Electromagnetic images of the Trans-Hudson orogen: the North American Central Plains anomaly revealed[1, 2]

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Abstract: Magnetotelluric studies of the Trans-Hudson orogen over the last two decades, prompted by the discovery of a significant conductivity anomaly beneath the North American Central Plains (NACP), from over 300 sites yield an extensive database for interrogation and enable three-dimensional information to be obtained about the geometry of the orogen from southern North Dakota to northern Saskatchewan. The NACP anomaly is remarkable in its continuity along strike, testimony to along-strike similarity of orogenic processes. Where bedrock is exposed, the anomaly can be associated with sulphides that were metamorphosed during subduction and compression and penetratively emplaced deep within the crust of the internides of the orogen to the boundary of the Hearne margin. A new result from this compilation is the discovery of an anomaly within the upper mantle beginning at depths of ~80–100 km. This lithospheric mantle conductor has electrical properties similar to those for the central Slave craton mantle conductor, which lies directly beneath the major diamond-producing Lac de Gras kimberlite field. While the Saskatchewan mantle conductor does not directly underlie the Fort à la Corne kimberlite, which is associated with the Sask craton, the spatial correspondence is close.

Résumé : Poussées par la découverte d'une importante anomalie de conductivité sous les plaines centrales de l'Amérique du Nord (« NACP »), les études magnétotelluriques de l'orogène trans-hudsonien au cours des deux dernières décennies, dans plus de 300 sites, constituent une base de données extensive à interroger et qui fournira des informations en 3D sur la géométrie de l'orogène du sud du Dakota du Nord jusqu'au nord de la Saskatchewan. L'anomalie des plaines centrales de l'Amérique du Nord est remarquable par sa continuité selon la direction, témoin de la similarité des processus orogéniques le long de la direction. Là où affleure le socle, l'anomalie peut être associée à des sulfures qui ont été métamorphosés durant la subduction et la compression puis mis en place, pénétrant profondément dans la croûte des internides de l'orogène jusqu'à la limite de la bordure Hearne. Un nouveau résultat de cette compilation est la découverte d'une anomalie à l'intérieur de la croûte supérieure commençant à des profondeurs d'environ 80–100 km. Ce conducteur du manteau lithosphérique a des propriétés semblables à celles du conducteur du manteau central des Esclaves qui se trouve directement en dessous du grand champ de kimberlite diamantifère du Lac de Gras. Alors que le conducteur du manteau de la Saskatchewan n'est pas situé directement sous la kimberlite de Fort à la Corne, laquelle est associée au craton Sask, la correspondance spatiale s'y rapproche.

[Traduit par la Rédaction]

Introduction

The Trans-Hudson orogen (THO) is the most prominent member of a remarkable series of Paleoproterozoic orogens, shown on a tectonic map of North America (Fig. 1), that welded together Archean cratons to form Laurentia at around 1.95–1.75 Ga. The orogen closed the Manikewan Ocean (Stauffer 1984), estimated from paleomagnetic studies to have been at least as large as the current Pacific Ocean (5500 ± 700 km, Symons 1998). In present-day coordinates, the Archean cratons on opposing coasts of the Manikewan Ocean were the Superior craton to the east and the Wyoming and Rae–Hearne cratons to the west, northwest, and north (Figs. 1, 2).

Trans-Hudson orogen transect (THOT) studies were initiated as part of Lithoprobe's Phase III activities with its theme of

Received 7 January 2004. Accepted 26 January 2005. Published on the NRC Research Press Web site at http://cjes.nrc.ca on 30 June 2005.

Paper handled by Associate Editor R.M. Clowes.

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[1]This article is one of a selection of papers published in this Special Issue on *The Trans-Hudson Orogen Transect of Lithoprobe*.
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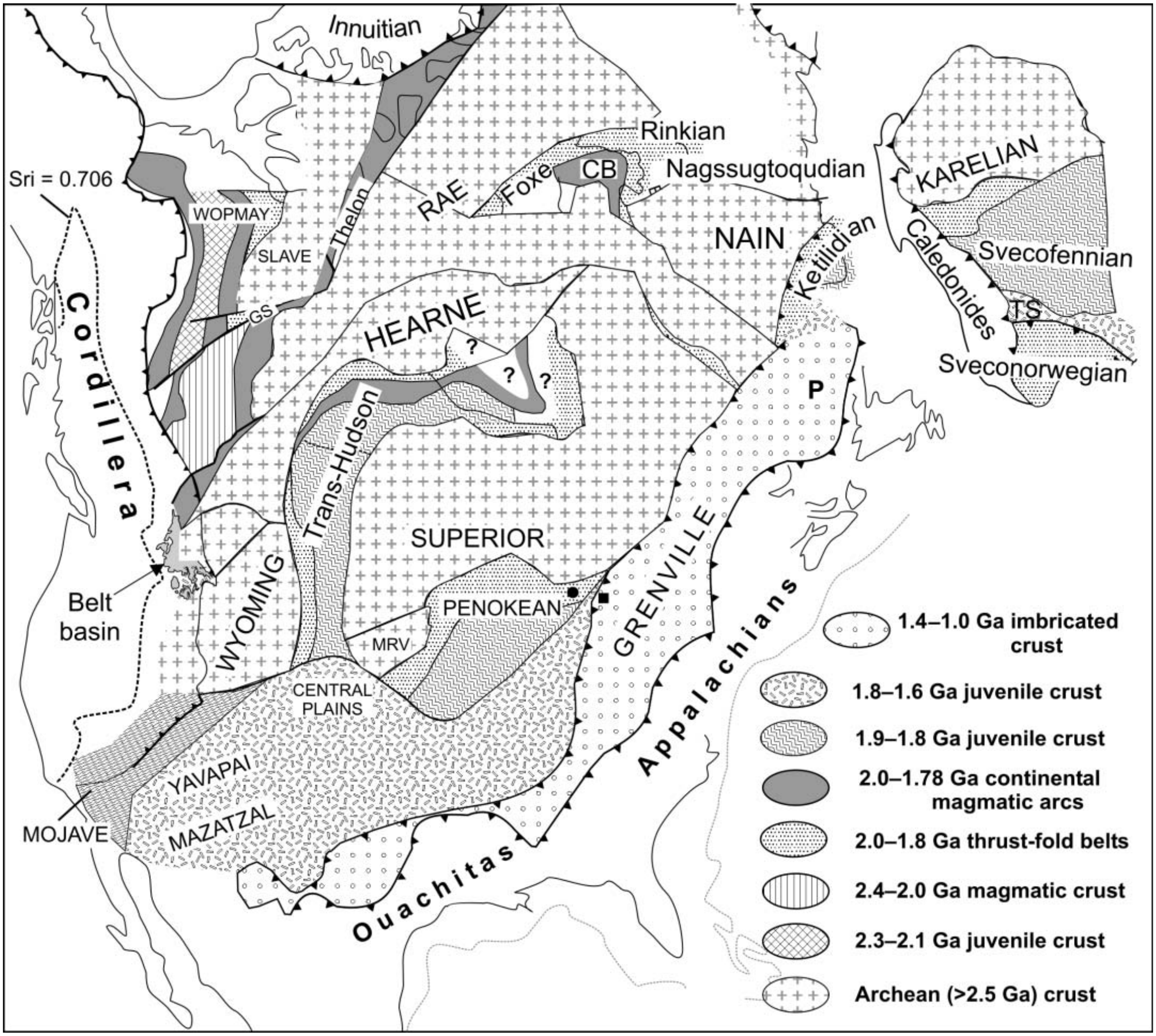
 doi: 10.1139/E05-018 © 2005 NRC Canada

Fig. 1. Tectonic map of North America (from Ross and Villeneuve 2003, and based on Hoffman 1988).



"The Evolution of a Continent" and, unequivocally, the tectonic history of the North American continent cannot be understood without full appreciation of the THO. One fundamental objective of THOT activities from the outset was establishing the spatial and structural relationships of the North American Central Plains (NACP) conductivity anomaly (see later in the text) — the largest continental-scale conductor ever delineated by electromagnetic studies. This objective was undertaken using a natural source electromagnetic method, magnetotellurics (MT), in profiling mode to obtain the crustal and uppermost mantle electrical resistivity structure along the Lithoprobe profiles.

In addition to the two MT surveys funded under the auspices of Lithoprobe, over the last 20 years a series of MT surveys over the THO has been funded by industry, the Geological Survey of Canada, and the US National Science Foundation's Continental Dynamics program. In total, high quality MT measurements have been made at 288 locations in the internides of the THO and on its flanking cratons, from the southern part of North Dakota to northern Saskatchewan and northern Manitoba (Fig. 2).

In this paper, we will briefly review early electromagnetic investigations using geomagnetic depth sounding (GDS) arrays and profiles and how the existence of the THO beneath the Phanerozoic sediments was first proposed based on these studies. We outline the series of MT investigations since the early 1980s, culminating in the Lithoprobe ones in the early and mid-1990s, and review the work already published from the studies. We then present and discuss new images of electrical parameters for certain depths derived from the total THO MT data set. This qualitative information will be followed by presentation and discussion of new two-dimensional (2-D)

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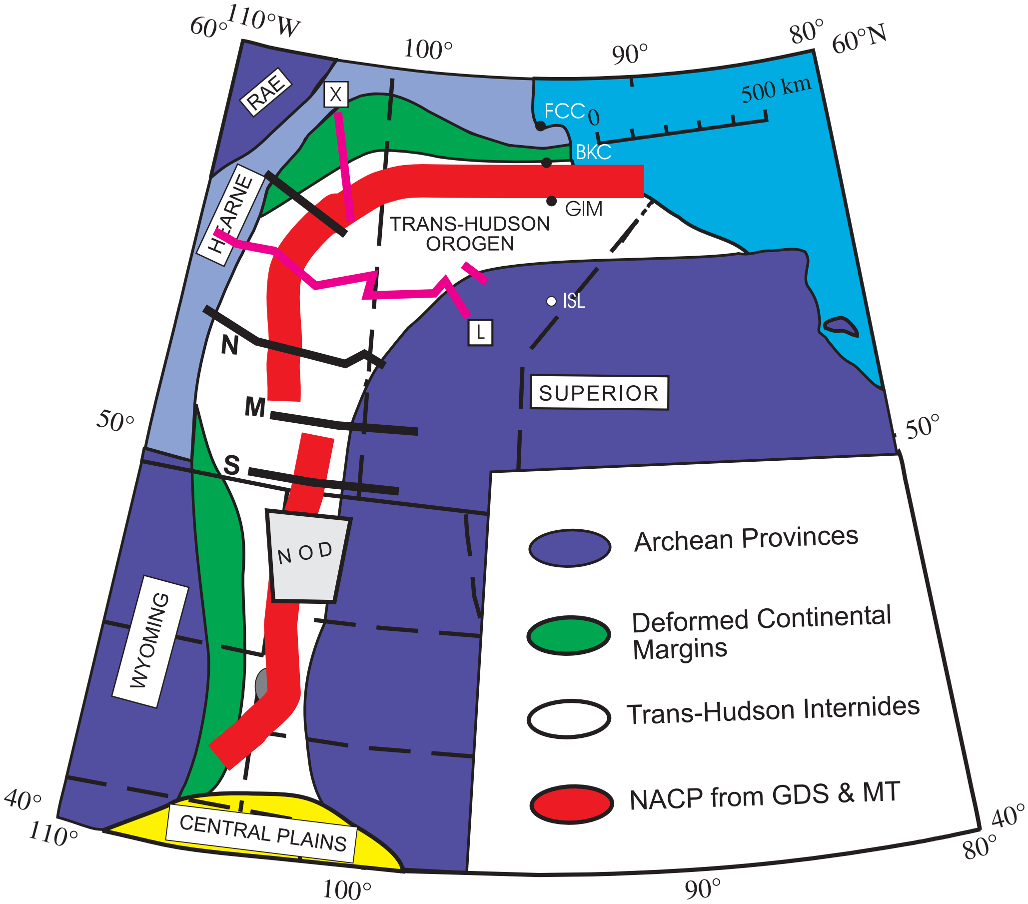
Fig. 2. The North American Central Plains (NACP) anomaly within the THO. Also shown are the locations of the MT surveys (NOD, S, M, N, L, and X), the GDS profile of Handa and Camfield (1984), and the stations used by Gupta et al. (1985). NOD, North Dakota profiles; GDS, geomagnetic depth sounding; TM, magnetotellurics. Magnetometer stations: BKC, Back; GIM, Gillam; FCC, Fort Churchill; ISL, Island Lake.



resistivity-depth models of the Earth from profiles crossing the THO. The new model of the whole orogen from the MT data recorded along the main Lithoprobe profile exhibits an anomaly in the upper mantle intriguingly similar to one discovered in the central part of the Slave craton. Finally, the role that the NACP plays in the orogenic process will be discussed, and the implications one can draw from its geometry in terms of tectonic history will be presented.

Brief description of magnetotelluric terminology

In the MT method, one measures components of the time-varying, natural electromagnetic field on the surface of the Earth. All thee components of the magnetic field are measured — magnetic north *Hx(t)*, magnetic east *Hy(t)*, and magnetic vertical *Hz(t)* — but only the two horizontal components of the electric field are measured in magnetic north *Ex(t)* and magnetic east *Ey(t)* directions. The five time series are Fourier transformed into the frequency domain, and spectral ratios are formed from the various cross-spectral estimates. From these ratios one derives the frequency-dependent 2×2 complex MT impedance tensor elements that relate the electric to the horizontal magnetic fields, and the 1×2 complex geomagnetic transfer functions (GTF) that relate the vertical magnetic field to the horizontal magnetic fields. The MT and GTF tensors from each site are subsequently analysed and interrogated for information about the subsurface below. The MT impedance elements are converted into frequency-dependent amplitudes and phases, and the amplitudes are scaled so that they give the true resistivity for a uniform half-space. For a non-uniform Earth, the frequency-dependent values are called apparent resistivities.

When the subsurface can be validly described by a 2-D regional Earth, then the impedance tensor, when aligned with the strike of the structures, adopts an anti-diagonal form (i.e., the two diagonal elements are zero). One off-diagonal element describes the flow of electric current *along* structures and is called the transverse-electric (TE) mode of induction. The other off-diagonal element describes the flow of current *across* structures and is called the transverse-magnetic (TM) mode. Methods of finding the strike direction are diverse, with modern ones considering how the impedance phases, rather than the impedance amplitudes, behave during rotation. The most common ones in use, namely Zhang et al. (1987), Bahr (1988), Groom-Bailey (1989), Chakridi et al. (1992), Smith (1995), and McNeice and Jones (1996, 2001), all have as their basis the galvanic distortion of the electric fields

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approach of Richards et al. (1982), which is a 2-D extension of the one-dimensional (1-D) distortion approach of Larsen (1977).

