THE DELINEATION OF THE SUPERIOR-CHURCHILL TRANSITION ZONE IN THE CANADIAN SHIELD

DAVID RANKIN† and DOMINIC KAO†

ABSTRACT

A magnetotelluric survey was carried out in Southern Saskatchewan-Manitoba to determine the boundary between the Superior and Churchill provinces which lies under approximately 2 km of sediments.

Evidence is presented for the existence of a well defined boundary between the Superior province and a transition zone lying approximately along the 100°30'W meridian.

INTRODUCTION

The boundary between the Superior and Churchill provinces of the Canadian Shield is rather well established in the exposed region of northern Manitoba. It is of considerable interest to determine its southern extension which lies buried under the Cretaceous and Paleozoic sediments, in order to better understand the tectonic history of the crust in this region.

Since the Thompson nickel belt, one of the world's major nickel deposits, lies in this boundary region and substantial oil and gas deposits occur in the sediments overlying this general trend in the south, there is also considerable economic interest in this study.

In the magnetotelluric method the naturally occurring electromagnetic variational field provides the energy source which is used to probe the interior of the earth. Under the approximately valid assumption that this source is a plane wave, only four components of the field need to be measured, although a fifth component, i.e. the vertical magnetic field, is also measured. For a linear system the four components of the fields are related through the generalized impedances Z_{ij}.

$$E_x = Z_{xx}H_x + Z_{xy}H_y \qquad (1)$$

$$E_y = Z_{yx}H_x + Z_{yy}H_y \qquad (2)$$

where E_x, E_y, H_x and H_y are the components at each frequency and where x and y are two horizontal coordinates in a Cartesian coordinate system with z perpendicularly downward.

From the measurements made at the surface of the earth one can determine quantities R_{ij}, called the apparent resistivities which are defined

$$R_{ij} = .2T\left|Z_{ij}\right|^2 \qquad (3)$$

where T is the period at which the Z_{ij} are measured. For certain models of electrical structure one can evaluate the appropriate R_{ij} and use these numerical results to fit to measured field results in order to interpret the data. For a one-dimensional model, i.e. a layered earth, it is relatively trivial to compute the resistivities and thickness of the various layers.

For a two-dimensional earth which is frequently a reasonable approximation, one can construct models with lateral inhomogeneties within an otherwise layered earth and compute numerical results for the principal directions, i.e. parallel and perpendicular to the axis of the symmetry of the two-dimensional model, or equivalently parallel and perpendicular to strike. In this case

$$R_{\bar{i}\bar{j}} = .2T\left|Z_{\bar{i}\bar{j}}\right|^2 \qquad (4)$$

† Department of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2J1

where the bars over the $\bar{i}, \bar{j}$ correspond to these two principal directions and yield a maximum value for one direction and a minimum value for the other. It may be further noted that in these two directions,

$$R_{\bar{x}\bar{y}} = .2T\left|\frac{E_{\bar{x}}}{H_{\bar{y}}}\right|^2 \tag{5}$$

$$R_{\bar{y}\bar{x}} = .2T\left|\frac{E_{\bar{y}}}{H_{\bar{x}}}\right|^2 \tag{6}$$

$$R_{\bar{x}\bar{x}} = R_{\bar{y}\bar{y}} = 0 \quad . \tag{7}$$

The computational cost of even the most trivial three-dimensional numerical model is prohibitive with present technology and of little practical use for interpretation of the three-dimensional and probably non-linear real earth. However, the previously described mathematical model has some value in many cases where principal directions exist. In this case one cannot use equations (5) and (6) but must revert to equation (4) and write

$$R_{12} = .2T\left|Z_{\bar{x}\bar{y}}\right|^2 \tag{8}$$

$$R_{21} = .2T\left|Z_{\bar{y}\bar{x}}\right|^2 \tag{9}$$

and the bars refer to those directions $\bar{x}, \bar{y}$ which again maximize $Z_{\bar{x}\bar{y}}$ and minimize $Z_{\bar{y}\bar{x}}$, but for which

$$Z_{\bar{x}\bar{x}} \neq Z_{\bar{y}\bar{y}} \neq 0. \tag{10}$$

Procedure and Analysis

A magnetotelluric study was carried out along a line in Southern Saskatchewan and Manitoba. The locations of the recording sites are shown on the map in Figure (1). Data were recorded digitally on magnetic tape at the two separate digitizing rates, 40/sec. and 1.25/sec. Each record consisted of 4096 points for each of the five channels H_x, H_y, H_z, E_x and E_y representing the Cartesian components of the magnetic and electric variational fields. The z direction is vertically downward from the assumed horizontal surface of the earth. When the data are Fourier analyzed

