A magnetotelluric investigation under the Williston Basin of southeastern Saskatchewan:[1] Discussion[2]

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Introduction

The recent publication by Maidens and Paulson consists of two distinct parts. the first part is a comparison of two processing schemes for magnetotelluric (MT) data, and as such I applaud the efforts of the authors for their very worthwhile addition to our knowledge. The second part is an interpretation of the responses derived from their five MT sites, located within the Williston Basin close to the Canada – United States border, with conclusions regarding the enigmatic North American Central Plains conductivity anomaly (known by the acronym NACP). It is about the latter that I have four comments to make to refute the statement made by Maidens and Paulson (p. 66) (italics added): "*Although there is no question about the existence of the major anomaly reported by Jones and Savage, there is a question about the name assigned to it.*"

Since its discovery in the mid-central United States during the late 1960's the NACP has been studied in Canada by a geomagnetic depth-sounding (GDS) array and two profiles (Alabi *et al.* 1975; Handa and Camfield 1984; Gupta *et al.* 1985) and, more recently, by MT surveys (Jones and Savage 1986; Jones and Craven, in preparation; Rankin and Pascal, in preparation). This feature, concluded to be linear and continuous over 2000 km from these GDS studies, has been interpreted variously as (*i*) associated with conductive minerals, such as graphite in schistose rocks in a belt mapped by Lidiak (1971) in the basement 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).

Certainly, interpretations of the tectonic history of the region (e.g., Green *et al.* 1985), in particular of the Trans-Hudson Orogen, would be remiss if they did not include a mechanism for the generation of this continental-scale feature. Accordingly, it is of the greatest import that the true location of the anomaly be known as precisely and as unequivocally as possible in order to aid paleotectonic reconstructions.

In their paper, Jones and Savage (1986) stated that at the latitude of the Canada – United States border the location of the NACP anomaly (Fig. 1), as mapped from the GDS work, was in error by some 75 km and that the entire centre of the anomaly was further to the east. Maidens and Paulson are of the opinion from interpretation of data from their five sites (Figs. 1, 2) that there are *two* anomalies: the NACP as mapped by the GDS work and apparently corroborated by their own observations, and the one mapped by Jones and Savage. This view would add further confusion to an already obscured understanding by the geoscientific community of the NACP anomaly, as exemplified by Kanasewich *et al.*'s (1987, pp. 2167–2168) comment on the apparent dichotomy between the GDS and MT observations.

The purpose of this discussion is to illustrate unequivocally that the anomaly in electrical conductivity, called by Gough and colleagues the NACP anomaly, is indeed at the location stated by Jones and Savage (1986) and, more recently, by Rankin and Pascal (in preparation). This will be undertaken by (*i*) discussing the resolution of the GDS observations of Alabi *et al.* (1975) in southern Saskatchewan; (*ii*) illustrating that based on the PanCanadian data no anomaly exists near 105°W longitude *after* the MT responses have been corrected for static shift; (*iii*) discussing the resolution of Maidens and Paulson's data for their one-dimensional (1D) models presented, and (*iv*) illustrating that 1D modelling of the E-polarization responses from two-dimensional (2D) data can result in "false conducting layers."

Geomagnetic depth-sounding observations

The MT observations by Jones and Savage (1986) (Fig. 1), and more recently by Rankin and Pascal (in preparation) (Fig. 1), indicated that the GDS location of the NACP 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. 1), not to its *west* as interpreted by Alabi (1974) and Alabi *et al.* (1975). This apparent discrepancy is quite easily explained 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 small or zero, whereas the perpendicular horizontal component, H_y (the co-ordinate 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 are contaminated by source-field effects, as were those of Alabi *et al.*

