Physics of the Earth and Planetary Interiors, 60 (1990) 169–194
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

The North American Central Plains conductivity anomaly and its correlation with gravity, magnetic, seismic, and heat flow data in Saskatchewan, Canada

Alan G. Jones and James A. Craven

Geological Survey of Canada, 1 Observatory Crescent, Ottawa, Ont. K1A 0Y3 (Canada)

(Received January 13, 1988; revision accepted June 6, 1989)

Jones, A.G. and Craven, J.A., 1990. The North American Central Plains conductivity anomaly and its correlation with gravity, magnetic, seismic, and heat flow data in Saskatchewan, Canada. Phys. Earth Planet. Inter., 60: 169–194.

The North American Central Plains conductivity anomaly (NACP) lies, virtually in its entirety, within the Trans-Hudson Orogen. Accordingly, should these two features prove to be contemporaneous, then the geometrical relationship between these two is of foremost importance to any evolutionary tectonic model proposed to explain the collision of the Superior and Churchill Provinces in the Hudsonian, and a model that does not include a mechanism for the generation of this anomaly is obviously untenable.

In order to map better the trend of the NACP in the Province of Saskatchewan, Canada, two magnetotelluric (MT) profiles were conducted over the NACP previously defined by magnetometer arrays and profiles. Data from these two profiles, along with an earlier MT profile just north of the U.S./Canadian border, suggest that the NACP is not a continuous feature, but rather that it exhibits a definite break at latitude 51° N. Other geophysical evidence examined herein is concordant with this characteristic. If a second MT anomaly mapped to the northwest of this break is, in fact, a manifestation of the *same* geological structure, then one possible interpretation is of a major NW–SE trending sinistral fault in the deep crust, previously undetected, with a movement of some 100–150 km along strike.

The MT data from the southernmost profile, after correction for static shift, are modelled in a 2D manner, and it is shown that the NACP is consistent with an arcuate structure in vertical section of high conductivity (> 2 S m^{-1}) beginning at a depth of 10 km centred on 103° W dipping down to the west reaching possibly the base of the crust. It is also shown that such an arcuate shape in section can explain an observed gravity high of 40 mgal. Such high conductivities cannot be explained in terms of connected fluids, as it would require implausibly high porosities (12–20%). A comprehensive interpretation of all the geophysical data would have to account for the observed characteristics of the anomalous region; which are, high electrical conductivity, positive density contrast, no magnetization, and high heat flow in the basement, in terms of a single causative body. One possible explanation is presented in terms of a zone of lithospheric weakness along which was emplaced low-density differentia from a mantle-derived body. An alternative explanation could be the phase transformation of obducted material into eclogite or serpentinite. However, difficulties exist with both of these explanations and further data are required.

1. Introduction

The enigmatic North American Central Plains conductivity anomaly (known by the acronym NACP), was first discovered in the late 1960s (Reitzel et al., 1970) by a geomagnetic depth sounding (GDS) array. Subsequent GDS studies (Camfield et al., 1970; Porath et al., 1970, 1971; Gough and Camfield, 1972; Alabi, 1974; Alabi et al., 1975; Camfield and Gough, 1975, 1977; Handa and Camfield, 1984; Gupta et al., 1985) suggested that the NACP is a linear feature, extending for over 2000 km. The NACP has been interpreted variously as: (i) associated with conductive minerals, such as graphite in schistose rocks in a belt mapped by Lidiak (1971), that lies within the

0031-9201/90/$03.50

Precambrian basement rocks beneath the Great Plains (Camfield et al., 1970; Gough and Camfield, 1972); (ii) due to the presence of saline water in fractured rocks (Handa and Camfield, 1984); and (iii) due to partial serpentinization of oceanic mafic and ultramafic rocks at the ridge crest of an ancient former oceanic crust (Gupta et al., 1985; see also Green et al., 1985).

Figure 1 illustrates the location of the NACP from the GDS experiments. Its location, and the correlation of its 'ends' with major Early Proterozoic zones of shearing and folding in the Precambian crust, suggested to Camfield and Gough (1977) that it may be the electromagnetic (EM) expression of a geosuture that formed during Early Proterozoic time due to the collision of two Archean plates. That deep-probing natural-source EM techniques can locate the boundaries of present, or former, plates was previously illustrated by Law and Riddihough (1971), which led Drury and Niblett (1980) to propose that EM methods were sensing the presence of porous (7–10% porosity) obducted oceanic crustal material saturated with highly saline fluid (sea water obducted with the oceanic sediments). This suggestion appears to have been given support by Kurtz et al.'s (1986) interpretation of their MT data on Vancouver Island that a conducting zone, coincident with a seismic reflection horizon (Green et al., 1987), is due to the presence of trapped saline fluids with porosity in the range 1.6–3.6%. (An alternative explanation for the conducting zone/seismic reflectivity has been offered by Hyndman (1988), who applies the suggestion of Jones (1987a) of the growth of an impermeable layer at the 400°C isotherm.)

The suggestion by Camfield and Gough (1977) of a plate boundary beneath the thick sedimentary Phanerozoic cover of the mid-North American continent was later united with the proposals for Proterozoic plate boundaries in the exposed Canadian Shield (Gibb and Walcott, 1971), and in

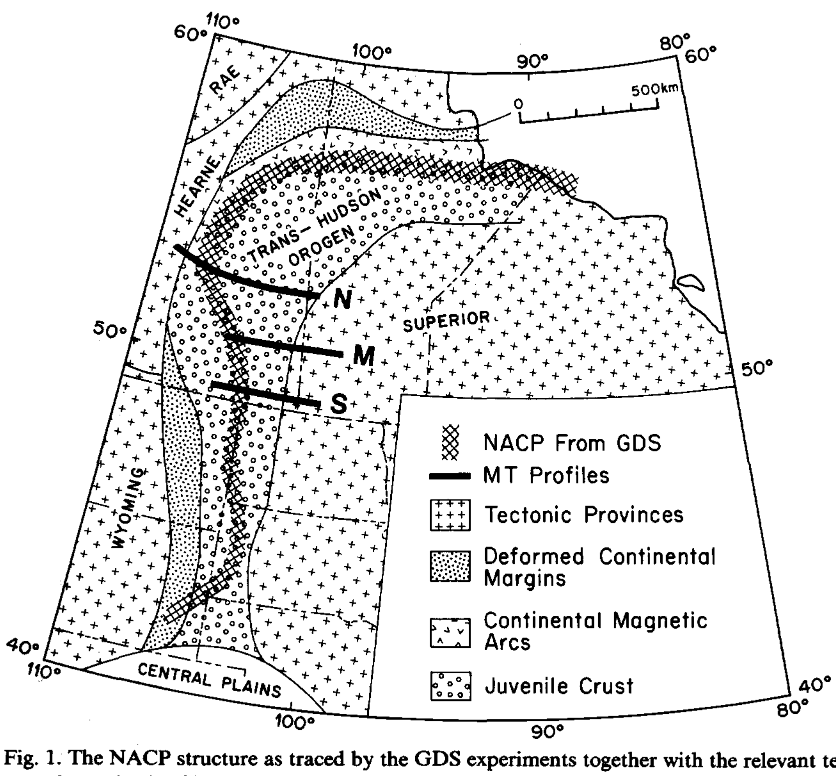

Fig. 1. The NACP structure as traced by the GDS experiments together with the relevant tectonic provinces; Rae, Hearne, (these two were formerly the Churchill province) Wyoming and Superior (from Hoffman 1988). It should be noted that throughout its entire length, the NACP resides within the postulated location of the Trans-Hudson Orogen.

southern Wyoming (Hills et al., 1975), into a single North American Hudsonian age suture zone, since termed the Trans-Hudson Orogen (THO: Hoffman, 1981). Where exposed in the Canadian Shield, the THO consists of alternating belts of volcanic rocks with associated granodiorite–tonalite intrusions and volcanogenic sedimentary rocks (T.M. Gordon and E. Froese, personal communication).

Extension of the Early Proterozoic THO, and associated suture zones, beneath the Palaeozoic sediments of the Williston Basin (WB) has since been confirmed by other evidence, principally interpretations of the Bouger gravity and magnetic compilations (Green et al., 1979, 1985; Dutch, 1983; Klasner and King, 1986; Thomas et al., 1987), but also by geochronological evidence from basement-reaching boreholes (Peterman, 1981).

The THO is interpreted by some to extend for over 5000 km, from central U.S. in the south, northward into Canada and there eastwards to Greenland. It is the largest coherently preserved and exposed Early Proterozoic orogenic belt in the world (Van Schmus et al., 1987). In central North America, it separates the Wyoming–Churchill (or 'Wyoming–Hearne' according to Hoffman (1988)) Archean province from the Superior province (Fig. 1). Formation of magmatic rocks within the THO occurred between 1910 Ma and 1830 Ma (Van Schmus et al., 1987).

The NACP should be considered a significant and important element of any evolutionary tectonic model for formation of the THO. Green et al. (1985) suggested that the anomaly 'is caused by buried slices of hydrated oceanic-type crustal material' which 'might also explain the spatially related seismic low-velocity zones'. However, detailed analyses of the refraction data (Morel-à-l'Huissier et al., 1987) were inconclusive concerning the relationship of the seismic low velocity zones to the NACP mapped by Jones and Savage (1986). It should be noted that 'hydrated' minerals are not intrinsically conducting (Olhoeft, 1981); it is the fluids released by dehydration reactions that cause the high conductivity.

Klasner and King (1986), in their study of the nature of the Precambrian basement rocks of the Dakotas, considered the NACP to be an important tectonic feature and used it to correlate the buried part of the THO in the Dakotas with the exposed Precambrian terrane of the cratons. They interpret their age data as concurring with those of Peterman (1981) in revealing Early Proterozoic rocks, mainly gneisses of unknown origin, in the western Dakotas but that, as yet, there is no evidence for oceanic crust there. In their lithotectonic subterrane IVA (see Fig. 3 and Table 1 of Klasner and King (1986)), defined by Precambrian chip samples and drill core in the northern part of North Dakota taken mostly at a longitude of 103° W (i.e. the 'new' location of the NACP as delineated by Jones and Savage (1986) and as modelled below), the rocks are predominantly granodioritic to tonalitic gneiss.

In this manuscript, we will illustrate the results obtained from three MT profiles recently conducted in the Province of Saskatchewan, Canada, and correlate this information in both a qualitative and a quantitative manner with other geophysical data for this region. A 2D model will be presented that satisfies the observed MT responses on the southernmost profile, and the correlation of this anomaly with gravity, aeromagnetic and geothermal data will be shown. Consideration will be given to the NACP at the Black Hills, and the GDS data of Porath et al. (1971), modelled in terms of a shallow highly conducting arcuate structure, will be presented. Finally, two possible tectonic interpretations are given for the NACP anomaly — one in terms of material derived from the mantle since the onset of subsidence of the Williston Basin (400 Ma), and the other in terms of phase-transformed obducted material during the THO (1.8 Ga). However, difficulties exist with both of these explanations and further data are required to elucidate the reason for the NACP anomaly.

2. Previous electromagnetic results

Figure 1 illustrates the location of the NACP determined from the GDS experiments, together with the recent tectonic map of North America presented by Hoffman (1988). It should be noted that the Churchill Province has been subdivided into the Hearne and Rae Provinces by Hoffman.

Primarily because of the large separation of the GDS stations, typically 150 km, this initial location of the NACP is crude. An MT survey (Jones and Savage, 1986) conducted just north of the U.S./Canadian border (Profile *S* in Figs. 1 and 2) provides more detailed control and indicates that the initial location was in error at that latitude by approximately 75 km, or half a GDS station spacing. Such a location error would appear to imply that the NACP structure should pass to the *east* of GDS station QUA (Fig. 2), not to the *west* of it, as interpreted by Alabi (1974) and Alabi, Camfield and Gough (1975; referred to hereafter as ACG). This apparent discrepancy is easily explainable when one realizes that above an anomaly caused by a zone of higher electrical conductivity, the vertical component of the time-varying magnetic field, H_z, is zero or close to zero, whereas the perpendicular horizontal component, H_y (the coordinate system used throughout is x north and y east), is maximally enhanced. Thus, close to an anomaly it is extremely difficult to determine on which side of the station the anomaly lies, especially when the data used, as were those of ACG, are contaminated by source-field effects. Furthermore, close examination of the data of ACG reveals that the anomaly is not well located in this region. Figure 3 (reproduced in part from Fig. 8 of ACG) clearly indicates that the maximum of the real part of the H_y component lies to the *east* of GDS station QUA (Fig. 2). Moreover, the ENE-pointing quadrature induction arrow, derived by ACG (1975, Fig. 9), for station QUA at a period of 68.3 min clearly indicates that the NACP passes to the *east* of that station. For stations south of QUA, ACG (1975, p. 828) comment that 'The quadrature-phase induction arrows proved unexpectedly successful in showing the presence of the NACP conductor along the whole length of the array, by pointing to it from both sides' — why

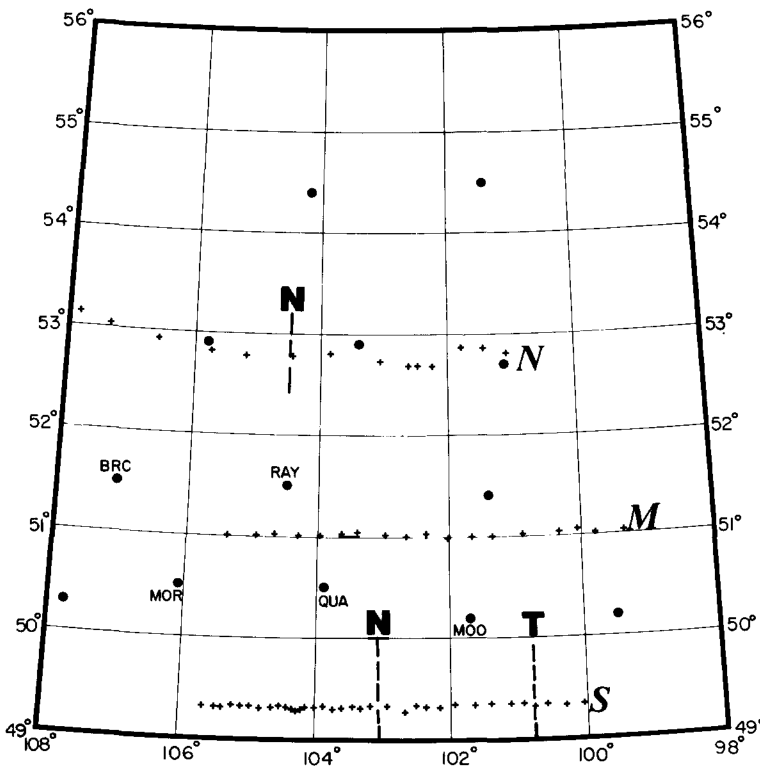

Fig. 2. Positions of the three MT profiles; *S*: South; *M*: Mid; and *N*: North Saskatchewan respectively. N and T refer to the location of the NACP and TOBE anomalies respectively as identified from the MT data. Also shown are the locations of some of the GDS sites of Alabi et al. (1975) referred to in the text; BRC, RAY, MOR, QUA, and MOO.