This galvanic distortion, caused by local, near-surface inhomogeneities, is the bane of the MT method. A number of methods have been proposed to extract the regional impedances from the distorted ones (see earlier in the text), and, of these, the method of Groom and Bailey (in Groom and Bailey 1989, 1991 and Groom et al. 1993) is the most appealing in that it undertakes a matrix factorization that separates parameters into those that are determinable and those that are not. The indeterminable parameters relate to the frequency-independent magnitude shifts called static shifts (Jones 1988*a*; Sternberg et al. 1988). The additional attraction of the Groom–Bailey approach is that it casts the problem into one of fitting a distortion model to the observations, and one can test statistically whether the distortion model is appropriate or not. The superiority of fitting a model over rotating the data into the defined strike coordinate system is amply demonstrated in Jones and Groom (1993) and McNeice and Jones (2001).

Once the regional 2-D responses have been derived in the appropriate strike coordinate system, they are then modelled using either forward trial-and-error fitting or non-linear, iterative inversion. Both of these approaches are used herein.

The North American Central Plains anomaly and its association with the Trans-Hudson orogen

One station in the corner of a GDS magnetometer array operated in September 1967, in the western USA, proved what has become known as "Gough's rule" (the GDS equivalent of Murphy's Law) of being highly anomalous (Reitzel et al. 1970). This station, located close to the town of Crawford in western Nebraska, displayed a large intensification of both the vertical (*Hz*) and east (*Hy*) components of the magnetic field data at all periods, and the Fourier spectra maps of Reitzel et al. (1970) are visually dominated by its response. The data were so anomalous that they caused problems for Porath et al. (1970) in their attempts to separate the array data into parts of origin external and internal to the Earth using 2-D Fourier integrals.

Fortunately for THO studies, the response at this station was not ignored (one may wonder what modern "robust interpretation" would have done!), much to the credit of those involved, but was taken into consideration in the design of an array operated in July 1969 in northwestern USA and southwestern Canada by Camfield et al. (1970). The main purpose of that array was to study the relationship between the North American craton and the exotic terranes of the Cordillera, and to link together GDS profiles in southwestern USA with those in southern British Columbia (see Jones 1993, for a review of the British Columbia studies). However, Camfield et al. (1970) chose to extend their array eastwards to study the single-station anomaly at Crawford. What they discovered was a large and very narrow anomalous structure running from the Black Hills of South Dakota north to the Canadian border along the boundary between Montana and the Dakotas.

They called this feature the NACP conductivity anomaly; it was the most prominent zone of enhanced conductivity found in any of their array studies. The anomalous part of the *Hy* field (*Hya*) was shown to be more than double the normal part of *Hy* (*Hyn*), which Camfield et al. (1970) argued, "cannot be accounted for by local induction in an elongated structure." The authors suggested that the NACP anomaly could not be explained by the sedimentary structures in the Williston basin, nor by currents in the upper mantle, and, noting that high conductivities had been observed in graphite bodies in western South Dakota (Mathisrud and Sumner 1967), proposed that its high conductivity and linear form could be because of a graphitic schist body in the basement. Analysis of daily variation (24-hour periodicity) data showed that the NACP anomaly persisted in *Hz*, but was weak in the *Hy* component (Camfield and Gough 1975). It was concluded that the NACP conductor channels current induced in regions of unknown geometry by *Hyn* at substorm periods and by *Hzn* at daily variation periods.

Data from a profile of stations from the GDS array across the NACP at the latitude of the Black Hills were modelled two-dimensionally by Porath et al. (1971) who found that the normalized *Hz* data (*Hz/Hyn*) at 50′ period (the period of maximum *Hz/Hyn* response) could be explained by a body of 0.1 Ω·m resistivity, 30 km wide, 3 km thick with its top at 2-km depth. Although Porath et al. (1971) believed the *Hz* results from the 2-D forward modelling code used (Wright 1969), they thought that the *Hy* results were erroneous as the anomalous east–west-directed magnetic field, *Hya*, was greater than the normal east–west-directed magnetic field, *Hyn*. Accordingly, they derived the anomalous horizontal fields from a transformation of the vertical fields using the Hilbert transform relationship. They were unable to explain the observed period-dependency of the normalized *Hz* amplitudes and concluded that the NACP conductor must connect large regions in which the currents were actually induced and subsequently "channelled" through the NACP.

Gough and Camfield (1972) considered that their graphitic schist interpretation for the source body of the NACP anomaly (Camfield et al. 1970) was strengthened by Lidiak's (1971) mapping of a metamorphic belt striking just west of north through the Black Hills. Rankin and Reddy (1973) undertook a 15 station MT survey of the Black Hills, and the two stations on the flanks of the Black Hills gave anisotropic apparent resistivity curves, with their minor curves (TE mode) indicating conducting layers beneath the sediments at depths of 12.3 km and 3 km to the east and west, respectively. In contrast, their MT data, albeit poor (only data from three of the 15 sites are shown in Rankin and Reddy 1973), from the station in the centre of the Black Hills gave isotropic apparent resistivities at around 1 Ω·m (0.4–35 Ω·m) in the period range 50–600 s.

In August and September 1972, a large 41 station GDS array, specifically to study the NACP anomaly, was operated from Wyoming and Nebraska to northern Saskatchewan and Manitoba, over 13° in latitude and 10° in longitude, by Alabi et al. (1975). This array defined a north–south concentration of electric current from the southern Rockies to just south of the exposed shield. Alabi (1974) and Alabi et al. (1975) suggested that the NACP anomaly marked a major structure in

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Table 1. Magnetotelluric surveys across the Trans-Hudson orogen and North American Central Plains conductivity anomaly.

Line	Survey	Year	Location	No. sites	Equipment	Frequency (Hz) or period (s) range
S	PanCanadian	1984	southern Saskatchewan	20	MT-16	384 Hz – 1820 s
S	PanCanadian	1985	southern Saskatchewan	17	MT-16	384 Hz – 1820 s
M, N	GSC	1987	central Saskatchewan	34 pairs	MT-16	384 Hz – 1820 s
L	Lithoprobe	1992	northern Saskatchewan and Manitoba	5652	V5+V5AMT	10 000 Hz – 1820 s
					V5AMT	10 000 Hz – 9 Hz
NOD	GSC (UW)	1992	North Dakota	64	LiMS	20 s – 10 000 s
L	U of M	1992	northern Saskatchewan	15	LiMS	20 s – 10 000 s
X	Lithoprobe	1994	northern Saskatchewan and Manitoba	30	V5+V5AMT	10 000 Hz – 1820 s

Note: GSC, Geological Survey of Canada; U of M, University of Manitoba; UW, University of Washington, Seattle, Washington.

the Precambrian basement spatially linking mapped faults in the Wollaston belt of northern Saskatchewan with the metamorphic belt mapped by Lidiak (1971) in the Black Hills.

This suggestion was elaborated on by Camfield and Gough (1977), who courageously and perceptively proposed that the NACP anomaly traces a Proterozoic plate boundary for some 1800 km beneath the Paleozoic sediments of the Central Plains of North America. In support of their interpretation, they cited Hills et al. (1975) who had suggested that there was a Proterozoic subduction zone in southeastern Wyoming. Camfield and Gough's (1977) suggestion ran counter to prevailing opinion at that time (Peterman 1979; references in Dutch 1983), but has been since proven correct primarily from basement samples in drill core (Peterman 1981; Van Schmus and Bickford 1981; Klasner and King 1986; Sims and Peterman 1986). Camfield and Gough (1977) reiterated their earlier interpretation that the NACP structure is likely because of graphitic sheets in highly metamorphosed and folded basement rocks. Unfortunately, the paper by Camfield and Gough (1977) has never received its due credit — they were the first to propose the continental-scale extension of what later was termed the THO beneath the Phanerozoic strata of the Williston basin.

To identify definitively the spatial correlation of the NACP anomaly with one of the domains of the Churchill Province of the exposed Precambrian structures in northern Saskatchewan, Handa and Camfield (1984) undertook a profile of seven GDS sites in July 1981, across the Wollaston fold belt into the THO internides (Fig. 2). Their stations were located in the belief that the NACP anomaly was associated with the Wollaston domain, and only two sites were positioned within the THO. As is always the case ("Gough's rule," again), the anomaly was found to lie between the two sites at the eastern end of the line: one on the Rottenstone domain and the other at the La Ronge – Glennie domains boundary (see Jones et al. 1993, for a domain map and further geological review of the exposed bedrock). The NACP anomaly was modelled two-dimensionally as a 10 Ω·m body with its top of 5–10 km depth and with a depth extent of some 20 km (i.e., a vertically integrated conductance of 2000 S).

Data from an International Magnetospheric Study chain of magnetometers running north–south alongside Hudson's Bay in Manitoba (dots in Fig. 2) were shown to exhibit a strong reversal in Hz between two stations; BCK (Back: 57.7°N, 94.2°W) and GIM (Gillam: 56.4°N, 94.7°W) (Gupta et al. 1985). These data were modelled two-dimensionally as a 25 Ω·m body at a depth of 5 km of weakly resolved thickness extent, but with a definite northward dip. On the basis of spatial correlation with exposed tectonic units of the THO internides, this anomaly was associated with the NACP structure mapped to the west.

Magnetotelluric data acquired across the Trans-Hudson orogen and NACP

Magnetotelluric data have been acquired across the THO and NACP as part of a number of projects. The dates, number of sites, and equipment used is listed in Table 1, and the profile locations are shown in Fig. 2.

The first of these, on profile S (Fig. 2), were two commercially contracted surveys, undertaken by Phoenix Geophysics Ltd., for PanCanadian Oil Company in 1984 and 1985 (Jones and Savage 1986). PanCanadian was interested in the possible basement control of sedimentary structures and the reported spatial relationship between the NACP mapped by the GDS studies and the prominent, major salt-collapse structure known as the Regina–Hummingbird Trough (Camfield and Gough 1977). The 1984 survey of 20 sites was based on the NACP location from the GDS studies, but the strongest responses were observed on the easternmost sites of the 1984 profile, not on the central sites as expected ("Gough's rule"!). Accordingly, a second survey was commissioned in 1985 of 17 sites to continue the MT profile to the east into Manitoba. The data from the 37 sites formed the COPROD2 study organized by Jones (1993), whereby different 2-D inverse codes were used by many authors on the same MT data.

MT measurements (not shown) were made just north of the PanCanadian profile by Maidens and Paulson (1988; see a discussion of their work in Jones 1988*b*) and by Rankin and Pascal (1990). The former interpreted static shift effects (Jones 1988*a*) in terms of structure, whereas the latter, notwithstanding their imaging of the NACP anomaly, concluded, somewhat perplexingly, that there was a gap in the NACP structure so that it did not cross their profile.

In 1987, Jones and Craven (1990) undertook a major regional-scale MT experiment in central Saskatchewan of 34 pairs of MT sites (the stations in each pair were approximately 1 km apart) on two profiles, profiles M and N (Fig. 2), crossing the NACP. These data were interpreted qualitatively in Jones and Craven (1990).

In 1992, a joint Geological Survey of Canada, Ottawa, Ont. and University of Washington, Seattle, Washington

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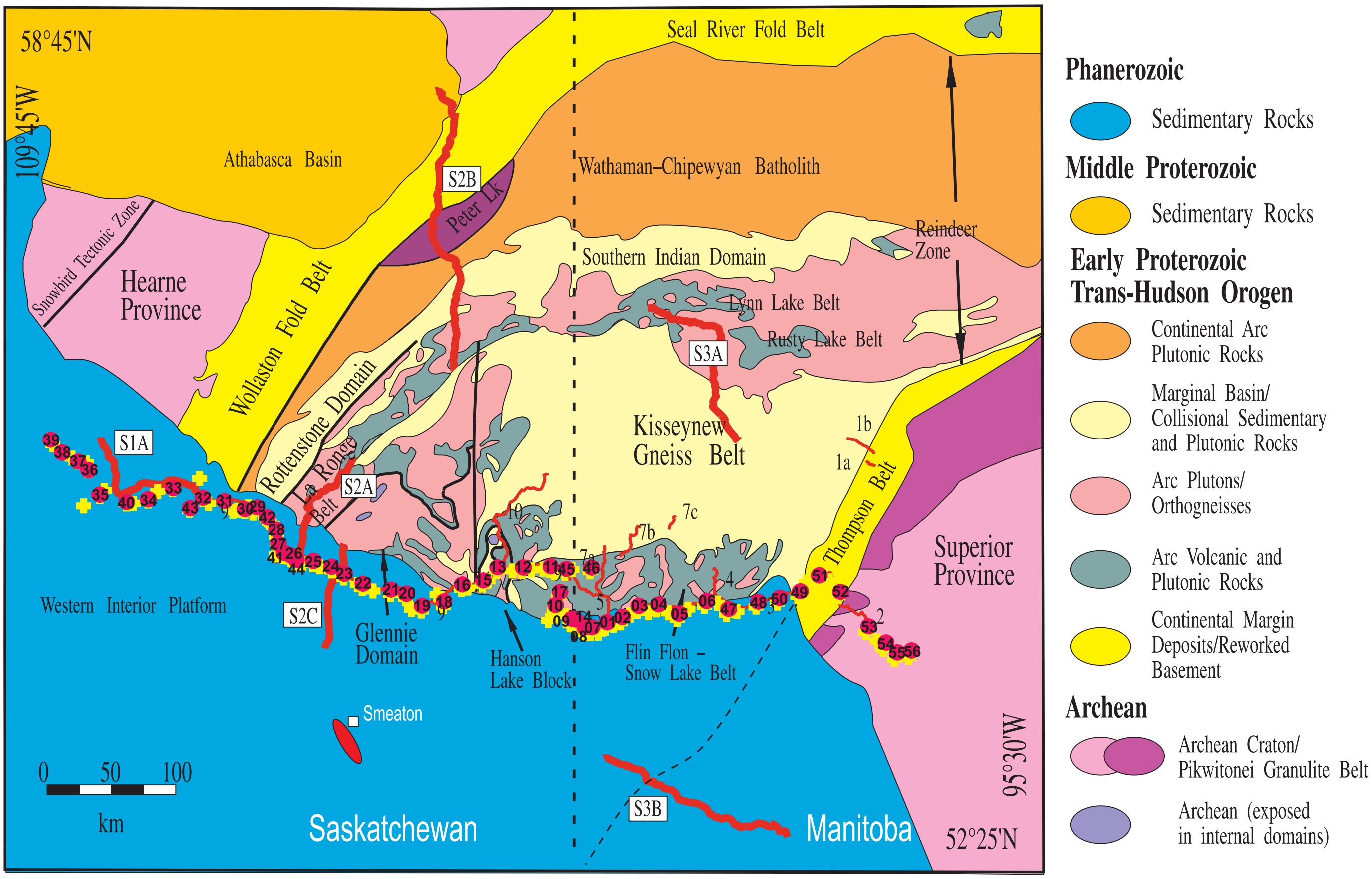
Fig. 3. Location of the Lithoprobe seismic reflection profiles in northern Saskatchewan and Manitoba. MT profile L was recorded along seismic profiles S1A, and MT profile X was recorded along seismic profile S2B. For profile L, the AMT+MT sites are numbered, AMT-only sites shown by crosses. Also shown is the location of the Fort à la Corne kimberlite (red ellipse south of Smeaton).



