Geoelectric structure of the northeastern Williston basin and underlying Precambrian lithosphere[1]

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Abstract: Magnetotelluric (MT) measurements were made in southern Manitoba, Canada, as part of the Portable Observatories for Lithosphere Analysis and Research Investigating Seismicity (POLARIS) project, to image the northeastern part of the Williston basin and underlying Precambrian lithosphere. Data collected at 21 sites along a 400 km east–west profile at 49.5°N and a 300 km north–south profile at 100°W were analyzed using robust spectral analysis, tensor decomposition, and two-dimensional inversion. The resulting resistivity models allow subdivision of the Williston basin into three layers: an upper layer of 1–5 Ω·m corresponding to Mesozoic and upper Paleozoic rocks, a 20–50 Ω·m layer corresponding to lower Paleozoic carbonate rocks, and a 2–3 Ω·m layer corresponding to the Ordovician Winnipeg Formation. Deeper penetrating MT responses, interpreted with other MT data, reveal a region in the westernmost Superior craton with a southwest–northeast geoelectric fabric that is oblique to subprovince boundaries. The observations can be explained by Proterozoic deformation extending several hundred kilometres east of the Superior boundary zone or by a separate Archean terrane adjacent to the boundary. The Thompson belt (TOBE) conductor in the south of the study area has previously been interpreted as part of the Superior boundary zone (SBZ). However, MT results show that the conductor does not extend continuously along the margin of the zone and MT studies to the north define conductors on the margin of the Sask craton. The results suggest the TOBE conductor is associated with the Sask craton margin. The MT results indicate significant along-strike variation of the SBZ in southern Manitoba.

Résumé : Des mesures magnétotelluriques ont été effectuées dans le Sud du Manitoba, Canada, dans cadre du Projet POLARIS (« Portable Observatories for Lithosphere Analysis and Research Investigating Seismicity »); le but était de former une image de la partie nord-est du bassin Williston et de la lithosphère précambrienne sous-jacente. Des données recueillies à 21 sites le long d'un profil est–ouest de 400 km de long à une latitude 49,5 °N et le long d'un profil nord–sud de 300 km de long à une longitude de 100 °O ont été étudiées par analyse spectrale robuste, par décomposition des tenseurs et par inversion bidimensionnelle. Les modèles de résistivité qui en découlent permettent une subdivision du bassin Williston en trois couches : une couche supérieure de 1 à 5 Ω·m, correspondant à des roches datant du Mésozoïque et du Paléozoïque supérieur; une couche de 20 à 50 Ω·m correspondant aux carbonates du Paléozoïque inférieur et une couche de 2 à 3 Ω·m, correspondant à la Formation de Winnipeg (Ordovicien). Des réponses magnétotelluriques à plus grande profondeur, interprétées avec d'autres données magnétotelluriques, révèlent une région, dans la partie la plus à l'ouest du craton du Supérieur, qui a une texture géoélectrique sud-ouest – nord-est, oblique aux limites de la sous-province. Les observations peuvent être expliquées par une déformation au Protérozoïque qui s'étend sur plusieurs centaines de kilomètres à l'est de la zone limite du Supérieur ou par un terrane archéen indépendant adjacent à la bordure. Le conducteur TOBE (ceinture de Thompson) dans le sud du secteur à l'étude avait été antérieurement interprété comme une partie de la zone de la limite du Supérieur. Toutefois, les résultats de la magnétotellurique montrent que le conducteur ne s'étend pas de manière continue le long de la limite de la zone; des études au nord définissent des conducteurs le long de la bordure du craton Sask. Selon les résultats, le conducteur TOBE serait associé à la bordure du craton Sask; ils indiquent aussi une variation importante le long de la direction de la zone limite du Supérieur dans le Sud du Manitoba.

[Traduit par la Rédaction]

Received 4 December 2008. Accepted 4 June 2009. Published on the NRC Research Press Web site at cjes.nrc.ca on 7 August 2009.

Paper handled by Associate Editor F. Cook.

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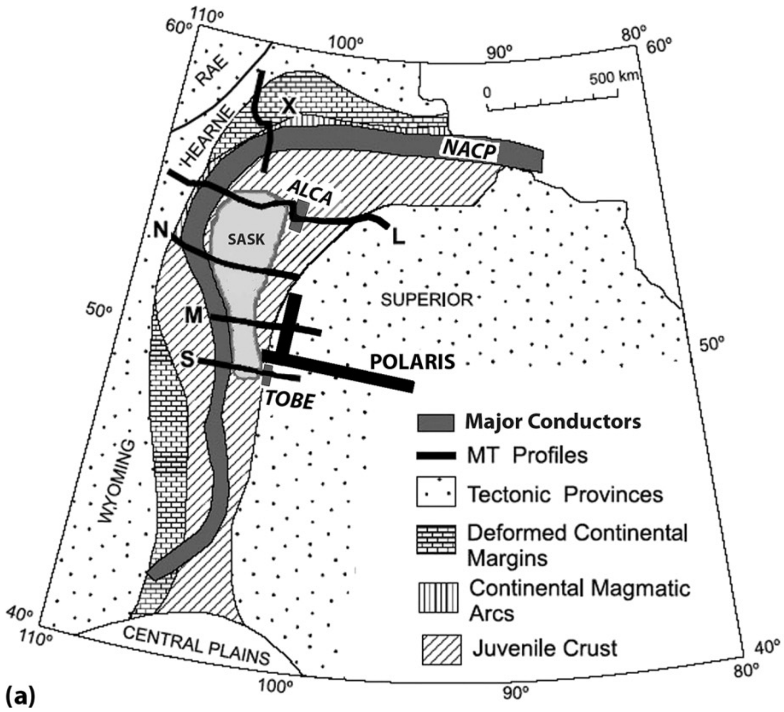
Fig. 1. Location of the 2004 POLARIS magnetotelluric survey. (*a*) Location relative to major Precambrian terranes (modified from Garcia and Jones 2005). Archean rocks are interpreted to underlie much of the central Trans-Hudson Orogen. The inferred position of the Archean Sask craton (Sask), is based on constraints discussed in Jones et al. (2005). The locations of major conductors (NACP, North American Central Plains; TOBE, Thompson belt; ALCA, Athapapuskow Lake conductivity anomaly) are also shown. MT, magnetotelluric. (*b*) Survey location relative to the Williston basin (modified from Lyatsky and Dietrich 1998).



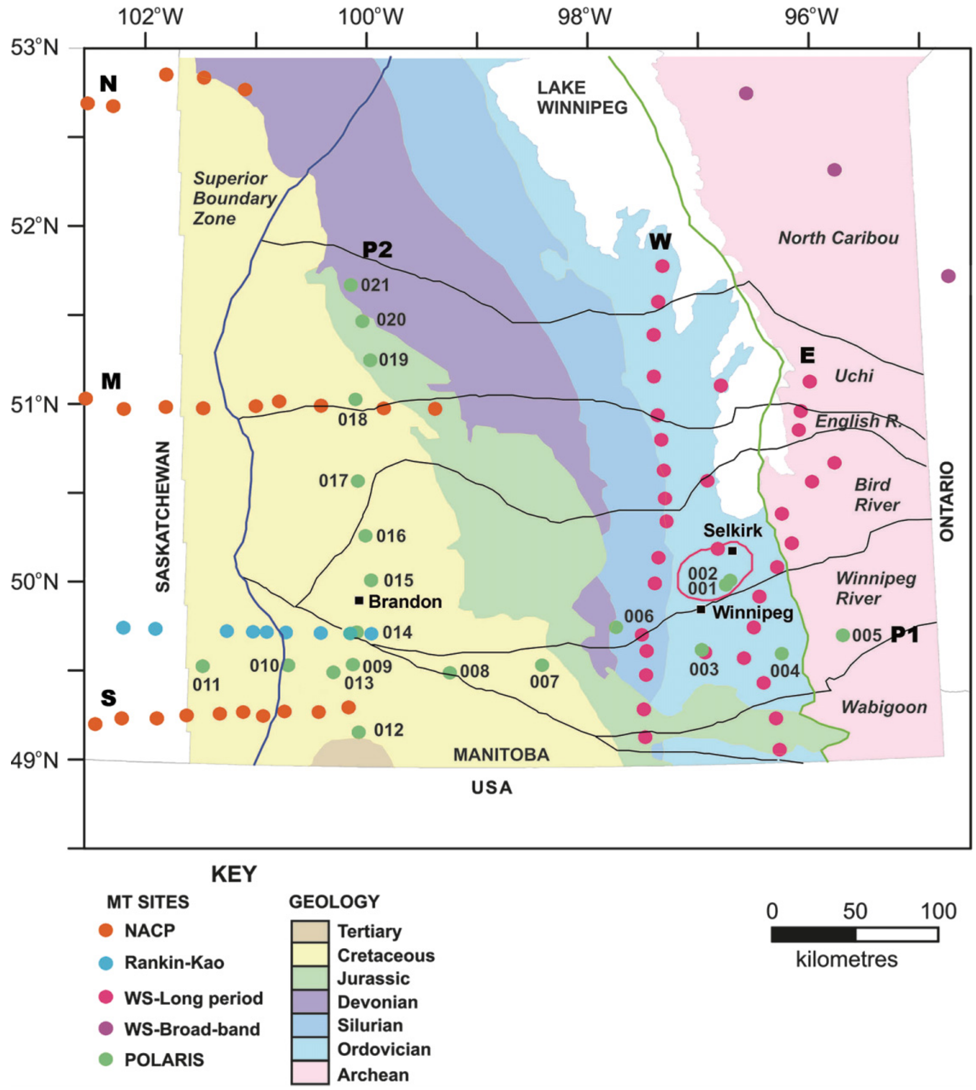
Introduction

In this study, which forms part of the Canadian POLARIS (Portable Observatories for Lithosphere Analysis and Research Investigating Seismicity) project, the magnetotelluric (MT) method is used to image the electrical resistivity structure of the northeastern part of the Williston basin and the underlying Precambrian lithosphere in Manitoba, Canada (Fig. 1). POLARIS is a Canadian university–government–industry geophysical consortium focused on investigation of the structure and dynamics of the Earth's lithosphere, earthquake ground motion, and geomagnetic hazards (Eaton et al. 2005). It has equipped Canada with a state-of-the-art geophysical instrument pool including six broadband MT systems.

Within the study area, the Williston basin overlies the westernmost part of the Superior craton, part of a smaller Archean continental fragment, the Sask craton, and eastern parts of the Proterozoic Trans-Hudson Orogen (THO), including the Superior boundary zone (SBZ), which records the collisional tectonics of the Proterozoic THO and Superior craton. The initial motivation for the POLARIS Manitoba MT survey was to define the resistivity structure of the eastern Williston basin for use in modelling geomagnetic-induced currents on powerlines and pipe-to-soil potentials on pipelines. In particular, we wished to examine whether the resistivity of major geological units was similar to that in central parts of the basin. The MT data set collected in the survey can be used to address important questions on the Precambrian geological structure. In particular, it can provide constraints on geological structure south of 52°N, where the magnetic and gravity response of the SBZ is different from that further north and on the exposed Precambrian Shield (White et al. 2005). Jones and Savage (1986) and Jones and Craven (1990) identified a conductivity anomaly in southern Manitoba that they interpreted to be associated with a southerly extension of the Thompson nickel belt, part of the SBZ on the exposed Precambrian Shield to the north. They called this feature the TOBE conductivity anomaly. Subsequent MT surveys on the exposed shield have not identified any major crustal-scale conductor in the TOBE or SBZ (White et al. 1999). The POLARIS MT data will help determine how the observed variation in resistivity is related to the Precambrian geological structures.

Electrical resistivity is particularly sensitive to certain minor constituents of rocks, such as small amounts of graphite or connected grains of metallic sulphides and oxides. Saline fluids, such as basinal brines, can decrease resistivity by allowing ionic conduction. The sensitivity of MT to these geological constituents means the method can provide unique geological information that is complementary to other geophysical methods. Two types of analyses are applied in this study. In "fabric-based" studies, interpretations of the electric fabric of the lithosphere, for example, defined using geoelectric strike directions or the continuity of electrical conductors, complement interpretations of potential-field data. In "modeling-based" studies, multidimensional resistivity models are fitted to the MT responses and used to define the geological structure. At shallow depth, the results are complementary to interpretation of well logs, and at greater depth, they are complementary to seismic studies and structural interpretations.

Fig. 2. Magnetotelluric (MT) site location and geology. The figure shows the site locations and site numbers (excluding the prefix "man") from the present survey and MT sites from NACP (North American Central Plains) surveys described in Jones and Craven (1990), the survey described by Rankin and Kao (1978), and long-period and broadband MT sites from the Lithoprobe Western Superior (WS) Transect survey. Dark letters denote profile names: N, north; M, middle; S, south; W, west; E, east; and POLARIS profiles P1 and P2. The coloured shading defines the bedrock geology, and the green line indicates the margin of the Williston basin. Solid black lines and italicized labels indicate the interpreted location of subprovinces of the Superior Province, the blue line indicates the eastern margin of the Superior boundary zone, and the red line indicates outline of the gravity anomaly associated with the Selkirk greenstone belt.