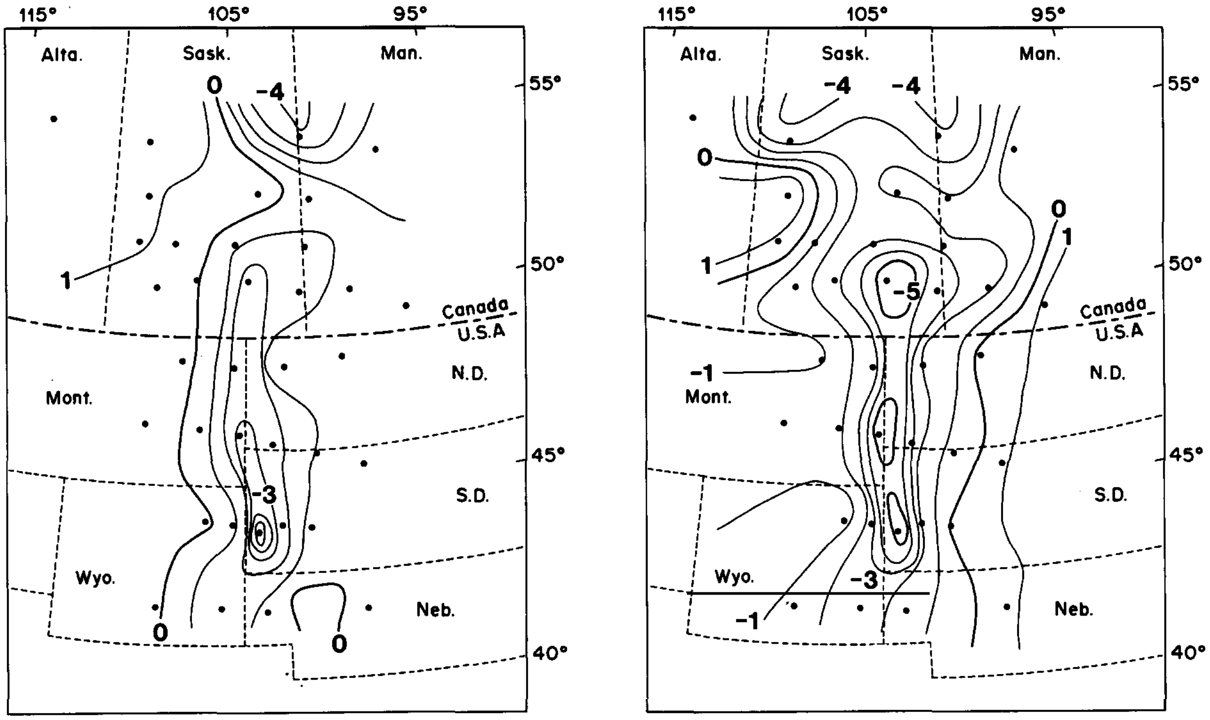

Fig. 3. Maps of the residual Fourier cosine coefficients of the eastward horizontal component, H_y, at periods of 68 and 170 min observed by Alabi et al. (1975) for one particular event. It should be noted that the maximum lies to the *east* of station QUA (Fig. 2), not to the west as concluded by Alabi et al. (1975).

this should not be accepted for QUA is not stated.

One other noteworthy feature in the GDS work of Alabi (1974) and ACG is that the *character* of the NACP changes markedly north of approximately 50° N. Figure 4 (reproduced from Fig. 6 of ACG) shows a concentration of contour lines south of the U.S./Canadian border which is in stark contrast to the dispersed attitude of the contours north of the border. This change in character is also evident in the Fourier transform maps determined from a magnetic event with a more uniform source-field (Fig. 7 of ACG), although the very existence of the NACP conductor is exhibited by the reversal in the vertical magnetic field components between GDS stations RAY and BRC and stations MOO and MOR of Fig. 2 (Alabi, 1974). Accordingly, source-effects cannot explain this along-strike variation.

This variation in character may indicate that the NACP dips more steeply to greater depth to the north, or it may infer that the NACP is not a continuous feature but rather that it is discontinuous, and that the contours of the map of Fig. 4 illustrate one of the breaks. This latter explanation, that the NACP is a discontinuous structure, was suggested recently by Thomas et al. (1987) in their interpretation of the horizontal gravity gradient map of central North America. They propose that the NACP 'could be the expression of a series of discontinuous, perhaps en echelon, conductors that have not been resolved by the coarse spacing of magnetometer stations'. We concur with this conclusion and will reinforce it by the arguments presented in this manuscript.

3. Magnetotelluric observations

All MT responses reported herein were obtained using PHOENIX© Real-Time MT data acquisition systems. Such a system records the time-varying MT fields in the period range

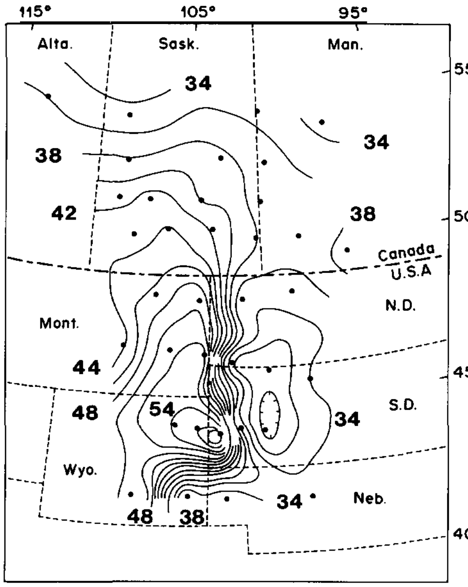

Fig. 4. Map of the Fourier transform phase of the vertical magnetic component, H_z, at a period of 68.3 min observed by Alabi et al. (1975) for one particular event. The concentration of the contours to the south of the U.S./Canadian border in contrast to their dispersed nature to the north should be noted.

0.0026–1820 s (frequency range of 384–0.0055 Hz), and derives and displays the MT response functions in real-time in the field. All data are of exceptional quality with standard errors generally less than a few percent.

Data for the southern profile (profile S, Figs. 1 and 2) were recorded during 1984 and 1985 by PHOENIX Geophysics of Toronto for Pan-Canadian Petroleum Limited of Calgary. At all thirty-five sites, seven-component MT measurements were made thus facilitating remote-reference processing (Gamble et al., 1978) of the data. Jones and Savage (1986) discussed the main features of these data, and illustrated that the NACP structure is some 75 km east of the location shown in Fig. 1 at the latitude of the U.S./Canadian border. Jones (1988a), analysing the high frequency portions (frequencies above 0.1 Hz) of these data, showed the correspondence between the 1D models and the well-log information, and presented a technique for static shift correction of MT data from a sedimentary-basin environment.

Data for the two other profiles (M and N, Figs. 1 and 2) were recorded during 1987 with the Geological Survey of Canada's PHOENIX system. At all thirty-four sites, sixteen along profile N and eighteen along profile M, ten-component MT measurements were made. This two station redundancy at each location enables us either (i) to choose those estimates of the responses that were least noise contaminated and exhibited least scatter for interpretation and modelling, or (ii) to combine the estimates from the two stations in a weighted manner (see, for example, Craven and Jones, 1989). In this report, we adopt the former of these techniques for profiles M and N.

Data recorded on all three profiles were re-edited to reject cross-spectral averages that contaminated the cumulative average. The data for profile S have been static shift corrected (Jones, 1988a), but those for profiles M and N have yet to be corrected in this manner. Accordingly, in this manuscript in order to avoid static shift effects, for these profiles we will consider the qualitative variation of phases of the MT impedance off-diagonal elements Z_{xy} and Z_{yx} alone, and quantitatively interpret the magnitudes and phases of those elements for profile S only. The data were all rotated into the geographical coordinate system, with the x-direction being true north and the y-direction true east, which is particularly appropriate for these profiles in that the dominant structural and geophysical strike of the region is north–south and that the dominant rotation direction of the MT impedances (defined by the usual Swift (1967) criterion) is within 5° of N–S. In this coordinate system, the Z_{xy} estimates represent the *E-polarization* mode of induction (i.e. north–south electric current flow) in the 2D anomalies, whereas the Z_{yx} ones are the *B-polarization* mode (east–west current flow).

Pseudo-sections of the phase responses observed along the three profiles are illustrated in Fig. 5. The phases range from 10° to 70°, and the ϕ_{yx} phases have been rotated into the first quadrant, from the third quadrant, for direct comparison with ϕ_{xy}. On these figures blue signifies a low phase lead of the horizontal electric field component over the perpendicular horizontal magnetic field component, which is indicative of a transition from shallow conductive to deeper resistive zones, whereas red signifies a high phase lead, and

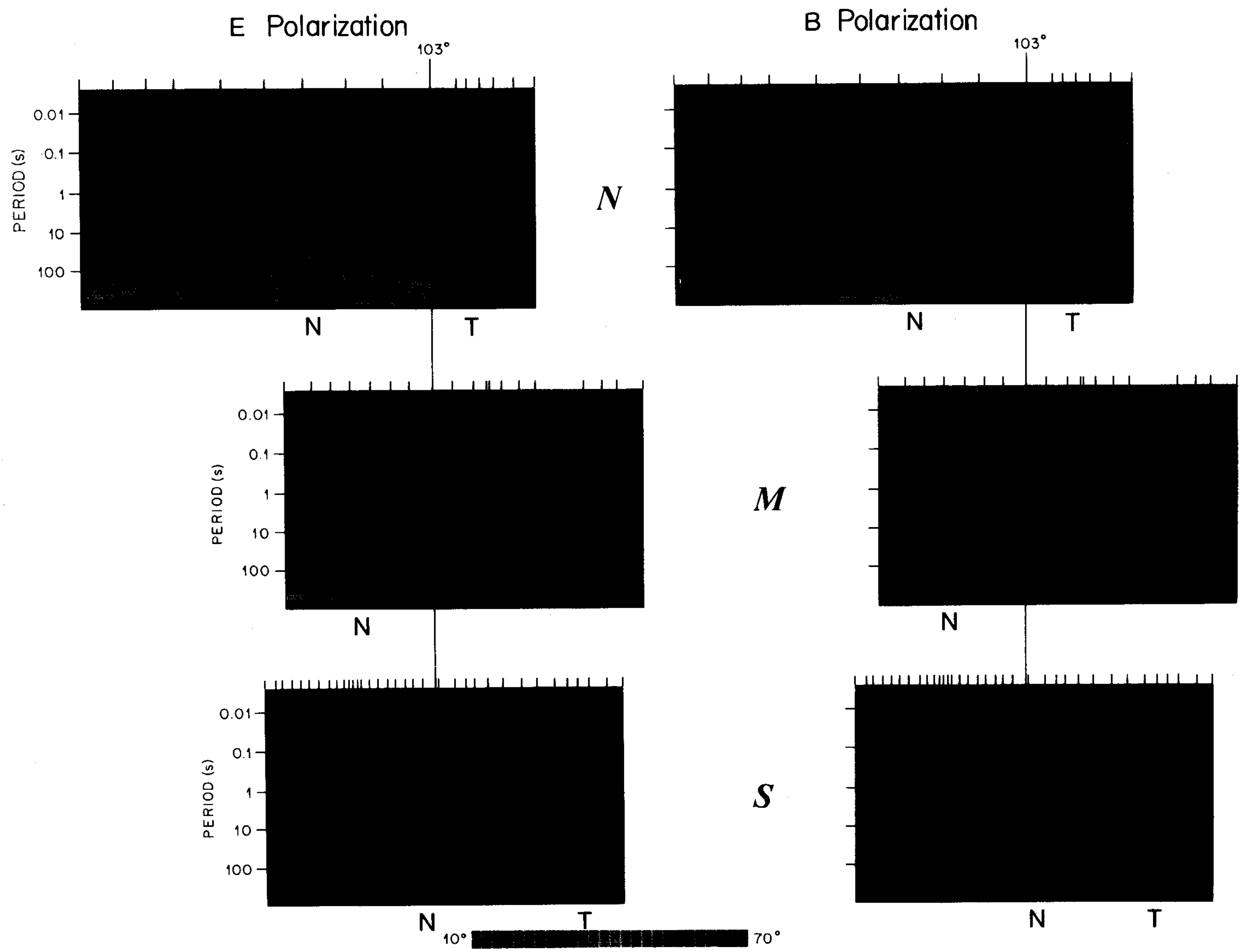

Fig. 5. Pseudo-sections of the phase of the *E-polarization* (left side) and *B-polarization* responses observed along the three profiles: top, *N*; middle, *M*; bottom, *S*. The MT site locations are marked by ticks above each pseudosection, as is the location of longitude 103° W. Also identified are the locations of the NACP (N) and TOBE (T) anomalies in the MT data. For profile *S*, there are no evident phase effects in the *B-polarization* data due to either the NACP or TOBE anomalies. For profile *M*, the NACP phase anomaly in the *E-polarization* data is small ($<10°$) compared to on the other two profiles ($>35°$).

accordingly the reverse situation. The 45° contour is illustrated in dark-yellow. The conjectured locations of the NACP and the TOBE (ThOmpson BElt, see Jones and Savage (1986)) anomalies on the profiles are indicated by the boldfaced letters **N** and **T** respectively. Noteworthy features of these pseudo-sections are discussed below.