(GSC–UW) study took place in North Dakota, (Wu 1994; Booker et al. 1997). There were a total of 64 long-period MT (LMT) sites recorded on three main east–west profiles marked as box NOD in Fig. 2.

In the same year, Lithoprobe MT data were acquired along the main east–west Lithoprobe THOT (Fig. 3). A total of 108 MT sites were recorded: 56 were audio MT (AMT, frequency range of typically 10 000 – 10 Hz) and MT (AMT+MT), and the other 52, spaced between the AMT+MT sites, were AMT only. In addition, LMT data were acquired at 15 locations along this profile by the University of Manitoba for lithospheric imaging.

Subsequently, 30 AMT+MT sites were recorded in 1994 (Fig. 3). Twenty-three were located along seismic line S2B (Fig. 1, profile X) to give a second crossing of the western boundary, whereas the other seven were located across the eastern boundary close to the town of Thompson.

Review of published results of the magnetotelluric work

The first publication coming from the MT surveys was that of Jones and Savage (1986), based on the PanCanadian MT dataset. Their qualitative paper showed that the maximum MT response was some 75 km to the east of the suggested location of the NACP based on the GDS work of Alabi et al. (1975).

Subsequently, Jones and Craven (1990) published 1-D and 2-D models of the MT responses from the PanCanadian data, and also showed the MT responses from the two profiles in central Saskatchewan. They concluded that the NACP was not a continuous feature, but that it was offset to the west in central Saskatchewan. They showed that the anomaly was peculiar with no response to east–west flowing electrical current, but a large response to north–south flowing current. They interpreted the PanCanadian data, using 2-D forward trial-and-error modelling, as mid-crustal blocks of conducting material in an arcuate form that were not connected. This arcuate geometry was used later by Nelson et al. (1993) in their interpretation of data from the COCORP (Consortium for Continental Reflection Profiling) seismic reflection line in North Dakota, just south of the USA–Canada border.

The PanCanadian MT dataset, corrected for static shifts (Jones 1988*a*), was distributed widely to members of the international electromagnetic community as a test data set for examining, comparing and contrasting 2-D modelling and inversion approaches as part of the first Magnetotelluric Data Interpretation Workshop (MT-DIW1) held in Victoria, New Zealand, in 1992. Models derived from the data set COPROD2 (Comparison of Profiles from Data – 2-Dimensional) are published in Agarwal and Weaver (1993), deGroot-Hedlin and Constable (1993), Ellis et al. (1993), Everett and Schultz

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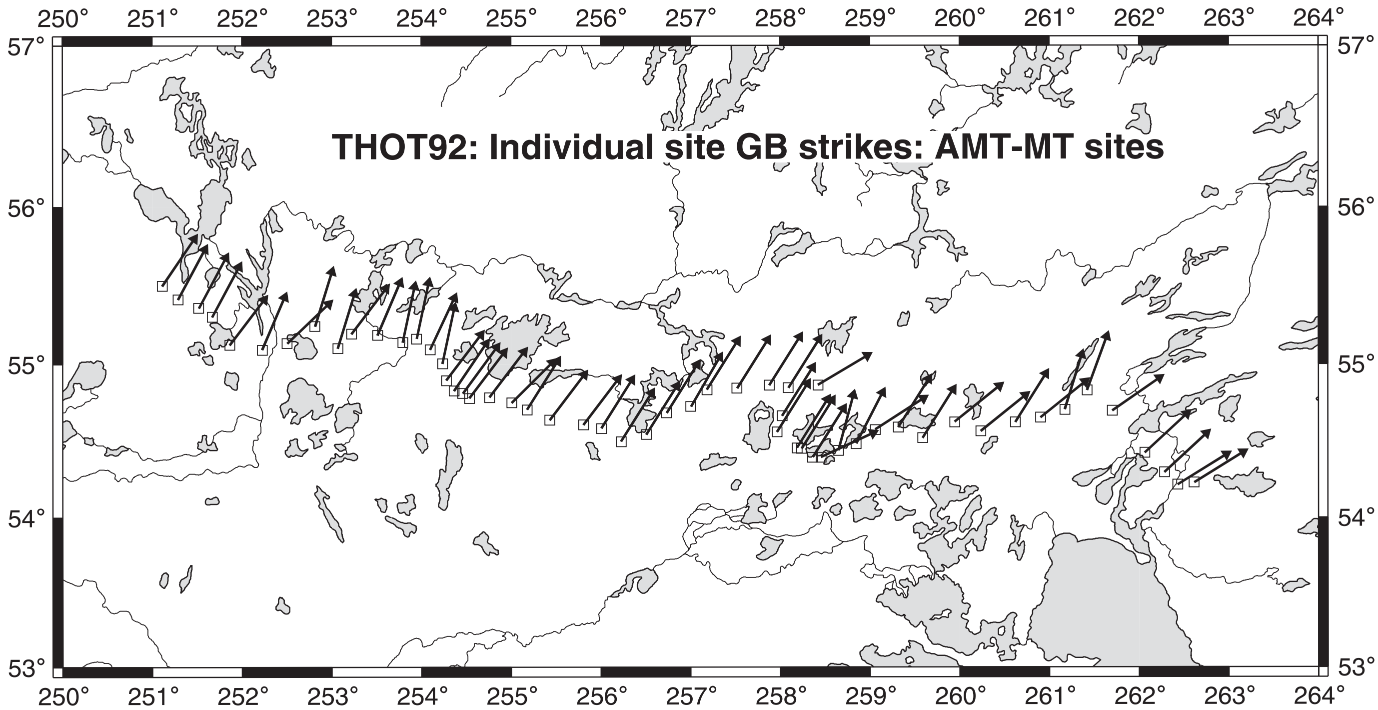
Fig. 4. Geoelectric strike directions for all AMT+MT sites along the Lithoprobe 1992 profile for the whole period range of 0.001 s (1000 Hz) to 1820 s.



(1993), Oldenburg and Ellis (1993), Rasmussen (1993), Schmucker (1993), Schnegg (1993), Takasugi et al. (1993), Uchida (1993), Wu et al. (1993), Zhao et al. (1993), Tournerie et al. (1995), Ogawa and Uchida (1996), and Pous et al. (1997). The models basically fall into two classes: in one class a number of anomalous conductive mid-crustal regions are electrically disconnected, and in the other class one or more conductive regions that are connected. Jones (1993) demonstrated that a very subtle (2°) minimum for the TM-mode phase data could only be replicated when the anomalies are disconnected. This conclusion was challenged by Agarwal et al. (1997), but their arguments about the effects of sedimentary structures would not lead to an isolated TM phase minimum as observed; therefore, they can be rejected.

The MT data along profile L acquired in 1992 by Lithoprobe crosses the whole orogen from one craton boundary to the other (Fig. 3). Grant (1997*a*) undertook comprehensive distortion analysis of all of the data using the Groom–Bailey approach with the multi-site, multi-frequency extension of McNeice and Jones (1996, 2001). The derived multi-frequency strike directions on a site-by-site basis for the AMT+MT sites are shown in Fig. 4. These directions are those that give the best fit for the whole period range from 0.001 s (1000 Hz) to 1820 s. Note the remarkable similarity of strike along the whole orogen, with a dominant strike direction of around 30° (±5°) in the western and central parts of the profile, and 45° (±5°) in the eastern part. Thus, a general average strike direction found for the whole profile is 35°.

From the regional data corrected for local distortions, Grant (1997*b*) presented preliminary forward models and inversion models, derived using Smith and Booker's (1991) rapid relaxation inversion (RRI) scheme with Wu et al.'s (1993) approach for solving for static shifts, for three separate segments of the profile. Jones et al. (1997*b*) presented resistivity models from the whole orogen, most of which are included in this paper (Fig. 10).

The detailed near-surface of the geometry of the NACP close to the exposed basement, as derived from the Lithoprobe 1992 MT data, was presented in Jones et al. (1993). Those authors demonstrated that the NACP is associated with mineralization in the western La Ronge domain and lies structurally above a bright, west-dipping, listric reflector followed to surface and identified as the Guncoat thrust, interpreted as a late-compressional feature, and structurally below the Rottenstone domain and the Wathaman batholith. The NACP stops abruptly almost exactly beneath the surface trace of the Needles Falls shear zone, a late dextral shear zone, and defines the location of the Rae–Hearne craton boundary.

Rock property studies of samples from the western La Ronge belt were undertaken by Katsube et al. (1996) and Jones et al. (1997*a*). They showed that the NACP is caused in this location by sulphides that migrated to fold hinges during compression and that are interconnected along strike but disconnected across strike. This property leads to very high electrical anisotropy, as observed in the field.

The data recorded on a second profile crossing the western margin along seismic line S2B were presented in Ferguson and Jones (1995) and modelled in Garcia (1998) and Garcia and Jones (2005).

MT responses on the Glennie domain (Fig. 3), a window to the putative Archean "Sask" craton that is interpreted to underlie most of the internides of the THO in northern

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Saskatchewan and northern Manitoba (Ansdell et al. 1995), were studied by Ferguson et al. (1996, 1997), Stevens and Ferguson (1997), and Ferguson et al. (2005). The 1-D modelling of Stevens and Ferguson (1997) identified a basement depth at ~200 m beneath relatively conductive (30 Ω·m) Phanerozoic sediments. The basement was found to be highly resistive (>1000 Ω·m), but with a localized region of lower resistivity that correlated spatially with a zone of high seismic reflectivity.

Responses from the Athapapuskow Lake shear zone and the Flin Flon area were presented in Ferguson et al. (1996, 1997, 1999). They identified a conductor, named the Athapapuskow Lake conductivity anomaly (ALCA), which extends for at least 40 km along strike, dips to the east and is resolved for at least 10 km downdip, and is > 2 km in thickness extent. From the seismic reflection data (White et al. 1994; Lucas et al. 1994), the ALCA as modelled lies within the Namew gneiss complex but dips at a greater angle (≥45°) than the seismic reflectivity (20°). The seismic reflection method is invisible to structures steeper than 45° and, in practice, structures dipping in excess of 30° are difficult to image. Specific identification of the ALCA with discrete airborne electromagnetic anomalies and with the results from boreholes allowed Ferguson et al. (1999) to associate the ALCA with graphitic and sulphidic rocks occurring within pelitic and psammitic gneisses in a supracrustal unit of the Namew gneiss complex. This conductor can thus be related to collisional tectonics between 1.87 and 1.84 Ga.

The eastern end of the profile crosses the Superior Boundary Zone, encompassing the Thompson belt. Data from here were modelled in 1-D by Cassels et al. (1997) and in 2-D by White et al. (1999). White et al. (1999) correlate the electrical resistivity model of the subsurface with the seismic reflection image, and taken together the data suggest a tectonic model with initially a lower plate collisional thrust belt setting at 1.88–1.81 Ga through lithospheric delamination at ~1.82–1.80 Ga to a steep transpressive plate boundary at 1.80–1.72 Ga.

The MT profiling in North Dakota resulted in high quality long-period responses that complimented those along the PanCanadian profile. Essentially, they showed the same results — discontinuous conductors in the mid-crust. Models were presented in Wu (1994), and are shown in Booker et al. (1997).

Three-dimensional images of the data

From the MT data available across the THO (Table 1), we can construct new images of electrical parameters for various depths. These images are approximations of the true parameters because of their method of construction, but yield robust information at the orogen-scale.

The MT apparent resistivity and phase data, as a function of period, are transformed to approximate 1-D resistivity-depth profiles using the Niblett–Bostick (N–B) transform (Niblett and Sayn-Wittgenstein 1960; Bostick 1977; Jones 1983). This transformation is performed on both the RhoXY–PhaXY data (north–south electric fields), the RhoYX–PhaYX data (east–west electric fields), and also the rotationally invariant arithmetic mean of the two, the RhoAV–PhaAV data. In addition, the data are rotated to determine the minimum and maximum values of N–B resistivity at the depth of interest, and also electrical anisotropy is derived from comparing the maximum resistivity with the N–B resistivity at an angle 90° from it. Maps have been constructed from the data using Wessel and Smith's GMT package (1991, 1998) and were smoothed using the blockmedian command with a 5′ search radius and then a grid constructed using the near-neighbour command with a 3° search radius.

Resistivity maps

Maps of electrical resistivity, as given by the N–B resistivity, at depths of 5, 10, 20, and 40 km are shown in Fig. 5. These maps are for the minimum resistivity at those depths, and the direction of minimum resistivity at the respective depth is shown by the direction of the arrow at each site. Overlain on each image is the proposed domainal structure of the orogen from M.D. Thomas (personal communication, 2003) based on potential field data (domain names in Fig. 6A). The general southward decreasing resistivity reflects the thickening to the south of the Phanerozoic basin sediments, know to have resistivities as low as 3 Ω·m (Jones 1988*a*, 1988*b*) and a total integrated conductance (depth extent in metres × conductivity in siemens/metre) in excess of 1000 S. Notwithstanding this screening effect, the NACP anomaly is clearly visible in these maps as it traces its way through North Dakota and Saskatchewan. The anomaly is strongest in North Dakota and weakens considerably to the north. There is a westward offset between lines M and N, as first reported in Jones and Craven (1990). The ALCA of Ferguson et al. (1999) is also apparent as a shallow feature in the 5-km map (Fig. 5A).

The black 500 Ω·m contour in each of the figures in the north-central part of Saskatchewan outlines a resistive region that is spatially coincident with the Sask craton. This body has a shape that can be mapped in three dimensions using the electrical information. On the 40-km depth map (Fig. 5D), the resistive region has reduced in size; its location coincides precisely with the Moho bulge first seen in the seismic reflection data (Lucas et al. 1993) and later in seismic refraction data (Németh et al. 1996; Németh 1999) and teleseismic receiver functions (Zelt and Ellis 1999).

