Electromagnetic image of the Trans-Hudson orogen — THO94 transect[1, 2]

Xavier Garcia and Alan G. Jones

Abstract: The North American Central Plains (NACP) anomaly in enhanced electric conductivity and its relationship with the Paleoproterozoic Trans-Hudson orogen (THO) has been studied under the auspices of Lithoprobe for over a decade. The NACP anomaly was the first geophysical evidence of the existence of the THO beneath the Phanerozoic sediments of the Central Plains. This anomaly, detected geomagnetically in the late 1960s, has been the subject of a number magnetotelluric studies from the early 1980s. The PanCanadian and Geological Survey of Canada experiments in the 1980s and the Lithoprobe experiments in the 1990s together comprise four east–west and one north–south regional-scale profiles in Saskatchewan perpendicular to the strike of the orogen. In this paper, data from the northernmost line, coincident with seismic line S2B, are analysed and interpreted, and are shown to be key in determining the northern extension of the NACP anomaly. Dimensionality analysis confirms the rotation of deep crustal structures eastward to Hudson Bay, as earlier proposed on the basis of broad-scale geomagnetic studies. On this profile, as with the profile at the edge of the Paleozoic sediments, the NACP anomaly is imaged as lying within the La Ronge domain, in contact with the Rottenstone domain, and structurally above the Guncoat thrust, a late compressional feature. The location of the anomaly together with the surface geology suggests that the anomaly is caused either by sulphide mineralization concentrated in the hinges of folds, by graphite, or by a combination of both. Our interpretation of the data is consistent with that from other profiles, and suggests that the NACP anomaly was formed as a consequence of subduction and collisional processes involving northward subduction of the internides of the THO beneath the Hearne craton. On the southern part of this profile, a resistive structure is identified as the Sask craton, suggesting that Proterozoic rocks are above Archean rocks in the THO.

Résumé : L'anomalie des plaines du centre de l'Amérique du Nord en conductivité électrique amplifiée et sa relation avec l'orogène trans-hudsonien (Paléoprotérozoïque) ont été étudiées dans le cadre du projet Lithoprobe depuis plus d'une décennie. Cette anomalie a été la première évidence géophysique de l'existence de l'orogène trans-hudsonien sous les sédiments phanérozoïques des plaines centrales. Cette anomalie, détectée par des techniques géomagnétiques à la fin des années 1960, a été le sujet de nombreuses études magnétotelluriques (MT) à partir du début des années 1980. Les expériences de PanCanadian et de la Commission géologique du Canada dans les années 1980, ainsi que celles du projet Lithoprobe dans les années 1990, comprennent ensemble, à l'échelle régionale, en Saskatchewan, quatre profils est-ouest et un profil nord-sud qui sont perpendiculaires à la direction de l'orogène. Dans cet article, les données de la ligne la plus au nord, coïncidant avec la ligne sismique S2B, sont analysées et interprétées; elles s'avèrent être une clé dans la détermination de l'extension vers le nord de l'anomalie des plaines du centre de l'Amérique du Nord. Une analyse dimensionnelle confirme la rotation de structures crustales profondes vers l'est, vers la baie d'Hudson, tel que proposé antérieurement sur la base d'études géomagnétiques à grande échelle. Sur ce profil, ainsi que sur le profil à la limite des sédiments paléozoïques, l'anomalie des plaines du centre de l'Amérique du Nord est imagée comme étant à l'intérieur du domaine de La Ronge, en contact avec le domaine de Rottenstone et en position structurale au-dessus du chevauchement Guncoat, un événement de compression tardive. Selon l'emplacement de l'anomalie et la géologie de surface, l'anomalie serait causée par une minéralisation de sulfures concentrée dans les charnières de plis ou par du graphite ou encore par une combinaison de ces deux hypothèses. Notre interprétation des données concorde avec celles d'autres profils et elle suggère que l'anomalie des plaines du centre de l'Amérique du Nord résulte des processus de subduction et de collision impliquant la subduction vers le nord des internides du transect de l'orogène trans-hudsonien sous le craton Hearne. Sur la partie sud de ce profil, une structure résistive est

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identifiée comme étant le craton Sask, suggérant que les roches protérozoïques soient au-dessus des roches archéennes dans le transect de l'orogène trans-hudsonien.

[Traduit par la Rédaction]

Introduction

During the decade 1984–1994, PanCanadian Oil Co. Ltd. (PanCanadian), the Geological Survey of Canada (GSC), and Lithoprobe undertook magnetotelluric (MT) measurements at more than 200 locations in Saskatchewan to study the enigmatic North American Central Plains (NACP) conductivity anomaly and its relationship with the Paleoproterozoic Trans-Hudson orogen (THO). This anomaly in enhanced conductivity was detected for the first time during the late 1960s and since then has motivated a number of electromagnetic (EM) studies (for a review, see Jones et al., 2005). It is spatially associated with the Paleoproterozoic THO and, in fact, was the first evidence of the continental projection of the orogen beneath the Phanerozoic sediments of the Central Plains (Camfield and Gough 1977). Using geomagnetic depth sounding (GDS) arrays, those authors interpreted the NACP anomaly as the geophysical signature of a Proterozoic continental collision. Prior to this, it was believed that the orogen extended from Hudson Bay only to ~55° latitude but its extension beneath the Phanerozoic sedimentary cover was identified from the study of geophysical data (initially GDS soundings, and later magnetic and Bouguer anomalies). However, because of the intrinsic limitations of the GDS method and the broad station-spacing, the conductivity, geometry, and geographic position of the NACP anomaly were determined only in a general manner.

The main target of the EM component of the Lithoprobe THO transect investigations was the delineation, definition, and tectonic understanding of the NACP anomaly. Through extensive studies, the NACP anomaly is known to extend from the Dakotas to northern Canada (Alabi et al. 1975; Camfield and Gough 1975; Jones et al. 1993, 2005). The MT soundings recorded by PanCanadian and the GSC in the mid-1980s, and by Lithoprobe in the early 1990s, were located in the Manitoba–Saskatchewan segment of the THO, between the USA–Canada border and Hudson Bay. These soundings are divided in five profiles named, from south to north, S (south), M (middle), N (north), L (Lithoprobe), and X (extra Lithoprobe) (Fig. 1).

Phoenix Geophysics recorded line S in 1984–1985 for PanCanadian. This profile has been interpreted, modelled, and discussed in Jones and Savage (1986), Jones (1988a, 1988b), and Jones and Craven (1990). Ten investigators have also interpreted line S as part of an MT modeling comparison (COPROD2, see Jones 1993, and references therein; Jones et al. 2005). Lines M and N were recorded by the GSC in 1987 and a qualitative interpretation of these two profiles is in Jones and Craven (1990), and the final interpretation is in Jones et al. (2005).

Phoenix Geophysics recorded the east–west line L across the whole orogen for Lithoprobe in 1992 (Fig. 2). This profile was analysed and modelled in Jones et al. (1993, 2005). In 1994, Phoenix Geophysics recorded line X, also named THO94,

for the Lithoprobe project (Figs. 2, 3). Line X is along seismic line S2B.

This paper describes the analysis, modelling, and interpretation of line X. Special emphasis has been placed on the location and interpretation of the NACP anomaly in the bend of the orogen. Modelling the MT data from the profile allows us to study the orogen and provides more information about the nature of the collision that created it. An extremely interesting feature detected by this work is the enigmatic Sask craton at the southern end of the profile.

The seismic reflection data on profile S2B is coincident with the MT profile X (Hajnal et al. 2005), and the initial interpretation, based on the main reflectors, has been taken for comparison with the MT resistivity model. This interpretation is a qualitative one; for more details and a quantitative interpretation see Hajnal et al. (2005) and Corrigan et al. (2005).

Geological context

Geologically, North America is cored by a collage of cratons that have been stable since 1.7 Ga (Hoffman 1988). Each of these cratons is an aggregate of crustal and lithospheric elements formed during the Archean, and each contains variable proportions of predominantly Mesoarchean rocks. Rifting processes during the Neoarchean, and consequent collisional deformations, determined the final dimensions of the provinces.

