

North American Central Plains conductivity anomaly within the Trans-Hudson orogen in northern Saskatchewan, Canada

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ABSTRACT

Magnetotelluric data acquired across the Paleoproterozoic Trans-Hudson orogen, northern Saskatchewan, image one of the world's longest crustal features, the North American Central Plains conductivity anomaly. Modeling shows the anomaly at this latitude to comprise two distinct, westward-dipping bodies of high conductivity lying structurally above a late collisional feature, the Guncoat thrust. The shallower of these bodies correlates with the western part of the La Ronge belt; the deeper body at mid-crustal depths underlies the Wathaman batholith, and its western boundary is close to the inferred subsurface extension of the subvertical Needle Falls shear zone. The anomaly is identified with interleaved, biotitic, metasedimentary rocks of the Nemeiben zone and Cree Lake belt and is interpreted to have been thrust beneath the margin during collision of the La Ronge arc with the Rae-Hearne continent via westward-directed subduction.

INTRODUCTION

The Paleoproterozoic Trans-Hudson orogen (Fig. 1) extends from South Dakota through Hudson Bay (Hoffman, 1988) into Greenland (Lewry and Stauffer, 1990), perhaps even Fennoscandia (Jones, 1993), and is a component of a worldwide network of coeval orogens that weld together Archean provinces. Where exposed, the orogen preserves a record of Paleoproterozoic continent-arc-continent collision tectonics, albeit cryptically, better than any other such feature. As part of the Lithoprobe multidisciplinary studies of the orogen, magnetotelluric (MT) measurements were made along an 800 km east-west profile (Fig. 1, profile L), from one bounding Archean craton (Superior) to the other (Rae-Hearne), to complement seismic reflection studies (Lucas et al., 1993).

One major objective of the Lithoprobe investigations is to locate and define the source of the enigmatic North American Central Plains conductivity anomaly discovered in the late-1960s by D. I. Gough and colleagues using magnetometer arrays (Alabi et al., 1975, and references therein). Camfield and Gough (1977) perceptively suggested that the anomaly marks a Proterozoic collision zone from the southern Rockies to northern Canada, which conflicted with a prevailing view that the Wyoming and Superior cratons were originally contiguous (references in Dutch, 1983). Subsequent potential-field data interpretations (e.g., Dutch, 1983; Green et al., 1985) and basement core analyses (Klasner and King,

1986) corroborated Camfield and Gough's (1977) proposal. The trace of the anomaly was thought to mark the eastern boundary of the Wyoming craton (Dutch, 1983; Klasner and King, 1986), but its relocation eastward by Jones and Savage (1986) showed that it lies within the orogen. Recent comparison of COCORP (Consortium for Continental Reflection Profiling) seismic images across the orogen with Jones and Craven's (1990) conductivity model for profile S (Fig. 1) confirmed the close relation of the anomaly with the orogen. Moreover, this comparison suggested that the anomaly is due to a source imbricated along east-vergent thrust faults and draped over the western flank of an Archean microcontinent (Nelson et al., 1993). Despite the evident significance of the anomaly, few tectonic models of the orogen attempted to explain this major geophysical feature.

In this paper, we illustrate and model the MT data acquired across the Central Plains conductivity anomaly and draw conclusions regarding the spatial correlation of the model with the exposed rocks just to the north.

GEOLOGIC SETTING

The Wollaston belt (Fig. 2) is interpreted to be Paleoproterozoic passive-margin metasedimentary rocks underlain by Archean crust. The internides of the orogen, the Reindeer zone, is composed mostly of accreted, subduction-generated, juvenile, arc volcanic and plutonic rocks with coeval and younger sedimentary rocks, formed during closure of the 5000-km-wide Manike-

wan ocean (Stauffer, 1984). The 1.85 Ga synkinematic Wathaman batholith straddles these two zones and is interpreted as a continental-margin magmatic arc (Bickford et al., 1990). The boundary between the hinterland rocks and the Reindeer zone is defined by the Needle Falls shear zone along which tens of kilometres of dominantly dextral-transcurrent displacement occurred. The tonalite-migmatite complex of the Rotenstone domain is a heterogeneous assemblage of plutonic rocks and subordinate injection-migmatized supracrustal rocks; its eastern part is a high-strain zone (the Birch Rapids straight belt). The La Ronge belt is a volcano-plutonic arc terrane that is considered to resemble a modern Andean-type arc (Thom et al., 1990).