Anisotropy maps

Maps of maximum electrical anisotropy, in percentage terms, for depths of 5, 10, 20, and 40 km are shown in Fig. 6. These maps are constructed by determining the direction of maximum N–B resistivity for a given depth, RhoNBmax, and deriving the resistivity in that direction and 90° from it, defined as RhoNBmin. The percentage anisotropy is derived on a logarithmic basis from

$$\text{anisotropy}\,(\%) = \frac{\log(\text{RhoNB max}) - \log(\text{RhoNB min})}{\log(\text{RhoNB max})} \times 100$$

The NACP in North Dakota has a very large anisotropy associated with it, in the order of > 80%. Electrical resistivity at 20 km in a north–south direction is more than three orders of magnitude lower than in an east–west direction. Smaller-scale zones of anisotropy are not evident in the figures from other parts of the orogen, but are known to exist (Jones et al.

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Fig. 5. Maps of the minimum resistivity at depths of 5, 10, 20, and 40 km. The resistive region in north-central Saskatchewan correlates spatially with the Sask craton. Tectonic domains defined by M.D. Thomas (personal communication, 2003). The lines at each MT site depict the minimum resistivity direction, which for the NACP anomaly is the strike direction. ALCA, Athapapuskow Lake conductivity anomaly.

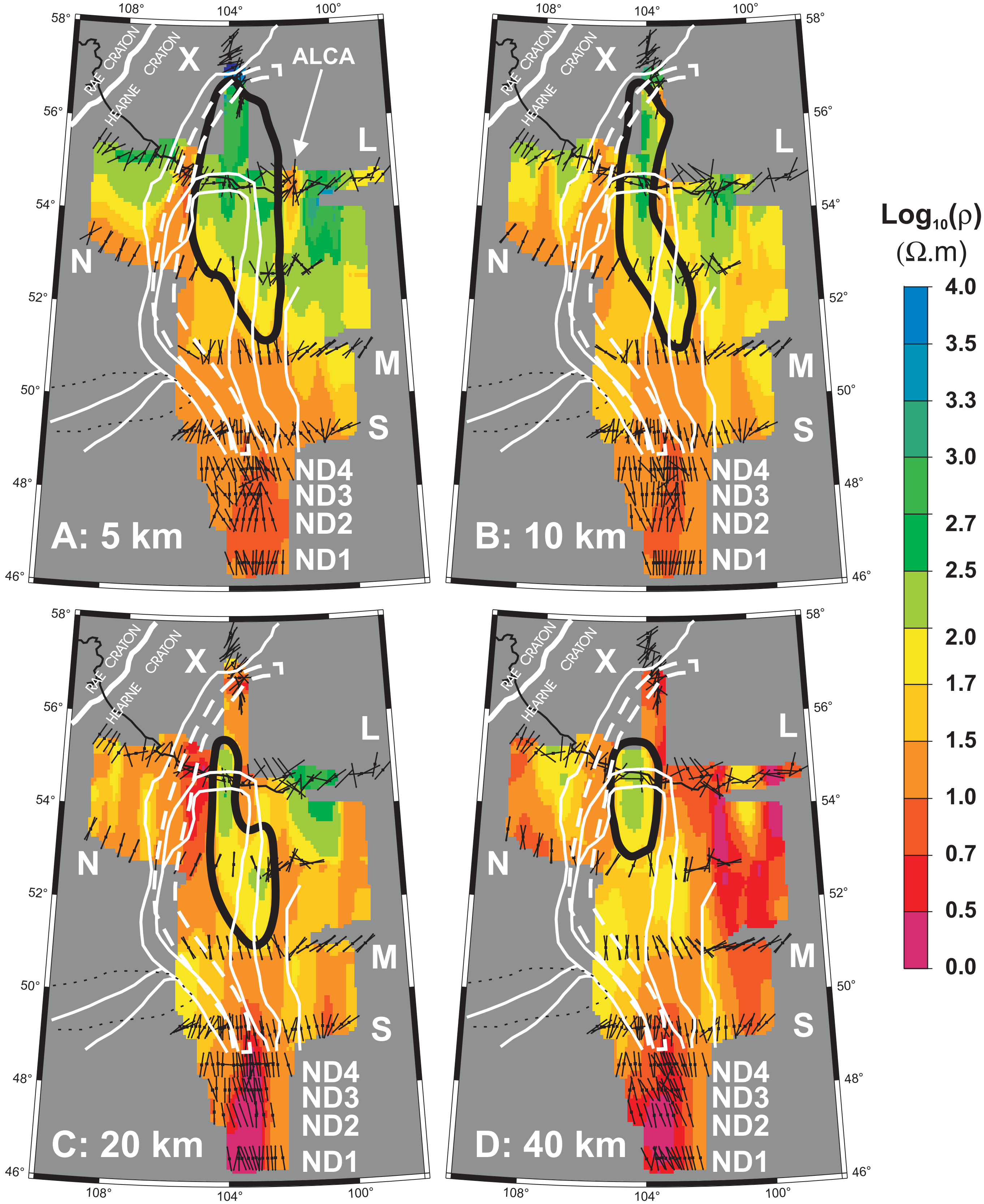

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Fig. 6. Maps of the resistivity anisotropy (in %) at depths of 5, 10, 20, and 40 km. Tectonic domains defined by Thomas (personal communication, 2003).

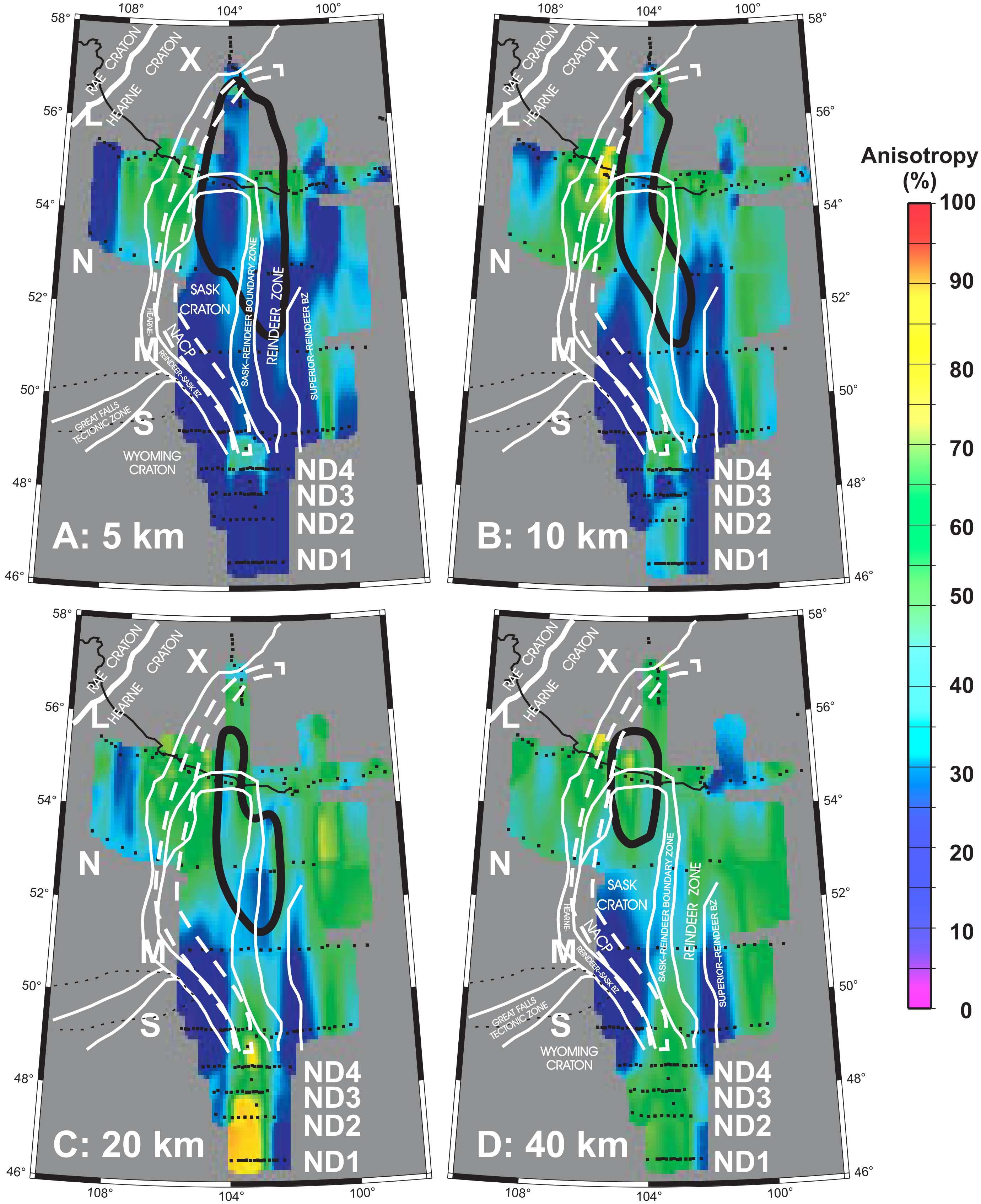

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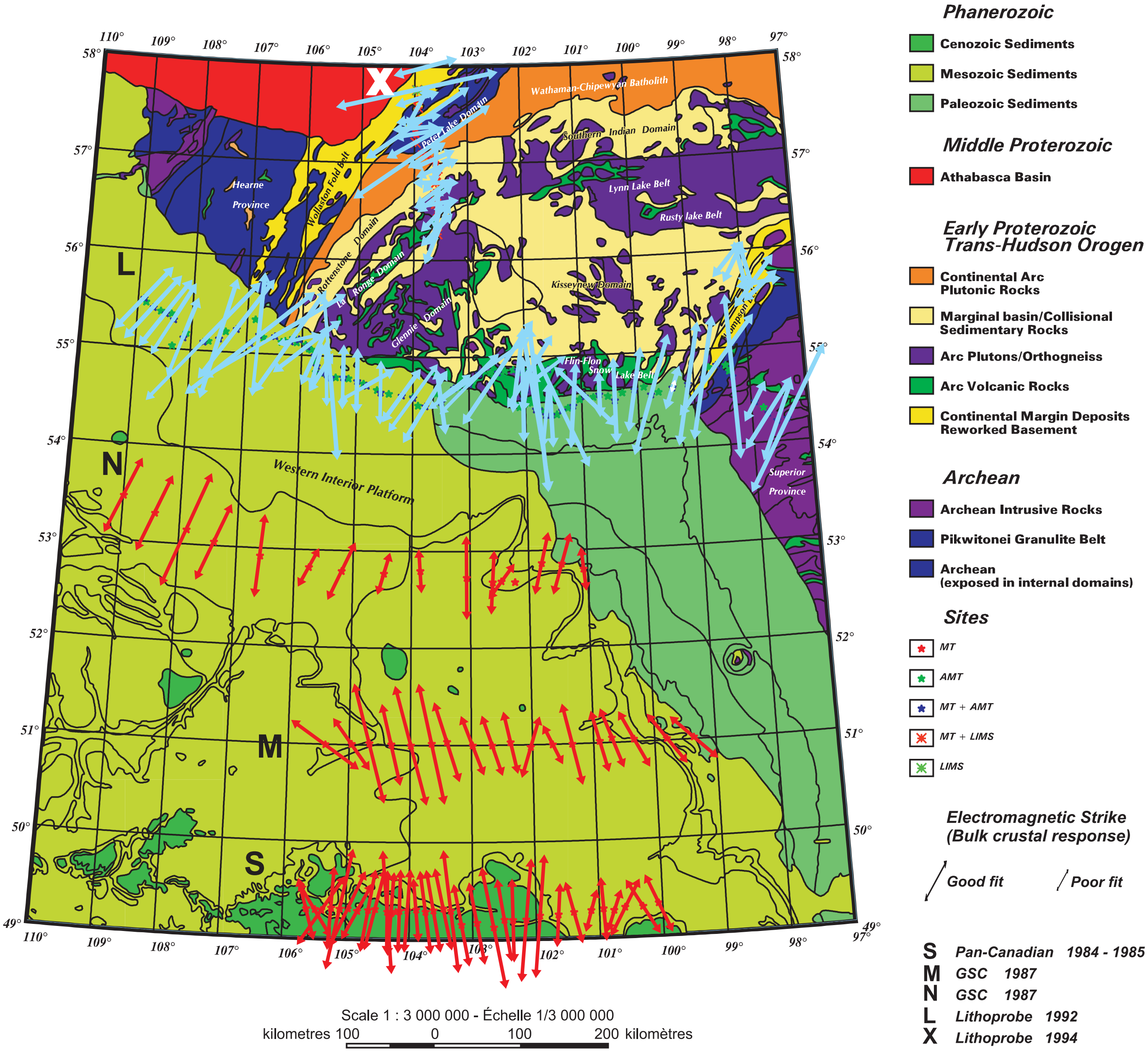
Fig. 7. Strike directions from all sites in Saskatchewan for the period range 10–1000 s.



1993 and later in the text). The 5′ smoothing and 3° search radius used in constructing the maps yields robust information at the scale of the orogen but masks these smaller features.

Strike directions

The geoelectrical strike of the subsurface gives useful qualitative information that can be interpreted geologically. An example is Marquis et al. (1995), who identified the North American basement beneath the thin terranes of the southern Canadian Cordillera based on their geoelectric strike responses. Figure 7 shows the strike directions for all sites in Saskatchewan, which are the best-fitting strike directions for the crust-penetrating periods of 10–1000 s using the multi-frequency decomposition code of McNeice and Jones (1996, 2001). Note that for line S, the arrows are pointing north–south. For line M, they infer a general strike direction of N20°W, and for line N one a direction of N20°E. For the western half of line L, the strike is N30°E (Fig. 4), and on line X, it rotates to N60°E. Thus, the locally dependent geoelectric strikes are consistent with the presumed geometry of the NACP within the THO and with features on the potential field map, which is not shown, but is traced in the domainal classification of M.D. Thomas (personal communication, 2003) in Figs. 5 and 6.