3.1. Profile S*: South Saskatchewan*

The depth of the base of a conducting zone can be given approximately by the Niblett–Bostick depth (Niblett and Sayn-Wittgenstein, 1960; Bostick, 1977; Jones, 1983a) for the apparent resistivity at the period where the phase response crosses from above 45° to below 45°. For profile S, this phase crossing occurs at a period of ~ 5 s to the west, and shallows to a shorter period of ~ 3.5 s to the east (Fig. 5, bottom). Accordingly, the base of the upper conductive layer — associated mainly with the top of the Lower Palaeozoic sequences of the WB (Jones, 1988a) — occurs at depths of approximately 1450 m and 1250 m respectively. The NACP and TOBE anomalies are clearly observable in the ϕ_{xy} phases, but not in the ϕ_{yx} phases, which is a manifestation of the horizontal EM 'thinness' of the two anomalies; that is, currents flowing along the y axis (i.e. east–west) are not affected sufficiently for these N–S trending anomalies to be seen at the ground surface. These MT responses are modelled quantitatively, with a 2D model, below, and a combined geophysical interpretation of the NACP structure with the gravity, magnetics and heat flow observed in this region is discussed.

3.2. Profile M*: Mid-Saskatchewan*

Along this profile (Fig. 5, middle) the conducting sediments (not *all* sediments but those of higher electrical conductivity — see above) are shallower, as evidenced by the shorter period of 2 s for their 'base'; which corresponds to a Niblett–Bostick depth of approximately 750 m. The phase anomaly just west of longitude 100° W is due to that particular site being located directly on top of the conducting shales of the Upper Cretaceous Faval Formation. For the basement structure, there is no strong indication in either the ϕ_{xy} or the ϕ_{yx} phases for either the NACP or the TOBE features. By extrapolating the trends of the potential field data (see Section 4), it is possible to infer that the minor phase anomalies in the ϕ_{xy} data, indicated by **N**, may be associated with this feature. However, this phase anomaly is small, of less than ~ 10°, compared to over 30° on profiles *S* and *N*. We interpret this as an 'edge effect' due to non-continuity of the NACP structure. One feature that is discernible in the contour plots is the lateral variation in the resistivity of the basement; to the east, the basement is more resistive than to the west, as demonstrated by the higher phases (darker shades of blue).

3.3. Profile N*: North Saskatchewan*

On the *N*-Saskatchewan profile, the conducting sediments are well mapped as they thin from west (7 s) to east (0.05 s); Niblett–Bostick depths of approximately 1200 m and 400 m respectively. Also apparent in the contour plots is the lateral variation in the resistivity of the basement, with the more resistive strata occurring to the east, as profile *M*. On these pseudo-sections it is again possible to discern two anomalies in the phases, labelled **N** and **T**. As with profile *S*, the anomaly that can be associated with the NACP (**N**) has a phase indicator in ϕ_{xy} only, not in ϕ_{yx} and thus the NACP is here also electromagnetically 'thin'. For the TOBE feature (**T**) however, there is a strong response in both phases which indicates that, at this latitude, the TOBE structure can sufficiently affect both the parallel (*E-polarization*) and perpendicular (*B-polarization*) currents to an extent that is observable on the surface. This variation along strike of the TOBE is also evident in the gravity data (see below and Fig. 6). Preliminary 1D modelling of the MT response observed at this location indicates that the top of the TOBE anomaly is at a depth of some 13.5 ± 0.5 km which clearly cannot be associated with the exposed rocks of the Thompson Nickel Belt but must be a deeper feature.

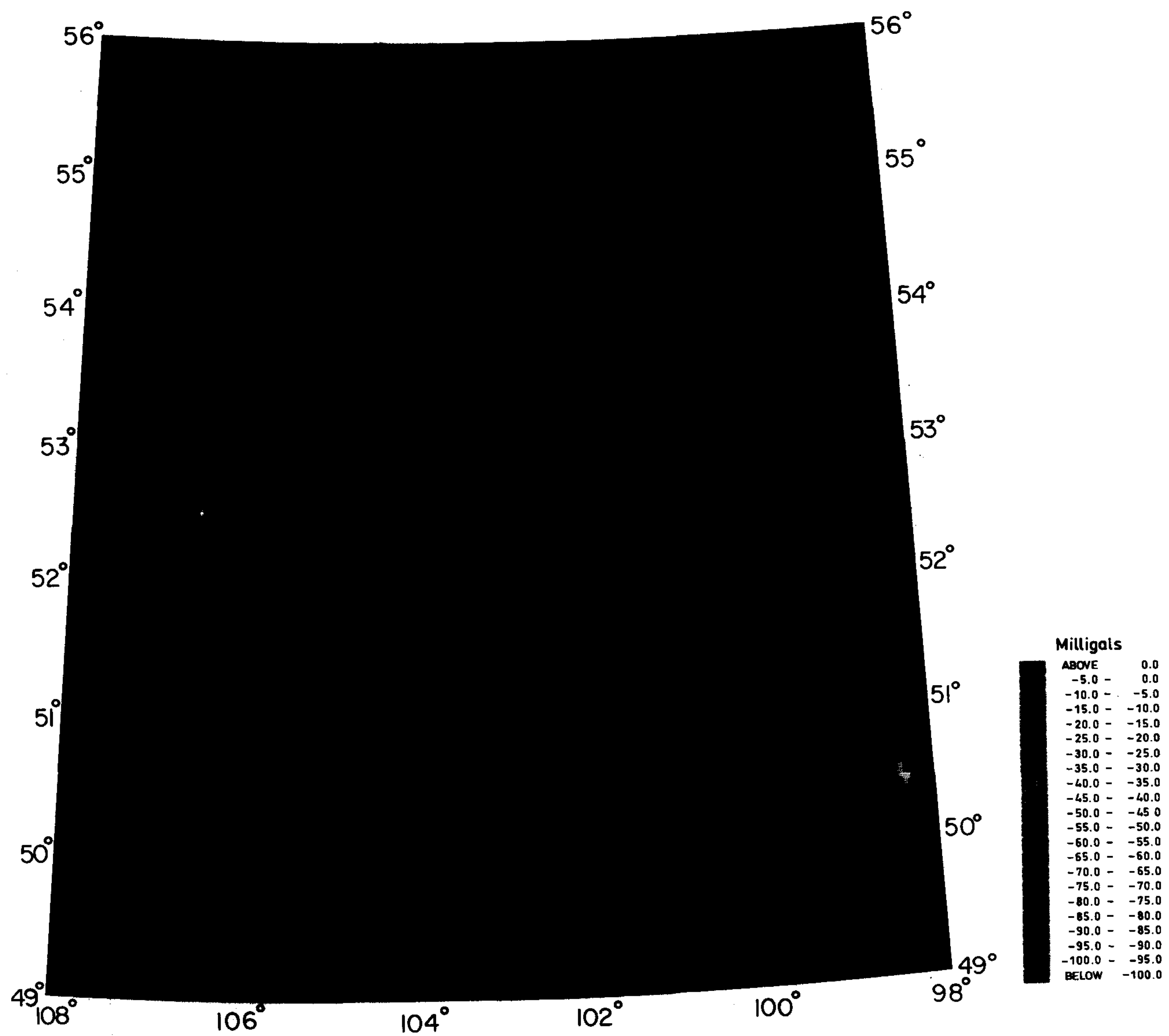

Fig. 6. Gravity pattern observed in southern and central Saskatchewan. Also shown are the locations of the MT profiles and the identified locations of the NACP (N) and TOBE (T) structures.

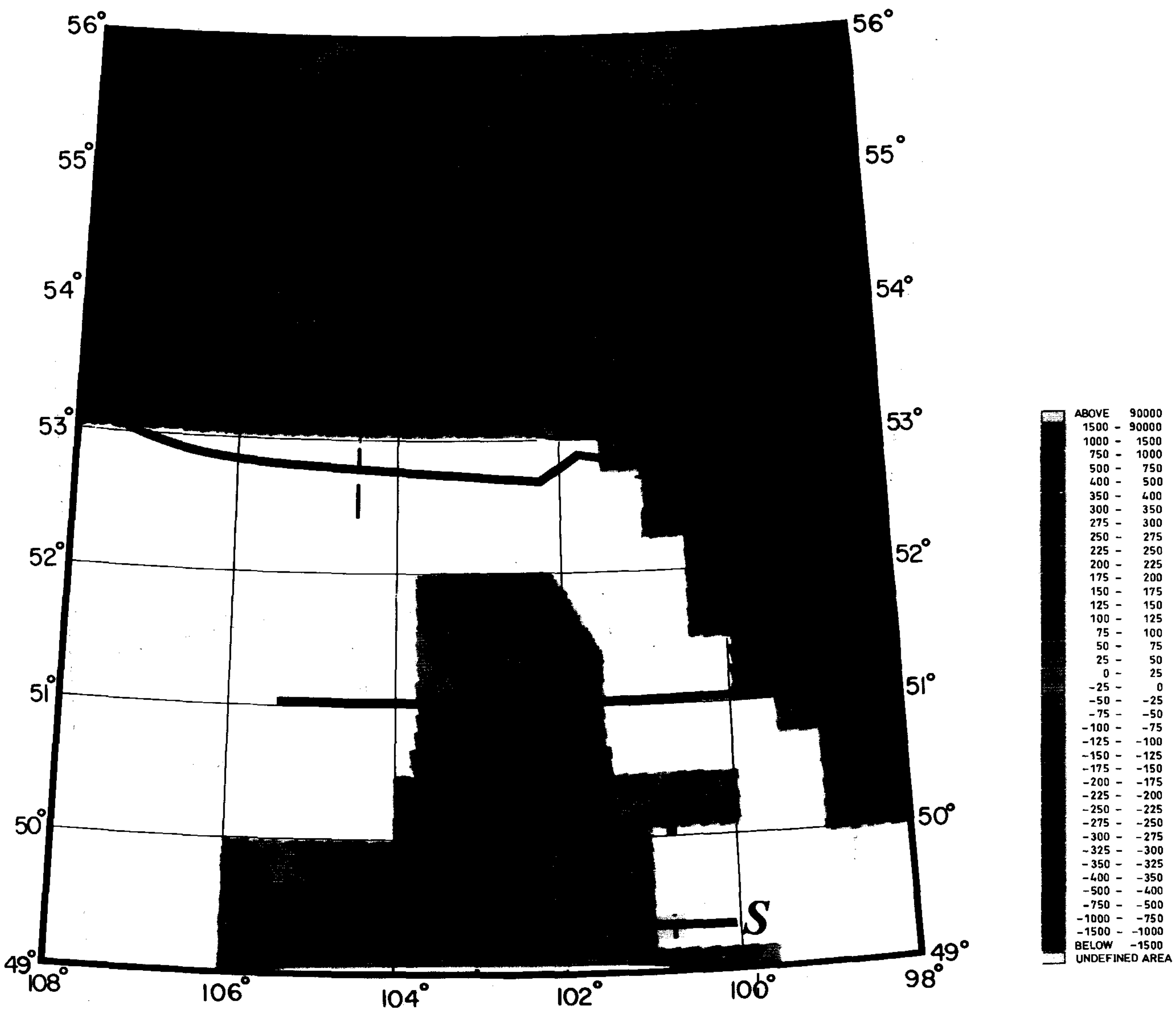

Fig. 7. Static total magnetic field pattern observed in southern and central Saskatchewan from the GSC database. Also shown are the locations of the MT profiles and the identified locations of the NACP (N) and TOBE (T) structures.

4. Qualitative correlation with other geophysical observations

In this section we describe other geophysical observations, i.e. gravity, magnetics, heat flow and seismic along the THO, and compare them with the MT data in a qualitative sense. A quantitative 2D modelling of the MT responses observed along profile *S*, and a combined geophysical interpretation of the available geophysical data, is given in the following section.