An Archean province can be defined as a continuous region of continental lithosphere that has been stable since the Archean and is surrounded by Proterozoic suture zones or orogens (Hoffman 1989). The North American Archean provinces were amalgamated during the Paleoproterozoic and the orogens formed by these collisions can be identified as deformed passive margins, accretion prisms, and thrust belts. Of the stitching orogens, the THO, which separates the Superior Province to the east from the Wyoming craton and Rae–Hearne provinces to the west, is unique in that a considerable width (up to 400 km) of young Proterozoic crust, including remains from island arcs and obducted ocean crust, remains today (Hoffman 1989).

Camfield and Gough (1977) interpreted the NACP conductive anomaly as the plate limit under the thick Phanerozoic sedimentary cover in the middle of the North American continent. This contributed to the discovery of Proterozoic plate boundaries (Hearne, Rae and Wyoming) that are exposed on the Canadian shield (Gibb and Walcott 1971) and to the south (Hills et al. 1975). Figure 1 shows the general trace of the NACP anomaly obtained from GDS and MT soundings. Its location, and the correlation of its ends within the Paleoproterozoic shear and fold areas in Precambrian crust, suggested to Camfield and Gough (1977) that it is the manifestation of a Paleoproterozoic-aged geosuture caused by the

Fig. 1. Basic tectonic units in central North America associated with the THO. Also shown are the locations of the NACP anomaly and the MT profiles in Saskatchewan. Profile X, also known as THO94, has been analysed and interpreted in this work.
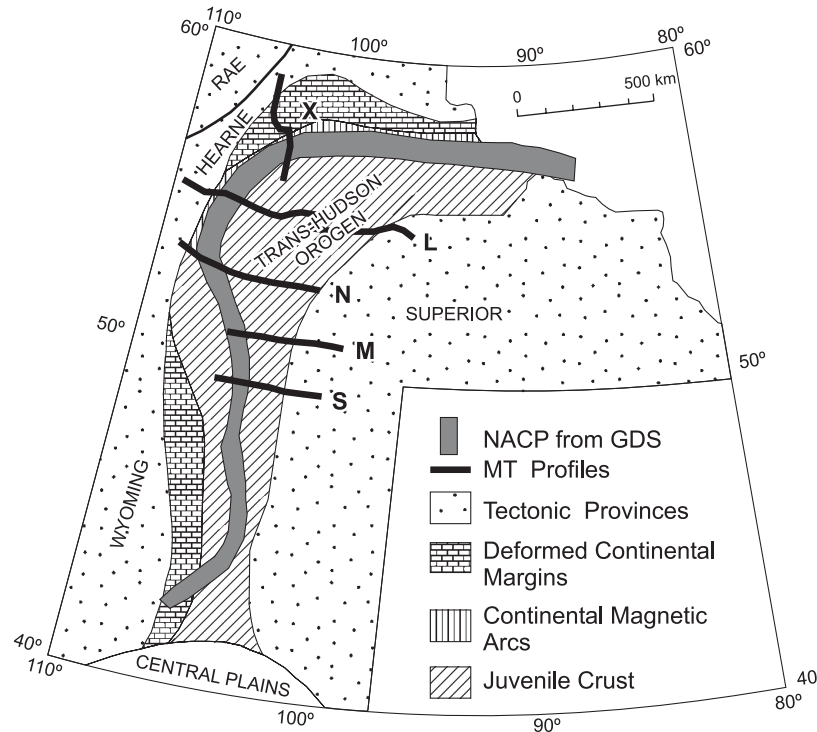

collision of two Archean plates. Later, based on this and other data, a continental-scale suture zone of Hudsonian age was proposed to transect the continent; it was named the THO by Hoffman (1981). Klasner and King (1986), in their study of the nature of the Precambrian basement rocks from the Dakotas, considered the NACP anomaly an important tectonic feature and used it to correlate the buried part of the THO in the Dakotas with the Precambrian terranes that surface in northern Saskatchewan and Manitoba. Thus, the NACP anomaly has played a significant part in the discovery of the extent of the THO, and even today it remains a significant element of the THO that requires explanation in any evolutionary model proposed for the orogen's development and history.

The THO can be divided in three segments: (1) Hudson Bay and northern Quebec toward the northeast, (2) Manitoba–Saskatchewan, and (3) the Dakotas toward the south. The 400-km-wide Manitoba–Saskatchewan segment is formed by four tectonic regions: a fold and foreland basin thrust belt to the east and southeast, an internal area formed by young Proterozoic crust, an Andean type batholith (Wathaman–Chipewan), and an internal belt to the west and northwest. Rocks in the Wollaston domain represent Proterozoic passive margin basinal metasedimentary sequences underlain by Archean crust. The Wathaman batholith is a Paleoproterozoic (1.86–1.85 Ga) calc-alkaline intrusion, with a maximum width of 100 km, constituted by an eroded Andean type magmatic arc, and developed over Archean crust that was accreted by the internal zone (Meyer 1987; Bickford et al. 1990). Between the Wathaman batholith and the orogen internides is the Needle Falls shear zone (NSFZ), a dextral-transcurrent directional fault active during northern collision of the

Superior continent (Hoffman 1988, 1989). The Wathaman batholith straddles the orogen internides (Reindeer zone) to the Wollaston belt.

The internides of the THO, named the Reindeer zone, formed during the closure of the 5000-km-wide Manikewan Ocean (Stauffer 1984; Symons et al. 1995) that existed between the Superior and the Rae–Hearne provinces. Based on U–Pb dating, the ocean opened at about 2.1 Ga (Halls and Heaman 1997) and closed at about 1.8 Ga, corresponding to the collisional phase of the orogen. The suture of the closing lies along the eastern boundary of the Wathaman batholith (Symons et al. 1994, 1995). The internal area of the THO has been interpreted using isotopic data and is formed of 1.9-Ga-young crust (Sangster 1978; Chauvel et al. 1987; Van Schmus et al. 1987). Figures 2 and 3 show the geology map of the region and study area respectively, with the main tectonic features and rock types indicated. Towards the north lies the Peter Lake domain of unknown origin. The internal belt exposes strongly deformed and metamorphosed Paleoproterozoic sediments of rift, shelf, and trench type, antiforms of the Archean basement, intrusions related to the Wathaman batholith, and anorogenic syenogranites (1.76 Ga). The Rottenstone domain is an assemblage of plutonic rocks and subordinate injection-migmatized supracrustal rocks related to the Wathaman batholith (Lewry et al. 1994). The La Ronge domain is a volcanic–plutonic arc terrane that is considered to resemble a modern Andean type arc (Thom et al. 1990). While the eastern part of the La Ronge domain is dominated by high-grade metasedimentary migmatites, the western part is mainly formed of low metamorphic grade mafic to felsic metavolcanic rocks and plutonic plutons (Lewry et al. 1994). The Kissenew domain is partially a