Lewry et al.'s (1990) revised subdivision of the Reindeer zone emphasizes the three-dimensional structure of the La Ronge belt and adjoining Glennie domain. The Cree Lake belt, comprising amphibolite-grade metasedimentary rocks, structurally overlies the upper greenschist-facies to lower amphibolite-facies Central Metavolcanic belt. This belt is underlain successively by the huge allochthonous Kyaska, Wapassini, and Cartier sheets postulated to be draped across Archean crust of unknown affinity and extent. The Wapassini nappe sheet is soled by porphyroclastic mylonitic gneiss of the Guncoat thrust.

Tectonic models of this region invoke pre-Wathaman arc-continent collision (ca. 1875–1855 Ma) via eastward(?) directed subduction, then polarity reversal to west-northwestward subduction of oceanic lithosphere between this arc-continent margin and the approaching Superior continental plate (Bickford et al., 1990), with an intervening Archean body of unknown derivation (Lucas et al., 1993).

Subsurface extensions of the significant lithologic boundaries, shear zones, and other tectonic features, beneath the Paleozoic cover (Fig. 2) are based on potential-field data (M. D. Thomas, 1992, pers. commun.) and recent Lithoprobe seismic reflection data interpretations (Lucas et al., 1993).

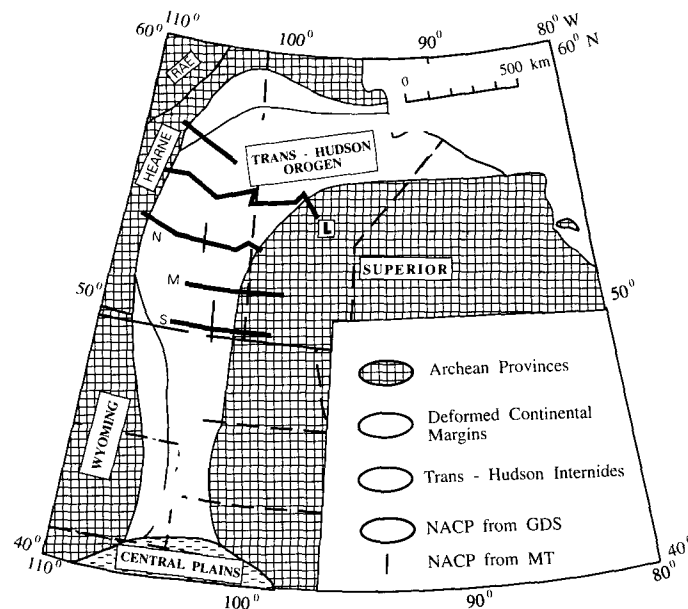


Figure 1. Tectonic framework of north-central North America (taken from Hoffman, 1988) with trace of North American Central Plains (NACP) anomaly deduced from regional geomagnetic deep sounding (GDS) measurements with high-density MT measurements in southern Saskatchewan (along profiles S, M, and N). The MT data discussed were acquired along profile L.

MT DATA ANALYSES AND INVERSION

MT data were acquired at 108 locations along an 800 km east-west profile (L, Fig. 1). At half of the stations, designated AMT-MT (AMT = audio-magnetotelluric) sites, MT fields were recorded in the frequency range 10 000 to 0.000 5 Hz; this range probes the conductivity structure from close to the surface (50 m) to deep within the mantle (100 km). At AMT-only sites, variations from 10 000 to 10 Hz were recorded; this range probes the upper crust. In this paper, modeling and interpretation in the frequency range of 100 to 0.1 Hz of a subset of 30 sites across the conductivity anomaly (Fig. 2) are discussed.

