved for publication by V.G. Milne, Director, Ontario Geological Survey, March 19, 1986.
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1. INTRODUCTION:

The use of traditional electromagnetic exploration and mapping techniques in Northern Ontario is hindered in many areas by the presence of an extensive, thick and conductive overburden layer. The AMT(Audio Frequency Magnetotelluric) method with it's greater depth penetration is particularly suitable in these environments. We have applied the AMT method, at six sites, to the mapping of the electrical structure of the basement rocks beneath a thick overburden layer. As well, for the purpose of characterizing the electrical structure of the overburden, we have carried out laboratory and in situ measurements of the electrical conductivity of the sand, silt and clay soils that comprise the overburden.

Our study area, shown in figure 1, has been limited to the eastern part of the Abitibi clay belt that lies within Ontario. This region is an economically important mining region but it is covered by extensive areas of thick conductive overburden. Thus it is an excellent area in which to apply the AMT technique.

Our work on this project can be grouped into the following catagories:

1. Regional AMT surveys with relatively large station spacings(.5-1 Km). These surveys have been carried out in the following areas: Moody Township (A), Bowman Township (E), Marter Township (B,C), Elk Lake (D), Night Hawk Lake (F), and Kirkland Lake (G).
2. A detailed AMT survey with short station spacings (25-150 m). This survey was carried out on the Night Hawk Lake geophysical test site.
3. Laboratory and in situ measurements of the complex resistivity of clays, sands and silts from the region.
4. Development of a tensor AMT system and initial tests at the Milton site.

2. DESCRIPTION OF THE AMT METHOD:

In the AMT method, the magnitude of the apparent resistivity is measured at each station for frequencies in the audio range (10 Hz.-10 kHz). The functional dependence of the apparent resistivity with frequency is used to deduce the variation of resistivity with depth in the subsurface. Anomalously conductive or resistive zones are outlined by the dependence of resistivity on the horizontal position. The AMT method has the advantage that a source transmitter is not required making the field operations relatively simple. As well the measurement time of 30 minutes per station, for a single orientation, is relatively short.

The apparent resistivity is determined at a set of 11 discrete frequencies from 13 Hz to 8.6 kHz. The apparent resisitivity is computed from simultaneous measurements, at a specific frequency, of the horizontal orthogonal components of the electric and magnetic field at the earths surface according to:

$$\rho_a = \frac{1}{2\pi f \mu} \left| \frac{E}{H} \right|^2$$

E-Magnitude of electric field at frequency f (volt/m)
H-Magnitude of magnetic " " " " (amp/m)
μ-Magnetic permeability (henry/m.)

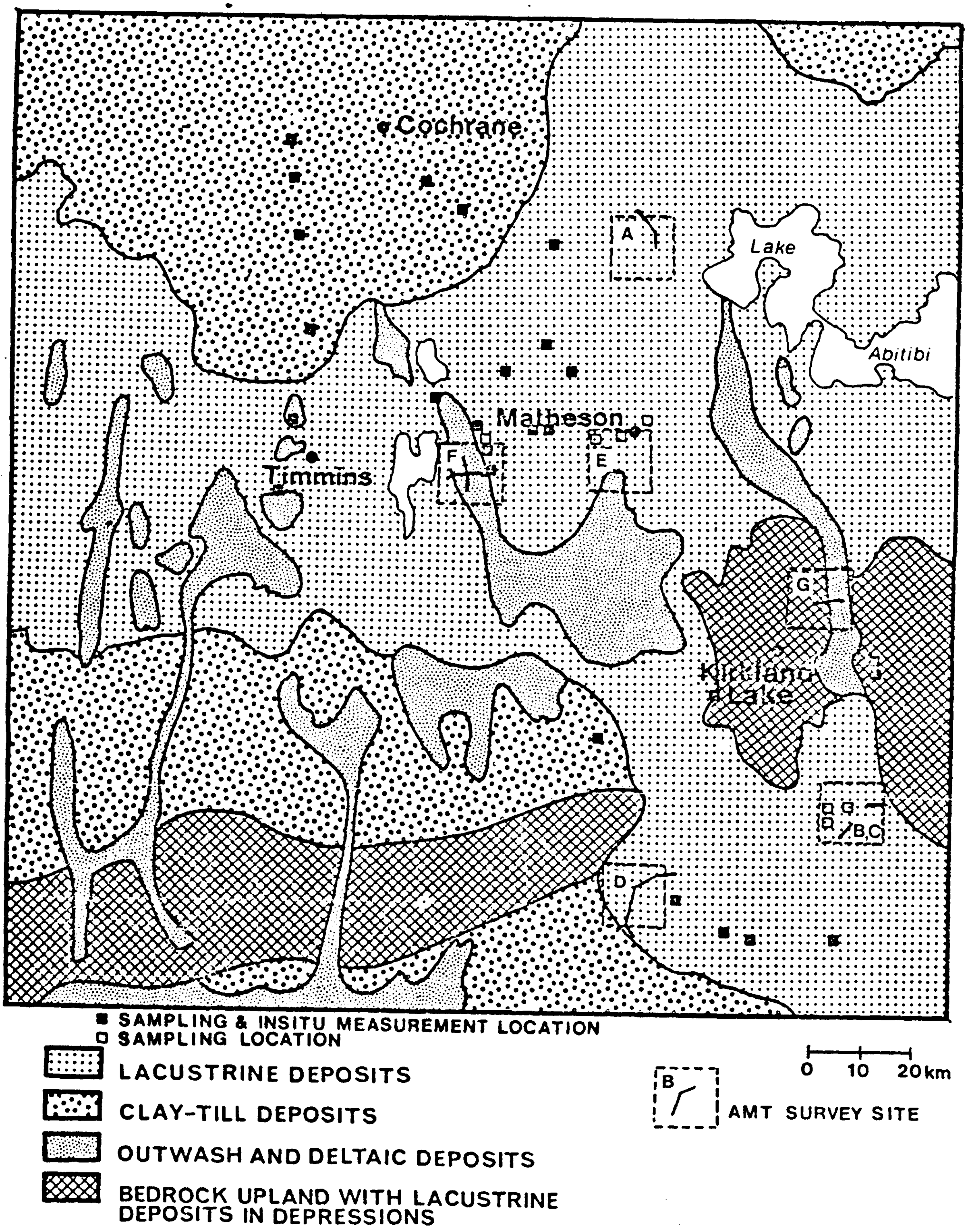

Figure 1. Study area showing the AMT survey sites and clay sampling locations for the electrical properties measurements.
AMT survey sites:
A- Moody Township, B,C- Marter Township, D- Elk Lake,
E- Bowman Township, F- Night Hawk Lake, G- Kirkland Lake.

An induction coil is used to measure the magnetic field and an electric dipole is used to measure the electric field. The apparent resistivity is measured for two orthogonal orientations of the electric and magnetic field sensors. The measurement of the apparent resistivity in two orthogonal directions permits one to determine if the earth can be successfully modeled with a layered earth structure. The survey lines are oriented approximately perpendicular to the known principal structural direction for the basement rocks.

The scalar AMT data can be plotted and viewed, for interpretation purposes, in many different forms. For the purposes of depth sounding, the apparent resistivity is plotted as a function of frequency. Then, for a one dimensional earth, a horizontally layered model, involving the layer thicknesses and resistivities as parameters, can be used to fit the data by an inversion technique. This procedure gives the resistivity variation for a depth range limited by the frequency range measured. When the apparent resistivity, at a fixed frequency, is plotted as a function of distance along the survey line, the resulting profile directly identifies lateral variations in resistivity. Two-dimensional forward modelling can be used to fit these profiles with a two-dimensional electrical model.

The Bostick transformation(Bostick, 1972) is used to compute an approximation to the variation of resistivity(the Bostick resistivity) with depth from the measured dependence of apparent resistivity on frequency.

In the tensor AMT method one, determines the elements of the impedance tensor Z_{ij} and associated apparent resistivity $_{ij}$ that relate the measured horizontal components of the electric and magnetic fields at frequency w.

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix} \qquad \rho_{ij} = \frac{1}{\omega\mu} |Z_{ij}|^2$$

The tipper defined by two complex coefficients A,B relates the measured vertical magnetic field to the horizontal field.

$$H_z = AH_x + BH_y$$

The tensor technique and the analysis and interpretation of the associated impedance tensor and tipper is discussed in Vozoff, 1972.

3. REGIONAL AMT SURVEYS:

3.1 Moody Township:

The 20 km north-south AMT survey line(43 stations) in this region crosses several different basement rock units mapped as metavolcanics, ultramafics , metasediments and felsic intrusives. These basement rocks have an approximately east-west geologic strike. The ratio of the apparent resistivity measured in the east-west direction to that measured in the north-south direction, which is shown in figure 2, clearly indicates the high degree of anisotropy over the metasediments and metamorphosed ultramafic rocks. The more conductive east-west direction, which is consistent with the geologic strike direction, may be related to the principal orientation of major fractures or to the presence of water-filled cracks which may be parallel to the fabric of steeply dipping metasediments. For the stations over the metavolcanics, fitted one dimensional models give a surface layer of 100 m of 450 ohm-m overburden overlying the metavolcanics with resistivities in the range 8000-50000 ohm-m. The two dimensional nature of the metasediments and ultramafics precludes fitting a layered earth model to these data.

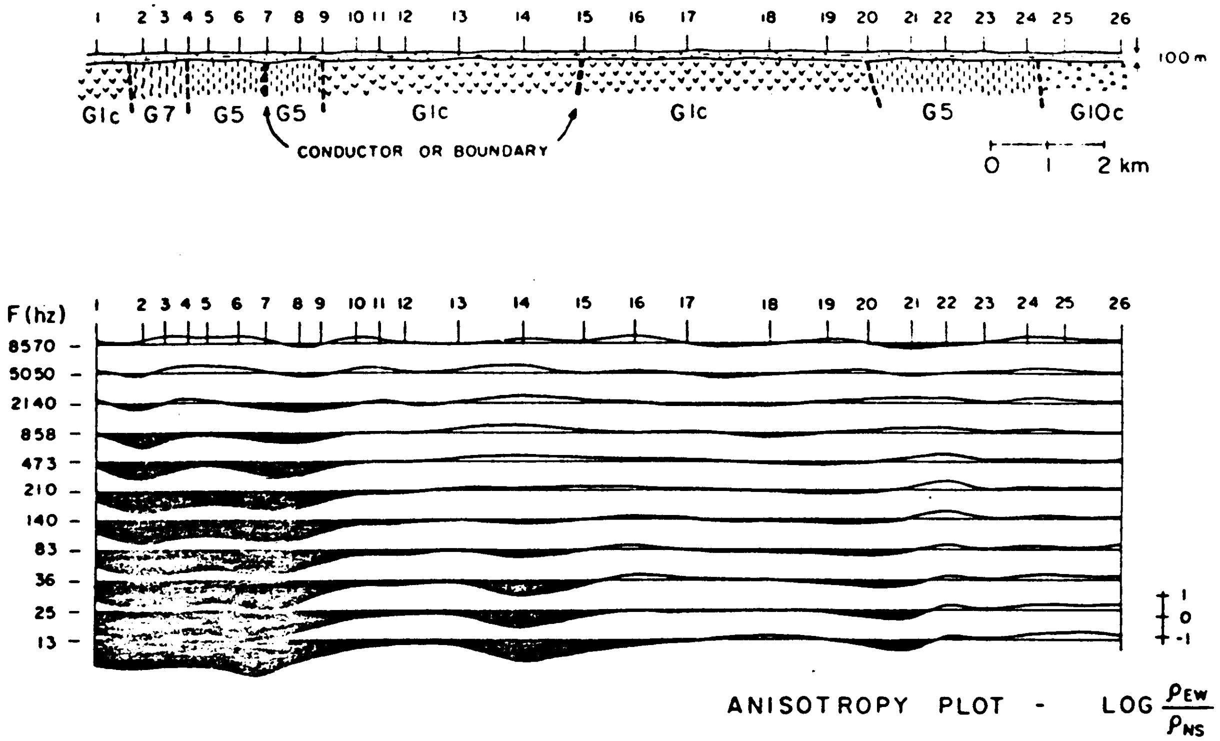

Figure 2. A sketch of the geologic section with the AMT stations and the anisotropy plot for the north-south profile in Moody township. Lithologic units (Early Precambrian): G1c-Metavolcanics, G7-Ultramafics, G5-Metasediments, G10c-Felsic Intrusives. All units are covered with approximately 100 m of overburden.

3.2 Marter Township:

Two profiles were completed in this region. The data for profile B indicate that the basement volcanics and the overburden are relatively homogeneous with no lateral variation. The sands and gravels are generally on the order of 100 m thick with resistivites of 800 to 3000 ohm-m. The basement rocks have resistivities of 20,000 to 60,000 ohm-m.

The data for profile C also indicate that the basement rocks in the area are relatively homogeneous in their electrical conductivity with little lateral variation. A one dimensional interpretation of the apparent resistivity data gives the bedrock basin structure shown in figure 3. This interpretation is consistent with the section obtained by drilling.

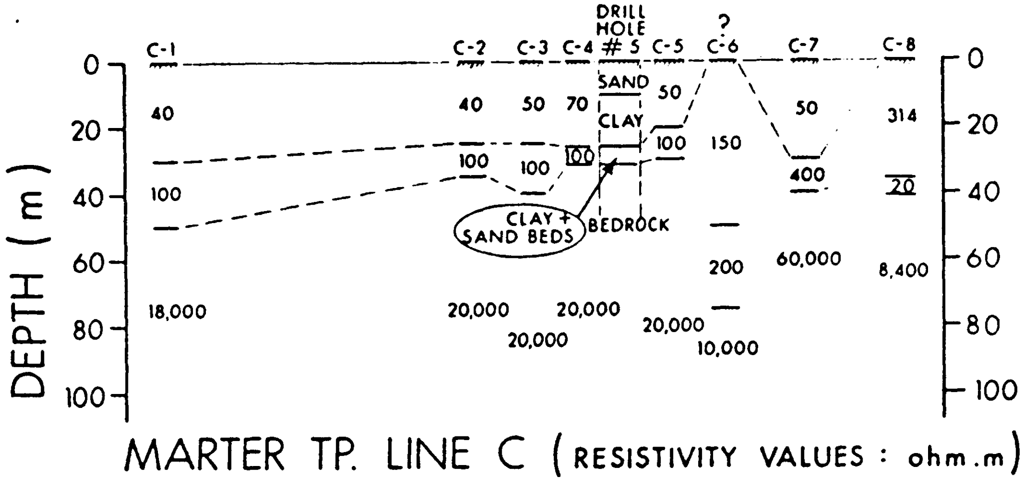

Figure 3. Electrical cross section obtained by one dimensional inversion of apparent resistivity data for profile C.

3.3 Elk Lake:

The profile in the Elk Lake region was selected to sample the Cobalt Group sedimentary rocks between intrusive rocks to the north and south, and to cross the Montreal River fault. The interpreted average electrical section for 8 stations from the Cobalt Group consists of 280 m of 2000 ohm-m Cobalt sedimentary rocks overlying a 100 m thick and 1000 ohm-m weathered layer. Underlying the weathered layer are Precambrian metavolcanics with resistivities of approximately 25,000 ohm-m. Our interpretation suggests that the Montreal River fault, which shows up clearly on the profiles, dips to the southwest.

3.4 Bowman Township:

In this region southwest of Matheson, 50 stations were placed approximately on a grid pattern over a rectangular area with dimensions of 13 km by 11 km. The surface material consists mostly of clay plain with some eskers and bedrock outcrop. The clay plain in the north has resistivities that are generally less than 100 ohm-m with 20-30 ohm-m in some localities. Contour plan maps of overburden thickness(figure 4) and resistivity, and basement resistivity were created from one-dimensional inversions of the data at each station. The map of the basement resistivities shows that for this area the felsic metavolcanics are more resistive than the intermediate to mafic volcanics and demonstrate that we are quite sucessfull at mapping through conductive clay cover.

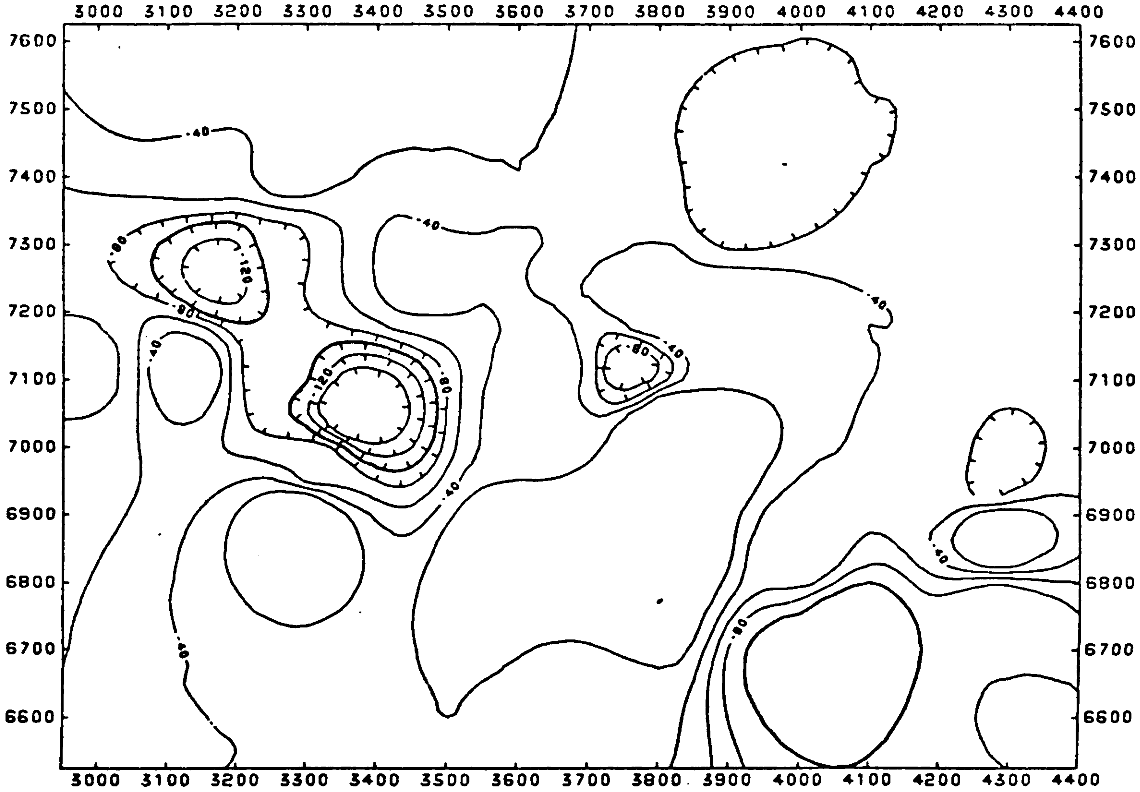

Figure 4. Overburden thickness(meters) for the Bowman township survey area derived from one-dimensional inversions of the apparent resistivity data. The distance scales are in meters.

3.5 Night Hawk Lake:

This regional survey of 37 stations covers the area surrounding the geophysical test site with a north-south and east-west profile centered on the test site. In general the interpretation shows there is a moderately resistive surface layer of 500 ohm-m(esker and outwash plain) overlying basement rocks with resistivities on the order of 10,000 ohm-m. The resistivity of the surface layer decreases to 100 ohm-m towards the west and to the south as a result of more clay in the overburden. There is a zone of highly resistive basement rocks that shows up clearly on the western leg of the east-west profile. This zone corresponds to a basement unit of strongly carbonatized volcanic rocks. In the northern part of this survey area one of our stations has a high degree of anisotropy perhaps reflecting the presence of the Destor-Porcupine fault in this region.

3.6 Kirkland Lake:

This survey of 13 stations was completed in Arnold and Morrisette Townships north of Kirkland Lake. Resistivities of the surface layer on the Munro esker are 10,000 to 50,000 ohm-m compared to 250 ohm-m for the clay rich overburden on the western boundary of the esker. The high resistivities seen in eskers provide a relatively transparent window that allows the AMT method to map with high resolution the underlying basement rocks.

4. NIGHT HAWK LAKE GEOPHYSICAL TEST SITE DETAILED SURVEY:

At the test site, 36 stations were measured on a rectangular grid with 150 by 200 m spacing. This detailed survey clearly delineated the known graphitic conductor(Barlow et al, 1982 and 1983) in the basement rocks. The conductive zone as outlined on the plan map (figure 5) of the contoured Bostick resistivity at a depth of 200 m appears to have a length of 700 m and to extend further to the west than previously thought. The AMT method is able to detect the presence of the conductive body beneath the clay cover where other methods fail. Detailed measurements using a 25 m station spacing put the northern and southern edge of the conductive body at 100 N and 200 S.

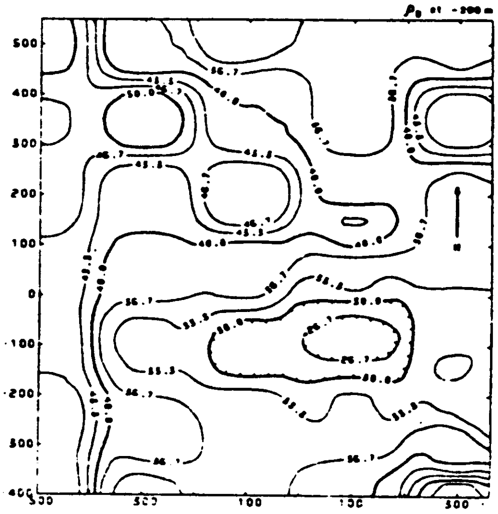

Figure 5. Bostick resistivity plan map at a depth of 200 m at the Night Hawk Lake test site. Contour labels are in units of 10 log ρ_a .

Two-dimensional modelling(figure 6) shows that a wedge shaped body of limited depth extent produces a magnetotelluric response similar to that observed in our data. One-dimensional modelling of our AMT data in the northern part of the grid away from the conductor gives a 400 ohm-m and 94 m thick overburden layer overlying 170 m of bedrock with a resistivity of 9400 ohm-m. The section is underlain by bedrock with a resistivity of 34,000 ohm-m. A controlled source AMT survey at the test site gives resistivity anomalies that are identical to those observed in our AMT survey(personal communication, Phoenix Geophysics).

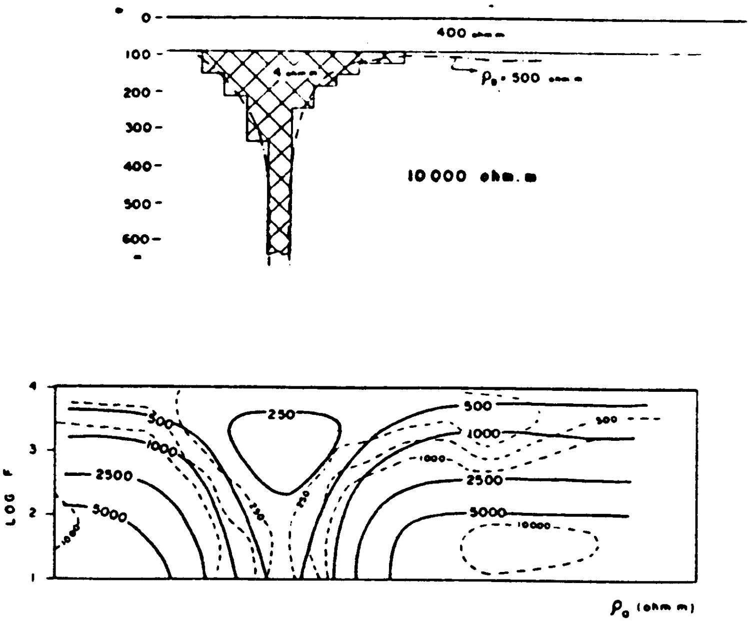

Figure 6. Two-dimensional model used to fit the apparent resistivity data over the conductive body and the psuedosection of the model response(solid lines) and the measured response(dashed lines).

5. Tensor AMT Measurements:

If the resistivity of the earth varies laterally as well as with depth(i.e. a one or two-dimensional earth) then the scalar AMT method is more difficult to interpret than the tensor AMT method. As well, the tensor method provides more information about the nature of the resistivity structure such as the strike directions for two dimensional structures and indicates whether the electrical structure is one, two or three-dimensional. However, the tensor technique requires more sophisticated instrumentation involving the simultaneous digitization of the signals measured on two electric field sensors and three magnetic field sensors and the computation of the magnitude and phase of the signals in narrow bands within the frequency range of interest. The greater degree of difficulty in carrying out tensor measurements has in the past limited their use to the low frequencies in which only one or two stations per day are measured. The amount of data analysis that can now be carried out in the field in a reasonable time using microcomputers allows the tensor AMT technique to be used more routinely.

As part of this project, we have developed a tensor AMT system capable of measuring the tensor apparent resistivity in the frequency range 1 Hz to 10 kHz. Field tests of this system have been carried out at the Milton test site. The principal components of the truck mounted system are a preamplifier, lowpass filter, data acquisition unit and a computer for data storage and analysis. The six channel system collects data at a maximum rate of 40 kHz. In our present system we measure two horizontal components of the electric and magnetic field and the vertical magnetic field. The full frequency range has been divided into four bands, 1-40 Hz; 40-400 Hz; 400-4000 Hz; 4-10 kHz.

The preamplifiers provide a selectable broadband signal amplification and have rejection filters for 60 and 180 Hz. The low-pass filters, for which the cut-off frequency can be set for the appropriate band, prevent aliasing of the power spectra by signals whose frequency content is above the band of interest. The data acquisition unit digitizes the analog signals on the five channnels and stores the results in it's own memory for each data cycle. The data cycle can be up to 1024 data samples in length. The data acquisition unit is independent of the computer, when collecting data, but all of the parameters of the digitization process such as cycle length, sample rate, and number of channels are controlled by the computer. At the completion of a data acquisition cycle, the data is transferred from the data acquisition unit to the computer memory and then a new data acquisition cycle is initiated. The impedance tensor and the associated apparent resistivities are calculated in the field to ensure that the data quality is acceptable and all auto and cross powers of the field components are saved for more detailed analysis in the laboratory.

Preliminary testing of the equipment at our Milton test site has been carried out. A typical record, showing the outputs of the electric and magnetic field sensors for a single data acquisition cycle, is displayed in figure 7. The signals displayed on the magnetic field channels, since they are the outputs of induction coils, are the time derivatives of the magnetic fields. In figure 8, the signal amplitudes for the 400 Hz to 4 kHz band display the characteristic decrease in signal strength in the 2-4 kHz band. Apparent resistivities are shown in figure 9.

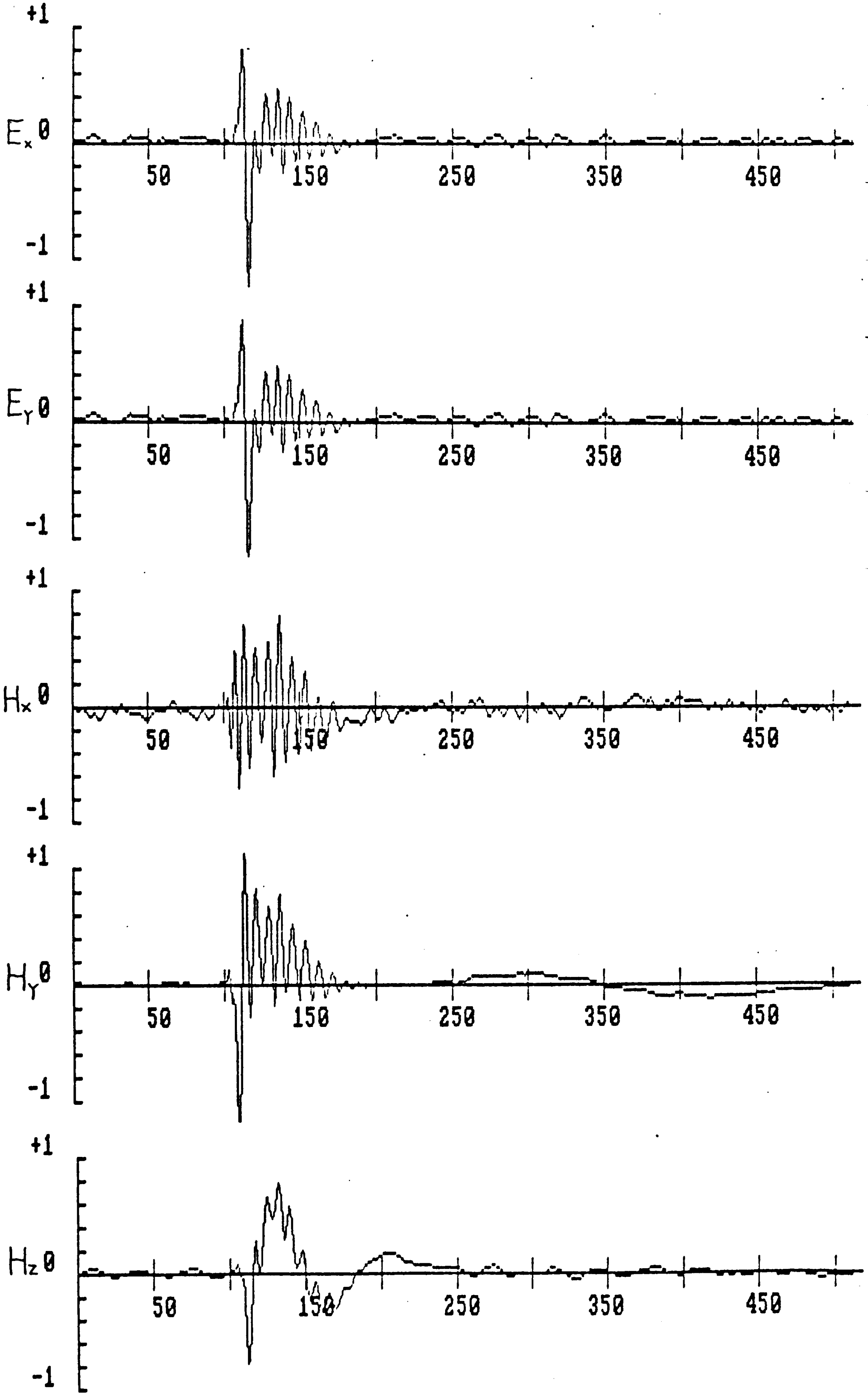

Figure 7. Signals measured on output of lowpass filter for band 3. The digitization interval and horizontal time scale unit is 25 usec.

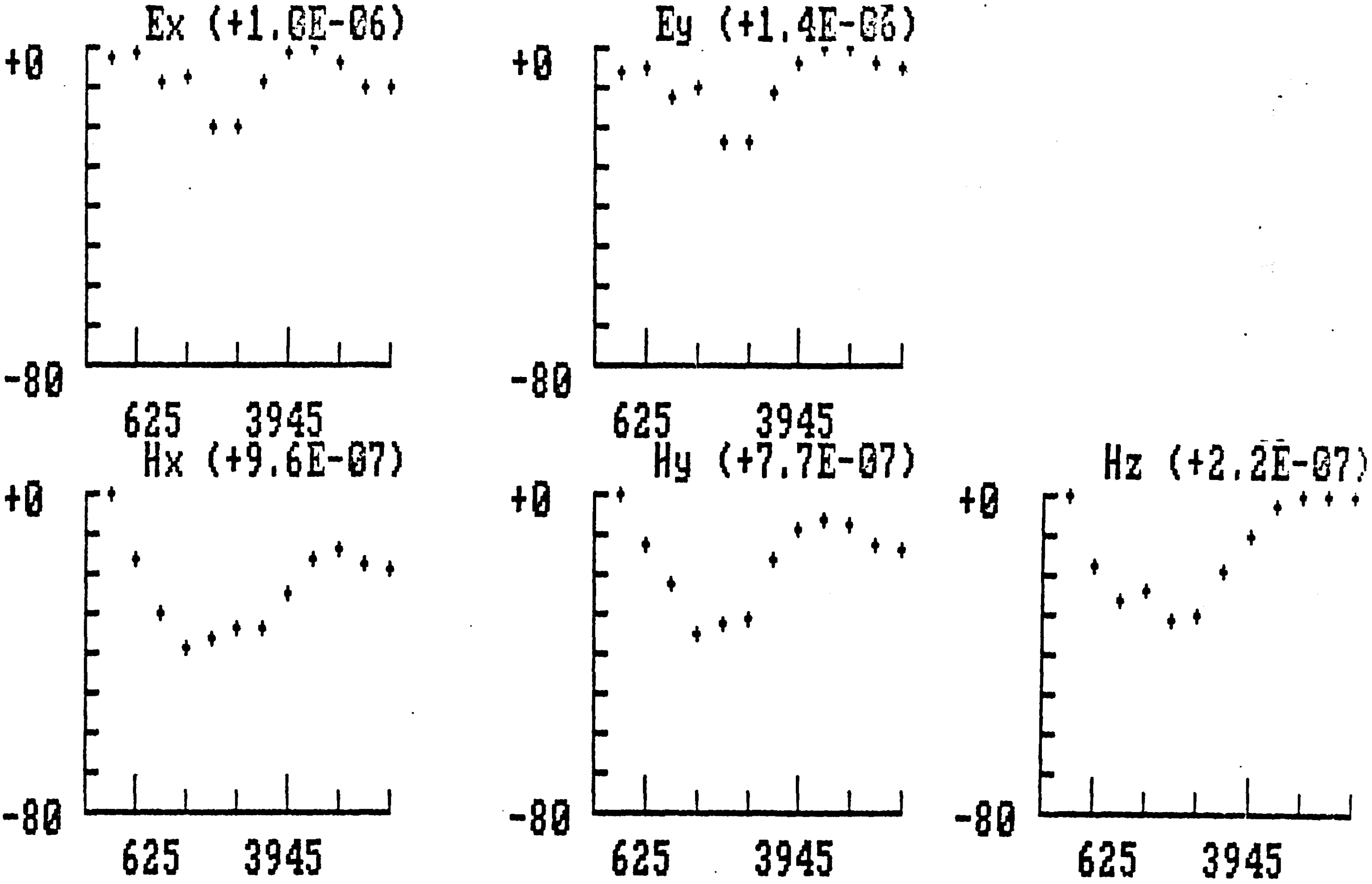

Figure 8. Amplitude of signals measured in band 3. The vertical scale is in db units with 0 db corresponding to the number shown in brackets. The electric field is in units of volt/m and the magnetic field units are amp/m.

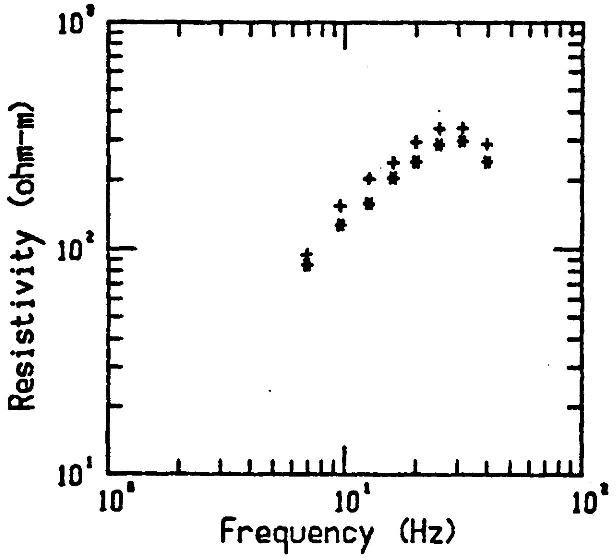

Figure 9. The tensor apparent resistivities ρ_{xy} (+) and ρ_{yx}(*) are plotted for band 1.

6. ELECTRICAL RESISTIVITY OF SURFICIAL DEPOSITS:

6.1 Introduction:

In addition to our AMT surveys, we have measured the resistivity of the sand, silt and clay components of the overburden with both laboratory and in situ measurements. There were two main goals in our work. One was to characterize the "typical" resistivities of the different overburden components, that is the clays, silts, and sands and from this to derive a typical electrical section and it's variability in the area. The other was to study the frequency dependence of the resistivity. We have concentrated most of our work on the clays and silts since they are the most conductive overburden component.

6.2 Overburden Stratigraphy:

In the Abitibi clay belt, the glaciolacustrine clays, silts and sands which were deposited in proglacial Lake Barlow-Ojibway generally form a horizontally stratified section. The clays and silts are commonly varved. The clays may be masked by sands from outwash deposits or derived from eskers. Clay pockets in buried bedrock valleys and between bedrock outcrops are probably quite common.

The distibution of overburden thicknesses obtained from drill hole logs in the assessment files at OGS is shown in figure 10. It is the clay and silt within the overburden that predominate in limiting the depth of penetration for EM methods. Measurements on the thickness of the clay layer within the overburden, which are not as numerous as the overburden thickness, indicate that 30 m of clay is typical in many areas.

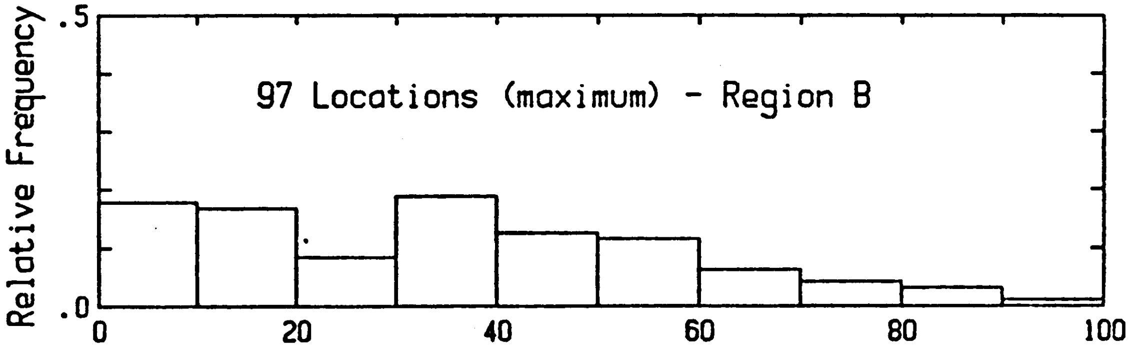

Figure 10. Typical overburden thickness for the map area. The maximum depth in each locality was taken ~~for~~ to produce this distribution.

6.3 Measurements Techniques:

Samples for the resistivity measurements were collected in 1" diameter plastic tubes, with the original moisture content preserved, from gravel pits, road cuts and exposures along rivers. The magnitude and phase of the resistivity was measured over the frequency range of .01 Hz to 1 MHz. The sand, silt and clay size fractions were determined by sieving and sedimentation analysis. The clay size fraction(<4 μm) typically contains 70% clay minerals. From X-ray diffraction work on a few of the clays it was determined that the principal clay minerals were chlorite (40%) and illite (30%).

6.4 Low Frequency Resistivity Measurements

The results of the low frequency(50 Hz) or DC conductivity measurements are shown in figure 11 in which one measurement per site, from the widely scattered localities has been plotted. The trend of increasing conductivity with increasing clay content along with a considerable degree of scatter for a fixed clay content is evident. This scatter is controlled mostly by the different pore water conductivities and formation factors for samples from different environments(Shainberg et al, 1980).

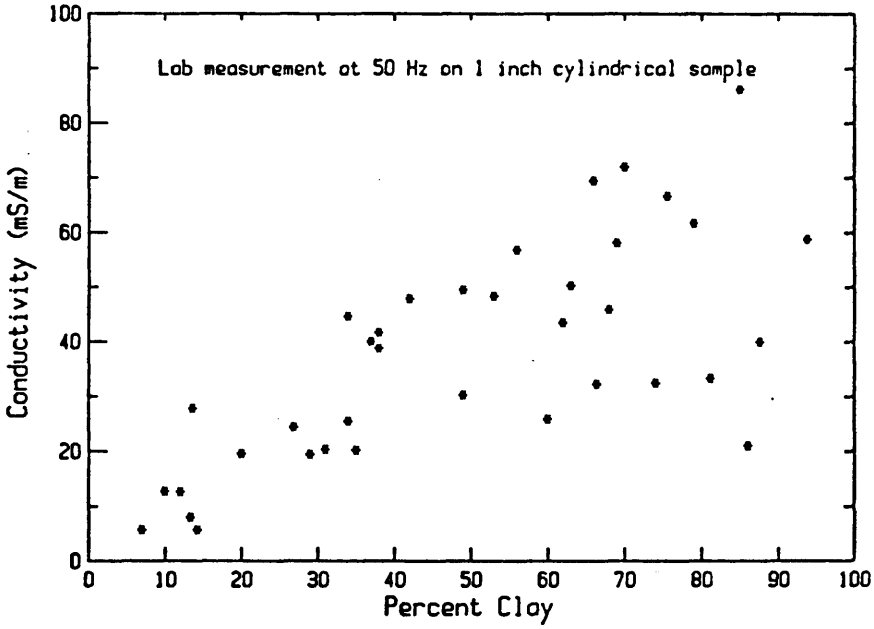

Figure 11. Low frequency (50 Hz) conductivity measurements as a function of clay content.

In figure 12 the distribution of resistivities for silts and clays are given. For the purposes of presenting the data, the samples have been divided into three classes. Clays contain more than 35% clay (clay size fraction), silts have less than 35% clay and less than 70% sand. The resistivities of the clays are tightly grouped with an average of 23 ohm-m whereas the resistivities of the silts are more variable.

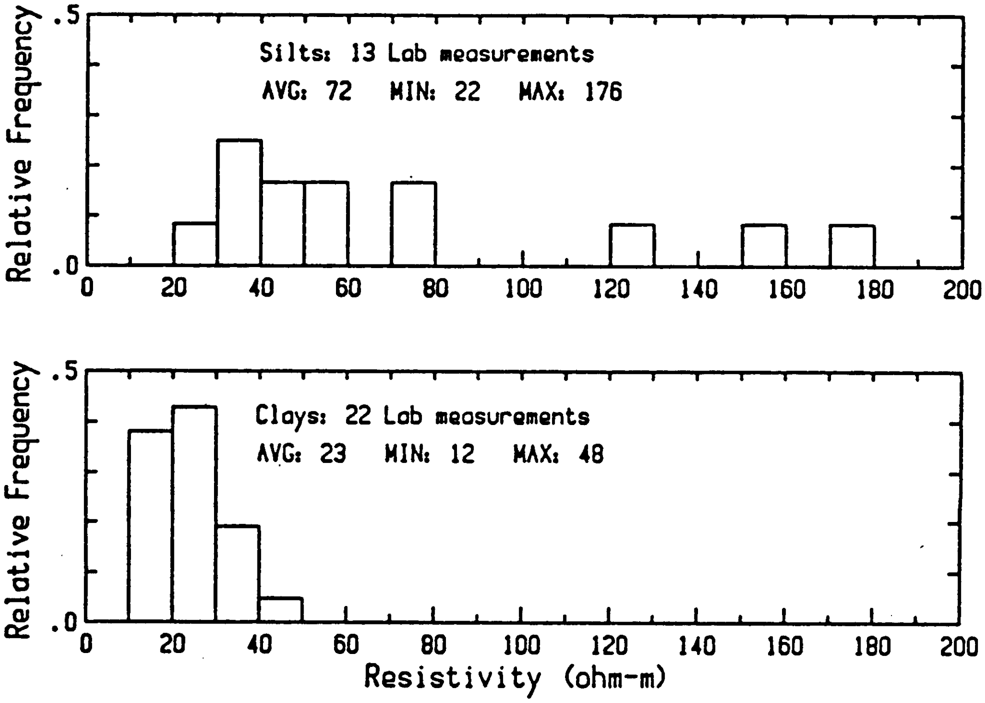

Figure 12. Distributions of clay and silt soil resistivities.