Fig. 2. Generalized geology map of the western part of the THO and bounding Hearne craton in northern Saskatchewan. The 1992 (profile L) and 1994 (profile X) MT profiles are shown. The white part of both profiles depicts the location of the conductor associated with the NACP. GcT, Guncoat thrust; BRSB, Birch Rapids straight belt; NFSZ, Needle Falls shear zone.
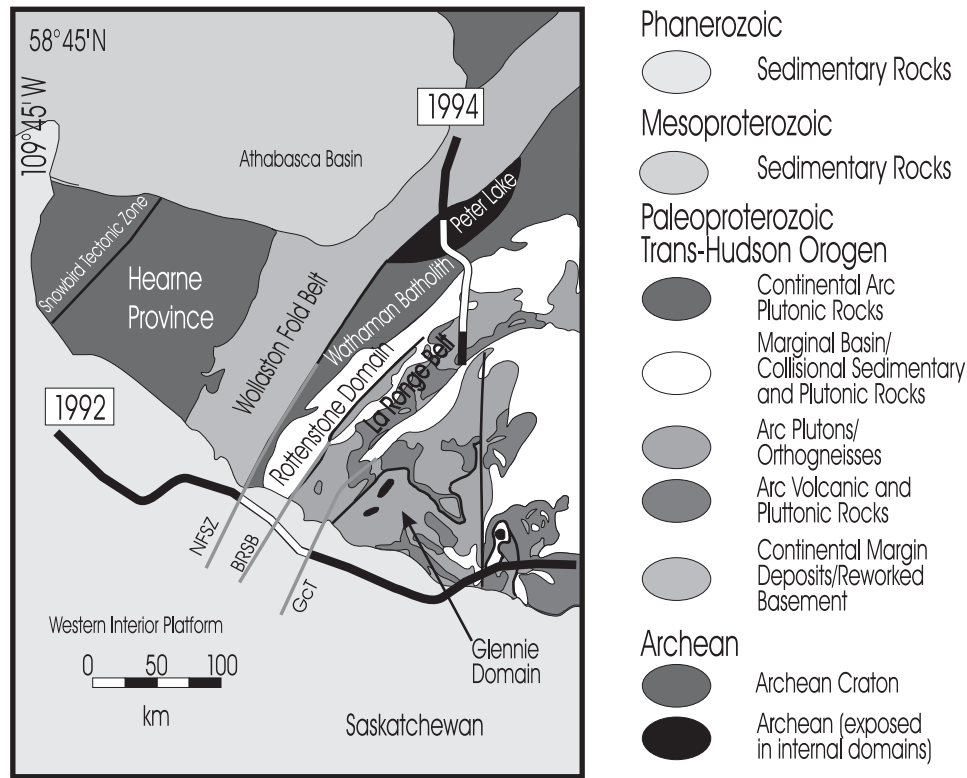
forearc basin to the La Ronge belt and on the northern part a remnant basin (Lewry et al. 1981), and contains high-grade metasedimentary migmatites (akin to the eastern La Ronge domain). Volcanic rocks are mainly present on the margins of this domain, although there are some thin continuous units in the north-central region and these may represent upthrusted rocks from an oceanic-type floor marginal to the adjacent La Ronge island arc on which the arc sediments were initially deposited.

The Glennie domain is characterized by arcuate belts of Paleoproterozoic supracrustal rocks, including island-arc volcanogenic assemblages among variably deformed and metamorphosed granitoid rocks. The western boundary of the Glennie domain is marked by the Stanley shear zone, a 1–4 km-wide, subvertical belt of mylonitic schists, gneiss, and late brittle faults (Lewry et al. 1990). The north-trending Tabbernor fault zone is on the eastern boundary of the Glennie domain, and is characterized by north–south folds, high metamorphic field gradients and early mylonitic to late brittle deformation (Elliot 1994). This fault is approximately parallel to the THO94 MT profile.

One major feature of the La Ronge domain is the Guncoat thrust — a thrust formed by tectonic schists and mylonitic gneisses, and interpreted to have a seismic signature that is 20 km wide by Baird and Clowes (1996). The Guncoat thrust has been suggested to define the contact between the Glennie and La Ronge domains (Hajnal et al. 1996).

Archean rocks in the internal belt are exposed uniquely in small windows in two blocks, the Hanson and Glennie domains. Their extension beneath the surface of the allo-

chtonous Proterozoic crust is imaged by seismic reflection studies that demonstrate that Archean rocks root the internides (Lucas et al. 1993) in a craton later named the Sask craton by Ansdell et al. (1995).

Tectonic models of this region suggest a pre-Wathaman eastward subduction (1875–1855 Ma) as a consequence of continent–arc collision, then polarity reversal towards the west-northwest, in which the oceanic lithosphere between this arc–continent margin and the Superior craton was subducted (Bickford et al. 1990). Later models include the Sask craton, of unknown affinity (Lucas et al. 1993). This tectonic history is challenged by Jones et al. (2005), who conclude that the geometry and nature of the NACP anomaly within the La Ronge domain suggest the predominance of westward-directed subduction throughout the subduction and collisional phases.

Data analysis and methods

Magnetotelluric data acquisition and processing

The MT method consists of recording the natural variations in time of electric and magnetic fields on the surface of the Earth. The relationship between orthogonal components of the electric and magnetic fields can be expressed as a tensor, and the amplitudes can be scaled to yield apparent resistivities at each frequency. The values of apparent resistivity give the true resistivity for a uniform Earth, and the frequency variation of the apparent resistivity curve can be interpreted to yield the variation of resistivity with depth. Further description of MT can be found in Jones et al. (2005).

Fig. 3. Geological map of the area of the 1994 S2B seismic profile and THO94 MT profile showing the lithologies, domains, and MT sites (green stars).
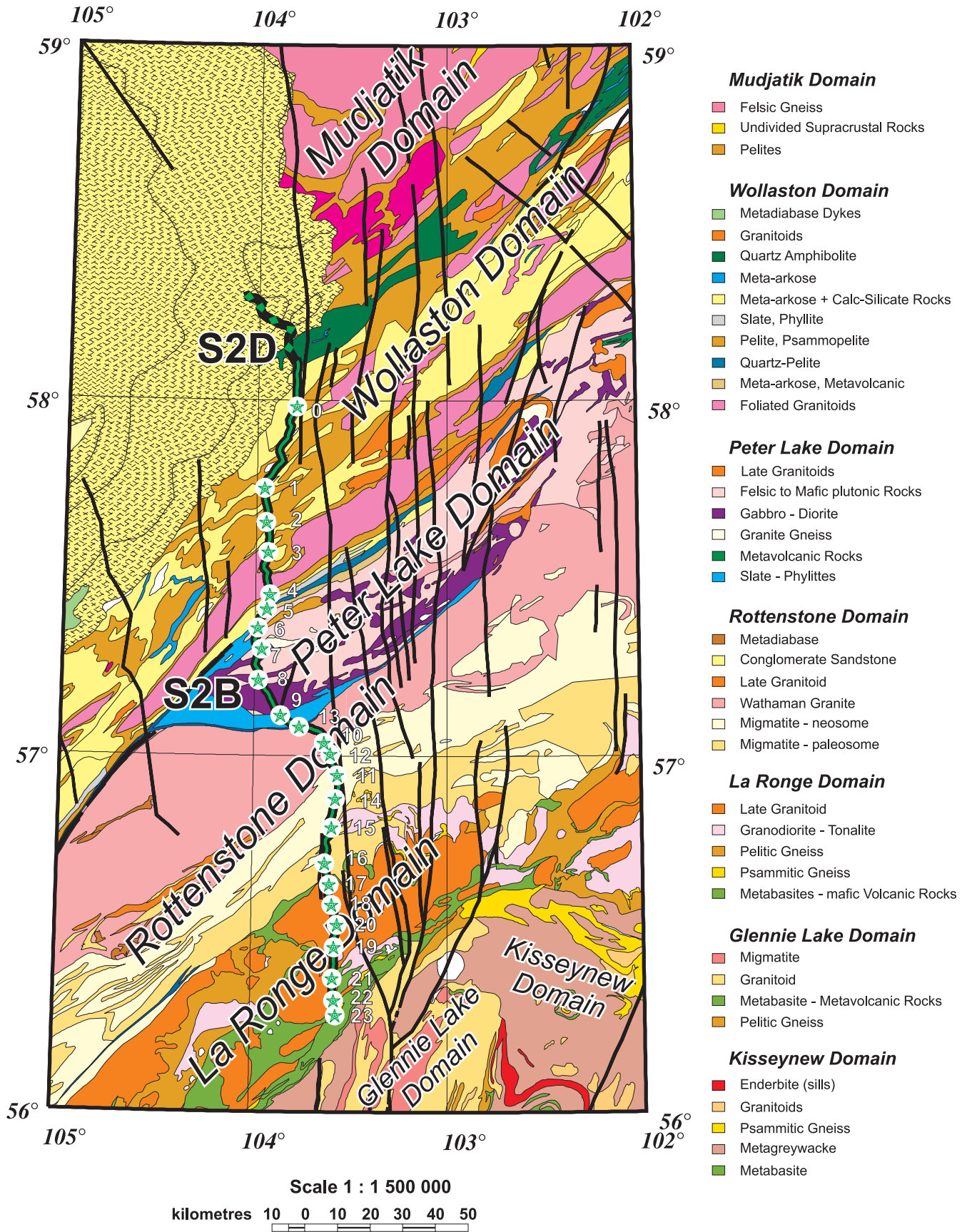
The profile comprises 23 audio-MT (AMT), covering the highest frequency range in MT studies, and MT stations and colocated long-period MT (LMT) stations (using GSC's LiMS (long-period magnetotelluric system) systems, Andersen and colleagues[5] 1988), with an additional LMT-only site (site 400). The site locations are shown on Fig. 3. Because of technical problems, only 10 of the LMT soundings were used. The distance between stations varied between 5 km and 10 km, covering an approximately north–south profile extending from 56° to 58° in latitude and ending just south of the Athabasca Basin (Figs. 2, 3). Geologically, the profile extends from the first structural unit of island-arc rocks in the internides of the THO (the La Ronge belt), almost to the contact with the Archean Hearne craton (Figs. 1, 2). Each station recorded 4 hours of AMT data (10 000 to 10 Hz), 2 nights in the MT period band (100 Hz to 500 s), and between 4 and 7 days in the LMT range (20 to 10 000 s). The AMT and MT data shared the same electric dipoles to avoid static shift problems when merging the data to obtain a unique set of data from 10 to 0.0005 Hz (2000 s). The final data consists of a combination of AMT data from 10 to 72 Hz, MT data from 48 to 0.0005 Hz, and the LMT data from 0.05 to 0.0001 Hz. The data from the different bands are consistent at overlapping frequencies, lying within the error bounds of each other. As the LMT instruments were not deployed for sufficiently long enough time, the longest period of good quality data was 2000 s (0.0005 Hz).