The MT time series were processed by using modern robust methods, and the resulting response functions, expressed as apparent resistivities and phases, were corrected for local distortion effects by using an extended multisite, multifrequency, Groom-Bailey analysis (Groom and Bailey, 1989; G. W. McNeice and A. G. Jones, unpublished). The geoelectric regional strike directions in three frequency decades are illustrated in Figure 3. Most stations show a preferred strike direction east of geographic north, and the strike angle that best fits all the sites over the whole 100–0.1 Hz frequency range is +22°. These results demonstrate that the bulk of the crust has an electrical strike direction consistent with local surface structural trends, in contrast to other regions, such as the Canadian Cordillera, where strike variation with

depth was observed (G. Marquis et al., unpublished).

The MT apparent resistivities and phases in the north-northeast direction, termed “E-polarization” data, detected currents flowing along strike, whereas the responses in the west-northwest direction, “B-polarization” data, sensed currents flowing across strike. The high E-polarization phases (Fig. 4) above 10 Hz for sites on the western La Ronge belt indicate that the upper crust is more conductive there than elsewhere. Strong lateral phase changes are evident at the Guncoat thrust and just to the west of the La Ronge belt–Rottenstone domain boundary. In contrast, B-polarization phases (Fig. 4) at these frequencies are below 45° and are laterally uniform. This apparent dichotomy is evidence that the enhanced conductivity lies in repetitive, subvertical sequences separated by more resistive units.

At 10–1 Hz frequencies, which penetrated to mid-crustal levels, the B-polarization phases indicate lateral conductivity variation on either side of the Needle Falls shear zone; this implies that the anomaly’s western boundary is beneath the shear zone’s surface projection. That both phases sensed the deeper enhanced conductivity suggests that the conductive sequences had become subhorizontal—i.e., the geometry of the anomaly follows the listric nature of the Guncoat thrust imaged by the seismic reflection data (Lucas et al., 1993).

After correction for distortion, the re-

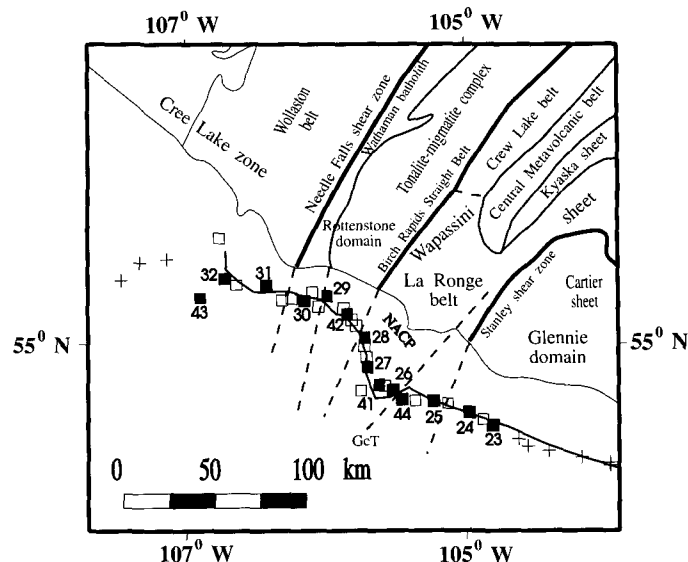


Figure 2. Western boundary of exposed Trans-Hudson orogen with seismic profile (solid line) and MT measurement locations. Solid squares indicate audio-magnetotelluric–magnetotelluric (AMT-MT) sites, with their site number; open squares are AMT-only sites. Crosses indicate locations of sites not used in the interpretation. Major lithotectonic domains are illustrated; La Ronge belt is subdivided into its new structural elements (after Lewry et al., 1990). GcT—Guncoat thrust.