4.1. Gravity data

Figure 6 is a Bouguer gravity anomaly map of the region with the three MT profiles marked. Apparent in the gravity field is the high that coincides exactly with the NACP structure at the latitude of the *S* profile. This high, of approximately 40 mgals relative to the 'regional', trends slightly west of due north, and terminates at the latitude of profile *M*. Along profile *N* there is no distinctive anomaly pattern that can be associated with the ϕ_{xy} phase anomaly identified as the NACP. There is a broad high in approximately the correct location, but nothing as definitive as for profile *S*. For the TOBE structure, there is a coincident gravity high on profile *S* that can be traced northwards across profile *M*, at the location of the minor ϕ_{xy} phase anomaly, and then northeastwards across profile *N* at its easternmost extremity. At this northern location, both the EM and gravity signatures are much more enhanced than those to the south.

4.2. Magnetic data

Figure 7 illustrates the available aeromagnetic data in the GSC database for the region. A more complete map, compiled and hand-contoured from a variety of sources of varying quality, is given in Green et al. (1985). The contour interval of Green et al.'s map is 200 mgals, and thus some of the fine structures discernible in Fig. 7 are not visible on Green et al.'s map. It is apparent, however, from both maps that the NACP of profile *N* does not correlate with the magnetic low (dark blue contour at ~106.5° W) which can be extrapolated to the exposed rocks of the Canadian Shield, but rather to its east between two magnetic high zones (red contours). Although the NACP is very crudely located by the widely-spaced magnetometer sites some 400 km further north of profile *N* on the exposed part of the Trans-Hudson orogen by Handa and Camfield (1984), there is here also the indication that the NACP correlates with a magnetic quiet zone, in this case the Reindeer-South Indian Lakes belt; a correlation that was earlier noted by Green et al. (1985). It should be noted that also along profile *S* the NACP correlates with a magnetic quiet zone (yellow and green contours).

4.3. Heat flow

The heat flow below the Palaeozoic surface for the region is illustrated in Fig. 8 (taken from Majorowicz et al. (1986)). Strong anomalies, of greater than 100 mW m^{-2}, are derived for locations east of Weyburn (to the southeast of Regina), and to the north-west and west of Regina, from the strong geothermal gradients, of greater than 25°C km^{-1}. Elevated temperatures, of 70°C at the 2 km depth level and up to 100°C at the 3 km

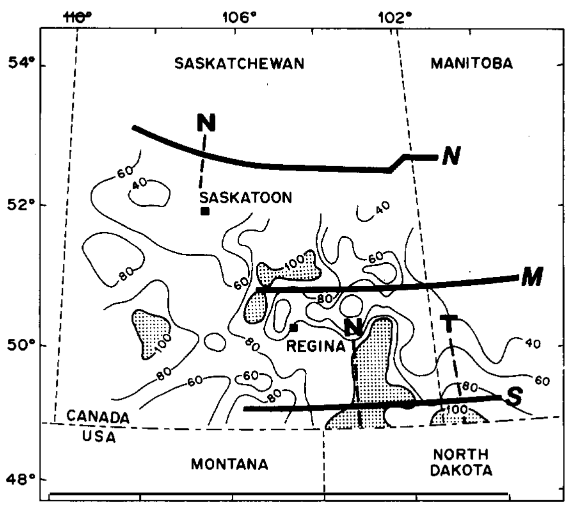

Fig. 8. Heat flow pattern, in mW m^{-2}, observed in southern and central Saskatchewan (redrawn from Majorowicz et al., 1986). Also shown are the locations of the MT profiles and the identified locations of the NACP (N) and TOBE (T) structures.

depth level, are extrapolated from these data. This makes the top of the Precambrian basement hotter here than anywhere else in Saskatchewan. Majorowicz et al. (1986) concluded that the blanketing effect of the sediments can only partially explain the Weyburn temperature high, and that as well as a hydrodynamic effect, there may also be a contribution from a high-temperature region in the crystalline crust. This is discussed further below.

It is apparent from Fig. 8 that a north–south trending geothermal anomaly occurs at the same location of the NACP at the latitude of profile *S*. This trend in the anomaly ends rather abruptly at ~ 50.5° N, at which the trend in the anomaly becomes northwest across profile *M*. There are insufficient data to know if there is a geothermal anomaly on profile *N* associated with the NACP.

4.4. Seismology

A comprehensive seismic refraction study was carried out across the THO/WB by the Canadian COCRUST (Consortium for Crustal Reconnaissance Using Seismic Techniques) group, and all the data were presented and comprehensively modelled by Morel-à-l'Huissier et al. (1987). The NACP was one of the primary targets of this experiment, but as a consequence of the unfortunate erroneous prior location of the NACP from the GDS work (see above) at the latitude of the seismic profile, there was no sampling of the NACP anomaly along its strike. The seismic properties of the crust beneath the nearest strike line (their line D) some 75 km to the west of the NACP were modelled as exhibiting virtually no lateral variation, and no unusual velocity effects. In contrast, a strike line just 50 km further to the west (line E), which was intended to sample the NACP, exhibits two crustal low-velocity zones, one at 10 km and the other at 22 km, at its southern extremity, but these pinch out some 120 km north of the U.S./Canadian border, near latitude 51.5° N.

In their paper, ACG considered the known earthquakes for the region with reference to the NACP, and concluded that there was a correlation, albeit tentative. The epicentral locations of the earthquakes recorded up to the end of 1988 for this region are illustrated in Fig. 9. The two largest were historical events from the last century on the order of magnitude 5 (stars), both located approximately within the WB but with very large uncertainty as to their actual position. All other recorded events occurred after 1968 and are located to within a precision of 0.2° (J.A. Drysdale, personal communication). ACG and Camfield and Gough (1977) refer to earthquakes of magnitude 3–4 in the zone 49–49.5° N, 104–106° W. However, this area is the location of the Regina-Hummingbird Trough and there is the possibility that these events are all associated with slumping/collapsing of solution cavities. Horner et al. (1973), however, argue against slumping for at least one of these, and prefer a deep crustal depth. The two tight clusters of magnitude 3–4, one of thirteen earthquakes at 50.75° N, 102° W and the other of six earthquakes at 52.1° N, 106.9° W, are believed to be induced by potash mining (Gendzwill et al., 1982; Drysdale et al., 1985; Drysdale and Horner, 1986). For most of the other seismic events in Saskatchewan, there is insufficient depth control to be certain of whether

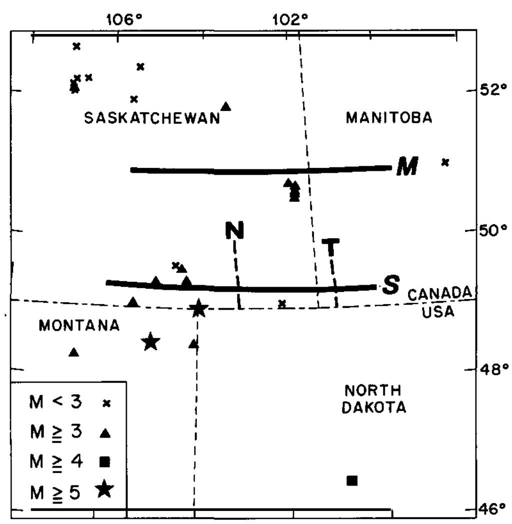

Fig. 9. Earthquake epicentres for central North America. Also shown are the locations of two of the MT profiles and the identified locations of the NACP (N) and TOBE (T) structures.

they occurred in the basement or the sediments. However, the small events, of less than magnitude 3, close to Saskatoon are well located in depth by the University of Saskatchewan seismic array, and some of these are definitely below the sediments and are within the crust. Given the paucity of events in this region one must conclude that the earthquake database is far too sparse for any quantitative, or even qualitative, inferences to be made.

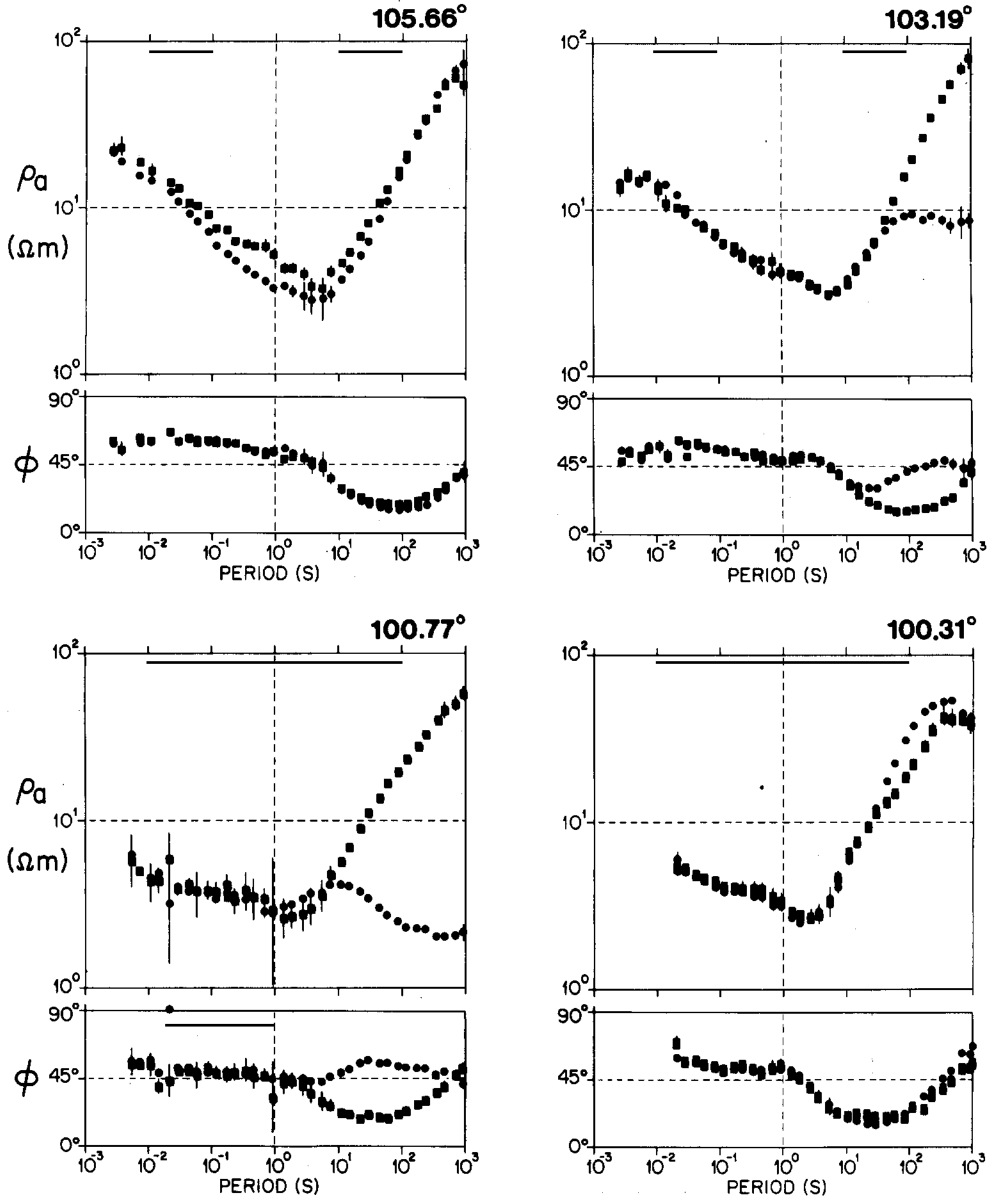

Fig. 10. Static shift corrected apparent resistivities of the *E-polarization* (dots) and *B-polarization* (squares) apparent resistivities and phases observed at four locations along the southernmost (S) profile. At either ends of the profile, i.e. at the sites at 105.66° and at 100.31°, the data are virtually 1D. The NACP structure is below the site at 103.19°, and the TOBE structure is below the site at 100.77°. It should be noted that the *B-polarization* data are insensitive to both the NACP and TOBE structures.