Phase plots

The regional impedances have both a magnitude (apparent resistivity) and a phase for each of the two modes of induction (i.e., TE, TM) at each frequency. The magnitudes and phases are not independent of each other, but in fact form a Hilbert

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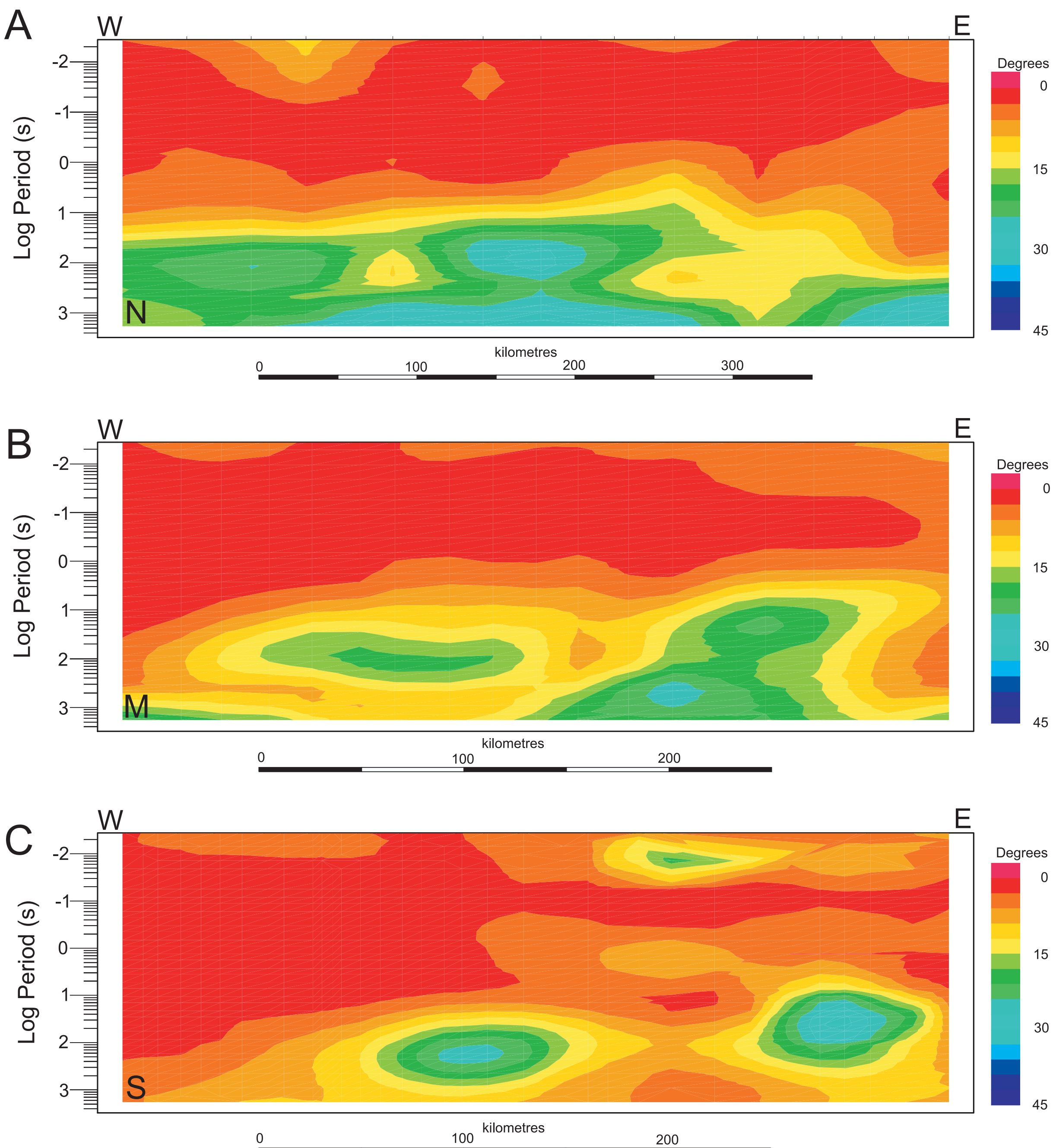
Fig. 8. Phase difference contoured pseudosections for profiles N (A), M (B), and S (C).



transform pair — that is from one of them one can derive an estimate of the other (to within the constant of integration). This relationship can be tested using Parker and Booker's (1996) Rho+ algorithm; Jones and Garcia (2003) used this algorithm to identify suspect data. However, the apparent resistivities can be plagued by frequency-independent magnitude scaling effects called static shifts, which are the remaining effect of local distortion that need to be removed by referring to other information (see, e.g., Jones 1988*a*). Accordingly, because the phase plots contain the same information as apparent resistivity plots but are not affected by static shifts, they are more commonly used for qualitative interpretation and can be thought of as analogous to unmigrated seismic reflection sections.

We display two types of contoured phase displays. The ordinate for both is the logarithm of period, which is a proxy for depth as electromagnetic fields attenuate exponentially with increasing penetration. For the northern two lines, L and X (Figs. 2, 3), we show the TE and TM phases as contoured plots (Fig. 9). For the southern three profiles (Fig. 2) however, we display the phase differences between TE and TM (Fig. 8). We do this because on these profiles there is virtually no observable TM response due to the crustal conductivity anomalies — only a TE response. This lack of TM

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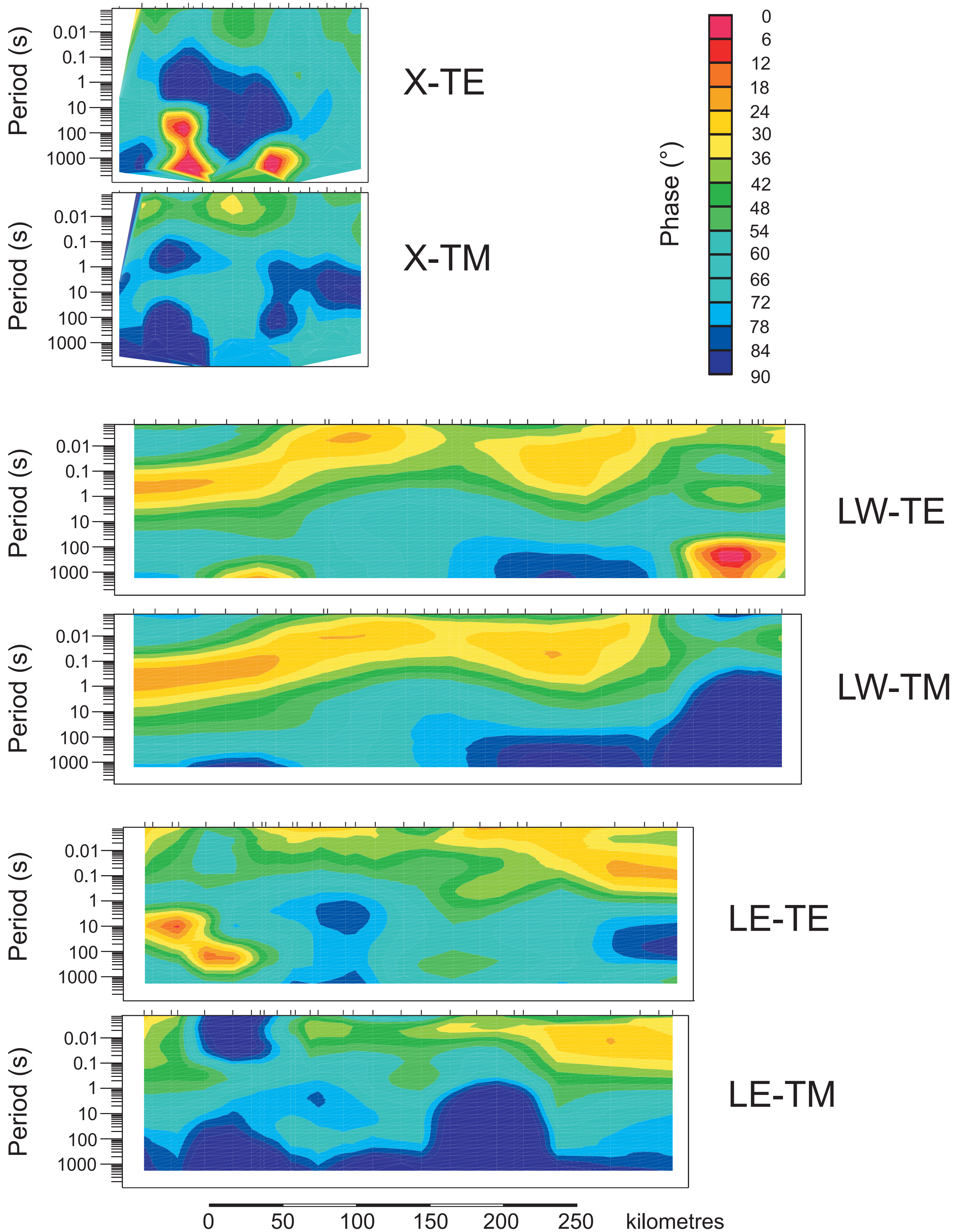
Fig. 9. TE- and TM- mode phase pseudosections for profiles L and X. Profile L is split into an east segment (LE) and a west segment (LW).



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response is taken as evidence for multiple unconnected conducting bodies rather than a single composite anomalous body, and is discussed in detail for the line S data in Jones (1993). Accordingly, a way of illuminating the anomalies and separating the background response is to plot the ϕ_{TE} – (ϕ_{TM} + 180°) (the 180° accounts for the TM phase being in the third quadrant) as contoured phase plots. For a 1-D rotationally invariant Earth, this phase difference will be zero. Departures from zero imply 2-D or 3-D structures.

Phase difference plots: lines S, M, and N

Phase difference contoured plots for lines N, M, and S are shown in Figs. 8A, 8B, and 8C, respectively. The phase difference between both polarizations for short periods is < 3° because of the 1-D electrical structure of the Phanerozoic sediments. These sediments shallow to the north and east. For long periods (>10 s), the phase differences between both polarizations are greater (>15°) because of the 2-D crustal electrical structure.

The S profile shows (Fig. 8C), for periods longer than 100 s, two zones where the phase differences are > 24°. The westernmost anomaly is associated with the NACP conductivity anomaly, and the easternmost one with the Thompson Belt anomaly (Jones and Craven 1990).

The M profile also shows (Fig. 8B) two zones of enhanced difference between phases at longer periods, although they are weaker than on the line S data. The western anomaly is associated with the NACP, and the eastern anomaly is because of a body close to the basement surface.

The N profile (Fig. 8A) differs from the previous two in showing a large phase difference anomaly in the westernmost part of the profile where the phase difference is > 20° (greens). This suggests the existence of anisotropic structures.

Phase plots: lines L and X

Phase data from each station have been interpolated along each line to produce 2-D phase contoured plots for both the TE and TM modes (Fig. 9). Phases > 45° indicate zones of increasing conductivity with depth, whereas phases < 45° indicate zones of decreasing conductivity with depth. The plots for profile X show the existence of isolated anomalies in the TE mode only (X-TE). From the intensive COPROD2 examination (Jones 1993), we can conclude evidence for strong electrical anisotropy, which is likely a manifestation of sub-vertical imbrication of conducting and resistive metasedimentary layers. Such an effect is also observed on the data from the eastern part of profile L (marked as LE-TE and LE-TM). In contrast, the TE and TM modes data from the western part of the profile are virtually identical, except for the TE phase anomaly at the easternmost edge (LW-TE), attesting to conductivity bodies that have significant connectivity laterally and vertically. These anisotropic features are however spatially too small to be evident in the anisotropy map (Fig. 6). Note the high phase anomaly at the longest periods for the LW-TE data. This is further discussed later in the text as anomaly G.

Resistivity models

Models to explain the observations were derived using two different philosophies: forward trial-and-error model fitting approach and automatic objective inversion. Whereas inversion schemes have the attraction of employing objective misfit and regularization criteria, there is a danger of not fitting subtle, significant features when a global misfit is sought. In comparison, detailed forward modelling exercises can be accomplished with due care being given to parts of the responses that are sensitive to the features of interest. This is possibly the case for the N line dataset because the objective algorithm will penalize attempts to introduce anisotropic structure (see later in the text). The forward models for all profiles are shown in Fig. 10, and the inversion model from profile L in Fig. 11.

2-D forward models

The forward models were produced from repeated attempts to fit the data obtained from a 2-D model to the measured data for each station — the forward trial-and-error fitting method. The model data were calculated using the code of Wannamaker et al. (1985) as part of the GEOTOOLS data interpretation package. Parts of the starting models for this process were produced from RRI inversions, but all subsequent models were modified “by hand” to fit observed features in the data.

Sedimentary structure

The models from the North Dakota profiles (NOD) and the three Saskatchewan profiles on the Phanerozoic sediments all show a conductive surface layer that is the Phanerozoic sediments. The thickness of the layers beneath each site has been taken from isopach maps of the depth to basement.

Crustal structure

The crust is, in general, resistive (>600 Ω·m). Conductive structures at depths greater than about 15 km are present in models for the NOD and S and M (Fig. 5) profiles. In the eastern zone of model N (Fig. 6), a conductive body is present; this body is the ALCA discussed by Ferguson et al. (1999) and associated with the Athapapuskow Lake shear zone.

North American Central Plains structure

The models all show a series of west-dipping conductive bodies in the middle crust associated with the NACP. The top of the structure is shallower in model M. and the amount of conducting material (conductance or depth-integrated conductivity) is less. To fit the data, the NACP must be modelled as a series of conductive bodies rather than a single feature (multi-body structure, Jones and Craven 1990, Jones 1993). The separation of the MT sites and the depth of the NACP prevent us from knowing whether the NACP is a macro-anisotropic structure or a micro-anisotropic one (Jones et al. 1997*a*). In addition, beneath the N line, the anisotropic structure extends to the western end of the line well into the presumed Wollaston domain, as expressed by the phase structure in Fig. 8A.

Inversion model: line L

The new regional lithospheric-scale model for line L was obtained using the RLM2DI inversion code of Rodi and Mackie (2001). The program seeks the smoothest conductivity profile such that the value of a functional, which includes the derivatives of the conductivity with respect to depth and

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Fig. 10. Two-dimensional forward resistivity models fitting the MT data (both modes) from all profiles.