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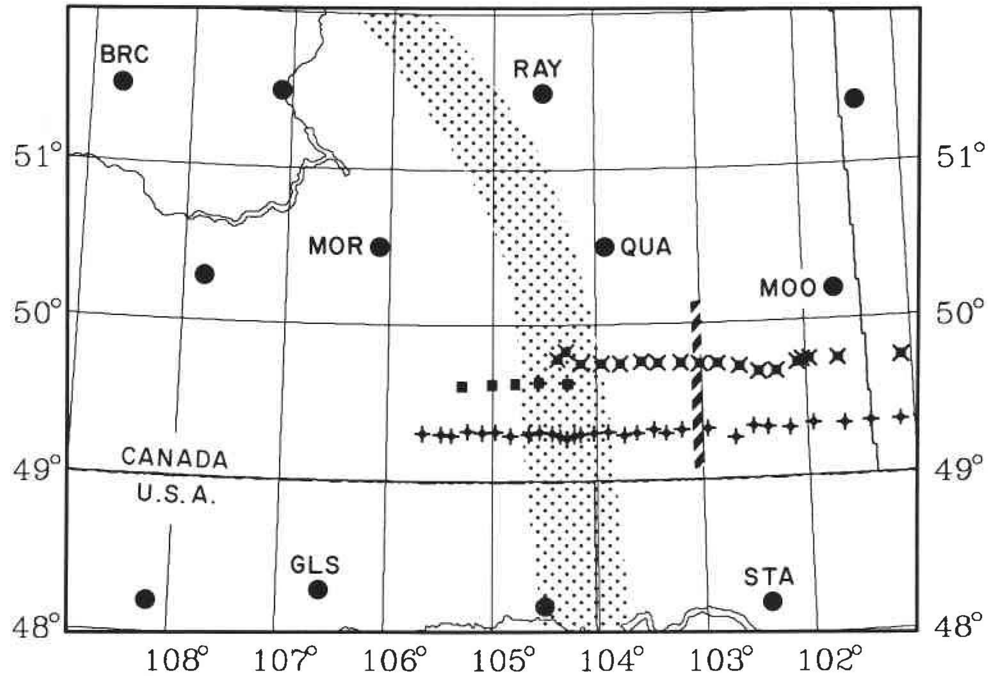

FIG. 1. Map of the area discussed in the text. Illustrated are the MT sites of Jones and Savage (1986) (pluses), Maidens and Paulson (squares), and Rankin and Pascal (in preparation) and the GDS sites of Alabi *et al.* (1975) (dots), with names beside those referred to explicitly. Also illustrated is Alabi *et al.*'s proposed location of the NACP from the GDS studies (crosshatch) and the correct location of NACP from the MT studies (thick dashed line) of Jones and Savage and of Rankin and Pascal.

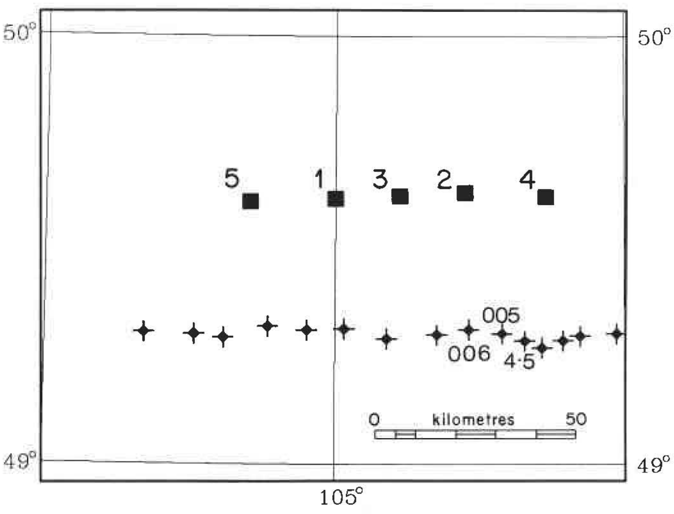

FIG. 2. Map of the five sites of Maidens and Paulson (numbered squares) and the 15 sites of Jones and Savage (1986) (pluses) between 104 and 105°30′W.

(1975). Furthermore, close examination of Alabi *et al.*'s data reveals that the anomaly was erroneously located by Alabi *et al.* in this region. Their Fig. 8 clearly indicates that the maximum of the real part of the H_y component for a relatively uniform field event lies to the *east* of GDS station QUA. Moreover, the east-northeast-pointing quadrature induction arrow, derived by Alabi *et al.* (their Fig. 9) for station QUA at a period of 68.3 min, clearly indicates that the NACP passes to the *east* of that station. Alabi *et al.* (1975, p. 828) commented 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."

One other major feature worthy of note in the GDS work of Alabi (1974) and Alabi *et al.* (1975) is that the *character* of the NACP changes markedly north of approximately 50°N. Figure 6 of Alabi *et al.* illustrates the phase of the vertical component of the magnetic field for a magnetic substorm, and it shows a concentration of contour lines south of the Canada – United States border that is in stark contrast to the dispersed nature of the contours north of the border. The *Z* phase is not nearly as spatially concentrated to the north. 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 Alabi *et al.*). The very existence of the NACP conductor at these latitudes is not in question, however; its presence is exhibited by the reversal in the phase of the vertical-field magnetograms between GDS stations RAY and BRC, stations MOO and MOR, and stations STA and GLS of Fig. 1 (see Alabi 1974, Figs. 4.5*b* and 4.5*c*). Accordingly, source effects cannot explain this along-strike variation.