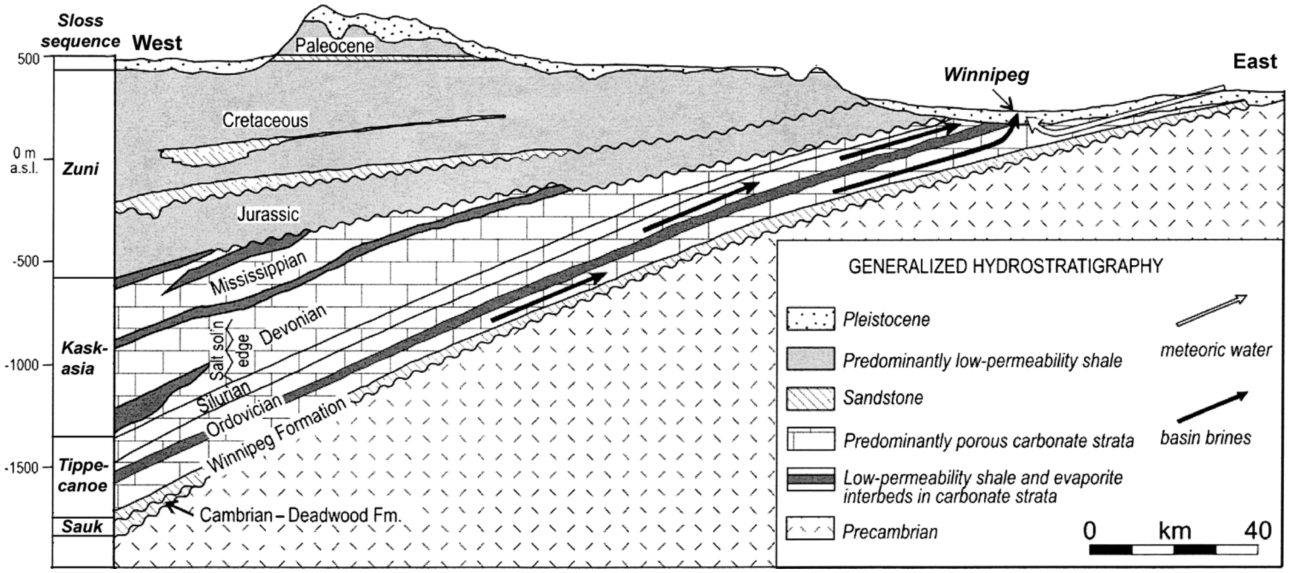


Geological setting

The MT survey imaged rocks ranging in age from Archean to Mesozoic (Fig. 2). The Precambrian setting is the western margin of the Superior Province and its boundary with the THO and the Sask craton. The structure of the Precambrian rocks of this region has been interpreted by the extrapolation of potential-field trends from exposed rocks outside the Williston basin (e.g., Green et al. 1979, 1985*a*, 1985*b*; Lyatsky and Dietrich 1998; Pilkington and Thomas 2001; Bourlon 2004; White et al. 2005; Li and Morozov 2007) and dating of drill-core samples from basement intersections (Stevenson et al. 2000; Percival et al. 2006). Considerable information has also been derived from seismic and electromagnetic studies, most recently from those done as part of the Canadian Lithoprobe project (e.g., Hajnal et al. 2005; Jones et al. 2005) and the United States COCORP projects (e.g., Nelson et al. 1993; Baird et al. 1996). The present configuration of the Precambrian terranes developed around 1.95–1.75 Ga, when convergent tectonics in the THO welded together the Archean Superior, Wyoming, and Hearne–Rae cratons and the smaller Sask craton to form part of Laurentia (e.g., Ansdell 2005).

The western part of the Archean Superior craton is characterized by roughly east–west-trending subparallel subprovinces of contrasting lithology, age, and metamorphic grade (Card and Ciesielski 1986). The subprovinces within the study area include the volcano-plutonic Wabigoon, Uchi, and Bird River – Separation Lake (BRSL) subprovinces, the plutonic Winnipeg River subprovince, and the metasedimentary English River subprovince. The interpreted extension of the BRSL subprovince into Manitoba includes a very prom-

Fig. 3. West–east cross section of southern Manitoba coincident with POLARIS profile 1, showing the generalized stratigraphy of the Williston basin and the hydrostratigraphy, including flow patterns of the major aquifers (modified from Grasby and Betcher 2002). a.s.l., above sea level.



inent 35 km long by 18 km wide elliptically shaped magnetic and gravity anomaly located at 97°W (Fig. 2). Drilling of this anomaly in the late 1950s and 1960s revealed the presence of gabbro, mafic volcanic rocks, and interflow sediments and iron formation, and indicated the anomaly was due to a small greenstone belt (W. Brisbin, University of Manitoba, personal communication, 2006). Herein, we refer to the belt as the Selkirk greenstone belt based on its proximity to the city of Selkirk, Manitoba (Fig. 2).

Archean rocks exposed in, and present beneath, the central THO are interpreted to represent part of a buried craton known as the Sask craton in Canada (Ansdell et al. 1995) and the Dakota block in the United States (Baird et al. 1996). In Canada, the Archean rocks occur in tectonic windows produced by late cross-folding and are separated from Proterozoic allochthons by mylonitic gneisses (Chiarenzelli et al. 1998). This geometry coupled with the wide occurrence of reworked Archean crust and its plutonic derivatives in sub-Phanerozoic drill cores farther south suggest that Archean rocks may underlie much or all of the central THO (Lewry et al. 1994). The Sask craton has been divided into seven separate domains on the basis of its potential-field signature (Li and Morozov 2007).

The THO is a Paleoproterozoic orogenic belt forming part of a major North American system extending from South Dakota, across Hudson Bay, into Greenland and Labrador (Hoffman 1987; Lewry and Collerson 1990), and possibly linking to a similarly aged orogen in Scandinavia (Jones 1993). The SBZ is a narrow, <50 km wide zone of reworked cratonic rocks forming the eastern margin of the orogen. Recent studies have suggested that the exact age and geometry of the zone called the THO in the United States differs significantly from that further north in Canada (e.g., Nelson et al. 1993; Baird et al. 1995, 1996; Nabelek et al. 2001; Hill 2006).

The Williston basin is a major intracratonic basin (e.g., Fowler and Nisbet 1985) centred on the THO. The basin was formed by subsidence throughout much of the Phanerozoic about the same centre in North Dakota (Fig. 1). In earlier studies (Fowler and Nisbet 1985), the basin was interpreted to have formed by continuous subsidence, but more recent work suggests an episodic subsidence (Zhu and Hajnal 1993; Osadetz et al. 2002). As a result of the tilting and subsidence, the sedimentary sequence thickens progressively towards the southwest corner of the study area (Fig. 3).

The oldest sedimentary rocks present in the Williston basin in Manitoba are the sandstones of the Cambrian Deadwood Formation, present only in the extreme southwest of Manitoba (McCabe 1978) and interpreted to form part of the Middle Cambrian to Upper Ordovician Sauk sequence (Rickets 1989). The basal unit of the overlying Tippecanoe sequence of Middle Ordovician clastics and Upper Ordovician and Silurian carbonates is the Winnipeg Formation that consists of sandstone and shale (McCabe 1971). The overlying Middle Devonian – Carboniferous Kaskasia sequence is dominated by carbonates, evaporites, and shale (McCabe 1971; Bezys and McCabe 1996). In Manitoba, this sequence is overlain unconformably by the Jurassic to Paleocene Zuni succession (Osadetz et al. 2002) that is dominated by shales. This succession is in turn overlain unconformably by Pleistocene deposits (Fig. 3).

The hydrostratigraphy in the eastern Williston basin is closely related to the stratigraphy (Fig. 3). The Phanerozoic rocks can be divided into three main hydrological zones (Render 1969; Grasby and Betcher 2002; Ferguson et al. 2007): a lower sandstone aquifer including the Deadwood and Winnipeg formations; upper and lower aquifers within the Paleozoic carbonate and evaporite units; and a zone including the Mesozoic formations, which, although relatively impermeable because of the high shale content, contain some aquifers in sandier units (Grasby and Betcher 2002).

Previous electromagnetic surveys

A number of large-scale electromagnetic surveys have taken place in the Williston basin since the early 1970s.

The focus of many of the surveys has been the North American Central Plains (NACP) conductivity anomaly, a major 2000 km long electrical conductivity anomaly lying with Precambrian crust of the THO to the west of the Superior Province (Fig. 1). Since its discovery using the lower resolution geomagnetic depth sounding (GDS) method (Reitzel et al. 1970), the NACP conductivity anomaly has been investigated using the higher resolution MT method (e.g., Jones et al. 1993). Jones et al. (2005) provide a synthesis of these surveys and a geological interpretation of the anomaly. Near the southern margin of the Precambrian Shield the resistivity structure associated with the anomaly has both an upper crustal (<20 km depth) part and a deeper crustal (25–35 km) part. The upper crustal part has been interpreted to be caused by sulphides in rocks deposited as an arc advanced on the Rae–Hearne hinterland. These rocks were metamorphosed during subduction and compression and emplaced within the crust of the orogen (Jones et al. 1997). The lower crustal part has been interpreted to represent metasedimentary rocks deposited on the margin of the Sask craton (Ferguson et al. 2005*b*). The NACP lies to the west of the present study area (Fig. 1).

The NACP surveys also defined the TOBE conductor in the Precambrian crust to the east of the NACP (Jones and Savage 1986; Jones and Craven 1990). This anomaly was first detected in an earlier MT survey by Rankin and Kao (1978), who interpreted it to represent part of a transitional zone separating the Superior and Churchill provinces. Ferguson et al. (1999) describe a conductive anomaly, the Athapapuskow Lake conductivity anomaly (ALCA), within the Namew gneiss complex to the north of the interpreted position of the TOBE conductor on Lithoprobe line L (Fig. 1). The ALCA lies well within the THO and close to highly resistive rocks interpreted to form part of the Sask craton (Ferguson et al. 2005*b*).

An extensive MT survey was completed across the western Superior Province as part of the Lithoprobe Western Superior Transect survey (Ferguson et al. 2005*a*). This survey included two north–south profiles of long-period MT sites in southern Manitoba, collected in 1998 (Fig. 2). The MT results from these profiles provide relatively poor resolution of the resistivity structure of the Precambrian crust, but GDS results from the survey identify the extension of a 600 km long east–west-trending conductive zone within the Superior Province. This anomaly is interpreted to be caused by a conductive component of the 2.7 Ga metasedimentary rocks of the English River subprovince. However, the anomaly is also quite close to the BRSL subprovince, and it is possible that greenstone rocks in this belt may contribute to the anomaly.

The MT surveys in the Williston basin have provided information on the resistivity structure of the Phanerozoic rocks. In a survey to the west of the present one, centred around 104°45′W, Maidens and Paulson (1988) compared one-dimensional (1-D) resistivity models derived from MT data and resistivity logs and found that the rocks of the Williston basin defined a three-layer resistivity structure corresponding reasonably well to Middle Devonian and older rocks (2–20 Ω·m), Late Devonian to Mississippian rocks (10–200 Ω·m), and Cretaceous units (2.0–3.2 Ω·m). Jones (1988) compared MT results with resistivity logs for sites along an east–west profile at 49°20′N (Fig. 1, profile S). The well logs also show a conductive unit (1–3 Ω·m) at the base of the sedimentary sequence in the Manitoba part of the study area. The resistivity of the upper Devonian rocks varies spatially and is lower in the east (3–10 Ω·m) than the west (30–100 Ω·m). The change is associated with leaching of the prairie evaporite by highly saline fluids in the east. Based on the well logs, the upper Mississippian to Cretaceous rocks have resistivities of 1–10 Ω·m and the Ordovician to Middle Devonian rocks have resistivities of 10–100 Ω·m with some more resistive zones.

A number of small-scale electromagnetic investigations of the rocks of the northeastern Williston basin of relevance to the present study have also been completed. Ground time-domain electromagnetic (TEM) profiles were completed in 1996 across the eastern margin of the basin (Hyde et al. 1997). Resistivity and induction logs were collected during oil exploration and development in the Williston basin, including numerous logs within the western part of the study area. Geophysical logs extending to the base of the basin were also collected as part of a stratigraphic study by Mwenifumbo et al. (1995). Results from these studies are discussed in the following text.

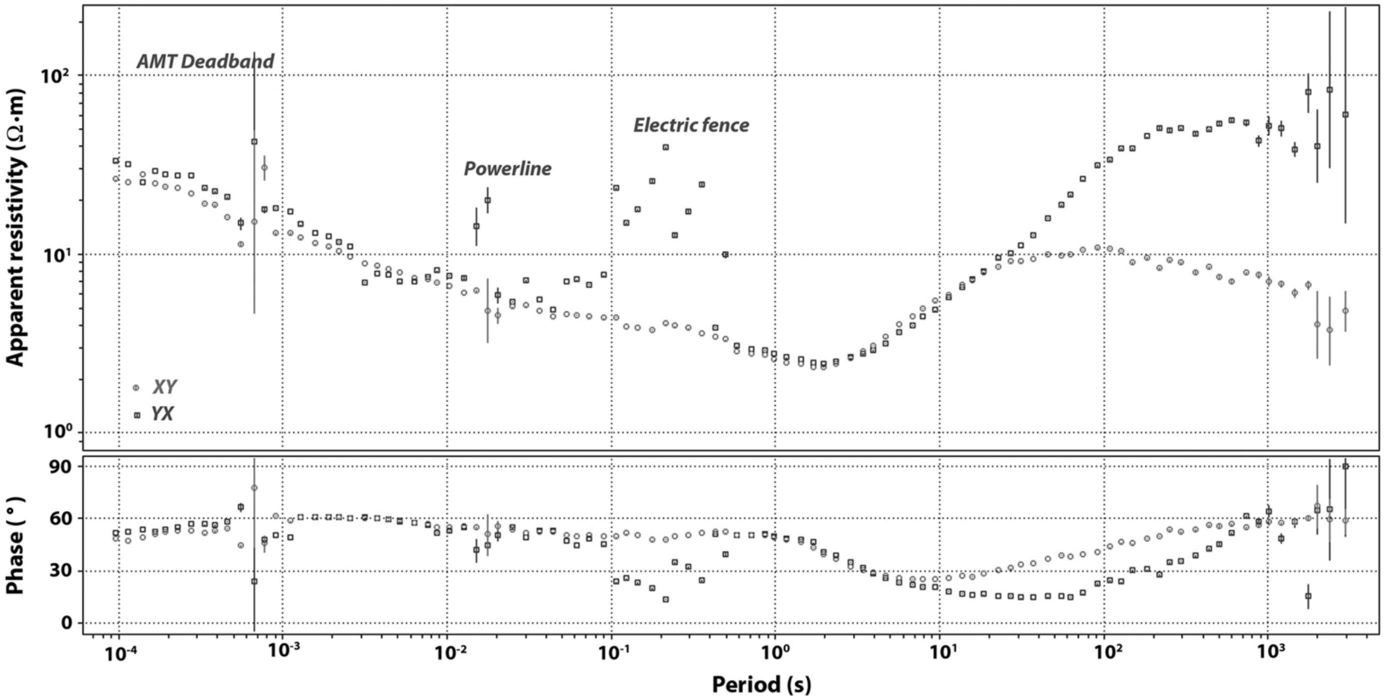
Magnetotelluric survey and data processing

The MT survey was completed in summer 2004 and involved data collection along two profiles: data were collected at a total of 21 sites along a 400 km east–west profile at 49.5°N and a 300 km north–south profile at 100°W (Gowan 2005). Figure 2 shows the locations of the sites, which are named using the convention "man*nnn*" where *nnn* is the site number. Broadband (300–0.001 Hz) MT data were acquired at all sites and audiofrequency MT data (10 000 – 10 Hz) were acquired at 12 of the sites.