We have also carried out in situ resistivity measurements using a Wenner array with a spacing of .5 m. These in situ measurements show that the lab measurements are consistently lower than the in situ measurements by approximately a factor of 2. We believe that this difference is due to both cracks in the near surface soil and to differences between the horizontal and vertical resistivity of the soil. Measurements on varved clays in this area by Kenney and Chan indicate that horizontal and vertical hydraulic conductivities can be different by up to a factor of 5, which would indicate that one could expect significant differences in resistivity.

6.5 Resistivity Frequency Dependence:

We have also measured the frequency response of the lab samples. Laboratory measurements of the frequency dependence of the resistivity of kaolinite, illite and and silty clay by Mehran and Arulanandan have shown a significant frequency dependence in the range 50 Hz to 100 kHz. Our samples, by contrast, generally show very little dispersion in their resistivity as can be seen in figure 13. One of our samples with a clay content of 94% displayed a curious negative PFE and positive phase angle.

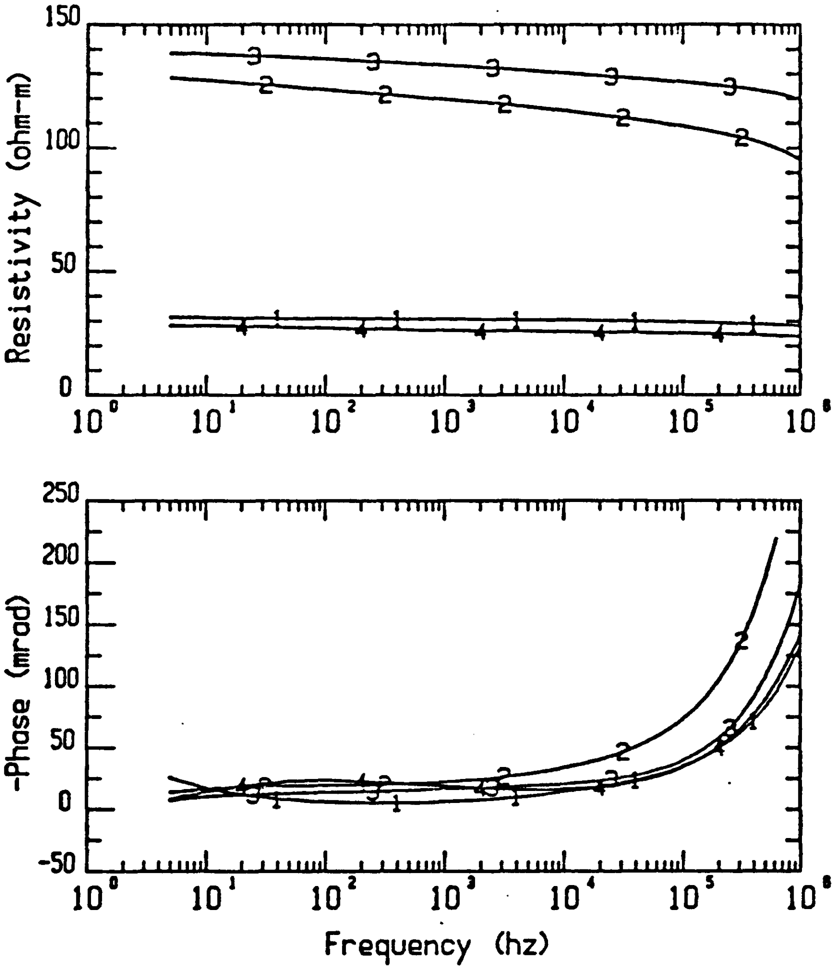

Figure 13. The frequency dependence of the phase and magnitude of the resistivity of some typical soil samples. Sample 1: Varved clay; clay 66%, silt 26%, sand 8%. Sample 2: Sandy Loam; clay 14%, silt 30%, sand 56%. Sample 3: Varved silt loam; clay 9%, silt 63%, sand 28%. Sample 4: Peat

6.6 Discussion:

These resistivity measurements have been useful in predicting a typical electrical section for the overburden in this region. Our measurements show that the clays have typical resistivities of 23 ohm-m and silts typically 70 ohm-m. The frequency dependence of the clays appears to be small and of little significance to most EM techniques. The relationship between the in situ and laboratory measurements requires further investigation.

7. CONCLUSIONS:

The AMT technique has been applied on a regional scale in a variety of different environments. The method has proven itself to be useful in mapping changes in rock lithology when these basement rocks are buried beneath significant thicknesses of conductive clay-rich overburden. In Moody Township , the method detected an area in which the basement rocks appear to be significantly more conductive in the east-west direction than in the north-south direction as reflected in the high anisotropy seen in the measured apparent resistivities. This is an area with a highly unusual electrical structure and for this reason merits further work with tensor AMT which is particularly useful in understanding two-dimensional structures.

At the Night Hawk Lake geophysical test site the AMT method was very successful in outlining the known graphitic conductor. Our results show that the anomolous zone extends further to the west, beneath increasingly conductive overburden, than had been previously mapped. This is another area in which tensor AMT measurements could provide additional information on the electrical structure.

The tensor AMT system that has been developed can now be applied to the areas outlined previously. There are some areas in which our existing tensor system can be improved. At present the data are acquired at a speed faster than that at which they can be processed. Thus the computational speed limits the amount of data that can be processed which in turn limits the quality of the computed apparent resistivities. The in field computational speed could be improved if a number of critical routines that presently run using a compiled Basic language are rewritten in assembly language.

Typical resistivities for the sand, silt and clay soil components of the overburden have been determined by laboratory and in situ measurements. The clays are the most conductive with an average resistivity of 23 ohm-m in the area and they have a relativeley low frequency dependence in their resistivity. It would be useful to study clays from other areas in Northern Ontario to obtain a broader picture of the variability of the resistivity of these glaciolacustrine soils. The significant differences observed between the in situ and laboratory measurements requires further study. The dependence of clay resistivities on depth of burial should also be studied.

8. REFERENCES:

Barlow R.B., Pitcher, D.H., and Wadge, D.R., 1982, Night Hawk Geophysical Test Range Results, Night Hawk Lake, District of Cochrane, Ontario Geological Survey, Miscellaneous Paper 106, p. 152-161.

Barlow R.B., 1983, Night Hawk Geophysical Test Range Results Using Two Electromagnetic Systems, Night Hawk Lake, District of Cochrane, Ontario Geological Survey, Miscellaneous Paper 100, p. 152-159.

Bostick, F.X., 1972, A simple almost exact method of magnetotelluric analysis, Proc. Workshop on Electrical Methods in Geothermal Exploration, p.174-183

Chan, H.T. and Kenny, C.T., 1973, Laboratory Investigation of the Permeability Rates of New Liskeard Varved Soil, Canadian Geotechnical Journal, Vol. 10, p.559-578.

Mehran,M., Arulanandan,K., 1977, Low frequency conductivity dispersion in clay-water-electrolyte systems, Clays and Clay Minerals, Vol.25, p39

Shainberg, I., Rhoades, J.D. and Prather, R.J., 1980, Effect of exchangeable sodium percentage, cation exchange capacity, and soil solution concentration on soil electrical conductivity, Soil Sci. Soc. Am. J., Vol. 44

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

Extended Bibliography:

Averill, S.A. and Thompson, I., 1981, Reverse circulation rotary drilling and deep overburden geochemical sampling in Marter, Catherine, McElroy, Skead, Gauthier and Hearst Townships, District of Timiskaming, Ontario Geological Survey OFR 5335

Boissonneau, A.N., 1966, Glacial history of northeastern Ontario-1. The Cochrane-Hearst Area, Can. Journ. of Earth Sciences, v. 3, p. 559-578

Cagniard L., 1952, Basic theory of the magneto-telluric method of geophysical prospecting: Geophysics, vol.18, p.605-635

Desaulniers, D.E., 1982, Clayey Quaternary Deposits in Northern Ontario- A Review, Atomic Energy of Canada TR-305

Hsu D., 1980, One dimensional and two dimensional interpretation of audiomagnetotelluric data: M.Sc. thesis, Geology Dept., University of Toronto

Hughes, O.L., 1961, Preliminary report on borings through Pleistocene deposits, Cochrane District, Ontario, Geol. Surv. Can., Paper 61-16

Ilkisik, O.M., Strangway, D.W., and Redman, J.D., 1983, Audiomagnetotelluric mapping in Precambrian terrain in the presence of clay-rich glacial overburden, Journal of Geomagnetism and Geoelectricity, Vol 35, p. 455-472.

Ilkisik, O.M. Hsu, D.T., Redman, J.D. and Strangway, D.W., 1982, Surface

Electromagnetic Mapping in Selected Positions of Northern Ontario, Ontario Geological Survey, Miscellaneous Paper 103, p. 98-114

Koziar, A., 1976, Applications of audio frequency magnetotellurics to permafrost, crustal sounding, and mineral exploration: Phd Thesis, Physics Department, University of Toronto

Koziar A., and Strangway, D.W., 1978, Shallow crustal sounding in the Superior province by audio-frequency magnetotellurics: Can. Journ. of Earth Sciences, 15, p.1701-1711

Nadler, A., and Frenkel, H., 1980, Determination of soil solution electrical conductivity from bulk soil electrical conductivity measurements by the four-electrode method, Soil Sci. Soc. Am. J., Vol. 44

Redman, J.D., Hsu, D., and Strangway, D.W., 1980, Audio frequency magnetotelluric measurements on the Eye-Dashwa lakes pluton Atikokan, Ontario: Internal report, Geology Dept., University of Toronto

Redman, J.D., Strangway, and Ilkisik, O.M. , 1984, Surface Electromagnetic Mapping in Selected Positions of Northern Ontario, Ontario Geological Survey, Miscellaneous Paper 121, p. 47-58.

Roy, K.K. and Elliot, H.M., 1980, Model studies on some aspects of resistivity and membrane polarization behaviour over a layered earth, Geop. Prosp., v. 28, p. 759-775

Strangway, D.W., Swift, C.M., and Holmer, R.C., 1973, An application of audio frequency magnetotellurics(AMT) to mineral exploration: Geophysics, Vol.38, p.1159-1175

Strangway, D.W., and Koziar, A., 1979, Audio-frequency magnetotelluric sounding-a case history at the Cavendish geophysical test range: Geophysics, Vol.44, p.1429-1446

Strangway, D.W., Redman, J.D., Holladay, S., and Horne, C., 1980, Audio frequency magnetotellurics at the Whiteshell Nuclear Research Establishment and Chalk River Nuclear Laboratories, A.E.C.L. Technical Record 71

Strangway, D.W., Redman, J.D. and Macklin, D., 1980, Shallow electrical sounding in the Precambrian crust of Canada and the United States: G.A.C. Special Paper 20, Proc. of Wilson Symposium on "The Continental Crust and its Mineral Deposits", p.273-301

Strangway, D.W., Ilkisik, O.M. and Redman, J.D., 1983, Surface Electromagnetic Mapping in Selected Positions of Northern Ontario, 1982-83, Ontario Geological Survey, Miscellaneous Paper 113, p. 159-173.

8. APPENDICES:

8.1 Appendix A

Papers Presented:

Dec./81- Geoscience Research Seminar, Ontario Geological Survey.
AMT sounding in the Clay Belt, D.T. Hsu, J.D. Redman, O.M. Ilkisik & D.W. Strangway.

Aug./82- Sixth workshop on electromagnetic induction in the earth and moon, International Association of Geomagnetism and Aeronomy.
Audio Frequency Magnetotellurics- A new method for the measurement of apparent resistivity, J.D. Redman and D.W. Strangway.
One and two-dimensional interpretation of AMT data from the precambrian of Northern Ontario, O.M. Ilkisik, J.D. Redman, D.T. Hsu & D.W. Strangway.

Dec./82- Geoscience Research Seminar, Ontario Geological Survey. Audiofrequency Magnetotelluric Mapping in Selected Positions Near Cochrane, Timmins and Kirkland Lake.

Sept./83-Society of Exploration Geophysicists, Annual meeting.
Audiomagnetotelluric Mapping in Precambrian Terrian in the Presence of Clay-rich Glacial Overburden, O.M. Ilkisik, D.W. Strangway and J.D. Redman
Electrical Resistivity of the Pleistocene Surficial Deposits in the Abitibi Clay Belt of Northern Ontario, J.D. Redman O.M. Ilkisik and D.W. Strangway

Dec./83- Geoscience Research Seminar, Ontario Geological Survey.
Electrical Resistivity of the Pleistocene Surficial Deposits in the Abitibi Clay Belt of Northern Ontario, D.W. Strangway, J.D. Redman & O.M. Ilkisik.

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AUDIOMAGNETELLURIC (AMT) SOUNDING IN THE CLAY BELT

Hsu, D., Redman, J.D., Ilkisik, M., Strangway, D.W., Departments of Geology and Physics, University of Toronto.

A series of surveys have been conducted in three clay-covered regions in the Abitibi greenstone belt. These surveys were carried out using the AMT technique which uses natural energy to conduct electromagnetic sounding. The source is distant lightning storms which roughly give a plane wave source field. Electric and magnetic field measurements in the frequency range from 10 hz. to 10 khz. permit sounding to varying depths depending upon the frequency. The data gives results in the form of resistivity versus frequency of sounding. Surveys in Bowman Township near Matheson were conducted on a two-dimensional grid and the data consistently show the presence of four layers, a thin resistive surface layer a few metres thick, followed by a very conductive layer of clay. Bedrock is at a depth of 50-100 m. and is very resistive. At depths of 5 km. or so the resistivity drops off again. This survey gives a map of the resistivity and the thickness of the clay and clearly outlines near surface features such as an esker.

A survey in Moody Township near Lake Abitibi again clearly outlines the clay properties and thickness but also shows that at the lower frequencies we are able to map the electrical resistivity of the basement beneath the clay cover. Over a region tentatively identified as metasediments, the bedrock is seen to be strongly anisotropic, perhaps reflecting anisotropy of the sediment itself.

In a third region, Marter Township near Englehart, a survey profile was able to clearly map a region of thickening clay in the overburden as well as to show high resistivity over a large esker. This profile was taken in an area where the overburden has been drilled in a program of the OGS and our results can be interpreted to be in general agreement.

1.2

Audio Frequency Magnetotellurics - A new method for the measurement of apparent resistivity.

J.D. REDMAN (Department of Physics, University of Toronto, Toronto, Ont.)
D.W. STRANGWAY (Department of Geology, University of Toronto, Toronto, Ont.)

A new approach to the determination of the magnitude of the apparent resistivity, for the AMT (audio-frequency magnetotellurics) method is described. One of the present limitations with the AMT method, resulting from the usual measurement procedure in which the phase of the electric and magnetic fields are not measured, is the lack of any means for assessing the reliability of the apparent resistivity estimate, such as could be obtained from the degree of correlation between the electric and magnetic field, if the phases were measured.

In the method described here, a series of pulses or events (E_i, H_i) are selected from the bandpass filtered electric and magnetic fields. The correlation coefficient, between the electric and magnetic field bandpass filtered signal, is computed for each pulse together with the integrated pulse magnitudes. Pulses with a low correlation coefficient are removed from the data sets composed of the E_i, H_i pulse magnitudes. A best fit straight line, in a least squares sense, is fitted to the reduced data set composed of the E_i, H_i pulse magnitudes. The slope of the line can be used directly to compute the apparent resistivity. The standard deviation of the slope estimate and the correlation coefficient for the data set provide the estimate of data quality desired. The method is applied to data collected on the Eye-Dashwa Lakes pluton near Atikokan, Ontario.

2.5

ONE AND TWO DIMENSIONAL INTERPRETATION OF AMT DATA FROM THE PRECAMBRIAN OF NORTHERN ONTARIO

J.D. REDMAN, O.M. ILKISIK, D.T. HSU, D.W. STRANGWAY (Dept. of Geology, University of Toronto.

Audiofrequency magnetotelluric (AMT) soundings have been conducted in Northern Ontario during the summer of 1981. The work is concentrated in Matheson, Lake Abitibi, Engelhart and Elk Lake regions. Apparent resistivities for frequencies from 13 Hz to 8570 Hz were measured at 101 stations.

Electromagnetic mapping in Precambrian terrain is difficult in many areas because of the presence of extensive conductive clay cover or because of the presence of extensive fluid-filled and hence conductive fractures.

A survey in Moody Township near Lake Abitibi clearly outlines the clay properties and thickness. Over a region, tentatively identified as metasediments, the bedrock is seen to be strongly anisotropic, perhaps reflecting anisotropy of the sediments themselves. If this is the case, it will be possible to recognize steeply dipping metasediments with the AMT method even when they are not exposed.

In a second region, Marter Township near Engelhart, two survey profiles mapped a region of thickening clay-rich overburden as well as located high resistivities over a large esker. These profiles were taken in an area where the overburden had been drilled in a program of the Ontario Geological Survey. Our results can be interpreted to be in general agreement.

Measurements in the Elk Lake area appear to be strongly affected by two contact zones, and they show inhomogeneity and anisotropy. The major feature in the area is the Montreal River Fault running through the town of Elk Lake. The shape of the profiles suggests that the fault dips to the southeast.

Surveys in Bowman Township, near Matheson, were conducted on a two-dimensional grid and the data consistently show the presence of four layers, a thin resistive surface layer a few meters thick, followed by a very conductive layer of clay. Bedrock is at a depth of 50-100 m and is very resistive. This survey gives a map of the resistivity and the thickness of the clay-rich glaciolacustrine sediments and clearly outlines near surface features such as an esker. At the lower frequencies we are able to map the electrical resistivity of the basement beneath the clay and/or esker cover.

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AUDIOFREQUENCY MAGNETOTELLURIC MAPPING IN SELECTED POSITIONS NEAR COCHRANE, TIMMINS AND KIRKLAND LAKE.

Strangway, D.W., Ilkisik, O.M., Redman, J.D.,
Department of Geology, University of Toronto.

During the 1982 field season, work continued on a multiyear electromagnetic mapping study in Northern Ontario. Audiofrequency magnetotelluric (AMT) data were collected at 114 stations from three different locations.

In Moody and Marathon Townships between Lake Abitibi and Cochran at the lower frequencies we are able to map the electrical resistivity of the basement beneath clay and/or esker cover. Anistropic behaviour of resistivity curves is typical for all stations on metasediments. This behaviour is so characteristic that it can be used for mapping of metasediments in the area even when they are covered by conductive glacial clays. The fitted models for isotropic resistivity curves were obtained by using Bostick Transformation and one-dimensional inversion techniques. These models show a 100 m. thick overburden with an average resistivity of 450 ohm-m. Underlying Precambrian metavolcanics have resistivity values in the range from 10000 to 50000 ohm-m. Most of the models imply that there is a relatively low resistivity layer at a depth of 8 km.

The Night Hawk Lake geophysical test site is located in the northeast corner of Thomas Township, near Timmins. There is a conductive graphite zone in the bedrock under about 90 m of glacial overburden. A total of 73 AMT measurements were made during the survey in this area. 36 of them were on a rectangular grid with 150 by 200 m spacing. In general there is a surface layer which has a moderate resistivity of about 500 ohm-m. At the lower frequencies, the apparent resistivity rises to about 10000 ohm-m. As we examine maps for each frequency, we see that at the center of the map, the graphitic conductive zone is well-defined with a resistivity value of less than 500 ohm-m. A representative map for 13 Hz is shown in Figure 1.

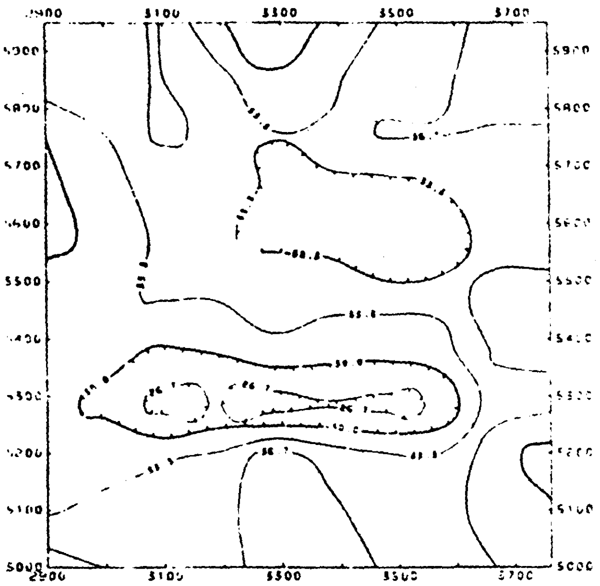

Figure 1. 13 Hz contour map of the apparent resistivity over a graphitic conductor in Night Hawk Lake test range. Contour units in 10 log ρa, coordinates in metres.

On the grid the dominant feature is that the high frequency (8570, 5050 Hz) resistivities are around 100 ohm-m in the west portion and around 500 ohm-m in the east portion of the maps. This is related to the increasing clay content in the glacial overburden towards the west. However as we examine maps for lower frequencies we can see the presence of the conductive body within the rhyolite with an east-west strike. The body appears to extend to the west at lower frequencies which are capable of penetrating the conducting clay. Another weak and small anomaly implies that another deeper and shorter conductive zone lies parallel and to the north of the main zone.

Measurements were made in Morrisette, Bisley and Arnold Townships near Kirkland Lake along an east-west profile perpendicular to the Munro esker zone. The dominant pattern is one of very high resistivities up to 10000 to 50000 ohm-m underneath the esker. In the west a surface resistivity value of about 250 ohm-m is representative of the relatively clay-rich overburden at the west boundary of the esker.

cont'd.....

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Audiomagnetotelluric Mapping in Precambrian Terrain in the Presence of Clay-Rich Glacial Overburden

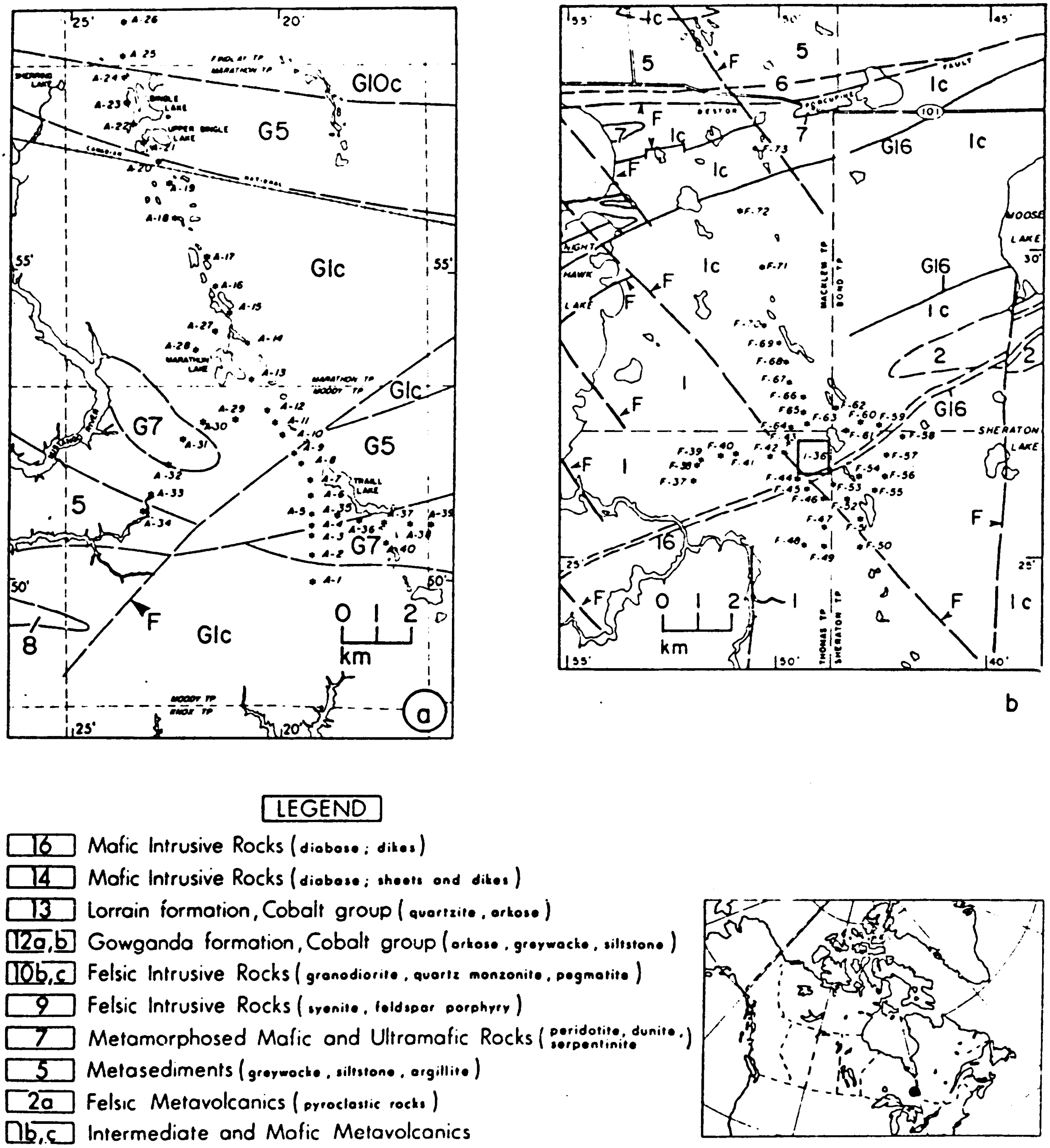
C1.2

O. M. Ilkisik, D. W. Strangway, and J. D. Redman
Univ. of Toronto, Canada

Audiomagnetotelluric (AMT) measurements were carried out in Northern Ontario within the framework of a project designed to describe the conductivity structure of the overburden (particularly in clay-rich regions) and Precambrian bedrock in the area. Because the system has no artificial source, field operations are rapid and simple to carry out. A survey in Moody and Marathon townships near Lake Abitibi clearly outlines the clay properties and thickness of glaciolacustrine deposits. The clay is extremely conductive (30-50 Ω-m) compared to sand and gravel deposits (500–600 Ω-m) of roughly 100 m thick overburden. There is a strong and uniform electrical anisotropy in an area believed to be underlain by metasediments. This is probably because of a preferred direction in steeply dipping metasediments. In a second region (the Night Hawk Lake geophysical test range near Timmins), there is a conductive graphite zone in the bedrock under about 90 m of glacial overburden. High frequency (8570, 5050 Hz) apparent resistivities are around 80 Ω-m in the western portion rising to 500 Ω-m in the eastern portion of the grid area, which covers the test target. This is related to the increasing clay content in the glacial overburden toward the west. However, at lower frequencies (473 to 13 Hz), we can see the presence of the conductive body within the rhyolite with an east-west strike. The body is detected to the west at the lower frequencies, which have penetrated the more conducting overburden.

Introduction

The method and instrumentation were described by Cagniard (1953) and Strangway et al (1973), respectively. Measurements were made at 11 discrete frequencies from 13 to 8570 Hz. A grounded electric dipole of 100 m was used to measure the electric field (*E*). Two induction coils, one optimized for low frequencies and the other for high frequen-



LEGEND

16	Mafic Intrusive Rocks (diabase; dikes)
14	Mafic Intrusive Rocks (diabase; sheets and dikes)
13	Lorrain formation, Cobalt group (quartzite, arkose)
12a,b	Gowganda formation, Cobalt group (arkose, greywacke, siltstone)
10b,c	Felsic Intrusive Rocks (granodiorite, quartz monzonite, pegmatite)
9	Felsic Intrusive Rocks (syenite, feldspar porphyry)
7	Metamorphosed Mafic and Ultramafic Rocks (peridotite, dunite, serpentinite)
5	Metasediments (greywacke, siltstone, argillite)
2a	Felsic Metavolcanics (pyroclastic rocks)
1b,c	Intermediate and Mafic Metavolcanics

FIG. 1. Bed rock geology maps (after Pyke et al, 1973) and locations of AMT sounding sites: (a) Moody and Marathon townships, near Lake Abitibi; (b) Night Hawk Lake geophysical test range.

cies, were used to measure the magnetic field (*H*). After prewhitening, analyzing, and measuring the ratio of the orthogonal *E* and *H* signals electronically, we calculate the scalar apparent resistivity (ρ_a) at each frequency (f) using the relationship $\rho^a = 0.2\, f \cdot (E/H)^2$. The measurements of the apparent resistivity as a function of frequency preserve the variation of the true resistivity with respect to the depth. This is a summary of AMT measurements made in Marathon and Moody townships near Lake Abitibi and at the Nigh Hawk Lake geophysical test range near Timmins, Ontario.

Moody and Marathon townships near Lake Abitibi

In Moody and Marathon townships between Lake Abitibi and Cochrane, 40 AMT measurements were done during the survey (Figure 1a). The oldest basement material is Earl Precambrian mafic metavolcanics which underlie much c

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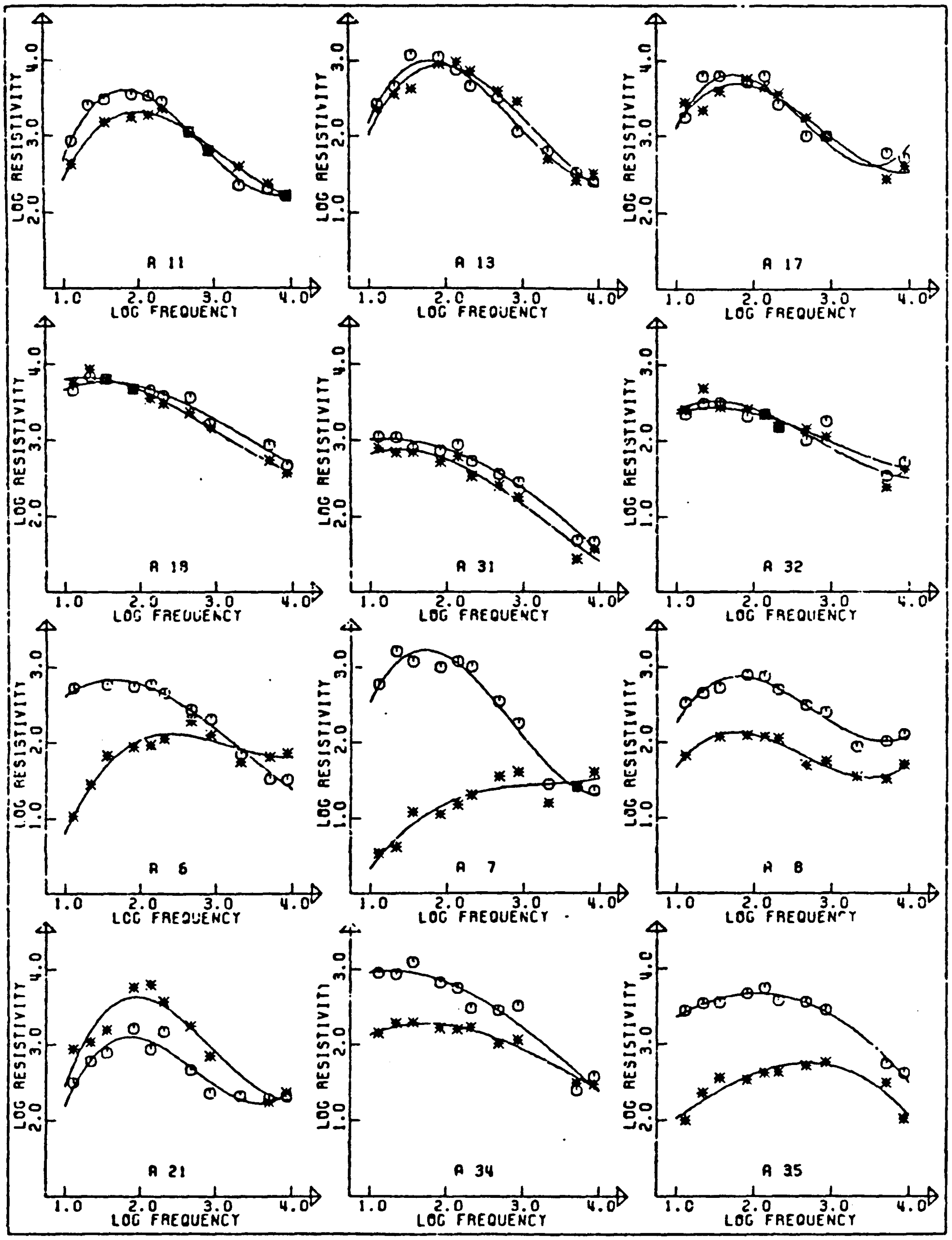

Isotropic

Anisotropic

FIG. 2. AMT sounding curves from Moody and Marathon townships. Circles are north-south (northerly) orientation and stars are east-west (easterly) orientation. Isotropic sites located mostly on mafic metavolcanics (unit 1c, G1c in Figure 1a) and anisotropic sites are on metasediments (unit 5, G5).

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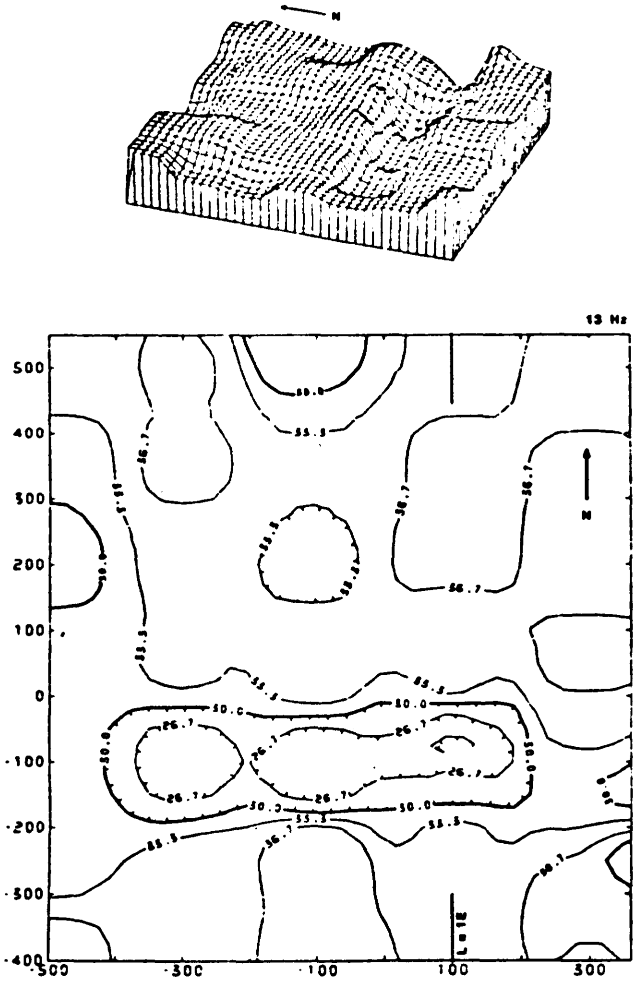

FIG. 3. Contour map of apparent resistivities at low frequency (13 Hz) with the block map at top.

the map area. The rocks were formed in a number of easterly trending eugeosynclines. At the lower frequencies we are able to map the electrical resistivity of the basement beneath the clay and/or esker cover. The resistivities of the metasediments (unit 5, G5) in the east-west orientation tend to be more conductive than in the north-south orientation (Ilkisik et al, 1983). This anisotropic behavior of resistivity curves is typical for all stations on metasediments (Figure 2). We assume that this phenomenon is associated with fracturing in steeply dipping metasediments. This behavior can be used for mapping of metasediments in the area even when they are covered by conductive glacial clays as at site A-34.

At site A-15 which is located on metavolcanics, the apparent resisitivity values are low for both orientations (east-west and north-south). In addition, A-28, A-27, and A-14 show strong anisotropy. This suggests a low resistivity structure within the metavolcanics with the preferred direction of east-west at station A-15.

The fitted models for isotropic resistivity curves were obtained by using the Bostick transformation approach and 1-D inversion techniques. These models show roughly an 80 100 m thick overburden with an average resistivity of 450 Ω m. The underlying Precambrian metavolcanics have resistivity values in the range from 8000 to 50,000 Ω-m.

Night Hawk Lake geophysical test range

The Night Hawk Lake geophysical test range is located in the northeast corner of Thomas township, near Timmins (Figure 1b). A total of 73 AMT measurements were made during the survey in this area. Thirty-six of them were on a rectangular grid with 150 by 200 m spacing. The grid system of the test range covers a known conductive zone in feldspar, porphyry, and rhyolite tuff, which is under 90 m of glaciofluvial overburden.

On the grid, the dominant feature is that high frequency (8570 Hz) resistivities are around 100 Ω-m in the western

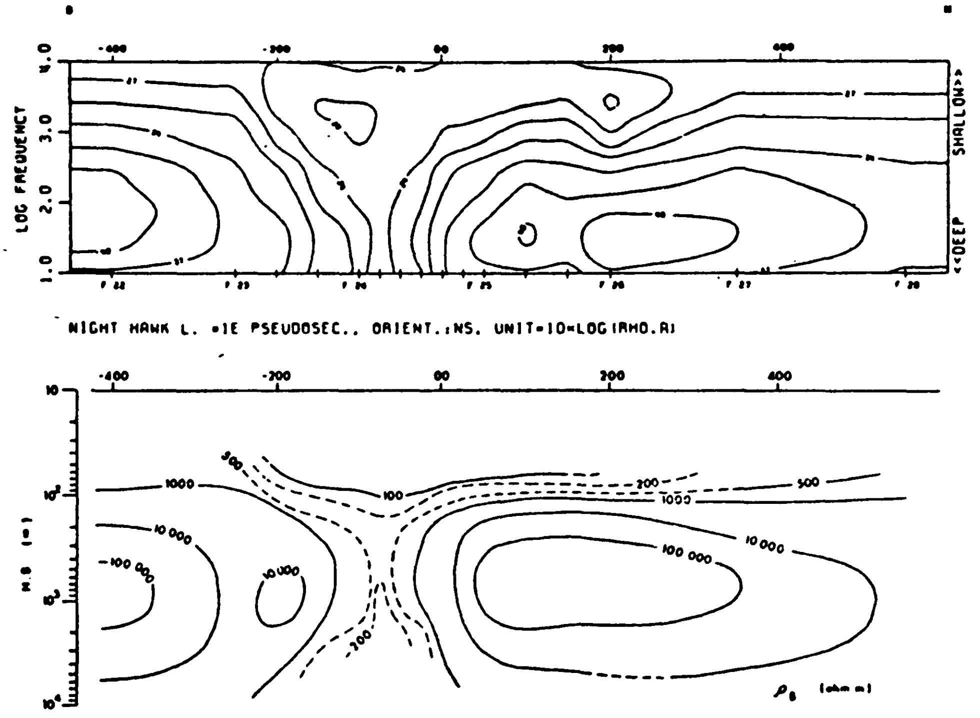

FIG. 4. Upper plot shows the apparent resistivity pseudosection along line 1E. Lower plot is Bostick resistivity cross-section along same line.

part and around 500 Ω-m in the eastern part of the map. This is related to the increasing clay content in the glacial overburden toward the west. However, if one examines maps for lower frequencies the presence of the conductive body can be seen within the rhyolite with an east-west strike (Figure 3). The body appears to extend to the west at the lower frequencies, which are capable of penetrating the conductive clay. The length of the body is not less than 700 m.

In Figure 4, the *E*-perpendicular data along line 1E are first presented as a pseudosection (upper plot) in which the apparent resistivity is contoured as functions of frequency and horizontal distance. This conductive zone is interpreted to be a "Y"-shaped body with a depth extent.

The lower plot in Figure 4 is an alternative presentation of the same data as a function of depth and distance using the Bostick transformation. This transformation is based on the asymptotic behavior of the apparent resistivity curves (Bostick, 1977). Transformation of the apparent resistivities from frequency domain to depth domain can be done by this formula:

$$h_B = 356\left(\frac{\rho_a}{f}\right), \ \rho_B = \rho_a \frac{1 - m}{1 + m},$$

and the approximate true resistivity or Bostick resistivity (ρ_B) at that depth is where ρ_a is the effective resistivity or Bostick resistivity (ρ_B) at the critical depth h_B. m is the gradient of (ρ_a versus f) data at each frequency. The Bostick transformation, in spite of its limitations, appears to work reasonably well in these areas where the resistivity contrasts are large. As can be seen in the pseudosection and the Bostick resistivity cross-section along line 1E (Figure 4) the north and south edges of the conductor are at about +100 m (100N) and −200 m (200S). The resistivity cross-section gives a better picture of the location and shape of the buried graphitic conductor near station F-24 (−100 m).

By using Bostick transformations and 1-D inversion techniques (Marquardt, 1963; Hsu, 1981), we found a layered earth section in the northern part of the grid area which gives a 95 m thickness of overburden with 30 m of clay-rich material at the west. Beneath the overburden, resistivity is in the range of 15,000 to 60,000 Ω-m. At the lowermost frequencies there appear to be lower resistivities at a depth of around 8–9 km.

References

Bostick, F. X., 1977, A simple almost exact method of magnetotelluric analysis: Proc. Workshop on Electrical Methods in Geothermal Exploration, Salt Lake City, p. 174–183, USGS contract 14-08-001-6-359.

Cagniard, L., 1953, Basic theory of the magnetotelluric method of geophysical prospecting: Geophysics, v. 18, p. 605–635.

Hsu, D. T., 1981, One-dimensional and two-dimensional interpretation of audiomagnetotelluric data: M.Sc. thesis, Univ. of Toronto.

Ilkisik, O. M., Redman, J. D., Hsu, D. T., and Strangway, D. W., AMT sounding through conductive glacial clays in the Canadian Shield: in press.

Marquardt, D. W., 1963, An algorithm for least squares estimation of nonlinear parameters: J. Soc. Indust. Appl. Math., v. 11, p. 431–441.

Pyke, D. R., Ayres, L. D., and Innes, D. G., 1973, Timmins-Kirkland Lake, Districts of Cochrane, Sudbury and Timiskaming: Ont. Geol. Surv. map 2205, Geological compilation series.

Strangway, D. W., Swift, C. M., and Holmer, R. C., 1973, The application of audio-frequency magnetotelluric (AMT) to mineral exploration: Geophysics, v. 38, p. 1159–1175.

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Electrical Resistivity of the Pleistocene Surficial Deposits in the Abitibi Clay Belt of Northern Ontario M1.2

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The conductive clays of the Abitibi clay belt of northern Ontario are a serious impediment to the application of electromagnetic techniques in the further exploration of an economically important mining region. For the purpose of obtaining a better understanding of the electrical properties of these surficial deposits, we made resistivity measurements of the different overburden components. These measurements were carried out both in situ, and in the laboratory. The purpose of these measurements was to characterize the "typical" resistivities and frequency dependence of the resistivity, for the overburden components (i.e., clay, silt, sand, and till). Typical resistivities at 50 Hz for the different soil classes are: clay, 20 Ω-m; silty clay, 50 Ω loam, 90 Ω-m; sand, 4000 Ω. The phase and magnitude of complex resistivity measured in the range .01 Hz to 1 MHz showed in general only a small frequency dependence.

Introduction

The conductive clays of the Abitibi clay belt of north Ontario are a serious impediment to the application of electromagnetic techniques in the further exploration of an economically important mining region. For the purpose obtaining a better understanding of the electrical proper of these surficial deposits, we made resistivity measurements of the different overburden components. These measurements were carried out both in-situ, and in the labo tory. The purpose of these measurements was characterize the "typical" resistivities and the frequency dependence of resistivity, for the overburden compone (i.e., clay, silt, sand and till). The clays were given the m attention in our work since they are the most conductive overburden component and thus provide the greatest hindrance to useful electrical surveys.

The surface expression of the surficial deposits were w mapped in the Abitibi clay belt by the Ontario Geological Survey (Northern Ontario Engineering Geology Terrain Study). The vertical electrical section of the overburden c be quite complicated. The glaciolacustrine clays, silts, a sands of the Abitibi clay belt were deposited in proglacial Lake Barlow-Ojibway. On the glaciolacustrine plain, t' overburden consists of horizontally stratified sand, silt, a clay layers. The clay and silt layers are commonly varved, showing a seasonal deposition pattern. In the northern part of the region around Cochrane, the clays are covered by clayey to silty till acquired during a local readvance of an i lobe. The varved clays in other areas may be masked by sand plains from outwash deposits or derived from eskers. In some areas, the clays lie in pockets or channels betwe bedrock outcrops.