This variation may indicate that the NACP conductor dips to greater depth to the north, or it may imply that the conductor is not a continuous feature but rather has breaks in it and that the contours on Fig. 6 of Alabi *et al.* (1975) are an expression of one of the "ends." This latter explanation, of 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 proposed that the conductor "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." Recent interpretation of MT data recorded along two more northerly pro-

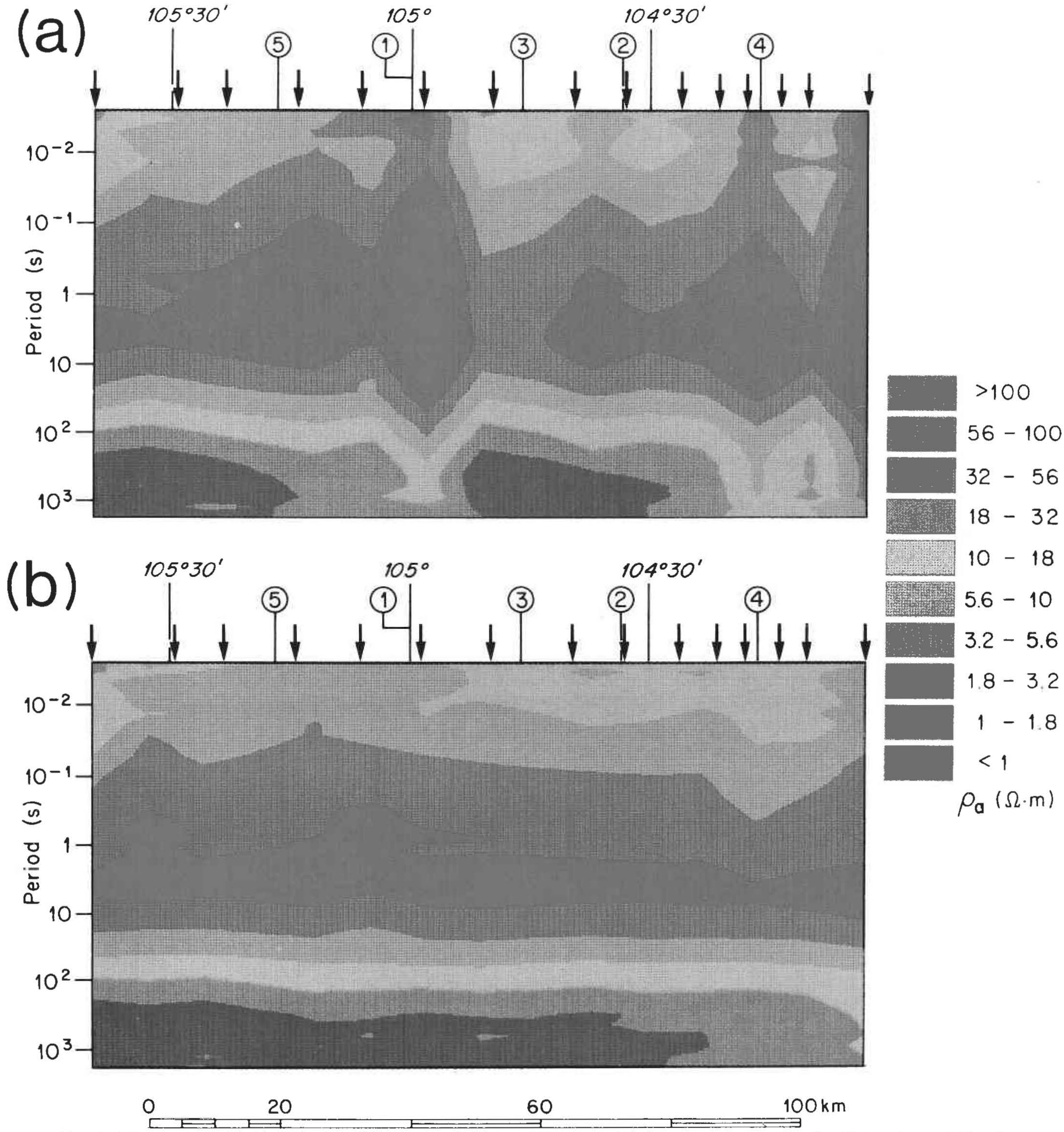

FIG. 3. The uncorrected (*a*) and static-shift-corrected (*b*) ρ_{xy} apparent-resistivity pseudosectons for the 15 locations of Fig. 2.

files in Saskatchewan (Jones and Craven, in preparation) appear to corroborate Thomas *et al.*'s (1987) suggestion.