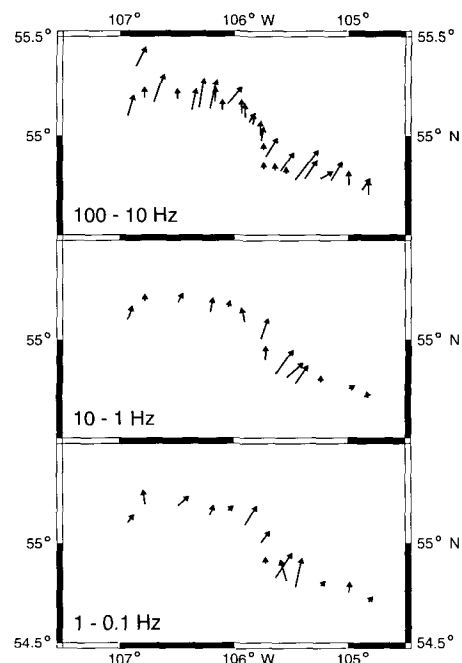


Figure 3. Strike directions obtained for three decades. Length of arrow is measure of how well data fit a Groom-Bailey distortion model; long arrows indicate excellent fits.

remaining unknown is the absolute levels of the apparent resistivity curves at each site, known as “static shifts” (Jones, 1988). The approach used was to fit the phase data well but permit a larger misfit to the apparent resistivity data. A small phase misfit will ensure that the model apparent resistivity

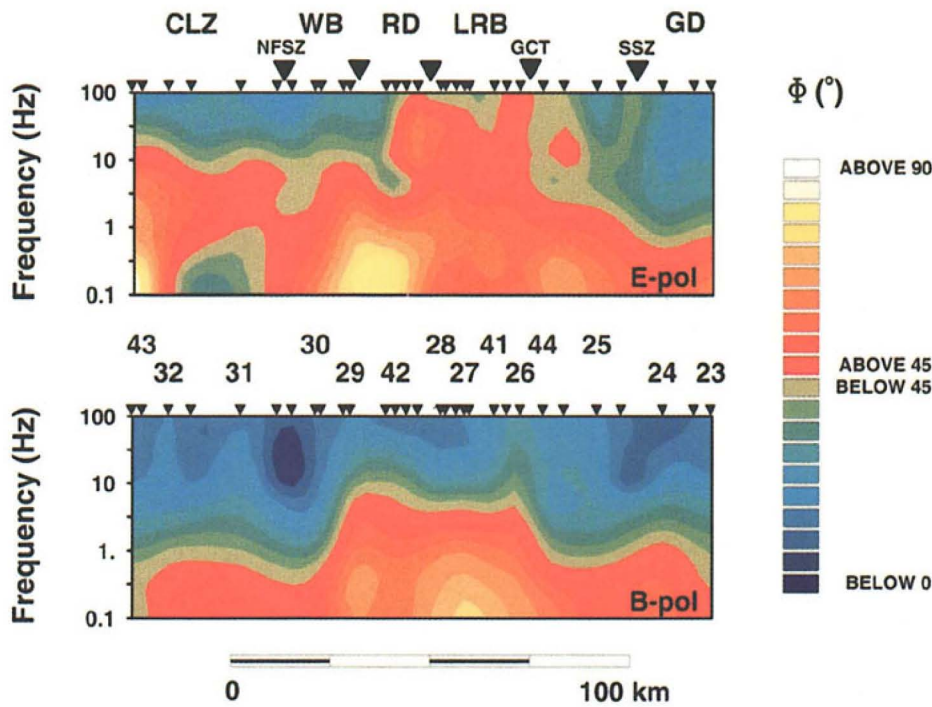


Figure 4. Pseudosections of E-polarization (upper diagram) and B-polarization (lower diagram) phases (Φ) from all sites shown in Figure 2. Phases above 45° indicate zones of increasing conductivity with depth; phases below 45° indicate converse. CLZ—Cree Lake zone, NFSZ—Needle Falls shear zone, WB—Wathaman batholith, RD—Rottenstone domain, LRB—La Ronge belt, GCT—Guncoast thrust, SSZ—Stanley shear zone, GD—Glennie domain.