The esker ridges composed principally of sands and gravels can extend through the complete vertical section lacustrine plain and may have, at their margins, clay and s lenses interfingering with the sands and gravels of the eskers.

The depth to bedrock and the thickness of the clay laye within the overburden are quite variable. A reverse circul tion drilling program carried out by the Ontario Geological Survey (Averill and Thompson, 1981) in an area south of Kirkland Lake, where there are numerous bedrock ou crops, found a maximum overburden thickness of 73 m. Th overburden stratigraphy is also quite variable. A typical section, observed in one hole was: 0–11 m clay, 11–14 m sil 14–62 m clay, 62–67 m silt, >67 m bedrock. In the Timmir area, a seismic survey (Killeen and Hobson, 1974) showed that bedrock topography buried beneath the clay cover is quite rugged with variations of 40 m in 1 km (with an averag overburden thickness of 30 m). Thus, it cannot be assume that the clay forms a uniform layer. In fact, it can be quite variable in thickness. A clay layer thickness of 30 m was shown to be typical, from drilling results and exposures, fc areas of glaciolacustrine plain in the Abitibi clay belt.

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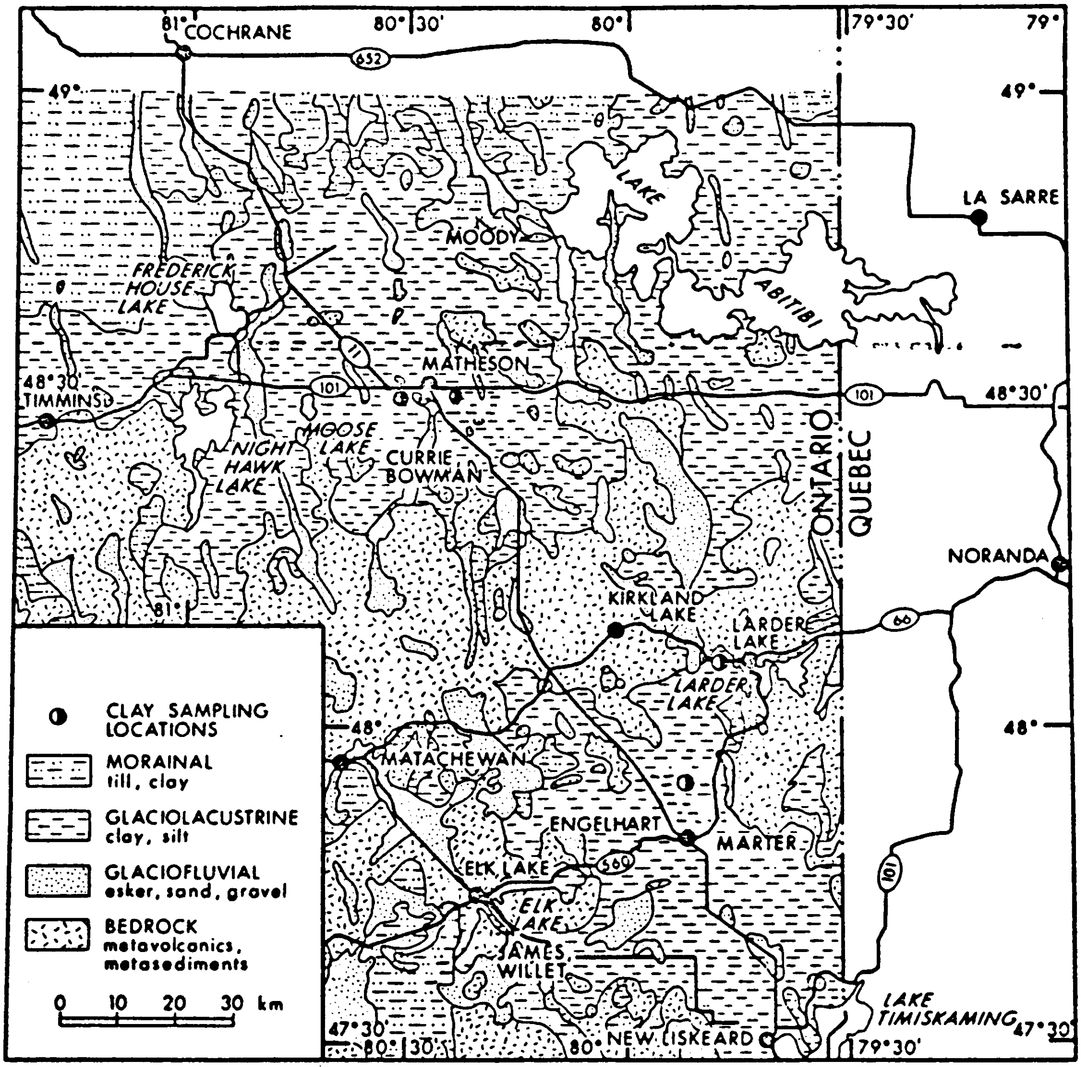

FIG. 1. Surficial geology and soil sampling locations.

The main purpose of this work is to characterize the resistivities of the sedimentary units of the overburden, with particular emphasis on the conductive clays.

Resistivity measurements

Samples to be used for resistivity measurements were collected from gravel pits, road cuts, and from exposures along rivers. In collecting the samples an attempt was made to preserve the samples in their original state. Surface material was removed to expose unweathered and undisturbed clay. Samples were obtained by pressing a plastic tube (1 inch diameter by 1 inch length) into the face of the clay. The samples were generally collected in an orientation that allowed the horizontal resistivity to be measured. The

Table 1. Clay, silt, and sand fractions determined by sieving and sedimentation analysis, the resistivity at 50 Hz, and the percent frequency effect (PFE) for representative samples. Clay fraction <4μm, silt fraction from 4 to 45μm, and sand >45μm.

Sample #	Site	Clay %	Silt %	Sand %	Soil class	Resistivity (Ω-m)	PFE
81-3	M	79.4	14.3	6.3	clay	35	1.0
81-4	M	93.8	6.1	.1	clay	17	−4.2
81-7	M	81.1	17.6	1.3	clay	30	2.0
81-8	L	55.5	40.8	3.7	silty clay	31	.9
81-13	L	66.4	25.9	7.7	clay	31	1.9
81-19	L	14.5	66.5	19.0	silt loam	132	2.0
81-24	L	62.2	32.9	4.9	clay	30	.1
81-29	L	9.2	62.6	28.2	silt loam	137	1.4
81-31	E	21.8	25.6	52.6	loam	33	.8
81-33	E	75.5	16.0	8.5	clay	15	−.3
81-35	E	26.9	66.1	7.0	silt loam	41	.5
81-40	E	14.1	29.6	56.3	sandy loam	125	3.0

L = Larder Lake dump site, M = Matheson area, and E = Englehart area.
PFE = $(\rho_{5\,\mathrm{Hz}} - \rho_{50\,\mathrm{Hz}})/\rho_{5\,\mathrm{Hz}} \times 100$

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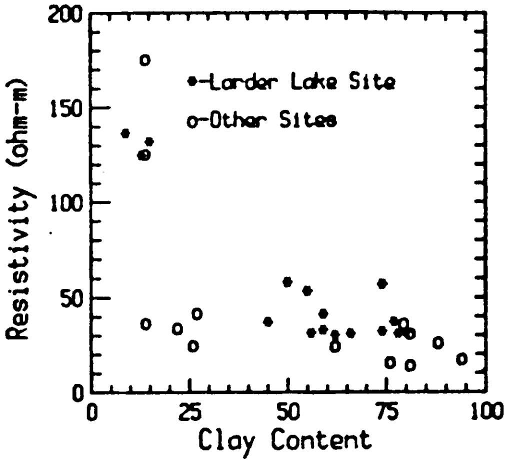

FIG. 2. The magnitude of the resistivity at 50 Hz is plotted as a function of the sample clay content (<4μm). The Larder Lake samples were collected from different depths within one varved clay layer.

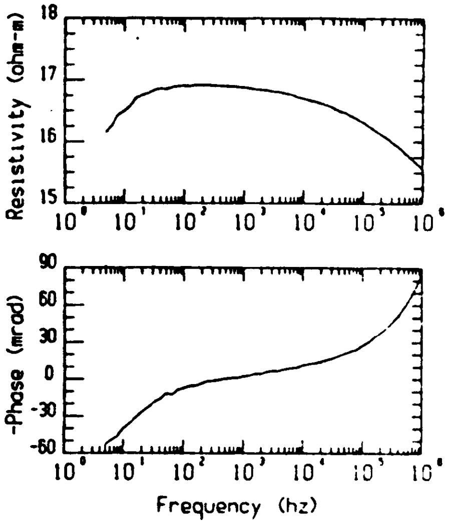

FIG. 4. Sample 81-4 which contains 94 percent clay exhibi an unusual positive phase and negative PFE at low frequencies.

samples were sealed in plastic bags to preserve their original moisture content.

The complex resistivity was measured over the frequency range of 5 Hz to 1 MHz. All measurements were carried out using the HP4192A impedance analyzer. Four electrode measurements, using separate current and potential electrodes, were made from 5 Hz to 10 kHz. Above 10 kHz, a four terminal and two electrode technique was used. Platinum mesh was used for the current electrodes and platinum wire for the potential electrodes. A current density of approximately .1 A/m was used for all measurements. The samples were encapsulated during the measurement process to prevent drying of the sample. The sand (>45 μm), silt (4–45 μm) and clay (<4 μm) size fractions were determined by sieving and sedimentation analysis.

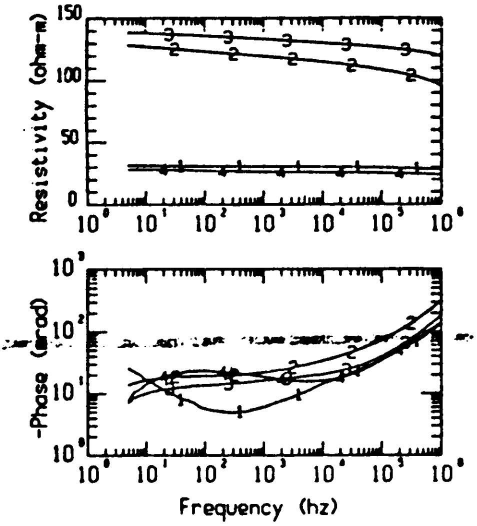

FIG. 3. The typical frequency dependence of the phase and magnitude of the complex resistivity of soil samples from the Abitibi clay belt are shown. The individual data points of which there are ten per decade in frequency, have been joined with straight line segments. The numbers given on the plots are for identification purposes: 1 – Clay (varved), Larder Lake; 2 – sandy loam, Englehart; 3 – silt loam (varved), Larder Lake; 4 – peat, Matheson.

Results of resistivity measurements and soil class for some representative samples from the Matheson, Larder Lake, and Englehart areas are given in Table 1. The 50 H resistivities for all the samples are shown in Figure 2 alo with their clay contents. For samples from the Larder Lake dump site, it can be seen that the silt (silt loam) samples that have low clay content have high resistivities that are on th order of 120–140 Ω-m whereas the clays have resistivities 30–60 Ω-m. These silt samples are from a varved layer in which the clay content increases from bottom to top. Whe one includes samples from other areas, then even the s samples have resistivities of the same order as the clay samples. This variability is probably related to the change in pore water resistivity for different environments. For san ples from the same environment, one would expect that th clay samples would have lower resistivities, as seen for the Larder Lake dump site samples. In general, measurements show that silts are more likely to have higher resistivitie than clays and tend to have a larger variability. The averag resistivity at 50 Hz for different soil classes at the sites studied was 24 Ω-m for clays (16 samples), 45 Ω-m for silt clay (4 samples), and 87 Ω-m for loams (9 samples of loam sandy loam, and silt loam). In-situ measurements at 1.1 Hz using a small Wenner array with a = .5 m where it was possible and a = .05 m for thin layers gave an averag resistivity for clays and silty clays of 59 Ω-m (21 sites) an 3700 Ω-m for sands (9 sites). AMT (audio-frequency magnetotellurics) surveys we carried out in these same areas typically give resistivities of 20–50 Ω-m for the conductiv clay layer.

In general, the soil samples have a resistivity that is relatively independent of frequency from 5 Hz to 1 MHz a shown in Figure 3 for different soil types. The comple resistivity was measured in the range .01 Hz to 1 MHz for a few samples. At the lower frequencies, resistivity was also relatively independent of frequency. Sample 81-4 (Figure 4 shows a significant and unusual frequency dependence i that the phase angle is positive at the lowest frequencies and the magnitude increases with frequency at the lowest frequencies. Negative PFE values similar to that observed i this sample were reported previously (Roy and Elliot, 1980) for clay soils with clay content greater than 90 percent.

The principal clay minerals contained in the clay size fraction for samples 81-3, 4 and 13 is chlorite (40 percent) and illite (30 percent). These clay minerals are typical for immature glaciolacustrine clays.

Conclusions

Previous studies of the Abitibi clay belt demonstrated that one can expect to have complicated electrical sections for the overburden. In our work we obtained "typical" resistivities, from laboratory and in-situ measurements, for the different sedimentary units within the overburden and showed that in general the frequency dependence of resistivity is quite small.

References

Averill, S. A., and Thompson, I., 1981, Reverse circulation rotary drilling and deep overburden geochemical sampling in Marter, Catherine, McElroy, Skead, Gauthier and Hearst Townships, District of Timiskaming; Ontario Geological Survey, OFR 5335.

Killeen, P. G., and Hobson G. D., 1974, Project EGMA seismic—Timmins, Ontario to Val d'Or Quebec: Geol. Surv. Can., paper 74–44.

Northern Ontario Engineering Terrain Study Data Base Maps, 1979: Ontario Geological Survey.

Roy, K. K., and Elliot, H. M., 1980, Model studies on some aspects of resistivity and membrane polarization behaviour over a layered earth: Geop. Prosp., v. 28, p. 759–775.

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ELECTRICAL RESISTIVITY OF THE SURFICIAL DEPOSITS IN THE ABITIBI CLAY BELT OF NORTHERN ONTARIO

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In conjunction with our application of Audio Frequency Magnetotellurics to electromagnetic mapping in Northern Ontario, we have carried out measurements on the resistivity of the surficial deposits in this region. The conductive clays of the Abitibi clay belt are a serious impediment to the application of EM techniques in an important mining region.

The glaciolacustrine clays, silts and sands generally form a horizontally stratified section. Overburden thicknesses of 50 m and clay layer thicknesses of 30 m are not uncommon. In some areas it is possible for the clays to be masked by sands from outwash deposits or derived from eskers. Considering the high bedrock relief, it is no doubt common to have clay pockets in buried bedrock valleys.

The principal aims of the electrical properties measurements were to characterize the "typical" low frequency resistivities of the clays, silts, and sands and to measure the frequency dependence of their resistivity in the range .01 Hz to 1 MHz. Samples of unweathered and undisturbed soils were collected from gravel pits, road cuts and exposures along rivers. The sand, silt and clay size fractions for these samples were determined by sieving and sedimentation analysis. The principal clay minerals are chlorite 40% and illite 30% which are typical for immature glaciolacustrine clays. The average DC (low frequency) resistivities are: clays(22 samples) 23 ohm-m, silts(13 samples) 72 ohm-m and sands 1000-5000 ohm-m (insitu measurements). Using the drill hole logs from the overburden drilling program south of Kirkland Lake and our resistivity measurements on silts and clays and sands one obtains overburden conductances of up to 2 seimens for this area. Insitu DC resistivity measurements using a Wenner array with a spacing of .5 m give consistently higher resistivities than lab measurements on samples from the same locations. We believe that this difference is due to both cracks in the near surface soil and to differences between the horizontal and vertical resistivity of the soil.

In general the samples show only a small frequency dependence in their resistivity in contrast with previous measurements on clays. The frequency effect between 5 and 50 Hz is typically less than 2.5%.

8.2 Appendix B

Publications:

Ilkisik, O.M. Hsu, D.T., Redman, J.D. and Strangway, D.W., 1982, Surface Electromagnetic Mapping in Selected Positions of Northern Ontario, Ontario Geological Survey, Miscellaneous Paper 103

Ilkisik, O.M., Strangway, D.W., and Redman, J.D., 1983, Audiomagnetotelluric mapping in Precambrian terrain in the presence of clay-rich glacial overburden, Journal of Geomagnetism and Geoelectricity, v. 35, 455-472.

Strangway, D.W., Ilkisik, O.M. and Redman, J.D., 1983, Surface Electromagnetic Mapping in Selected Positions of Northern Ontario, 1982-83, Ontario Geological Survey, Miscellaneous Paper 113

Redman, J.D., Strangway D.W., and Ilkisik, O.M. , 1984, Surface Electromagnetic Mapping in Selected Positions of Northern Ontario, Ontario Geological Survey, Miscellaneous Paper 121

Thesis(enclosed under separate cover):
Redman, J.D., 1982, Audio Frequency Magnetotelluric Measurement Techniques, Geophysics Dept., Univ. of Toronto.

Publications to be completed and submitted:
Ilkisik, O.M., Strangway, D.W., and Redman, J.D., Audiomagnetotelluric mapping in the Night Hawk Lake Geophysical Test Range -a Case History to Geophysics.

Ilkisik, O.M., Redman, J.D. and Strangway, D.W., The detection of bedrock conductors beneath conductive overburden, to Geophysics.

Redman, J.D., and Strangway D.W., Electrical properties of the glaciolacustrine clays of Northern Ontario, to Geophysics.

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Grant 118 Surface Electromagnetic Mapping in Selected Positions of Northern Ontario

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ABSTRACT

In the summer of 1981, an audio-magnetotelluric (AMT) survey was completed in four locations in northern Ontario. Apparent resistivities, for frequencies from 13 Hz to 8570 Hz, were measured at 101 stations.

A survey in Moody Township near Lake Abitibi clearly outlined the clay properties and thickness, and also showed that, at the lower frequencies, we are able to map the electrical resistivity of the basement beneath the clay and/or esker cover. At one locality, the response of the bedrock is strongly anisotropic, perhaps reflecting anisotropy of the metasediments. If this proves to be the case, it then will be possible to recognize steeply dipping metasediments with the AMT method when they are not exposed.

In Marter Township near Engelhart, two survey profiles mapped a deposit of clay-rich overburden, and located high resistivities over a large esker. These profiles were taken in an area where the overburden had been examined by a rotary drilling program in 1979 by the Ontario Geological Survey. Our results can be interpreted to be in general agreement.

Measurements in the Elk Lake area appear to be strongly affected by two contact zones, and they show inhomogeneity and anisotropy. The major feature in the area is the Montreal River Fault, which runs under the town of Elk Lake. The shape of the profiles suggests that the fault dips to the southwest. However additional field work is needed to examine the complexities introduced by major fluid-filled faults.

Surveys in Bowman Township, near Matheson, were conducted on a two-dimensional grid and the data consistently showed the presence of four layers. A thin resistive surface layer a few metres thick is followed by a very conductive layer of clay. Bedrock is at a depth of 50-100 m and is very resistive; the resistivity drops sharply at depths of several kilometres. This survey provided a map of the resistivity and the thickness of the clay-rich glaciolacustrine sediments and clearly outlines near surface features such as an esker.

In addition to the AMT survey, we have collected 42 clay samples from sites in Larder Lake and in Marter Township to study their electrical properties. Laboratory measurements show that in the Kirkland Lake area, the clays have resistivities on the order of 20 ohm-m, in agreement with the high frequency AMT data over clay-rich overburden.

INTRODUCTION

An audio-magnetotelluric (AMT) survey in northern Ontario was carried out during the summer of 1981. The purpose of the survey was to conduct surface electromagnetic mapping in selected positions in the clay belts of northern Ontario, where a large proportion of the Early Precambrian volcanic-sedimentary formations are mantled by glaciolacustrine deposits. The main interest was to characterize the electrical structure of the extensive clay-covered regions, the electrical properties of the clay itself, and to test the capability of penetrating through this conductive top layer to identify anomalies in the bedrock below. There are major problems encountered using some types of conventional EM mapping methods. A second interest was to study the region covered by the Huronian Supergroup, its resistivity characteristics, and the possibility of determining its thickness and thus mapping the surface topography of the Early Precambrian basement.

The work in northern Ontario concentrated in Bowman Township near Matheson, in Moody Township near Lake Abitibi, in Marter Township near Engelhart and around James Township near Elk Lake (Figure 1). The audio-magnetotelluric method was used successfully in each of these areas, to map the thickness of clay-rich overburden and to unambiguously determine some of the characteristics of the underlying bedrock.

Additionally, we have collected 42 clay samples from sites in Larder Lake and in Marter Township to study the electrical properties and their frequency dependence.

One profile in Moody Township (A, Figure 1) in the Great Clay Belt, and two in Marter Township (B and C) in the Little Clay Belt, are composed of 15, 9 and 8 sites respectively. An extensive, reverse-circulation, rotary drilling program was completed in 1979 (Averill and Thompson 1981). The surficial geology in Marter Township is therefore well known. The fourth profile, which is along Highway 560 near the town of Elk Lake and extends south to Willet Township, includes 19 AMT stations. Eleven of these are located in the area covered by the Huronian Supergroup.

A detailed grid survey including 50 sites was completed in Bowman Township and the eastern part of Currie Township to map the resistivity variation both laterally and vertically.

AMT METHOD AND FIELD PROCEDURE

Natural fields in the audio-frequency band (10 - 10^4 Hz) are due to thunderstorm energy propagating in the earth-ionosphere cavity. They occur more or less worldwide and propagate around the world. This implies that the AMT sources can be approximated as plane waves vertically incident to the earth's surface. Cagniard (1953) showed how natural electromagnetic fluctuations could be used as sources for probing the electrical structure of the earth. Using this approach, it was possible to measure the ratio of the electric field to the magnetic field and thus to determine the apparent resistivity. At one particular frequency the apparent resistivity (ρ_a) is defined using the relationship:

$$\rho_a = \frac{1}{\omega\mu}\left\{\frac{E}{H}\right\}^2$$

E: electric field in volts/m
H: magnetic field in ampereturns/m
ω: angular frequency ($2\pi f$)
μ: magnetic permeability

Information on the variation of apparent resistivity with depth is related to electromagnetic wave penetration, referred to as skin depth. The skin depth is an inverse function of frequency. It is given as:

$$\delta = 503\left\{\frac{\rho}{f}\right\}^{1/2}$$

δ: skin depth in m
ρ: resistivity in ohm-m
f: frequency in hertz

To obtain the electrical structure of the earth, depth sounding data, derived from the apparent resistivity as a function of frequency, have to be modelled by either one-, two- or three-dimensional models. For a one-dimensional structure, the model consists of horizontal layers with the resistivity and thickness of each layer as model parameters. Two-dimensional structures can have resistivity variations in the direction perpendicular to the geologic strike and/or with depth. Three-dimensional modelling, which is closest to many real geologic situations, can have structures in any form with various resistivities; however computing models in three dimensions is expensive. For mapping purposes, one-dimensional interpretation at stations distributed on a grid is a necessary step in order to get a plan view of any three-dimensional structure that may be present.

Instrumentation to operate in the audio-frequency range (10 – 10^4 Hz) was first described by Strangway and Vozoff (1969) and by Strangway *et al.* (1973). This instrumentation has since been improved and in the recent past, several surveys have been conducted in various parts of North America (Strangway *et al.* 1980).

In the surveys reported here, an 82 m dipole was employed for measuring the electric field. The magnetic field was measured with two induction coils, one optimized for the low frequency range and the other optimized for the high frequency range. The magnitude of the apparent resistivities was measured at the discrete frequencies of 13, 22, 36, 83, 140, 210, 473, 858, 2140, 5050 and 8570 Hz (referred to in some of the figures as channel A,B,C,D,K,E,F,G,H,I and J respectively). Two orthogonal data sets at each site were measured to search for lateral anisotropies. The data sets indicated as NS and EW in the figures have the electric dipole laid out in north-south and east-west orientation respectively and the magnetic coils lined up perpendicular to these dipole orientations. The data were plotted in log ρ - log f format for a general qualitative overview.

The errors in apparent resistivity measurements for real field data determined from tests of repeatability are sometimes of the order of 30-40 percent. In this survey, anomalously low apparent resistivities, associated with low source signal levels, were sometimes found at 2140 and 5050 Hz. Low apparent resistivities at 13 and 22 Hz caused by wind noise was a problem in some measurements, particularly in Marter Township. Interference from power lines at 60 Hz was occasionally a problem in Bowman and in Marter Townships. Those poor quality data points were identified by examining the sounding curves in the field, and were removed or remeasured.

SURFICIAL GEOLOGY

The clay belts are an important subdivision of the Canadian Shield physiographic province and record the site of glacial Lake Barlow-Ojibway. Surficial geology is shown in Figure 1. In Marter Township, a reverse-circulation rotary drilling program was completed in 1979 (Averill and Thompson 1981). The surficial geology in that area is thus well known. Glacial Lake Barlow-Ojibway, a major proglacial body of meltwater, covered the area during part of the Wisconsin recession. The Matheson till (Table 1) is the lowermost unit known in the area; it consists of sandy boulder till with minor gravel and lies directly on bedrock of Precambrian age. It is an almost continuous sheet except for local discontinuities around bedrock hills. Glaciofluvial deposits overlie the Matheson till or lie directly on bedrock. They are confined mainly to broad north-trending esker ridges and broad sand and gravel plains. The most extensive deposits of Lake Barlow-Ojibway are the varved clays and silts which form plains and an interconnected network surrounding bedrock outcrops. In general, the lower part of the Barlow-Ojibway formation consists of bedded silt and the upper part of laminated clay. Shore and nearshore deposits ranging from fine sand to gravel and boulders form the uppermost part of this formation. Clay and till glaciolacustrine sediments known as the Cochrane Formation, cover the northern part of the research area. The youngest unit of Wisconsin age consists of organic deposits which contain shell, marl and peat (Hughes 1961).

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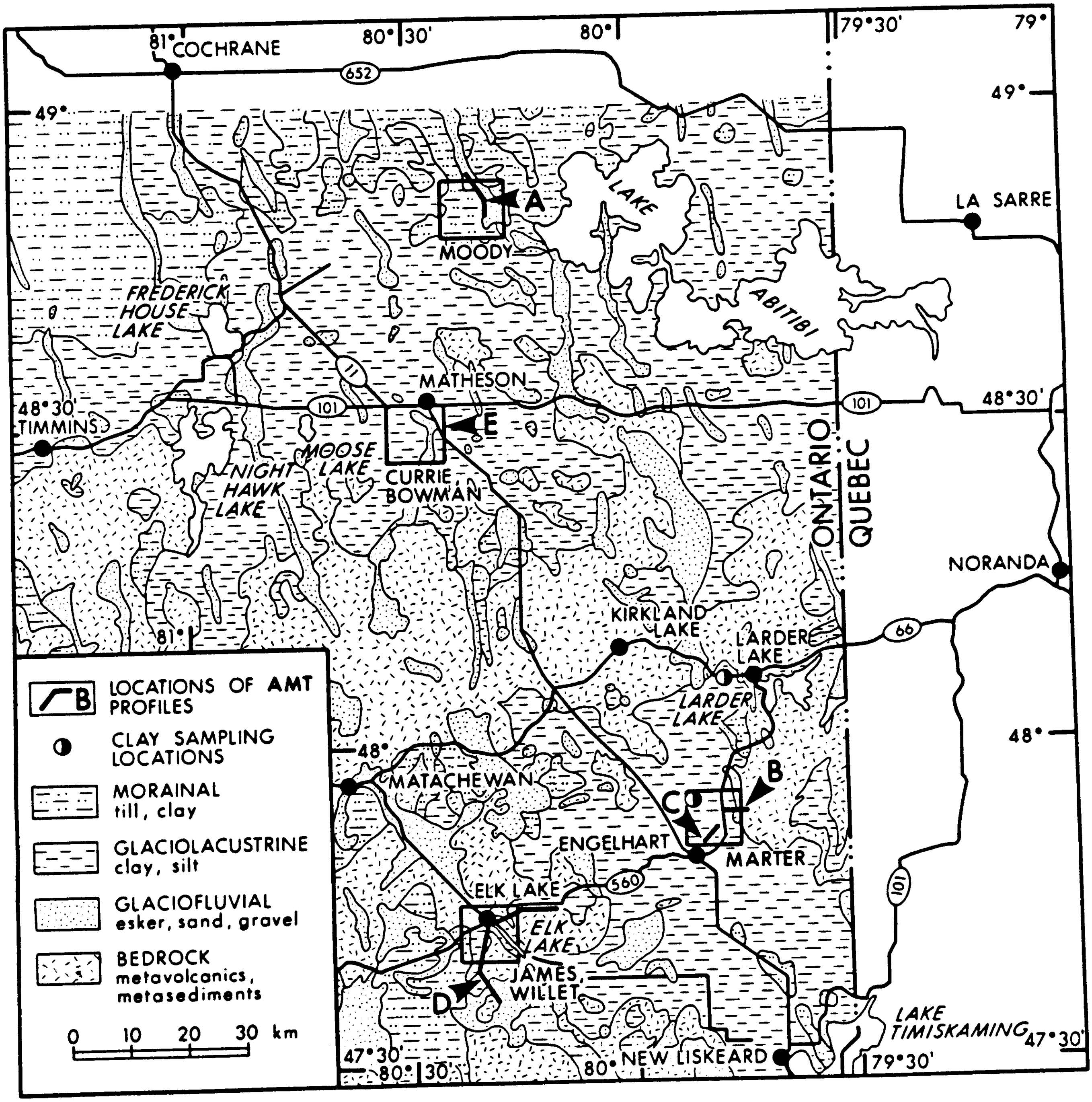

Figure 1. Geographic location and simplified surficial geology map (modified from Roed and Hallett 1979; Lee 1979a,b).

Table 1. Wisconsin deposits in study area (after Averill and Thompson 1981; Hughes 1961).

ORGANIC DEPOSIT

- Shell, marl, peat

COCHRANE FORMATION

- Clay till, glaciolacustrine sediments

BARLOW-OJIBWAY FORMATION

- Silt, sand
- Varved clay, massive clay (megavarve)

GLACIOFLUVIAL DEPOSITS

- Sand, gravel, esker

MATHESON FORMATION

- Sandy boulder till, gravel

BEDROCK GEOLOGY

The bedrock geology of the individual study areas is shown in Figures 2a-d. The oldest rocks in the Superior Province, where most of the survey was carried out, are volcanic and sedimentary rocks of Early Precambrian age. These rocks were deposited in a number of easterly trending eugeosynclines which are possibly of different ages and tectonically independent. Early Precambrian mafic metavolcanics strike east and consist of massive and pillowed flows, with minor related breccia and tuff. The lavas are conformably overlain by greywacke and argillite. All of these rocks are overlain unconformably by thinly bedded alternations of greywacke, shale with a few beds of quartzites, and conglomerate of variable thickness at or near the base. The Early Precambrian rocks are folded along easterly trending axes. These folds appear to be modified in places by crossfolds of various orientations, and are cut by several easterly trending faults and some younger faults trending northwest, north-northwest, and northeast. The youngest rocks of Early Precambrian age are felsic intrusions which are primarily granitic and syenitic in composition. The Huronian Supergroup of Middle Precambrian age is a sequence of sedimentary and volcanic rocks that lies unconformably on the Early Precambrian basement, which was deeply eroded and has a rugged topography. The Huronian rocks are undeformed or very gently folded. The Cobalt Group, the uppermost group of the Huronian Supergroup, is composed of four formations, of which the lowest two are most extensively exposed and best known. The Gowganda Formation consists of paraconglomerate, argillite, siltstone, subarkose and greywacke. It overlaps the other parts of the Huronian and lies unconformably on Early Precambrian rocks. The Lorrain Formation overlies the Gowganda conformably and is composed predominantly of quartzite and arkose.

INTERPRETATION

AMT data interpretation consists of two main stages. The first is a general qualitative overview of the data obtained, and is usually first done in the field. It is convenient to represent the measurements on a (log ρ log f) scale. By polynomial fitting, the bad readings can be detected and poor data rejected. The pseudosections based on the polynomial fits provide a rough idea of the two-dimensional distribution of resistivity. The residual plots, frequency-by-frequency, represent the resistivity values determined by subtracting the mean value for each line from the observed value. In the case of some two-dimensional effects, the anisotropy (TE/TM) plots provide a meaningful picture.

The second stage of interpretation is the fitting of a layered earth model at each station by one-dimensional inversion methods to get the best parameters that fit the data obtained. We have been using a nonlinear, least-squares estimation method (Marquardt 1962; Hsu 1981) to invert AMT data.

Another simple form of presentation for AMT data in the depth domain is the Bostick transformation (Bostick 1977). The result is an approximate depth-resistivity cross-section which contains information on the quality of data and the homogeneity of the subsurface. The application of this transformation, as well as the inversion method, to invert the data, saves labor, time and money and provides the maximum use of the data.

In stratified environments, one-dimensional modelling along a survey line is generally enough to give a two-dimensional configuration, but apparent resistivities can be influenced by lateral anomalous conductors. In such a case, layered model interpretations would be in error (Kryzan and Strangway 1977). Two- or three-dimensional modelling can have structures in any form with various resistivities. For mapping purposes, one-dimensional interpretation for stations distributed on a grid is necessary in order to get a plan view of any three-dimensional structures present. However, some two-dimensional test models have been set up by using network solution techniques (Madden and Thompson 1965), helping us to understand the actual apparent resistivity curves.

MOODY TOWNSHIP (PROFILE A)

Profile A is north-south, roughly parallel to an esker ridge. Ground moraine, essentially till and clay, dominates. The strike of the bedrock formations is approximately perpendicular to the profile. The north part (north of site A-9) of

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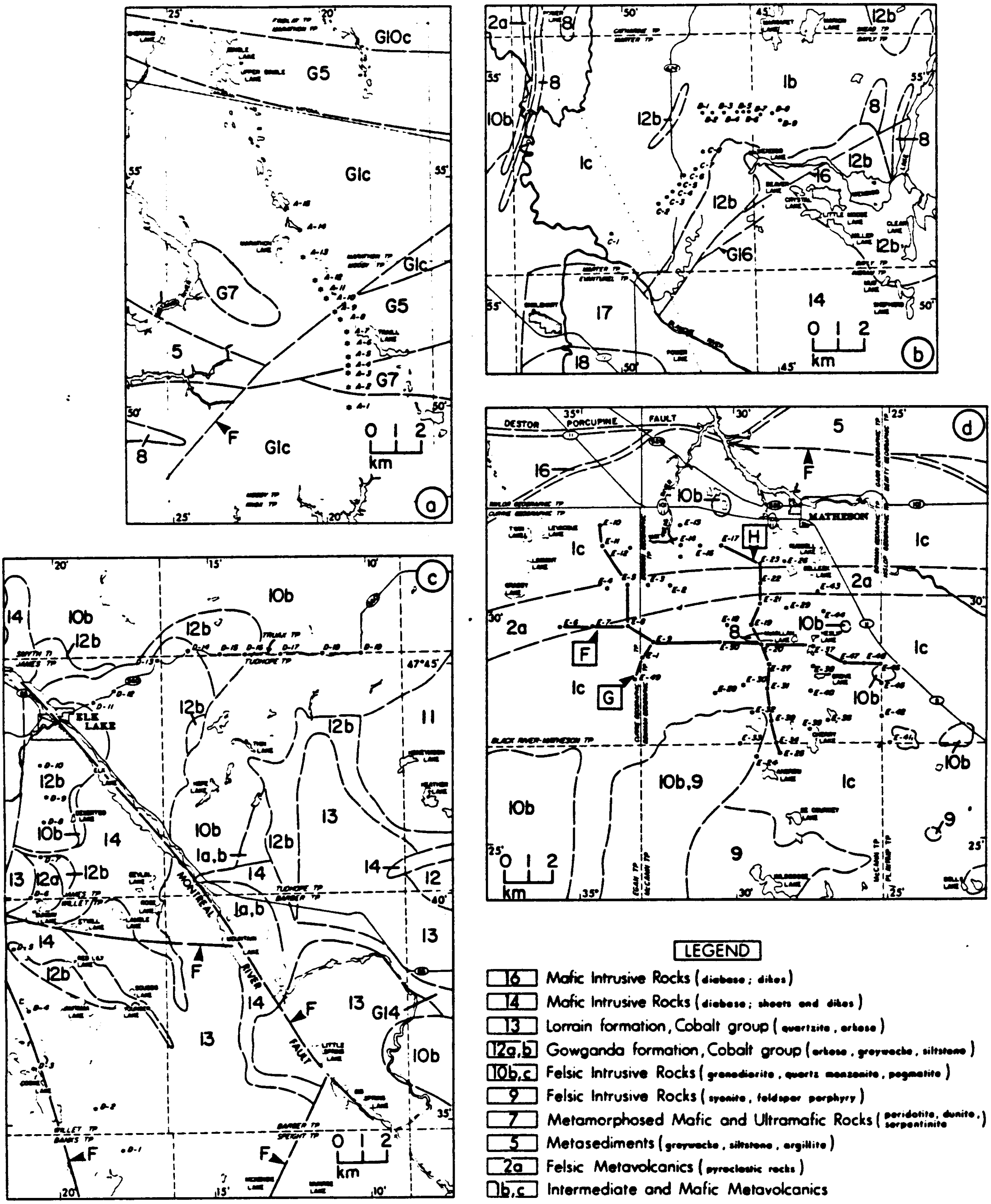

Figure 2. Bedrock geology maps (after Pyke et al. 1973) and the locations of AMT sounding sites: **a.** Profile A in Moody Township; **b.** Profiles B and C in Marter Township; **c.** Profile D in Elk Lake area; **d.** Grid E in Matheson Township.

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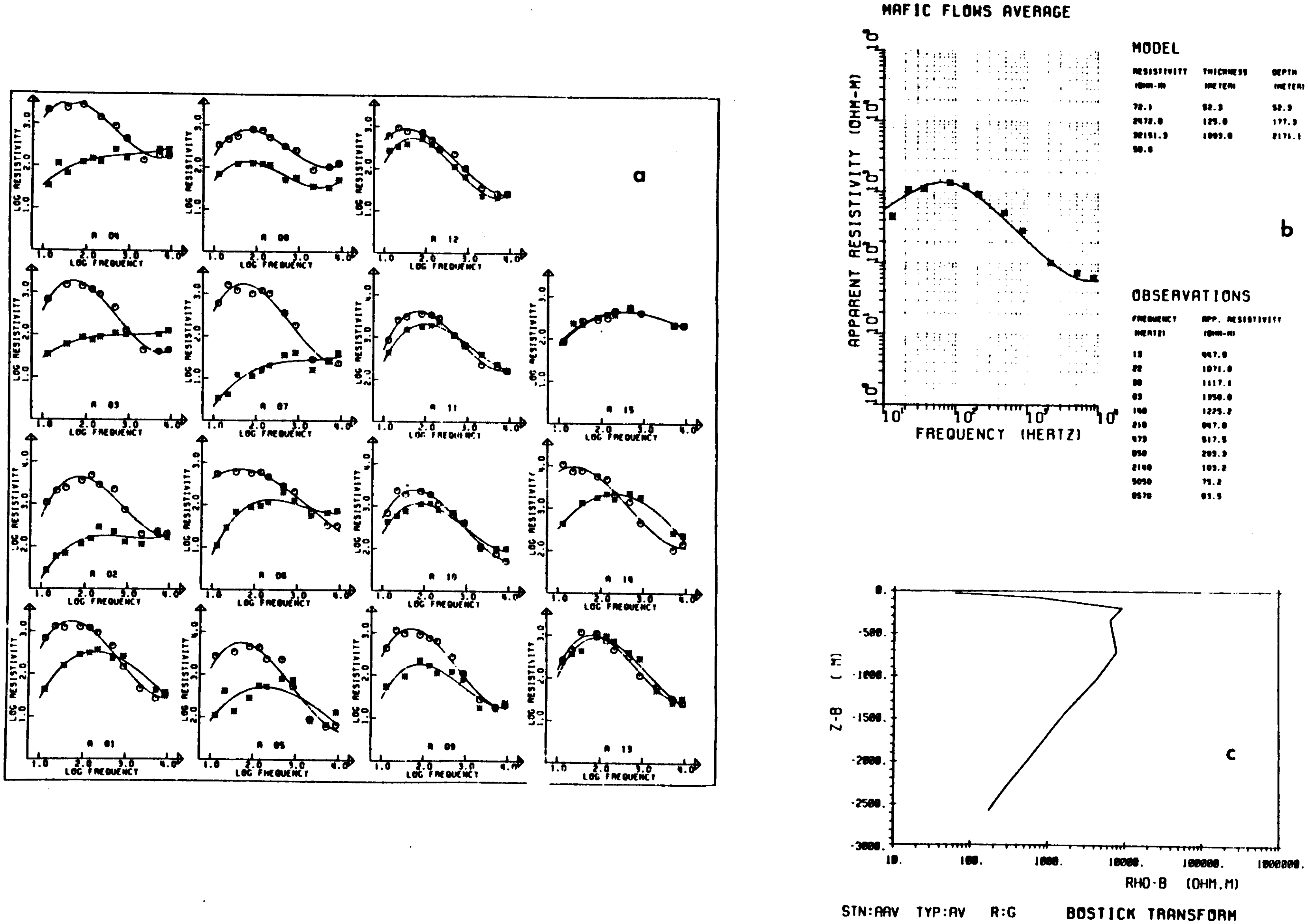

Figure 3. a. AMT sounding curves of Profile A. Circles are NS (northerly) orientation and stars are EW (easterly) orientation data; **b.** One-dimensional inversion model for line segment on metavolcanic rocks. Apparent resistivities are averaged using data from sites A-10, A-11, A-12 and A-13; **c.** Bostick resistivity depth cross-section computed from the same averaged data.

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Profile A overlies metavolcanics. The field data for both northerly and easterly orientations (Figure 3a) are very similar at sites A-10, A-11, A-12, A-13 and A-15. This indicates that there are no significant two-dimensional effects in this part of the profile. It can therefore be reasonably approximated by a one-dimensional structure. An average, which is computed by averaging the square root of apparent resistivities at each frequency for each of these sites and then averaging for the section, is used to represent the resistivity variation with depth in this profile segment. The fitted model using the one-dimensional inversion technique suggests that there is about 50 m of overburden with a resistivity of around 70 ohm-m (Figure 3b). A highly fractured weathered layer about 100 m thick with resistivity about 2400 ohm-m lies beneath. The uppermost part of the bedrock has a resistivity of approximately 32 000 ohm-m. The Bostick transformation shows that the resistivity of the bedrock drops to 2000 ohm-m at a depth of about 2000 m (Figure 3c).

The sounding curves of Profile A in Moody Township show that there is very strong anisotropy at sites south of site A-9. This phenomenon occurs without exception in the low frequency range, and implies a peculiar characteristic of the metasediments and metamorphosed mafic and ultramafic rocks (G5 and G7 respectively in Figure 2a). The rocks are more resistive in the NS (north-trending) electrode orientation than in the EW (east-trending) orientation. This may be due to the two-dimensional structure of this area. The resistivities of the metavolcanics and of the metasediments are not significantly different in NS orientation. However, in the EW orientation, the metasediments tend to be more conductive than the metavolcanics, suggesting a preferred direction of fracturing or of structure. At least two faults, one through A-9 and one near A-3, have been suggested by other geophysical interpretations (Pyke *et al.* 1973). Easterly trending, vertically bedded Early Precambrian rocks could be an explanation of the anisotropic behaviour of the apparent resistivity data.