Jones and Savage's (1986) magnetotelluric responses and their static-shift correction

Figure 2 illustrates the locations of 15 of the 35 MT sites recorded by PHOENIX Geophysics of Toronto for PanCanadian Petroleum Limited and reported by Jones and Savage (1986). Also shown on the figure are the locations of the five sites occupied by Maidens and Paulson, which are on a parallel east–west profile some 25 km north of the PanCanadian profile. Although there are no aeromagnetic data for this region in the Canadian data base, the compilation by Green *et al.* (1985), which included industrial data, indicates that there is little reason for expecting a structure beneath Maidens and Paulson's profile grossly different from that beneath Jones and Savage's. The gravity data of Thomas *et al.* (1987) also indi-

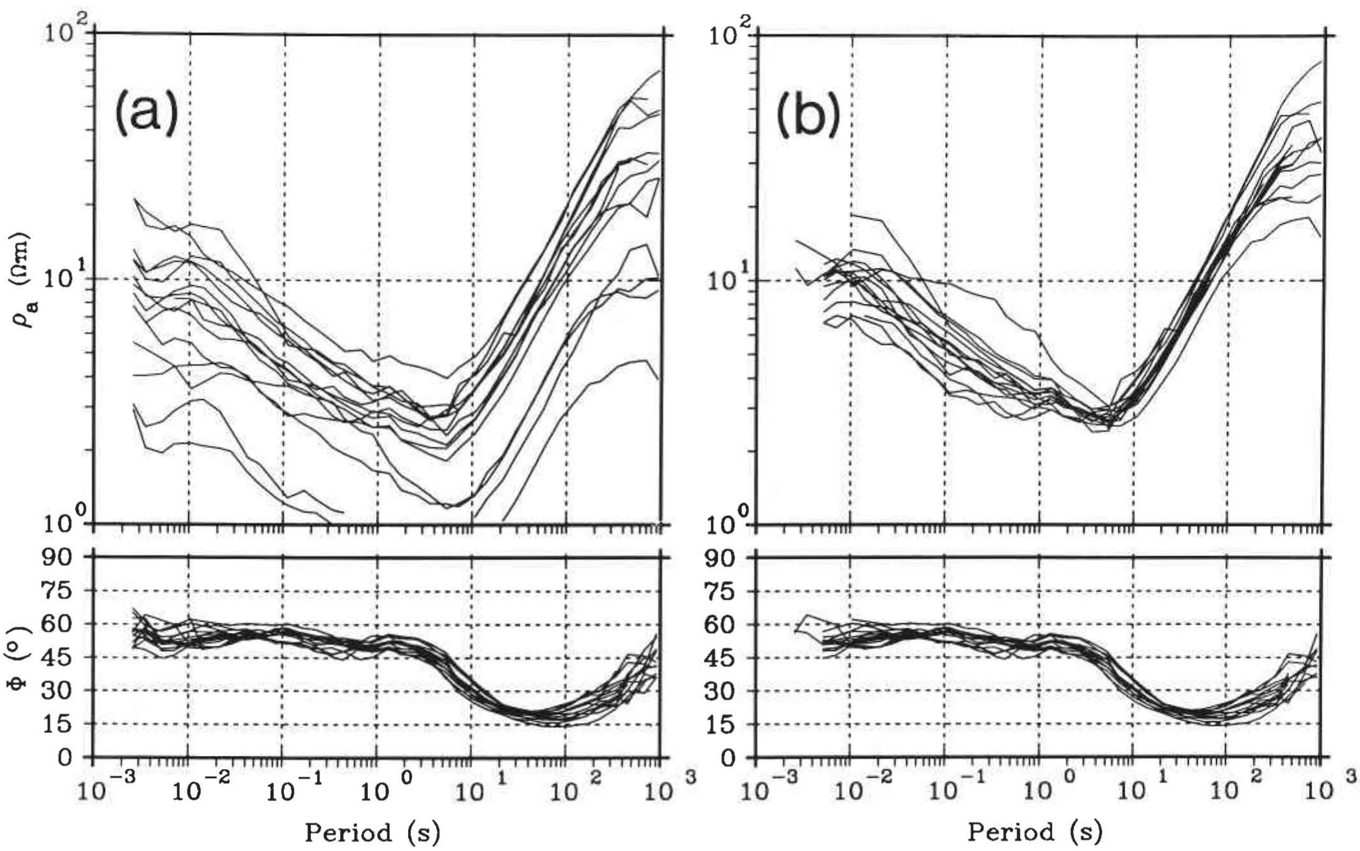

FIG. 4. Composite plots of Jones and Savage's (1986) ρ_{xy} and ϕ_{xy} responses from all 15 locations illustrated in Fig. 2. (*a*) Uncorrected responses; (*b*) static-shift-corrected ones.

cate a similar density structure beneath both MT profiles.

In Fig. 3*a* is illustrated the Jones and Savage (1986) ρ_{xy} MT apparent-resistivity responses in pseudosection form in a geographical co-ordinate system, i.e., the ρ_{xy} estimates are those responding to north–south-flowing current through the 2D electrical-conductivity structure and are thus the E-polarization responses. (The apparent-resistivity pseudosections of the complete profile can be found in Jones (1988).) In the main, only the E-polarization responses are considered herein because the B-polarization responses are insensitive to the NACP structure and because Maidens and Paulson considered E-polarization 1D inversions alone for their geological interpretation. Figure 4*a* also illustrates these responses together with their associated phases.

Note that whereas the phases do not vary laterally (Fig. 4*a*), the apparent-resistivity pseudosection (Fig. 3*a*) shows a lot of "vertical structure" and apparently indicates that there is a lot of lateral variation. In particular, in the pseudosection there appear to be "anomalies" at ≈ 104°30′ and 105°W.