The LMT data from this profile were severely affected by ionospheric current systems, particularly the auroral electrojet. To compensate for this the data were processed using a remote reference robust processing technique that, besides eliminating noise in the output channel (electric), included eliminating noisy sections in the magnetic channels (Garcia et al. 1997). The AMT and MT data were processed by the contractor (Phoenix Geophysics) using a robust technique based on Jones and Jödicke (1984) and method 6 in Jones et al. (1989).

Dimensionality and distortion analysis

Galvanic distortion of the regional electric and magnetic fields is caused by shallow inhomogeneities. Charges accumulate on the boundaries of these inhomogeneities and create a secondary electric field that superposes on the regional electric field. The effect of galvanic distortion is different on the electric and magnetic fields. In the strike direction, the electric field distortion is independent of frequency and manifests itself as a multiplicative shift of the apparent resistivity curves without any phase effects (the so-called static shift effect in MT, Jones 1988a). However, the local distorted field is not necessarily parallel to the regional one and this can introduce a rotation of the responses (Jones and Groom 1993), making the task of estimating the dimensionality and the appropriate strike angle in the case of two-dimensional (2-D) structures difficult. Magnetic field distortion is dependent on frequency, but it vanishes for low frequencies and therefore is not considered for most studies.

Electric field distortion has been discussed by several authors (Larsen 1977; Zhang et al. 1993; Bahr 1988; Groom and Bailey 1989, 1991). None of these authors considered in depth the effects of magnetic distortion because, at the periods in which the induced currents are affected by inhomogeneities, it is expected that the magnetic field effect is not significant. Singer (1992) studied the circumstances that control its importance, and Chave and Smith (1994) designed an algorithm to decompose electric and magnetic galvanic distortion and applied it successfully to real data.

In the present work, an analysis of the distortion has been undertaken to estimate the 2-D strike angle and dimensionality and the distortion parameters to recover the undistorted regional responses. Initially, the algorithm of Chave and Smith (1994) was used to estimate the effect of magnetic distortion. It was found that magnetic distortion is not significant (Garcia 1998). Thus, for the final galvanic decomposition the multi-site, multi-frequency algorithm of McNeice and Jones (2001) was used. This algorithm is based on the Groom and Bailey parametric decomposition that provides not only a physical basis for the decomposition but also a statistic validity of the model can be tested.

Following Groom et al. (1993) and Jones and Dumas (1993), the procedure we followed to perform the decompositions comprised an initial decomposition of each individual site allowing the parameters to vary with frequency. In this way we observed which parameters are demonstrably independent of frequency for a certain range. Subsequently, we performed frequency independent decompositions for different ranges at each site. This allowed us to compare results and seek correlations between sites. Then we continued by decompositions in which neighbouring sites were analysed together to find a common strike angle. Finally, all the sites were decomposed together to find a regional strike angle for the frequency range that we were interested in studying. This procedure allowed us to find the angle that presents the smallest error when the decomposition of all the stations is realized, while at the same time, local variations affecting a few stations are also located. The McNeice and Jones (2001) algorithm corrects the data for galvanic distortion and also derives the regional 2-D responses in the regional strike coordinate system. One parameter remained unknown after the decomposition — the gain or static shift. To recover this parameter we needed more information; in our case, it has been recovered as part of the 2-D inversion.

Figure 4 shows graphically the result of the galvanic decomposition for the three-decade period range 0.01–10 s. Comparing this map with the geology map of the area (Fig. 3), it can be appreciated that a good correlation of the surface geology strike direction with a geoelectric average strike angles exists. The length of the arrow denotes how well the data are fit by the distortion model; long arrows indicate an excellent fit of the distortion model to the data and short arrows indicate a poor fit owing to either overly optimistic error estimates (see Chave and Jones 1997) or to 3-D inductive effects because of complex 3-D geometry of conductive structures. The decomposition analysis suggests a regional strike angle of 60° for the frequencies corresponding to EM-wave penetration

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[5] Andersen, F., Boerner, D.B., Harding, K., Jones, A.G., Kurtz, R.D., Parmelee, J., and Trigg, D. LIMS: long period intelligent magnetotelluric system. 9th Workshop on EM Induction, Sochi, USSR, October 24–31, 1988. A talk presented at the workshop. Unpublished.