On the other hand, sand associated with narrow esker ridges interfingers laterally with glaciolacustrine clays. The stations in the southern part of Profile A are on the glaciolacustrine cover, but are not far from an esker ridge. This local and near surface resistivity variation could have produced an edge effect in the southern part of Profile A and hence could be a cause of this anisotropy.

The study suggests that the most probable explanation is that the metasediments are themselves strongly anisotropic. In this case it will be possible to characterize steeply dipping metasediments with the AMT method even when they are not exposed. Additionally, it should be possible to map bedrock in detail beneath regions covered by eskers using the AMT method. Similar mapping would not be possible using conventional expanding electrode array systems because of the lateral effects and the need for deep penetration.

MARTER TOWNSHIP (PROFILES B AND C)

The sounding curves of Profiles B and C in Marter Township all show a general similarity in both the NS and the EW orientations. The overall similarity of sounding indicates that the basement volcanic rocks and overburden are both homogeneous in the area. Only Wisconsin deposits are present as glacial overburden. Profile B crosses the south end of the Munro esker east of site B-6. This is a major feature that can be traced northward 300 km to James Bay. In Marter Township, the esker is confined to regional bedrock highs and consists entirely of sand (drill hole No. 6, Averill and Thompson 1981). Pseudosections along Profile B are given in Figure 4a. Apparent resistivities of about 1000 ohm-m were obtained on the esker at higher frequencies. A one-dimensional interpretation was not done for site B-6 because of the obvious two-dimensional structure in the vicinity. A depth-resistivity cross-section compiled using the Bostick transformation method is given in Figure 4b. Together with one-dimensional inversion fits along Profile B, these data reveal that the sand and gravel in this area is up to 100 m thick. Its resistivity ranges from 800 to 3000 ohm-m. The bedrock generally has a layer several hundred metres thick, of medium resistivity, overlying a highly resistive unfractured section of bedrock with resistivities up to 100 K ohm-m. There may be minor clay beds deep beneath the very thick sand and gravel in the eastern part of the profile area.

The pseudosections of Profile C in Figure 5a show the same homogeneity in both orientations as those of Profile B, also implying that there is no major lateral variation. The high frequency readings, however, are different from those in Profile B and are about 100 ohm-m, or less. The pseudosections and residual plots of Profile C reveal that the apparent resistivities are continuously decreasing southwesterly. This implies either that the overburden is getting thicker, or that the resistivity of the top conductive layer is getting lower. Drill hole No. 5 (Averill and Thompson 1981) is located at the same site as C-4 and has been used to control the model of the site and to determine the resistivities of the layered earth. The cross-section shown in Figure 5b was obtained by a one-dimensional interpretation at each site and reveals a basin structure corresponding to that detected by drilling. The basin has its edge at the northeast end of the line near site C-8. The model suggests that there is a 50 m thick overburden at the southwest end of the survey line near site C-1 and that the thickness decreases northeasterly to about 30 m at site C-5. The bedrock resistivity, from the model, is very homogeneous at about 20 000 - 60 000 ohm-m throughout the survey line.

ELK LAKE AREA (PROFILE D)

In the Elk Lake area, station locations were chosen to sample different rock types in the northern part of the profile. The apparent resistivity profiles in Figure 6a show that, in this part of the survey line from site D-13 to D-19, the structure is very complicated electrically. Site D-15 and D-16 lie on a sliver of Cobalt Group sedimentary rocks about 2000 m wide, sandwiched between younger mafic intrusive rocks (14 in Figure 2c) and older felsic

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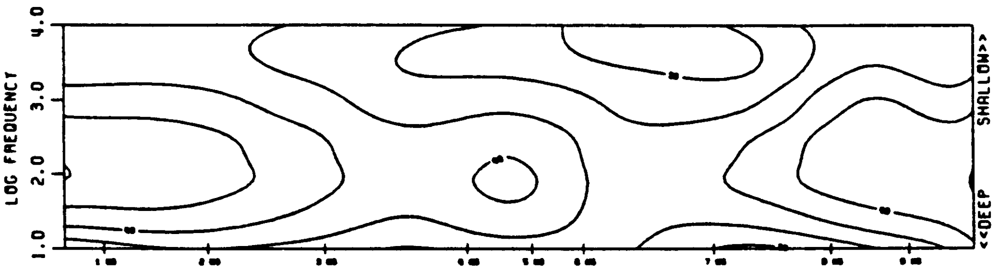

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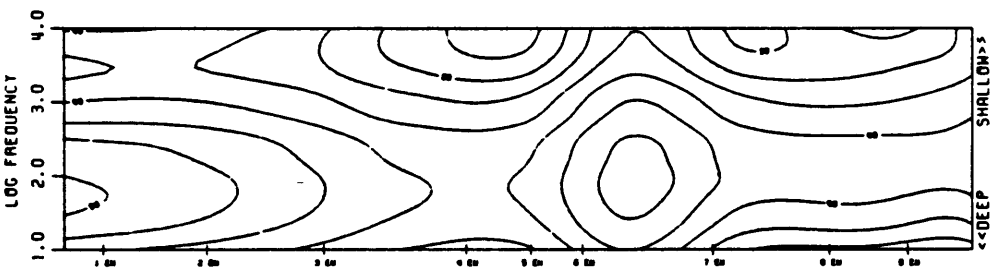

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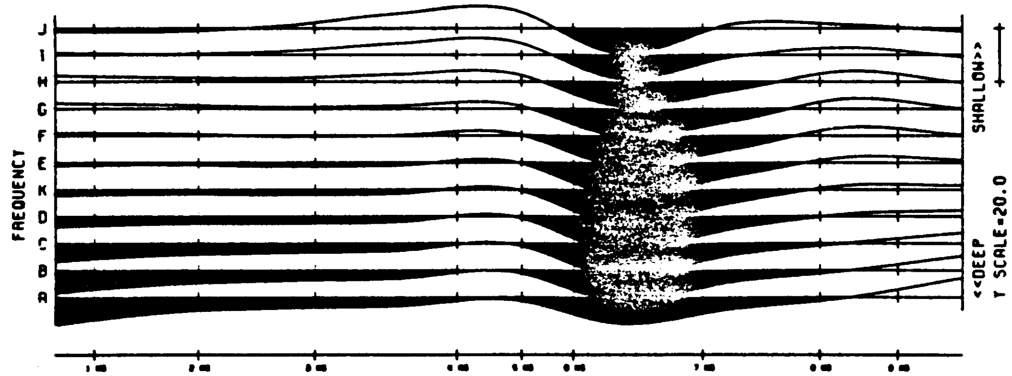

MARTER TP. LINE-B TE/TM PLOT Y=10*LOG(RHO.NS/RHO.EW)

Figure 4a. *Apparent resistivity pseudosections and TE/TM plot for Profile B. Station locations along the horizontal axis and frequency on the vertical axis.*

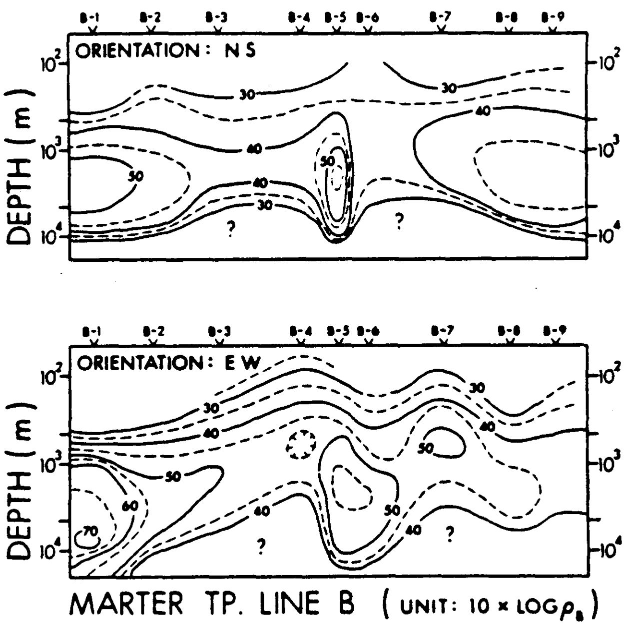

Figure 4b. *Bostick resistivity cross-sections along Profile B, (unit is 10 log a).*

intrusive rocks (10b). The measurements in the section appear to be strongly affected by the two contact zones and show inhomogeneity and anisotropy. The mafic intrusive rocks (sites D-11 to D-14) tend to be more resistive than Cobalt Group sedimentary rocks and felsic intrusive rocks (sites D-17 to D-19). The major feature in the area is the Montreal River Fault running under the town of Elk Lake. It is reflected in the apparent resistivity readings at site D-10 and in the high frequency readings of D-11. The shape of the profiles suggests that the fault dips to the southwest. The section on the southern part of the survey line lies on the Cobalt Group sedimentary rocks. Similarity is shown from site to site, especially in the low frequency range. The model fit of an averaged apparent resistivity set in Figure 6b, computed from sites D-1, D-2, D-3, D-4, D-5, D-6, D-8 and D-9, suggests that the top Cobalt sedimentary rocks have a thickness of about 280 m and a resistivity of about 2000 ohm-m. Beneath them could lie a highly fractured weathered layer, with resistivity less than 1000 ohm-m and about 100 m thick. The underlying Early Precambrian metavolcanics have resistivity values in the 25 000 ohm-m range.

BOWMAN TOWNSHIP (GRID SURVEY E)

In Bowman Township, the main features of the surficial geology are a clay-covered plain, eskers and bedrock outcrop (Figure 7b). Each unit shows different electrical characteristics. The three subdivisions are clearly outlined on contour maps of apparent resistivities in Figures 7a and 7c. A contour map of frequency J (Figure 7a) generally reflects the surficial geology, and shows a highly conductive clay-covered plain in the northwestern part of the area with resistivities less than 100 ohm-m. A high-resistivity region in the southwestern part of the area has resistivities higher than 3000 ohm-m. An intermediate resistive region is located to the east of the other two regions. The contour maps at lower frequencies such as the map of frequency C (Figure 7c) shows roughly the same pattern as that of frequency J, indicating that they are affected by the surface material.

The averaged apparent resistivity pseudosections for three Profiles F, G and H are given in Figure 7d. Sounding curves for the northwest segment of the map and the pseudosection for line G, show a typical two-layer structure: an extremely conductive layer on top of an extremely resistive half space. High frequency readings of 20-30 ohm-m reflect the top conductive clay-rich overburden. The similarity of two sets of data for the NS and EW orientations indicates the homogeneity in the glaciolacustrine plain. Anisotropy generally appears at esker-complex sites, for example E-37 on Profile F and E-24 and E-25 on Profile H. Apparent resistivities at high frequencies are mostly about 100-300 ohm-m, then rise to around 10 000 ohm-m at some sites. Strong anisotropy was observed at sites near bedrock outcrops. High apparent resistivities in the 10 000 ohm-m range were obtained at high frequencies, indicating the thin overburden and the very resistive bedrock.

The averaged data from the two orientations was employed to determine a best estimate of the electrical structure at each site. It is a good approach to interpreting data from such a glaciolacustrine-deposit covered plain because of the obvious one-dimensionality shown on the two sets of data. The top two layers, with resistivities of 10 to 40 ohm-m and thicknesses in the 20-100 m range, are very conductive clay-containing overburden of varying composition. The composition varies from a sand and boulder-rich resistive unit to a very conductive clay unit. The third highly resistive layer at 20-100 m beneath the surface is associated with bedrock having resistivity in the 10 000 - 50 000 ohm-m range. For those sites on eskers and those near bedrock outcrop, one-dimensional interpretation may be risky and misleading when strong anisotropy exists. The determination of the top layer resistivity is reliable, because of the general agreement of high frequency data on both directions.

Three block maps, showing surface resistivity, bedrock topography, and bedrock resistivity, and a contour map of bedrock topography were created by using the appropriate model parameters of the one-dimensional interpretation (Figure 8a-d). Those sites with apparent resistivity differences at frequency D of more than a factor of 5 were left out due to the unsuitability for one-dimensional modelling. The real surface resistivity map (Figure 8b) which is similar to the frequency J apparent resistivity contour map in Figure 7a, reflects the resistivity variation of surface material in the top few tens of metres. The three types of material with their characteristic resistivities are clearly outlined. The bedrock topography map was cre-

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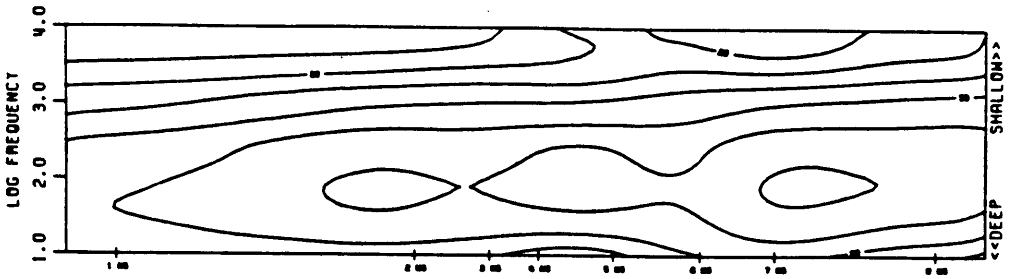

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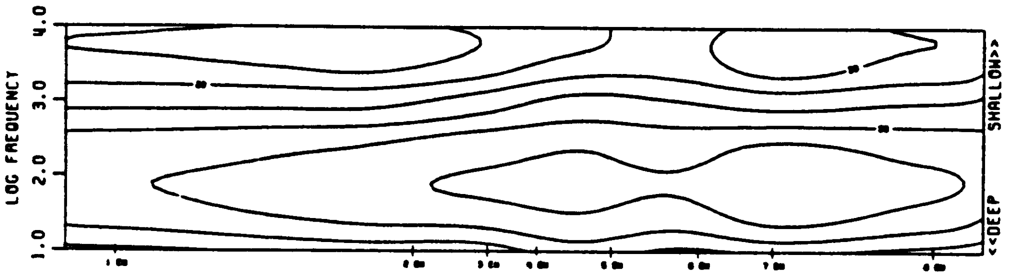

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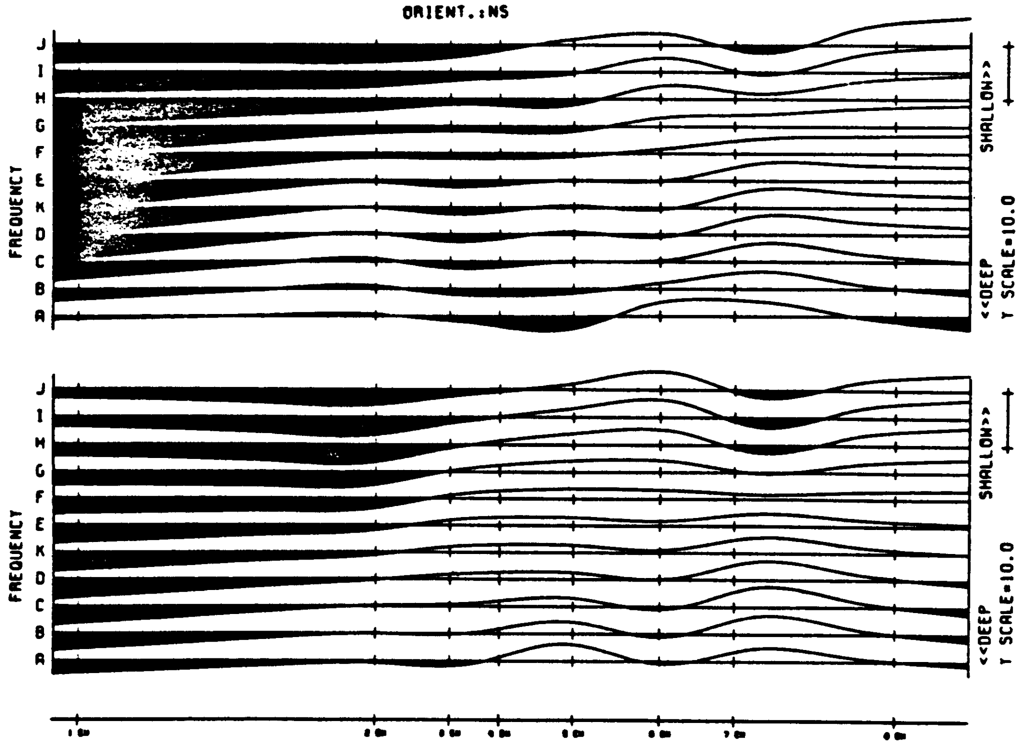

MARTER TP. LINE-C RESIDUAL PLOT. ORIENT.:EW. Y=10*LOG(RHO.A/RHO.AV)

Figure 5a. Apparent resistivity pseudosections and residual plots for Profile C.

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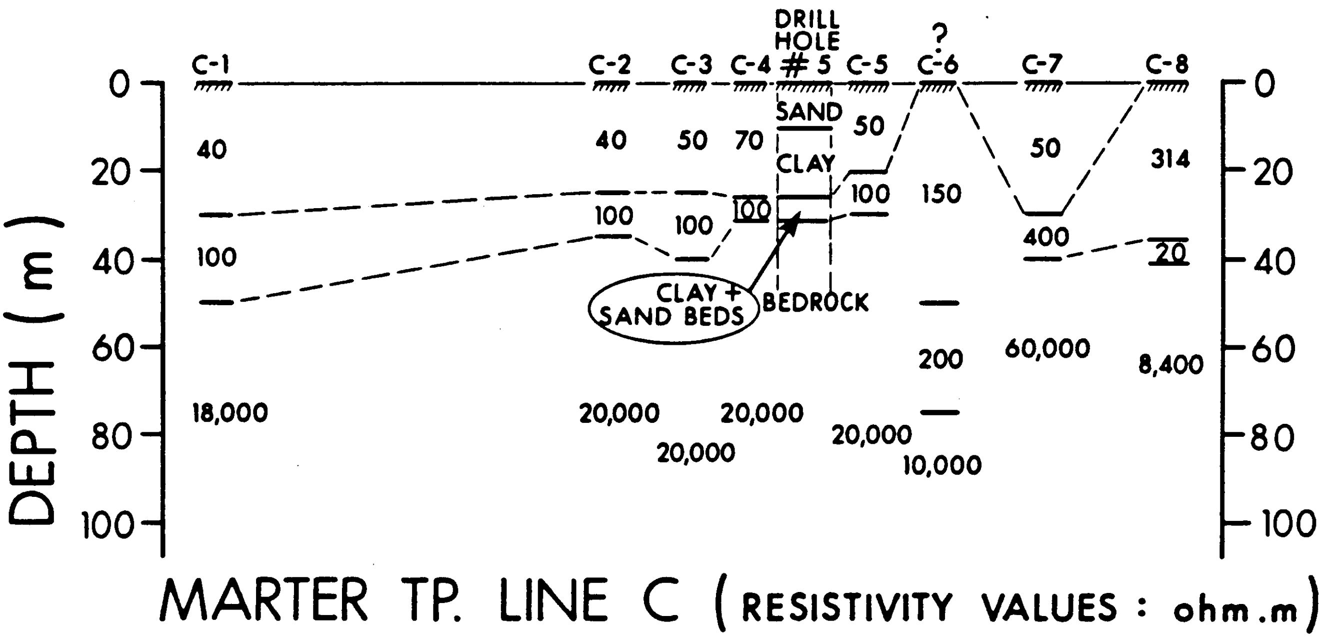

Figure 5b. *Two-dimensional configuration for Profile C derived from one-dimensional inverse models.*

ated by contouring the thickness of the top one or two conductive layers, representing the thickness of overburden in one-dimensional interpretation. Elevation correction was not applied and the surface was assumed to be flat, which is roughly the case in this area. The maps show that a bedrock valley, 100 m below surface in the northwest quadrant of the area, trends northwesterly near sites E-4, E-5, E-8 and E-9. Another bedrock topographic low at the southeastern corner of the area is near sites E-35, E-36 and E-42. These two bedrock topographic lows could imply that valleys in the older metavolcanics are separated by the younger intrusive rocks. The bedrock topography in the rest of the survey area has no significant variation in elevation. The area of bedrock exposures has an overburden thickness of less than 20 m. The areas covered by clay and by sand and/or gravel show no signficant differences in bedrock topography; all the bedrock in both these areas is in the range of a few tens of metres below the surface. The bedrock resistivity map (Figure 8a) indicates that the resistivities of bedrock in this area are extremely high in the range of 10 000 to 100 000 ohm-m. The lateral variation is not significant. Comparing the bedrock resistivity map (Figure 8a) with the bedrock geology map (Figure 2d), the felsic metavolcanics (2a) in this area tend to be more resistive than the intermediate and mafic metavolcanics (1c). The felsic metavolcanics form a ridge of high resistivity, trending roughly east in the north-central part of the area. The intrusive rocks in the south (10b, 9) have homogeneous resistivity of about 10 000 ohm-m.

ELECTRICAL PROPERTIES OF CLAY

In applying EM exploration techniques, in areas where there is an extensive clay cover, it would be useful to have a better understanding of the electrical properties of the clays. The clays are the most conductive component of the overburden, with the exception of saline alluvium, which is not known to exist in the area studied. In the Kirkland Lake area, the clays have resistivities on the order of 20 ohm-m, whereas the sands, gravels and tills have resistivities in the range of 100 to 1000 ohm-m. Thus, clay is the most important component of the overburden, in terms of limiting the depth of exploration by EM methods.

Mehran and Arulanandan (1977) measured a strong frequency dependence for the resistivity of kaolinite, illite, and a silty clay in the frequency range 50 Hz to 100 KHz. The conductivity dispersion, which was defined in this case as the difference between the conductivity at 100 KHz and at 50 Hz, was dependent upon the water content, the type of electrolyte, and the electrolyte concentration. The measured conductivity dispersions were on the order of 30 to 60 percent, decreasing with increasing

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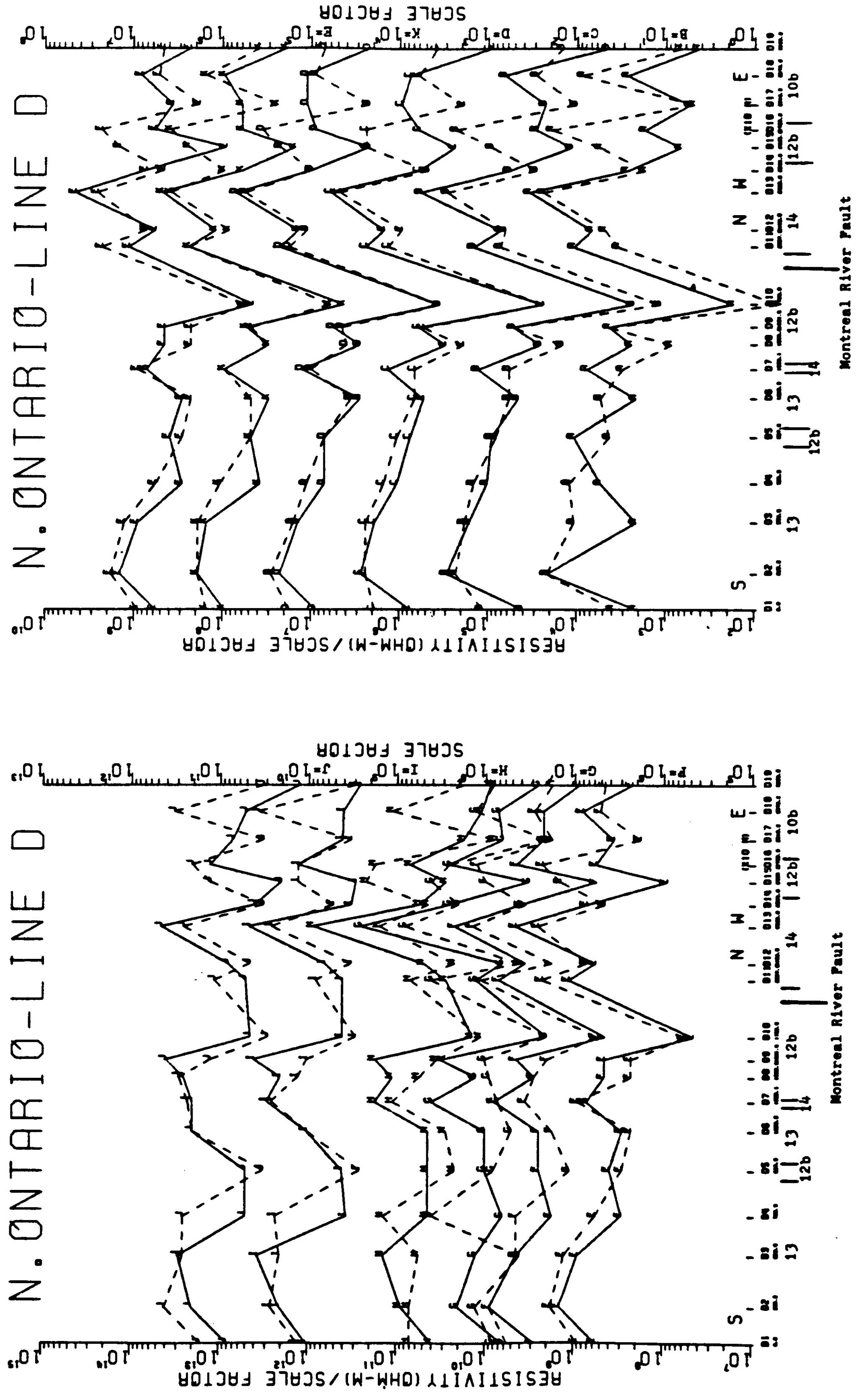
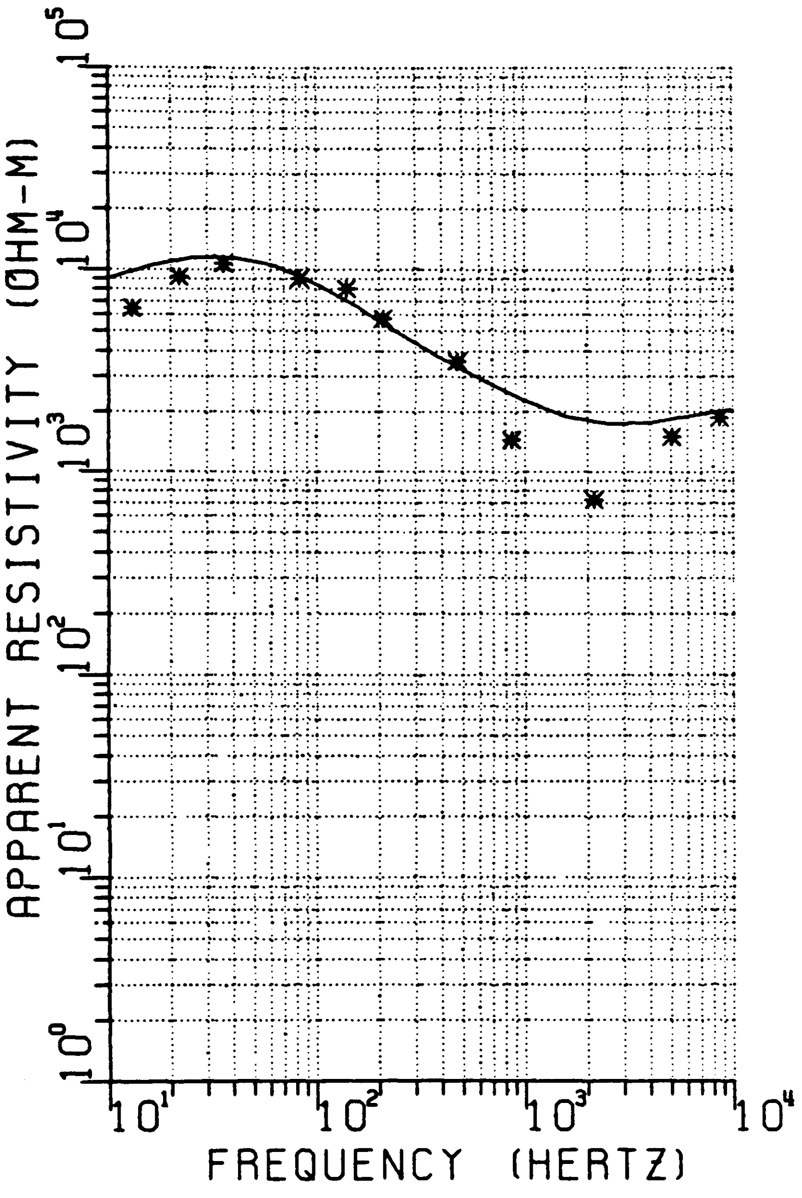


Figure 6a. *Apparent resistivity profiles along Profile D for each frequency channel. Each curve is offset from the others so that the individual profiles can be followed (NS oriented data; Solid lines; EW oriented data, dashed lines).*

HURONIAN SUPERGROUP



MODEL

RESISTIVITY (OHM-M)	THICKNESS (METER)	DEPTH (METER)
2059.3	281.2	281.2
1554.1	157.2	438.4
24338.1	7968.7	8407.1
2561.2		

OBSERVATIONS

FREQUENCY (HERTZ)	APP. RESISTIVITY (OHM-M)
13	6474.3
22	9226.4
36	10753.2
83	9013.2
140	8076.8
210	5760.1
473	3548.6
858	1440.2
2140	727.4
5050	1503.3
8570	1863.5

Figure 6b. *One-dimensional model for line segment on Huronian Supergroup metasediments. Apparent resistivities are averaged using data from sites D-1 to D-9.*

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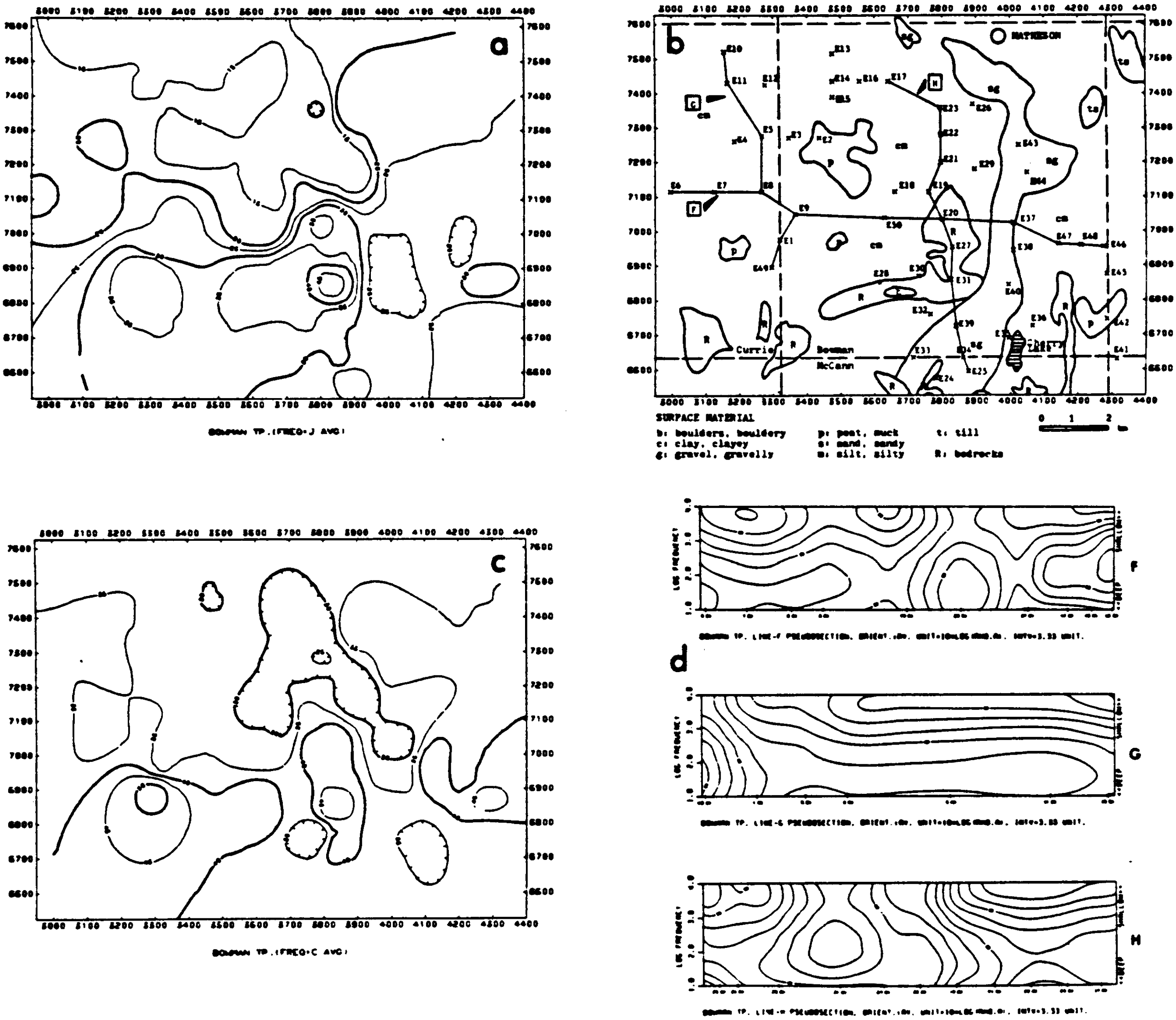

Figure 7. a. Contour map of apparent resistivities at high frequency (J = 8570 Hz); **b.** Surficial geology of the survey area in Bowman Township; (x) represent AMT site location; **c.** Contour map of apparent resistivities at low frequency (C = 83 Hz); **d.** Averaged apparent resistivity pseudosections for Profiles F, G and H.

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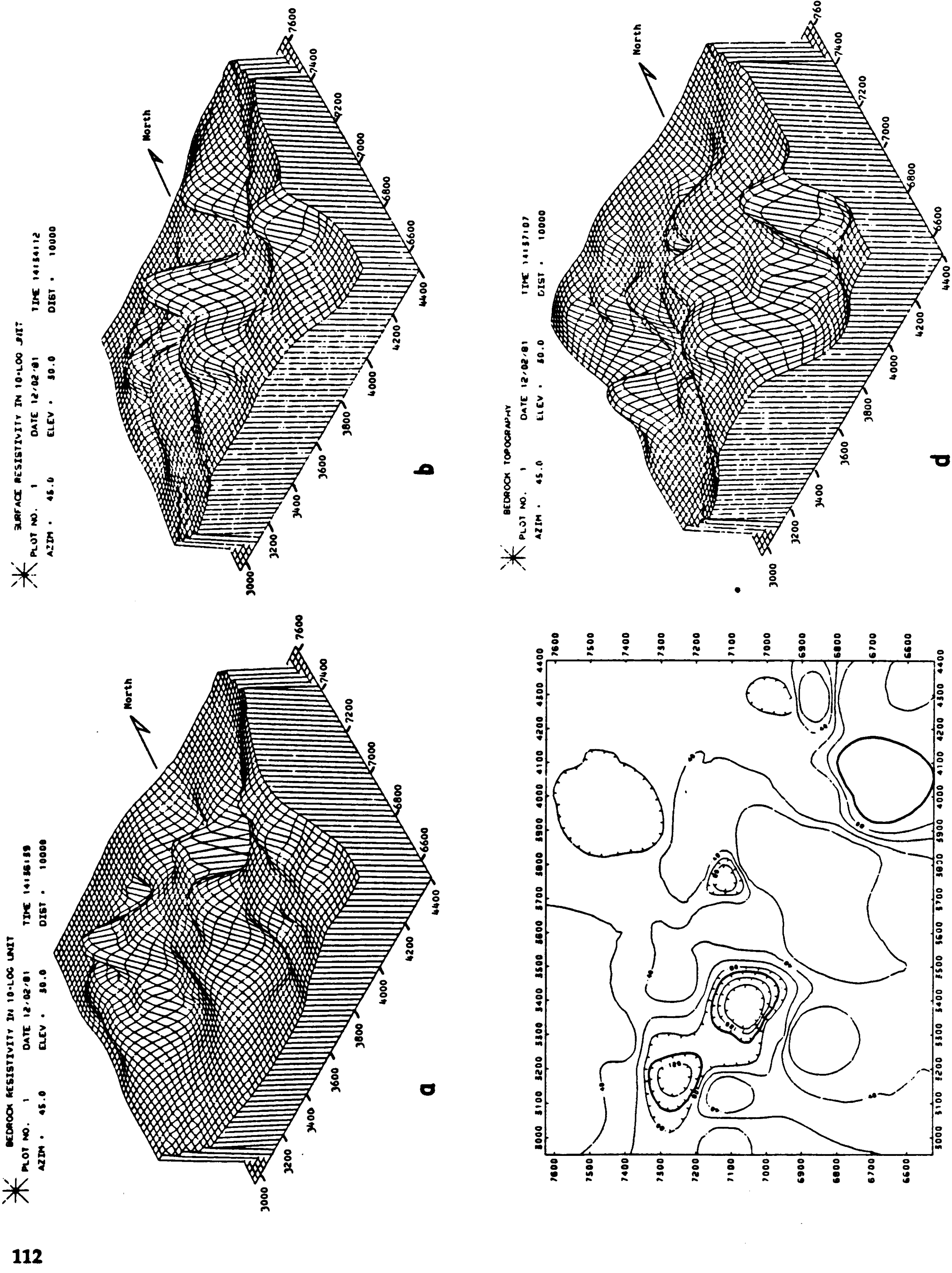

Figure 8. a. Block map of bedrock resistivity; **b.** Block map of surface resistivity; **c.** Contour map of bedrock topography; **d.** Block map of bedrock topography. Block maps were created by model parameters of the one-dimensional interpretation.

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with increasing water content and with increasing electrolyte concentration. Silty clay gave the highest dispersion and illite the lowest. If a similar conductivity dispersion phenomenon exists in the glaciolacustrine clays, it could cause serious limitations in the interpretation of some EM methods. Thus it would be useful to have measurements of the magnitude and the frequency dependence of the resistivities of clays from northern Ontario.

Samples were collected from nine sites near Larder Lake, Matheson, and Engelhart. Some samples were taken from a vertical soil profile that was exposed in the Larder Lake dump and others were collected from road cut exposures and from exposures along rivers.

In collecting the samples, an attempt was made to preserve the samples in their original state. When a suitable site was found, the surface material was removed to expose fresh undisturbed clay. Samples were obtained by pressing a plastic tube (2.5 cm diameter by 2.5 cm length) into the face of the clay. The sample was then placed in a plastic bag that was heat-sealed later in the day, so as to preserve the original moisture content of the sample.

The complex resistivity was measured over the frequency range 5 Hz to 10^6 Hz. This range more than covers the frequencies used in most EM exploration methods. The samples were encapsulated during the measurement process to prevent them from drying.

All the measurements were carried out using the HP4192A impedance meter. Four terminal measurements were made between 5 Hz and 10 KHz, and above 10 KHz a two terminal technique, employing platinum electrodes, was used. Two of the samples measured gave the results shown in Figure 9. The resistivity magnitude changes little with frequency. Sample KL-36 had a clay content of 26 percent, a water content of 13 percent, and a resistivity of 24 ohm-m at 100 Hz and 22 ohm-m at 100 KHz. Sample KL-11 had a clay content of 77 percent, a water content of 31 percent, and a resistivity of 36 ohm-m at 100 Hz and 34 ohm-m at 100 KHz.

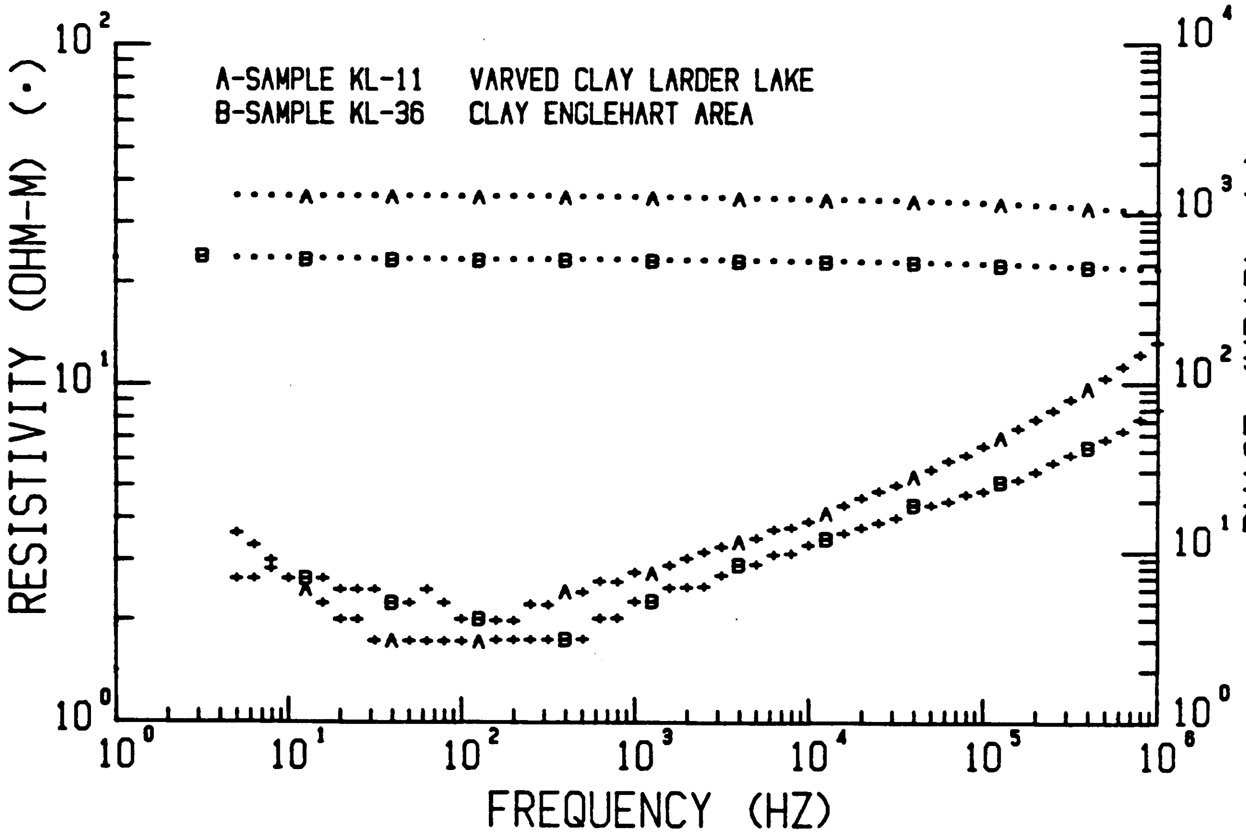

Figure 9. The dependence of the resistivity magnitude and phase on frequency for two clay samples, one of which was a varved clay. The dots and crosses are the actual measurements.

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CONCLUSIONS

With the AMT method, we have been able to characterize, in the areas surveyed, the conductivity structure of clay-rich overburden and Precambrian Shield rocks underneath.

In Moody Township near Lake Abitibi, the survey showed a strong and uniform electrical anisotropy in an area believed to be underlain by metasediments. If this is true, then it will be possible to map out concealed, steeply dipping metasediments with the AMT method. There are many highly resistive eskers in northern Ontario which could be used as electrical sounding windows into the bedrock using this method.

Good correlation with known surficial geology in Marter Township near Engelhart was obtained when estimating the overburden thickness with the AMT approach. The ability to sound through conductive overburden and to detect conductors beneath has been proved to be possible. The resolving power, however, has to be improved by careful field measurements and careful model parameter selection. An approximate depth-resistivity diagram could be computed by applying the Bostick transform to field data to aid in interpreting survey results.

There are narrow conductive zones within the bedrock in the Elk Lake area that are interpreted as conductive fault zones. To determine the thickness of Huronian Supergroup rocks overlying Early Precambrian basement, further detailed studies are required.