This apparent contradiction between the lack of lateral phase variation compared with the great lateral variation of apparent-resistivity responses is reconciled by appreciation of a phenomenon named "static shift" (see Jones 1988 and references therein), which describes the effect on apparent-resistivity curves caused by local near-surface three-dimensional (3D) inhomogeneities. These small features cause apparent resistivities to be multiplied by the same factor at all frequencies, such that on a log-ordinate scale the apparent-resistivity curve is moved either up or down whilst retaining its shape. Static shifts do not affect phase curves, and accordingly more recent interpretations of MT data have tended to give more emphasis to the phase responses than to the apparent resistivities themselves. Note in Fig. 4*a* that the apparent-resistivity curves all have the same shape but are shifted vertically up and down from each other.

When such static-shifted apparent-resistivity data are interpreted in terms of a 1D layered Earth, the estimates of layer depths and resistivities are no longer independent but become related by the formula (Larsen 1977)

$$\frac{d_s^2}{\rho_s} = \frac{d^2}{\rho}$$

where d and ρ are the true layer depths to base and the resistivity, respectively, and d_s and ρ_s are the static-shifted incorrect estimates of them. If the effect of the static shift is to *increase* the apparent resistivities, then both d_s and ρ_s are *overestimates* of d and ρ. Conversely, a *decrease* in apparent resistivities causes both d_s and ρ_s to be *underestimated.* Thus, if the apparent-resistivity and phase data are not available in a published article, inspection of the resulting 1D models may indicate potential difficulties due to static shift.

Jones (1988) describes in detail a scheme for correcting MT apparent resistivities for static shift should there exist within the section beneath the profile a layer whose lateral variation in electrical conductivity can be described in a parametric fashion. As an example of this scheme, the Williston Basin MT data along Jones and Savage's (1986) profile were corrected by assuming that a conducting layer within the sedi-