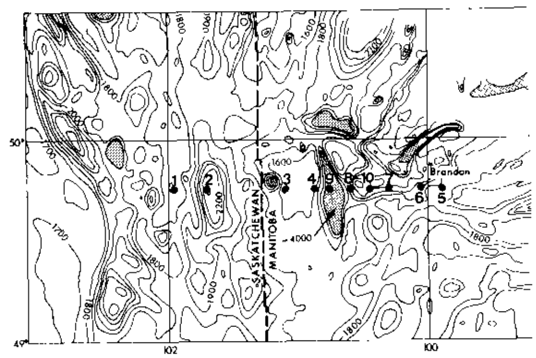

Fig. 1. Vertical magnetic intensity map. The location and number of the recording sites are shown. Map after Green et al. (1978).

and smoothed over period bands using a modified constant-Q filter, power and cross-power estimates are obtained in two bands spanning a period range between 0.5 and 1750 sec. with considerable overlap between them. The impedances Z_{ij} are obtained by what is in some sense least squares fitting by equations (1) and (2). The Z_{ij}'s thus obtained correspond to the measuring directions and can be rotated into any other direction by the appropriate orthogonal transformation operations, and in practice into the principle directions $\bar{x}, \bar{y}$ to obtain the $Z_{\bar{x}\bar{y}}$ and $Z_{\bar{y}\bar{x}}$ which appear in equations (8) and (9). These procedures are described in detail in Peeples and Rankin (1973) except that we now prefer to maximize $|Z_{\bar{x}\bar{y}}|$ directly rather than minimizing the diagonal tensor elements.

A minimum of ten good records were obtained at each station, which by definition are records for which the ordinary coherency between the E and orthogonal H components is larger than .9 over a considerable spectral range. As is well known the scatter in the apparent resistivities is considerably in excess of that which is to be expected from the measured coherencies. The effect of averaging the powers and cross-powers over ten records usually results in relatively stable values of the $R_{\bar{i}\bar{j}}$. The subject of ordinary and multiple coherencies has been extensively discussed by Reddy and Rankin (1974). From the multiple coherencies the confidence limits at, for example, the 95 percent confidence level can be computed.

Results and Interpretation

Figures (2), (3) and (4) display the results for stations 1, 9 and 5 respectively. These results are representative of the changing structure as one proceeds eastward along the profile. The solid lines are the calculated results based on the one-dimensional models for each of R_{12} and R_{21}, except at station 9 where no reasonable model can be calculated for R_{21}. The circles give the measured values, the error bars represent the 95% confidence intervals as computed from the multiple coherencies for the F-type distribution of R_{ij}. The validity of using the one-dimensional model calculations in a piecewise sense for continuous resistivity variations has been demonstrated by Rankin, Reddy and Schneider (1976) and the section shown in Figure (5) displays the results for the ten stations as calculated in this way. This section was put together using the model result based on R_{12} which does not differ significantly from the result which is obtained by taking the average of R_{12} and R_{21} for the western end of the profile. However for the stations east of 3 the averaged value requires a shallower depth to the lower boundary of the section than for the value of R_{12} alone. The dashed line indicates the depth for the averaged value. The details of the model can be adjusted to a certain extent by varying both conductivity and thickness in the appropriate sense and we have fitted the thickness of the first conducting layer in our model to agree with the thickness of the sediments as determined from geologic evidence. The general eastward thinning of the sediments is confirmed by our results.

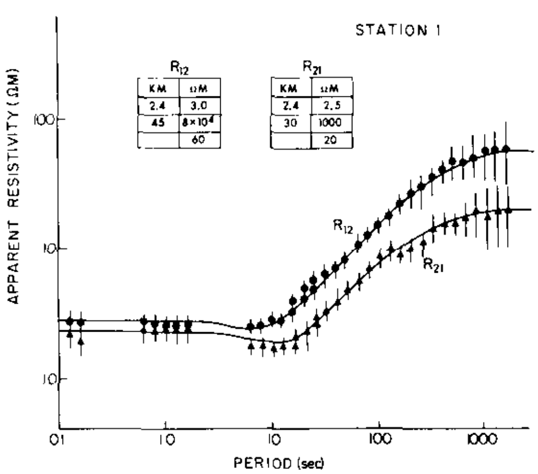

Fig. 2. The apparent resistivities in the principal directions are shown as circles and triangles. The solid lines correspond to the calculated results for the indicated one-dimensional models.

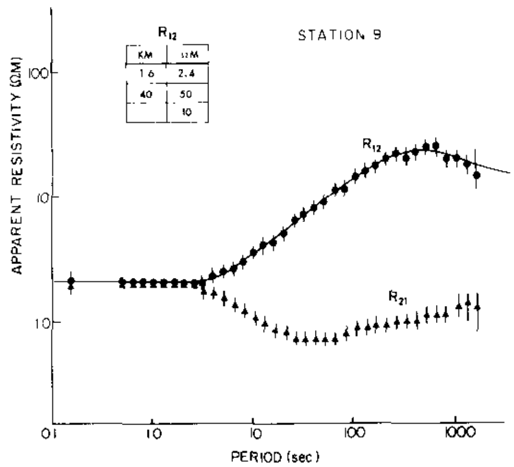

Fig. 3. The apparent resistivities in the principal directions are shown as circles and triangles. The solid line corresponds to the indicated one-dimensional model for R_{12} only.