The MT survey used Phoenix Limited MTU5a equipment with MTC50 MT coils for the broadband MT recordings and AMTC30 AMT coils for the audio-magnetotelluric (AMT) recordings. Recordings were made of the three components of the magnetic field and two horizontal components of the electric field. The electric field was measured using dipoles that were all approximately 100 m long. Data acquisition was done simultaneously at pairs of sites to enable remote-reference noise reduction (Gamble et al. 1979). It typically involved recordings made over two consecutive nights, although the duration varied from one night to three nights. At two sites, man004 and man019, incorrect wiring of electrode lines meant that it was not possible to obtain tensor MT responses, but the recorded magnetic field data from these sites are still useful for GDS studies and for serving as a remote references to other sites.

The MT data were processed using robust remote-reference algorithms supplied by Phoenix and based on the coherence-sorted cascade decimation method of Wight and Bostick (1981) and the heuristic robust approach of Jones (Jones and Jödicke 1984; Jones et al. 1989, method 6). At sites with both AMT and MT data collection, the response is defined over seven decades: for the period range from 10^{-4} to $\sim$2000 s and for sites with only MT data collection for the range from 10^{-2} to 2000 s. At a number of sites, the response is poor in the AMT deadband (around 10^{-3} s,

Fig. 4. Unedited magnetotelluric response for site man010. The square symbol denotes the *xy* impedance term relating the north electric field to the east magnetic field; the circle symbol denotes the *yx* impedance term relating the east electric field and north magnetic field.



e.g., Garcia and Jones 2002), and at most sites, because of the limited duration of the recordings, it is poor at periods longer than 2000 s.

The fundamental MT response is the MT impedance, which is the complex-valued transfer function between orthogonal components of the electric and magnetic fields. The transfer functions between the two components of the horizontal electric field and the two components of the horizontal magnetic field define four impedance terms that can be expressed as a tensor. Each MT impedance term can be used to estimate an apparent resistivity, which is a volumetrically averaged resistivity over the penetration depth of the signals. The phase of the impedance, i.e., the phase lead of the electric over the magnetic field, also provides information on the underlying resistivity structure; the phase is 45° for a uniform half space. Figure 4 shows the unedited apparent resistivity and phase responses for a typical MT site from the 2004 MT survey. The two components shown relate orthogonal components of the electric and magnetic field and are the nonzero components of the response measured over a horizontally layered resistivity structure. The impedance responses exhibit the effect of noise from powerlines and electric fences, higher levels of noise in the AMT deadband around 10^{-3} s and the MT deadband near 1 s, as well as increased noise at longest periods (>100 s). Poor response estimates were removed from the responses prior to subsequent analysis.

Magnetotelluric responses

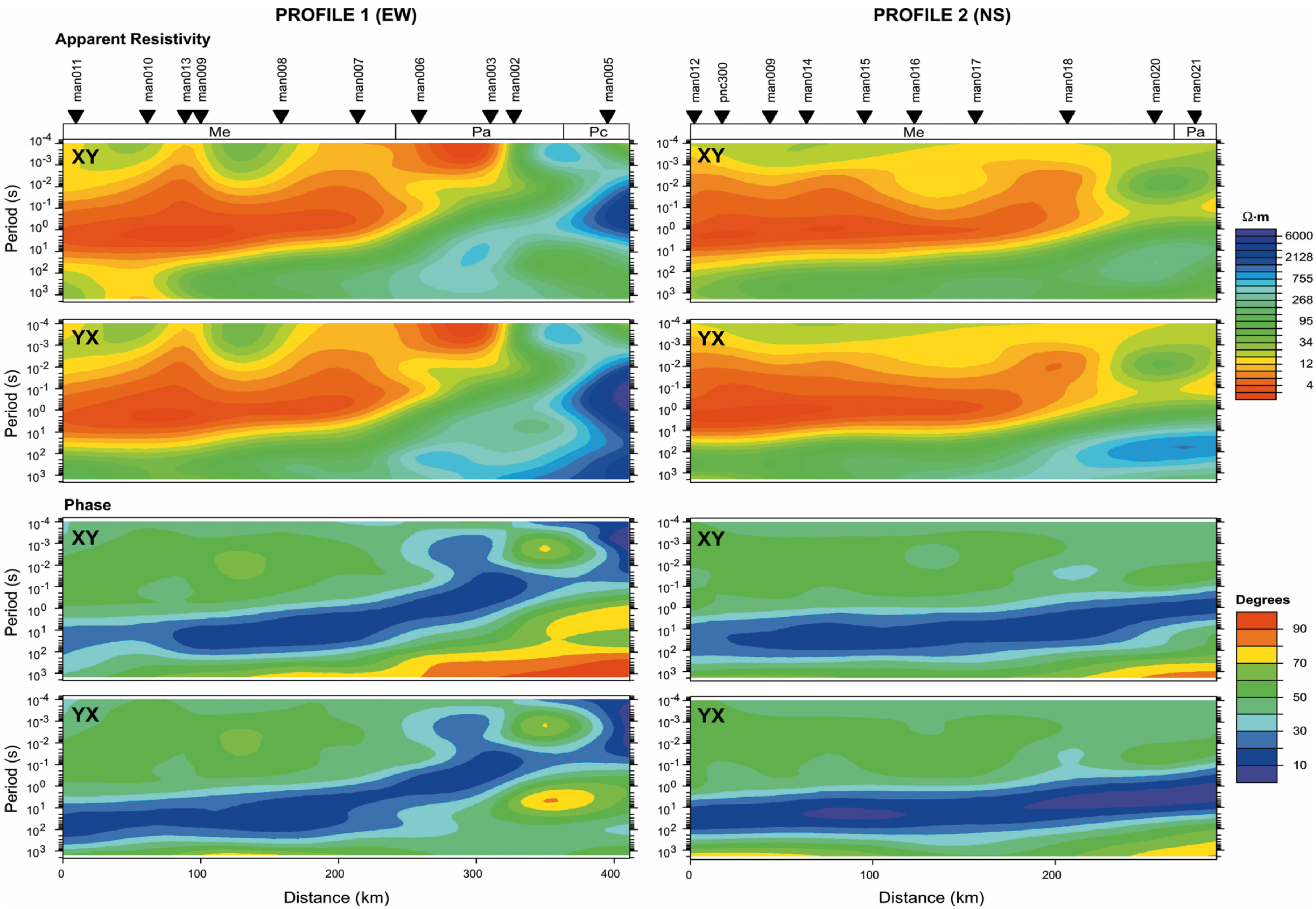
Apparent resistivity and phase

Figure 5 shows the apparent resistivity and phase data for POLARIS profiles 1 and 2 (Fig. 1) as contoured pseudosections. The vertical axis corresponds to the period increasing downwards. As the depth of penetration increases with increasing period, the apparent resistivity pseudosections show a smoothed image of the true structure. Results are shown for the *xy* impedance component, which is indicative of north–south electric currents and charges on east–west boundaries, and for the *yx* component, which is indicative of east–west electric currents and charges on north–south boundaries. The shape of the phase response is primarily related to gradients in conductivity; for MT responses from 1-D (horizontally layered) and two dimensional (2-D) conductivity structures, it must lie between 0° and 90°. In 1-D, the phase exceeds 45° if the conductivity increases with depth and is <45° if the conductivity decreases with depth.

The apparent resistivity pseudosections show that the MT response in southern Manitoba is dominated by a conductive zone that lies at the surface and thickens to the southwest (Fig. 5, profile 1 plots). The eastern edge of the conductive rocks lies between man002 and man005, correlating with the mapped edge of the Phanerozoic rocks of the basin. At the western end of profile 1 and the southern end of profile 2 the conductive responses are observed to periods exceeding 100 s; this conductive zone corresponds to the rocks of the northeastern Williston basin. The similarity of *xy* and *yx* responses over much of the conductive zone indicates that the rocks are approximately flat lying.

Although to first order the responses are indicative of lateral uniformity, there are significant variations within the conductive zone. The most conductive response, in which the apparent resistivity reaches values <3 Ω·m, occurs at a period of around 1 s in the western half of profile 1 and the southern half of profile 2. This minimum becomes less conductive and occurs at shorter periods to the east and north,

Fig. 5. Apparent resistivity and phase pseudosections for the *xy* and *yx* impedance components for both profiles. Increasing period corresponds to increasing signal penetration, and site man009 lies near the intersection of the two profiles. Profile 2 includes data from a Jones and Craven (1990) site pcn300. The bar at the top of the sections shows the geological divisions of the surface geology: Me, Mesozoic; Pa, Paleozoic; Pc, Precambrian. The responses show the more conductive Phanerozoic rocks becoming thicker towards the west and the south.



and its lateral extent correlates approximately with the mapped extent of Mesozoic rocks.

The phase responses are qualitatively consistent with the apparent resistivity responses. The highest phase response is observed at periods just shorter than those at which the lowest resistivity (highest conductivity) is observed and in the same geographical area. At longer periods, there is a zone of very low phase corresponding to the transition to larger apparent resistivity values.

The resistive responses (>1000 Ω·m) observed at longer period in the apparent resistivity pseudosections are related to Precambrian basement. One highly significant feature in the apparent resistivity response from the Precambrian rocks is the more conductive response observed in the *xy*-mode at periods exceeding ~100 s at man010 on profile 1 (Fig. 5, left column). This response is not observed in the *yx*-mode, indicating that it is caused by a 2-D or three dimensional (3-D) structure. The higher conductivity observed in the *xy*-mode provides an indication that the conductive direction is closer to north–south. Comparison of the location of this feature with previous MT survey results (e.g., Jones and Craven 1990) indicates that it is the TOBE anomaly.

Geoelectric strike directions

To generate a subsurface image from observed MT responses, one must first understand whether the electrical structure is 1-D, 2-D, or 3-D. The MT impedance tensor can be interrogated to examine the dimensionality of structures causing the response and, for 2-D or quasi-2-D structures, the direction of geoelectric strike. Maxwell's equations governing electromagnetic fields over a 2-D structure can be separated into two independent modes. These modes involve electric current flow parallel to strike, called the transverse electric (TE) mode, and electric flow perpendicular to strike, called the transverse magnetic (TM) mode.

Geoelectric strike, and its variation with period (a proxy for depth), can be determined from the observed MT response using several methods. In the Groom–Bailey (GB) tensor decomposition method (Groom and Bailey 1989), geoelectric strike is determined simultaneously with a parameterization of the distortion of the response caused by small-scale, near-surface heterogeneities. In strike determination methods there is a 90° ambiguity in the strike orientation. This ambiguity can be removed by plotting the results in the direction of highest phase. For MT sites located near isolated linear conductors in a resistive medium, at the shortest periods for which the feature affects the response, the direction of highest phase will correspond to the strike direction. However, at a 2-D boundary between two large regions of different conductivities the highest phase direction on the more resistive side will be parallel to strike, whereas those on the more conductive side will be perpendicular to strike (see Hamilton et al. 2006, fig. 5).

The geoelectric strike in the Precambrian basement of southern Manitoba was determined by applying the GB method to the portion of the response extending from the divergence of the *xy* and *yx* responses, corresponding to the onset of 2-D or 3-D effects, to the longest periods available. This range corresponded to periods from around 100–1000 s at sites in the southwest of the survey area but extended to shorter periods at sites to the north and east. The results were combined with data from southern Manitoba and adjacent regions obtained in earlier surveys and plotted in the direction of maximum phase (Fig. 6*a*).

The geoelectric strikes exhibit reasonably consistent azimuths within three large areas.