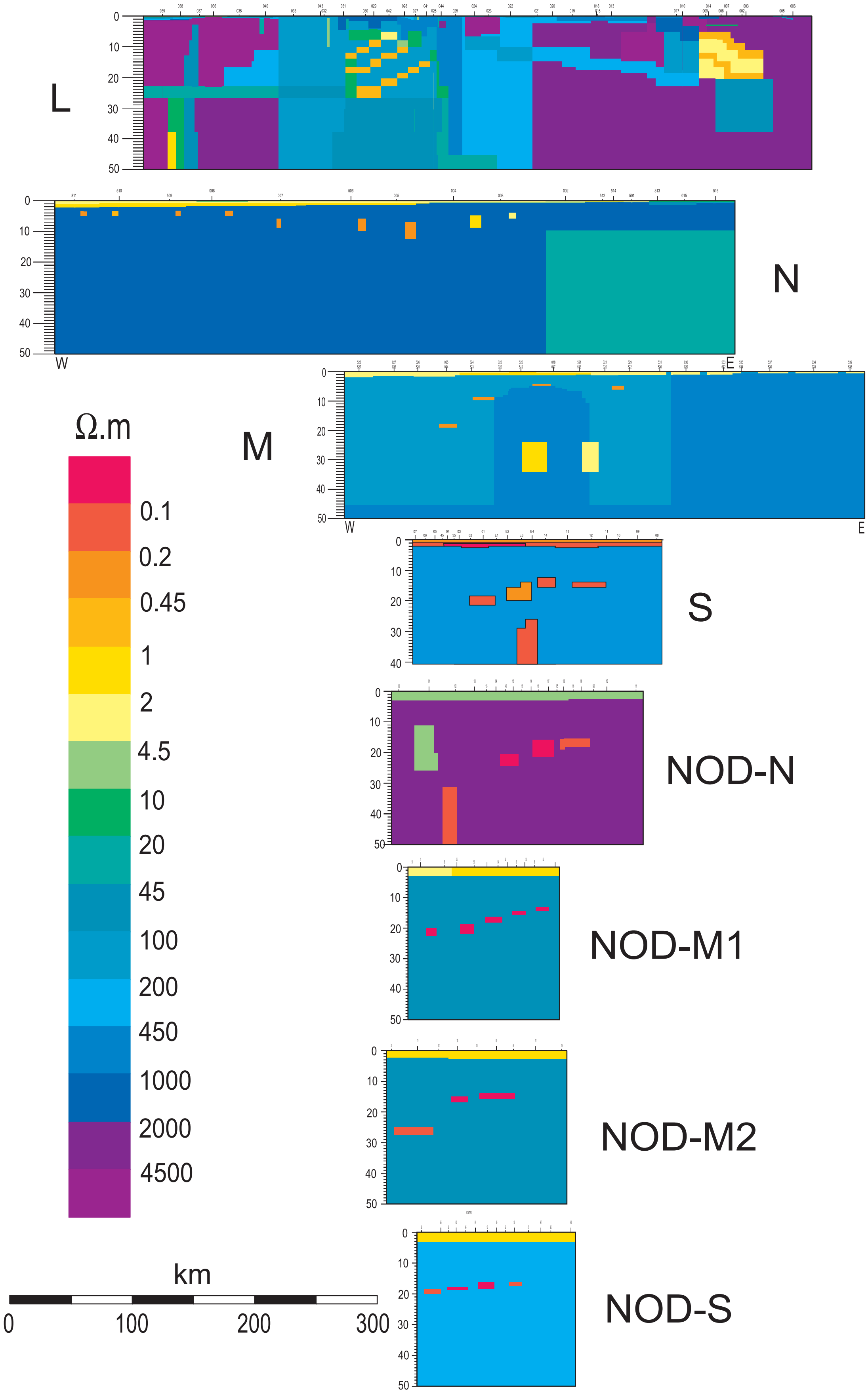

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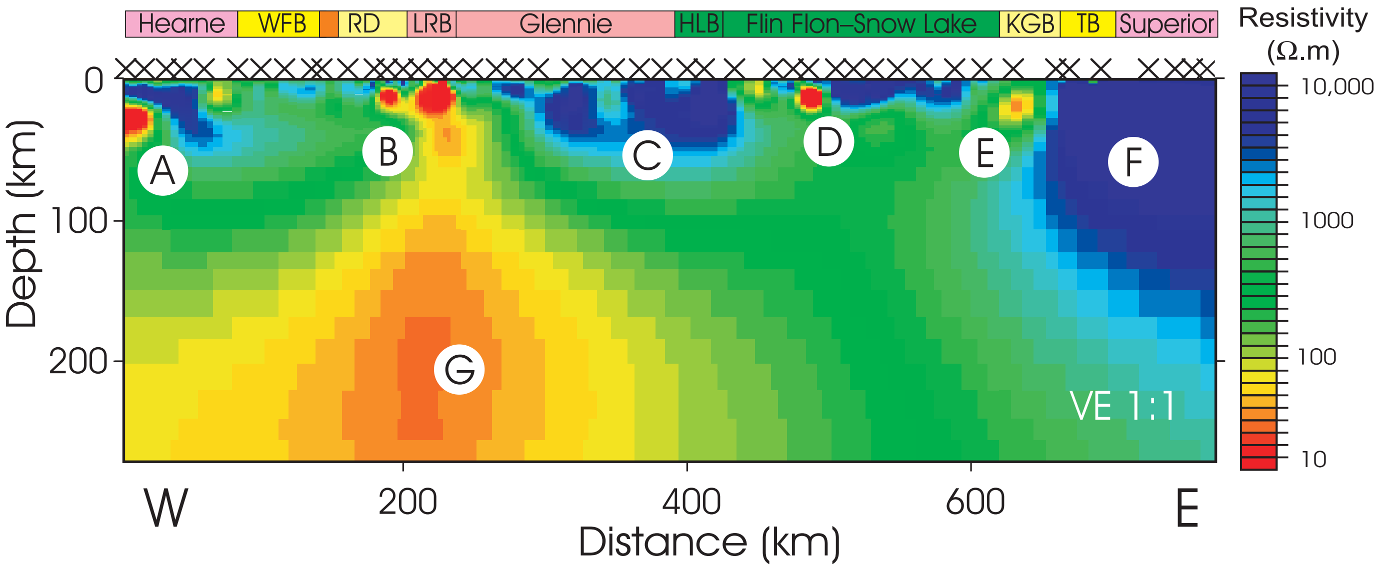
Fig. 11. Two-dimensional inversion resistivity model for profile L. The seven labelled features are discussed in the text. WFB, Wollaston fold belt; RD, Rottenstone domain; LRB, La Ronge belt; HLB, Hanson Lake block; KGB, Kisseynew gneiss belt; TB, Thompson belt. VE, vertical exaggeration.



in the horizontal direction along the profile, is minimized simultaneously with misfit. Beginning with the responses obtained from a 2-D start model, RLM2DI iteratively solves for small changes in the conductivity below each site, such that each newer model produces a smaller residual error between the modelled data and measured data at each station.

The best fitting model found is shown in Fig. 11, without any vertical exaggeration. This model simultaneously fits the TE, TM, and GTF data, as well as possible over eight decades of period from 10 000 Hz to 10 000 s from 47 of the 56 AMT+MT sites along the profile. The MT data observed and the model responses are shown in Fig. 12. The model clearly fits the apparent resistivity data well over the whole bandwidth, and most of the phase data, but systematically underfits the long period phase data. This is in keeping with the minimum structure concept of the modelling algorithm — more features and structure are permissible in the mantle, but not fewer. Seven features are identified in the model, labelled with letters from A to G. The tectonic domain is shown along the top using the same colour scheme as Fig. 3.

High resistivity is observed in the upper crust of the Hearne craton, and feature A indicates that the lower crust of the Hearne craton is, away from the orogen boundary, anomalously conductive with resistivity of 10 Ω·m and lower. The cause of lower crustal conductivity is contentious (e.g., Jones 1992; Duba et al. 1994; Yardley and Valley 1997; Wannamaker 1997), and candidates fall into two camps: (1) ionic conduction in saline waters and partial melts and (2) electronic conduction in graphitic, sulphidic, and iron oxide metasediments or in carbon-grain boundary films. For old, cold, cratonic lower crust, partial melt can readily be excluded and petrological arguments are against free fluids existing in Precambrian regions. Thus, we must consider tectonic emplacement of metasediments deep into the crust during an orogenic event as the likely cause of lower crustal conductivity. A conducting lower crust is also observed beneath the Hearne craton at its northern limit south of Baker Lake (Jones et al. 2002*a*), but not beneath the Rae craton to the north of the Hearne craton (Jones et al. 2002*a*) nor beneath the Anton complex of the Slave craton (Jones and Ferguson 2001).

Feature B is the NACP anomaly within the crust, and a more detailed model of its geometry is given in Jones et al. (1993).

Feature C is the highly resistive crust beneath the Glennie domain and the Hanson Lake block. This feature we can associate with the Sask craton, and note that there is no conductive lower crust associated with it. This feature is discussed in more detail in Ferguson et al. (2005).

Feature D is the ALCA discussed in Ferguson et al. (1999).

Feature E is a mid-crustal anomaly in the Kisseyney gneiss belt. There are too few sites on this anomaly for precise geometric definition.

Feature F is the highly resistive crust associated with the Superior craton. A more detailed geometry of this boundary is presented in White et al. (1999).

Feature G is perhaps the most novel of the features in the model and is an unexpected result. Prior interpretations of the MT data focussed primarily on crustal features for comparison with the seismic reflection images. However, this model, derived from including the longer period data to 10 000 s, shows the existence of a low conductivity region within the upper mantle of the western internides of the orogen directly beneath the crustal structures associated with the NACP anomaly. Feature G comes primarily from the TE-mode apparent resistivity data and is evident in the apparent resistivity minimum observed in the pseudosection in Fig. 12 (left column, top plot).

Discussion

North American Central Plains

The NACP zone of enhanced conductivity has been imaged electrically from the USA–Canada border to northern Saskatche-

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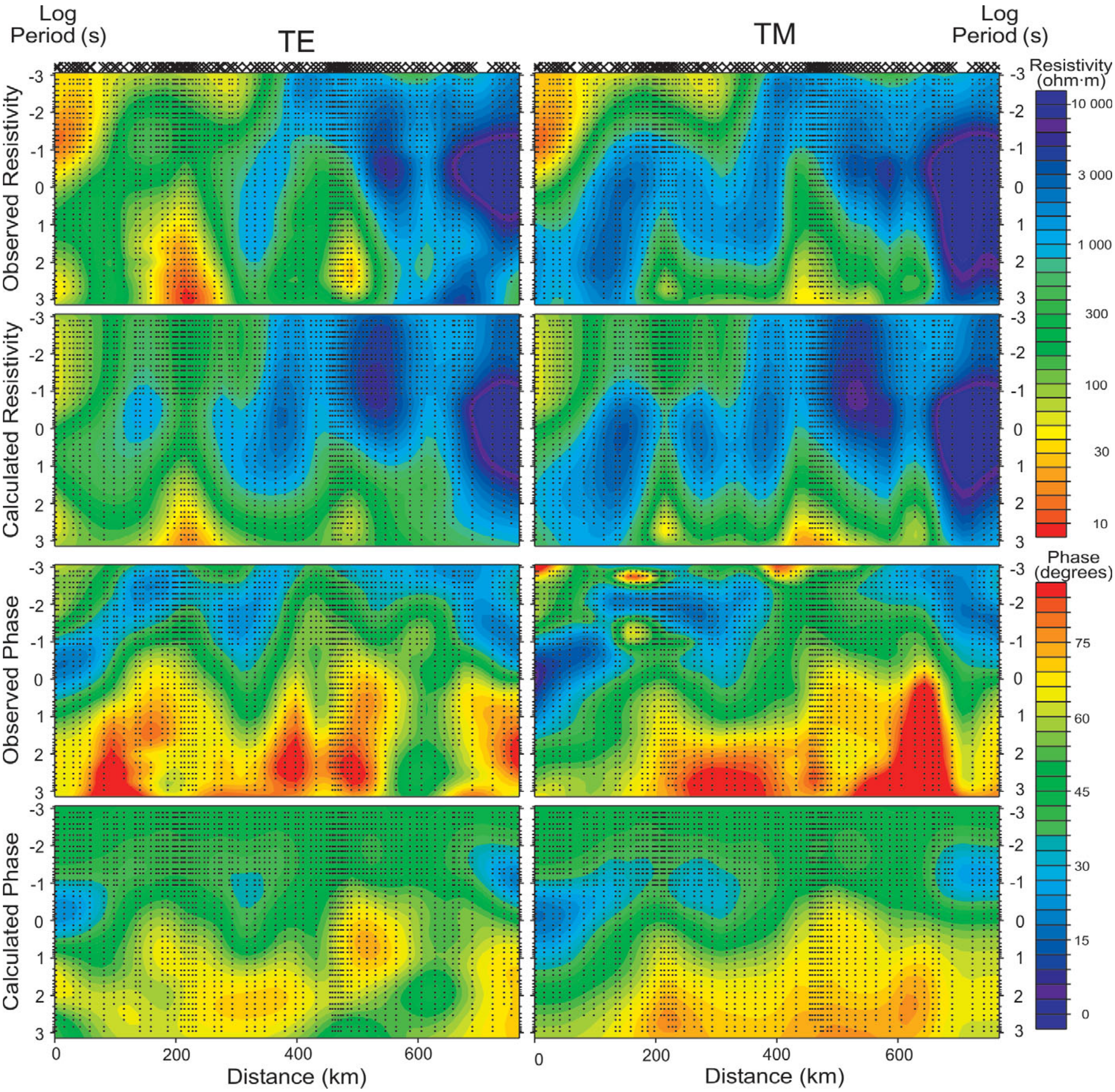
Fig. 12. Pseudosections of the observed and modelled MT data. Left column, TE-mode data and model responses. Right column, TM-mode data and model responses.



wan on five crossing profiles. Although in a gross sense the anomaly appears to be the same on all lines, in detail it displays an internal structure that varies along strike. Jones and Craven (1990) suggested that it was absent along line M in their qualitative interpretation of the data. However, distortion analysis showed that the correct interpretation frame should be –20°, not 0° as used by Jones and Craven (1990). This difference is insignificant for the larger impedance of the two, which in this case is the TM impedance, but is highly significant for the smaller impedance, the TE impedance. It is the TE impedance which is precisely the one that is sensitive to the presence of the anomaly. This confirms that care must be taken when determining the appropriate interpretation coordinate system for MT data.

Deep crustal conductor

All models, except for line N, display distinct, and mostly separate, bodies of enhanced conductivity deep in the crust, from 25–35 km, beneath the overlying arcuate mid-crustal anomalies previously imaged. The nature of this deep anomaly is unknown. Note that following the interpretation of the seismic reflection data by Lucas et al. (1993) and Nelson et al. (1993), they lie within the Archean Sask craton that is interpreted to root the orogen (Lucas et al. 1993; Ansdell et

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al. 1995). This suggests that either (1) the presumed metasediments are Archean in age, or (2) the Archean remnants are thin and underlain by younger (Paleoproterozoic?) rocks containing metasedimentary sequences. As the strikes of these deep crustal bodies are in exactly the same direction as the upper crustal ones, we suggest that the latter explanation is more likely.