Maps produced by using grid survey data in Bowman Township near Matheson show a conductive region (clay-rich overburden) in the northwestern part of the area. A high resistivity region (bedrock outcrop) occurs in the southwestern part, and an intermediate resistivity region (esker) occurs east of the other two locations. Some bedrock valleys in the northwestern part of the area were detected at depths of 50 - 100 m. Bedrock resistivity is typically 10 to 100 Kohm-m. High frequency data give resistivities of 20 to 30 ohm-m over clay-rich overburden. This value is in general agreement with resistivities measured in clay samples. The value of the clay resistivity seems fairly uniform in study areas ranging from Lake Abitibi to Engelhart.

ACKNOWLEDGMENTS

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REFERENCES

Averill, S.A. and Thomson, I.
1981: Reverse Circulation Rotary Drilling and Deep Overburden Geochemical Sampling in Marter, Catherine, McElroy, Skead, Gauthier and Hearst Townships; District of Timiskaming, Ontario Geological Survey, Open File Report 5335, 276p.
Bostick, F.X., Jr.
1977: A Simple and Almost Exact Method of MT Analysis (Abstract); Workshop on Electrical Methods in Geothermal Exploration, Utah.
Cagniard, L.
1953: Basic Theory of the Magnetotelluric Method of Geophysical Prospecting; Geophysics, Vol. 18, p. 605-635.
Hsu, D.T.
1981: One-Dimensional and Two-Dimensional Interpretation of Audiomagnetotelluric Data; Unpublished M.Sc. Thesis, University of Toronto.
Hughes, O.L.
1961: Preliminary Report on Borings Through Pleistocene Deposits, Cochrane District, Ontario; Geological Survey of Canada, Paper 61-16.
Kryzan, A. and Strangway, D.W.
1977: Magnetotelluric Studies in the Geotraverse Area; Unpublished Proceedings, 1977 Geotraverse Conference, University of Toronto, 121-131.
Lee, H. A.
1979a: Northern Ontario Engineering Geology Terrain Study Data Base Map: Iroquois Falls; Ontario Geological Survey, Map 5027, Scale 1:100 000.
1979b: Northern Ontario Engineering Geology Terrain Study Data Base Map: Kirkland Lake; Ontario Geological Survey, Map 5030, Scale 1:100 000.
Madden, T. and Thompson, W.
1965: Low-Frequency Electromagnetic Oscillations of the Earth-Ionosphere Cavity; Rev. Geophy. Space Phys. Vol. 3, p. 211-254.
Marquardt, D.W.
1962: An Algorithm for Least Squares Estimation of Nonlinear Parameters; Journal Society Indust. Applied Mathematics, Vol. 11, p.431-441.
Mehran, M. and Arulanandan, K.
1977: Low Frequency Conductivity Dispersion in Clay-Water-Electrolyte Systems; Clays and Clay Minerals, Vol.25, p. 39.
Pyke, D.R., Ayres, L.D. and Innes, D.G.
1973: Timmins-Kirkland Lake, Districts of Cochrane, Sudbury and Timiskaming; Ontario Geological Survey, Map 2205, Geological Compilation Series, Scale 1 inch to 4 miles.
Roed, M.A. and Hallett, D.R.
1979: Northern Ontario Engineering Geology Terrain Study Data Base Map: Elk Lake; Ontario Geological Survey, Map 5020, Scale 1:100 000.
Strangway, D.W. and Vozoff, K.
1969: Mining Exploration with Natural Electromagnetic Fields; Mining and Groundwater Geophysics, Geological Survey of Canada, Economic Geology Report, Vol. 26, p. 109-122.
Strangway, D.W., Redman, J.D. and Macklin, D.
1980: Shallow Electrical Sounding in the Precambrian Crust of Canada and the United States; in The Continental Crust and its Mineral Deposits, edited by D.W. Strangway, Geological Association of Canada, Special Paper 20.
Strangway, D.W., Swift, C.M. and Holmer, R.C.
1973: The Application of Audio Frequency Magnetotellurics (AMT) to Mineral Exploration; Geophysics, Vol. 38, p.1159-1175.

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Grant 118 Surface Electromagnetic Mapping in Selected Positions of Northern Ontario, 1982-1983

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ABSTRACT

Audiomagnetotelluric (AMT) data have been collected at 114 stations from 3 different locations during a multiyear electromagnetic mapping study in the clay-covered regions of Northern Ontario.

In Moody and Marathon Townships near Lake Abitibi, the resistivity at all stations shows an anistropic behaviour related to metasediments and to metamorphosed ultramafic rocks. This can be detected even when the ultramafic rocks are covered by conductive clays. One-dimensional models show approximately a 100 m thickness of overburden, with an average resistivity of 450 ohm-m. Underlying Precambrian metavolcanics have resistivity values in the range of 10 000 to 50 000 ohm-m. Conductors within the metavolcanics can be detected.

The Night Hawk Lake geophysical test site is located in the northeastern corner of Thomas Township, near Timmins. There is a conductive graphitic zone in the bedrock under about 90 m of glacial overburden (Barlow *et al.* 1982). A total of 73 AMT measurements were made in this area. Thirty-six (36) were on a rectangular grid with 150 by 200 m spacing. On the grid, the dominant feature is that the high frequency (8570, 5050 Hz) resistivities are around 100 ohm-m in the western portion of the area. This is related to increasing clay content in the glacial overburden towards the west. However, as we examine lower frequencies, we can see the presence of the conductive body within the rhyolite, with an east-west strike. The body appears to be traceable westward at lower frequencies, which are more effective at penetrating the conductive clay.

Measurements were made in Morrisette, Bisley, and Arnold Townships near Kirkland Lake along an east-west profile perpendicular to the Munro Esker. The dominant pattern shows high resistivities, up to 10 000 to 50 000 ohm-m, underneath the esker.

Measurements of the electrical resistivity and its frequency dependence have been made on representative samples of clays and sands. In the laboratory, clays have an average resistivity (at 50 Hz) of 24 ohm-m; silty clays - 45 ohm-m; and loams - 87 ohm-m. These results are similar to results measured in the AMT field work and using local in situ measurements. The frequency dependence is quite small in these samples, although 1 sample shows an unusual negative percent frequency effect.

INTRODUCTION

During the 1982 field season, work continued on a multiyear electromagnetic mapping study in northern Ontario. Parts of the glaciated Canadian Shield have very high resistivities beneath a thin and relatively conductive surface material. We applied the audiomagnetotelluric (AMT) technique to define vertical and horizontal changes within this surficial unit and to map characteristics of the bedrock.

An interference analyzer described by Strangway *et al.* (1973) was used to measure the scalar resistivities at discrete frequencies of 13, 25, 36, 83, 140, 210, 473, 858, 2140, 5050, and 8750 Hz. Electrode spacing was 100 m during normal surveys and 50 m for detailed surveys.

This report presents a summary of progress based on audiomagnetotelluric measurements made in Moody and Marathon Townships near Lake Abitibi (A), the Night Hawk Lake geophysical test range east of Night Hawk Lake (F), and Morrisette, Bisley, and Arnold Townships near Kirkland Lake (G).

Two resistivity soundings were carried out, using a Schlumberger array, at the Night Hawk Lake test site. Thirty-five (35) additional samples were collected from the Cochrane, Timmins, and Elk Lake areas for laboratory measurements. In situ measurements of low frequency resistivity, using a small Wenner array, were made at these sample sites.

DATA PROCESSING AND INTERPRETATION

The data were processed for presentation in several formats. A cubic polynomial was fitted by least-squares to measured ρ_a values versus discrete frequencies. The polynomial fitted 10 log ρ_a values were then computed as a function of log f (decreasing downward) and distance along the lines, and then contoured as pseudosections. These figures illustrate lateral and vertical variations simultaneously. Although not presented here, residual resistivity plots (difference of observed and averaged resistivity at each particular frequency along the line) were also prepared. These plots are especially useful in locating the low resistivity zones. Plots of the ratio of the east-west to north-south components illustrate the anisotropy.

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We have interpreted the apparent resistivity smoothed data with the Bostick transformation algorithm. Transformation of the apparent resistivities from frequency domain to depth domain can be done using

$$h_B = \left(\frac{\rho_a}{\omega\mu_o}\right)^{1/2} \cong 356\left(\frac{\rho_a}{f}\right)^{1/2} \qquad (1)$$

(Bostick 1977; Jones in press). This formula for the effective depth h_B became popular after Bostick (1977) formulated the concept of the "Bostick resistivity" ρ_B corresponding to depth h_B

$$\rho_B = \rho_a \frac{1-m}{1+m} \qquad (2)$$

where m is the gradient of the $(\rho_a$ vs $f)$ data on a logrithmic scale.

Combining the top of 2 layers using Kirchoff's Law into a single fictitious layer with the same total conductivity, i.e.

$$S' = S_1 + S_2 \quad \text{where} \quad S = \frac{h}{\rho}$$

we can calculate the effective resistivity

$$\rho_{Ei} = \frac{\Delta h_{Bi}}{\Delta S_i} \qquad (3)$$

These resistivity values of ρ_E are almost identical to the Bostick resistivity values.

By taking into account the energy attenuation of the electromagnetic waves at a certain depth interval, and assuming that ρ_{Ei} represents only a given portion of the true resistivity, it is possible to calculate an almost true resistivity corresponding to that depth interval by

$$\rho_{I1} = \rho_{a1}$$

$$\rho_{Ii} = \frac{\rho_{Ei}}{e^{-\frac{2(\pi)^{1/2}}{503}\left(\sum_{n=1}^{i-1}\frac{\Delta h_{Bn}}{(\rho_{In})^{1/2}}\right)} - e^{-(2)^{1/2}}} \qquad (4)$$

$$i = 2, N$$

where N is the number of observations (Ilkisik and Strangway in preparation). Figure 8b is an example of the application of this technique.

The calculations of ρ_B or ρ_E and ρ_I are very simple and can be done in the field using a hand calculator. This provides a quick real-time quantitative interpretation using only the scalar apparent resistivities. These calculations are also useful as an initial guess for expensive inversion and 2-dimensional model programs.

We have derived a set of contour maps for the grid areas. These maps are useful presentations of the observations as a single frequency slice through the region; and together with pseudosections they represent a 3-dimensional 'picture' of the area.

Another technique, singular value decomposition (SVD) analysis of AMT data, gives us the important model parameters and their effects through the frequency range for a certain geologic section (Edward *et al.* 1980; Jones 1982).

We have been using a nonlinear, least-squares estimation method (Marquardt 1963; ZXSSQ routine from IMSL) to invert AMT data. Although the applicability of 2-dimensional models depends on real geologic structures, especially in Precambrian terrain, along some lines we attempted to use mostly E perpendicular responses. For 2-dimensional calculations, a computer program was used, based on impedance networks (Madden and Swift 1969).

DISCUSSION OF RESULTS

MOODY AND MARATHON TOWNSHIPS

In Moody and Marathon Townships between Lake Abitibi and Cochrane, 15 AMT stations were surveyed during the summer of 1981 (Ilkisik *et al.* 1982). During the summer of 1982, an additional 28 AMT stations were completed. The oldest basement material is early Precambrian mafic metavolcanics which underlie much of the map area (unit 1 in Table 1). The geologic strike of the bedrock is east-west which is approximately perpendicular to the profile. Most of the stations lie along the northern part of the Munro esker. Conductive clays cover the regions east and west of this roughly north-south oriented esker.

By using the audiomagnetotelluric system at the lower frequencies, we are able to map the electrical resistivity of the basement beneath the clay and/or esker cover. The resistivity curves from the sites which are located on the metasediments and metamorphosed ultramafic rocks (units G5 and G7 respectively in Figure 1a) show, without exception, an anisotropic behaviour in the low frequency range. This is true even in the areas covered by conductive glacial clay as at sites A-33 and A-34.

The measured scalar resistivities in the east-west orientation tend to be lower than in the north-south orientation. Pseudosections in both directions give rise to the sketched geologic section. The anisotropy plot is given in Figure 2. We assume that this lower resistivity is associated with the presence of foliation in anisotropically distributed minerals such as biotite, or with water-filled cracks, which may be parallel to the fabric of steeply dipping metasediments.

We measured a low resistivity anomaly for both the east-west and north-south orientations at site A-15 (Figure 1a) on metavolcanics. In addition, A-14, A-27, and A-28 show strong anisotropy. This suggests a low resistivity structure within the metavolcanics with an east-west strike at station A-15.

Fitted models for isotropic resistivity curves (as at site A-18) were obtained by using Bostick transformation and 1-dimensional inversion techniques. These models show roughly a 100 m thick overburden with an average resistivity of 450 ohm-m. Underlying Precambrian metavolcanics have resistivity values in the range from 8000 to 50 000 ohm-m. Most of the models imply that there is a relatively low resistivity layer at a depth of 8 km.

THE NIGHT HAWK LAKE GEOPHYSICAL TEST RANGE

The Night Hawk Lake geophysical test range is located in the northeastern corner of Thomas Township, east of Timmins. A total of 73 AMT measurements were made during the survey in this area. Thirty-six (36) of them were on a

TABLE 1 TABLE OF LITHOLOGIC UNITS FOR THE STUDY AREAS (*see* FIGURE 1) (AFTER PYKE ET AL. 1973).

Period	Short Description	Unit No. (+)
PHANEROZOIC		
Paleozoic		
Silurian	Limestone, sandstone, shale	18
Ordovician	Shale, limestone	17
PRECAMBRIAN		
Late Precambrian		
Mafic Intr. R.	Diabase: dikes	16
Middle Precambrian		
Alkalic Intr. R.	Syenite, nepheline, syenite	15
Mafic Intr. R.	Diabase, granophyre, sheets and dikes	14
Huronian	Lorrain form, quartzite, arkose	13
"	Gowganda form, arkose, greywacke	12 a,b
Early Precambrian		
Mafic Intr. R.	Diabase: dikes	11
Felsic Intr. R.	Granodiorite,qz. monzonite, pegmatite	10 a,b,c
"	Syenite, feldspar porphyry	9
Metamorphosed Ultramafic R.	Gabbro, diorite, lamporphyre	8
"	Peridotite, dunite, serpentinite	7
Metasediments	Conglomerate, greywacke	6
"	Greywacke, siltstone, argillite	5
Metavolcanics	Trachyte, flows, tuff, breccia	4
"	Serpentinized peridotite flows	3
"	Pyroclastic rocks (Rhyolitic, dacitic)	2 a,b
"	Basaltic and andesitic flows, tuffs	1 a,b,c

(+) The letter "G" preceding rock unit no. on the maps indicates interpretation from geophysical data in drift covered areas.

rectangular grid with 150 by 200 m spacing. In Figure 3, the apparent resistivity contour map is given for a frequency of 473 Hz. As we examine the maps at each frequency, it is noted that there is a surface layer which usually has a moderate resistivity of about 500 ohm-m. At the lower frequencies, the apparent resistivity rises to about 10 000 ohm-m. At the centre of the map, the graphitic conductive zone is well defined with a resistivity value of less than 500 ohm-m (Figure 3).

In Figures 4a and 4b, we present north-south and east-west pseudosections for averaged resistivity values. Along the north-south profile (F/NS, Figure 4a) the major feature is the zone of low resistivity at the middle. This zone reflects the graphitic conductor. Low resistivities in the south result from the presence of clay-rich surficial material. Figure 4b is an east-west pseudosection (F/EW) which corresponds to the location of the clay-covered areas. The high resistivity zone around sites F-40 and F-41 correspond to measurements made on bedrock outcrops of strongly carbonatized volcanic rocks (unit 1c).

On the grid, the dominant feature is that the high frequency (8570 Hz) resistivities are around 100 ohm-m in the western part of the area (Figure 5a) and around 500 ohm-m in the east. This is related to the increasing clay content in the glacial overburden towards the west. However, as we examine maps for lower frequencies carrying information about greater depths, we can see the presence of the east-striking conductive body within the rhyolite. The body appears to be traceable westward at lower frequencies (Figure 5b). These frequencies are capable of penetrating the conducting clay. Figure 5c illustrates the Bostick resistivity distribution at 200 m depth from the surface. This corresponds to the approximately true bedrock resistivity values. The length of the conductive body is about 700 m.

In Figures 6a and 6b, pseudosections and Bostick transforms of resistivity data up to 1000 m in depth are given along 100E (Line #1E). The low resistivity anomaly on the sections is well correlated with the known graphitic conductive zone. We originally used 150 m station separation. Later we added detailed measurements using 25 m station separation. This detail in the vicinity of the conductor suggests that there is a broad body with a limited depth extent and that the northern and southern edges of the conductor are at about 100N and 200S. We made many attempts to find the true shape of the body. The most important problem for a 2-dimensional interpretation of our data is a clay-rich layer, which lies along the western side of the grid, perpendicular to the strike of the graphitic zone. Two-dimensional model calculations for this clay-rich unit of the glacial overburden show that there is no significant effect of the clay-rich layer at high frequencies 200 m from its edge. We found the "Y"-shaped body (Figure 6c) 2-dimensional response (Figure 6d) gave better fits than rectangular or "V"-shaped bodies. The anomaly found using the Bostick resistivity cross-section (Figure 6b) corresponds well to a full 2-dimensional model (Figure 6c).

We applied 1-dimensional inversion to the data from the north of the grid area which displays an isotropic behaviour. The layered earth section indicates a 95 m thick overburden with 30 m of clay-rich material at the west. Beneath the overburden, the resistivity is in the range of 15 000 to 60 000 ohm-m. Although our data might have higher noise at the lowermost frequencies, there appear to be lower resistivities at a depth of around 6 to 7 km. The existence of clay-rich material at the surface could also affect this interpretation of the structure (Kaufman and Keller 1981).

Two resistivity soundings were carried out using a Schlumberger array at the test site. The results for station 00 on line 500W (50 m south of AMT site F-4) are given in Figure 7a. It was not possible to obtain as good a fit for this station. The 2-layer and 4-layer models give different thicknesses of the clay-rich layer (50 and 30 m respectively). The results for station 200N on line 300E (F-34) are given in Figure 7b. These data can be fitted with a lay-

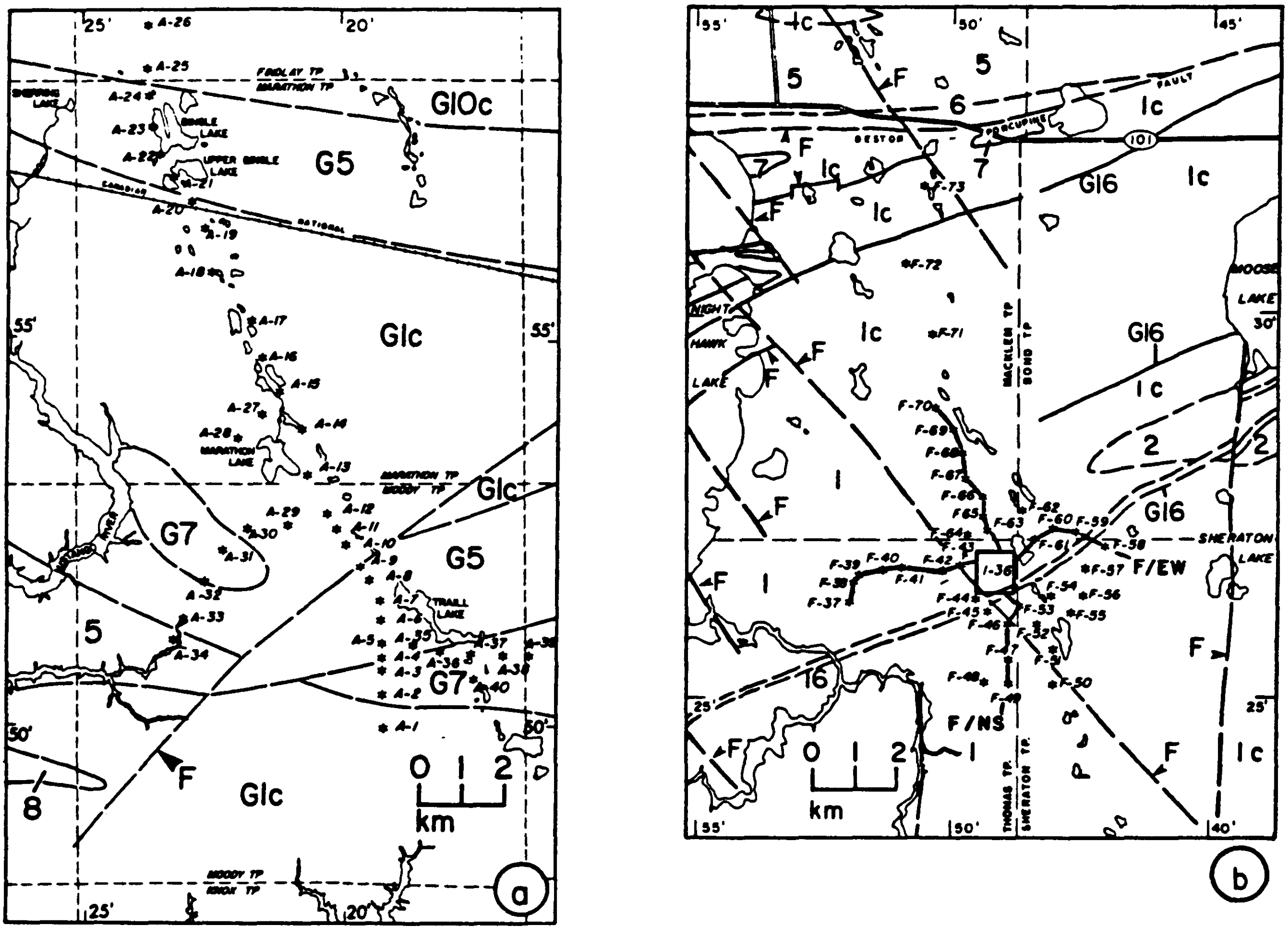

Figure 1. The bedrock geology map of: (a) Moody and Marathon Townships; (b) the area east of Night Hawk Lake (after Pyke et al. 1973). Legend is given in Table 1.

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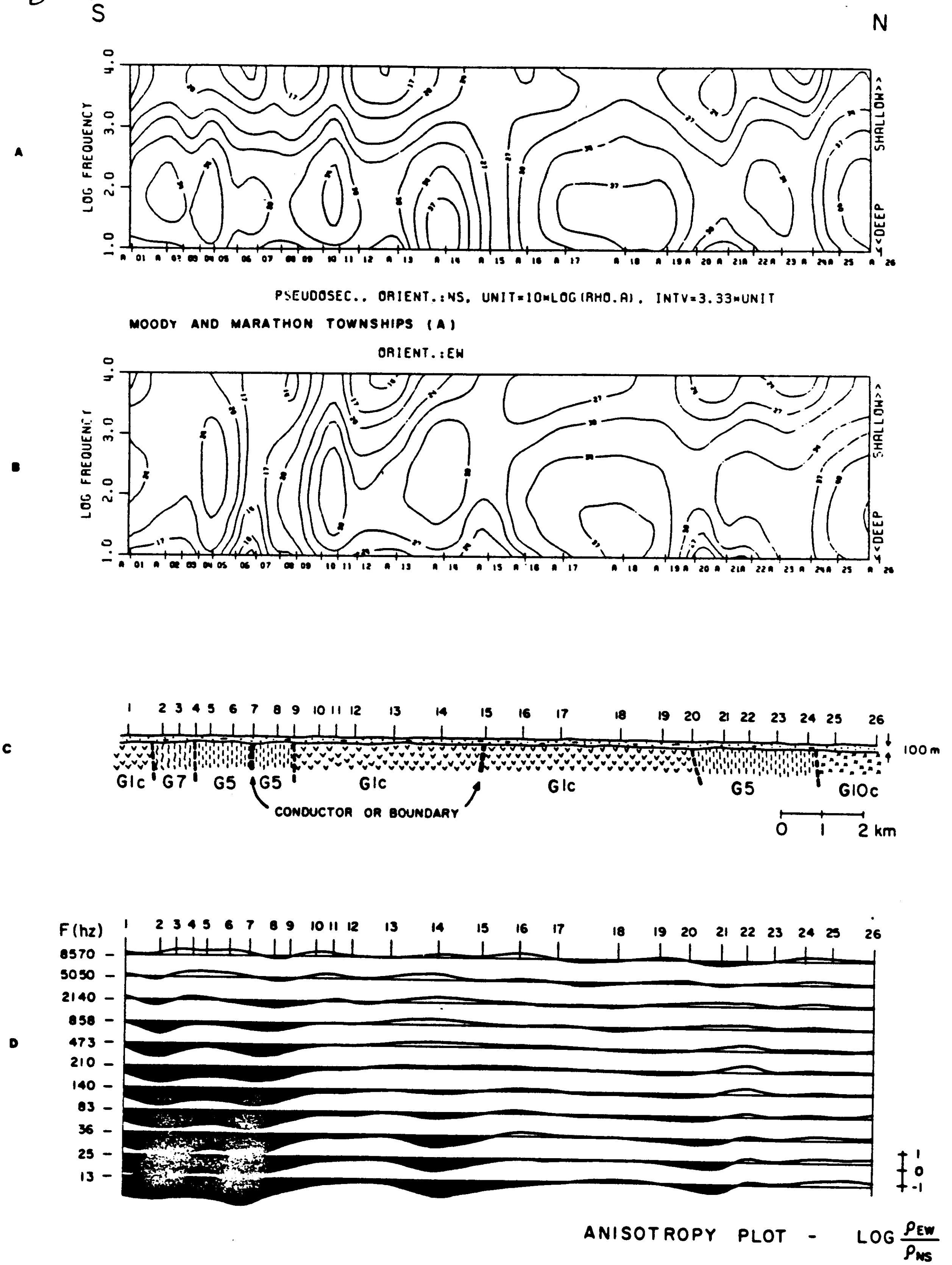

Figure 2. The pseudosections from Moody and Marathon Townships along north-south orientation in NS and EW modes, (a) and (b) respectively; a sketch geologic section (c), and the anisotropy plot (d).

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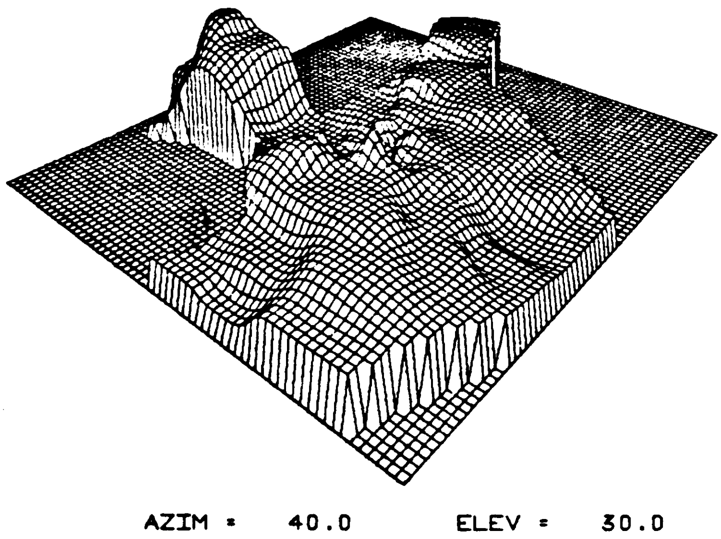

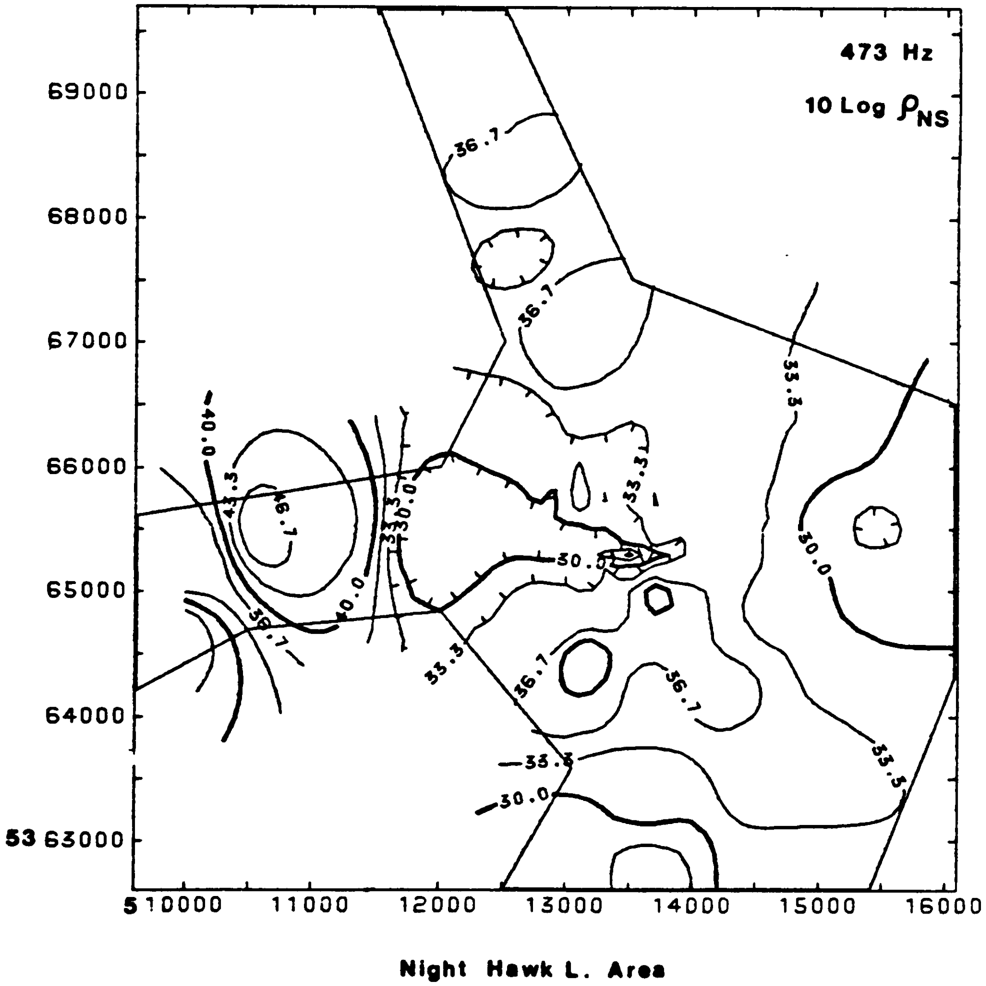

Figure 3. The apparent resistivity map at 473 Hz from east of Night Hawk Lake.

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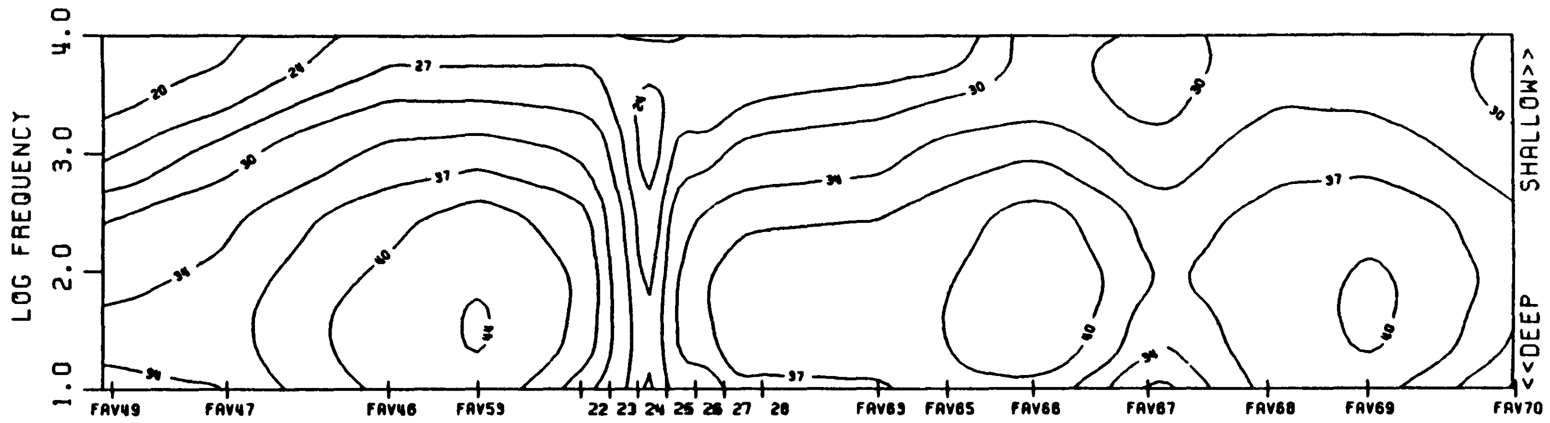
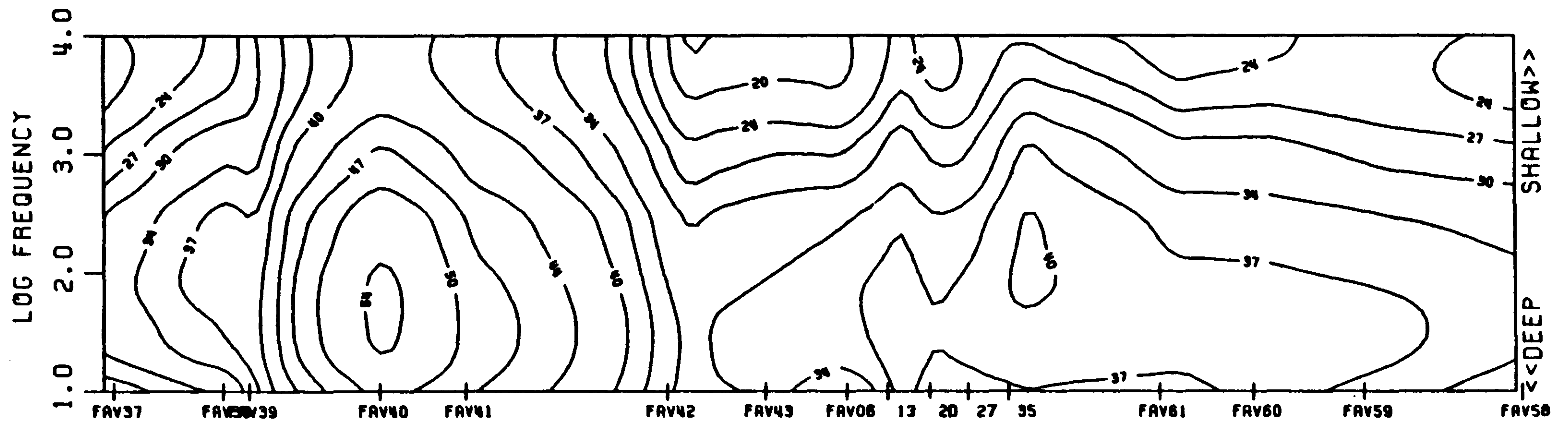


a) NIGHT HAWK L. F/NS PSEUDOSEC., ORIENT.:AV, UNIT=10×LOG(RHO.A), INTV=3.33×UNIT



b) NIGHT HAWK L. F/EW PSEUDOSEC., ORIENT.:AV, UNIT=10×LOG(RHO.A), INTV=3.33×UNIT

Figure 4. The averaged apparent resistivity pseudosections along north-south (F/NS) orientation (a), and east-west (F/-EW) orientation (b), from Night Hawk Lake area.

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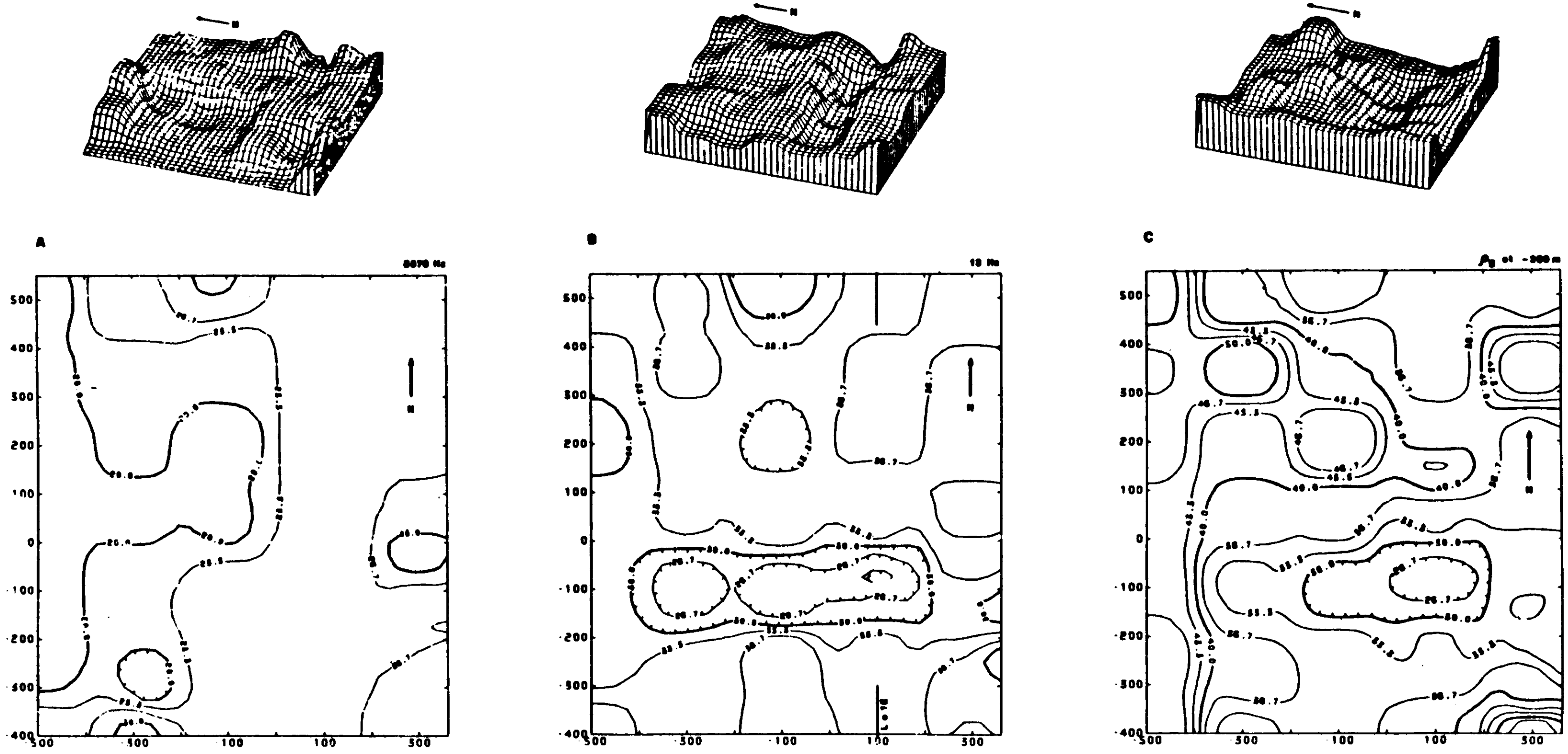

Figure 5. The apparent resistivity contour maps of the Night Hawk Lake geophysical test site; (a) for 8570 Hz which corresponds to the shallow information; (b) for 13 Hz which is the deeper information, and (c) Bostick resistivity map at 200 m depth. Low resistivity anomaly in (b) and (c) corresponds to graphitic conductor. (Contour labels are 10 logp).

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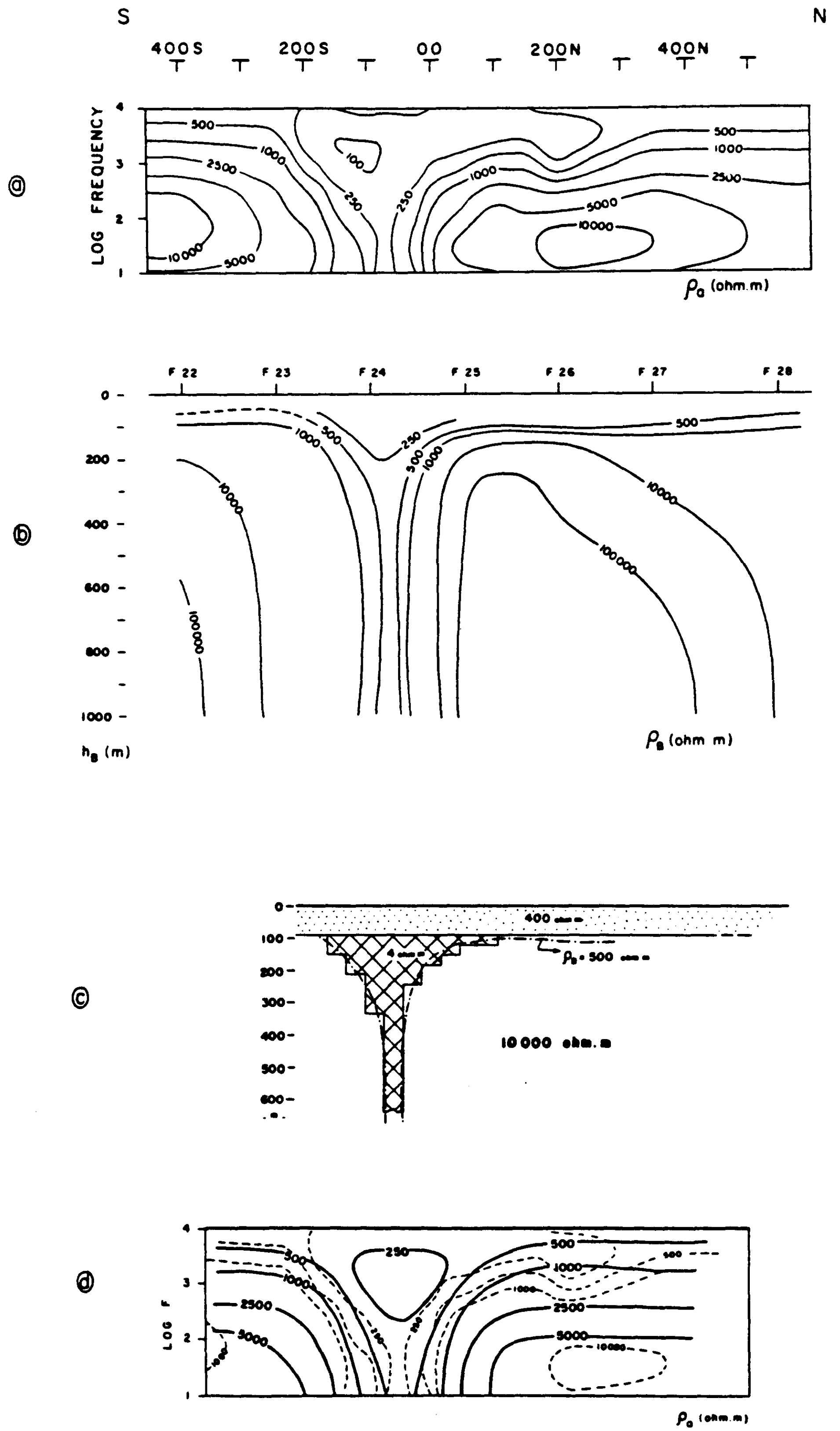

Figure 6. The pseudosections (a) and the Bostick resistivity cross-section (b) along 100E (Line #1E). The northern and southern edges of the body are at about 100 N and 200 S. (c) The fitted 2-dimensional model of the graphitic conductor. (d) 2-dimensional model response (full lines) and the measured data (dashed lines).