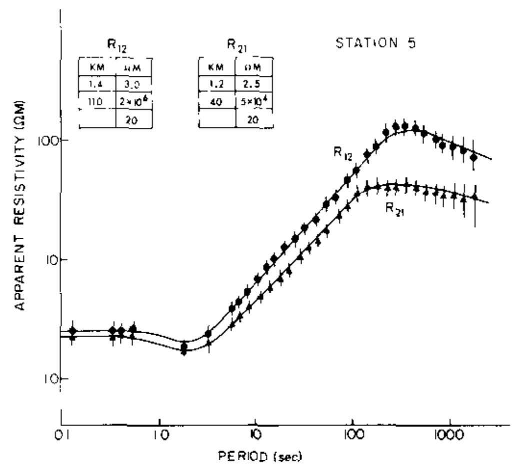

Fig. 4. The apparent resistivities in the principal directions are shown as circles and triangles. The solid lines correspond to the calculated results for the indicated one-dimensional models.

Further analysis of the high frequency data is being carried out with a view to providing a more detailed interpretation of the sedimentary section.

As pointed out above, it is also possible to adjust the thickness and resistivities of the basement rocks, however it is not possible to escape the conclusion that there are resistivity contrasts of two to four orders of magnitude as shown. The extremely large change of depth of the "resistivity" basement which occurs between stations 8 and 10 is similarly valid.

In the absence of any evidence of orogenic activity since the Archean, there is no reason to attribute the extremely high basement conductivity to any source other than mineralization. The most likely form is iron oxides. Sulfides of themselves are very highly resistive and the abundant salt solutions which are found in the near surface environment are unlikely to be present at depth.

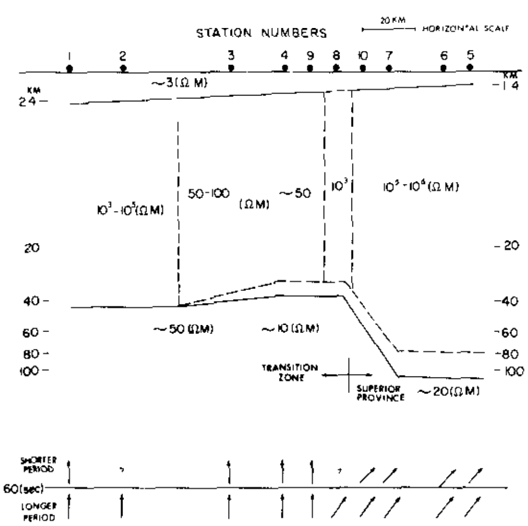

Fig. 5. The resistivity-depth cross-sections based on the one-dimensional models for R_{12} and on the average between R_{12} and Ra_{21}. The arrows show the principal directions at each station.

Extensive iron deposits are known to occur in the Superior province and the extremely large magnetic intensity anomaly under station 9 is evidence of highly concentrated magnetite. The anomalously high conductivity in this region suggests mineralization of a similar concentration.

The eastern edge of this conductivity anomaly is located approximately at the same place as the sudden thickening of the resistivity structure. There is a strong suggestion that this is a boundary between the Superior province and a transition zone which separates the Superior and Churchill provinces. Supporting evidence exists for this interpretation in the principal axis diagrams which appear in Figure (5). The arrows under stations 10, 7, 6 and 5 are normal in the sense that they coincide with the principal direction of conductivity which prevails over Alberta and most of Saskatchewan, i.e. 50°± 5°; the arrows pointing north, i.e. 0°± 5°, are anomalous. The upper row of arrows correspond to periods shorter than 60 sec. and the lower row longer than 60 sec. Under station 2 no good short period data is available whereas under station 8 there is no significlant anisotropy corresponding to periods shorter than 60 sec. The change-over in direction occurs at approximately the same location as that of the conductivity anomaly and the depth anomaly.

The depth to the lower conducting layer, approximately 40 km, at the western end of the profile and its thinning eastward is in rough correspondence with the Moho as obtained from seismic refraction results. However, it is not essential that the sudden deepening to ~100 km at the eastern boundary region also be related to the Moho. In fact this may well correspond to the so-called low velocity layer.

There is some indication in the seismic refraction results from the joint seismic program on the Churchill-Superior boundary (private communication) that there may be a discontinuity in Moho depth in approximately the same region. It should be borne in mind that the magnetotelluric and seismic methods do not necessarily map the same horizons; nevertheless, it is encouraging to note that both methods indicate anomalous behaviour in the same region. The results of the seismic reflection study of this area are not yet available.

A westward extension of this profile would be required in order to determine the boundary between the transition zone and the Churchill province. A more detailed analysis of the data is currently being carried out with a view to providing a more detailed interpretation of the sedimentary section.

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