Fig. 4. Geoelectric strike directions in the period band 0.01 Hz to 100 s for each site. The length of each arrow indicates how well the data fit the distortion model. Long arrows indicate excellent fit and short arrows indicate poor fit.
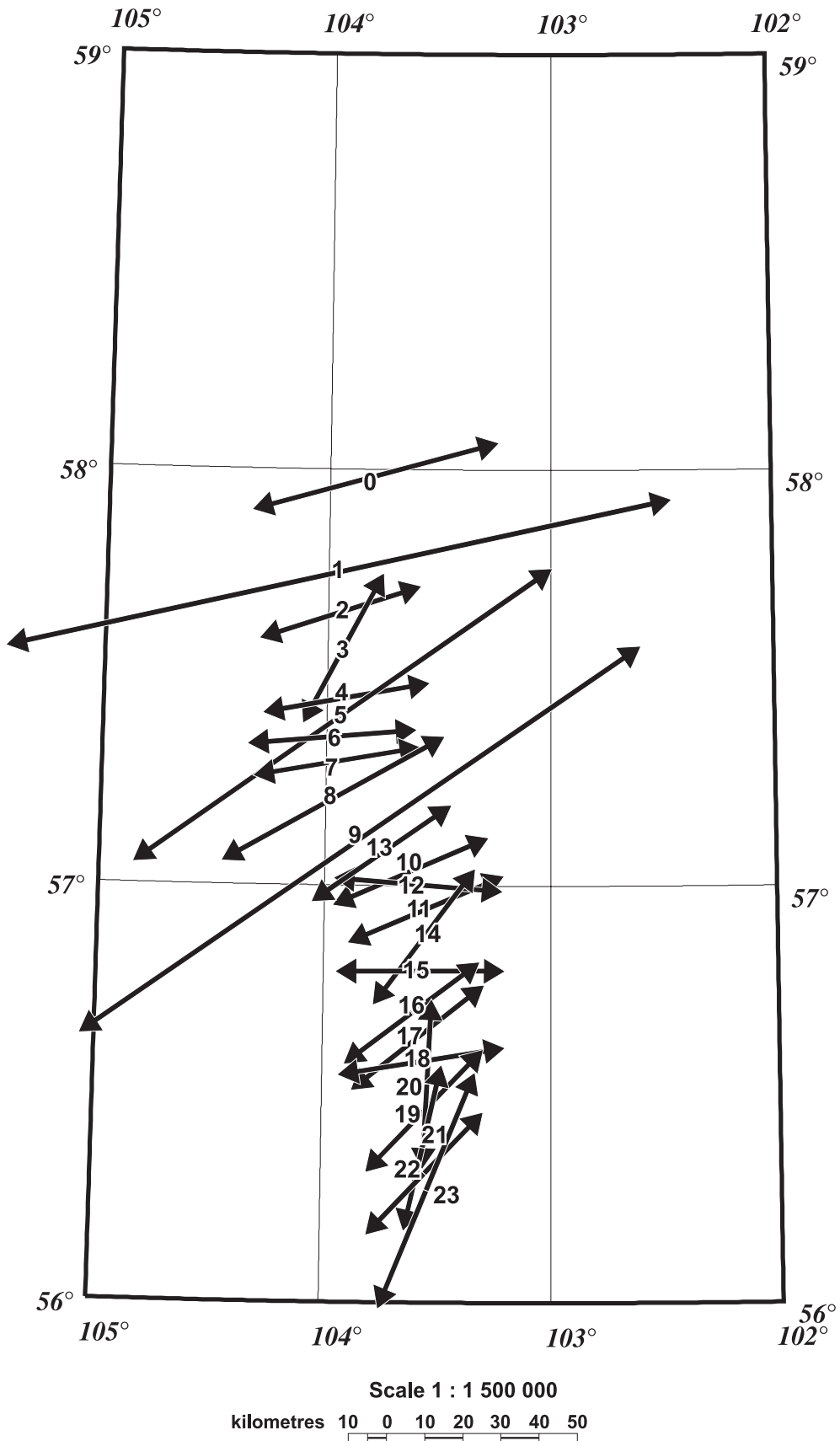
in the upper 70 km. At greater depths, an angle of 40° is more appropriate. In the location of the MT profile, the THO rotates to the northeast towards Hudson Bay (Hoffman 1989), as does the NACP anomaly (Gupta et al. 1985). An MT strike angle of 60° confirms the eastward rotation of the crustal structures, while a deeper angle of 40° does the same for deeper structures in the upper lithospheric mantle.

2-D inversion

After decomposition analyses, the data were fit to a distortion model with an assumed regional strike of 60° and projected onto a profile of azimuth of –30°. The two MT modes of induction are thus the transverse electrical (TE) mode (currents flowing parallel to strike) with the electric field at an azimuth of N060°E, and the transverse magnetic (TM) mode (currents flowing across strike) with the electric field at an azimuth of N030°W. In these coordinates, the apparent resistivity pseudosections are plotted in Figs. 5a and 5b. The data display generally a resistive upper crust (blue colour) with a few isolated conductors within it (red and yellow colours), and more conductive deeper structure.

The body interpreted as the NACP anomaly can be identified in these pseudosections as a conductive structure at the contact region between the La Ronge and Rottenstone domains (ellipse at 10–1 Hz between sites 16 and 17). The EM-skin depth provides an approximate depth of measurement at a particular frequency; in this case, the skin depth at which we find the anomaly is ~10 km. This anomaly is better detected with the TE mode (top left pseudosection, Fig. 5a). Jones et al. (2005) show an analysis of the electrical anisotropy of the THO and demonstrate that the NACP is an anisotropic feature, mostly towards the southern part and decreasing in the northern part of the orogen.

The algorithm used for the 2-D inversion of the distortion-corrected data is based on a rapid relaxed inversion approach of Smith and Booker (1988). This algorithm searches for the smoothest model that fits the data to an acceptable level. Thus, ideally the true crustal resistivity variations below the study area have to be at least the ones obtained from the inversion model. For the inversions, we omitted data that displayed large scatter, high noise, phases out of the appropriate quadrants, and manifestations of 3-D effects. Data at some stations exhibit severe galvanic distortion effects caused by the channelling of electrical current preferentially in one orientation, and those data were also omitted. The reduced dataset contained responses from 1000 Hz to 300 s, but only the data from 1000 Hz to 10 s (equivalent to ~60 km) were used in the inversion given the focus of the study.

The first series of inversions used only the MT phases because they are not affected by static shifts that can plague the MT apparent resistivity curves (Jones 1988a). The best model found was used as the starting model for the next series of inversions in which the TM resistivities were included. Subsequently, all data were included using the best model from the previous inversions as the start model. The final step consisted in the modification of the alpha parameter that controls how the 2-D Laplacian functional depends on lateral structure. A low value of alpha penalizes the vertical model making the structures more horizontal, although this tends to increase the misfit.