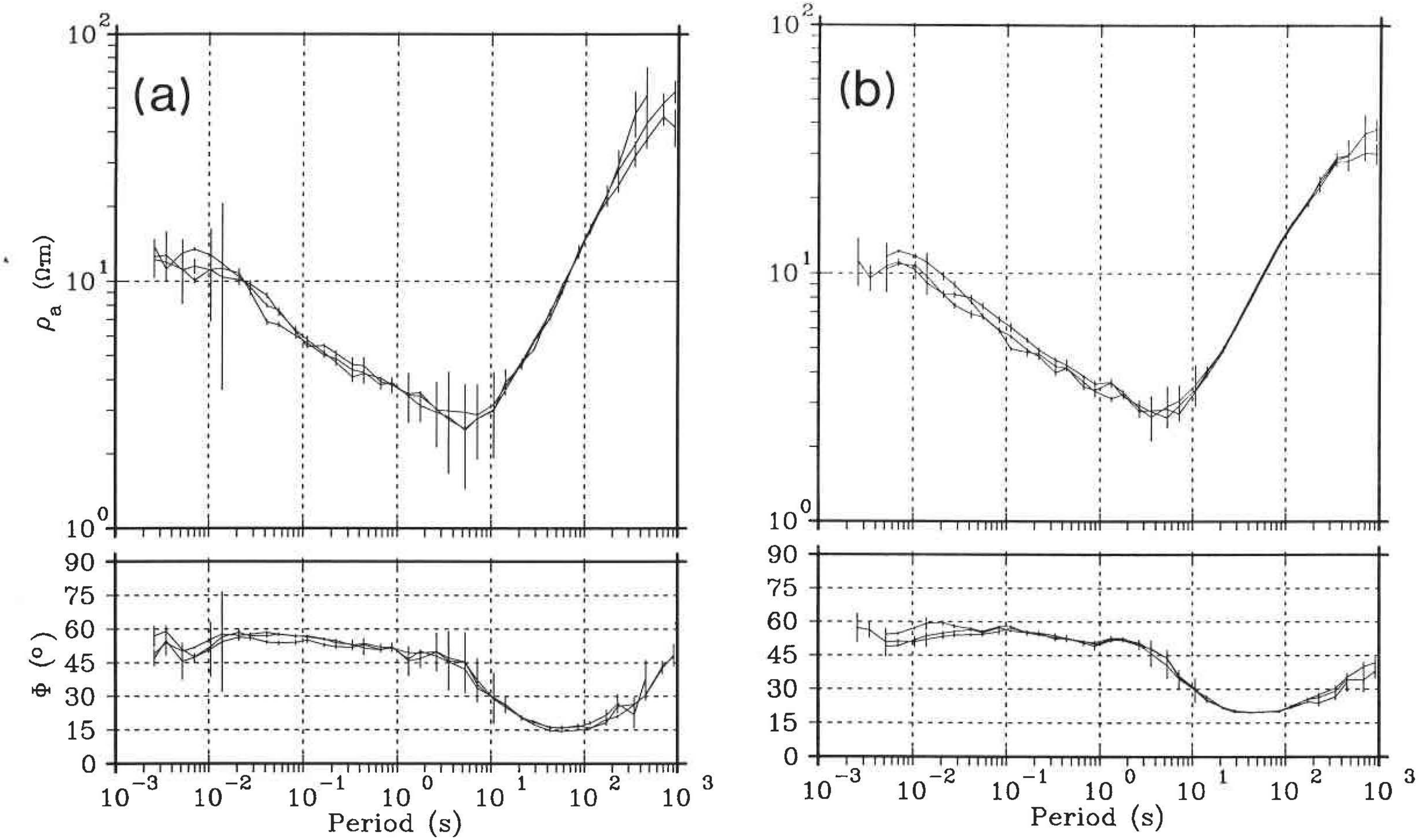

FIG. 5. Static-corrected apparent-resistivity and phase information from Jones and Savage's sites 006, 005, and 4.5 (Fig. 2). The error bars are ±1 standard error. At the longest periods there is no statistical difference between the E-polarization (*a*) observations from the three locations or between the B-polarization (*b*) ones.

ments had a resistivity of 3 Ω · m, which was the modal value of the estimates of the resistivity for this layer. The validity of this assumption of lateral uniformity of this zone was illustrated by the LATEROLOG information for the basement-reaching boreholes coupled with the structural cross section along the profile made available by PanCanadian Petroleum Limited (Fig. 12 of Jones 1988). Cartwright (1985), quite independently, also adopted a value of 3 Ω · m for the second layer to adjust the apparent-resistivity curves up or down for the westernmost 18 sites (Fig. 1) to correct for static shift.

In Figs. 3*b* and 4*b* are illustrated the ρ_{xy} apparent resistivities after correction by static shift. Obviously the "vertical" features exhibited in the pseudosection of Fig. 3*a* are not present, and the concentration of apparent-resistivity curves in Fig. 4*b* is in stark contrast to the wide separation of the curves in Fig. 4*a*.