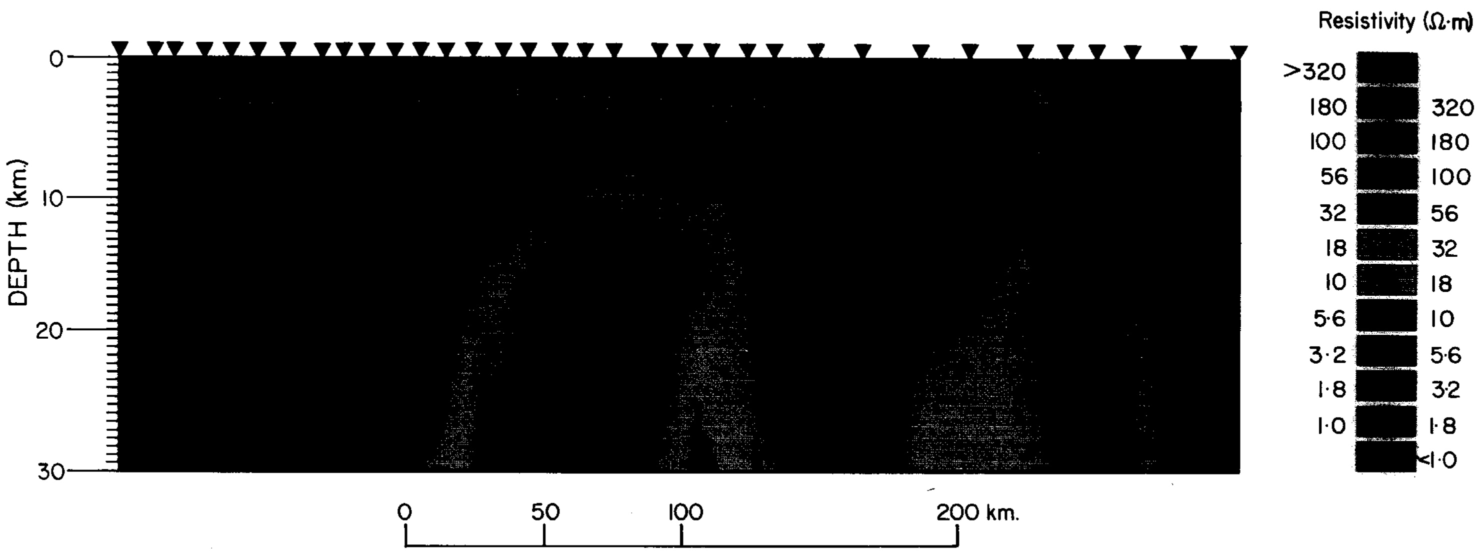

Fig. 11. Pseudo 2D section compilation of the 1D Occam (Constable et al., 1987) inversions of the *E-polarization* apparent resistivities and their phases observed at the 35 locations along the southernmost (*S*) profile. The two anomalies are the NACP and the TOBE structures.

5. Modelling of MT responses from profile *S*

This section presents the 1D and 2D modelling undertaken on the static shift corrected responses (see Jones, 1988a). The phases of the *E-polarization* and *B-polarization* responses are illustrated in Fig. 5, and the static shift corrected apparent resistivities at four locations along the profile are illustrated in Fig. 10. Two of these four locations are at either extremity of profile *S*, and the data from both are 1D in that the two modes of polarization give the same response at each site. In contrast, the station at 103.19° is directly over the NACP, and 100.77° over the TOBE, anomalies, and the data from both exhibit 2D effects. However, note that the *B-polarization* apparent resistivities and phases exhibit no laterally varying structure.

5.1. 1D inversion

Using the 'Occam' algorithm that inverts the responses to a least structure model in a $\delta\sigma/\delta z$ sense (Constable et al., 1987), the *E-polarization* responses from the 35 locations on profile *S* were inverted. These models are compiled and presented in pseudo 2D section format, with linear depth on the ordinate, in Fig. 11. These inversions are *least structure* in a gradient sense, and therefore any structure that is apparent in them must exist. However, one must beware of interpreting the *E-polarization* responses off the flank of a 2D body because of 'false conducting layers' (Berdichevsky and Dmitriev, 1976; Jones, 1988b). Also, it must be remembered that the *B-polarization* data are totally insensitive to the structure generating the anomalous responses, and so this inversion must be treated with caution.

Notwithstanding these caveats, the NACP and TOBE features are well imaged by the Occam 1D inversions. The top surface of the NACP structure is arcuate with a minimum depth of approximately 10 km at longitude 103° W. It dips sharply to the west at an angle of some 60°. In contrast, the TOBE feature is vertical with its top surface virtually at the base of the Palaeozoic sediments. For both structures, there is the inference of increasing conductivity with depth to a maximum (20 km for NACP, 5 km for TOBE), below which there is a decrease in conductivity.

5.2. 2D forward modelling

Two-dimensional trial-and-error forward modelling of the MT responses was undertaken using Madden's EMCDC code (Madden, 1973) modified for use on a CONVEX mini-supercomputer. *E-polarization* and *B-polarization* responses were calculated at seven periods over the two decades $10-10^3$ s (three points/decade), and then interpolation to six points/decade for contouring purposes. The interpretation was thus by total response matching of the apparent resistivity and phase pseudo-sections for the data and model response, and not just at chosen periods.

Owing to their lateral separation of over 100 km, modelling of the two anomalies, NACP and TOBE, can be undertaken independently. A model that explained the anomalous MT responses above the TOBE structure was found very quickly due to the simple response and because the anomaly was insufficiently sampled spatially, i.e. there are only some three or four sites with data that are indicative of the structure, and they have station separations of over 10 km. The TOBE structure must be thin, of less than 5 km laterally, with an integrated lateral conductance (thickness times conductivity) or around 10000 S. Its top is reasonably well located at the base of the Palaeozoic sediments at 2 km (see Jones, 1988a). Its base is not well resolved, but it must exceed 4 km in total vertical dimension. More exact features of the body must await a more detailed MT survey of the feature.

The NACP can be much better resolved from the data as it is deeper and has a far greater spatial extent. Using Fig. 11 as a basis, an initial model was constructed to describe the observations from the twenty-two sites centred above the body at periods greater than 10 s. The *E-polarization* apparent resistivity and phase data from these sites are illustrated in Fig. 12 (left side).

Critical to the 2D modelling of the NACP feature from these data are the following points.

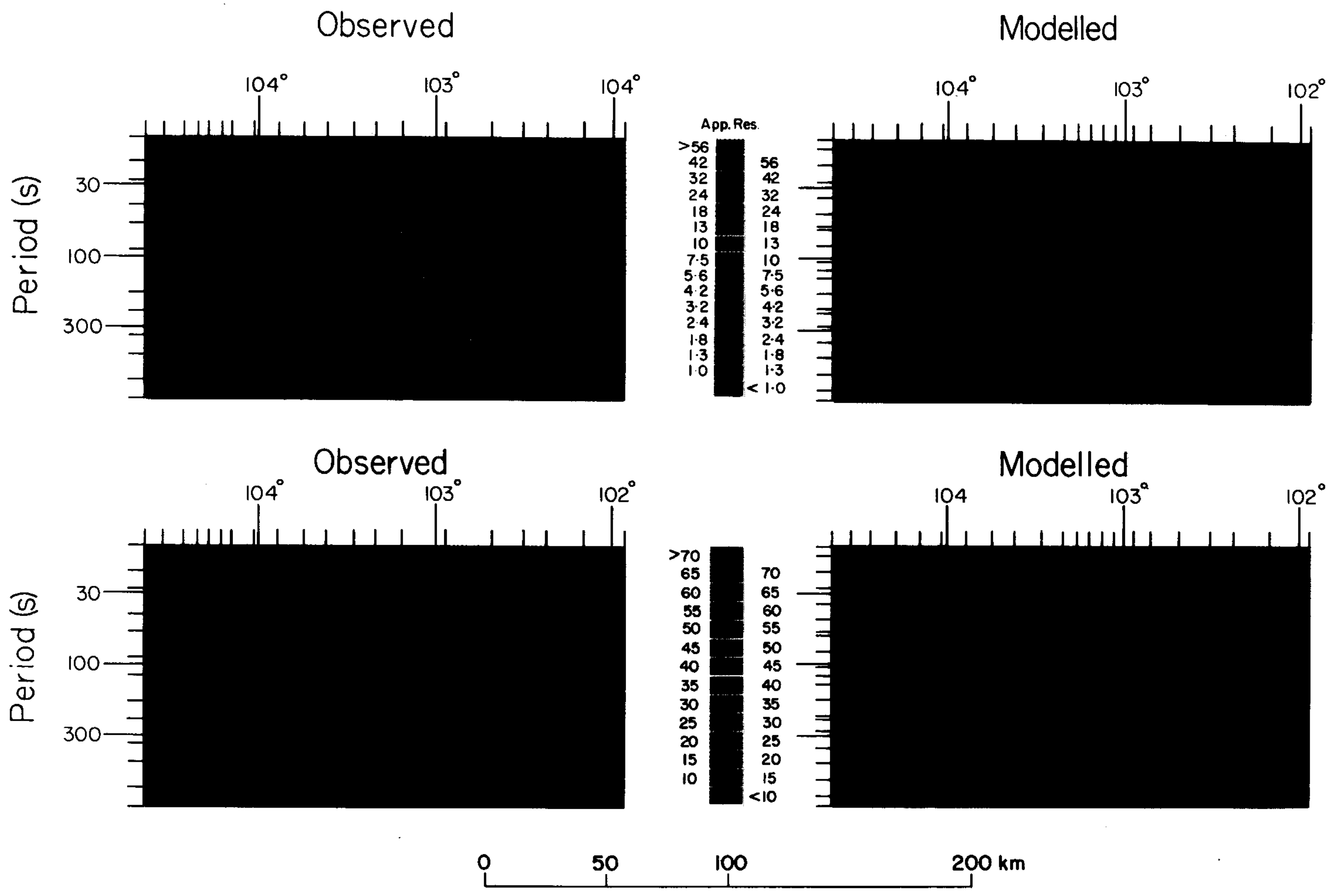

Fig. 12. The observed *E-polarization* responses (upper left: apparent resistivities; lower left: phases) and the theoretical responses (upper right, apparent resistivities; lower right, phases) of the model illustrated in Fig. 13a.

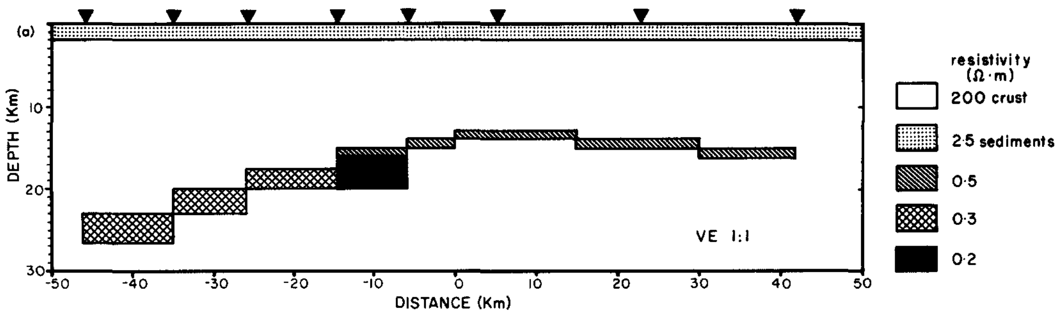

Fig. 13a. A single-body 2D model derived to explain the MT observations along profile *S* of the NACP feature.

1. The *B-polarization* responses (Figs. 6 and 10) are insensitive to the presence of the NACP structure. This dictated that the anomalous zone of enhanced electrical conductivity must be 'thin' in an electromagnetic sense, both vertically and laterally, such that deviations of current flowing through it are not observable on the surface (due to the thick sequence of conducting sediments in the WB).

2. The zone of enhanced conductivity is closest to the surface, along profile *S*, at longitude 103.25° ± 0.1°.

3. The structure must increase its conductance with depth. The top layer has a vertical conductance (vertically-integrated conductivity) of the order of 2000 S, which increases by a factor of 2–3 at a depth of 16–18 km.

4. There must be a zone of increased vertical conductance some 10 km to the west of longitude 103.25°. This zone, of some 10 000 S, is evident in the 1D Occam inversion (Fig. 11).

By trial-and-error forward modelling, a single-body model was found which fit well the *E-polarization* and *B-polarization* data (Fig. 13a). The *E-polarization* response of this model, and its comparison with the observed data, are illustrated as contoured apparent resistivities and phases in Fig. 12. Note the arcuate nature of the body in vertical section view, as predicted by the 1D inversions, and the asymmetry. The body must be vertically thin and of very high conductivity — from 2 to 5 S m^{-1}. Although the model found is by no means unique (see below), it does have the property that there is no *B-polarization* response to it detectable on the surface. If the anomaly is modelled with greater vertical extent but smaller conductivity, i.e. keep the depth-integrated conductivity constant but 'spread' it out in depth, then the *E-polarization* responses fit the observed data, but an effect in the theoretical *B-polarization* becomes evident, which is unacceptable. For the *B-polarization* mode of induction, obviously the effects of the charges on the boundaries are attenuated by the thick conducting sediments of the

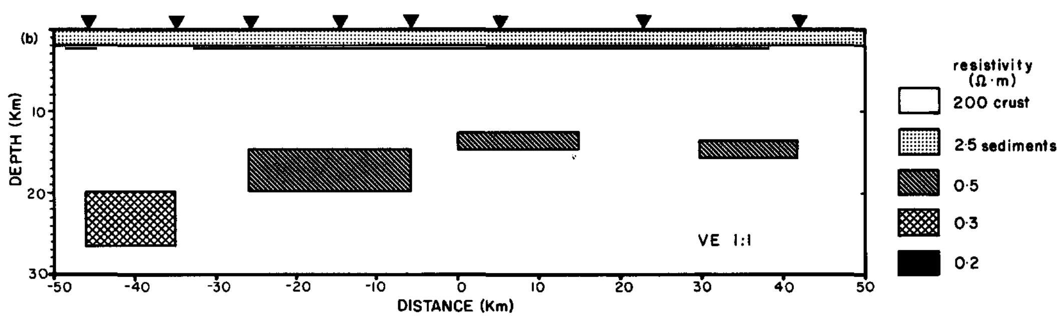

Fig. 13b. A multi-body 2D model derived to explain the MT observations along profile *S* of the NACP feature.

Williston Basin, whereas for the *E-polarization* mode the currents flowing along the body are not so strongly attenuated.