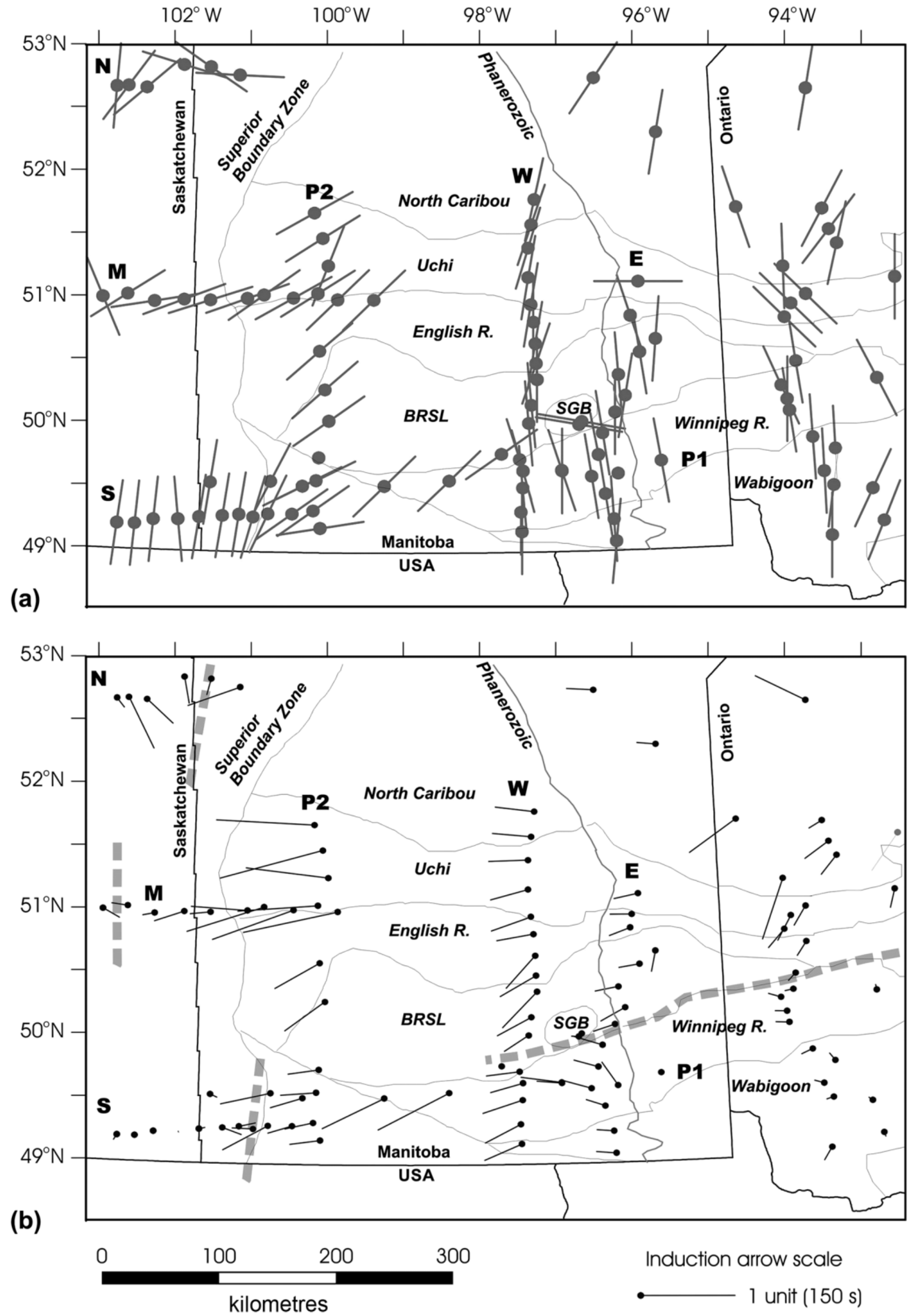
(1) In the east of the study area, east of 98°W, the azimuths are dominantly north to north-northeast. Recalling the 90° ambiguity between the direction of maximum phase and the true geoelectric strike, the observed results are consistent with a roughly east–west geoelectric strike, parallel to the subprovince boundaries in the Superior Province.
(2) In the west of the study area in the SBZ, the azimuths tend to be north–south or east–west and with the 90° ambiguity are consistent with a geoelectric strike subparallel to the boundary of the SBZ. Further west into the THO, the strikes tend to be more irregular.
(3) In the southwest of the Superior Province, between 98°W and the SBZ, there is a large area in which the azimuths have a dominantly southwest–northeast orientation. In many places, this azimuth is oblique to nearby subprovince boundaries.

The MT responses can be transformed from a period dependence to an approximate depth dependence using transforms such as the Niblett-Bostick transform (e.g., Jones 1983). Maps of strike directions for different depths across Canada have been computed using this transform. The strike direction for each depth was determined by rotating the apparent resistivity and phase data through 180°, deriving the transformed resistivity depth data, and choosing the direction corresponding to the smallest value of resistivity at the given depth. The results (not shown here) reveal that the three zones defined previously in the text are observed at both crustal (~30 km) and mantle lithosphere (~100 km) depths. There are some local deviations from the large-scale trends in strike direction within the study area; for example, a locally anomalous strike is observed at two sites located at the margin of the Selkirk greenstone belt.

A second response in MT studies is the tipper response that defines the transfer function between the vertical component of the magnetic field and the horizontal components. For a uniform source field, this response is negligible in 1-D structures, but it becomes significant for 2-D and 3-D structures. Induction arrows provide a graphical representation of this transfer function. In 2-D structures, the arrow will be perpendicular to the strike and, when plotted according to the sensible Parkinson (1962) convention, the arrow corresponding to the real (in-phase) portion of the transfer function will point towards more conductive regions.

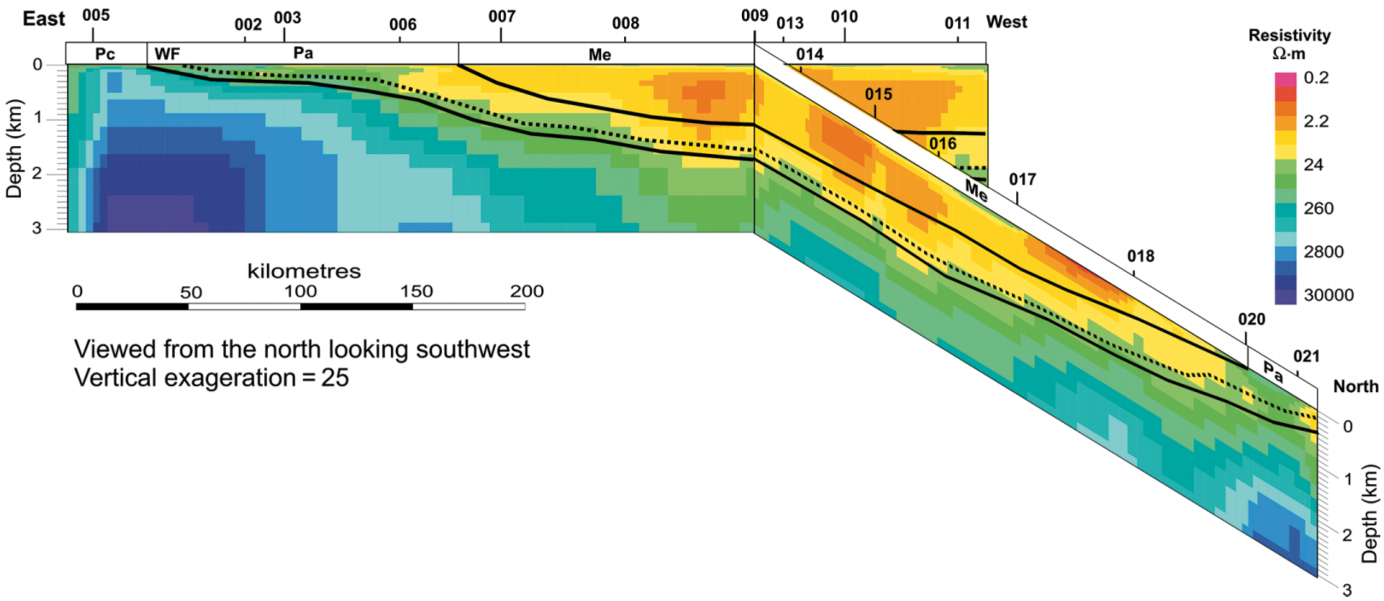
Figure 6*b* shows the induction arrows for southern Manitoba and adjacent areas for a period of 150 s. In the southwestern part of the study area, the induction arrows are small, indicating the effect of the thick sequence of gently dipping rocks of the Williston basin — an approximately 1-D geoelectric structure. Between 98°W and 95°W in the Superior Province, the induction arrows almost all exhibit a westward component to their azimuth. Within this region,

Fig. 6. Indications of geoelectric strike in the longer period magnetotelluric responses using data from the present survey and from earlier surveys. (*a*) The map shows the azimuths derived using Groom–Bailey analysis of long period (>10 s) data. The results define directions that are either parallel or perpendicular to the electrical strike in the Precambrian basement. The response is plotted in the direction of maximum phase, which commonly corresponds to the conductive direction. SGB, Selkirk greenstone belt; BRSL, Bird River – Separation Lake subprovince. (*b*) Induction arrows plotted using the reversed real component for a period of 150 s. These arrows point towards linear conductive structures and the length of the arrows provides an indication of the proximity to, and strength of, the conductivity contrast. Thick grey broken lines show the location of significant induction arrow reversals.



the north–south component of the arrows undergoes a reversal across a line coinciding with the southern margin of the BRSL subprovince. This reversal can be traced ~600 km to the east (Ferguson et al. 2005*a*) and, as noted previously in the text, suggests the presence of a long linear conductive zone near the southern margin of the BRSL subprovince and, further to the east, the English River subprovince. Arrows on profile 2 (Fig. 6, P2) do not show any north–south reversal so the POLARIS induction arrow data provide no evidence that this conductor extends west of 98°W.

Fig. 7. Shallow part of the two-dimensional resistivity models presented as a fence diagram. Annotations show the interpreted geological structure. Abbreviated site names are used, other abbreviations are defined in Fig. 5. WF, Winnipeg Formation.



The induction arrows in the western part of the study area exhibit a reversal in their east–west component, suggesting the presence of north–south-trending linear conductors. On POLARIS profile 1 and NACP line S (Fig. 6, profiles P1 and S), the reversal occurs near the interpreted location of the eastern margin of the SBZ. To the north on NACP line M, the reversal occurs further west at a location <100 km west of the eastern margin of the SBZ. Although there is no reversal at 150 s period (or other periods) at the margin of the SBZ, the induction vectors do show a significant decrease in size at this location, suggesting the existence of a significant change in the resistivity structure. On NACP line N, there is an indication of an arrow reversal at 102°W. This location is again some distance west of the SBZ.

Geoelectric structure

Magnetotelluric inversions

The observed MT responses at short to intermediate periods are consistent with the electromagnetic responses of 1-D conductivity structures, and initial inversions of the data used 1-D approaches. Because of possible local distortion effects and the non-uniqueness inherent in MT inversions, the 1-D models determined for adjacent sites exhibited discontinuities that make interpretation difficult. Therefore, the responses for each profile were modelled using a 2-D algorithm in which a function involving both the data misfit and the roughness of the resulting model is penalized. The resulting 2-D models will be consistent with locally 1-D responses while providing smoothing constraints that reduce any discontinuities among adjacent sites that are not required by the data.

The data were inverted using modelling profiles corresponding to the data acquisition profiles (i.e., the geoelectric strike is assumed to be perpendicular to the profile). Thus the TE mode was set to correspond to the electric field perpendicular to the profiles. This approach will produce reasonable resistivity models for the gently dipping Phanerozoic rocks, but structures appearing in the Precambrian basement will not necessarily have their true form as they are strongly 2-D and require data to be in the strike direction of the 2-D structure.

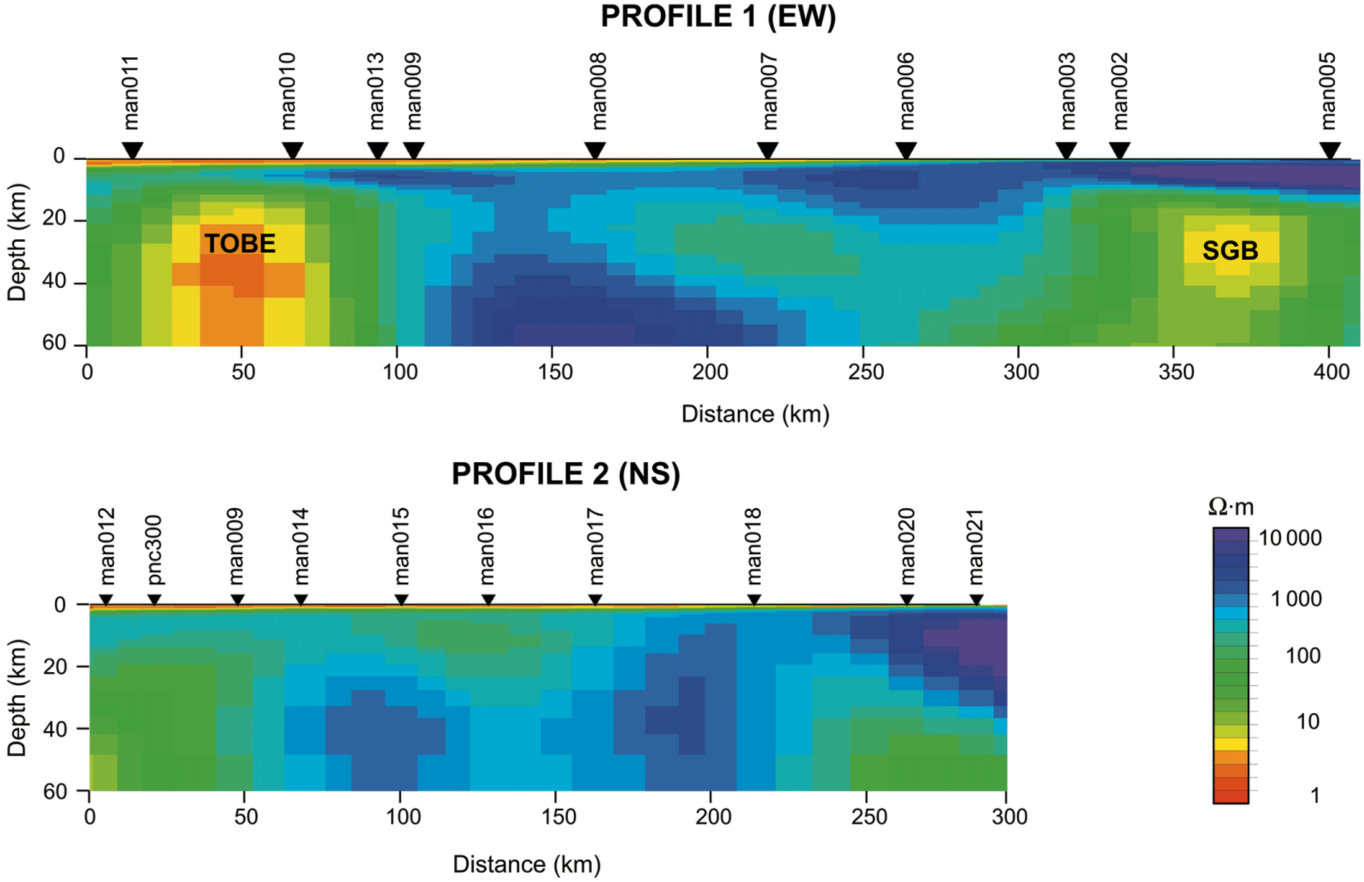
The 2-D inversions were done using the non-linear conjugate gradient code of Rodi and Mackie (2001). The input data consisted of the TE and TM impedance values, interpolated at five periods per decade We assigned apparent resistivity and phase errors equivalent to 5% errors on the impedance. Inversions were run for a range of values of the smoothness parameter (τ), which controls the trade-off between data misfit and model roughness, and it was determined that for both profiles a value of τ = 10 produced a model centred on the region of maximum curvature of the roughness versus misfit curve.