The final model represents a trade-off between a laterally consistent model and an optimum fit, and is shown in Fig. 6. The misfit of this model to the data is shown in the form of apparent resistivity pseudosections in Figs. 5c and 5d. The pseudosections from the model responses in the lower row can be compared with the data pseudosections in the top row. The overall fit is good, achieving a root mean square (RMS) of 5 with an error floor of 4% in apparent resistivity, equivalent to just over 1° in phase. Thus, the model fits the data to an average level of about 5°. The poorest fit is at frequencies affected by current channelling effects. We have identified these on stations 7 and 6, although they also affect neighbouring stations. Severe channelling effects occur when recording data in the vicinity of a strong narrow conductor. The fact that this body is very conductive implies that currents travel along it and there is no energy across it. Chouteau and Tournerie (2000) provide a good review of extreme current channelling effects on MT data. The minimum structure limitation imposed by the inversion code means that a large conductor with reduced conductivity replaces a smaller conductor with high conductivity. Thus, the conductors under stations 7 and 16 have to be carefully examined because they are larger than they should be according to the limitation.
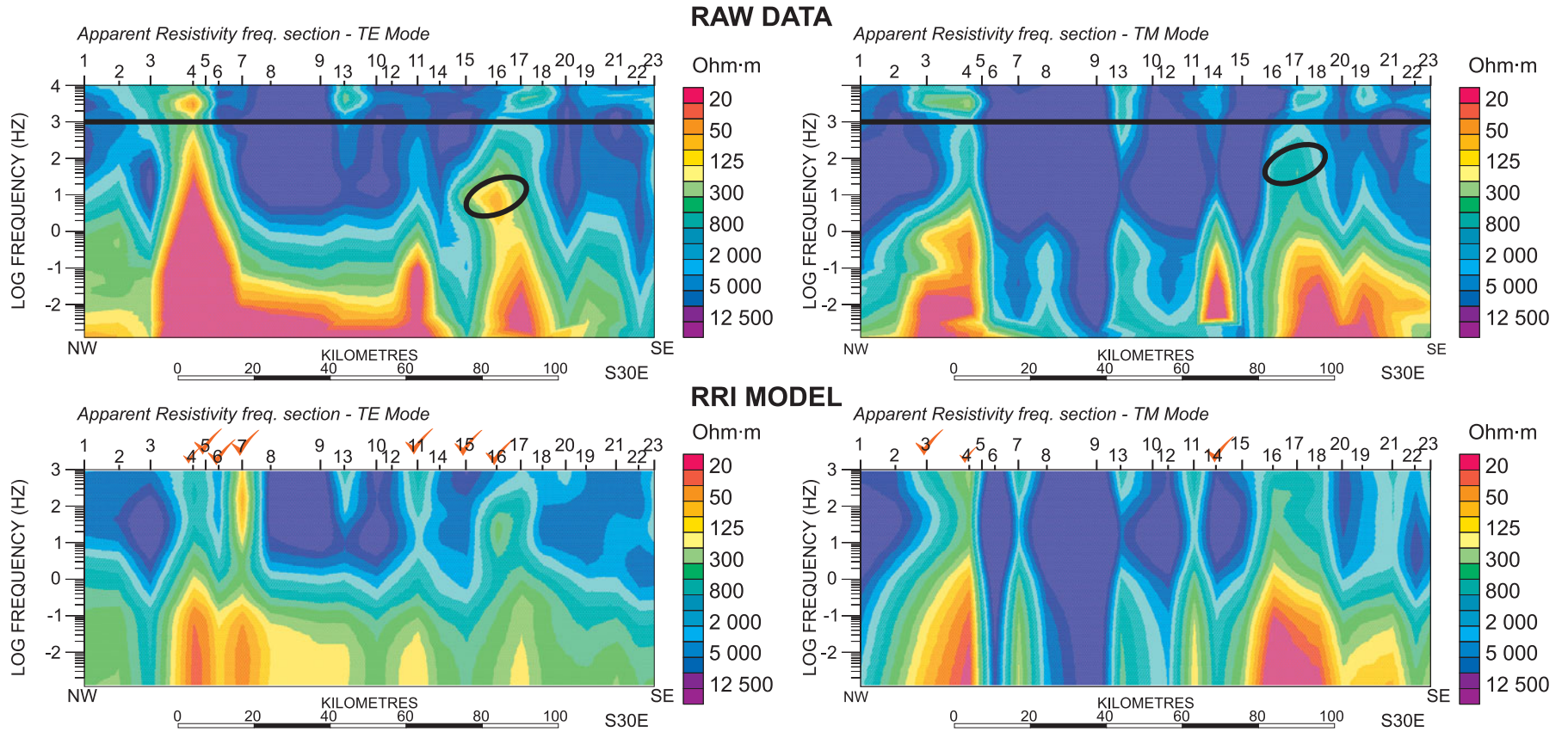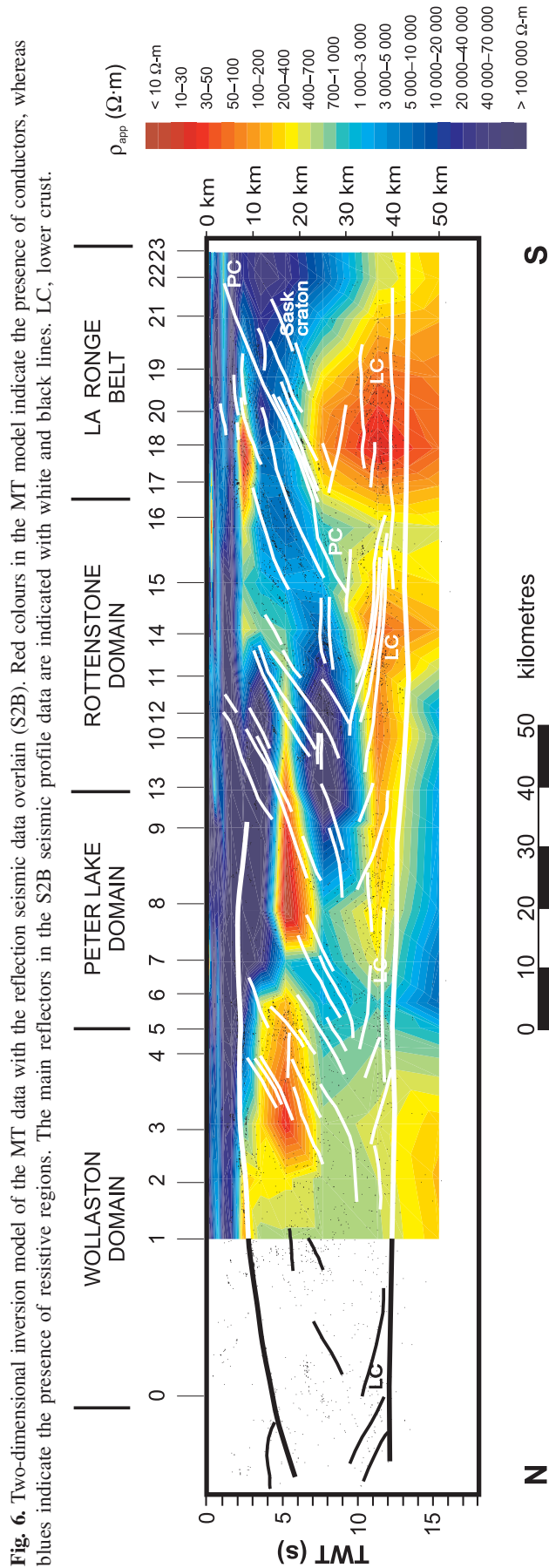
Interpretation

Figure 6 shows the final inversion model, and the shallower part of the inversion model is shown in Fig. 7 (note vertical exaggeration of 10:1). In general, the shallow structures exhibit high resistivity (>10 000 Ω.m). On the surface, the less resistive regions (700–3000 Ω.m) can be associated with the granitic domains of the Wollaston and Peter Lake domains, whereas the most resistive structures correspond spatially to domains that contain gneisses (Rottenstone and La Ronge domains). The low resistivity in granites is likely caused by the presence of saline fluids in fractures and (or) to the presence of sulphides. In the La Ronge belt there is known and mapped associated mineralization, with economic deposits of gold, nickel, and copper in disjointed veins and disseminated sulphides. Station 13 is located on top of a shear zone (Parker Lake shear zone), and it shows the highest conductive area on the surface (~100 Ω.m). Meteoric fluids that filter through the fault could cause this localized high conductivity feature. Under station 5, which is coincident with the NFSZ, there is an important change in resistivity at depth. This was also observed by Jones et al. (1993) for line L, from resistive on the cratonic side to conductive on the internides side of the boundary.

Under sites 7 and 6, there are two highly conductive bodies at 1 km depth with resistivities < 1 Ω.m. These are some of the bodies that presumably cause the current channelling effects seen on the data.

The MT model shows some remarkable geometrical similarities to the seismic reflection section (Fig. 6). In the upper and middle crust, identifiable reflectors occur mainly in resistive (blue colour) regions. To the south at the location of the north-dipping reflection fabric is a north-dipping resistive region. The north-dipping reflectors are truncated at depth by horizontal to slightly south-dipping reflection fabric; this fabric correlates with an increase in conductivity. At

Fig. 5. (Top): MT data (apparent resistivities) after galvanic decomposition and determination in the regional strike angle (N060°E). The thick black line indicates the upper frequency data used in this work (from 1000 to 0.01 Hz). (Bottom): apparent resistivities correspondent to the model from Fig. 6. The stations that have a coloured tick on the name have some of their response errors incremented nine orders of magnitude, so the inversion algorithm dismisses them. These data showed extreme current channelling effects. Station 4 had all its data removed for inversion. In these pseudosections cool colours (blues to purple) denote high resistivities (>2000 Ω.m), whereas warm colours (yellow to reds) indicate low resistivities (<200 Ω.m). Greens show intermediate resistivities (200–2000 Ω.m). freq., frequency.

Fig. 6. Two-dimensional inversion model of the MT data with the reflection seismic data overlain (S2B). Red colours in the MT model indicate the presence of conductors, whereas blues indicate the presence of resistive regions. The main reflectors in the S2B seismic profile data are indicated with white and black lines. LC, lower crust.

mid-crustal depths beneath the western part of the La Ronge belt and extending beneath the Peter Lake domain are conductive features identified later in the text as the NACP anomaly. Where these conductors exist, the reflection data are transparent. Reflectors end just above them and start again just below them.

North American Central Plains conductivity anomaly

Below line X, the NACP anomaly is the elongated structure at 8-km depth located under the contact between the La Ronge belt and the Rottenstone and Peter Lake domains (Fig. 5). The resistivity of these bodies is < 10 Ω.m, extending beneath sites 11 to 20, and it is < 50 km wide and < 2 km thick, being more conductive toward the southeastern end.

Jones and Craven (1990) noted that the NACP located on MT profiles M, N, and S correlates well with a magnetically quiet region. In the northern part of the orogen the situation is different. Line L detects the anomaly over a magnetic minimum at latitude 55°. This minimum disappears where the orogen is exposed, but then further north in our study area (line X location) the NACP is situated under the La Ronge domain and correlates with a magnetically quiet area.