Alternatively, the data could equally be modelled by more than one body. An example of such a multi-body model that fit the data almost equally well is illustrated in Fig. 13b. The discontinuous nature of the model ensures that the currents flowing east–west are not affected sufficiently for the structure to be detectable in the *B-polarization*

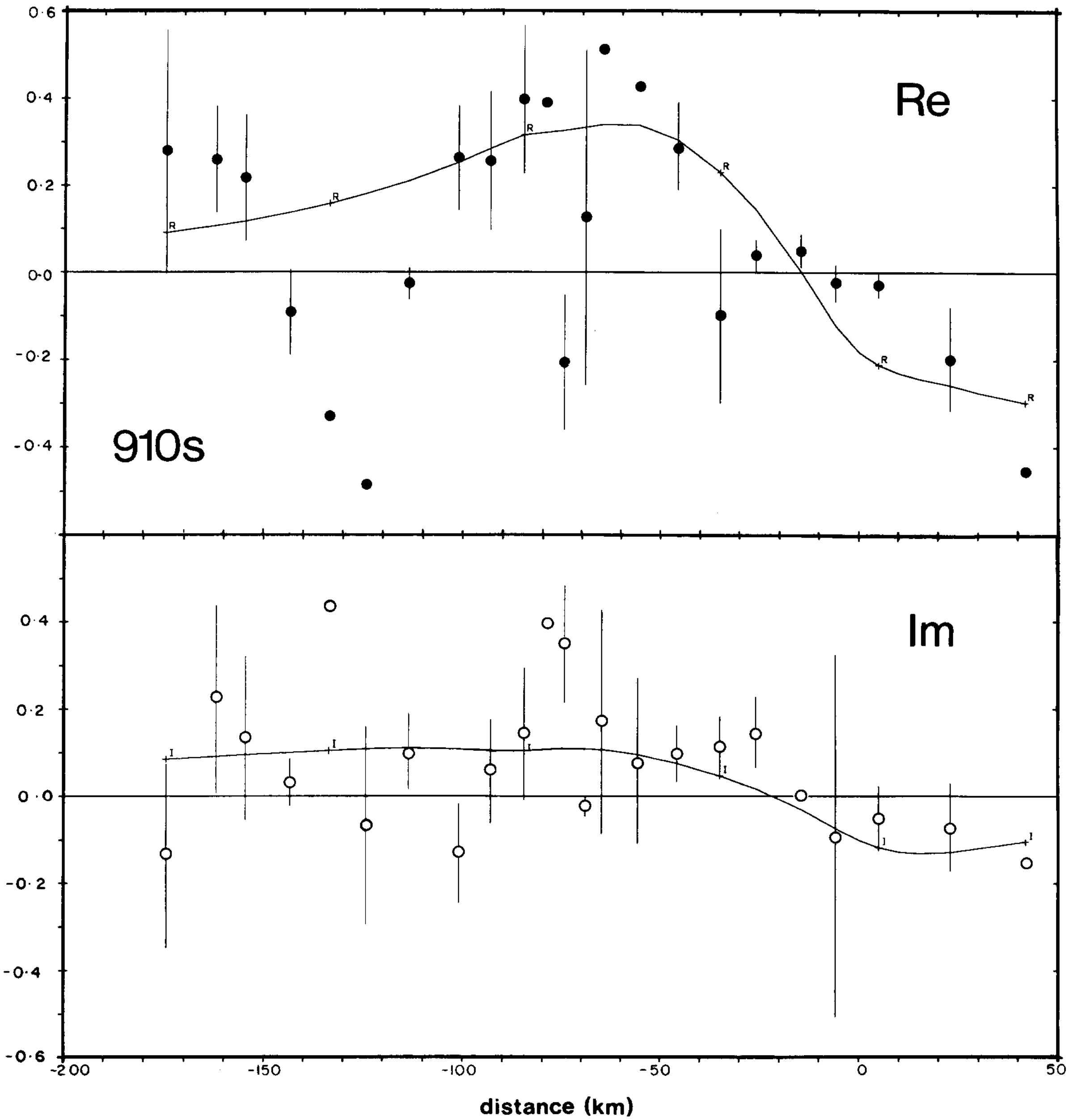

Fig. 14. The GDS transfer functions, with 68% confidence intervals, for current flowing north–south observed at 910 s at the sites on profile *S*. The solid line is the theoretical response to the model illustrated in Fig. 13a.

responses. The arcuate nature of the top of the model is still required, as is the high conductivity, and these two must be a feature of any single-body or multi-body model that satisfies the data.

5.3. GDS responses

Although the 2D trial-and-error modelling concentrated solely on the MT data, the theoretical GDS response of the resulting single-body model (Fig. 13a) compares well with the observations (Fig. 14) at a period of 910 s. The data are scattered at these long periods, but the shape of the responses agree well. These statements are equally true for the multi-body model (Fig. 13b) also.

Both models (Figs. 13a,b) exhibit a maximum response in the real parts of both the anomalous east–west horizontal magnetic field and the vertical magnetic field at a period of ~ 2000 s, which is in reasonable agreement with the comment by Alabi that the anomaly 'has a peak response near a period of one hour' (Alabi, 1974, p. 202). However, because the GDS transfer functions represent the ratio of the *total* horizontal magnetic field to the vertical magnetic field, the maximum of the real GDS transfer function response to this model is not at this period, but is at ~ 1000 s — although the difference in the transfer functions between 1000 s and 1 h is within usual data errors (±0.05) for these estimations.

5.4. Gravity data interpretation

The gravity data along profile *S* are illustrated in Fig. 15 (solid line). Owing to the well-known non-uniqueness associated with modelling gravity data, we decided to use the data only to determine if anomalies in the data could be modelled by bodies of the same general character as that imaged by the MT data.

The general eastward increasing gravity trend in Fig. 15 can be attributed to the thinning sediments of the Williston Basin with a density contrast (compared to the 'host' background rock) of -180 kg m^{-3}. These sediments can be modelled by a thinning wedge as illustrated in Fig. 15. There are two positive anomalies in the gravity

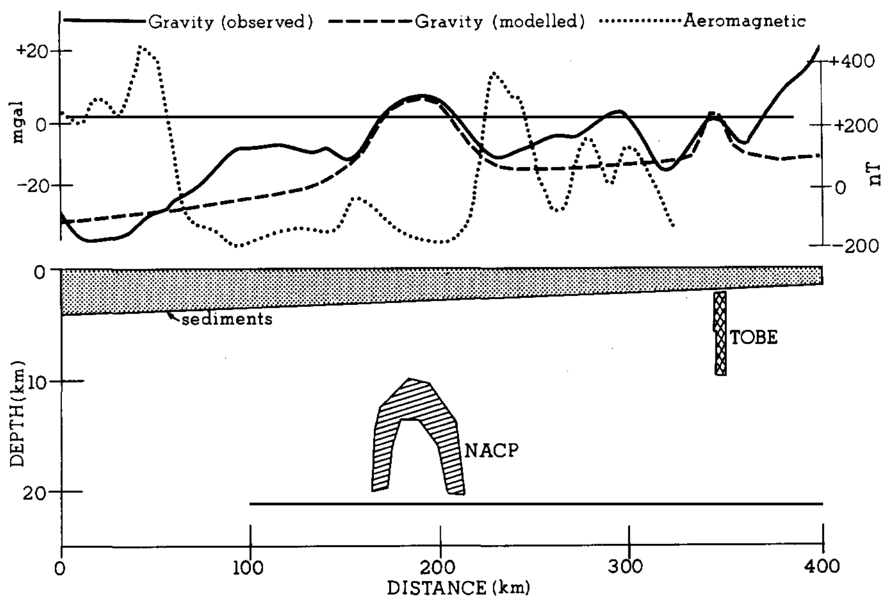

Fig. 15. Upper part. The gravity (solid line) and aeromagnetic (dotted line) data observed along profile *S*. The dashed line represents the response to the gravity model illustrated in the lower part of the figure. Lower part. A model that explains two of the observed anomalies in the gravity data. The sediments are modelled with a density contrast of -180 kg m^{-3}, the NACP with $+270$ kg m^{-3}, and the TOBE with $+180$ kg m^{-3}.

data that lie directly above the NACP and TOBE conductivity anomalies — these are at distances of 180 km and 350 km on Fig. 15. The anomaly centred on 180 km is of 50 km in spatial wavelength, whereas the anomaly centred on 350 km is much narrower, of 6 km spatial wavelength.

By placing an arcuate structure with its top surface at 10 km and with a shape similar to that of the NACP anomaly (Fig. 13a), but of slightly smaller spatial wavelength, and a positive density contrast of 270 kg m^{-3}, the gravity anomaly can be explained almost totally (Fig. 15, dashed line). The differences in spatial wavelength between the models from these two techniques is not significant given the inherent non-uniquenesses of the two methods. The actual density difference is, of course, dependent on the thickness of the limbs of the structure. However, a lower bound is given by modelling the structure as 'filled-in', which gives a density contrast of 110 kg m^{-3}.

For the TOBE anomaly, a thin vertical structure, of dimensions similar to those of the body that describe the MT observations, with a positive density contrast of 180 kg m^{-3} can explain quite well the gravity data (Fig. 15, dashed line).

5.5. Aeromagnetic data

The aeromagnetic data above the NACP in this region are anomalously featureless (Fig. 15, dotted line; also Fig. 7). This eastern edge of this magnetic quiet zone appears to correlate with the eastern edge of the NACP structure as modelled by the MT data (Fig. 13). The western edges of the two do not have the same correlation.

5.6. Geothermal data

The heat flow data along profile S is plotted in Fig. 16, together with two 2D models of the crustal structure of geothermal effects to explain the observations (Majorowicz et al., 1989). The heat flow data have been normalized to an assumed regional heat flow of 60 mW m^{-2}, and the shape of the anomalous bodies have been dictated by the MT results of both ourselves and of Rankin and Pascal (1990) (see Majorowicz et al., 1989). The two models represent either anomalous heat generation of $\Delta A = 4$ μW m^{-3} (Fig. 16A), or anomalous thermal conductivity causing a rise in the isotherms (Fig. 16B). The interpretation favoured by

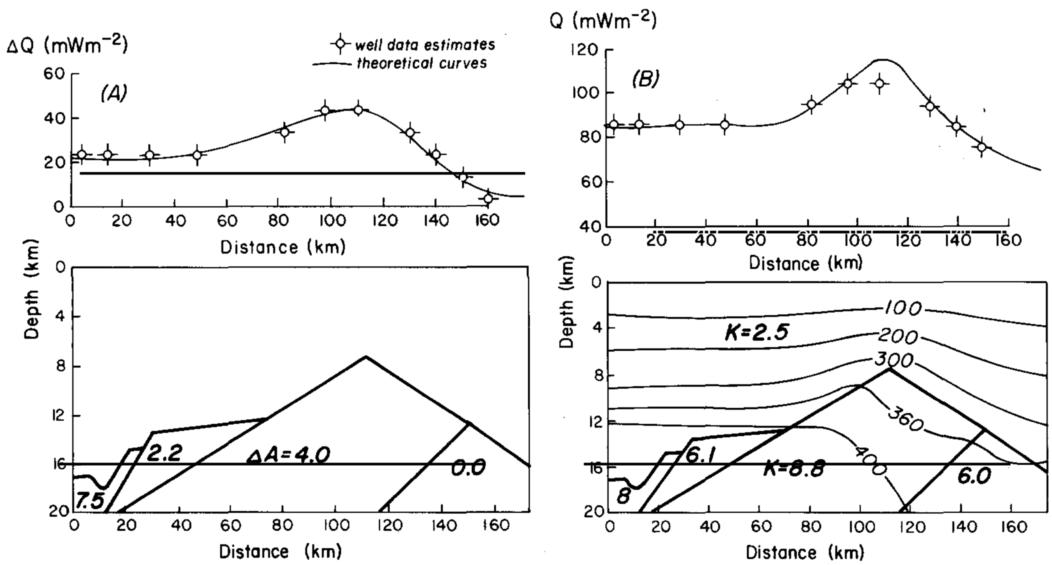

Fig. 16. The heat flow data across the profile S and its interpretation in terms of (A) anomalous heat generation model, and (B) anomalous thermal conductivity structure (taken from Majorowicz et al., 1989).

Majorowicz et al. (1989) is of the former, with mineralization and redistribution of radiogenic elements in the crust during the THO collision.

6. Porath's Black Hills data

It has long been contended by Gough and his colleagues that the NACP structure 'defies' 2D modelling. Given that we are able to model our data from profile S by a 2D model, we wish to examine the basis of that statement with particular reference to the GDS data from across the Black Hills.

Illustrated in Fig. 17 are the vertical-to-normal east–west horizontal (Z/D_n, crosses) and anomalous-to-normal east–west horizontal (D_a/D_n, pluses) magnetic field ratios observed by Porath and co-workers (Porath, Gough and Camfield, 1971; hereafter called PGC) at a period of 3000 s for five locations crossing the Black Hills of South Dakota. These are amplitude data only, and it was noted by PGC that the phases of the fields are virtually zero, i.e. these data are equal to the real parts of the ratios. Note that the D_a/D_n response reaches a maximum of ~ 2.35, i.e. the anomalous horizontal magnetic field is 2.35 times as large as the normal horizontal magnetic field.