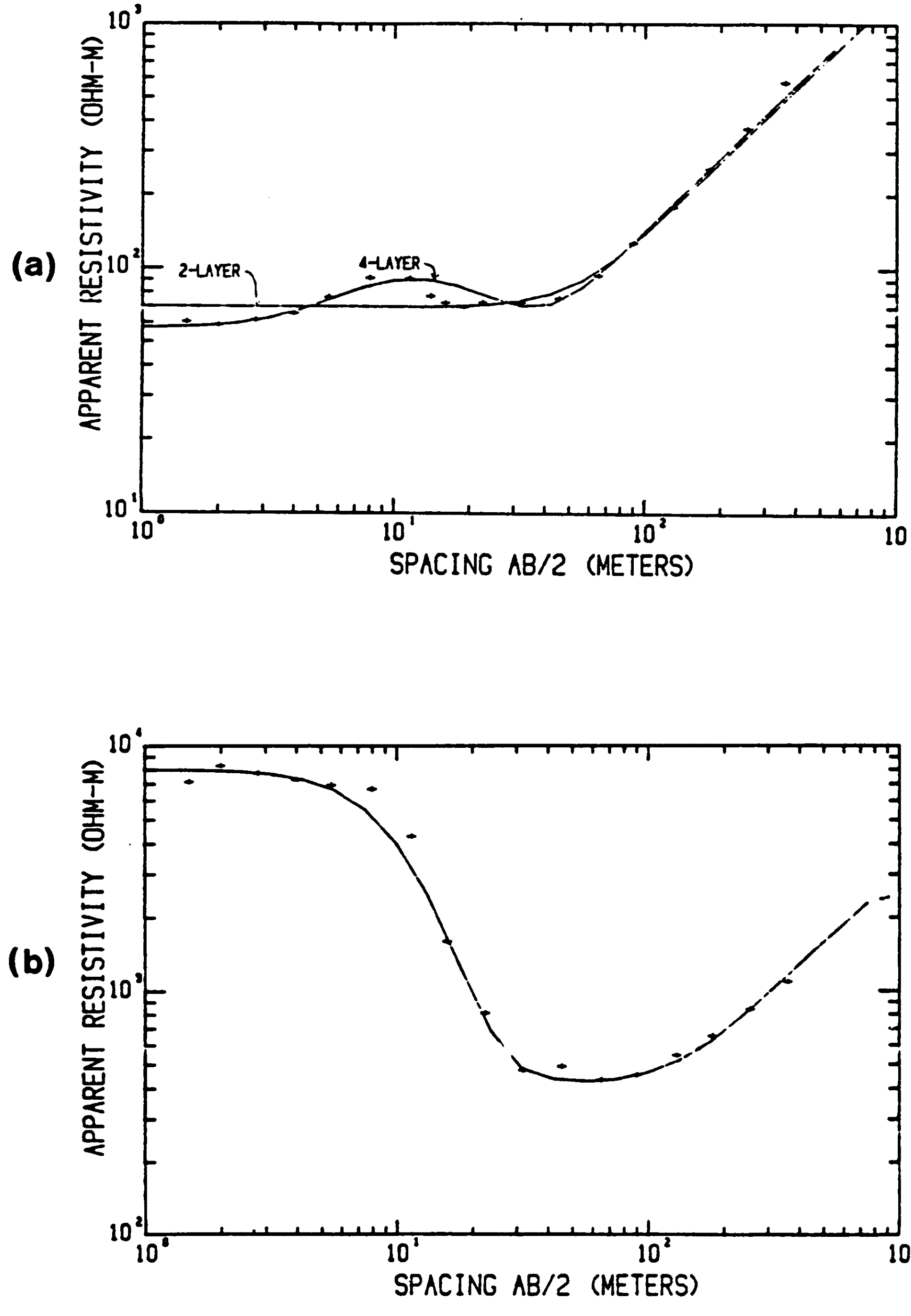

Figure 7. Resistivity sounding at Night Hawk Lake test site, using a Schlumberger array: (a) at Line 500W station 00 (50 m south of F-4); (b) at line 300E station 200N (F-34).

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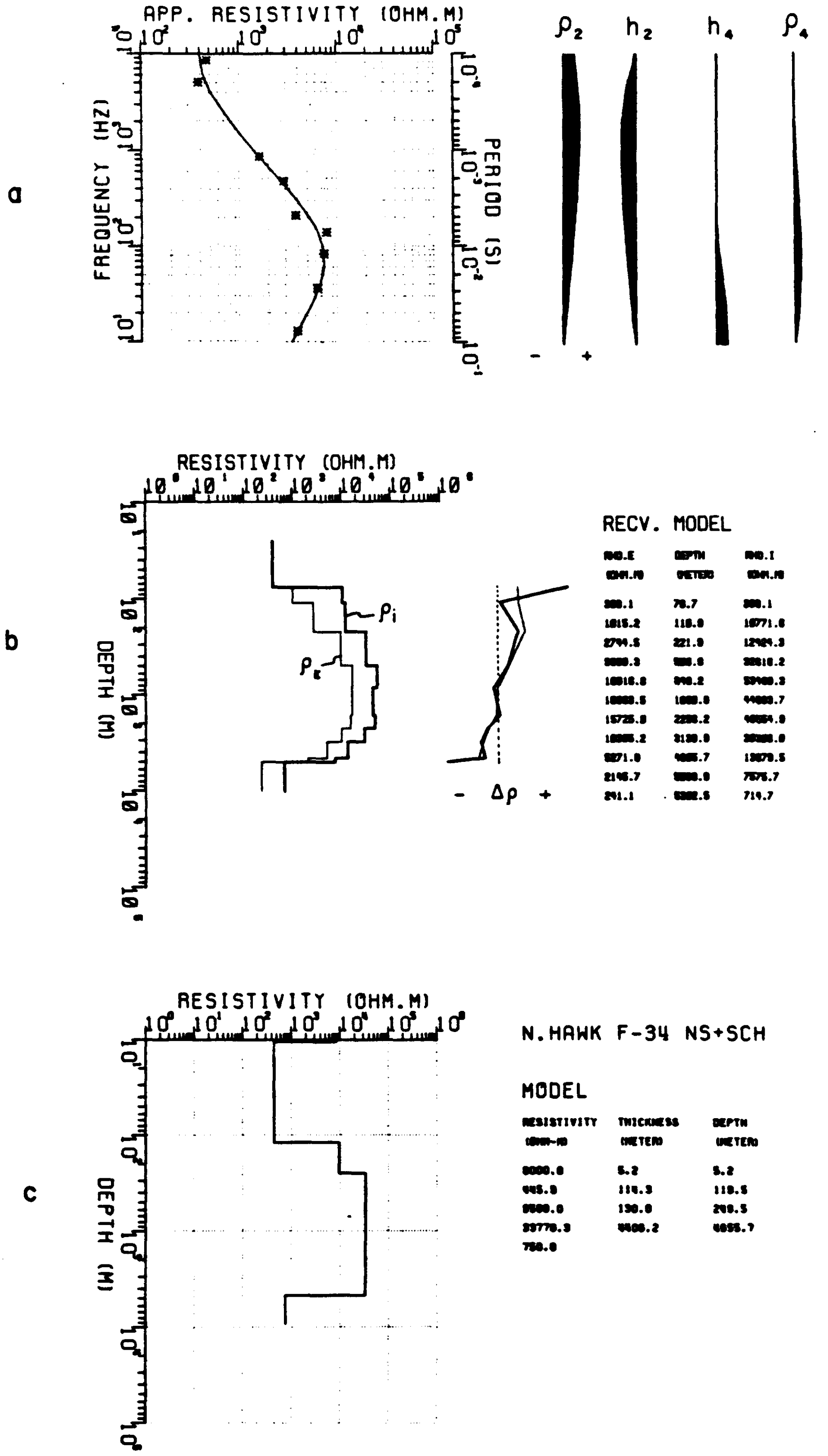

RECV. MODEL

RHO.E (OHM.M)	DEPTH (METER)	RHO.I (OHM.M)
300.1	78.7	300.1
1015.2	118.0	10771.0
2794.5	221.0	12424.3
[illegible]	[illegible]	[illegible]
10016.0	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
15725.0	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
2146.7	[illegible]	7575.7
291.1	[illegible]	719.7

N.HAWK F-34 NS+SCH

MODEL

RESISTIVITY (OHM-M)	THICKNESS (METER)	DEPTH (METER)
8000.0	5.2	5.2
445.9	114.3	119.5
9500.0	130.0	249.5
33770.3	4406.2	4655.7
750.0		

Figure 8. (a) AMT measurements vs. frequency at line 300E station 200N (asterisks), together with the best model response (full line) and the effects of the most important model parameters derived from SVD analysis. (b) Illustration of directly recovered model from data. ρ_E, effective resistivity; ρ_I interval resistivity. The plot of $\Delta\rho$ gives an approximate depth to the layers. This model is used to guess initial model for inversion together with SCH results; (c) Best fitted inverse model based on AMT and Schlumberger measurements.

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TABLE 2 THE COMPARISON OF INVERSION RESULTS OF AMT DATA WITH AND WITHOUT SCHLUMBERGER RESISTIVITY MEASUREMENTS FROM SITE F-34 (LINE 300E-STATION 200N, ORIENTATION NORTH-SOUTH).

Inverted model based on:

1) The effective and interval resistivity calculations and only AMT data			2) The effective and interval resistivity calculations, AMT data and Schlumberger resistivity data		
Layer	ρ(ohm-m)	h(m)	Layer	ρ(ohm-m)	h(m)
-	-	-	1	8000.0	5.2
1	396.3	93.6	2	445.9	114.3
2	9429.6	169.8	3	9500.0	130.0
3	33564.4	4230.0	4	33778.3	4406.2
4	750.0		5	750.0	

ered earth model consisting of a very resistive 8000 ohm-m upper layer corresponding to a thin sandy layer (5.2 m), a 120 m thick intermediate layer with a resistivity value of 410 ohm-m, and the very resistive bedrock ($\rho >$ 10 000 ohm-m). The inversion results of AMT data from the same site (F-34) with the inversion results of AMT and Schlumberger information are given in Table 2.

Figure 8 illustrates some stages in the 1-dimensional interpretation at site F-34. The plots of apparent resistivity versus frequency (and period) are given together with the best model response in Figure 8a. The most important model parameters around site F-34 are found by singular value decomposition (SVD) analysis. Total conductivity (h/ρ) of the overburden is the most important parameter at high frequencies (500 to 10 000 Hz). Using the effective and interval resistivity calculations (Figure 8b) together with some geologic information from the area, we can calculate the thickness and the resistivity of the overburden. Even the thickness or the resistivity of the Precambrian bedrock is well defined at frequencies of 200 Hz or less. Using the AMT data, interval resistivity calculations, SVD analysis, and combining the results of Schlumberger resistivity sounding at site F-34, our best 1-dimensional result is given in Figure 8c. This model gives a 5.2 m thick resistive (8000 ohm-m) layer at the top. The next layer is less resistive (446 ohm-m) and 114 m thick, representing sandy (which might have some clay content) overburden. The depth to the bedrock is 120 m at this site. We found 9500 ohm-m for the top 130 m of the bedrock, compared to 34 000 ohm-m at greater depths. This might represent weathered or fractured bedrock. It appears that the deeper parts of Precambrian basement at a depth of 5 to 6 km have relatively low resistivity values.

KIRKLAND LAKE AREA

We have done a total of 13 measurements along an east-west profile in Morrisette and Arnold Townships near Kirkland Lake. Most of the stations are at very sandy locations on the Munro esker and are fairly resistive. A surface resistivity value of about 250 ohm-m is representative of the relatively clay-rich overburden at the western boundary of the esker, while very high resistivities of 10 000 to 50 000 ohm-m are found at sites on the esker.

ELECTRICAL RESISTIVITY OF SURFICIAL DEPOSITS

In our previous report (Ilkisik *et al.* 1982), we presented the results of laboratory measurements on the electrical properties of clays. This work has been extended to include laboratory and in situ measurements of all overburden components (clay, silt, sand, and till). The purpose of these measurements was to characterize the "typical" resistivities and the frequency dependence of resistivity for the overburden components. The clays, being the most conductive overburden component of the Abitibi clay belt, have been given the most attention in our work, since they provide the greatest hindrance in the useful application of electromagnetic exploration techniques.

The surface expression of the surficial deposits has been well mapped in the Abitibi clay belt by the Ontario Geological Survey (Northern Ontario Engineering Geology Terrain Study); however, the vertical electrical section of the overburden can be quite complicated. The glaciolacustrine deposits of the Abitibi clay belt were formed in proglacial Lake Abitibi-Ojibway and consist of horizon-

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tally stratified sand, silt, and clay layers. The clay and silt layers are commonly varved, showing a seasonal deposition pattern. In the northern part of the region around Cochrane, the clays are covered by a clayey to silty till acquired during a local readvance of an ice lobe. The varved clays in other areas may be masked by sand plains from outwash deposits or derived from eskers. In some areas, the clays lie in pockets or channels between bedrock outcrops.

The esker ridges which are composed principally of sands and gravels can extend through the complete vertical section of the glaciolacustrine plain and may have, at their margins, lacustrine clay and silt lenses interfingering with their sands and gravels.

The depth to bedrock and the thickness of the clay layers within the overburden are quite variable. In the Timmins area, a seismic survey (Killeen and Hobson 1974) has shown that the bedrock togography buried beneath the clay cover is quite rugged with variations of 40 m in 1 km (with an average overburden thickness of 30 m). In fact, the overburden can be quite variable in thickness. Drilling results and exposures for areas of glaciolacustrine plain in the Abitibi clay belt indicate that the clay layer thickness within the overburden is quite variable with 30 m being a typical value (Averill and Thompson 1981; Hughes 1961; Desaulniers 1982).

RESISTIVITY MEASUREMENTS

Samples to be used for the resistivity measurements were collected from gravel pits, road cuts, and from exposures along rivers. The procedure used in collecting the samples and the technique for measuring the complex resistivities in the frequency range 5 Hz to 1 MHz are discussed in Ilkisik *et al.* (1982). The complex resistivities were measured at a current density of .1 A/m. The sand (>45 µm), silt (4 µm - 45 µm), and clay (>4 µm) size fractions were determined by sieving and sedimentation analysis.

A summary of the complex resistivity measurements and grain size analysis for samples from the Matheson, Larder Lake, and Englehart areas is given in Table 3. The percent frequency effect (PFE) observed is generally small but significant for some samples.

The 50 Hz resistivities for all the samples are shown in Figure 9 along with their clay contents. For samples from the Larder Lake dump site, it can be seen that the silt (silt loam) samples with low clay content have high resistivities that are on the order of 120 to 140 ohm-m, whereas the clays have resistivities of 30 to 60 ohm-m. These silt samples are from a varved layer in which the clay content increases from bottom to top. When one includes samples from other areas, then even the silt samples have resistivites of the same order as the clay samples. This variability is probably related to the change in pore water resistivity for different environments. For samples from the same environment, one would expect that the clay samples would have lower resistivities, as seen for the Larder Lake dump site samples. In general, the measurements show that the silts are more likely to have higher resistivities than the clays and tend to have a larger variability.

TABLE 3 CLAY SILT AND SAND FRACTIONS DETERMINED BY SIEVING AND SEDIMENTATION ANALYSIS, THE RESISTIVITY AT 50 Hz, AND THE PERCENT FREQUENCY EFFECT (PFE). CLAY FRACTION < 4 µm, SILT FRACTION FROM 4 µm TO 45 µm, AND SAND > 45 µm. PFE = $(\rho_{5\,Hz} - \rho_{50\,Hz})/\rho_{5\,Hz}$ X 100.

Sample #	Site	Clay %	Silt %	Sand %	Soil Class	Resistivity (ohm-m)	PFE
81-2	M	87.6	10.9	1.5	clay	25	.67
81-3	M	79.4	14.3	6.3	clay	35	1.0
81-4	M	93.8	6.1	.1	clay	17	-4.2
81-5	M	80.7	19.2	.1	clay	13	1.7
81-7	M	81.1	17.6	1.3	clay	30	2.0
81-8	L	55.5	40.8	3.7	silty clay	31	.9
81-11	L	77	16	7	clay	37	.4
81-12	L	80.1	16.3	3.6	clay	32	1.0
81-13	L	66.4	25.9	7.7	clay	31	1.9
81-14	L	78.4	21.0	.6	clay	31	1.4
81-15	L	59.2	38.9	1.9	clay	41	2.4
81-16	L	44.9	51.4	3.7	silty clay	37	.5
81-17	L	54.5	42.0	3.5	silty clay	53	.1
81-18	L	13.3	66.7	20.0	silt loam	125	.9
81-19	L	14.5	66.5	19.0	silt loam	132	2.0
81-21	L	59.1	39.1	1.8	clay	33	.7
81-22	L	73.9	23.9	2.2	clay	32	-0.2
81-23	L	74.3	25.4	.3	clay	57	.5
81-24	L	62.2	32.9	4.9	clay	30	.1
81-25	L	49.9	45.6	4.5	silty clay	58	.1
81-29	L	9.2	62.6	28.2	silt loam	137	1.4
81-30	E	62.0	37.4	.6	clay	23	1.0
81-31	E	21.8	25.6	52.6	loam	33	.8
81-32	E	13.6	33.6	52.8	sandy loam	36	1.3
81-33	E	75.5	16.0	8.5	clay	15	-0.3
81-35	E	26.9	66.1	7.0	silt loam	41	.5
81-36	E	26.0	67.5	6.5	silt loam	24	1.2
81-39	E	14.2	42.3	14.1	loam	175	3.8
81-40	E	14.1	29.6	56.3	sandy loam	125	3.0

L - Larder Lake dump site
M - Matheson area
E - Englehart area

The average resistivity at 50 Hz for the different soil classes at the sites studied was 24 ohm-m for clays (16 samples), 45 ohm-m for silty clay (4 samples), and 87 ohm-m for loams (9 samples of loam, sandy loam, and silt loam). In situ measurements at 1.1 Hz using a small Wenner array with a = .5 m where it was possible and *a* = .05 m for thin layers gave an average resistivity for clays and silty clays of 59 ohm-m (21 sites) and 3700 ohm-m for sands (9 sites). AMT surveys which we have carried out in these same areas typically give resistivities of 20 to 50 ohm-m for the conductive clay layer.

In general, the soil samples have resistivities that are relatively independent of frequency from 5 Hz to 1 MHz and have a small phase. For a few samples, the complex resistivity was also measured in the range .01 Hz to 5 Hz (Figure 10). At frequencies less than 5 Hz, the resistivity was also relatively independent of frequency with small phase. Sample 81-13 is typical of the clays measured in that the phase and PFE are small. Sample 81-4 has an unusual frequency dependence in that the phase angle is positive at the lowest frequencies and the magnitude increases with frequency at the lowest frequencies. Negative PFE values similar to that observed in this sample have been reported previously (Roy and Elliot 1980) for clay soils with clay content greater than 90%. The silty clays that we have measured, typified by sample 18-16, have small phase and PFE. The loams have a relatively large PFE and phase as shown by sample 81-40. Only 1 peat sample (81-1), which has a significant phase and PFE, has been measured. From the work that we have completed, there is an indication that there may be significant differences in the frequency response for different soil classes. In addition, we have observed that there is considerable variation in frequency response within each soil class.

The principle clay minerals contained in the clay size fraction for samples 81-3, 81-4, and 81-13 are chlorite (40%) and illite (30%). These clay minerals are typical for immature glaciolacustrine clays.

CONCLUSIONS

The results reported here show the effectiveness of the AMT technique for mapping of conductivity structure in the Precambrian bedrock in glacial drift areas.

In Moody Township near Lake Abitibi, steeply dipping metasediments show a strong anisotropy even when covered by conductive clay-rich drift. A conductive fracture zone with an east-west strike was detected within the metavolcanics at station A-15.

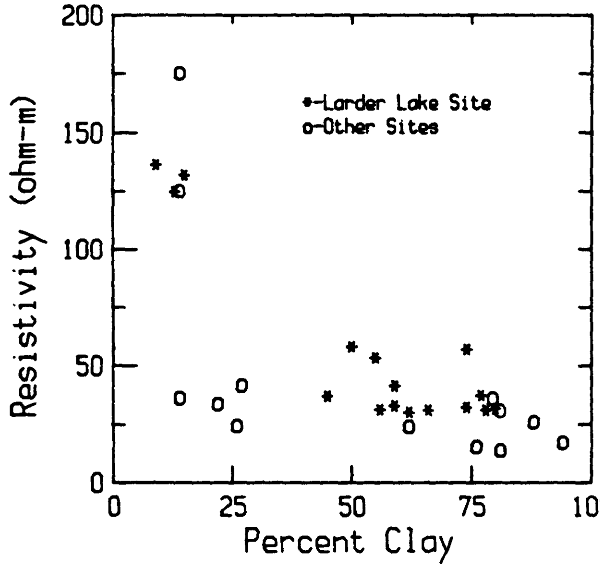

Figure 9. The magnitude of the resistivity at 50 Hz is plotted as a function of the sample clay content (<4µm). The Larder Lake samples were collected from different depths within 1 varved clay layer.

At the Night Hawk Lake geophysical test site, the apparent resistivity at high frequencies clearly illustrates clay-rich overburden along the western side of the grid area. The apparent resistivity maps for lower frequencies and the Bostick resistivity map for a 200 m depth shows the known graphitic conductor with an east-west strike. The detailed pseudosections, Bostick resistivity cross-sections, and 2-dimension model calculation suggest that there is a "Y"-shaped broad body with a limited depth extent and that the northern and southern edges of the conductor are at about 100 N and 200 S.

One-dimensional inversion of AMT data in the northern part of the grid and the results of Schlumberger resistivity measurements indicate a 90 to 120 m thick overburden with 30 m of clay-rich material at the western side of

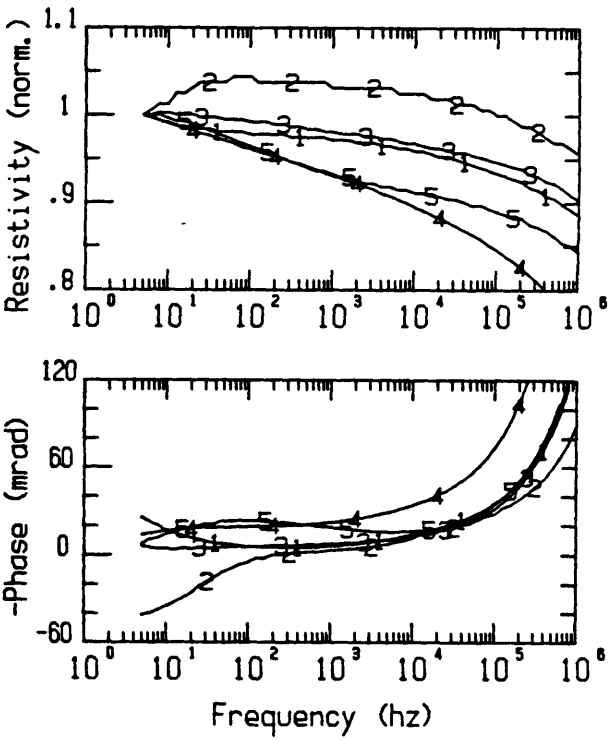

Figure 10. The typical frequency dependence of the phase and magnitude (normalized to the resistivity at 5 Hz) of the complex resistivity of soil samples from the Abitibi belt are shown. The individual data points of which there are 10 per decade in frequency have been joined with straight line segments. The numbers given on the plots are for identification purposes: 1 Clay (varved), Larder Lake (81-13); 2 - Clay, Matheson (81-4); 3 - Silty Clay, Larder Lake (81-16); 4 - Sandy loam, Englehart (81-40); 5 - Peat, Matheson (81-1). Resistivities (ohm-m) at 5 Hz: 1 - 32 ohm-m; 2 - 16 ohm-m; 3 - 37 ohm-m; 4 - 129 ohm-m; 5 - 28 ohm-m.

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the grid. Beneath the overburden, the resistivity is in the range of 15 000 to 60 000 ohm-m.

Our study and Singular Value Decomposition analysis of typical models show that the most important and hence best predicted model parameter is total conductance of the glacial material. The low resistivity zones, faults, or anisotropy in the bedrock are also detectable, since the AMT technique is very sensitive to lateral resistivity variations.

Previous studies of the Abitibi Clay Belt have demonstrated that one can expect to have complicated electrical sections for the overburden. In our work we have obtained "typical" resistivities, from laboratory and in situ measurements, for the different units within the overburden, and have shown that, while in general the frequency dependence of the resistivity is small, there is a significant percent frequency effect (PFE) and phase observed in some of the samples.

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REFERENCES

Averill, S.A., and Thompson, I.
1981: Reverse Circulation Rotary Drilling and Deep Overburden Geochemical Sampling in Marter, Catherine, McElroy, Skead, Gauthier, and Hearst Townships, District of Timiskaming; Ontario Geological Survey, Open File Report 5335.

Barlow, R.B., Pitcher, D.H., and Wadge, D.R.
1982: Night Hawk Geophysical Test Range Results, Night Hawk Lake, District of Cochrane; p.152-161 *in* Summary of Field Work, 1982, by the Ontario Geological Survey, edited by John Wood, Owen L. White, R.B. Barlow, and A.C. Colvine, Ontario Geological Survey, Miscellaneous Paper 106, 235p.

Bostick, F.X., Jr.
1977: A Simple and Almost Exact Method of MT Analysis (Abstract); Workshop on Electrical Methods in Geothermal Exploration, Utah.

Desaulniers, D.E.
1982: Clayey Quaternary Deposits in Northern Ontario: A Review; Atomic Energy of Canada, TR-305.

Edwards, R.N., Bailey, R.C., and Garland G.D.
1980: Crustal and Upper Mantle Conductivity Studies With Natural and Artifical Sources; p. *in* The Continental Crust and its Mineral Deposits, edited by D.W. Strangway, Special Paper 20, Geological Association of Canada, p.273-301.

Hughes, O.L.
1961: Preliminary Report on Borings Through Pleistocene Deposits, Cochrane District, Ontario; Geological Survey of Canada, Paper 61-16.

Ilkisik, O.M., Hsu, D.T., Redman, J.D., and Strangway, D.W.
1982: Surface Electromagnetic Mapping in Selected Positions of Northern Ontario; Grant 118, p.98-114 *in* Geoscience Research Grant Program, Summary of Research 1981-1982, edited by E.G. Pye, Ontario Geological Survey, Miscellaneous Paper 103, 219p.

Ilkisik, O.M., and Strangway, D.W.
in preparation: On the Recovery of the True Resistivity Distribution Using Scalar Resistivity Values in AMT (Audiomagnetotellurics).

Jones, A.G.
1982: On the Electrical Crust-Mantle Structure in Fennoscandia: No Moho and the Asthonosphere Revealed?; Geophys. J.R. Astr. Soc. 68, 371-388.

in press: On the Equivalence of the "Niblett" and "Bostick" Transformations in the Magnetotelluric Method; Journal of Geophysics.

Kaufman, A., and Keller, G.V.
1981: The Magnetotelluric Sounding Method; Elsevier, New York, 595p.

Killeen, P.G., and Hobson, G.D.
1974: Project EGMA Seismic, Timmins, Ontario to Val d'Or, Quebec; Geological Survey of Canada, Paper 74-44.

Madden, T.R., and Swift, C.M.
1969: Magnetotelluric Studies of the Electrical Conductivity Structure of the Crust and Upper Mantle; p.469-479 *in* American Geophysical Union Monograph 13, The Earth's Crust and Upper Mantle.

Marquardt, D.W.
1963: An Algorithm for Least Squares Estimation of Nonlinear Parameters; J. Soc. Indust. Appl. Math. 11, 431-441.

Northern Ontario Engineering Terrain Study Data Base Maps
1979: Ontario Geological Survey

Pyke, D.R., Ayres, L.D., and Innes, D.G.
1973: Timmins-Kirkland Lake, Districts of Cochrane, Sudbury, and Timiskaming; Ontario Geological Survey, Map 2205, Geological Compilation Series, Scale 1 inch to 4 miles.

Roy, K.K., and Elliot, H.M.
1980: Model Studies on Some Aspects of Resistivity and Membrane Polarization Behaviour Over a Layered Earth; Geophysical Prospecting, Volume 28, 759-775.

Strangway, D.W., Swift, C.M., and Holmer, R.C.
1973: The Application of Audio-Frequency Magnetotellurics (AMT) to Mineral Exploration; Geophysics, Volume 38, 1159-1175.

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J. Geomag. Geoelectr., 35, 455–472, 1983.

AMT Sounding Through Conductive Glacial Clays in the Canadian Shield

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In the summer of 1981, a scalar audio-magnetotelluric survey was completed in four locations in Northern Ontario. Apparent resistivities, for frequencies from 13 Hz to 8,570 Hz, were measured at 101 stations.

A survey in Moody Township near Lake Abitibi clearly outlines the clay properties and thickness, and also shows that, at the lower frequencies, we are able to map the electrical resistivity of the basement beneath the clay and/or esker cover. Over a region, tentatively identified as metasediments, the bedrock is seen to be strongly anisotropic, reflecting anisotropy of the sediments themselves.

In a second region, Marter Township near Engelhart, two survey profiles mapped a region of thickening clay-rich overburden as well as located high resistivities over a large esker. These profiles were taken in an area where the overburden had been drilled in a program of the Ontario Geological Survey. Our results can be interpreted to be in general agreement. A similar example reported from eastern Manitoba shows that the near-surface apparent resistivity is typically as low as 10 ohm-m reflecting the conducting clay. The resistivity then rises sharply to values of 1,000 ohm-m to 10,000 ohm-m reflecting the Precambrian bedrock.

Surveys in Bowman Township near Matheson, were conducted on a two-dimensional grid and the data consistently show the presence of four layers, a thin resistive surface layer a few meters thick, followed by a very conductive layer of clay. Bedrock is at a depth of 50–100 m and is very resistive. This survey gives a map of the resistivity and the thickness of the clay-rich glaciolacustrine sediments and clearly outlines near surface features such as an esker.

In addition to the AMT survey, we have collected clay samples from sites in Larder Lake and in Marter Township to study their electrical properties. Laboratory measurements show that in the Kirkland Lake area, the clays have resistivities on the order of 20 ohm-m in agreement with the high frequency AMT data over clay-rich overburden.

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1. Introduction

Natural fields in the audio-frequency band (10–10^4 Hz) are due to thunderstorm energy propagating in the earth-ionosphere cavity. They occur more or less worldwide and propagate around the world. CAGNIARD (1953) showed how natural electromagnetic fluctuations could be used as sources for probing the electrical structure of the earth. At one particular frequency, the apparent resistivity (ρ_a) is defined using the relationship

$$\rho_a = \frac{1}{\omega\mu}\left(\frac{E}{H}\right)^2$$

E: electric field in volts/m
H: magnetic field in ampere-turns/m
ω: angular frequency ($2\pi f$)
μ: magnetic permeability

Instrumentation to operate in the audio-frequency range (10–10^4 Hz) was first described by STRANGWAY and VOZOFF (1969) and by STRANGWAY *et al.*(1973). This instrumentation has since been improved and in the recent past several surveys have been conducted in various parts of North America (STRANGWAY *et al.*, 1980, in press). Although the scalar audio-magnetotelluric method is best suited to the areas where the geology is reasonably isotropic, it has been used as a reconnaissance technique to locate anomalies and for quantitative interpretation if the region is laterally uniform.

In the surveys reported here an 82 m dipole was employed for measuring the electric field. The magnetic field was measured with two induction coils, one optimized for the low frequency range and the other optimized for the high frequency range. We measured the magnitude of the apparent resistivities at the discrete frequencies of 13, 22, 36, 83, 140, 210, 473, 858, 2140, 5050 and 8570 Hz. Two orthogonal data sets at each site were measured to search for lateral anisotropies. NS and EW data sets have the electric dipole laid out in north-south and east-west orientation respectively and the magnetic coils lined up perpendicular to these dipole orientations.

The errors in apparent resistivity measurements for real field data determined from tests of repeatability are of the order of 30–40%. In this survey anomalously low apparent resistivities associated with low source signal levels were sometimes found at 2,140 and 5,050 Hz and were removed or remeasured.

The purpose of these studies was to conduct surface electromagnetic mapping in selected positions in the clay belts of the Canadian Shield where a large proportion of the interesting volcanic belts are mantled by glaciolacustrine deposits. The main purpose was to characterize the electrical structure of the extensive clay-covered area, the electrical properties of the clay itself, and to test the capability of penetrating through this conductive top layer in order to identify anomalies beneath.

A schematic geoelectrical section which is typical of many parts of the survey area is given in Fig.1. Near surface layers are highly conductive, and mask the

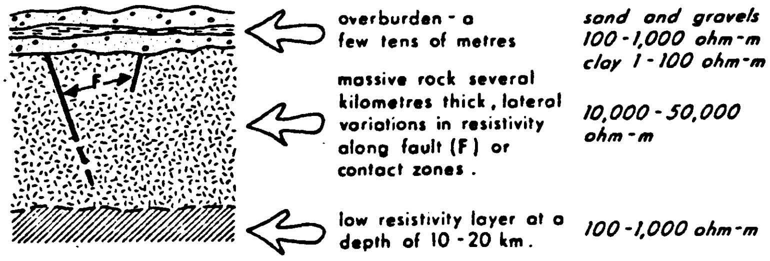

Fig. 1. Geoelectrical model for typical Precambrian terrain.

subsurface due to the presence of glacial clays or water-filled pore spaces in sandy overburden. The Precambrian bedrock has very high and relatively uniform resistivities. Faulting and fracturing in some regions could cause many lateral variations. In addition to ours, most studies (Kryzan and Strangway, 1977) suggest that when depths of 15 to 20 kilometers are reached, the resistivity may drop to lower values.

Strangway *et al.*, 1980, report a similar survey on conductive clay-rich overburden and precambrian Shield rocks at the Whiteshell Nuclear reactor site in eastern Manitoba, blanketed by about 10 m of clay left by glacial Lake Agassiz (Fig. 2a). The lacustrine clay unit thickens towards the west. A pseudosection in TM mode along L.4N from the area illustrates near surface apparent resistivity as low as 10 ohm-m, reflecting the presence of conducting clay (Fig. 2b). The resistivity then rises sharply to values of 1,000 ohm-m to 10,000 ohm-m, reflecting the bedrock a few tens of metres down. It has been possible to see through the conducting blanket to the resistive bedrock, but only dimly.

Even a thin layer of clay affects the ability to penetrate to great depths, and restricts us to mapping the clay resistivity and thickness and the upper few kilometres of bedrock. There are many other causes of local resistivity variations near the surface which make deep interpretations difficult (Kaufman and Keller, 1981).

Our work in Northern Ontario concentrated in Bowman Township near Matheson, in Moody Township near Lake Abitibi and in Marter Township near Engelhart (Fig. 3). We have used the audio-magnetotelluric method in each of these regions and have been able to map the thickness of clay-rich overburden and to unambiguously determine some of the characteristics of the underlying bedrock.

Additionally, we have collected 42 clay samples from sites in Larder Lake and in Marter Township to study the electrical properties and their frequency dependence.

We report now on the results of our individual surveys in the presence of highly conductive near-surface layers.

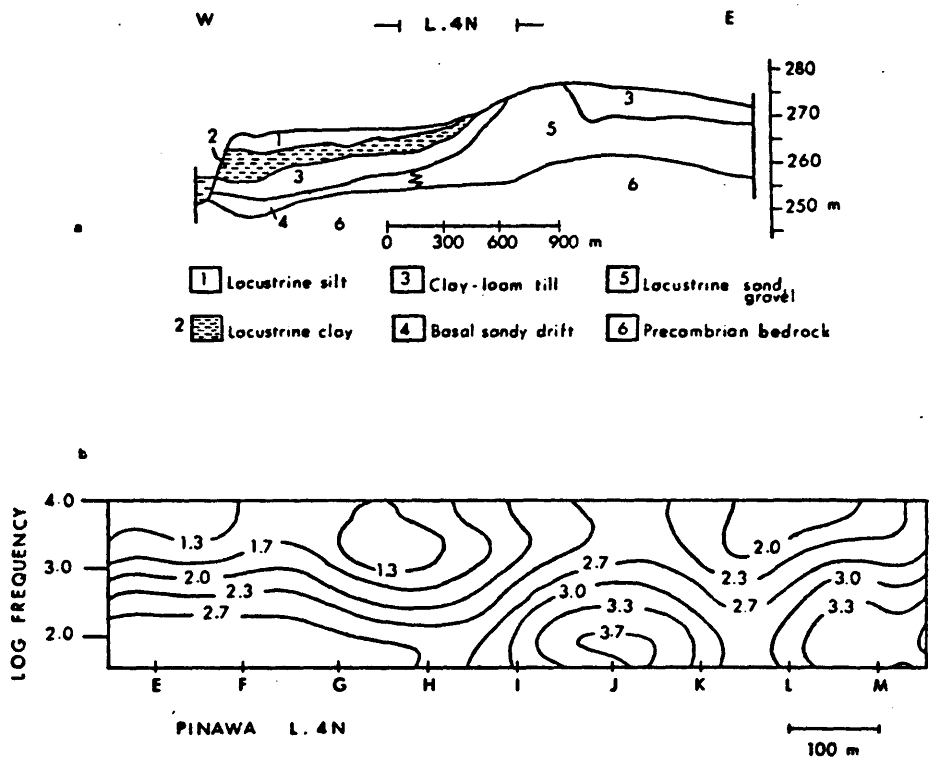

Fig. 2. a. Cross-section of overburden based on drilling (after GRISAK and CHERRY, 1975); b. Pseudosection in TM mode along L-4N from the Pinawa (after STRANGWAY *et al.*, 1980). Contour values in log ρ_a.

2. General Geology

2.1 *Surficial Geology*

The clay belts are an important subdivision of the Canadian Shield physiographic province and record the site of glacial Lake Barlow-Ojibway. A surficial geology map is shown in Fig. 3. Glacial Lake Barlow-Ojibway, a major proglacial body of meltwater, covered the area during part of the Wisconsin recession. The Matheson till (see Table 1) is the lowermost unit known in the area and consists of sandy boulder till with minor gravel lying directly on bedrock of Precambrian age. It occurs as an almost continuous sheet except for local discontinuities around bedrock hills. Glaciofluvial deposits lie on the Matheson till or directly on bedrock. They are confined mainly to broad north-trending esker ridges and broad sand and gravel plains. The most extensitve deposits of Lake Barlow-Ojibway are the varved calys and silts which occur as plains and as an interconnected network surrounding bedrock outcrops. In general, the lower part of the Barlow-Ojibway formation consists of bedded silt and the upper part

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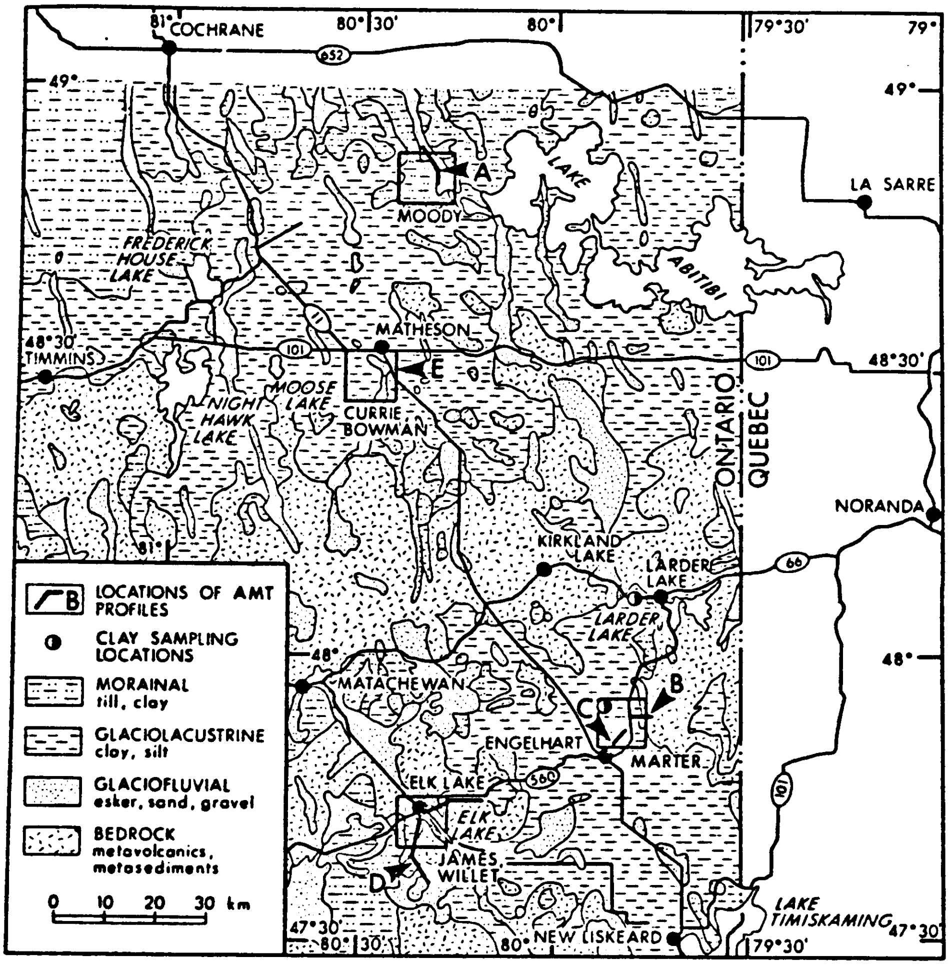

Fig. 3. Geographic location and simplied surficial geology map (modified from ROED and HALLETT, 1979; LEE, 1979a, b).

of laminated clay. Shore and nearshore deposits ranging from fine sand to gravel and boulders form the uppermost part of this formation. Clay and till glaciolacustrine sediments cover the northern part of the research area which is known as the Cochrane Formation. The youngest unit of Wisconsin age consists of organic deposits which contain shell, marl and peat (HUGHES, 1961).

2.2 *Bedrock geology*

The bedrock geology maps in the areas studied are given in Figs. 4a–c (see Table 2 for legend). The oldest rocks in the Superior Province, where most of our survey area is located, are volcanic and sedimentary rocks of Archean age. These rocks were formed in a number of easterly trending eugeosynclines that

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Table 1. Wisconsin deposits in study area (after AVERILL and THOMPSON, 1981; HUGHES, 1961).

Organic deposit
    —Shell, marl, peat
Cochrane formation
    —Clay till, glaciolacustrine sediments
Barlow-Ojibway formation
    —Silt, sand
    —Varved clay, massive clay (megavarve)
Glaciofluvial deposits
    —Sand, gravel, esker
Matheson Formation
    —Sandy boulder till, gravel

Table 2. Table of lithologic units for the study areas in northern Ontario (after PYKE, AYRES and INNES, 1973)

Period	Short Description	Unit No.(+)
Phanerozoic		
Paleozoic		
Silurian	Limestone, sandstone, shale	18
Ordovician	Shale, limestone	17
Precambrian		
Late Precambrian		
Mafic Intr. R.	Diabase: dikes	16
Middle Precambrian		
Alkalic Intr. R.	Syenite, nepheline, syenite	15
Mafic Intr. R.	Diabase, granophyre, sheets and dikes	14
Huronian	Lorrain form., quartzite, arkose	13
„	Gowganda form., arkose, greywacke	12a, b
Early Precambrian		
Mafic Intr. R.	Diabase: dikes	11
Felsic Intr. R.	Granodiorite, qz. monzonite, pegmatite	10a, b, c
„	Syenite, feldspar porphyry	9
Metamorphosed Ultramafic R.	Gabbro, diorite, lamporphre	8
„	Peridotite, dunite, serpentinite	7
Metasediments	Conglomerate, greywacke	6
„	Greywacke, siltstone, argillite	5
Metavolcanics	Trachyte, flows, tuff, breccia	4
„	Serpentinized peridotite flows	3
„	Pyroclastic rocks (Rhyolitic, dacitic)	2a, b
„	Basaltic and andesitic flows, tuffs	1a, b, c

(+) The letter "G" preceding rock unit no. on the maps indicates interpretation from geophysical data in drift covered areas.