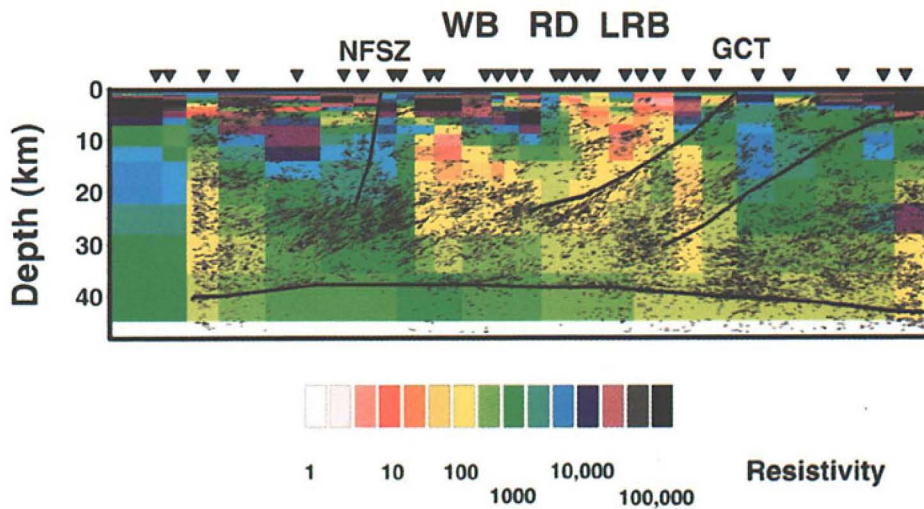


Figure 5. Final model fitting data from sites shown in Figure 2 together with seismic data and major seismic interfaces (Lucas et al., 1993). Note spatial correlation of shallower zone of low resistivity with La Ronge belt (LRB), and second zone lying beneath a resistive zone, concluded to be Wathaman batholith (WB), which is truncated on its western boundary by the Needle Falls shear zone (NFSZ). Both zones lie structurally on top of Guncoast thrust (GCT). RD = Rottenstone domain.

curves have the same *shape* as the observed curves, but allow a frequency-independent shift. Thus, the model must reflect the regional trends in the apparent resistivity data without trying to overfit local irregular features caused by static shifts.

E- and B-polarization data in the range 100–0.1 Hz (ten frequencies) for the AMT-MT sites, and 100–10 Hz (four frequencies) for the AMT-only sites (856 data

in total), were modeled two-dimensionally by using the rapid-relaxation inverse (RRI) algorithm of Smith and Booker (1991). The RRI algorithm seeks the smoothest model that fits the data, and thus the resistivity variation within the Earth must be at least what is depicted in the model. Error tolerances for apparent resistivity were set to 25%; statistical studies of static shifts show that a standard error of 20%–25% is typical.

The model derived is illustrated in Figure 5. This model fits the phase data to better than 1.5° on average, and the misfit residuals (not shown) are reasonably well distributed.

There are clearly two zones of enhanced conductivity (low resistivity) in the model. The upper zone lies close to the surface and extends to ~5–10 km depth with a westerly dip. To its west, the lower zone lies between depths of 10 and 15 km with its western boundary approximately below the Needle Falls shear zone. Above this zone lies a highly resistive body, extending to ~5 km depth and thickening to the east, which we associate with the Wathaman batholith.

Modeling of all the data between frequencies of 1000 and 10 Hz for sites on the western La Ronge belt shows that the enhanced conductivity is in subvertical zones inter-laminated with more resistive ones, as suggested by the phase pseudosections (Fig. 4).