Maidens and Paulson refer to Cartwright (1985), who identified from the data recorded at site 005 (Fig. 2) an anomaly in the PanCanadian data with its western edge near 104°32′W. Note that in the static-shifted data (Fig. 3*a*) there is indeed an anomaly at that location—but the supposed "anomaly" is purely due to static shift, and once the data have been corrected, this anomaly disappears (Figs. 3*b*, 5*a*, 5*b*). The static-corrected E-polarization (Fig. 5*a*) and B-polarization (Fig. 5*b*) data for Jones and Savage's (1986) sites 006, 005, and 4.5 indicate that, to within statistical error, there is no lateral variation in electrical conductivity beneath these locations. This is also confirmed by the phase data, which show virtually identical responses from these locations. Thus, this apparent contradiction between Jones and Savage's statements and those of Cartwright (1985), which apparently "puzzled" Maidens and Paulson (p. 66), is due to Cartwright's perhaps overzealous interpretation of the PanCanadian MT data in order to find an anomaly in the region of the NACP anomaly as defined by the GDS observations (Fig. 1). Cartwright (1985) concluded that "The possibility exists that other, less significant basement conductors are present under (sites 006, 005 and 4.5), but their individual responses are rendered unrecognizable by the relative proximity of the very large conductive structure thought to lie close to (103°W)."

Maidens and Paulson's data and their interpretation

Although Maidens and Paulson do not show all their data, their pseudosections of the apparent resistivities ρ_{xy} and ρ_{xy} do display evidence of static shift in their high-frequency parts (frequencies > 0.1 Hz), which is not consistent with the well logs from the region or with the phase responses observed by Jones and Savage (1986) (Figs. 4*a*, 4*b*). Unfortunately, Maidens and Paulson chose not to display the phase information from all of their sites, but the phase data that they do illustrate (their Fig. 3), which they describe as "typical," exhibit erratic and ill-defined phases at the longest periods (>500 s).

Quite apparent in Maidens and Paulson's 1D inversions (their Fig. 5) is the correlation between increasing resistivity from east to west of the conducting second layer with increasing resistivity in the layer directly below it and with increasing depth to the layer in the mid-crust beneath the zone held at 1000 Ω · m in the inversions. Obviously, their model parameters correlate in the manner discussed above for data affected by static shift.

Maidens and Paulson's contention that there exists a boundary within the lower crust between their sites 5 and 1 (Fig. 2), with resistivities less than 100 Ω · m to the east and some 250 Ω · m to the west, obviously would be supported by their longest period data. Their ρ_{xy} contoured pseudosections (their Fig. 4) indicate that there is little reason to expect such a dramatic change at this location, and indeed there would appear to be little difference between the longest period apparent resistivities calculated for their sites 5 and 3. Accordingly, we must surmise that the resolution of this zone comes from their longest period phase data alone, which, as discussed above, may be suspect.

One-dimensional modelling of two-dimensional data

Maidens and Paulson based their conclusions on 1D modelling of E-polarization data from a 2D body. As recognised many years ago by Berdichevsky and colleagues (see, for example, Berdichevsky and Dmitriev 1976), off the flank of a conducting 2D body within the Earth, a 1D interpretation of the E-polarization data leads to "false conducting layers," i.e., the erroneous interpretation that there exists a conducting layer within the resistivity sequence below the recording location, whereas the conducting body is, in fact, off to the side. Reflection seismologists term this effect in their data "side-swipe."

Figure 6 illustrates the theoretical E-polarization apparent resistivities, in pseudosection form, to the body also illustrated in Fig. 6. Apparent in the figure is that the longest period apparent resistivities off the flank of the body imply an increasing resistivity with increasing westward location, whereas the lower part of the model is completely uniform to the west of the body. One-dimensional inversion of these data would imply a laterally varying lower crust. This effect is merely side-swipe.

Note that in Maidens and Paulson's models (their Fig. 5), derived from a 1D inversion of the E-polarization responses, there is a general increase in the resistivity of the deepest layer from east to west, which can be attributed to side-swipe from the NACP conductor centred on 103°W.

Conclusions

The following points have been made in this discussion:

(1) Alabi *et al.*'s (1975) data are very ambiguous in the vicinity of the MT profiles, and accordingly little confidence should be given to the precise location of the NACP from these GDS observations. Particularly, no confidence should be placed on the locations of the east and west boundaries of the structure in Fig. 3 of Alabi *et al.*, reproduced, in part, in Fig. 1 here.