Anisotropic crust

The upper crust in the western Hearne craton beneath line N appears to be electrically anisotropic. Whether this is also true beneath the western part of line LW needs to be tested, as the smooth inversion algorithm will not produce such a feature.

Mantle conductor

The upper mantle anomaly shown in Fig. 11 is a new result in this synthesis. Such a mantle conductor must also be present beneath South Dakota and North Dakota to explain the persistence of the NACP anomaly in Hz at diurnal (24-hour) periodicity observed by Camfield and Gough (1975). The top of the anomaly is at about 80–100 km. Its depth extent is poorly resolved, and the apparent extension into the deep lithosphere may be an artefact of the smoothing inversion algorithm.

Conductivity anomalies in the upper mantle that are not associated with the asthenosphere are rare. Jones et al. (2001, 2003) discovered an anomaly in the central Slave craton, Northwest Territories, Canada, at depths of 80–140 km, and associated it with carbon in graphite form above the graphite–diamond stability field. A similar anomaly was found beneath the North Caribou Terrane of the western part of the Superior Province, Ontario, Canada (Craven et al. 2001).

Given the existence of the Sask craton, and the discovery of diamondiferous kimberlites at the Fort à la Corne kimberlite near Smeaton (Fig. 3), perhaps there is also some genetic relationship here with a conductor in the mantle and diamondiferous kimberlites. The existence of the conductor is evidence of an interconnected conductive phase for which the most likely candidate is carbon in graphite form. The diamonds are evidence of carbon in diamond form. This conductor begins at approximately the same depth as the Slave one, about 80–100 km, and has a width of about 50–80 km. Its depth extent is poorly resolved, but if graphite is the cause then its base should be at the graphite–diamond stability field, which is at about 140 km for this region (B. Kjarsgaard, personal communication, 2003) based on a geotherm of 41–42 mW/m^2 and phase calculations of Kennedy and Kennedy (1976).

Conclusions

Magnetotelluric studies, conducted as part of Lithoprobe and other programs, have demonstrated that the NACP conductivity anomaly is an integral part of the THO. Its discovery was the first indirect evidence for the existence of a Proterozoic collisional orogenic zone beneath the Phanerozoic sediments of the central plains of the USA and Canada. Its total known length extent, from South Dakota through North Dakota and Saskatchewan to eastern Manitoba, is over 2200 km, and recent work on Baffin Island suggests that a correlative anomaly can be found there in equivalent strata (Jones et al. 2002*b*; Evans et al. 2003*a*, 2005). The existence of the NACP testifies to the similarity of orogenic process along the entire length of the orogen.

The geometry of the NACP anomaly can be used to deduce geometries of structures related to subduction and collisional compression. For example, at the location of the Lithoprobe seismic reflection line the west-dipping geometry of the conductive structures, and their position above a late-collisional feature, the Guncoat thrust, implies that the subduction was predominantly west-dipping. The cessation of conductive structures directly below the Needle Falls shear zone defines the craton boundary. A resistive anomaly in north-central Saskatchewan can be spatially related to the Sask craton, and the geometry of the anomaly defines the geometry of the craton with depth.

A new result from the inversion of the longer period data along profile L is the identification of an upper mantle conductor at a depth of some 80–100 km. This conductor is similar in electrical resistivity and depth to one identified beneath the central part of the Slave craton (Jones et al. 2001, 2003) and one identified beneath the North Caribou Terrane in the western part of the Superior Province (Craven et al. 2001). Given the existence of the Sask craton and the Fort à la Corne kimberlite, the correlation is intriguing and further supports the suggestion made by Jones and Craven (2004) for a new deep-probing magnetotellurics being a new method for area selection for diamond exploration.

Clearly, the NACP anomaly has contributed significantly to understanding the THO, and it amply rewarded the examination of the one anomalous station observed in the corner of the 1967 GDS array.

Acknowledgments

Many people contributed significantly to the acquisition and processing of the data presented herein. In particular, John Booker, Trevor Boyce, Angela Chen, Jim Craven, Rob Ellis, Colin Farquharson, Nick Grant, Gary McNeice, Martyn Unsworth, Nong Wu, and Sheng Yu participated in the fieldwork in the USA and Canada. Phoenix Geophysics acquired the data along the Lithoprobe profiles, and Gerry Graham and George Elliot are thanked for their attention to detail. Gerry Ross is thanked for providing Fig. 1 and Mike Thomas for the tectonic domain divisions in Figs. 5 and 6. Reviews by Phil Wannamaker, Colin Farquharson, and Associate Editor Ron Clowes are greatly appreciated.

References

Agarwal, A.K., and Weaver, J.T. 1993. Inversion of the COPROD2 data by a method of modeling. Journal of Geomagnetism and Geoelectricity, **45**: 969–983.

Agarwal, A.K., MacDonald, K.J., and Weaver, J.T. 1997. COPROD2 revisited: can the B-polarization phase distinguish between single- and multi-body anomalies? Journal of Geomagnetism and Geoelectricity, **49**: 745–756.

Alabi, A.O. 1974. A study of the North American Central Plains conductivity anomaly. Unpublished Ph.D. thesis, University of Alberta, Edmonton, Alta.

Alabi, A.O., Camfield, P.A., and Gough, D.I. 1975. The North

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American Central Plains anomaly. Geophysical Journal of the Royal Astronomical Society, **43**: 815–834.
Ansdell, K., Lucas, S.B., Connors, K., and Stern, R. 1995. Kisseyney metasedimentary gneiss belt, Trans-Hudson orogen (Canada): back-arc origin and collisional inversion. Geology, **23**: 1039–1043.
Bahr, K. 1988. Interpretation of the magnetotelluric impedance tensor: regional induction and local telluric distortion. Journal of Geophysics, **62**: 119–127.
Booker, J.R., Aprea, C.M., Unsworth, M.J., and Wu, N. 1997. Electrical conductivity structure in major continental tectonic zones. Geowissenschaften, **15**: 111–115.
Bostick, F.X. 1977. A simple almost exact method of MT analysis. *In* Workshop on electrical methods in geothermal exploration. US, Geological Survey, Contract No. 14080001-8-359, pp. 174–183 (Reprinted in Vozoff, 1986).
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. Geophysical Journal of the Royal Astronomical Society, **41**: 193–218.
Camfield, P.A., and Gough, D.I. 1977. A possible Proterozoic plate boundary in North America. Canadian Journal of Earth Sciences, **14**: 1229–1238.
Camfield, P.A., Gough, D.I., and Porath, H. 1970. Magnetometer array studies in the northwestern United States and southwestern Canada. Geophysical Journal of the Royal Astronomical Society, **22**: 201–222.
Cassels, J., Ferguson, I.J., and Jones, A.G. 1997. Signal processing and interpretation of magnetotelluric data from the Superior Boundary Zone. *In* Trans-Hudson Orogen Transect. Report of the 7th Transect Meeting, Saskatoon, Sask., Canada, May 1–2, 1997. Lithoprobe Report 62, pp. 251–268.
Chakridi, R., Chouteau, M., and Mareschal, M. 1992. A simple technique for analysing and partly removing galvanic distortion from the magnetotelluric impedance tensor: application to Abitibi and Kapuskasing data (Canada). Geological Journal, **108**: 917–929.
Craven, J.C., Kurtz, R.D., Boerner, D.E., Skulski, T., Spratt, J., Ferguson, I.J., Wu, X., and Bailey, R.C. 2001. Conductivity of western Superior Province upper mantle in northwestern Ontario. Geological Survey of Canada, Current Research 2001-E6, p. 6.
deGroot-Hedlin, C., and Constable, S. 1993. Occam's inversion and the North American Central Plains electrical anomaly. Journal of Geomagnetism and Geoelectricity, **45**: 985–999.
Duba, A., Heikamp, S., Meurer, W., Nover, G., and Will, G. 1994. Evidence from borehole samples for the role of accessory minerals in lower-crustal conductivity. Nature (London), **367**: 59–61.
Dutch, S.I. 1983. Proterozoic structural provinces in the north-central United States. Geology, **11**: 478–481.
Ellis, R.G., Farquharson, C.G., and Oldenburg, D.W. 1993. Approximate inverse mapping inversion of the COPROD2 data. Journal of Geomagnetism and Geoelectricity, **45**: 1001–1012.
Evans, S., Jones, A.G., Spratt J., and Katsube, J. 2003. Central Baffin electromagnetic experiment (CBEX): Phase 2. Geological Survey of Canada Current Research, **2003-C24**: 10.
Evans, S., Jones, A.G., Spratt, J., and Katsube, J. 2005. Central Baffin electromagnetic experiment (CBEX) maps the NACP in the Canadian arctic. Physics of the Earth and Planetary Interiors, **150**: 227–237.
Everett, M.E., and Schultz, A. 1993. Two dimensional nonlinear magnetotelluric inversion using a genetic algorithm. Journal of Geomagnetism and Geoelectricity, **45**: 1013–1026.
Ferguson, I.J., and Jones, A.G. 1995. 1994 electromagnetic measurements on the Trans Hudson Orogen Transect. *In* Trans-Hudson Orogen Transect. Report of the 5th Transect Meeting, Regina, Sask., Canada, April 3–4, 1995. Lithoprobe Report 48, pp. 162–169.
Ferguson, I.J., Stevens, K.M., Cassells, J.P., Wu, X., Shiozali, I.X., and Jones, A.G. 1996. THOT MT studies: eastern segment. *In* Trans-Hudson Orogen Transect. Report of the 6th Transect Meeting, Saskatoon, Sask., Canada, April 1–2, 1996. Lithoprobe Report 55, pp. 10–25.
Ferguson, I.J., Sheng, Y., Wu, X., Shiozaki, I.X., and Jones, A.J. 1997. Electrical conductivity soundings in the central Flin Flon Belt, Trans-Hudson Orogen, Canada. *In* Trans-Hudson Orogen Transect. Report of the 7th Transect Meeting, Saskatoon, Sask., Canada, May 1–2, 1997. Lithoprobe Report 62, pp. 147–167.
Ferguson, I.J., Jones, A.J., Sheng, Y., Wu, X., and Shiozali, I. 1999. Geoelectric response and crustal electrical-conductivity structure of the Flin Flon Belt, Trans-Hudson Orogen, Canada. Canadian Journal of Earth Sciences, **36**: 1917–1938.
Ferguson, I.J., Stevens, K.M., and Jones, A.J. 2005. Electrical-resistivity imaging of the central Trans-Hudson Orogen in eastern Saskatchewan, Canada. Canadian Journal of Earth Sciences, **42**: this issue.
Garcia, X. 1998. Models de distorsió i efectes de fonts no uniformes en els mètodes magnetotel · lúric i de font controlada [Distortion models and non-uniform source effects in the magnetotelluric and controlled source methods]. Unpublished Ph.D. thesis, University of Barcelona, Barcelona, Spain (in Catalan).
Garcia, X., and Jones, A.G. 2005. Electromagnetic image of the Trans-Hudson orogen — THO94 transect. Canadian Journal of Earth Sciences, **42**: this issue.
Grant, N.J. 1997*a*. Processing, interpretation and databasing of magnetotelluric data from the Trans-Hudson Orogen: site-by-site and multi-site, multi-frequency Groom-Bailey decompositions. *In* Trans-Hudson Orogen Transect. Report of the 7th Transect Meeting, Saskatoon, Sask., Canada, May 1–2, 1997. Lithoprobe Report 62, pp. 62–105.
Grant, N.J. 1997*b*. Processing, interpretation and databasing of magnetotelluric data from the Trans-Hudson Orogen: rapid 2D inversion of the THO92 regional datasets: a summary of results and methodology. *In* Trans-Hudson Orogen Transect. Report of the 7th Transect Meeting, Saskatoon, Sask., Canada, May 1–2, 1997. Lithoprobe Report 62, pp. 16–61.
Gough, D.I., and Camfield, P.A. 1972. Convergent geophysical evidence of a metamorphic belt through the Black Hills of South Dakota. Journal of Geophysics Research, **77**: 3168–3170.
Groom, R.W., and Bailey, R.C. 1989. Decomposition of magnetotelluric impedance tensors in the presence of local three-dimensional galvanic distortion. Journal of Geophysics Research, **94**: 1913–1925.
Groom, R.W., and Bailey, R.C. 1991. Analytical investigations of the effects of near-surface three-dimensional galvanic scatterers on MT tensor decomposition. Geophysics, **56**: 496–518.
Groom, R.W., Kurtz, R.D., Jones, A.G., and Boerner, D.E. 1993. A quantitative methodology for determining the dimensionality of conductive structure from magnetotelluric data. Geophysical Journal International, **115**: 1095–1118.
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. Geophysical Journal of the Royal Astronomical Society, **81**: 33–46.
Handa, S., and Camfield, P.A. 1984. Crustal electrical conductivity in north-central Saskatchewan: the North American Central

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Plains anomaly and its relation to a Proterozoic plate margin. Canadian Journal of Earth Sciences, **21**: 533–543.

Hills, F.A., Houston, R.S., and Subbarayudu, G.V. 1975. Possible Proterozoic plate boundary in southern Wyoming. Geological Society of America (Abstracts), **7**: 614.

Hoffman, P. 1988. United plates of America, the birth of a craton: early Proterozoic assembly and growth of Proto-Laurentia. Annual Review Earth and Planetary Science, **16**: 543–603.

Jones, A.G. 1983. On the equivalence of the “Niblett” and “Bostick” transformations in the magnetotelluric method. Journal of Geophysics, **53**: 72–73 (Reprinted in Vozoff, 1986).

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

Jones, A.G. 1988*b*. Discussion of “A magnetotelluric investigation under the Williston Basin” by J.M. Maidens and K.V. Paulson. Canadian Journal of Earth Sciences, **25**: 1132–1139.

Jones, A.G. 1992. Electrical conductivity of the continental lower crust. *In* Continental lower crust. *Edited by* D.M. Fountain, R.J. Arculus, and R.W. Kay. Elsevier, Amsterdam, The Netherlands, pp. 81–143.

Jones, A.G. 1993. The COPROD2 dataset: tectonic setting, recorded MT data and comparison of models. Journal of Geomagnetism and Geoelectricity, **45**: 933–955.

Jones, A.G., and Craven, J.A. 1990. The North American Central Plains conductivity anomaly and its correlation with gravity, magnetics, seismic, and heat flow data in the Province of Saskatchewan. Physics of the Earth and Planetary Interiors, **60**: 169–194.