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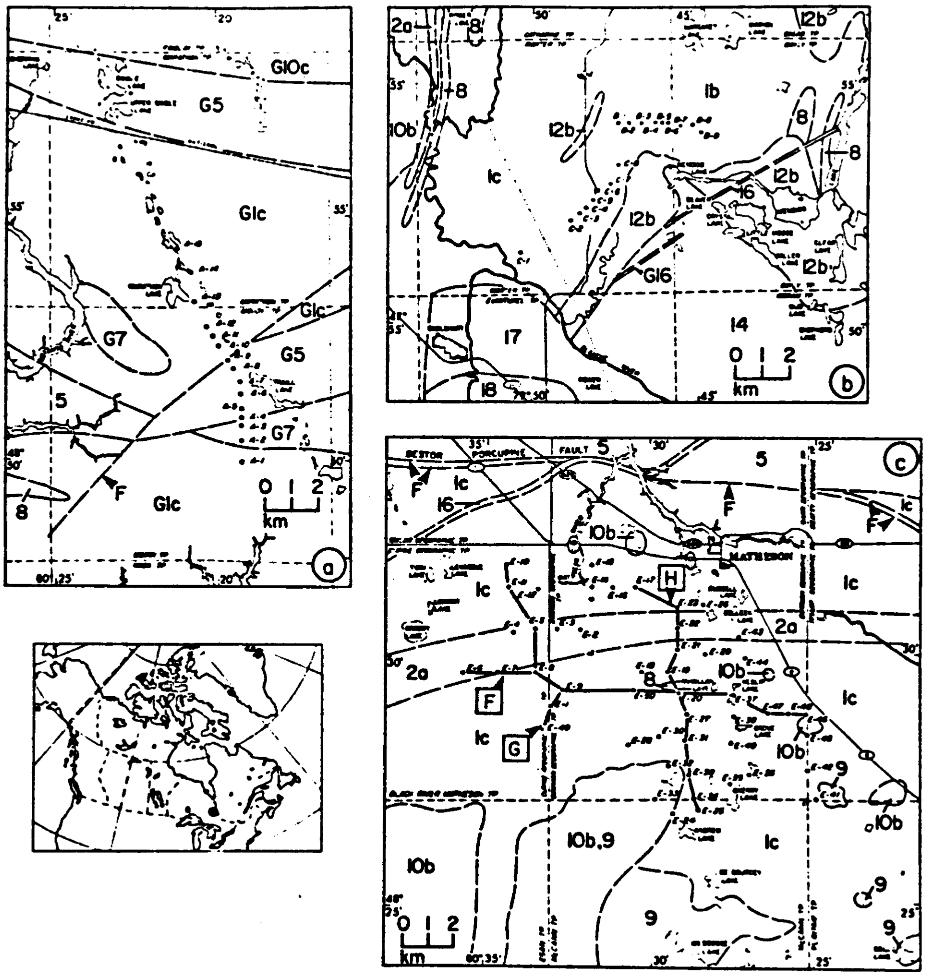

Fig. 4. Bedrock geology maps (after PYKE, AYRES, and INNES, 1973) and the locations of AMT sounding sites: a. Profile A in Moody Township; b. Profiles B and C in Marter Township; c. Grid E in Matheson Township. Legend given in Table 2. The letter "G" preceding rock unit no. indicates interpretation from geophysical data.

were possibly of different ages and tectonically independent. Early Precambrian mafic metavolcanics (1b, 1c) occur with an easterly trending strike. Basic lava flows are massive or exhibit flow structures such as pillow selvedges with minor related phases of breccias and basic tuff. The lavas are conformably overlain by sediments (5) composed of greywacke and argillite. They are overlain unconformably by thinly bedded alternations of greywacke, and shale of various types with a few beds of quartzites and conglomerate of variable thickness at or near the base. The Archean rocks are folded along an easterly trending axis. These

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folds appear to be modified in places by crossfolds of various orientations, and are cut by several easterly trending faults and some younger faults trend northwest, north-northwest, and northeast. The youngest rocks of Early Precambrian age are felsic intrusives (9, 10c) that are primarily granitic and syenitic in composition. The Huronian supergroup of Middle Precambrian age is a sequence of sedimentary and volcanic rocks of Aphebian age that lies unconformably on the Archean, which is deeply eroded and has a rugged topography.

3. Interpretation

AMT data interpretation consists of two main stages, the first is a general qualitative overview of the data obtained. This is usually done in the field. It is convenient to represent the measurements on a log ρ_a-log$f$ scale. By polynomial fitting, we can reject poor measurements. The pseudosections based on the polynomial fits provide a rough idea of the two-dimensional distribution of resistivity. Contour maps of the apparent resistivity as measured at each frequency are a particularly useful way of displaying the anomalies of the region.

The second stage is the fitting of a layered earth model at each station by one-dimensional inversion methods. We have been using a nonlinear, least-squares estimation method (Marquardt, 1963; Hsu, 1981) to invert AMT data.

Another simple form of presentation for AMT data in the depth domain is the Bostick transformation (Bostick, 1977). The result is an approximate depth-resistivity cross section which contains information on the quality of data and the homogeneity of the subsurface. The application of this transformation, as well as the inversion method to invert the data, saves labor, time and money and provides the maximum use of the data.

In stratified environments, one-dimensional modelling along a survey line is generally adequate; however, apparent resistivities are influenced by lateral conductivity changes, particularly at low frequencies. In such a case layered model interpretations would be in error (Kryzan and Strangway, 1977). For mapping purposes, one-dimensional interpretation for stations distributed on a grid is necessary in order to get a plan view of any three-dimensional structures present.

3.1 Moody Township (Profile A)

Profile A is north-south, roughly parallel to an esker ridge. Field data are given in Fig. 5. The ground moraine in this area is essentially of till and clay. The geologic strike in the bedrock is approximately perpendicular to the profile. The southern part of Profile A shows a very strong anisotropy. This anisotropic behaviour of resistivity curves is typical for sites A-1 through A-9 on metasediments and metamorphosed ultramafic rocks (G5 and G7 respectively in Fig. 4a). This phenomenon occurs without exception in the low frequency range. The resistivites of the metasediments measured in EW orientation tend to be more conductive than when measured in the NS orientation. We assume that this phenomenon is associated with fracturing in steeply dipping metasediments. The presence of

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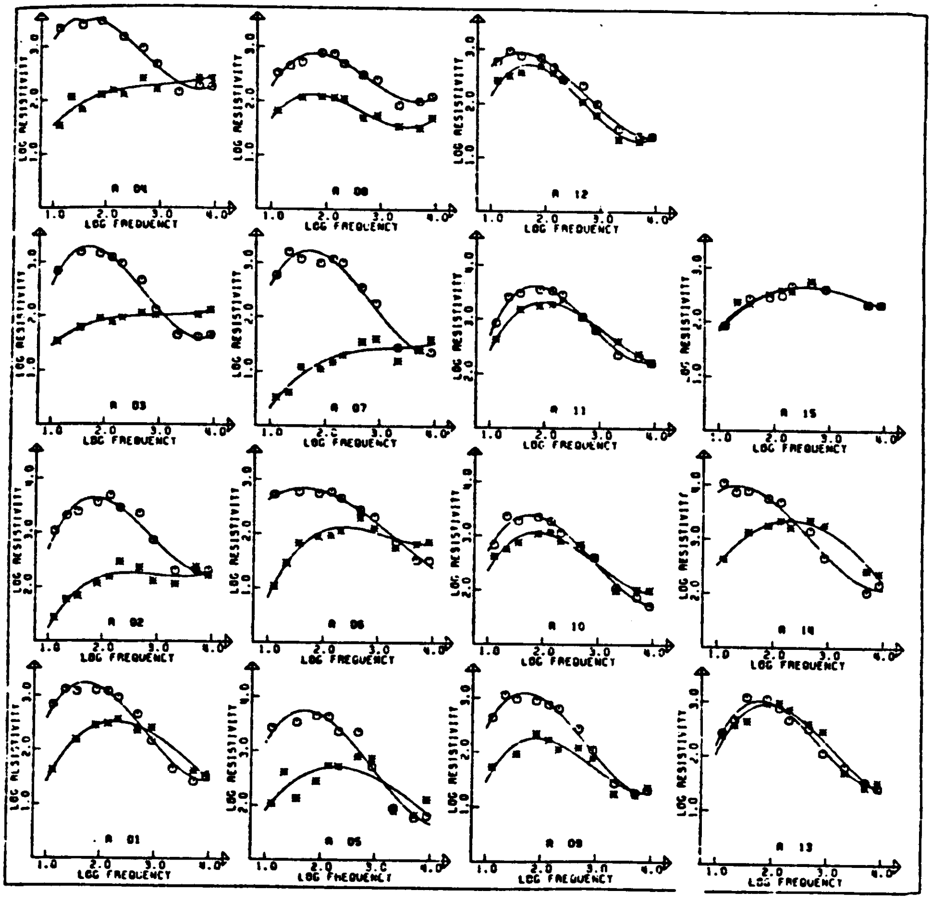

Fig. 5. AMT sounding curves of Profile A where circles are NS orientation and stars are EW orientation data.

foliation in anisotropically distributed minerals such as biotite or water in crack systems which may be parallel to the fabric could play a crucial role.

The north part (north of site A-9) of Profile A lies on metavolcanic rocks. The field data for both NS and EW orientations are very similar at sites A-10, A-11, A-12 and A-13. The fitted models using the one-dimensional inversion technique for these isotropic resistivity curves suggest that there is about 50 meters of overburden with a resistivity of around 70 ohm-m. A second layer about 100 meters thick with resistivity around 2,400 ohm-m lies beneath. Although there is no outcrop in the area, one possible explanation of this layer is a fractured or weathered uppermost part of the Precambrian bedrock. The underlying Precambrian metavolcanics have resistivity values in the range from 10,000 to 50,000 ohm-m.

There is a low resistivity zone around station A-15. In addition, A-14 shows

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strong anisotropy. This suggests a conductive fracture zone within the metavolcanics with a preferred EW direction at station A-15.

3.2 Marter Township (Profiles B and C)

The sounding curves of Profiles B and C in Marter Township all show a general similarity in both the NS and EW orientations. The overall similarity of sounding indicates that the basement volcanics and overburden are both homogeneous in the area. Only Wisconsin deposits are present as glacial overburden. Profile B crosses the south end of the Munro esker east of site B-6. This is a major feature that can be traced northward 200 miles to James Bay. An almost true depth-resistivity cross-section compilied using the Bostick transformation method is given in Fig. 6. Cross-sections which are based on NS and EW orientated data correlate well. Together with one-dimensional inversion fits along Profile B, these data reveal that the sand and gravel in this area is up to 100 meters thick. Its resistivity ranges from 800 to 3,000 ohm-m. The bedrock generally has a layer several hundred meters thick, of medium resistivity which overlies a highly resistive unfractured section of bedrock with resistivities up to 100,000 ohm-m. There may be minor clay beds beneath the very thick sand and gravel in the eastern part of the profile.

The pseudosections of Profile C in Fig. 7a for each orientation are similar to that for Profile B, implying that there is no major lateral variation. The high

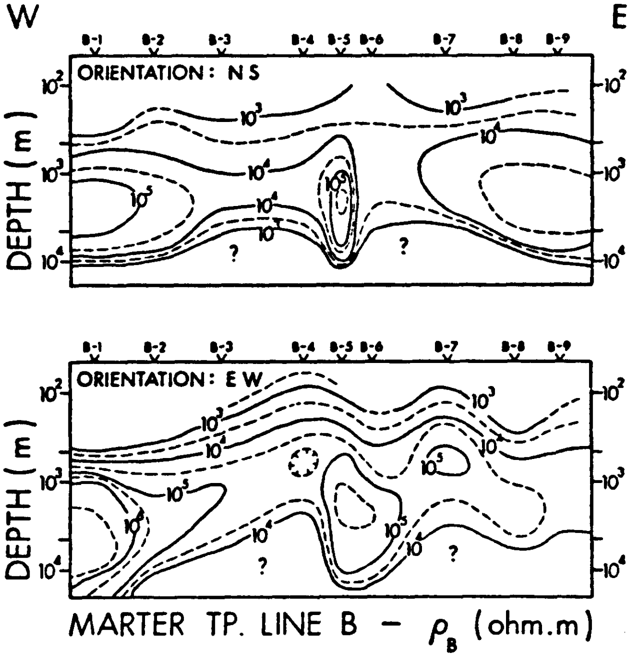

Fig. 6. Bostick resistivity cross-sections along Profile B.

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frequency readings are around 100 ohm-m, or less. The pseudosections and residual plots of Profile C reveal that the apparent resistivities are continuously decreasing southwesterly. This implies either that the thickness of the overburden is increasing, or that the top conductive layer resistivity is decreasing. The cross-section shown in Fig. 7b was obtained by a one-dimensional interpretation at each site and reveals a basin structure corresponding to that detected by drilling (AVERILL and THOMSON, 1981). The basin has its edge at the northeast end of

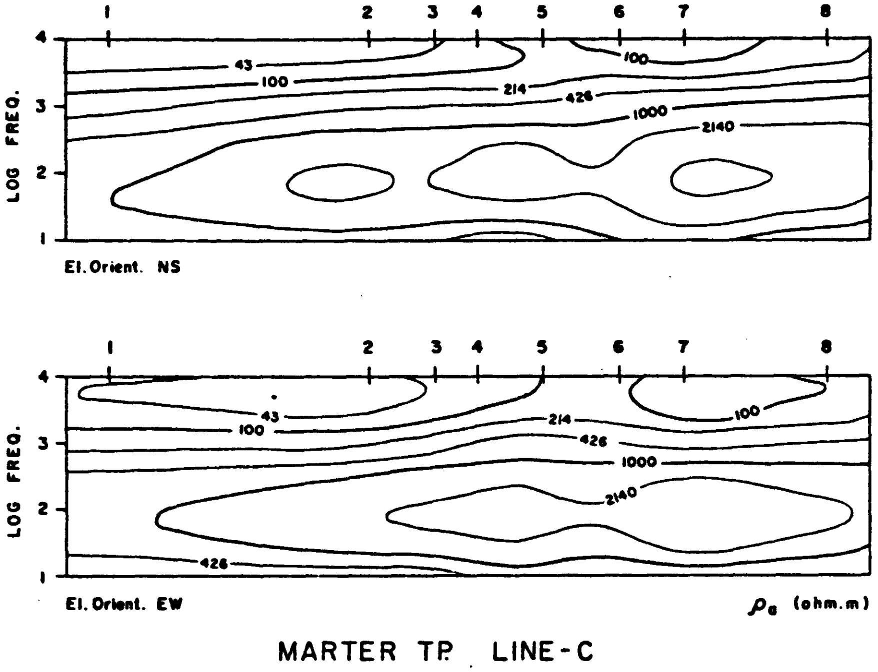

Fig. 7a. Apparent resistivity pseudosections for Profile C.

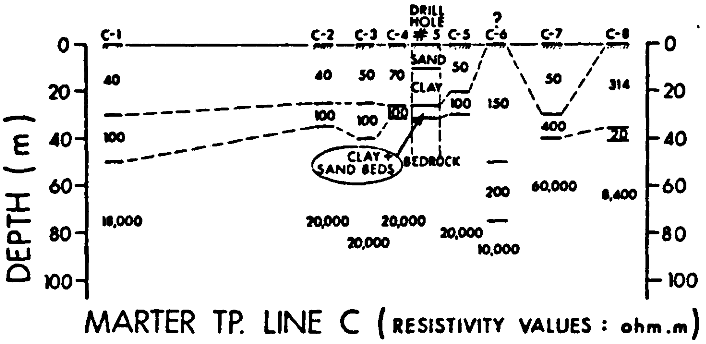

Fig. 7b. Two-dimensional configuration for Profile C derived from one-dimensional inverse models.

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the line near site C-8. The model suggests that there is a 50 meter thick overburden at the southwest end of the survey line near site C-1 and that the thickness decreases northeasterly to about 30 meters at site C-5. The bedrock resistivity, from the model, is about 20,000 - 60,000 ohm-m throughout the survey line.

3.3 Bowman Township (Grid survey E)

In Bowman Township, the main features of the surficial geology are a clay-covered plain, eskers and bedrock outcrops (Fig. 8b). Each unit shows different electrical characteristics. The three subdivisions are clearly outlined on contour maps of apparent resistivities in Figs. 8a and 8c. A contour map of the resistivity at 8,570 Hz (Fig. 8a) which generally reflects the surficial geology, shows a highly conductive clay-covered plain in the northwestern part of the area with resistivities less than 100 ohm-m. Drill results near to the west border of our grid area gives 40 meters overburden with approximately 15 meters of clay in it (Brereton and Elson, 1979). A high resistivity region lies in the southwestern part with resistivities higher than 3,000 ohm-m and reflects bedrock outcrops. The esker material with the resistivities of about 200 to 1,000 ohm-m appears on the eastern side of the previously mentioned two regions.

The contour maps at lower frequencies such as the map of 36 Hz (Fig. 8c) shows roughly the same pattern as that of 8,570 Hz, indicating that they are affected by the surface material.

The averaged apparent resistivity pseudosections for 3 Profiles F, G and H are given in Fig. 8d. Sounding curves on the northwest segment of the map and the pseudosection for line G, show a typical two-layer structure, an extremely conductive layer on top of an extremely resistive half space. High frequency readings of 20–30 ohm-m reflect the top conductive clay-rich overburden. The similarity of two sets of data for NS and EW orientation indicates the homogeneity in the glaciolacustrine plain. Anisotropy generally appears at esker sites, for example E-37 on Profile F and E-24 and E-25 at the south. Apparent resistivities at high frequencies are mostly around 100–300 ohm-m, then rise to around 10,000 ohm-m at some sites. Strong anisotropy was observed at sites near bedrock outcrops. High apparent resistivities in the 10,000 ohm-m range were obtained at high frequencies indicating the thin overburden and the very resistive bedrock.

The averaged data from two orientations was employed to determine a best estimate of the electrical structure at each site. This is a good approach to interpreting data from areas covered by glaciolacustrine deposits because of the obvious one-dimensionality shown on the two sets of data. The top two layers, with resistivities of 10 to 40 ohm-m and thicknesses in the 20–100 meter range are due to the very conductive clay-containing overburden. Our field observations and laboratory tests show that the variation of resistivities appear to be due to varying compositions of the overburden. It varies from a sand, boulder-rich more resistive unit to a very conductive clay unit. The third highly resistive layer at 20–100 meters beneath the surface is associated with bedrock having a resistivity value in the 10,000–50,000 ohm-m range. For those sites on esker

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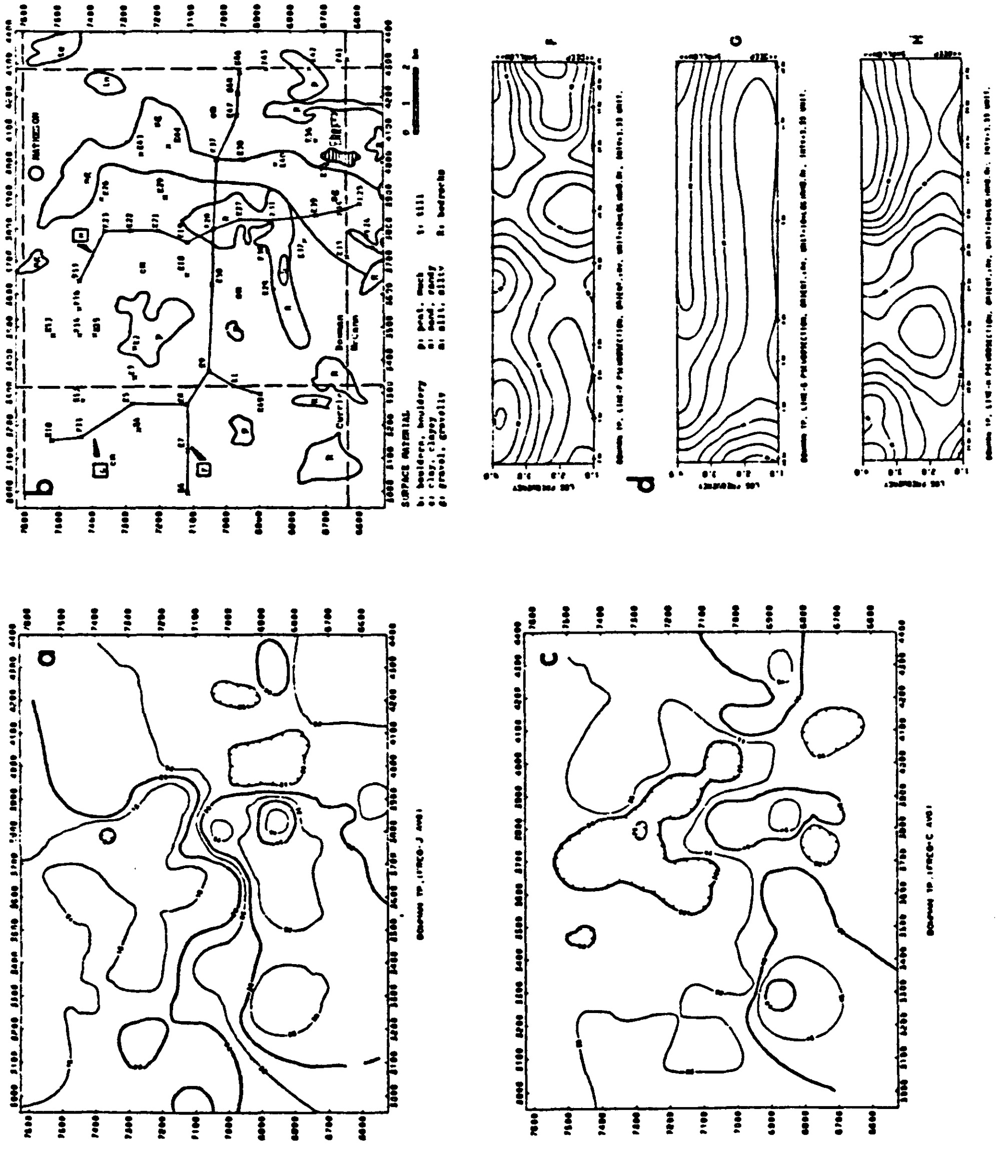

Fig. 8. a. Contour map of apparent resistivities at high frequency (*J* = 8570 Hz); b. Surficial geology of the survey area in Bowman Township; (x) represent AMT site location; c. Contour map of apparent resistivities at low frequency (*C* = 36 Hz); d. Averaged apparent resistivity pseudosections for Profiles F, G and H.

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and those near bedrock outcrop, one-dimensional interpretation may be risky and misleading when strong anisotropy exists. The determination of the top layer resistivity is reliable, due to the general agreement of high frequency data in both directions.

Three sets of block maps, surface resistivity, bedrock topography, bedrock resistivity and a contour map of bedrock topography were created by using the appropriate model parameters of the one-dimensional interpretation (Figs. 9a–d). Those sites with an apparent resistivity difference for the two orientations at 83 Hz of more than a factor of 5 were left out due to the unsuitability for one-dimensional modelling. The real surface resistivity map (Fig. 9b) which is similar to the 8,570 Hz apparent resistivity contour map (Fig. 8a) reflect the resistivity variation of the surface material (compare Fig. 8b) in the top few tens of meters. The three types of material (clay, sand and bedrock) with their characteristic resistivities are clearly outlined. The bedrock topography map was created by contouring the thickness of the top one or two conductive layers, representing the thickness of overburden from a one-dimensional interpretation. The maps show a bedrock valley running northwest-southeasterly with bedrock 100 meters beneath the surface near site E-4, E-5, E-8 and E-9. Another bedrock topographic low at the southeastern corner of the area is near sites E-35, E-36 and E-42. The bedrock resistivity map indicates that the resistivities of bedrock in this area are extremely high, in the range of 10,000 to 100,000 ohm-m. The lateral variation is not significant. Comparing the bedrock resistivity map (Fig. 9a) with the bedrock geology map (Fig. 4c), the felsic metavolcanics (2a) in this area tend to be more resistive than the intermediate and mafic metavolcanics (1c). The felsic metavolcanics with a resistivity high, run roughly east-west in the north-central part of the area. The instrustives in the south (10b, 9) have a resistivity of around 10,000 ohm-m and are homogeneous in the area we sampled.

4. Electrical Properties of Clay

In applying EM exploration techniques, in regions where there is an extensive clay cover, it is important to have a good understanding of the electrical properties of the clays. The clays are the most conductive component of the overburden, with the exception of saline alluvium, which occurs in desert areas. In the Kirkland lake area, the clays have resistivities on the order of 20 ohm-m, whereas the sands, gravels and tills have resistivities in the range of 100 to 1000 ohm-m. The clay is the most important component of the overburden, in terms of limiting the depth of exploration of EM methods.

Samples were collected from 9 sites in gravel pits, road cuts and exposures along rivers near Larder Lake, Matheson and Engelhart. In collecting the samples, an attempt was made to preserve the samples in their original state. The surface material was removed to expose fresh undisturbed clay. Samples were obtained by pressing a plastic tube (1 inch diameter by 1 inch length) into the face of the clay. The sample was then placed in a plastic bag that was heat-sealed later

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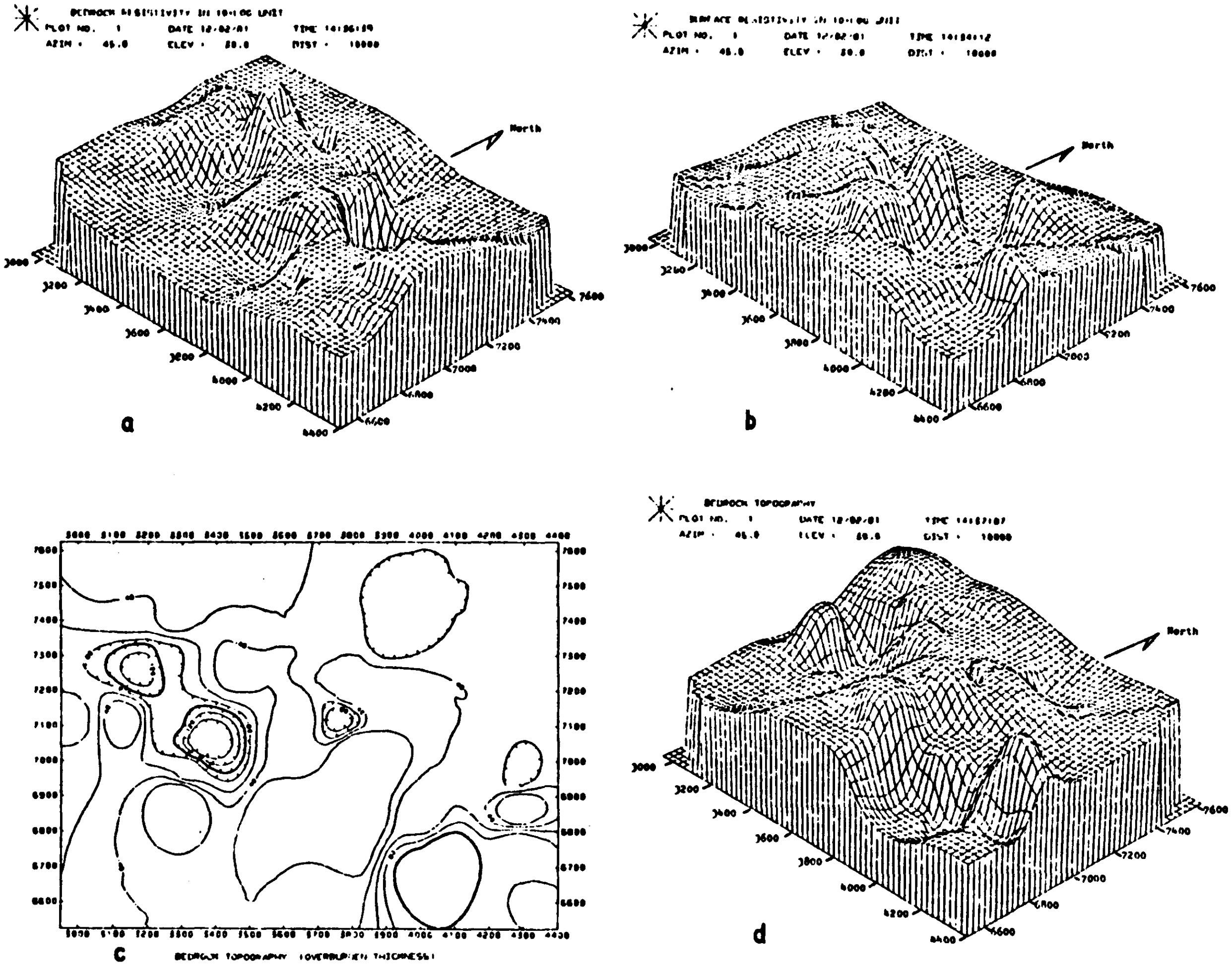

Fig. 9. a. Block map of bedrock resistivity; b. Block map of surface resistivity; c. Contour map of bedrock topography; d. Block map of bedrock topography. Maps were created by model parameters of the one-dimensional interpretation.

in the day. The purpose of the heat sealing was to preserve the original moisture content of the sample.

The complex resistivity was measured over the frequency range 5 Hz to 1 MHz. The samples were encapsulated during the measurement process to prevent them from drying. All the measurements wre carried out using the HP4192A impedance analyzer. Four terminal measurements were made between 5 Hz and 10 KHz, and above 10 KHz a two terminal technique, employing platinum electrodes, was used.

The soils show only a small frequency dependence in their resistivities. The typical frequency dependence of the phase and magnitude of the complex resistivity for different soil types is shown in Fig. 10. The particular clay sample (1) shown had a clay content of 66% and its clay minerals are principally chlorite (40%) and illite (30%). The average resistivities at 50 Hz for the different soil types at the sites studied was 24 ohm-m for clays (16 samples), 45 ohm-m for silty

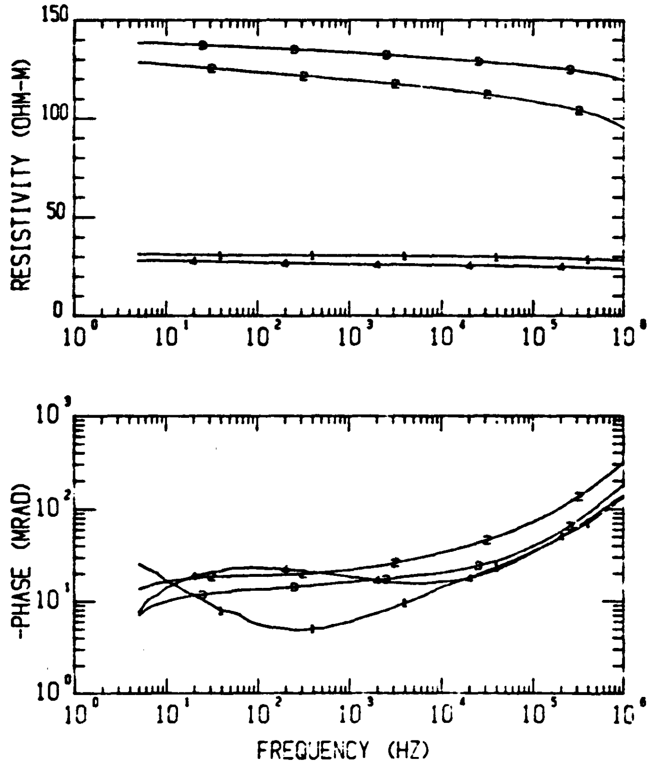

Fig. 10. The typical dependence of the phase and magnitude of the complex resistivity of soil samples from Northern Ontario are shown. The individual data points, of which there are ten per decade in frequency, have been joined with straight line segments. The numbers given on the individual plots are for identification purposes: 1 - Clay (varved), Larder Lake; 2 - Sandy-loam, Engelhart; 3 - Silt-loam (varved), Larder Lake; 4 - Peat, Matheson.

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clay (4 samples), and 87 ohm-m for loams (9 samples of loam, sandy loam and silt loam).

5. Conclusions

In many parts of the Canadian Shield there are extensive near surface clay deposits left behind by glacial lakes. This clay-rich overburden is conductive relative to the bedrock, but varies from place to place. There are also many highly resistive eskers in the area which provide electrical sounding windows into the bedrock. Using the AMT method, it is possible to locate large, uniform regions with high resistivities to provide the most useful sites for deep sounding techniques.

Moody Township near Lake Abitibi, a region believed to be underlain by metasediments, shows a strong and uniform electrical anisotropy. It is thus possible to map out steeply dipping metasediments, even when they are not exposed.

Good correlation with known surficial geology in Marter Township near Engelhart in Northern Ontario (and at the Whiteshell Nuclear Reactor site in Eastern Manitoba) was obtained when estimating the resistivity and thickness of the clay-rich overburden. It is possible to sound through conductive overburden, although it is difficult to sort out the lateral variation in the bedrock from those within the conductive clay unit.

Maps produced by using the grid survey data in Bowman Township near Matheson show a conductive region in the northwestern part of the area (clay-rich overburden). There is a high resistivity region in the southwestern part of the area (bedrock outcrop) and an intermediate resistivity region is located on the eastern side of the two regions (esker). Bedrock valleys in the northwestern part of the area could be detected at depths of 50–100 m. The resistivity of the Precambrian bedrock is typically 10,000 ohm-m to 100,000 ohm-m. High frequency data give resistivities of 20–30 ohm-m over the clay-rich overburden. These values are in general agreement with resistivities measured on clay samples. The resistivity value of the clay itself seems fairly uniform in regions ranging from Lake Abitibi to Engelhart.

Depending on the changes in the clay content and pore water, the resistivity of the overburden may vary rapidly laterally and make the deep sounding results ambiguous. Hence a better understanding of the electrical properties of clay, sand, silt and loam is useful.

We found the audiomagnetotelluric method (AMT) is very useful as a mapping device in Precambrian terrains. Pseudosections and Bostick resistivity cross-sections provide a better understanding of two-dimensional structures in the survey area. Since the technique has the capacity for very high lateral resolution and greater depth penetration when compared to controlled source electromagnetic techniques, the measured and/or inverted maps on a grid outline contacts, faults, graphitic or sulphide zones with high precision.

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REFERENCES

AVERILL, S. A. and I. THOMSON, Reverse circulation rotary drilling and deep overburden geochemical sampling in Marter, Catherine, McElroy, Skead, Gauthier and Hearst townships; District of Timiskaming, Ontario Geological Survey, OFR 5335, 276 pp., 1981.

BOSTICK, F. X., A simple and almost exact method of MT analysis (Abstract), Workshop on electrical methods in geothermal exploration, Utah, 1977.

BRERETON, W. E. and J. A. ELSON, A late Pleistocene plant-bearing deposit in Currie Township, near Matheson, Ontario, *Can. J. Earth. Sci.*, 16, 1130–1136, 1979.

CAGNIARD, L., Basic theory of the magnetotelluric method of geophysical prospecting, *Geophysics*, 18 605–635, 1953.

GRISAK, G. E. and J. A. CHERRY, Hydrologic characteristics and response of fractured till and clay confining a shallow aquifer, *Can. Geotech. J.*, 12 23–43, 1975.

HSU, D. T., One-dimensional and two-dimensional interpretation of audiomagnetotelluric data, M. Sc. Thesis, Univeristy of Toronto, 1981.

HUGHES, O. L., Preliminary report on borings through Pleistocene deposits, Cochrane District, Ontario, Geological Survey of Canada, Paper 61-16, 1961.

KRYZAN, A. and D. W. STRANGWAY, Magnetotelluric studies in the geotraverse Area, *Proc. 1977 Geotraverse Conference*, University of Toronto, 121-131, 1977.

KAUFMAN, A. and G. V. KELLER, *The Magnetotelluric Sounding Method*, 595 pp., Elsevier, New York, 1981.

LEE, H. A., Northern Ontario Engineering Geology Terrain Study Data Base Map: Iroquois Falls, Ontario Geological Survey, Map 5027, Scale 1:100,000, 1979a.

LEE, H. A., Northern Ontario Engineering Geology Terrain Study Data Base Map: Kirkland Lake, Ontario Geological Survey, Map 5030, Scale 1:100,000, 1979b.

MARQUARDT, D. W., An algorithm for least squares estimation of nonlinear parameters, *J. Soc. indust. Appl. Math.*, 11, 431–441, 1963.

PYKE, D. R., L. D. AYRES, and D. G. INNES, Timmins-Kirkland Lake, Districts of Cochrane, Sudbury and Timiskaming: Ontario Geological Survey, Map 2205, Geological Compilcation Series, Scale 1 inch 4 miles, 1973.

ROED, M. A. and D. R. HALLETT, Northern Ontario Engineering Geology Terrain Study Data Base Map: Elk Lake, Ontario Geological Survey, Map 5020, Scale 1:100,000, 1979.

STRANGWAY, D. W., The audiofrequency magnetotelluric (AMT) sounding, *Meth. Expl. Geophys.*, 5 (in press).

STRANGWAY, D. W. and K. VOZOFF, Mining exploration with natural electromagnetic fields, Mining and groundwater geophysics, *GSC Econ. Geol. Rep.*, 26, 109-122, 1969.

STRANGWAY, D. W., C. M. SWIFT, and R. C. HOLMER, The application of audio frequency magnetotellurics (AMT) to mineral exploration, *Geophysics*, 38, 1159-1175, 1973.

STRANGWAY, D. W., J. D. REDMAN, and D. MACKLIN, Shallow electrical sounding in the Precambrian crust of Canada and the United States, in *The Continental Crust and its Mineral Deposits*, edited by D.W. Strangway, Geol. Assoc. of Canada, Spec. Paper 20, 1980.

Grant 118 Surface Electromagnetic Mapping in Selected Positions of Northern Ontario

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ABSTRACT

In conjunction with our application of audio frequency magnetotellurics to electromagnetic mapping in northern Ontario, we have carried out measurements on the electrical resistivity of the surficial deposits (clays, silts, and sands). The conductive clays of the Abitibi clay belt, which are quite extensive in our study area, are known to be a serious impediment to the application of EM techniques in this important mining region.

The glaciolacustrine clays, silts and sands generally form a horizontally stratified section. Overburden thicknesses of 50 m and clay layer thicknesses of 30 m are not uncommon. We have characterized the 'typical' low frequency resistivities of the clays, silts, and sands and measured the frequency dependence of their resistivity in the range of 0.01 Hz to 1 MHz. We have determined the sand, silt and clay size fractions for these samples. The average DC (low frequency) resistivities are: clays (22 samples) 23 ohm metres, silts (13 samples) 72 ohm metres and sands 1000-5000 ohm metres (*in situ* measurements). *In situ* DC resistivity measurements using a Wenner array with a spacing of 0.5 m give consistently higher resistivities than laboratory measurements on samples from the same locations. We believe that this difference is due to both cracks in the near surface soil and to differences between the horizontal and vertical resistivity of the soil.

In general the samples show only a small frequency dependence in their resistivity in contrast with previous measurements on clays. The frequency effect between 5 and 50 Hz is typically less than 2.5%.

INTRODUCTION

In the previous summaries of our research we have reported on the results of audio frequency magnetotelluric (AMT) surveys. The principal aim of these surveys has been to apply the AMT technique to mapping the electrical structure of the basement buried beneath thick conductive overburden. In this report we will discuss laboratory and *in situ* measurements of the resistivity of the overburden components and their relationship to the electrical structure of the overburden.

The area in which we have concentrated our study encompasses a large part of the Abitibi clay belt shown in Figure 1. The conductive clays of the clay belt (lacustrine deposits) are a serious impediment to the application of electromagnetic (EM) techniques in this area and a better understanding of these conductive surficial deposits will be useful in the interpretation of EM data. There were two main goals in our work. One was to characterize the 'typical' resistivities of the different overburden components, that is clays, silts, and sands, and from this to derive a typical electrical section. The other was to study the frequency dependence of the resistivity. We have concentrated most of our work on characterizing the clays and silts since they are the most conductive overburden component.

OVERBURDEN DEPTHS AND STRATIGRAPHY

For the purpose of identifying 'typical' overburden depths and clay thicknesses we have reviewed the available literature on the survey area. In the Abitibi clay belt, the glaciolacustrine clays, silts and sands which were deposited in proglacial Lake Barlow-Ojibway generally form a horizontally stratified section. The clays and silts are commonly varved showing a pattern of seasonal deposition. In the northern part of the region around Cochrane, clayey and silty tills cover the clays. These were deposited during a local re-advance of the ice sheet. In other areas it is possible for the clays to be masked by sands from outwash deposits or from eskers. Clay pockets in buried bedrock valleys and between bedrock outcrops are probably quite common.

The surficial material and landforms have been mapped at a scale of 1:100,000 for the Ontario Geological Survey (Gartner *et al.* 1979). There is also a series of drift thickness maps (Baker 1979) published by Ontario Geological Survey in which the data have been obtained from assessment files (Assessment Files Research Office, Ontario Geological Survey, Toronto). The drift thickness maps presently available cover the area (region A in Figure 1) near Kirkland Lake. The distribution of overburden thicknesses for data taken from these maps is shown in Figure 2. For each of the 221 locations, we have taken the maximum depth for all drill holes near that location. The purpose of this approach was to emphasize the deepest re-

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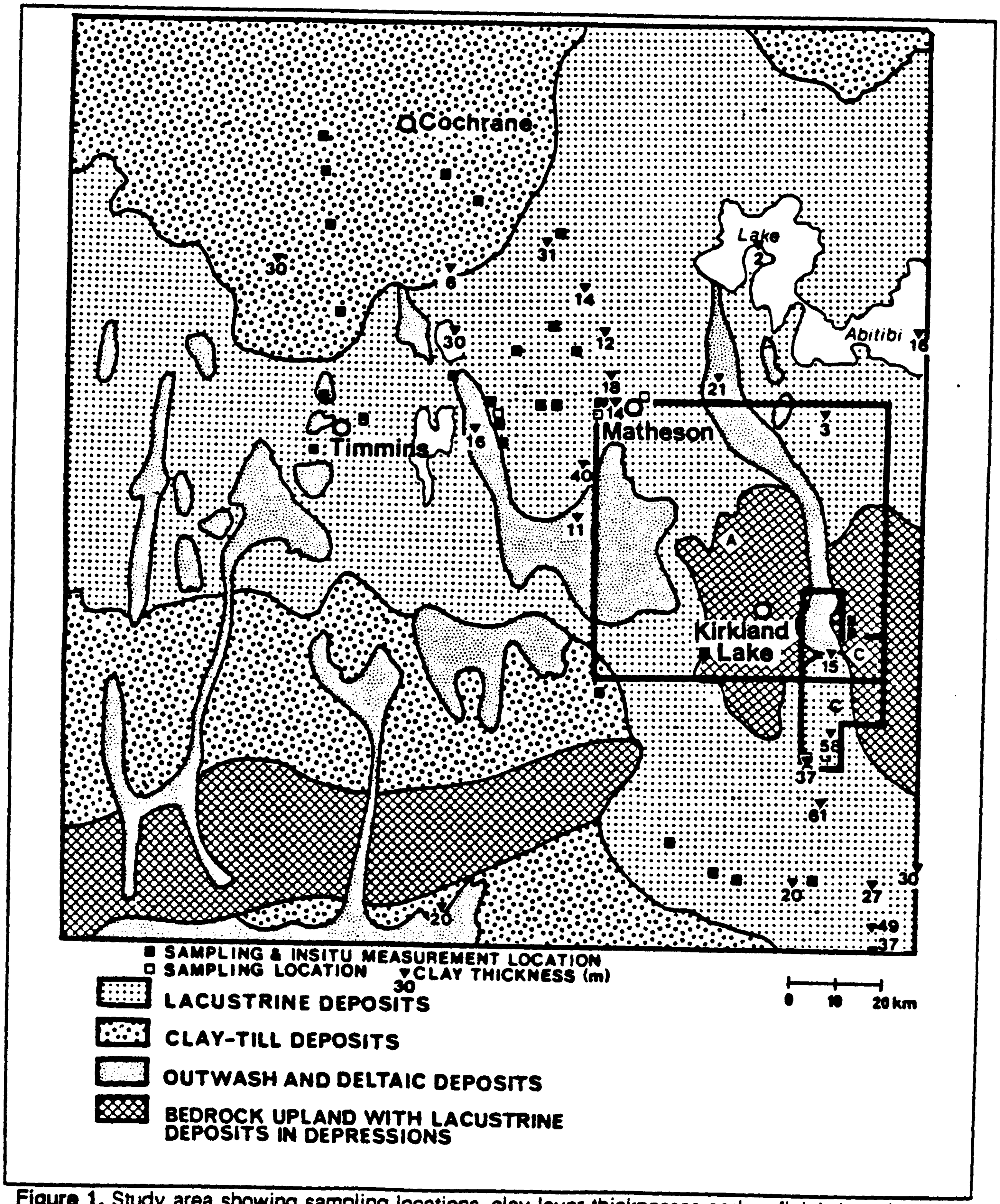

Figure 1. Study area showing sampling locations, clay layer thicknesses and surficial deposits.