(2) After correction for static shift, it is evident from the PanCanadian data set that the maximum response from the NACP anomaly occurs at 103°W longitude at the latitude of the Canada – United States border. This is also corroborated by the independent work of Rankin and Pascal (in preparation) along their profile (Fig. 1) farther to the north. There is *no* anomaly at 104°32′W as reported by Cartwright (1985)—this is an overzealous interpretation by Cartwright of the data from Jones and Savage's (1986) site 005 to delineate an anomaly at the GDS location of the NACP anomaly.

(3) Maidens and Paulson's interpretation of an anomaly near 105°W longitude appears to rely solely on possibly suspect long-period phase estimates at one of their sites. Such "single-station" anomalies should always be treated with utmost caution.

(4) One-dimensional interpretation of the E-polarization responses off the flank of a 2D body, as undertaken by Maidens

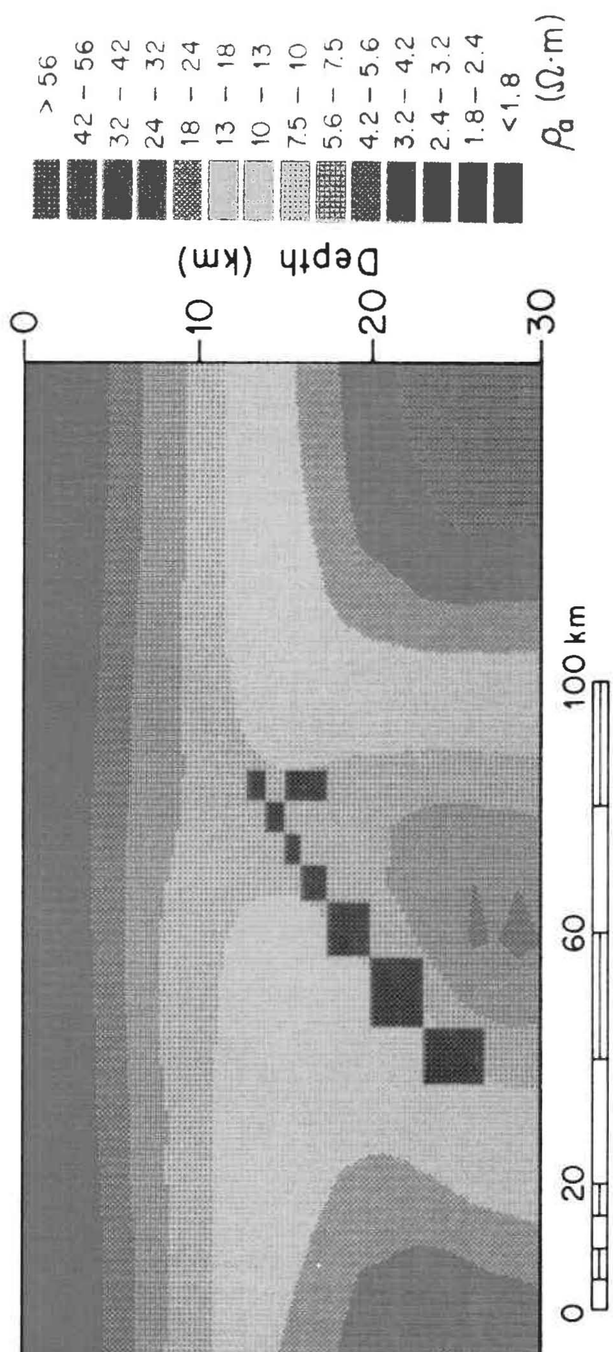

FIG. 6. The theoretical E-polarization apparent-resistivity pseudosection in the period range 10–1000 s for the 2D model illustrated (depth scale on right side).

and Paulson, results in "false conducting layers."

The location of the NACP detailed by Jones and Savage (1986) and by Rankin and Pascal (in preparation) at 103°W (thick dashed line in Fig. 1) correlates with various other geophysical parameters (as discussed in detail in Jones and Craven (in preparation)), in particular with an anomaly in heat flow (Majorowicz *et al.* 1986).

Finally, the existence of a zone of some hundreds of ohm metres in the lower continental crust is becoming a ubiquitous feature of analyses of MT data around the world and should no longer be considered *anomalous* (see Jones 1981, 1987). Indeed, more anomalous are observations of zones of some thousands of ohm metres in the continental lower crust.

Contrary to the interpretation of Maidens and Paulson, the anomaly detected by Alabi *et al.*'s GDS observations *is* at 103°W, and its name *is* the NACP!

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