PGC commented that this situation, of the anomalous horizontal magnetic field above an anomaly being larger than the normal field, cannot be explained by induction alone, and accordingly these data were incompatible with each other in that no 2D induction model could be found to explain both responses. Forward modelling was attempted, however, using Wright's (1969) programme but with derivation of the anomalous horizontal field through Hilbert transformation of the vertical field (Siebert and Kertz, 1957). Therefore they concluded that the spectre of current channelling had to be invoked to explain the observations.

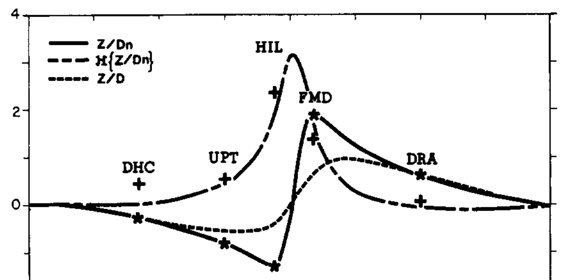

Fig. 17. The GDS Z/D_n (crosses) and D_a/D_n (pluses) responses observed at 3000 s at stations across the Black Hills of South Dakota by Porath et al. (1971). The full line is an interpolation of the Z/D_n data onto a regular spacing, and the long and short dashed line is its Hilbert transformation.

However, it is now known that the anomalous horizontal field can be larger than the normal horizontal field above a 2D body by induction alone (see, for example, Dupis and Thera, 1982; Jones, 1983b).

In order to test the statement by PGC concerning the apparent incompatibility of these data, this Hilbert transformation coupling between the anomalous fields was investigated. The Z/D_n data were interpolated onto a regular spacing using quasi-Hermite splines (IMSL routine IQHSCU), which have the property of being continuous with a continuous first derivative, but not a continuous second derivative. This interpolation procedure was found to result in a curve which passed through all the data points but which had little apparent extraneous structure (Fig. 17, full line). The interpolated regularly-spaced Z/D_n data were then Hilbert transformed by Fourier transformation, exchanging the real and imaginary parts (with the necessary sign convention), and inverse Fourier transformation. The resulting Hilbert-transformed curve is illustrated in Fig. 17 (long and short dashed line), and, to within observational accuracy, it passes through the D_a/D_n data. Accordingly, one can be confident that these data are, in fact, compatible, and that a model which can explain one set of responses must, by induction, also explain the other. Also illustrated in Fig. 17 is the GDS transfer function Z/D calculated from the derived responses. The maximum in the transfer function is ~ 0.9, which is large.

The data published by PGC were scaled and are illustrated at three periods in Fig. 18. The error bars on the data at periods of 1500 s and 3000 s represent the scatter from the two events analysed (their Fig. 2). The data are not of suffi-

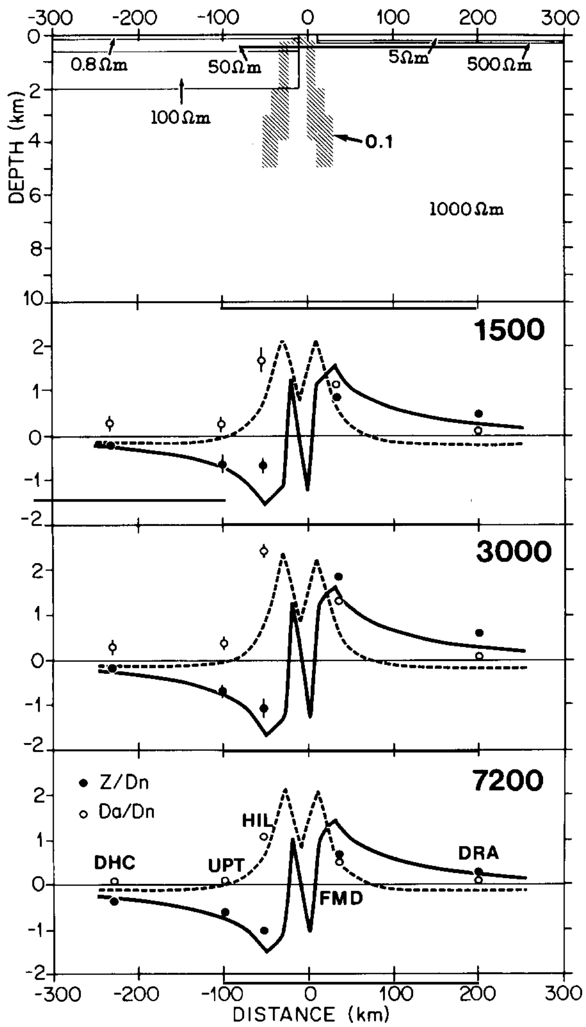

Fig. 18. A 2D model of the GDS responses observed by Porath et al. (1971). The model consists of an arcuate feature, of 0.1 Ω m, buried within a host with a sedimentary structure as interpreted by Rankin and Reddy (1973). The data are the Z/D_n (solid circles) and D_a/D_n (open circles) responses observed at three periods at stations across the Black Hills of South Dakota. The responses to the model are given by the full and dashed lines for Z/D_n and D_a/D_n respectively.

cient quality to warrant extensive 2D modelling. However, it is of interest to note that a feature with the same shape as under profile S, i.e. an arcuate shape of 80 km width of 0.1 Ω m, buried in a host with a sedimentary structure as interpreted by Rankin and Reddy (1973), can explain well the observations at all periods (Fig. 18). Illustrated in Fig. 18 are the real parts of the ratios only, the imaginary parts were less than 10% of the real parts over the whole period range, which is in accord with the observational evidence of zero phase for these anomalous fields above the anomaly (see above). This in-phase relationship between the anomalous fields is not surprising given Summers' (1981, 1982) discussion of current channelling which demonstrated how this occurs for highly conductive anomalies.

It must be emphasized that there is virtually no resolution whatsoever of the shape of this highly conducting body beneath the Black Hills from these data — a block of 0.1 Ω m, 80 km wide and 4 km thick would also adequately explain the observations. Such a block body would not have the extreme variations in the ratios Z/D_n and D_a/D_n for distances close to 0 km as for the arcuate shape. However, an arcuate shape was chosen to be consistent with the body imaged beneath profile S. Obviously, further MT profiles need to be undertaken in the Dakotas to improve our image of the NACP at these latitudes.

7. Conclusions

We have presented a qualitative summary of the MT phase responses observed along three profiles across the NACP and TOBE structures. These responses, displayed as contoured pseudo-sections, indicate the following features.

(1) The lateral variaton of the sediments.
The base of the conducting zone on profile S was shown to be the base of the Upper Palaeozoic strata (the Ashern Dolomite) by Jones (1988a). Well revealed in the pseudo-sections is the thinning of the sediments from west to east.

(2) The lateral variation of the basement.
On the profiles M and N the basement is apparently more resistive to the east than to the west. Such a feature may not be resolveable in the data from profile S due to the masking effect of the TOBE anomaly, although there is the indication in the ϕ_{xy} phases from the easternmost site that this is also true at the latitude of this profile. Thus, from the tectonic map of Fig. 1 we can infer that the mid-crust of the Superior province is

more resistive than the mid-crust of the Trans-Hudson Orogen.

(3) The variation along strike of the NACP.
The MT data presented herein shows conclusively that the NACP is not the linear continuous feature inferred from the GDS work (Fig. 1). In contrast, from these three MT profiles in Saskatchewan it is apparent that there is a break at ~ 51° N, with a shift to the North and West for a possible continuation of the same structure. If the features observed on profiles *S* at ~ 103° W and on *N* at ~ 105.15° W, but which are absent from profile M, are indeed manifestations of the *same* geological structure, then one possible interpretation is for a massive NW–SE trending sinistral fault in the deep crust, with a movement along strike of some 100–150 km, cutting the NACP at 51° N. Dextral NE–SW trending faults in the basement, with a small movement along strike of some 20 km, are interpreted to exist beneath the sedimentary cover of the Dakotas (Klasner and King, 1986) from displacements of a magnetic low boundary zone. An alternative geometry for the NACP could include a 'bend' to the northwest (see Fig. 1) such that it was missed by profile *M*. If this is the case however, the NACP must be at least 50 km west of the western end of profile *M* as there are no phase effects evident in the data from profile *M*.

(4) The correlation of the NACP with other geophysical data.
In this paper, we have shown that the location of the NACP on profile *S* correlates with a gravity high, a magnetic quiet zone, and a geothermal anomaly. In the MT, gravity, magnetic and heat flow data there is concurring evidence for a non-continuous geophysically-observable feature that appears to terminate at ~ 51° N. Furthermore, from these other geophysical datasets we have conjectured a NW–SE trending sinistral fault in the deep crust, which displaces the NACP feature some 100–150 km along strike, from 51° N, 102° W to 52° N, 106° W. This feature is also apparent in the tectonic boundary lineations drawn on the compiled aeromagnetic and Bouguer gravity anomaly maps by Green et al. (1985).

From analysis and modelling of the available geophysical data along profile *S*, we can conclude that an anomaly exists within the crust directly below 103° W in southern Saskatchewan. The anomaly has the following characteristics.

(1) Its top surface is at a depth of ~ 10 km.

(2) It has a width of some 80 km.

(3) It appears to be arcuate in section.

(4) It is asymmetric with a higher conductance to the west compared to the east.

(5) If it is a single body, then it must be thin, not more than a few kilometres in thickness. Any greater thickness extent is not permissible.

(6) It must be highly conductive, of conductivity greater than 1 S m^{-1}.

(7) An explanation of such high conductivities in terms of conducting fluids, such as Archean brines with a 20 wt% NaCl solution at 375° (see Kurtz et al., 1986), requires implausibly high porosities of the order of 12–20%.

(8) If the positive gravity high is due to the same feature, then the anomaly has a density contrast (compared to the host rock) of approximately 270 kg m^{-3}.

(9) There appears to be no magnetic high or low associated with the anomaly. On the contrary, the NACP body is in a magnetically quiet region. Nevertheless, the apparent lack of information is, in itself, information.

(10) If the same structure is causing the MT anomaly as well as the thermal anomaly, then the feature is either due to enhanced heat generation or to enhanced thermal conductivity.

Various possible explanations could be proposed to explain the MT, the gravity, the aeromagnetic, and the thermal data independently of each other. However, there is a reasonable probability that the collocation of all four of these anomalies is due to a single cause. Also, this single cause must explain the very long extent of the NACP and its association with the Trans-Hudson Orogen. A complete interpretation of these datasets is out of the bounds of this paper and will be the subject of further study, but two possible 'end-member' explanations can be examined; where the term end-member is used because in one scenario the conducting material comes from deep below, i.e. the mantle, whereas in the other the material comes from the surface.

One possible explanation for the NACP

anomaly, originally suggested by Fowler and Nisbet (1985) to explain the subsidence of the WB, is of a slab of oceanic, mafic continental, or continental margin crust that was overthrust during the Hudsonian orogeny and that, at deep crust ambient $P-T$ conditions, recrystallized to eclogite over a very prolonged time scale. Independently, Gupta et al. (1985) and Green et al. (1985) also considered the role of obducted oceanic rocks, in their case suggesting that these rocks underwent serpentinization. However, experimental data on eclogite suggest that at mid-crustal temperatures its conductivity is two order of magnitude too small (Lastovickova and Parchomenko, 1976), and Olhoeft (1981), in a very careful laboratory study, illustrated that hydrated minerals are not intrinsically conducting but that it is fluids released by dehydration reactions that are the cause of the high conductivities measured in laboratories. As proposed by Jones (1987a), fluids released by such reactions could become trapped beneath an impermeable barrier which forms at temperatures of around 400 °C. Such temperatures are in reasonable agreement with the geotherms from the model of anomalous thermal structure (Fig. 16B) presented by Majorowicz et al. (1989). Additionally, if these rocks are above their Curie temperature, then there would exist a magnetic quiet zone as observed. However, the porosities required for conductivities greater than 2 S m^{-1} are implausibly high (12–20%, depending on the pore geometry). Also, this would not explain the present-day heat flow anomaly.

Another possible explanation for the NACP structure could be the fairly recent (compared with the THO at 1.8 Ga) intrusion of a magmatic body from the mantle into the crust along a zone of previous weakness, i.e. the THO. Ahern and Mrkvicka (1984) proposed the emplacement of a hot body into the subcrustal lithosphere at ≈ 400 Ma to explain the subsidence of the Williston Basin. One possible scenario then for the crustal body is for low density differentia from this subcrustal body to have become emplaced in the mid crust. As the body cooled to ambient temperatures, it would have a higher density (this explains the gravity observations). Vigorous fluid circulation subsequent to the injection of the body could lead to removal of the magnetic grains (this explains the aeromagnetic data). The body could have a concentration of radiogenic elements, leading to a higher than background heat generation (not likely, but explains the geothermal data). Finally, the body could have a concentration of highly conductive minerals from the mantle, with carbon being one potential candidate (Duba and Shankland, 1982). To explain conductivities of the order of 2–5 S m^{-1} only requires a graphitic carbon fraction of the order of 0.1% (extrapolating from Fig. 3 of Duba and Shankland (1982)). However, although this scenario may well explain a body beneath the centre of the Williston Basin, it is not likely that such an emplaced body would extend from the Black Hills to northern Canada — which is the traced NACP from GDS studies (Fig. 1).

Finally, a more exotic theory for the generation of the WB is by meteoritic impact (Sears and Alt, 1989), and Jones (1987b) has examined the potential for the generation of conducting anomalies in the lower crust from such energetic impacts. However, such a theory raises more questions than it answers with regard to the NACP structure.