Figures 7 and 8 show the resistivity models obtained in the inversions, and Fig. 9 shows the fit of the model response to the data at representative sites. The overall root mean square (rms) misfit for profile 1 is 1.97, and for profile 2 it is 1.83. The short period part of the data is fitted quite well (Fig. 9); most of the misfit arises at long periods corresponding to signal penetration into the Precambrian basement. For profile 1, the misfit is smaller at western sites in the vicinity of the TOBE conductor. For this part of the profile, the model response reproduces all of the major features in the data, and the maximum rms misfit for individual sites is 1.57 at man013. In contrast, for the eastern end of the profile near the Selkirk greenstone belt, rms misfit of approximately 3.0 is observed at man003 and man002. For profile 2, the largest rms misfit is observed on the northern half of the profile (Fig. 9). The poor fit to the long-period data along parts of the profiles is not surprising considering that the inversions have not been done allowing for the true basement strike; this reinforces the need for careful interpretation of the basement structures in the model.

Phanerozoic sedimentary rocks

Figure 7 shows the upper 3 km of the resistivity model for each profile on an enlarged vertical scale. The models for

Fig. 8. Two-dimensonal resistivity model for the east–west and north–south profiles. SGB, Selkirk greenstone belt; TOBE, Thompson belt.



both profiles have a similar form with a wedge of conductive rocks that increases in thickness to the south and west.

The results define significant zones within the near-surface rocks. The easternmost part of profile 1, corresponding to the region of the Precambrian Shield, is relatively resistive, as inferred from the pseudosections. Further to the west and at the northern end of profile 2, in the region in which Paleozoic rocks outcrop, the resistivity structure is characterized by a moderately conductive response (30–100 Ω·m). A thin conductive layer (<10 Ω·m) occurs at several hundred metres depth (e.g., Fig. 7, beneath site man002 and man020). This layer can be reliably interpreted as a unit near the base of the Paleozoic rocks and, on the basis of the hydrostratigraphy of the region discussed previously in the text, it can be correlated with the saline aquifer in the Winnipeg Formation. The MT response provides reliable detection of the integrated conductivity thickness product of the layers (e.g., Jones 1982; Weidelt 1985), but resolution of the individual thickness and conductivity is poor. The resistivity models indicate that the integrated conductance of the conductor in the Winnipeg Formation is in the range of 10–20 S.

The structure of the resistivity models changes further to the south and west in the region of subcrop of Mesozoic rocks. In this part of the survey area, there is a zone of very conductive rocks (Fig. 7, orange colour) extending from near surface to a depth that increases to ~1000 m in the far southwestern part of the study area. The resistivity of this layer is <5 Ω·m, and in some parts <2 Ω·m, and the integrated conductance of this zone reaches values of 400 S. Based on the known geological structure, the conductor is interpreted to be associated with the Mesozoic shale-dominated Zuni succession (Osadetz et al. 2002) and with conductive rocks in the underlying Paleozoic sequence. This large conductive wedge is overlain by a thin layer varying from 0 to 100 m thick with resistivity of 5–30 Ω·m; this layer is interpreted to be surficial Pleistocene deposits.

Electromagnetic signals are absorbed by conductive media and, as a consequence, the MT method provides poor resolution of more resistive regions beneath conductive layers and of the sharpness of the resistivity change at the base of such layers. The gradual change in resistivity below the conductive wedge is a function of this limited resolution and the smoothing included in the inversion. Based on the known geological structure (Fig. 3), the Winnipeg Formation conductor and the more resistive Ordovician rocks are interpreted to extend to the southeast beneath the conductive Mesozoic rocks (Fig. 7).

Higher resolution studies

High-resolution information on the resistivity structure of rocks of the Williston basin in southern Manitoba is available from geophysical well logs. The density of suitable well logs is quite high in the southwest of the province in oil producing areas, and more sparsely distributed logs are available to the east and the north. Figure 10 shows resistivity logs for a location near man006 in the region of subcrop

Fig. 9. Comparison of the response of the smooth two dimensional model with the inverted data at representative sites from the survey. This 2-D model reproduces the shorter period part of the data set and at some sites fits the more complex responses occurring at longer periods. App., apparent; rms, root mean square misfit; TE, transverse electric; TM, transverse magnetic.

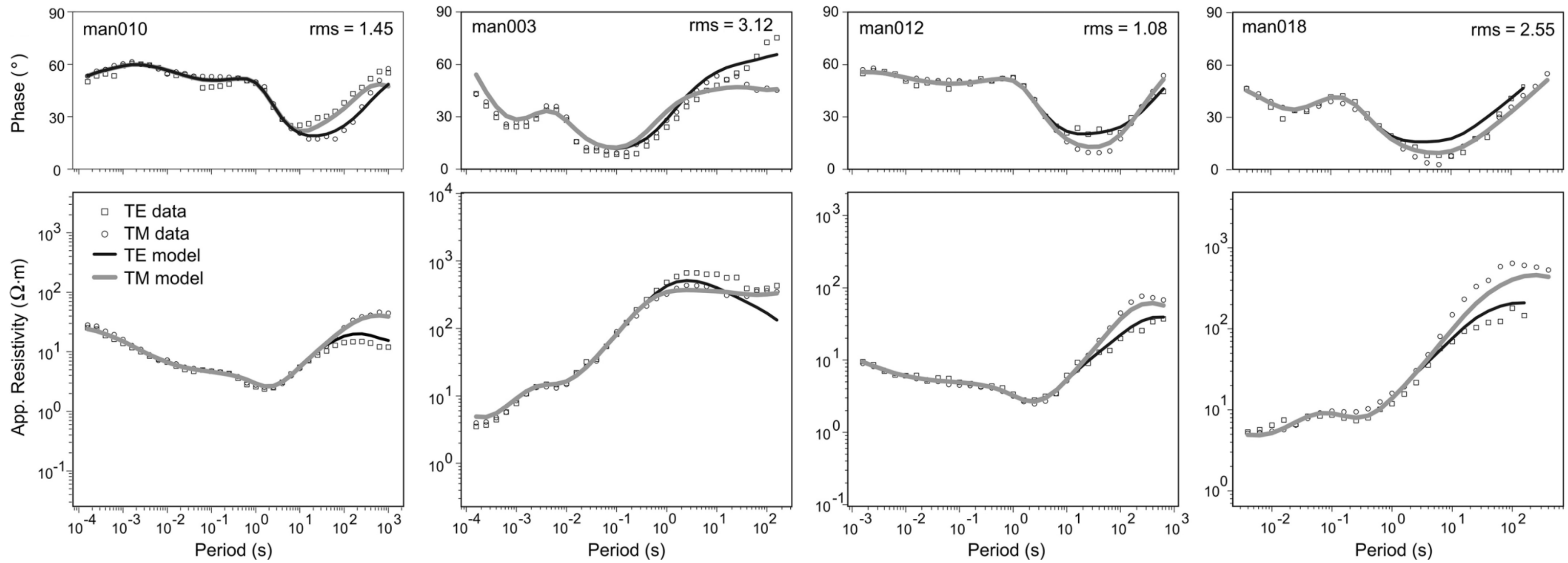


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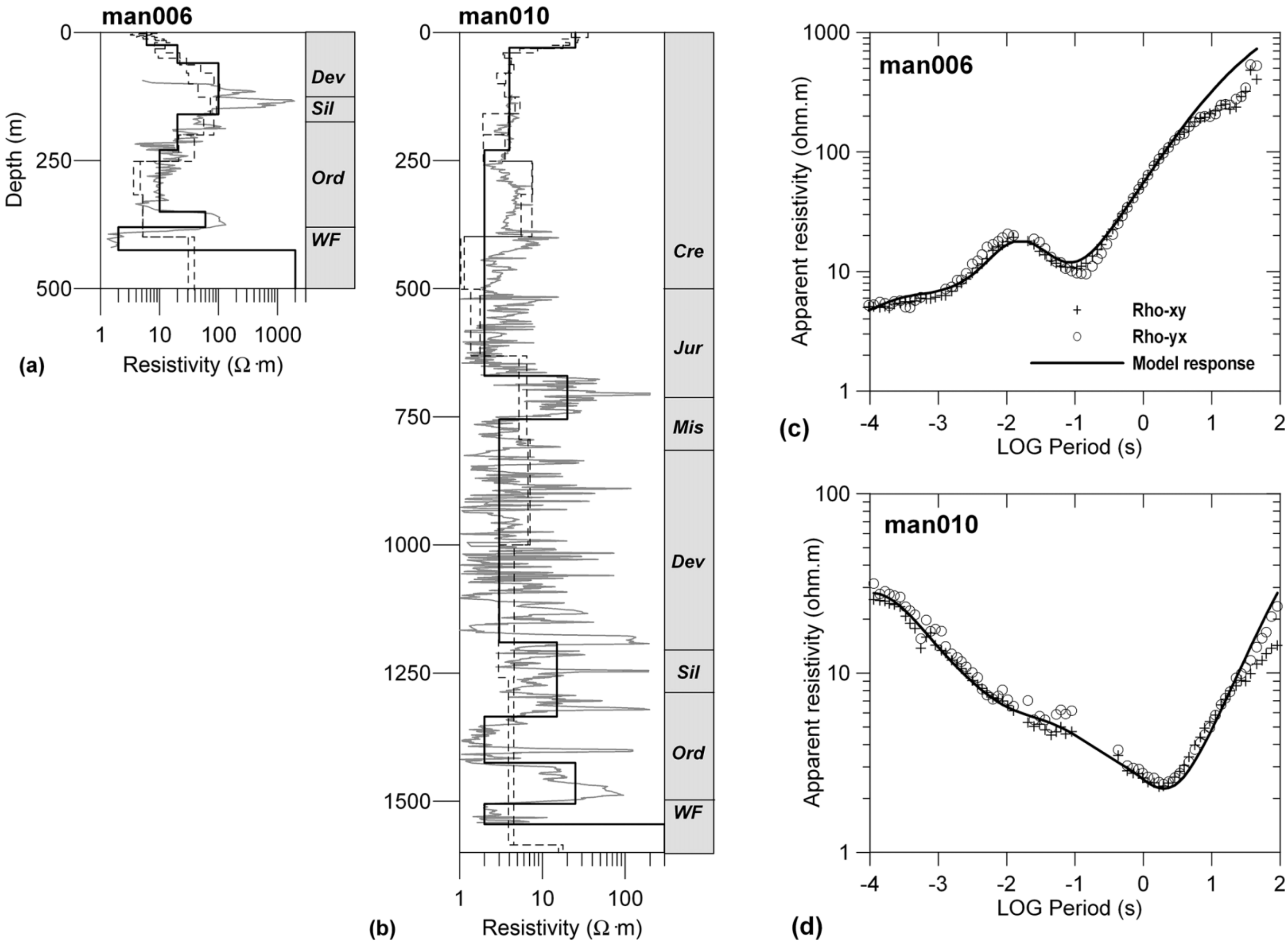
Fig. 10. Comparison of observed magnetotelluric responses, one-dimensional models, and Laterolog well logs. (*a*) Log response for a well near man006 (grey line), 1-D Occam models derived from *xy* and *yx* responses (broken grey lines) and simplified model based on well-log and forward modelling (solid black line). (*b*) Log response for a well near man010, 1-D Occam models derived from *xy* and *yx* responses and simplified model based on well-log and forward modelling. The bars at the right of (*a*) and (*b*) show the Winnipeg Formation (WF) and geological divisions: Ord., Ordovician; Sil, Silurian; Dev, Devonian; Mis, Mississippian; Jur, Jurassic; Cre, Cretaceous. (*c*) Comparison of observed and forward model apparent resistivity responses for man006. (*d*) Comparison of observed and forward model apparent resistivity responses for man010.



of Devonian rocks and for a location near man010 in a region of Mesozoic subcrop.

The well logs show small-scale variability that is not resolvable by the larger-scale electromagnetic responses. Figure 10 compares the observed well logs with models derived from 1-D Occam inversion of the *xy* and *yx* responses. Occam inversions yield the smoothest possible models that fit the data to a specified level of misfit (Constable et al. 1987). It is instructive to use forward modelling to examine the consistency of the well-log and surface responses. Figure 10 shows simplified 1-D resistivity models developed iteratively for each of the two sites that are consistent with both the well-log data and the MT observations. At both sites, the MT responses are sensitive to near-surface layers that are not included in the well logs so the near surface parts of the 1-D models are based on the MT data alone. Figure 10 also shows a comparison of the responses of these models with the MT observations.

At site man006, comparison of the 1-D Occam models and well-log data suggests the MT data, when analyzed alone, provides good resolution of the resistivity structure between 100 and 300 m depth. The Occam models do not show the small-scale variability present in the well-log data, but they correctly resolve relatively resistive Devonian and Silurian rocks overlying relative conductive Ordovician rocks and the decrease in resistivity over the depth range from 150 and 250 m depth. The Occam models also show a large increase in resistivity at 400 m depth, in quite good agreement with the expected depth to basement at the site. At site man006, the 1-D Occam inversions of the MT data do not resolve the conductive rocks in the Winnipeg Formation. However, the incorporation of well-log data into a 1-D resistivity model that fits the observed MT data allows the development of a model that includes this feature. This model includes a layer of conductive (2 Ω·m) rocks at 380–420 m depth.