Jones, A.G., and Craven, J.A. 2004. Area selection for diamond exploration using deep-probing electromagnetic surveying. Lithos, **77**: 765–782.

Jones, A.G., and Ferguson, I.G. 2001. The electric Moho. Nature (London), **409**: 331–333.

Jones, A.G., and Garcia, X. 2003. The Okak Bay MT dataset case study: a lesson in dimensionality and scale. Geophysics, **68**: 70–91.

Jones, A.G., and Groom, R.W. 1993. Strike angle determination from the magnetotelluric tensor in the presence of noise and local distortion: rotate at your peril! Geophysical Journal International, **113**: 524–534.

Jones, A.G., and Savage, P.J. 1986. North American Central Plains conductivity anomaly goes east. Geophysical Research Letters, **13**: 685–688.

Jones, A.G., Craven, J.A., McNeice, G.A., Ferguson, I.J., Boyce, T., Farquharson, C., and Ellis, R.G. 1993. The North American Central Plains conductivity anomaly within the Trans-Hudson orogen in northern Saskatchewan. Geology, **21**: 1027–1030.

Jones, A.G., Katsube, J., and Schwann, P. 1997*a*. The longest conductivity anomaly in the world explained: sulphides in fold hinges causing very high electrical anisotropy. Journal of Geomagnetism and Geoelectricity, **49**: 1619–1629.

Jones, A.G., Garcia, X., Grant, N.J., Ledo, J., and Ferguson, I.J. 1997*b*. Regional electric structure of the Trans-Hudson Orogen. *In* Trans-Hudson Orogen Transect. Report of the 7th Transect Meeting, Saskatoon, Sask., Canada, May 1–2, 1997. Lithoprobe Report 62, pp. 130–146.

Jones, A.G., Ferguson, I.J., Chave, A.D., Evans, I.J., and McNeice, G.W. 2001. The electric lithosphere of the Slave craton. Geology, **29**: 423–426.

Jones, A.G., Snyder, D., Hanmer, S.I., Asudeh, D., White, D.J., Eaton, D., and Clarke, G. 2002*a*. Magnetotelluric and teleseismic study across the Snowbird Tectonic Zone, Canadian Shield: a Neoarchean mantle suture? Geophysical Research Letters, **29**(17): doi: 10.1029/2002GL015359, 10-1-10-4.

Jones, A.G., Spratt, J., and Evans, S. 2002*b*. CBEX: Central Baffin electromagnetic experiment. Geological Survey of Canada, Current Research, 2002-C19.

Jones, A.G., Lezaeta, P., Ferguson, I.J., Chave, A.D., Evans, R.L., Spratt, J., and Garcia, X. 2003. The electrical structure of the Slave craton. Lithos, **71**: 505–527.

Katsube, T.J., Jones, A.G., Scromeda, N., and Schwann, P. 1996. Electrical charachteristics of rock samples from the La Ronge Domain of the Trans-Hudson Orogen, northern Saskatchewan. Geological Survey of Canada, Current Research No. 1996-E, pp. 159–169.

Kennedy, C.S., and Kennedy, G.C. 1976. The equilibrium boundary between graphite and diamond. Journal of Geophysics Research, **81**: 2467–2470.

Klasner, J.S., and King, E.R. 1986. Precambrian basement geology of North and South Dakota, relationship to exposed Precambrian terranes, tectonic implications. Canadian Journal of Earth Sciences, **23**: 1083–1102.

Larsen, J.C. 1977. Removal of local surface conductivity effects from low frequency mantle response curves. Acta Geodaetica, Geophysica et Montanistica Hungarica, **12**: 183–186.

Lidiak, E.G. 1971. Buried Precambrian rocks of South Dakota. Geological Society of America Bulletin, **82**: 1411–1420.

Lucas, S.B., Green, A.G., Hajnal, Z., White, D., Lewry, J., Ashton, K., Weber, W., and Clowes, R. 1993. Deep seismic profile across a Proterozoic collision zone: surprises at depth. Nature (London), **363**: 339–342.

Lucas, S.B., White, D., Hajnal, Z., Lewry, J., Green, A., Clowes, R., Zwanzig, H., Ashton, K., Schledewitz, D., Stauffer, M., Norman, A., Williams, P.F., and Spence, G. 1994. Three-dimensional collisional structure of the Trans-Hudson Orogen, Canada. Tectonophysics, **232**: 161–178.

Maidens, J.M., and Paulson, K.V. 1988. A magnetotelluric investigation under the Williston Basin of south-eastern Saskatchewan. Canadian Journal of Earth Sciences, **25**: 60–67.

Marquis, G., Jones, A.G., and Hyndman, R.D. 1995. Coincident conductive and reflective lower crust across a thermal boundary in southern British Columbia, Canada. Geophysical Journal International, **120**: 111–131.

Mathisrud, G.C., and Sumner, J.S. 1967. Underground induced polarisation survey surveying at the Homestake mine. Mining Congress Journal, **53**: 66–69.

McNeice, G., and Jones, A.G. 1996. Multi-site, multi-frequency tensor decomposition of magnetotelluric data. Society of Exploration Geophysicists 66th Annual General Meeting, Denver, Colo., November 10–15.

McNeice, G., and Jones, A.G. 2001. Multisite, multifrequency tensor decomposition of magnetotelluric data. Geophysics, **66**: 158–173.

Nelson, K.D., Baird, D.J., Walters, J.J., Hauck, M., Brown, L.D., Oliver, J.E., Ahern, J.L., Hajnal, Z., Jones, A.G., and Sloss, L.L. 1993. Trans-Hudson orogen and Williston basin in Montana and North Dakota: new COCORP deep profiling results. Geology, **21**: 447–450.

Németh, B. 1999. Structure of the lithosphere within the Trans-Hudson Orogen (results of the 1993 Lithoprobe Trans-Hudson refraction experiment). Unpublished Ph.D. thesis, University of Saskatchewan, Saskatoon, Sask.

Németh, B., Hajnal, Z., and Lucas, S.B. 1996. Moho signature from wide-angle reflections; preliminary results of the 1993 Trans-Hudson Orogen refraction experiment. Tectonophysics, **264**: 111–121.

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

Oldenburg, D.W., and Ellis, R.G. 1993. Efficient inversion of magnetotelluric data in two dimensions. Physics of the Earth and Planetary Interiors, **81**: 177–200.

Ogawa, Y., and Uchida, T. 1996. A two-dimensional magnetotelluric inversion with assuming Gaussian static shift. Geophysical Journal International, **126**: 69–76.

Parker, R.L., and Booker, J.R. 1996. Optimal one-dimensional inversion and bounding of magnetotelluric apparent resistivity and phase measurements. Physics of the Earth and Planetary Interiors, **98**: 269–282.

Peterman, Z.E. 1979. Geochronology and the Archean of the United States. Economic Geology, **74**: 1544–1562.

Peterman, Z.E. 1981. Dating the Archean basement in northeastern Wyoming and southern Manitoba. Geological Society of American Bulletin, **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. Geophysical Journal of the Royal Astronomical Society, **19**: 237–260.

Porath, H., Gough, D.I., and Camfield, P.A. 1971. Conductive structures in the northwestern United States and south-west Canada. Geophysical Journal of the Royal Astronomical Society, **23**: 387–398.

Pous, J., Ledo, J., Marcuello, A., and Queralt, P. 1997. Two-dimensional forward modeling of the NACP anomaly (COPROD2R data). Journal of Geomagnetism and Geoelectricity, **49**: 739–744.

Rankin, D., and Pascal, F. 1990. A gap in the North American Central Plains conductivity anomaly. Physics of the Earth and Planetary Interiors, **60**: 132–137.

Rankin, D., and Reddy, I.K. 1973. Crustal conductivity anomaly under the Black Hills: a magnetotelluric study. Earth and Planetary Science Letters, **20**: 275–279.

Rasmussen, T. 1993. Two-dimensional Occam model of COPROD2 data — first order description of resolution and variance. Journal of Geomagnetism and Geoelectricity, **45**: 1027–1037.

Reitzel, J.S., Gough, D.I., Porath, D.I., and Anderson, C.W., III. 1970. Geomagnetic deep sounding and upper mantle structure in the western United States. Geophysical Journal of the Royal Astronomical Society, **19**: 213–235.

Richards, M.L., Schmucker, U., and Steveling, E. 1982. Entzerrung der Impedanzkurven von magnetotellurischen Messungen in der Schwäbischen Alb. *In* Protokol über das 9 Kolloquium Elektromagnetizche Tiefenforschung (Abstracts from 9th Electromagnetic Deep Sounding Symposium, Neustadt, Weinstraβe, Federal Republic of Germany, March 22–26. pp. 27–40.

Rodi, W., and Mackie, R.L. 2001. Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion. Geophysics, **66**: 174–187.

Ross, G.M., and Villeneuve, M.E. 2003. Provenance of the Mesoproterozoic (1.45 Ga) Belt basin (western North America): another piece in the pre-Rodinia paleogeographic puzzle. Geological Society of America Bulletin, **115**(10): 1191–1217.

Schmucker, U. 1993. 2D modeling with linearized integral equations. Journal of Geomagnetism and Geoelectricity, **45**: 1045–1062.

Schnegg, P.-A. 1993. An automatic scheme for 2-D magnetotelluric modelling, based on low-order polynomial fitting. Journal of Geomagnetism and Geoelectricity, **45**: 1039–1043.

Sims, P.K., and Peterman, Z.E. 1986. Early Proterozoic Central Plains orogen: a major buried structure in north-central United States. Geology, **14**: 488–491.

Smith, J.T. 1995. Understanding telluric distortion matrices. Geophysical Journal International, **122**: 219–226.

Smith, J.T., and Booker, J.R. 1991. Rapid inversion of two and three-dimensional magnetotelluric data. Journal of Geophysics Research, **96**: 3905–3922.

Stauffer, M.R. 1984. Manikewan: an Early Proterozoic ocean in central Canada, its igneous history and orogenic closure. Precambrian Research, **25**: 257–281.

Sternberg, B.K., Washburne, J.C., and Pellerin, L. 1988. Correction for the static shift in magnetotellurics using transient electromagnetic soundings. Geophysics, **53**: 1459–1468.

Stevens, K., and Ferguson, I.J. 1997. 1-D interpretation of high frequency magnetotelluric data across the Glennie Domain of the Trans Hudson Orogen Transect. *In* Lithoprobe Seventh Trans-Hudson Orogen Transect Workshop, Saskatoon, Sask., Canada, May 1–2, 1977. Lithoprobe Report 62, pp. 197–205.

Symons, D.T.A. 1998. Precambrian plate tectonic models; shifting the paleomagnetic paradigm for orogens such as the Trans-Hudson in Canada. Physics and Chemistry of the Earth, **23**: 753–759.

Takasugi, S., Sato, T., and Honkura, Y. 1993. Two-dimensional forward modelling for the COPROD2 MT data. Journal of Geomagnetism and Geoelectricity, **45**: 957–962.

Tournerie, B., Gilbert, D., and Virieux, J. 1995. Inversion of the COPROD2 magnetotelluric data using a Diffusuve-to-Propagative Mapping (DPM). Geophysical Research Letters, **22**: 2187–2190.

Uchida, T. 1993. 2-D inversion of COPROD2 magnetotelluric data by use of ABIC minimization method. Journal of Geomagnetism and Geoelectricity, **45**: 1063–1071.

Van Schmus, W.R., and Bickford, M.E. 1981. Proterozoic chronology and evolution of the midcontinent region. *In* Precambrian Plate Tectonics. *Edited by* A. Kroner. Elsevier, Amsterdam, pp. 261–296.

Vozoff, K. (*Editor*). 1986. Magnetotelluric methods. Society Exploration Geophysics. Reprint Ser. No. 5: Tulsa, Okla. ISBN 0-931830-36-2.

Wannamaker, P.E. 1997. Comment on "The petrologic case for a dry lower crust" by B.W.D. Yardley and J.W. Valley. Journal of Geophysical Research, **102**: 12 173 – 12 185.

Wannamaker, P.E., Stodt, J.A., and Rijo, L. 1985. PW2D: Finite element program for solution of magnetotelluric responses of two-dimensional Earth resistivity structure. Earth Science Laboratory, Utah Research Institution, Salt Lake City, Ut.

Wessel, P., and Smith, W.H.F. 1991. Free software help map and display data. EOS Transactions of the American Geophysical Union, **72**: 441.

Wessel, P., and Smith, W.H.F. 1998. New, improved version of the Generic Mapping Tools released. EOS Transactions of the American Geophysical Union, **79**: 579.

White, D.J., Lucas, S.B., Hajnal, Z., Green, A.G., Lewry, J.F., Weber, W., Bailes, A.H., Syme, E.C., and Ashton, K. 1994. Paleo-Proterozoic thick-skinned tectonics: LITHOPROBE seismic reflection results from the eastern Trans Hudson Orogen. Canadian Journal of Earth Sciences, **31**: 458–469.

White, D.J., Jones, A.J., Lucas, S.B., and Hajnal, Z. 1999. Tectonic evolution of the Superior Boundary Zone from coincident seismic reflection and magnetotelluric profiles. Tectonics, **18**: 430–451.

Wright, J.A. 1969. The magnetotelluric and geomagnetic response of two-dimensional structures. GAMMA 7, Institute of Technology, University of Braunschweig, Braunschweig, Federal Republic of Germany, p.102.

Wu, N. 1994. High-resolution electromagnetic images of conductivity structure in the mid-lower crust and upper mantle — a magnetotelluric experiment conducted primarily in North

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Dakota. Unpublished Ph.D. thesis, University of Washington, Seattle, Wash.
Wu, N., Booker, J.R., and Smith, J.T. 1993. Rapid two-dimensional inversion of COPROD2 data. Journal of Geomagnetism and Geoelectricity, **45**: 1073–1087.
Yardley, B.W.D., and Valley, J.W. 1997. The petrologic case for a dry lower crust. Journal of Geophysics Research, **102**: 12 172 – 12 185.
Zelt, B.C., and Ellis, R.M. 1999. Receiver-function studies in the Trans-Hudson Orogen, Saskatchewan. Canadian Journal of Earth Sciences, **36**: 585–603.
Zhang, P., Roberts, R.G., and Pedersen, L.B. 1987. Magnetotelluric strike rules. Geophysics, **52**: 267–278.
Zhao, G., Tang, J., and Zhan, Y. 1993. Two dimensional modelling by using COPROD2 magnetotelluric data. Journal of Geomagnetism and Geoelectricity, **45**: 963–968.

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