The NACP conductive anomaly was discovered during the late 1960s using GDS array studies (Reitzel et al. 1970). The GDS arrays and profiles that followed (Camfield et al. 1970; Porath et al. 1970, 1971; Gough and Camfield 1972; Alabi et al. 1975; Handa and Camfield 1984; Gupta et al. 1985) suggested that the NACP was morphologically linear and extended for some 2000 km, but that its origin was not fully known along its entire length. Later studies using the MT technique have shown that the anomaly is in the crust and has a geometry that can be spatially identified with specific domains of the internides of the THO.

The NACP anomaly has been explained by five different theories:

(1) Association with graphite present in schistose rocks in a belt traced by Lidiak (1971), located within Precambrian basement rocks under the Great Plains (Camfield et al. 1970; Gough and Camfield 1972; Handa and Camfield 1984);
(2) Trapped saline water in fracture rocks (Handa and Camfield 1984);
(3) Partial serpentinization of mafic and ultramafic oceanic rocks on the ridge crest of a preexistent oceanic crust (Gupta et al. 1985; Green et al. 1987);
(4) Association with carbonated and metamorphosed slate rocks, deposited in foreland basins (Boerner et al. 1996); and
(5) Presence of sulphides in the fold hinges of the collision zone between the La Ronge volcanic arc and the internal zones of the Wyoming and Rae–Hearne Archean cratons (Jones et al. 1997, 2005).

Detailed analysis of reflection data by Morel-à-l'Huisser et al. (1990) was not conclusive in associating the low-velocity zones with the NACP, as located by Jones and Savage (1986). Hydrated minerals are not intrinsically conductive (Olhoeft 1981), instead the fluids released by dehydration processes cause the high conductivity. Interpretations based on ionic conduction in fluids (saline brines or partial melts) can also be rejected given the age and spatial extent of the anomaly.

Green et al. (1985) suggested that the anomaly is caused

Fig. 7. A zoom of the upper 10 km of the two-dimensional model in Fig. 6 (note the large vertical exaggeration (vertical:horizontal or V:H) of 10:1). NACP, North American Central Plains anomaly.
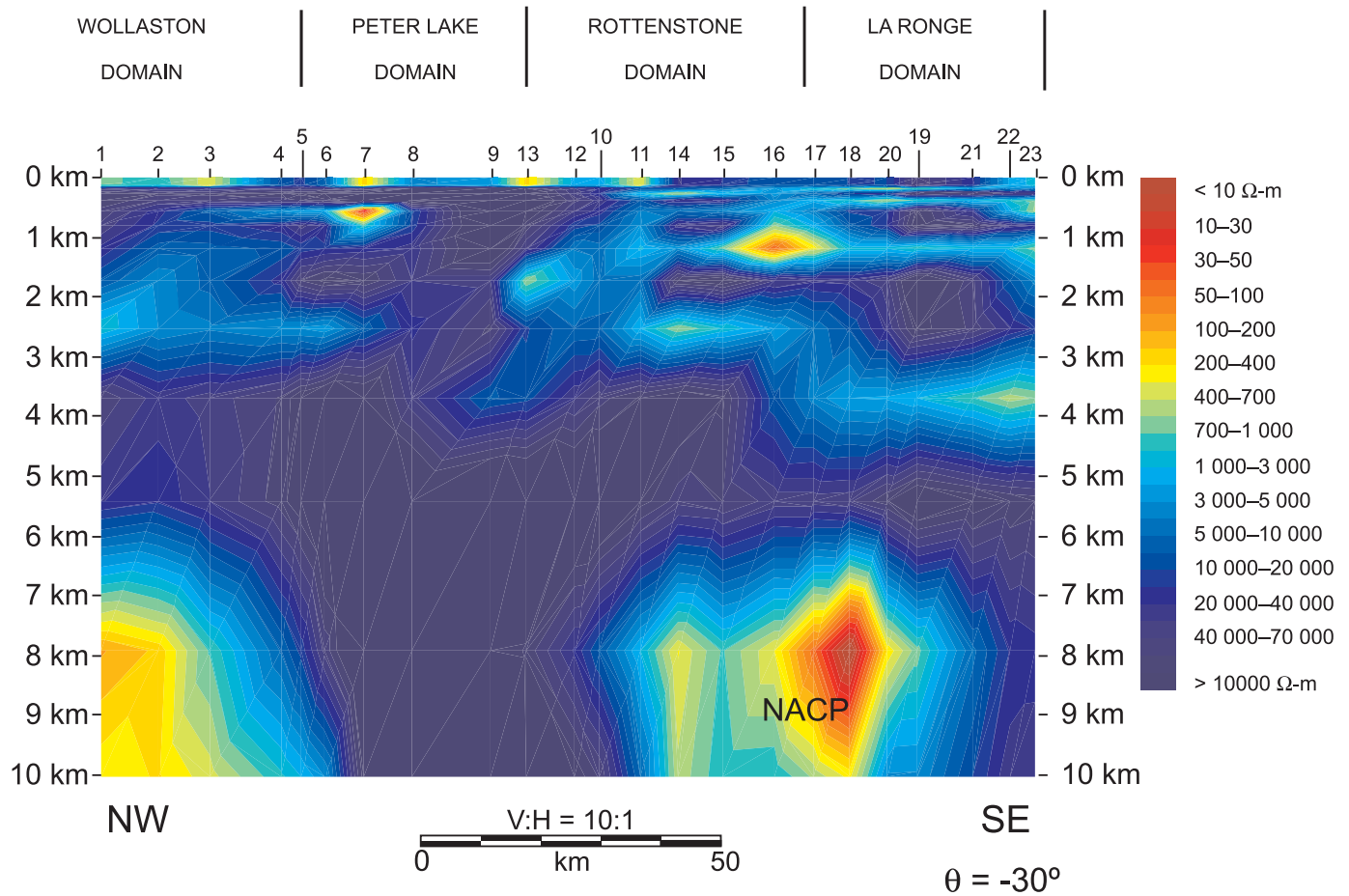
by pieces of hydrated oceanic type crustal material, which also explains the low seismic velocity observed. Klasner and King (1986) interpreted the geochronologies similarly to Peterman (1981) in revealing Paleoproterozoic rocks, mainly gneiss of unknown origin, but they could not find any evidence of oceanic crust. From the drill cores obtained above the location of the NACP by Jones and Savage (1986) in northern North Dakota, the rocks are mostly granodioritic to tonalitic gneiss.

Given its age and location and the reasons exposed earlier, there are only two possible causes for the enhanced electrical conductivity: graphite and (or) sulphide-rich metasediments (theories 1, 4, and 5).

The graphite model agrees with the model suggested by Lidiak (1971) and Boerner et al. (1996) for parts of the Churchill Province. Graphite has been found on the surface on the La Ronge and especially Rottenstone domains (D. Corrigan, personal communication, 2003) although, in hand samples, the graphite is not conductive or well-interconnected (Katsube et al. 1996). This lack of conductivity enhancement may be owing to the process of uplifting and exposing the rocks and thereby damaging the interconnectivity of the graphite network (Katsube and Mareschal 1993).

In northern Saskatchewan, at the location of MT profile L, there are iron-rich biotitic gneisses at the surface. The presence of these pyrite-rich metasediments, and the location of the

NACP anomaly on top of the Guncoat thrust, suggests that the anomoly is associated with massive deposits of pyrite on the fold hinges (Jones et al. 1997). Both profiles L and X have similar lithologies, and the seismic images and MT profiles are also similar; the only difference is the presence of graphite in the Rottenstone domain, which excludes a single origin for this anomaly in the northern part of the orogen.

The previous models from MT profiles S, M, and N show that the anomaly is in the crust and that the top is at some 10-km depth (Jones et al. 2005). On profile S, the NACP was modelled as an arcuate feature with a wavelength of ~80 km (Jones and Craven 1990). A characteristic and enigmatic feature of the NACP is that it has little observable effect on the MT response for currents flowing perpendicularly to its strike (i.e., east–west), only to currents flowing parallel to the strike (Jones 1993). This has been explained as a lack of connection between different conductive bodies (Jones 1993), and is a manifestation of tectonic imbrication. Wu (1994) and Jones et al. (2005) analysed and modelled MT data from a series of profiles in central and northern North Dakota. Their models are similar to those from line S — a series of discrete bodies in the mid-crust that have an arcuate shape. COCORP (Consortium for Continental Reflection Profiling) seismic studies in northern North Dakota showed that there is a geometrical relation between this arched shape feature and the tectonic units along the THO in the Williston basin,

south of the border between Canada and the USA (Nelson et al. 1993). It was shown that the conductive bodies lie over a non-reflective region, interpreted as an Archean body of unknown origin (possibly the southern extension of the Sask craton?).