The shallow resistivity model for man010 is more complex than for man006. The 1-D Occam models resolve several basic, but important, aspects of the model. They show a relatively resistive 20–35 Ω·m surface layer overlying a 1600 m thick layer of relatively conductive (1–20 Ω·m) rocks. The Occam models also provide some resolution of significantly increased conductivity in Jurassic and Cretaceous (Zuni) rocks. It is possible to develop a more complex model that fits the finer detail of the well-log data and also provides a good fit to the observed MT responses. This model includes relatively conductive rocks of Devonian–Mississippian age (Kaskasia), conductive rocks in the upper part of the Ordovician, and conductive rocks corresponding to the Winnipeg Formation that are not resolved by 1-D Occam inversion of the MT data.

The consistency of the MT results with the well-log data means that the MT method could be used to interpolate conductive units between wells. In particular, in situations in which there were significant changes in a single conductive unit between two well locations, the MT response could provide an indication of the sharpness and location of those changes.

Precambrian crust

Information on the resistivity structure of the Precambrian crust can be extracted from the deeper parts of the 2-D models shown in Fig. 8. The basement along profile 1 shows two significant conductive features. The first conductor is in the eastern part of the profile and is required to fit the data at site man002. This conductor is interpreted to be caused by enhanced conductivity in the Selkirk greenstone belt, which is located adjacent to man002 (Fig. 2); therefore, it represents an off-profile 3-D structure mapped into the 2-D profile. The geometry of the structure in Fig. 8 provides little information on the true structure, but the result does indicate the presence of substantial electrical conductance within the belt.

The second conductor appearing along profile 1 is a conductor located beneath site man010. Comparison of the location with previous studies allows this conductor to be interpreted as part of the TOBE conductor (e.g., Jones and Craven 1990). The TOBE conductor strikes approximately north–south, perpendicular to the profile, so the 2-D inversion model has a suitable orientation for correctly imaging this structure. However, with the relatively large site spacing and the limited period range of the MT data, the structure is imaged with quite low resolution.

The basement resistivity structure imaged along profile 2 is relatively resistive. This result provides a reliable indication of the absence of any high-conducting features striking at high angle to the profile. Because of the masking effect of the conductive sedimentary rocks, the MT data will not be able to fully resolve structures that have relatively high resistivity. Also, because the orientation of the 2-D section is not perpendicular to the expected geoelectric strike in the Precambrian rocks, the geometry of the highly resistive zones observed in the model (Fig. 8) is unlikely to match the true geometry.

Geological interpretation

Resistivity structures in the northeastern Williston basin

The MT inversion models resolved the major resistivity divisions in the northeastern Williston basin, including conductive rocks in the lower Ordovician Winnipeg Formation, more resistive rocks in the lower Paleozoic, and conductive upper Paleozoic and Mesozoic sequences. The more detailed resistivity models obtained by comparing well-log and MT responses (Fig. 10) provide information on the resistivity of smaller scale geological units.

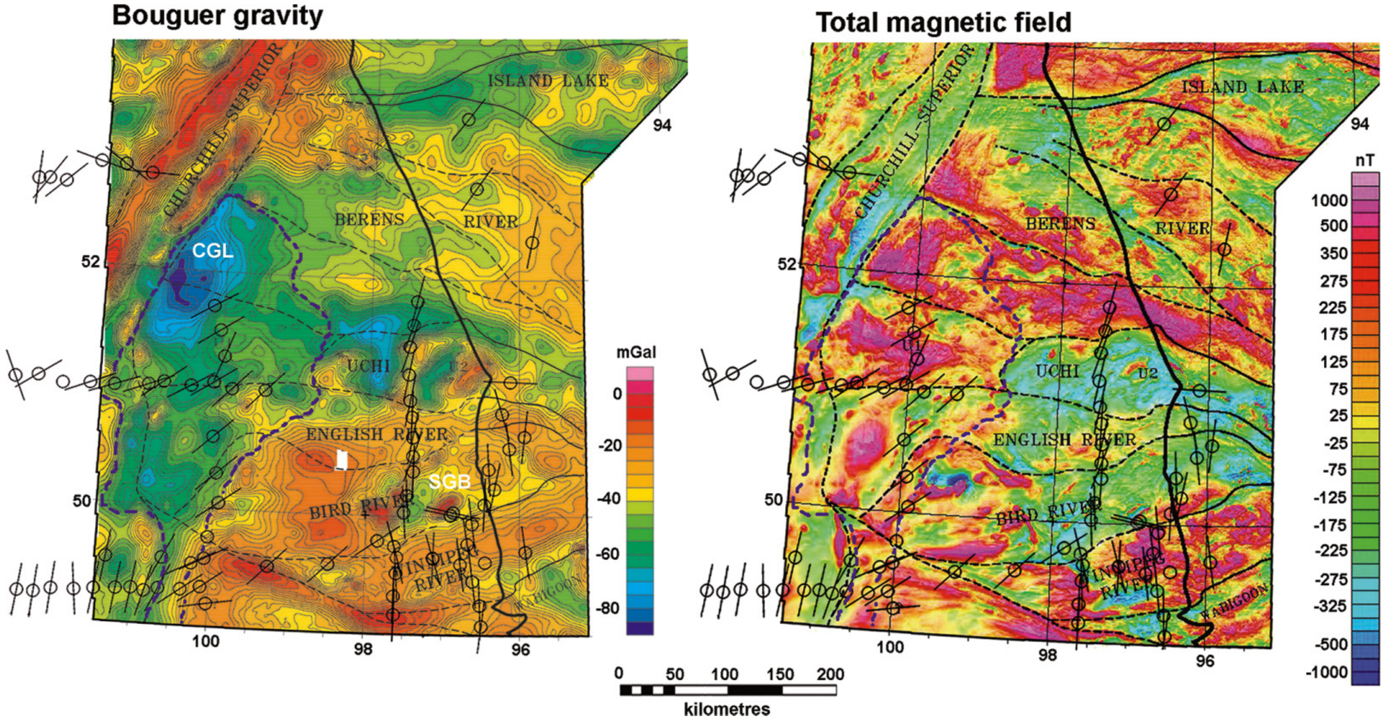
The resistivity determined for the lower Paleozoic units in this study can be compared with results from previous studies. The TEM profiles of Hyde et al. (1997) are located to the north and south of the present MT survey but provide results for the same units. Hyde et al. (1997) observed resistivity values of <5 Ω·m at depths corresponding to the Winnipeg Formation, which are in good agreement with those of the present study.

Moving to younger geological units, Hyde et al. (1997) fitted their data with models in which the resistivity of the dolomitic Ordovician and Silurian rocks are in the range of ~20–50 Ω·m. These values are higher than the 10–20 Ω·m in the MT-constrained models for man006. Resistivity logging of a well in Winnipeg (Fig. 2) yielded resistivity of around 100 Ω·m for the same units (Mwenifumbo et al. 1995). Although the results are for different locations, the rocks units are expected to be similar, so the increasing resistivity observed using MT, TEM, and resistivity logging suggests the existence of scale-dependence of resistivity, with smaller scale measurements yielding more resistive responses. Such scale dependence has been observed previously in other rock types (e.g., Jones 1995) and is expected in situations in which the conductive components within the rocks have a fractal distribution.

On a regional scale, the results of the present study for the Winnipeg Formation are in agreement with those of Jones (1988), who showed conductive Lower Ordovician rocks in the eastern part of the Williston basin. The relatively resistive lower Paleozoic layer resolved by the MT data in eastern Manitoba was observed by Jones (1988) to extend across the Williston basin. The MT models from the present study are also in agreement with those of Maidens and Paulson (1988) from sites in Saskatchewan in showing an overlying layer of conductive Paleozoic (Kaskasia) rocks. However, the models from the present study differ from those of Maidens and Paulson (1988) in that they do not include the relatively resistive (10–200 Ω·m) sequence of Late Devonian to Mississippian rocks noted in Saskatchewan. As shown by Jones (1988), who used well-log results, this difference is explained by the removal of the prairie evaporite in the east. Finally, the MT results from the present study agree with MT and well-log results from the west in showing a thick sequence of conductive Mesozoic (Zuni) rocks.

It is instructive to examine the geological sources of enhanced conductivity in the Phanerozoic rocks. The high conductivity of the Winnipeg Formation can be attributed to both its shale content and salinity of the pore water. Stratigraphic studies in central Manitoba indicate that, near site man006, the lower 50% of the formation consists of interbedded sandstone and shale, and the upper 50% of the formation consists of clean sandstone of the Carman Sand unit (McCabe 1978; Ferguson et al. 2007). Hydrogeological studies in the area indicate the groundwater has a relatively high salinity of ~100 $g \cdot L^{-1}$ (Ferguson et al. 2007). The shale and saline groundwater will both contribute to the enhanced con-

Fig. 11. Comparison of geoelectric strike directions with Bouguer gravity and total magnetic field in southern Manitoba (modified from Pilkington and Thomas 2001). The region outlined in a blue broken line encloses a zone of consistent southwest–northeast geoelectric strike, negative gravity anomalies, and positive total magnetic field anomalies. CGL, Camperville gravity low; SGB, Selkirk greenstone belt.



ductivity in the Winnipeg Formation observed in central Manitoba.

In western Manitoba, well logs in the vicinity of man010 indicate that the Winnipeg Formation has a similar conductivity and thickness as in central Manitoba. However, in western Manitoba, the formation has a higher shale content, with both the upper and low parts being basinal shale facies, and the salinity of the pore water is higher than to the east, around 200 g·L^{-1} (Ferguson et al. 2007). It appears that in western Manitoba the increased contribution to the conductivity from increased shale content must be balanced by a significant decrease in ionic conduction caused by a decreased effective porosity.

A comparison of the well-log resistivity models for man006 and man010 (Fig. 10) indicates the presence of conductive Ordovician rocks in western Manitoba that are not present further to the east. This change likely reflects the increasing thickness of the Gunn member and decreasing thickness of the Penitentiary member of the Stony Mountain Formation with increasing distance to the southwest. The Gunn member is made up of interbedded limestone and calcareous shale, whereas the Penitentiary member is composed of dolostone (Bezys and McCabe 1996).

The enhanced conductivity observed in the well logs and in the MT models in the Devonian–Mississippian Kaskasia rocks can be attributed largely to their shale content. In his synthesis of well-log resistivity data, Jones (1988) shows that this conductive sequence extends some distance into eastern Saskatchewan. The high conductivity of the Mesozoic Zuni sequence can again be attributed to the shale content. This conductive sequence extends west from Manitoba into Alberta (e.g., Jones 1988).

Selkirk greenstone belt

The Selkirk greenstone belt is imaged as a conductive feature in the 2-D resistivity models (Fig. 8). However, because of the 3-D form of the belt, its geometry in the 2-D model will be incorrect. The MT results demonstrate that the belt contains a significant volume of electrically conductive rocks and forms a suitable target for more detailed 3-D MT studies. Imaging of the belt will require a 2-D grid of sites and 3-D modelling to both image the feature and to account for mutual electromagnetic induction involving the belt and the conductive Winnipeg Formation rocks.

The enhanced conductivity in the Selkirk greenstone belt likely includes a significant contribution from iron formations. The strong magnetic signature of the belt, with narrow (<2 km wide) anomalies exceeding 1000 nT at the ground surface 200 m above the Precambrian rocks, suggests the presence of iron formations; drill-hole data has confirmed their presence (W. Brisbin, University of Manitoba, personal communication, 2006). Drill core also reveals the presence of some sulphide mineralization, which may provide a second contribution to the enhanced electrical conductivity. Basic measurements of drill-core resistance using a multimeter indicate the iron formation and sulphide mineralization have low resistivity.

The observed results suggest that individual greenstone belts within the BRSL subprovince provide a contribution to the 600 km long conductivity anomaly crossing the western Superior Province. However, careful examination of the MT responses near other small belts shows that long-period induction vectors point away from the individual belt and towards the southern margin of the BRSL subprovince. This observation suggests the presence of a deep-seated conductivity anomaly associated with the subprovince margin.

Fig. 12. Location of the Thompson belt (TOBE) anomaly between 49°N and 50°N. (*a*) Position of TOBE superimposed on gravity and magnetic data. Magnetotelluric lines are labelled in the upper panel and original site numbers in the bottom panel. (*b*) Plot of distance to the TOBE versus observed transverse electric – transverse magnetic (TE–TM) split in apparent resistivity using data from Rankin and Kao (1978), Jones and Craven (1990). and the present survey. NACP, North American Central Plains; POLARIS, Portable Observatories for Lithosphere Analysis and Research Investigating Seismicity; SBZ, Superior boundary zone.

Resistivity structure in the westernmost Superior Province

The region of southwest–northeast geoelectric strikes observed in the westernmost Superior Province defines a zone with distinctly different large-scale geoelectric structure from the east–west-trending structures observed to the east. The region has minimum dimensions of around 200 km in the east–west direction and 400 km in the north–south direction. The observed geoelectric strikes can be confidently attributed to the resistivity structure of the underlying crust because their azimuth is not aligned with any larger scale, but more distant, tectonic feature.

Lithological model

The observed MT responses can be explained in terms of either a primary lithological origin or in terms of subsequent deformation. Gravity and magnetic data support the lithological interpretation. The region of the Superior Province adjacent to the SBZ south of ~53°N is characterized by regional-scale, large-magnitude gravity lows (>50 mgal) and large-magnitude magnetic highs (>1000 nT). The minima within the gravity lows are spatially offset from the maxima in the magnetic highs, e.g., the gravity minimum at 50.3°N, 101°W (Fig. 11). The gravity lows in the area include the Camperville gravity low, a large 100 km × 50 km anomaly adjacent to the SBZ (Surasky and Minkus 2000; Hosain and Bamburak 2002). It is possible to define a distinct region in the westernmost Superior Province characterized by consistent southwest–northeast geoelectric strike, negative anomalies, and positive magnetic anomalies (Fig. 11). Neodymium model ages in the area range from 3.1 to 2.74 Ga (Stevenson et al. 2000; Percival et al. 2006).