Obviously, many questions need to be answered before the tectonic history of the region, and in particular the role of the NACP, can be unravelled.

Is there a geothermal high along the whole length of the NACP?

Is there a gravity high along the whole length of the NACP? Certainly the high in Fig. 6 on profile *S* is not readily traceable on profile *N*.

Is there an aeromagnetic quiet zone along the whole length of the NACP?

To what extent does the Williston Basin modify and alter the NACP structure — if at all?

It is hoped that these questions will become addressed as both LITHOPROBE (Hajnal and Lewry, 1988) and COCORP (Brown et al., 1989) direct their attention to the Williston Basin and the Trans-Hudson Orogen over the next few years.

Acknowledgements

We wish to acknowledge Pete Savage of Pan-Canadian Petroleum Ltd., Calgary, for the MT data from profile *S*, and we thank all those farmers who kindly let us perform our 'magic' on their land during the recording of profiles *M* and *N* in the summer of 1987. The field crew for these latter profiles included three summer students, Rob Stevens, Blair Walker and John Glasko, and a Chinese visitor, Nong Wu, and we are grateful to all of them for their hard work and pleasant dispositions.

The potential field maps and the earthquake epicentres of the region were provided by staff of the Geophysics Division, GSC, Geological Survey of Canada Publication No. 42287.

References

Ahern, J.L. and Mrkvicka, S.R., 1984. A mechanical and thermal model for the evolution of the Williston Basin. Tectonics, 3: 79–102.

Alabi, A.O., 1974. A Study of the North American Central Plains Conductivity Anomaly. PhD Thesis, University of Alberta.

Alabi, A.O., Camfield, P.A. and Gough, D.I., 1975. The North American Central Plains anomaly. Geophys. J.R. Astron. Soc., 43: 815–834.

Berdichevsky, M.N. and Dmitriev, V.I., 1976. Basic principles of interpretation of magnetotelluric sounding curves. In: A. Ádâm (Editor), Geoelectric and Geothermal Studies. KAPG Geophysical Monograph, Akadémiai Kiadó, pp. 165–221.

Bostick, F.X., 1977. A simple almost exact method of MT analysis. In: Workshop on Electrical Methods in Geothermal Exploration. U.S. Geol. Survey, Contract No. 14080001-8-359.

Brown, L.D., Kaufman, S., Nelson, K.D. and Oliver, J., 1989. Intracratonic basins, Proterozoic layered complexes, and fluids in the crust: A three component program of COCORP deep seismic reflection research. NSF Grant Application.

Camfield, P.A. and Gough, D.I., 1975. Anomalies in daily variation magnetic fields and structure under north-western United States and south-western Canada. Geophys. J.R. Astron. Soc., 41: 193–218.

Camfield, P.A. and Gough, D.I., 1977. A possible Proterozoic plate boundary in North America. Can. J. Earth. Sci., 14: 1229–1238.

Camfield, P.A., Gough, D.I. and Porath, H., 1970. Magnetometer array studies in the northwestern United States and southwestern Canada. Geophys. J.R. Astron. Soc., 22: 201–222.

Constable, S.C., Parker, R.L. and Constable, C.G., 1987. Occam's inversion: a practical algorithm for generating smooth models from electromagnetic sounding data. Geophysics, 52: 289–300.

Craven, J.A. and Jones, A.G., 1990. The Magdalen Basin and associated fault systems below Prince Edward Island imaged by the magnetotelluric technique. Can. J. Earth Sci., in preparation.

Drysdale, J.A. and Horner, R.B., 1986. Canadian Earthquakes — 1984. Seism. Ser. Earth Phys. Branch, No. 93.

Drysdale, J.A., Horner, R.B., Wetmiller, R.J., Stevens, A.E., Rogers, G.C. and Basham, P.W., 1985. Canadian Earthquakes — 1983. Seism. Ser. Earth Phys. Branch, No. 92.

Drury, M.J. and Niblett, E.R., 1980. Buried ocean crust and continental crust geomagnetic induction anomalies: a possible association. Can. J. Earth Sci., 17: 961–967.

Duba, A.G. and Shankland, T.J., 1982. Free carbon and electrical conductivity in the Earth's mantle. Geophys. Res. Lett., 9: 1271–1274.

Dupis, A. and Thera, A.L., 1982. Natural electromagnetism in the Rhine Graben. Geophys. J.R. Astron. Soc., 68: 545–557.

Dutch, S.I., 1983. Proterozoic structural provinces in the north-central United States. Geology, 11: 478–481.

Fowler, C.M.R. and Nisbet, E.G., 1985. The subsidence of the Williston Basin. Can. J. Earth Sci., 22: 408–415.

Gamble, T.D., Goubau, W.M. and Clarke, J., 1978. Magnetotellurics with a remote reference. Geophysics, 44: 53–68.

Gendzwill, D.J., Horner, R.B. and Hasegawa, H.S., 1982. Induced earthquakes at a potash mine near Saskatoon, Saskatchewan. Can. J. Earth. Sci., 19: 466–475.

Gibb, R.A. and Walcott, R.I., 1971. A Precambrian suture in the Canadian Shield. Earth Planet. Sci. Lett., 10: 417–422.

Gough, D.I. and Camfield, P.A., 1972. Convergent geophysical evidence of a metamorphic belt through the Black Hills of South Dakota. J. Geophys. Res., 77: 3168–3170.

Green, A.G., Cumming, G.L. and Cedarwell, D., 1979. Extension of the Superior-Churchill boundary zone into southern Canada. Can. J. Earth Sci., 16: 1691–1701.

Green, A.G., Hajnal, Z. and Weber, W., 1985. An evolutionary model of the western Churchill Province and western margin of the Superior Province in Canada and the north-central United States. Tectonophysics, 116: 281–322.

Green, A.G., Milkereit, B., Mayrand, L., Spencer, C., Kurtz, R.D. and Clowes, R.M., 1987. Lithoprobe seismic reflection profiling across Vancouver Island. Geophys. J.R. Astron. Soc., 89: 85–90.

Gupta, J.C., Kurtz, R.D., Camfield, P.A. and Niblett, E.R., 1985. A geomagnetic induction anomaly from IMS data near Hudson Bay, and its relation to crustal electrical conductivity in central North America. Geophys. J.R. Astron. Soc., 81: 33–46.

Hajnal, Z. and Lewry, J.F., 1988. The Trans-Hudson Orogen and the Intracratonic Williston Basin LITHOPROBE Project. LITHOPROBE Grant Proposal.

Handa, S. and Camfield, P.A., 1984. Crustal electrical conductivity in north-central Saskatchewan: the North American Central Plains anomaly and its relation to a Proterozoic plate margin. Can. J. Earth Sci., 21: 533–543.

Hills, F.A., Houston, R.S. and Subbarayudu, G.V., 1975. Possible Proterozoic plate boundary in southern Wyoming. Geol. Soc. Am. (Abstracts), 7: 614.

Hoffman, P., 1981. Autopsy of Athapuscow aulacogen: a failed arm affected by three collisions. In: F.H.A. Campbell (Editor), Proterozoic Basins of Canada. Geological Survey of Canada, Paper 81-10, pp. 97–102.

Hoffman, P., 1988. United plates of America, the birth of a craton: early Proterozoic assembly and growth of Laurentia. Ann. Rev. Earth. Planet. Sci., 16: 543–603.

Horner, R.B., Stevens, A.E. and Hasegawa, H.S., 1973. The Bengough, Saskatchewan, earthquake of July 26, 1972. Can. J. Earth Sci., 10: 1805–1821.

Hyndman, R.D., 1988. Dipping seismic reflectors, electrically conducting zones and trapped water in the crust over a subducting plate. J. Geophys. Res., 93: 13,391–13,405.

Jones, A.G., 1983a. On the equivalence of the "Niblett" and "Bostick" transformations in the magnetotelluric method. J. Geophys., 53: 72–73.

Jones, A.G., 1983b. The problem of "current channelling": a critical review. Geophys. Surv., 6: 79–122.

Jones, A.G., 1987a. MT and reflection: an essential combination. Geophys. J.R. Astron. Soc., 89: 7–18.

Jones, A.G., 1987b. Are impact-induced lower crustal faults observable? Earth Planet. Sci. Lett., 85: 248–252.

Jones, A.G., 1988a. Static-shift of magnetotelluric data and its removal in a sedimentary basin environment. Geophysics, 53: 967–978.

Jones, A.G., 1988b. Discussion of "A magnetotelluric investigation under the Williston Basin of south-eastern Saskatchewan" by J.M. Maidens and K.V. Paulson. Can. J. Earth Sci., 25: 1132–1139.

Jones, A.G. and Savage, P.J., 1986. North American Central Plains conductivity anomaly goes east. Geophys. Res. Lett., 13: 685–688.

Klasner, J.S. and King, E.R., 1986. Precambian basement geology of North and South Dakota. Can. J. Earth Sci., 23: 1083–1102.

Kurtz, R.D., DeLaurier, J.M. and Gupta, J.C., 1986. A magnetotelluric sounding across Vancouver Island sees the subducting Juan de Fuca plate. Nature, 321: 596–599.

Lastovickova, M. and Parchomenko, E.I., 1976. The electric properties of eclogites from the Bohemian Massif under high temperatures and pressures. Pageoph., 114: 451–460.

Law, L.K. and Riddihough, R.P., 1971. A geographical relation between geomagnetic variation anomalies and tectonics. Can. J. Earth Sci., 8: 1094–1106.

Lidiak, E.G., 1971. Buried Precambrian rocks of South Dakota. Geol. Soc. Am. Bull., 82: 1411–1420.

Madden, T.R., 1973. Instruction Manual for EMCDC and EMUVC (EMCAL). Exploration Aids Inc., Needham, Mass., 31 pp.

Majorowicz, J.A., Jones, F.W. and Jessop, A.M., 1986. Geothermics of the Williston Basin in Canada in relation to hydrodynamics and hydrocarbon occurrances. Geophysics, 51: 767–779.

Majorowicz, J.A., Jones, F.W. and Ertman, M.E., 1989. Model of terrestrial thermal effects in the area of the crustal electrical conductors of the Williston Basin. Can. J. Explor. Geophys. (in press).

Morel-à-l'Huissier, P., Green, A. and Pike, C., 1987. Crustal refraction surveys across the Trans-Hudson orogen/Williston Basin of south central Canada. J. Geophys. Res., 92: 6403–6420.

Niblett, E.R. and Sayn-Wittgenstein, C., 1960. Variation of the electrical conductivity with depth by the magnetotelluric method. Geophysics, 25: 998–1008.

Olhoeft, G.R., 1981. Electrical properties of granite with implications for the lower crust. J. Geophys. Res., 86, 931–936.

Peterman, Z.E., 1981. Dating of Archean basement in northeastern Wyoming and southern Montana. Geol. Soc. Am. Bull., 92, 139–146.

Porath, H., Oldenburg, D.W. and Gough, D.I., 1970. Separation of magnetic variation fields and conductive structures in the western United States. Geophys. J.R. Astron. Soc., 19, 237–260.

Porath, H., Gough, D.I. and Camfield, P.A., 1971. Conductive structures in the northwestern United States and south-west Canada. Geophys. J.R. Astron. Soc., 23, 387–398.

Rankin, D. and Reddy, I.K., 1973. Crustal conductivity anomaly under the Black Hills: a magnetotelluric study. Earth Planet. Sci. Lett., 20: 275–279.

Rankin, D. and Pascal, F., 1990. A gap in the North American Central Plains conductivity anomaly. Phys. Earth Planet. Inter., 60: 132–137.

Reitzel, J.S., Gough, D.I., Porath, D.I. and Anderson, III, C.W., 1970. Geomagnetic deep sounding and upper mantle structure in the western United States. Geophys. J.R. Astron. Soc., 19: 213–235.

Sears, J.W. and Alt, D., 1989. Impact origin of large intracratonic basins, the stationary Proterozoic crust, and the transition to modern plate tectonics. Contributed paper at '8th Internat. Conf. Basement Tectonics (in press)'.

Siebert, M. and Kertz, W., 1957. Zur Zerlegung eines lokalen erdmagnetischen Feldes in äusseren und inneren Anteil. Nachr. Akad. Wiss. Göttingen, II, Math. Phys. K1., 87–112.

Summers, D.M., 1981. Interpreting the magnetic fields associated with two-dimensional induction anomalies. Geophys. J.R. Astron. Soc., 65: 535–552.

Summers, D.M., 1982. On the frequency response of induction anomalies. Geophys. J.R. Astron. Soc., 70: 487–502.

Swift, C.M., 1967. A magnetotelluric investigation of an electrical conductivity anomaly in the south-western United States. PhD Thesis, Department of Geology and Geophysics MIT, Cambridge, Mass.

Thomas, M.D., Sharpton, V.L. and Grieve, R.A.F., 1987. Gravity patterns and Precambrian structure in the North American Central Plains. Geology, 15: 489–492.

Van Schmus, W.R., Bickford, M.E., Lewry, J.F. and MacDonald, R., 1987. U-Pb geochronology in the Trans-Hudson Orogen, northern Saskatchewan, Canada, Can. J. Earth Sci., 24: 407–424.

Wright, J.A., 1969. The magnetotelluric and geomagnetic response of two-dimensional structures. GAMMA 7, Inst. Geophys. Met., Technical University of Braunschweig, p. 102.