It is open to debate whether the conductive structure beneath the Wathaman Batholith, under stations 7, 8, 9, and 13, is the northern extension of the NACP. Because of the extreme channelling effects caused by this anomaly, it can be considered as a narrow structure of very high conductivity (<1 Ω.m). The fact that the resistivity model shows a clear break of 20 km in width and 10-km vertical extent of 700–1000 Ω.m between both structures suggests that they are not related and they most likely have different origins. This structure seems to be linked to subduction of the Rottenstone domain, a terrane that is related to the Wathaman batholith (Lewry et al. 1994).

Wollaston and Peter Lake domains

These two domains are characterized by the presence of surficial conductive anomalies in an otherwise highly resistive upper crust (>10 000 Ω.m). These conductors have been interpreted as mineralized zones because of their presence in the surface as biotitic gneisses rich in pyrite (Jones et al. 1997). Within the Peter Lake domain are two of the distorting bodies that made the analysis of the data difficult by generating severe current channelling effects. Because of the regional nature of our survey with wide station spacing, the geometries of these small conductors are not well resolved with the 2-D inversion; their actual size and resistivity should be estimated with either follow-up local AMT studies and (or) the aid of other geophysical methods.

The seismic data display a prominent reflector in the upper crust, extending almost horizontally from the north of the profile until the southern limit of the Peter Lake domain. This reflector has been named the Wollaston reflector; it has been interpreted in Mandler and Clowes (1997) as laminar intrusions and horizontal diabase dykes, suggesting the presence of large quantities of plutonic material intruded into the crust. In the Wollaston domain, this reflector appears to define the base of resistive rocks and transition to more conducting rocks, and thus is more suggestive of a major lithological change rather than an simply intrusive structure. However further south beneath the Peter Lake domain this geometrical relationship is weaker. Accordingly, the combined interpretation would suggest that beneath the Wollaston domain the instrusive was emplaced between two lithologies, whereas beneath the Peter Lake domain it intruded within a single lithology.

The Needle Falls shear zone characterizes the contact zone between the Wollaston and Peter Lake domains. There is a substantial change in the resistivity of the crust coincident with this fault, being 1000 Ω.m under the Peter Lake domain and 200–400 Ω.m under the Wollaston domain. Under the Peter Lake domain, there is a highly resistive (>10 000 Ω.m) body, which we interpret as the Wathaman batholith. The base of this structure is coincident with the deepening structures from the La Ronge domain. The top of this batholith is difficult to distinguish from the surface rocks of the Peter Lake domain using EM methods because both are highly resistive. This result confirms the results from the analysis of the magnetic data. The magnetic map (Hajnal et al. 1996) shows two regions of high magnetic anomaly within the Wollaston and Peter Lake domains that could be caused by the presence in depth of the Wathaman batholith, as discussed by Morel-à-l'Huisser et al. (1990) and Jones et al. (1993). Similarly, the gravity data (Hajnal et al. 1996) shows a minimum of the Bouguer anomaly coincident with a magnetic anomaly, which is caused by the presence of the Wathaman batholith at depth.

Based on the geological data reviewed in the introduction, the conductive anomaly under the Wathaman batholith is related to the pre-batholith Archean crust and the anomaly is owing to the presence of minerals in the fractures of that structure.

La Ronge and Rottenstone domains

The MT model shows a resistive (>10 000 Ω.m) structure located at 7-km depth at the southern end of the profile and deepening to the north consistent with the reflection fabric. The La Ronge domain is formed dominantly by gneisses and island-arc rocks. The deepening structure can be interpreted as the sediments deposited in the old Archean Manikewan Ocean that, during the continental collision and the consequent subduction of the oceanic crust under the Sask and Superior cratons, were carried and later accreted to the continent. The reflection profile shows a strong north deepening grain that soles into horizontal reflectors, beginning at about 11 s, above the Moho. On the profile along line L (1992 profile in Fig. 2; Lucas et al. 1993), such reflectors have been interpreted as a west-directed subduction structure (Green et al. 1985; Lucas et al. 1993; Lewry et al. 1994). One of the reflectors within the La Ronge domain was identified as the subsurface expression of the Guncoat thrust, a late compressional feature (Lewry and Slimmon 1985; Jones et al. 1997).

On the southern part of the profile there is a resistive (>10 000 Ω.m) wedge-like structure that cannot be distinguish from the deepening structure. This is coincidental with a similar wedge feature on the seismic profile and has been interpreted as the Sask craton (Hajnal et al. 2005). The Sask craton seems to be more conductive on the bottom part just on the contact with the lower crust structure.

At 20-km depth on the southern part of the profile, there is a body more conductive (>50 Ω.m) than the structures above (interpreted as the Sask craton). This conductive structure extends horizontally to the north until approximately the NFSZ. It is probably related to the old oceanic crust that was obducted under the Sask craton and the high conductivity can be explained by the presence of interconnected graphite. Assuming that the high conductivity of the lower crust at the southern part is caused by the presence of fluids implies that these fluids have been trapped in the rocks since the formation of the orogen. Once the subduction stopped and the region stabilized, fluids migrated and the argument for water is invalid (Jones 1992). The velocity analysis (Nemeth 1999) shows no change in velocity of this structure, which discards also the possibility of eclogites attached to the base of the Sask craton.

Conclusions

In this paper, we have analysed and interpreted data from the THO94 MT experiment. Although there are several local inhomogeneities that make a detailed analysis of the data difficult, the galvanic distortion decomposition suggests that the data can generally be interpreted validly with a 2-D model with a strike of N60°E, which confirms the rotation of the deepest structures within the crust towards the Hudson Bay, as is seen in the surface geology.

After galvanic analysis, the data were inverted using a 2-D inversion code. The fit of the model to the data is good, even given the severe current channelling caused by extremely high-conductive bodies. This code provides the minimum model that can explain the data, but it correlates well with regional scale geology and with other geophysical data.

One of the keys for understanding the THO is the NACP anomaly. The anomaly has been critical for delineating the THO under the Phanerozoic sedimentary cover of the NACP. In the north, it has been associated with metasediments in the western part of the La Ronge belt. In this work, we detect the anomaly on top of the Guncoat thrust. Previous studies suggested a width of 80 km for the NACP, which is reasonably consistent with the distance between sites 7 and 20 but would imply two conductive segments to the NACP. In this work, we favoured a shorter anomaly of some 30 km between sites 15 and 20, and suggest a different origin for the conductive anomaly under the Wathaman batholith.

Beneath the La Ronge domain, a resistive structure deepens under the Hearne craton to the north, consistent with northward-directed subduction of the oceanic crust of what was the Manikewan Ocean. This body appears to truncate at the NFSZ, a directional fault that was active after collision. North of this fault, the model is more conductive, suggesting a major reworking with emplacement of sulphides and (or) graphite. The resistive structure under the La Ronge domain has a wedge shape in the southern part that has been interpreted as the remains of the Sask craton. The top boundary contact of the Sask craton with the shallow structures under the La Ronge domain is impossible to define as they are both resistive. The Sask craton may increase in conductivity with depth, and it is emplaced on top of a flat conductive structure that could be the remains of old oceanic crust subducted under the Superior craton. This lowermost crustal conductive structure has been observed in the profile at the southern end, but further interpretation is required of the LMT data to confirm this.

One important result in the study of the THO is that Archean basement is separated from Proterozoic by mylonitic gneisses (Chiarenzelli et al. 1996). This suggests that Archean rocks may underlie most of the Reindeer zone (Lewry et al. 1994). In this work, based on the location of the high resistive structure under the La Ronge domain, we suggest that within the crust in the southern part of the profile the rocks are Archean in age.

Acknowledgments

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