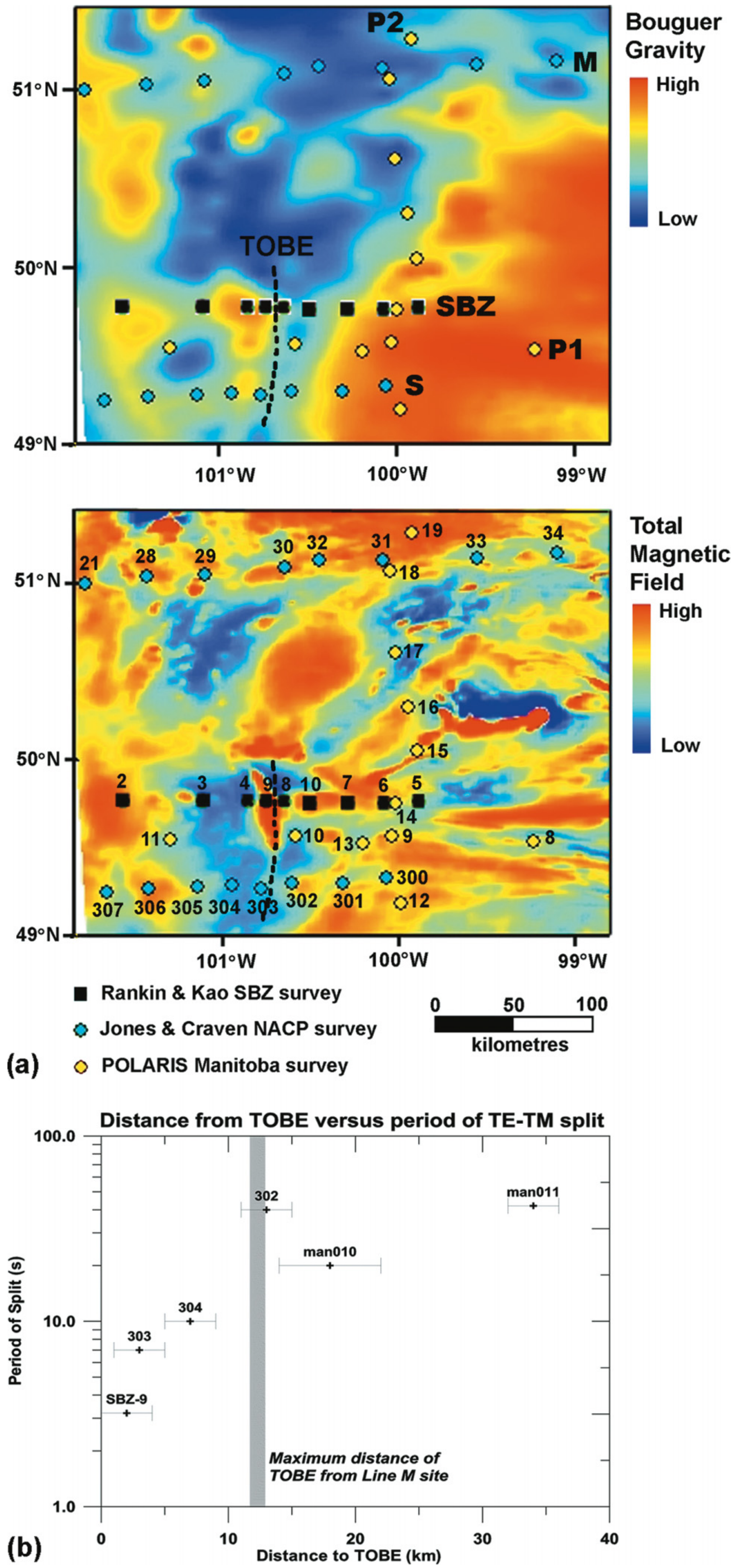
Based on the preceding, it can be hypothesized that the region forms part of a coherent Archean terrain. At a broad scale, the gravity and magnetic responses are consistent with this being a granite–greenstone terrain. The Camperville gravity low requires the presence of a large body of relatively low-density material, e.g., a 10 km thick body of granitic rocks (Hosain and Bamburak 2002). The existence of a northeast–southwest striking granite–greenstone terrain adjacent to the SBZ south of 53°N could be explained by southwards deflection of the southern margin of the Uchi subprovince west of 98°W, but this interpretation would also require some changes to the interpreted boundaries of English River, BRSL, and Winnipeg River subprovinces in this area. Such change is supported by the fact that the regional conductor at the southern margin of BRSL subprovince is not observed crossing POLARIS profile 2 (Figs. 6, 8). In this case, the conductor would be expected to cross profile 1, where it would be difficult to observe because of the pervasive westward trend of the induction arrows (Fig. 6*b*). However, the change is not supported by the observed trends of potential-field responses in the area (e.g., Pilkington and Thomas 2001, Li and Morozov 2007).

Deformational model

The present geometry of the SBZ is interpreted to have resulted from initial westward subduction, followed by collisional orogeny, and subsequent prolonged convergence resulting in underthrusting of Paleoproterozoic lithosphere beneath the Superior craton (e.g., White et al. 1999). The direction of final convergence of the Superior craton relative to the Reindeer zone is interpreted to have been north-northwest in present-day coordinates, and a seismic reflection profile crossing the SBZ at 53°N shows east-southeast-dipping structures extending over 100 km in the lowermost crust and mantle lithosphere beneath the Superior craton (fig. 2 in White et al. 2002). The strike of such structures would be similar to the observed southwest–northeast geoelectric strikes, so the underthrusting provides a plausible explanation for the observed strike directions. Although not tightly constrained by the data, the conductive crust east of the TOBE conductor (beneath man013 and man009) in the 2-D resistivity models supports this interpretation (Fig. 8).

The seismic reflection data from 53°N suggests that east of the SBZ the underthrust Reindeer zone rocks lie at depths exceeding 35 km beneath the Superior craton. This depth may to be too large to explain the geoelectric strikes observed at shorter periods, which, as noted earlier in the text, correspond to crustal depths. However, to the east of the SBZ, south-southeast-dipping reflections are also observed at 53°N in the upper crust (White et al. 2002); these would correspond to structures with an appropriate orientation to explain the shorter period geoelectric strikes. Alternatively, the shorter period response may be attributed to late brittle deformation. In the Proterozoic Wopmay orogen in the Northwest Territories, a region of pervasive southwest to northeast geoelectric strikes at crustal depths can be correlated with late regional-scale transcurrent faulting (Wu et al. 2005). There is evidence for such structures in the Superior Province east of the Manitoba–Ontario border, where there is a suite of geoelectric strikes interpreted by Ferguson et al. (2005*a*) to be related to Paleoproterozoic northeast-trending brittle strike-slip faulting (Williams et al. 1992). However, it is of note that such strikes are not observed extending continuously to the SBZ.

Seismic refraction and teleseismic data provide evidence that the crust and lithosphere in the westernmost Superior Province differs from that further east in the province. Seismic refraction results from Lithoprobe and earlier surveys suggest that the crust in southwestern Manitoba is around 40 km thick (Morel-à-l'Hussier et al. 1987; Németh et al. 2005), and compilations of seismic refraction results show that the crust in the area is thicker than at the same latitude in central and eastern Manitoba and further to the north in the THO (Kanasewich et al. 1987). The presence of thick crust beneath and adjacent to the SBZ can be explained by the underthrusting of the Superior craton by Reindeer zone crust (White et al. 2002, 2005; Németh et al. 2005). Pre-



Bouguer Gravity
High
Low
P2
M
TOBE
SBZ
P1
S
51° N
50°N
49°N
101°W
100°W
99°W
Total Magnetic Field
High
Low
Rankin & Kao SBZ survey
Jones & Craven NACP survey
POLARIS Manitoba survey
0 50 100
kilometres
(a)
Distance from TOBE versus period of TE-TM split
Period of Split (s)
Distance to TOBE (km)
Maximum distance of TOBE from Line M site
302
man011
man010
304
303
SBZ-9
(b)

liminary shear-wave splitting results from the Brandon station (Fig. 2) of the Manitoba Teleseismic Array (Frederiksen et al. 2007) at 49.8°N, 100°W have a much smaller split (0.53 s) than sites in eastern Manitoba (typically >1.4 s), indicating a change in the fabric of the deep Superior lithosphere at a location at least 100 km east of the SBZ. The seismic observations tend to support the deformation model for the explanation of the geoelectric strikes by demonstrating continuous Proterozoic modification of the crust and mantle lithosphere extending from the SBZ into the Superior craton. However, the observations do not exclude the alternative lithological explanation, in which one would also expect a different structural fabric in the crust and lithosphere from that observed further east into the Superior craton.

Thompson belt conductor

In models based on MT surveys conducted between 49°N and 50°N, the TOBE anomaly has been modelled as a relatively narrow (<20 km) conductor extending vertically from the top of the Precambrian basement to depths of more than tens of kilometres (Rankin and Kao 1978; Jones and Craven 1990). However, the resolution of the structure is severely limited by the overlying conductive sedimentary rocks, and the form determined for the conductor depends on the lateral and vertical smoothing used in the MT inversions. The observed data can also be modelled in terms of a vertically compact body located at a depth of around 15 km (e.g., Jones et al. 2005). However, when it is modelled as a compact body, the feature must have extremely low resistivity (<0.2 Ω·m), suggesting that this model is less probable. The results from the present survey are consistent with the previous interpretations, but with the larger site spacing of the survey, they do not provide as good resolution of the width of the feature as the earlier surveys (Fig. 8).

The TOBE conductor has a clear signature in the MT data. It causes a separation of the TE and TM modes at longer periods, with the TE mode showing decreased apparent resistivity and increased phase. The response for site man010 (Fig. 4) provides a good example. The period at which the split between the two modes occurs increases with distance from the TOBE anomaly, providing a means of accurately locating the body relative to the MT sites (Fig. 12). Using this response, the location of the TOBE conductor can be pinpointed with an accuracy of a few kilometres between 49.3°N (line S) and 49.7°N (the Rankin and Kao 1978 profile). Along most of this 50 km strike length, the conductor lies on the eastern flank of a narrow north–south-trending gravity high, and along the northern half, it lies on the eastern flank of a narrow local north–south-trending magnetic high (Fig. 12).

Resistivity structure of the Superior boundary zone and margins of the Sask craton

The MT data indicates that the SBZ does not form a simple north–south boundary south of 52°N. Extrapolating the trend of the TOBE conductor northwards from the Rankin and Kao (1978) profile at 49.75°N, the conductor would be expected to cross line M at 51°N, around sites 29 or 30 (Fig. 12). However, there is no evidence of a north–south conductor at these sites and, based on the relationship between the period of the mode split and the distance to the anomaly (Fig. 12), it is possible to exclude the possibility of the conductor extending undetected between sites on this profile. Examination of a line M pseudosection (Jones and Craven 1990) shows that the easternmost conductor on this profile occurs at 102°W, more than 100 km west of the TOBE conductor. Induction arrow data for line M also provides support for the absence of any conductors east of 102°W (Fig. 13).

Figure 13 shows the relative position of the TOBE anomaly and line M conductors superimposed on a Bouguer gravity map showing features of the SBZ interpreted from potential-field data by White et al. (2005). Although there is some east–west deflection of the interpreted location of the SBZ between 50°N and 51°N (Fig. 13), the TOBE conductor lies on the east side of the interpreted location of the SBZ, and the line M conductor lies on the west side of the interpreted location. This observation has important ramifications for the interpretation of the source of the conductor and of the geometry of the SBZ in this region. It is necessary to examine two alternative hypotheses explaining the observations:

(1) firstly, that the TOBE conductor is associated with the eastern margin of the SBZ but is discontinuous and does not extend north of 50°N in southern Manitoba; and,
(2) alternatively, that the TOBE conductor and line M conductors represent the same feature and are associated with the margin of the Sask craton.

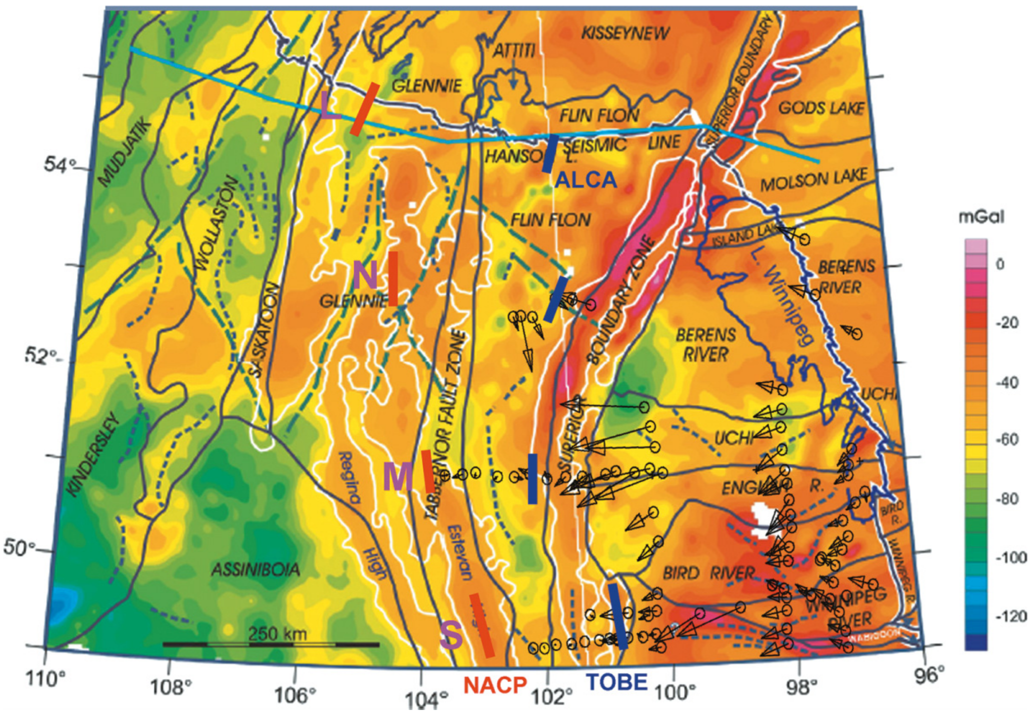
The second hypothesis requires the SBZ to be a very narrow feature (<20 km) with only a weak potential-field signature at latitudes south of 51°N in the study area. Although the two hypotheses require different interpretations of the locations of the SBZ, both require considerable along-strike variability in the SBZ in southern Manitoba. Geophysical and geological evidence supporting each hypothesis will now be examined with the results providing greater support for the second hypothesis.