INTERPRETATION

Handa and Camfield (1984) and Gupta et al. (1985) demonstrated that the Central Plains anomaly was associated with either the Rottenstone domain, the La Ronge belt, or both, rather than the Wollaston domain (Alabi et al., 1975). The phase pseudosections (Fig. 4) and the resistivity model (Fig. 5) clearly show that the anomaly's eastern boundary is between sites 26 and 44 and the western boundary of the shallower anomaly is slightly to the west of site 28 (Fig. 2). These findings spatially confine the anomaly to the western segment of the La Ronge belt bounded by two high-strain packages: the Guncoast thrust and the Birch Rapids straight belt. The anomaly is modeled as two distinct bodies, similar to the multibody model of Jones and Craven (1990). The westward dip agrees with the observations along profile S (Jones and Craven, 1990) and with the northward dip at Hudson Bay (Gupta et al., 1985).

The exposed La Ronge belt between the Guncoast thrust and the Birch Rapids straight belt is the Nemeiben zone of the Wapassini sheet. This zone comprises mainly granodioritic-granitic gneisses interleaved with minor, discontinuous pelitic to psammitic sedimentary and plutonic rocks (Lewry and Slimmon, 1985). Within the metasedimentary sequences are economic deposits of gold, nickel, and copper in disjointed vein and disseminated sulfide mineralization. The Crew Lake belt rocks are also predominantly biotitic pelitic to psammitic metasedimentary rocks, with associated mineralization. In contrast, the supracrustal rocks of the tonalite-migmatite complex are less migmatized than those in the La Ronge belt, and there are no significant mineralization occurrences. Conductors mapped by airborne

electromagnetic surveys (Standing, 1973) correlate spatially with surface exposures of the biotitic metasedimentary rocks in both the Nemeiben zone and the Cree Lake belt.

Accordingly, we associate the Central Plains conductivity anomaly with sedimentary sequences deposited between the advancing La Ronge arc and the Hearne-Rae Archean hinterland. This interpretation implies that subduction sense during arc-continent collision was westward-directed. The presumed shelf and slope-rise metasedimentary rocks of the Rottenstone domain are more resistive. Structurally, the conductivity model (Fig. 5) establishes that the La Ronge domain underlies the whole of the Rottenstone domain and Wathaman batholith, and that the La Ronge domain's western boundary is the Needle Falls shear zone. Also, the model implies that the late, compressional Guncoat thrust is a reactivated subduction-related feature. The first-order relative continuity and similarity of the conductivity anomaly along its whole length (Fig. 1) suggest that there was uniform deposition for >2000 km. Along-strike discontinuities have been recognized, however, such as the interpreted 150 km sinistral offset shown between profiles S and N in Figure 1 (Jones and Craven, 1990).

CONCLUSIONS

Analysis and modeling of high-quality MT data from a profile crossing the North American Central Plains conductivity anomaly in northern Saskatchewan demonstrate that the anomaly is associated with biotitic metasedimentary rocks within which is dis-jointed vein and disseminated sulfide mineralization. These sediments were probably deposited between the advancing La Ronge arc and the Archean hinterland and were subsequently thrust beneath the intervening shelf and slope-rise material of the Rottenstone domain to the present location of the Needle Falls shear zone. This interpretation suggests that subduction sense during initial arc-continent collision was directed westward, rather than eastward. The enhanced conductivity appears to be associated with sulfide mineralization, not graphite (Camfield and Gough, 1977); the only occurrences of graphite in the region are in the high-strain zones, the Birch Rapids straight belt and the Guncoat thrust (J. F. Lewry, 1993, personal commun.), which do not appear to display enhanced conductivity. We also note that graphitic pelites from the Wopmay orogen were highly resistive (Camfield et al., 1989).

MT studies of ancient subduction-collision zones (Jones, 1993) show that some of these have associated conductivity anomalies (Trans-Hudson, Fennoscandian, Southern Cape, Iapetus), whereas others do not

(Penokean, Wopmay). The lack of a conductivity anomaly implies that (1) there was insufficient material in the accretionary prism, (2) the wedge was not thrust beneath the continental masses during collision, or (3) the sedimentary rocks underwent a different metamorphic history, so that no conducting material was formed from migmatizing fluids.

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