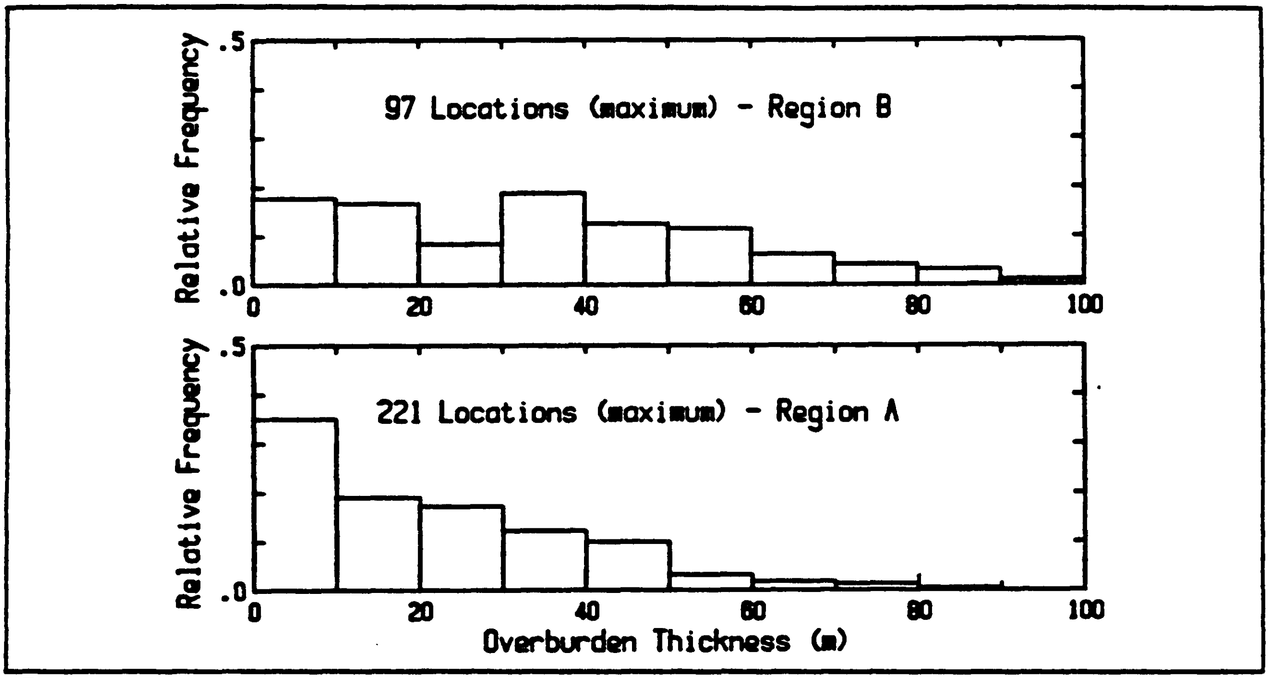

Figure 2. Overburden thickness distributions for two regions. Region A is around Kirkland Lake and region B is the remaining area outlined on Figure 1. The data were obtained from Ontario Geological Survey drift thickness maps (Maps P.2477-2480, Baker 1981) and assessment files.

gions at each locality. These results are probably still biased towards thinner overburden than is typical for the area since drilling prospects are more likely to be in areas of thinner overburden. It is clear that in this area overburden depths of greater than 50 m are not uncommon. There was one hole drilled in Gauthier Township with a depth to bedrock of 242 m. A sampling of assessment files from the rest of the area (region B) show that depths of 30 m are common.

It is the clay and silt within the overburden that predominate in limiting the depth of penetration for EM methods. Figure 1 shows typical clay and silt layer thicknesses. These data, which are taken from available literature, were obtained from drill holes and exposures. For example, near Frederick House, 93 holes were drilled giving an average clay thickness of 35 m. A reverse circulation drilling program carried out by Averill and Thompson (1981) for the Ontario Geological Survey south of Kirkland Lake (region C), where there are numerous bedrock outcrops, found a maximum overburden thickness of 73 m and maximum clay layer thickness of 58 m. The overburden sections observed in the holes in this region show that the overburden stratigraphy is quite variable. The clay and silt layers are often buried under varying thicknesses of sand. For this area in general, seismic data and drilling results show that there can often be significant bedrock relief. Thus conductive clay-filled channels and valleys may be common.

RESISTIVITY MEASUREMENT TECHNIQUE

Samples for the resistivity measurements were collected from gravel pits, road cuts and exposures along rivers at the sample sites shown in Figure 1. When collecting the samples, surface material was removed to expose unweathered and undisturbed clay. Samples were obtained by pressing a 1-inch plastic tube into the face of the clay. The samples were from homogeneous units so that even a small sample was representative of the whole unit. The samples were collected in an orientation that allowed the horizontal resistivity to be measured. They were also heat-sealed in plastic bags to preserve their original moisture content.

The magnitude and phase of the resistivity was measured over the frequency range of 5 Hz to 1 MHz. Some measurements were also carried out in the range 0.01 Hz to 1 MHz. The Hewlett-Packard HP4192a impedance analyzer was used in these measurements for frequencies above 5 Hz. Four electrode measurements, using separate current and potential electrodes, were made from 5 Hz to 10 kHz. Above 10 kHz, a four terminal and two electrode technique was used. Platinum mesh was used for the current electrodes and platinum wire for the potential electrodes. A current density of approximately 0.1 A/m^2 was used for all measurements.

We have chosen to classify our samples according to the fraction of sand (>45 μm), silt (4 μm to 45 μm) and clay (<4 μm) size particles they contain. This grain size analysis was done by using standard techniques of sieving and sedimentation analysis. The sand size fraction is obtained by wet sieving the sample through a 45 μm sieve. The sample containing the remaining silt and clay fraction is dispersed in a column of distilled water containing a dispersant (Calgon). The mixture is allowed to settle until all particles with grain sizes greater than 4 μm have settled. The supernatent is decanted and the amount of clay in the decanted liquid is determined by evaporating the liquid in an oven and weighing the sediment. Corrections are made for the amount of dispersant in the sediment. This sedimentation process is repeated three times to remove all of the clay size fraction. The remaining sediment, in the cylinder at the end of this process, is dried to determine the silt content.

The clay size fraction typically contains 70% clay minerals. From X-ray diffraction analyses of a few of the clays it was determined that the principal clay minerals were chlorite (40%) and illite (30%). When reference is made to the amount of sand, silt or clay, we are referring to the grain size and not to the mineralogy of the sample.

LOW FREQUENCY RESISTIVITY MEASUREMENTS

The results of the low frequency (50 Hz) or DC resistivity measurements are shown in Figure 3. One measurement per site has been plotted from the widely scattered localities shown on Figure 1. The presentation of the results as both conductivities and resistivities allows details in the data to be seen at both low and high clay contents. The trend of increasing conductivity with increasing clay content along with a considerable degree of scatter for a fixed clay content is evident, This scatter is controlled primarily by the different pore water conductivities and formation factors for samples from different environments.

In Figure 4 the distribution of resistivities for silts and clays are given. For the purposes of presenting the data, the samples have been divided into three classes. Clays contain more than 35% clay (clay size fraction), silts have less than 35% clay and less than 70% sand. The resistivities of the clays are tightly grouped with an average of 23 ohm metres, whereas the resistivities of the silts are more variable. AMT surveys that we have carried out typically gave 20-50 ohm metres for the most conductive layers in the overburden section, which are presumably clays.

A relatively simple model has been given by Shainberg *et al.* (1980) to explain the dependence of the DC or low frequency conductivity (σ) of soils on pore water conductivity and surface conductivity. In this electrical model, two conductive paths in parallel are used to describe conduction in a soil. One conduction path is through the pores assuming the matrix is an insulator. The other path consists of surface conduction through the exchangeable cations on the surface of the clay particles in series with a conduction path through the pore water between the soil particles.

$$\sigma = \sigma_w F^{-1} + \sigma_s' \sigma_w (K\sigma_s' + \sigma_w)^{-1}$$

where: $\sigma_s' = \mu_+ C\rho(\theta F)^{-1}$

μ_+ - Mobility of specific cation in diffuse double layer ($cm.sec.V^{-1}.m^{-1}$)

C - Cation exchange capacity (meq/g)

ρ - Soil density (g/cm^3)

θ - Porosity

σ_w - Conductivity of pore water (mS/cm)

σ_s' - Apparent surface conductivity (mS/cm)

F - Formation factor

K - Function of fractional length of solid phase ($K \cong 0.3$)

In Figure 5 the dependence of soil conductivity on pore water conductivity is shown for two soil samples. The plot shown is based on the above model fitted to measured values which are essentially equivalent. One would expect the varved clays to show a similar dependence on pore water conductivity but to be more consolidated and thus have higher formation factors than observed in these soils. We measured a pore water conductivity of 0.13 S/m on

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one of our clay samples (62% clay, 34% silt and 4% sand).

The Shainberg model implies that the scatter in the observed conductivity for a fixed clay content must be related to different pore water conductivities, formation factors and cation exchange capacities (related not to clay content but to different clay mineralogy and ionic species) for samples from different environments. The clays in the region are from a common source and were deposited in the same environment (i.e. Lake Barlow-Ojibway); therefore it is likely that the clay mineralogy is the same for all samples. Thus the scatter is related to different pore water conductivities and formation factors. Our measurements on the resistivities of the soil samples from the region are considered to be typical. Deviations from the typical values can be predicted by using the Shainberg model.

Using the drill hole logs from the overburden drilling program south of Kirkland Lake and using our laboratory resistivity measurements on silts, clays and sands and a reasonable estimate for the tills, one can estimate overburden conductances for this area (Figure 6). These results show that conductances of 1 to 2 siemens are not uncommon for the area. There have been reports of some overburden in the Abitibi region containing salt water which would clearly make a significant difference in the resistivities. Marine clays in the Hawkesbury area of Ontario have resistivities of 2 ohm metres (Dyck 1974) compared with the average of 23 ohm metres we have seen in the Abitibi clay belt.

We have also carried out *in situ* resistivity measurements using a Wenner array with a spacing of 0.5 m. The comparison between our laboratory measurements and these *in situ* measurements are shown in Figure 7a. The laboratory measurements are consistently lower than the *in situ* measurements by approximately a factor of 2. We believe that this difference is due to cracks in the near surface soil which would increase the resistivity on the large scale and to differences between the horizontal and vertical resistivity of the soil. Measurements on varved clays in this area by Chan and Kenny (1973) indicate that horizontal and vertical hydraulic conductivities can be different by up to a factor of 5, which would indicate that there could be similar differences in resistivity. A similar difference between laboratory and *in situ* measurements is shown in Figure 7b for samples taken through an exposed 2 m thick varved clay layer.

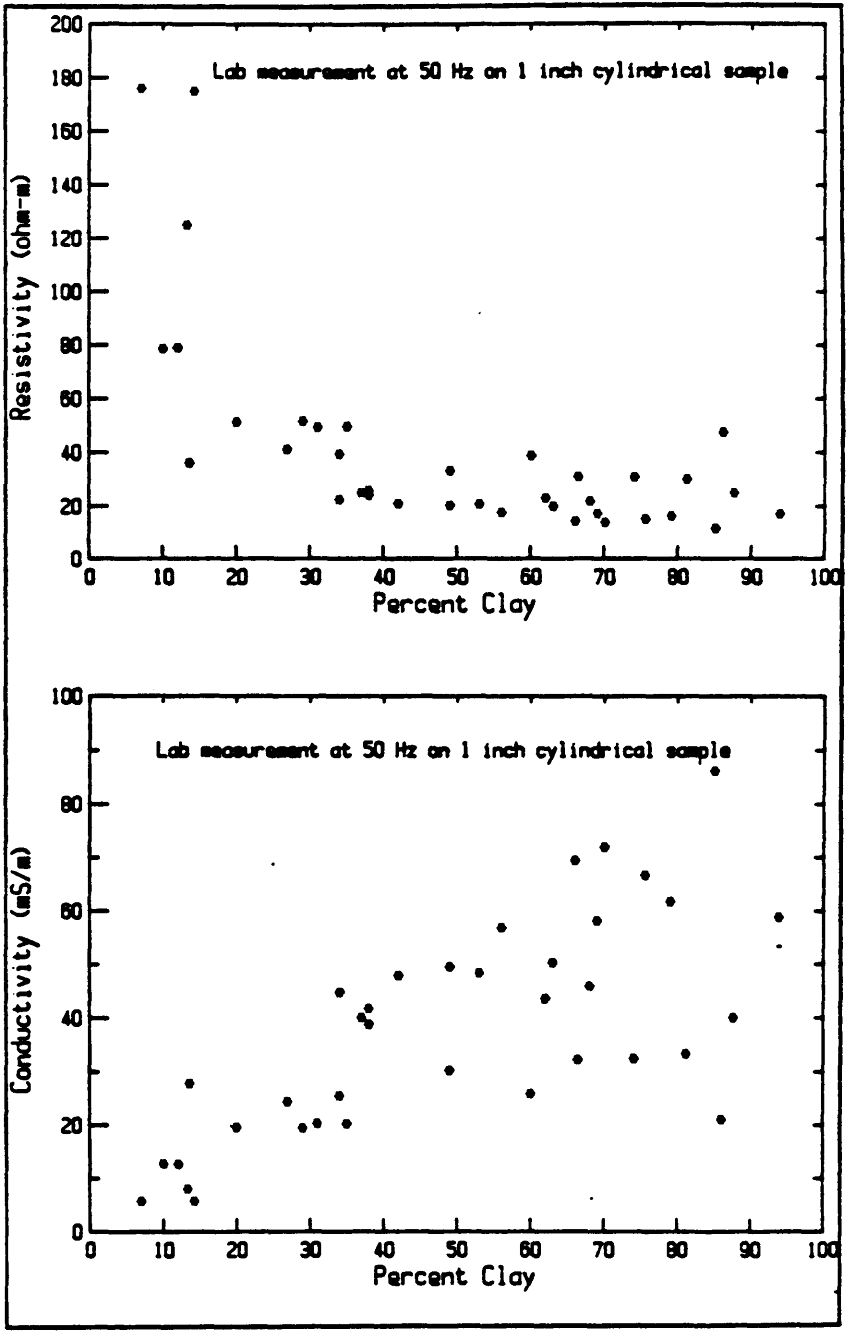

Figure 3. The magnitude of the resistivity (top) and conductivity (bottom) at 50 Hz are plotted as a function of clay content. One data point is shown for each sampling location.

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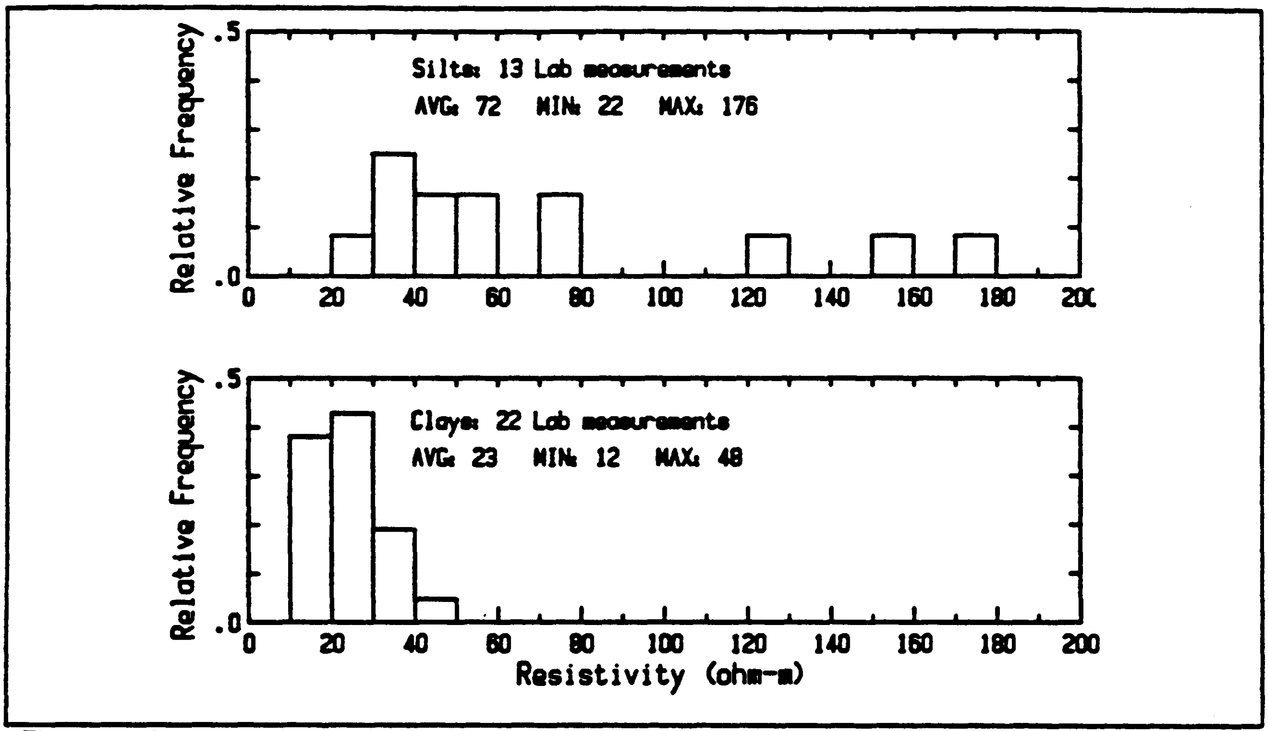

Figure 4. The distribution of resistivities at 50 Hz for silts and clays. The silts are more variable and have higher resistivities.

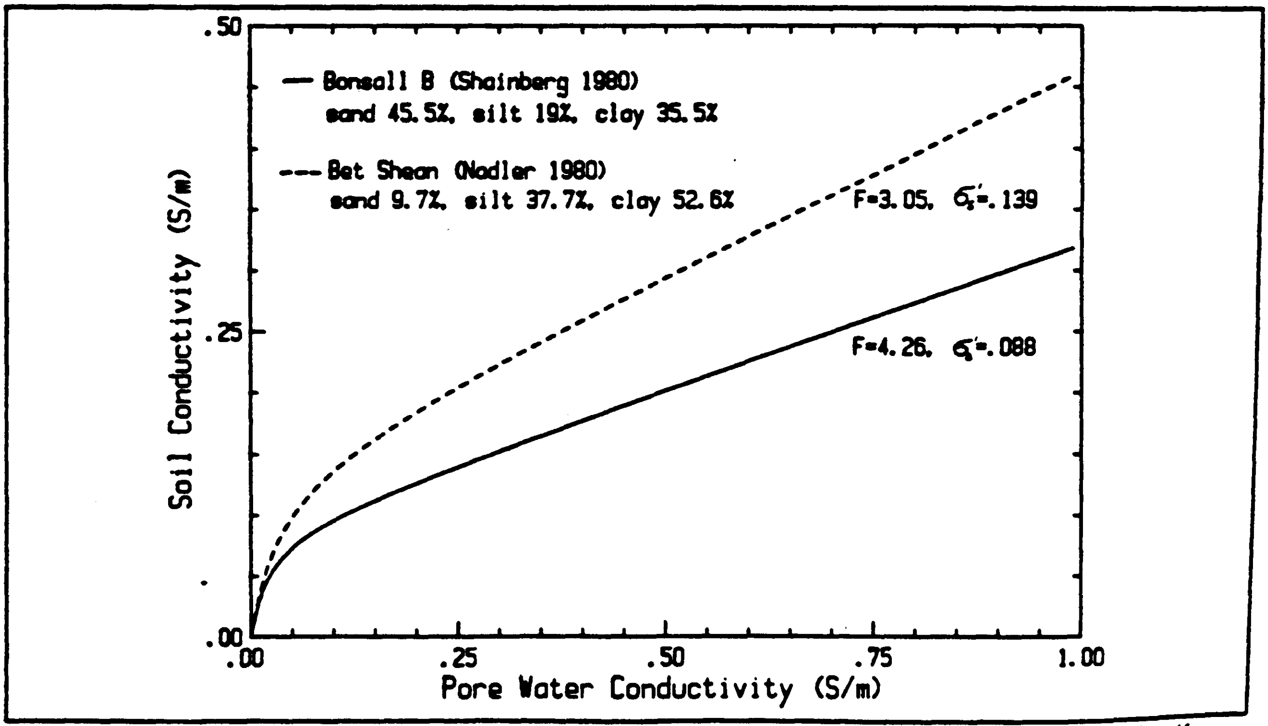

Figure 5. Typical dependence of soil conductivity on pore water conductivity for two soils (from Nadler and Frenkel 1980, and Shainberg *et al.* 1980).

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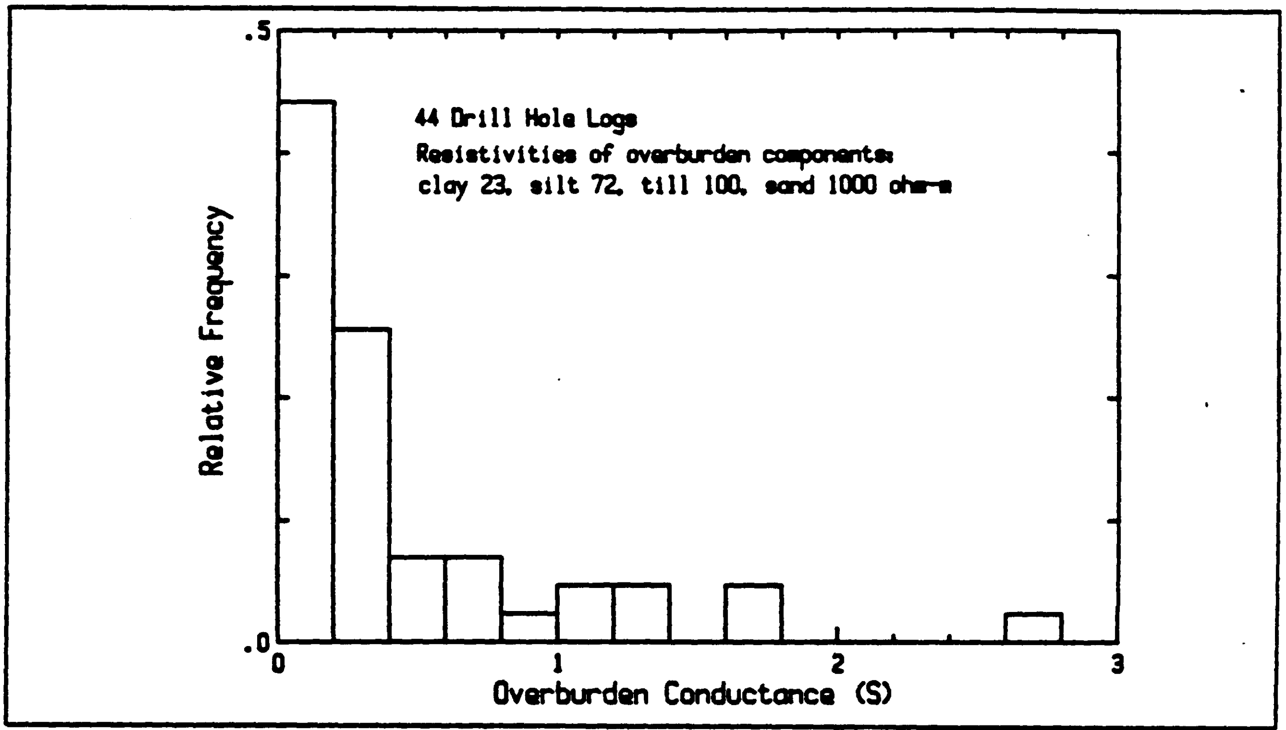

Figure 6. Estimated overburden conductances for region C (see Figure 1) southeast of Kirkland Lake.

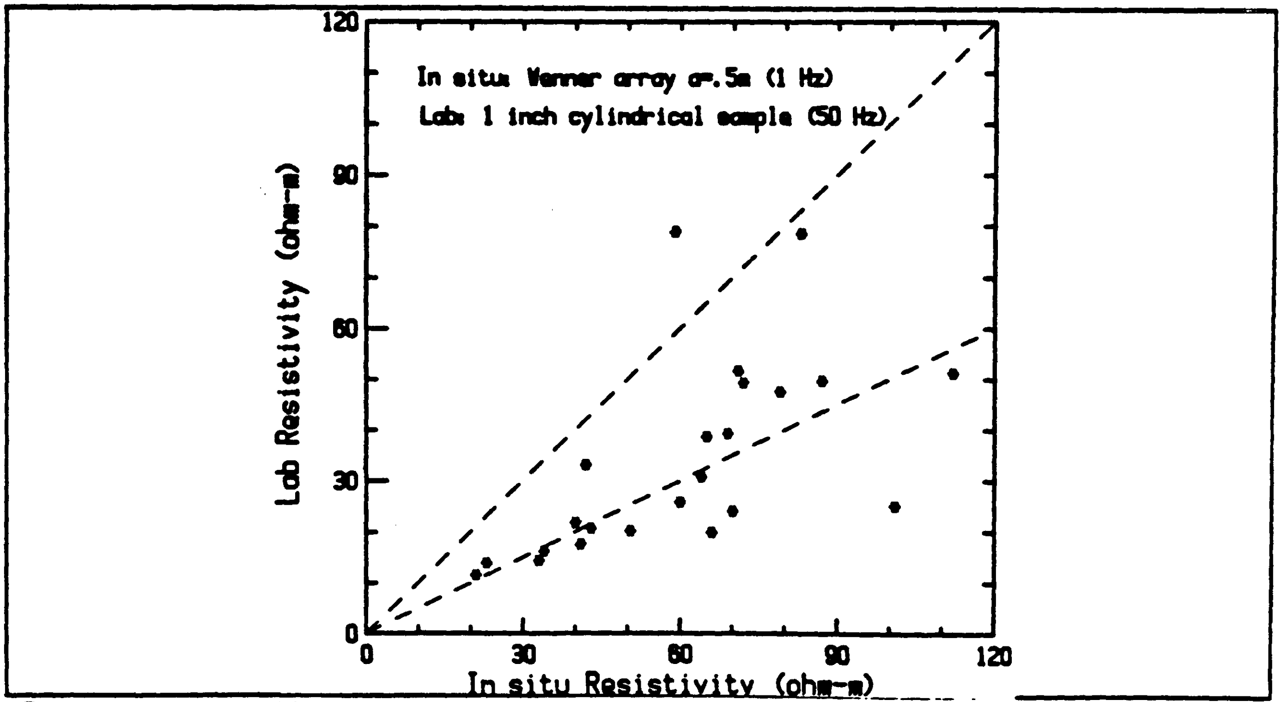

Figure 7a. Relationship between the *in situ* and laboratory measurements of the resistivity using a Wenner array with a = 0.5 m for the *in situ* measurements. The sample sites are shown on Figure 1.

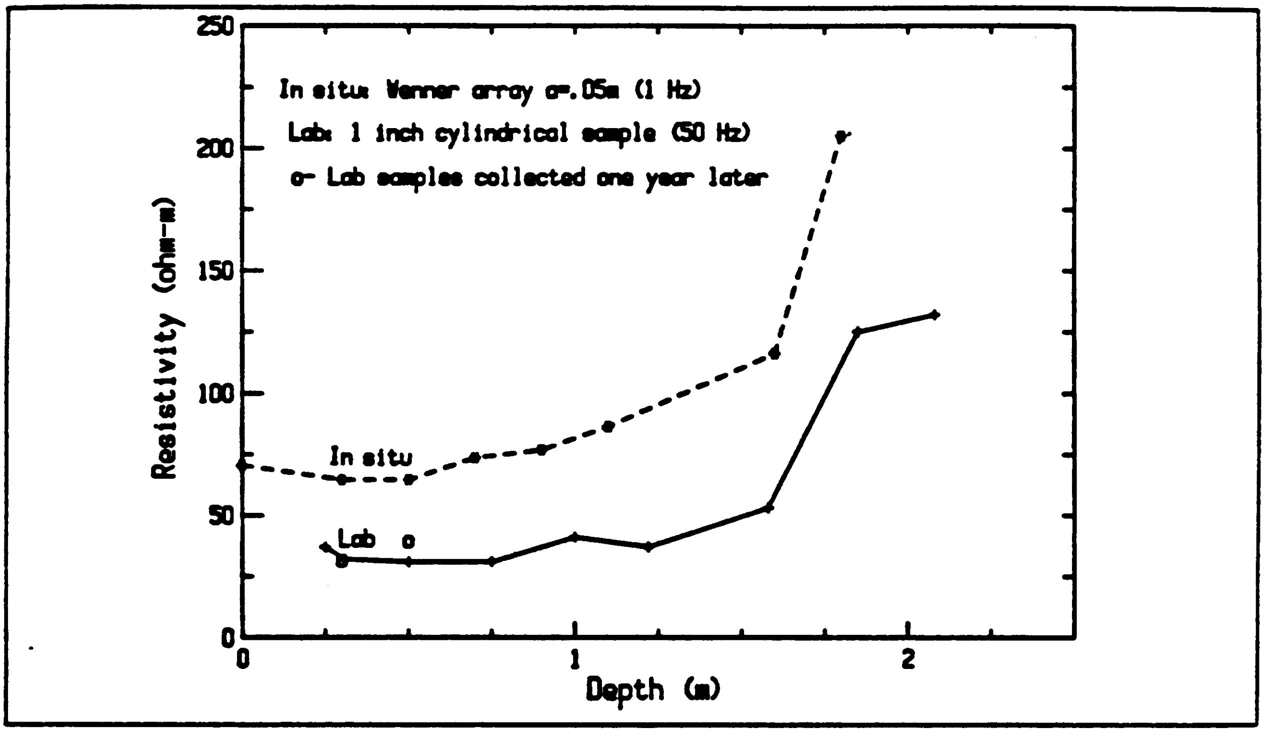

Figure 7b. Comparison of *in situ* and laboratory measurements of resistivity through a 2 m clay layer. For the *in situ* measurements a Wenner array, with a = 0.05 m, was used.

RESISTIVITY FREQUENCY DEPENDENCE

We have also measured the frequency dependence of the complex resistivity of laboratory samples. Laboratory measurements on the frequency dependence of the resistivity of kaolinite, illite and silty clay by Mehran and Arulanandan (1977) show a significant frequency dependence in the range 50 Hz to 100 kHz. Their measurements show that the magnitude of the resistivity dispersion increases with decreasing water content, electrolyte concentration and cation exchange capacity. Their measurements on silty clay gave a frequency effect of 17% between 100 Hz and 1 kHz. The dispersions that they observed are much larger than anything we have seen, our largest being 4% between 5 Hz and 50 Hz (Figure 9). In general, these samples show little dispersion in their resistivity as can be seen in Figure 8. Although, as we have reported previously (Strangway *et al.* 1983), one of our samples showed a curious negative percent frequency effect (PFE) and positive phase angle.

For the purpose of comparing directly the resistivity dispersion observed in our samples with the results of Mehran and Arulanandan (1977), we homo-ionized one of our samples with Na^+ and compared the result with another sample from the same location. The sample was homo-ionized (all exchangeable cations replaced with Na^+) by treating with 1 mol NaCl solution, followed by leaching with distilled water and then treatment with 0.01 mol NaCl solution. The frequency dependence (Figure 10) is similar to that of the untreated sample. The untreated sample has a small dispersion (negative phase peak and decreasing resistivity) at low frequencies that is not present in the treated sample. The treated sample has a higher phase response at the highest frequencies but this is simply a result of it having a lower DC resistivity. The frequency effect (between 50 Hz and 100 kHz) in the treated sample is 6% which is quite small compared with 25% obtained by Mehran and Arulanandan (1977) for an illite clay.

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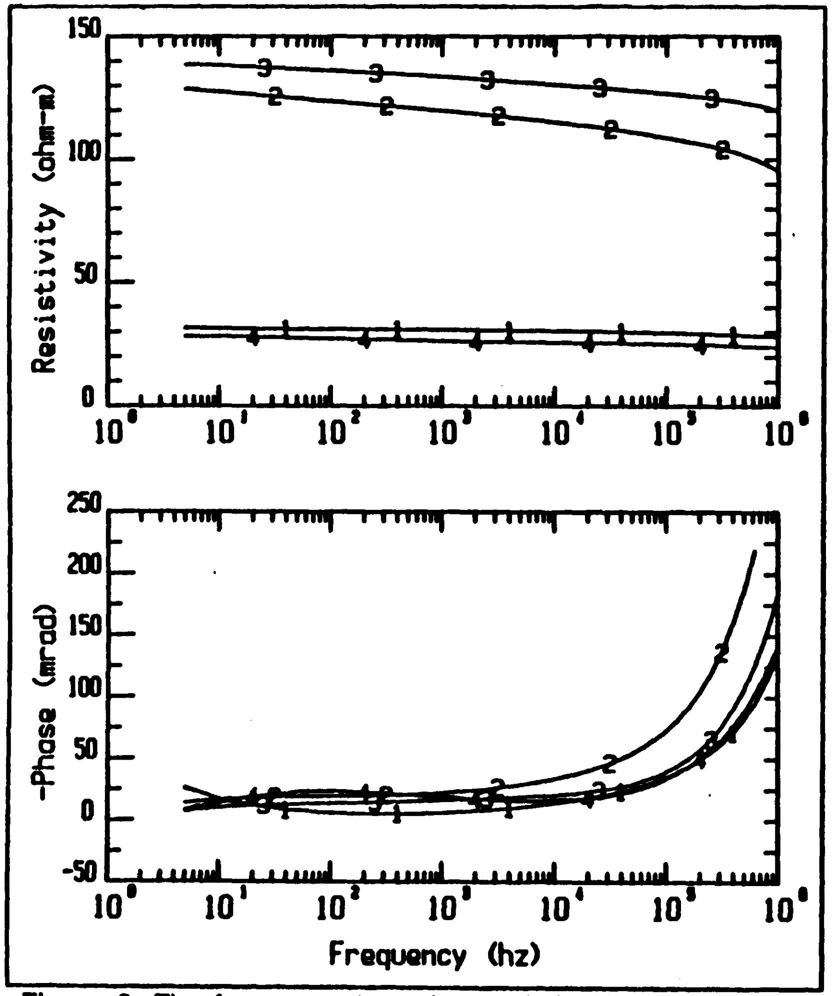

Figure 8. The frequency dependence of the phase and magnitude of the resistivity of typical soil samples. The measured data points, of which there are 10 per decade, have been joined by straight line segments. Sample 1: varved clay (clay 66%, silt 26%, sand 8%); sample 2: sandy loam (clay 14%, silt 30%, sand 56%); sample 3: varved silt loam (clay 95, silt 63%, sand 28%); sample 4: peat.

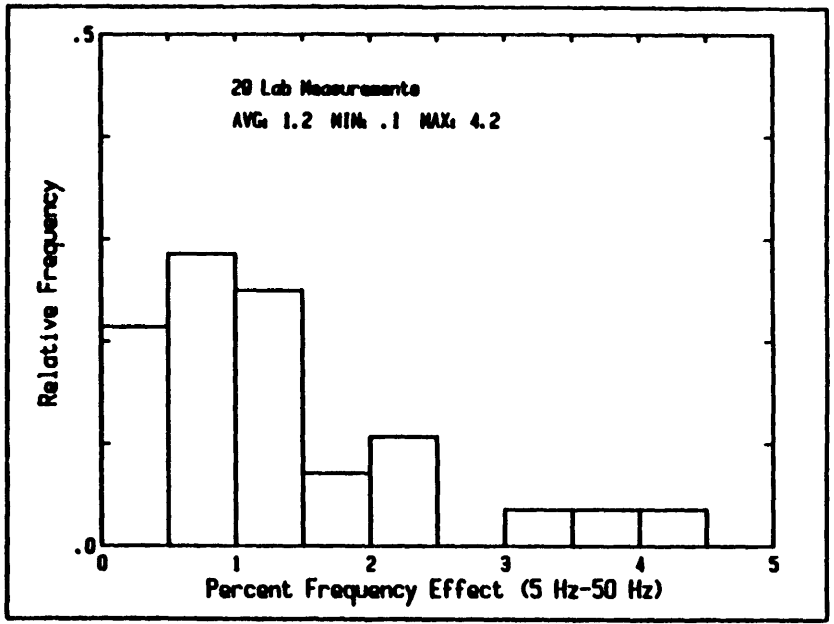

Figure 9. The distribution of percent frequency effect (PFE) observed in laboratory samples,
PFE = $(\rho_{5Hz} - \rho_{50Hz})/\rho_{5Hz} \times 100$.

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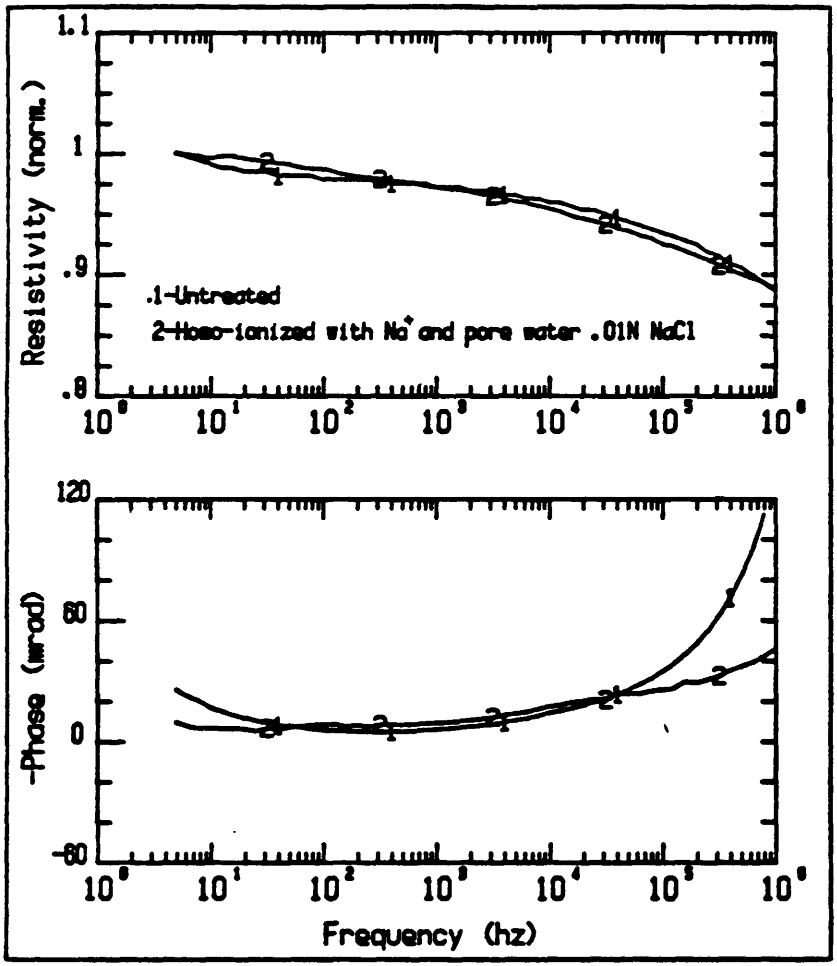

Figure 10. The frequency dependence of the resistivity for a homo-ionized and untreated clay sample. The resistivity at 5 Hz (normalizing value) is 32 ohm metres for the untreated sample and 9 ohm metres for the treated sample.

CONCLUSIONS

These resistivity measurements should be useful in predicting a typical electrical section for the overburden in this region. Our measurements show that the clays have typical resistivities of 20 ohm metres and silts typically 70 ohm metres. The relationship between the *in situ* and laboratory measurements will require more investigation to provide a satisfactory explanation for the differences observed. In general, the frequency dependence of the clays appears to be small and of little significance to most EM techniques.

REFERENCES

Averill, S.A., and Thompson, I.
1981: Reverse Circulation Rotary Drilling and Deep Overburden Geochemical Sampling in Marter, Catherine, McElroy, Skead, Gauthier and Hearst Townships, District of Timiskaming; Ontario Geological Survey, Open File Report 5335.

Baker, C.L.
1981: Drift Thickness of the Magusi River, Larder Lake, Ramore, and Kirkland Lake Areas, and the Cochrane and Timiskaming Districts; Ontario Geological Survey, Maps P.2477-P.2480, Drift Thickness Series, Scale 1:50,000, Compilation 1979-1980.

Boissonneau, A.N.
1966: Glacial History of Northeastern Ontario - I. The Cochrane-Hearst Area, Canadian Journal of Earth Sciences, Volume 3, p.559-578.

Chan, H.T., and Kenny, C.T.
1973: Laboratory Investigation of the Permeability Rates of New Liskeard Varved Soil; Canadian Geotechnical Journal, Volume 10, p.453-472.

Desaulniers, D.E.
1982: Clayey Quaternary Deposits in Northern Ontario - A Review; Atomic Energy of Canada, TR-305

Dyck, A.V.
1974: Surficial Conductivity Mapping with the Airborne Input System; Canadian Institute of Mining and Metallurgy, Bulletin, Volume 67, p.104-109.

Gartner, J.F. *et al.*
1979: Northern Ontario Engineering Geology Terrain Study Data Base Maps; Ontario Geological Survey, Maps 5000-5093, scale 1:100,000.

Hughes, O.L.
1961: Preliminary Report on Borings Through Pleistocene Deposits, Cochrane District, Ontario; Geological Survey of Canada, Paper 61-16.

Ilkisik, O.M., Hsu, D.T., Redman, J.D., and Strangway, D.W.
1982: Surface Electromagnetic Mapping in Selected Positions of Northern Ontario; *in* Summary of Research 1981-1982, edited by E.G. Pye, Ontario Geological Survey, Miscellaneous Paper 103.

Mehran, M., and Arulanandan, K.
1977: Low Frequency Conductivity Dispersion in Clay-Water-Electrolyte Systems; Clays and Clay Minerals, Volume 25, p.39.

Nadler, A., and Frenkel, H.
1980: Determination of Soil Solution Electrical Conductivity from Bulk Soil Electrical Conductivity Measurements by the Four-Electrode Method; Soil Science Society of America, Journal, Volume 44.

Roy, K.K., and Elliot, H.M.
1980: Model Studies on Some Aspects of Resistivity and Membrane Polarization Behaviour Over a Layered Earth; Geophysical Prospecting, Volume 28, p.759-775.

Shainberg, L., Rhoades, J.D., and Prather, R.J.
1980: Effect of Exchangeable Sodium Percentage, Cation Exchange Capacity, and Soil Solution Concentration on Soil Electrical Conductivity; Soil Science Society of America, Journal, Volume 44.

Strangway, D.W., Ilkisik, O.M., and Redman, J.D.
1983: Surface Electromagnetic Mapping in Selected Positions of Northern Ontario; *in* Summary of Research 1982-1983, edited by E.G. Pye, Ontario Geological Survey, Miscellaneous Paper 113.