Hypothesis 1: the Thompson belt conductor is part of the eastern Superior boundary zone

Some of the existing interpretations of the potential-field data in southern Manitoba provide support that the TOBE conductor is associated with the eastern SBZ. The SBZ over much of its length in the area is characterized by paired gravity highs (e.g., White et al. 2005). The western high is relatively continuous and correlates with a positive magnetic anomaly, particularly between 51°N and 53°N. The eastern high is discontinuous and tends to have a neutral to negative magnetic signature. The magnetic lows are interpreted to be caused by removal of magnetite during Proterozoic metamorphic overprinting, and they are accompanied by very narrow highs interpreted to be associated with iron formations and metamorphosed mafic rocks of the Ospwagan group (White et al. 2005) that are Paleoproterozoic rift margin rocks (White et al. 1999).

The TOBE conductor is observed to lie on the flank of a narrow magnetic high and a gravity high (Fig. 12*a*), supporting its interpretation as part of the SBZ. The conductor could plausibly be explained by enhanced conductivity asso-

Fig. 13. Location of significant conductivity anomalies and induction arrow responses at 100 s period superimposed on an interpreted gravity response. The gravity response and its interpretation are modified from White et al. (2005), the white lines delineate features in the response, the solid grey lines delineate interpreted geological boundaries and the broken grey lines indicate lineations. Red bars show the location of the North American Central Plains (NACP) anomaly on NACP lines S, M, and N and Lithoprobe line L (shown in blue). Blue lines show conductors identified to the east of the NACP. ALCA, Athapapuskow Lake conductivity anomaly; TOBE, Thompson belt.



ciated with iron formations. The observation that these characteristic potential-field signatures are truncated at 50°N is consistent with the hypothesis that the TOBE conductor is also truncated at this latitude.

Hypothesis 2: the Thompson belt conductor lies on the eastern flank of the Sask craton

Evidence supporting the hypothesis that the TOBE conductor is associated with Sask craton comes from MT results from the study area, MT results from surveys to the north and south of the study area, and re-examination of the potential-field data.

The results from POLARIS profile 1 in the present study show clearly that the TOBE conductor lies at the transition between southwest–northeast strikes observed in the westernmost Superior Province and north–south strikes observed further to the west. Examination of the geoelectric strike data in Figs. 6 and 11 shows that, on line M at 51°N, the southwest–northeast-trending azimuths extend to the location of the conductor on line M, west of 102°W. In the absence of any MT information between the two profiles, the combined results suggest a continuity of the conductor between the profiles.

Surveys to the north and south of the study area have identified conductors lying on or near the flanks of the Sask craton and the Dakota block. Figure 13 shows the location of the easternmost conductor on line N of Jones and Craven (1990), as defined by induction arrows and pseudosection data. The conductor lies at 102°W, ~50 km west of the interpreted location of the SBZ and closer to some interpreted locations of the eastern margin of the Sask craton (e.g., Jones et al. 2005). On line L, to the north at 55°N (Figs. 1, 13), the ALCA conductor lies adjacent to resistive rocks interpreted to form part of the Sask craton (Ferguson et al. 2005*b*). The NACP conductor has been accurately delineated by MT in a number of studies in the present area, as well as further south in North Dakota and further north on additional Lithoprobe transects (see Jones et al. 2005 for a review). The NACP crosses lines S, M, N, and L (Fig. 13) and lies close to and above the western flank of the Sask craton. Results from North Dakota show the NACP lying on the western flank of the Dakota block, another older continental fragment within the THO (Wu et al. 1993; Wu 1994). The observation of conductors on other profiles crossing the margin of the Archean continental blocks provides support for the hypothesis that the eastern conductor observed on line S, the TOBE conductor, is also associated with the Sask craton.

The absence of a conductor in the SBZ on profiles to the north of the study area calls into question the hypothesis that the TOBE conductor is associated with the SBZ. Data from line L, which crosses the SBZ at the southern margin of the exposed shield at 54.5°N, delineated a very shallow conductor (<3 km depth), but the minimum crustal-scale resistivity deeper in the SBZ is only around 600 Ω·m, which is much less conductive than the TOBE anomaly. Similar values were observed on a profile crossing the SBZ at Thompson at around 56°N (White et al. 1999). There is thus no additional evidence in MT results beyond that observed on line S to suggest the presence of a conductor associated with the SBZ.

Re-examination of the potential-field data also reduces support for the hypothesis that the TOBE anomaly is associated with the SBZ. Examination of Fig. 12 shows that the TOBE anomaly clearly extends to the south of the narrow magnetic anomaly to which it is adjacent, weakening the argument that both the conductive anomaly and magnetic high are associated with iron formations of the Ospwagan group. At a larger scale, the form of the magnetic and gravity anomalies changes significantly south of 52°N, e.g., the gravity highs are considerably smaller (White et al. 2005; Li and Morozov 2007). Although part of this change may be due to the presence of thicker sedimentary basin rocks in the south, the observations reduce the confidence with which the TOBE conductor can be associated with the SBZ on the basis of potential-field correlations.

Tectonic implications

We conclude that there is a greater weight of evidence supporting the hypothesis that the TOBE conductor is associated with the Sask craton than that supporting the hypothesis that it is part of the SBZ. This revised association has significant tectonic implications; for example, the interpretation requires the SBZ at latitudes between 50°N and 51°N to be less than about 30 km wide and to be confined to the zone between the TOBE conductor and the westernmost sites at which the characteristic southwest–northeast geoelectric strike from the westernmost Superior craton is observed. The potential-field anomalies in this zone are much weaker than further north on the SBZ. The revised association of the TOBE conductor would also require the potential-field responses observed west of the TOBE anomaly at these latitudes to be those of the Sask craton. Additional support for the interpretation is based on neodynium model ages for two basement core intersections west of the TOBE conductor at (49°25′N, 101°20′W) and (50°N, 101°20′W), which are 2.87 and 2.96 Ga, respectively (Stevenson et al. 2000; Percival et al. 2006). In contrast, a model age of 2.13 Ga, determined to the south of the mapped position of the TOBE conductor at (49°5′N, 101°W), is more consistent with the age of rifting of the margin.

The geophysical data provide evidence for significant along-strike variations of the SBZ that are independent of the interpretation of the TOBE conductor. The potential-field data show significant changes south of 52° (e.g., White et al. 2005, Li and Morozov 2007); there is strong evidence in the potential-field data for an eastward deflection of the belt between 52° and 50° (Lyatsky and Dietrich 1998; White et al. 2005, Li and Morozov 2007), and the MT results show a change in the position of the conductor relative to potential-field signatures. The observations indicate that it is inappropriate to interpret the SBZ in southern Manitoba as being uniform in the along-strike direction.

The geometry of the SBZ also shows significant variations on seismic reflection profiles further north at 53°N and 55°N. For example, at 53°N, the data suggest preservation of east-verging structures, whereas these structures appear to have been completely reoriented at 55°N by more extensive convergence that is interpreted to be caused by the presence of the Thompson promontory (White et al. 2002).

There are several possible contributions to along-strike variation in the SBZ in southern Manitoba. Firstly, the overall trend of the Superior margin between 49°N and 51°N is roughly north-northwest in present-day coordinates; this is parallel to the interpreted convergence of the Superior craton and Reindeer zone. It is probable that this difference in orientation will have caused significantly different structures to develop during the later stages of formation of the SBZ than those formed further to the north where the collision was oblique. Secondly, in southern Manitoba, it is possible that in the upper crust the Sask craton lies adjacent to the SBZ rather than the juvenile Reindeer zone rocks further to the north (Ansdell 2005). Finally, on a larger scale, the SBZ in southern Manitoba lies in, or close to, a change in the major cratons involved in the formation of the THO. In North Dakota, the orogen formed during the collision of the Wyoming craton and the Superior craton, and it developed after the Hearne–Superior and Medicine Hat Block – Superior collisions to the north (e.g., Nabelek et al. 2001; Hill 2006). Seismic reflection profiles from North Dakota (at 48.5°N) show significant differences from profiles to the north, particularly in terms of the Moho signature. They have been interpreted to indicate that the orogen underwent different late-stage tectonics than areas further to the north, with a crustal root developed during the continental collision being incompletely removed (Baird et al. 1995, 1996).

Discussion

The preceding interpretations have not completely resolved two overarching questions:

(1) whether the geoelectric signatures of the westernmost Superior Province are caused by lithology or deformation, and

(2) whether the TOBE conductor is associated with the SBZ or the Sask craton.

The collection of additional MT data in western Manitoba may constrain the answer to the first question by resolving better the size of the region with the southwest–northeast geoelectric strikes and its spatial relationship to the SBZ and to interpreted subprovince boundaries within the Superior Province. The interpretation of the results will require careful integration of results from MT, potential fields, the available seismic reflection, seismic refraction, and teleseismic and geological models. In contrast, the collection of just a small amount of additional MT data in Manitoba, between 50°N and 51°N, 101°W and 102°W, will provide a definitive answer to the second question. The results of such a study will also provide important constraints on the form of the SBZ south of 52°N and may necessitate renaming of the "TOBE" conductor.

If the TOBE conductor can be reliably associated with the Sask craton, the result will demonstrate the presence of conductors located on the east and west margin of the Sask craton or Dakota block on every transect crossing these Archean continental fragments. There is already sufficient data to raise the question as to why there is such a consistent presence of conductors on the Sask craton – Dakota block margin compared with other margins, such as the SBZ. The presence of large-scale crustal conductors requires appropriate source rocks, such as sedimentary rocks formed from sediments deposited in reducing environments with enhanced carbon and sulphide content (e.g., Boerner et al.

1996). However, the observations of multiple conductors in a very similar setting on the flanks of the Archean blocks suggest that the geometry of the subsequent deformation and (or) the nature of the associated metamorphism also may be a key factor.

Studies of rocks from the extension of the THO in the Black Hills in South Dakota by Nabelek et al. (2001, 2006) suggest that graphitic metapelites were developed during east–west compression at relatively low pressures as a result of the occurrence of low H_2O activity and the presence of CH_4 and CO_2. They interpret the metamorphism to have been driven by strain heating. If the conductors observed on the flanks of the Dakota block – Sask craton to the north are attributed to the presence of graphitic rocks, the results suggest the larger scale occurrence of these metamorphic conditions.

Conclusions

Results from a POLARIS MT survey in Manitoba have been analyzed using both 1-D and 2-D modelling approaches and a “fabric”-based approach in which the geoelectric strike and induction arrow data and the observed continuity of conductors are integrated with additional geophysical and geological models.

The results have successfully imaged the large-scale resistivity structure of the northeastern part of the Williston Basin and extend the resistivity structures determined in earlier MT studies further west in the basin all the way to its eastern margin. The results show that in central and eastern Manitoba, MT data alone provide good resolution of the conductive Winnipeg Formation that is located at the base of the basin. The resistivity models for this area also differ from those further west in the basin because of the absence of moderately resistive Devonian–Mississippian rocks. More detailed information on the resistivity structure becomes available from the MT data when they are combined with resistivity data from well logs.

In terms of Precambrian studies, the POLARIS MT data provide an important spatial connection between earlier MT measurements in the THO to the west and north and measurements in the western Superior Province to the east and north, and they have been analyzed in association with these other data. The results delineate a 200 km $\times$ 400 km region in the westernmost Superior Province with a geoelectric fabric that contrasts with that further east in the Superior Province. These observations may be explained by either deformation during the THO or by the existence of a granite–greenstone terrain with a southwest–northeast fabric in the westernmost Superior. The MT results, in conjunction with potential-field data, show that the SBZ exhibits significant along-strike variability in southern Manitoba. As for along-strike variations that were observed further north in the SBZ in seismic reflection studies, the changes can be explained by the geometry of the continental margins involved in the Proterozoic orogeny. The results of the present study suggest that the TOBE conductor, previously interpreted to be associated with the SBZ, may in fact be a feature resulting from the deformation and metamorphism of sedimentary rocks on the margin of the Sask craton. This latter suggestion has the remarkable corollary that both margins of the THO are characterized by conductivity anomalies along most of their lengths, implying similar processes of continental extent during the orogenesis.

Acknowledgements

The authors thank Ibrahim Gafar, Mulu Serzu, Andrew Frederiksen, Ashley Krakowka, Matt Bodnar, and Nancy Ballantyne for participating in POLARIS MT data collection; Claire Samson, Isa Asudeh, and Gail Atkinson for coordination of MT instruments and POLARIS program; the Manitoba Geological Survey for providing the resistivity well logs; and Manitoba Conservation and farmers who provided access to sites. Comments from Mike Thomas, Phil Wannamaker, Zoli Hajnal, and Fred Cook led to significant improvement of the manuscript. The research was supported by a Natural Science and Engineering Research Councilof Canada Discovery Grant (105748) to IJF, and the manuscript was completed while he was a Senior Visiting Gledden Fellow at the University of Western Australia. Organizations supporting POLARIS include the Canadian Foundation for Innovation, governments of Ontario and British Columbia, and universities, including the University of Manitoba.

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