Paleoproterozoic tectonic processes revealed through electromagnetic studies of the North American Central Plains (NACP) conductivity anomaly: from continental to hand sample scale

Alan G Jones, Jon Katsube, Geological Survey of Canada; Ian Ferguson, University of Manitoba*

Summary

Two and a half decades of study of the North American Central Plains (NACP) conductivity anomaly, fmm its initial discovery in the late 1960s to rock property measurements this year. reveal tectonic processes operating during the closure of the Manikewan ocean as part of the Paleoproterozoic Trans.Hudson orogeny. These processes include subduction and compression of sediments deposited during a hiatus in volcanism as the first of the advancing arcs approached the Archean continental margin. Mapping of the anomaly. for over 1500 km from the southern Dakotas to northern Manitoba, illustrates that these processes were active along the whole margin.

Introduction

An anomalous observation on one station of a magnetometer may study in 1967 led to the discovery of what is possibly the longest zone of enhanced electrical conductivity in the world. namely the North American Central Plains (NACP) anomaly (Fig. 1). This anomaly has since been tracked from southern South Dakota through North Dakota and Saskatchewan over to northern Manitoba (Alabi et al., 1975; Handa and Camfield, 1984; Gupta et al., 1985; Jones and Craven. 1990; Jones et al., 1993). and possibly has a counterpart in Scandinavia (Jones, 1993a). Camfield and Cough (1977). in an insightful paper, suggested that the NACP is the geophysical marker for a Proterozoic collision zone from the southern Rockies to northern Canada a proposal that conflicted with then prevailing thought that the Wyoming and Superior cratons were contiguous. Their idea was proven to be correct, and the NACP lies wholly within what is now termed the Trans-Hudson orogen (THO), extending from South Dakota through Hudson Bay (Hoffman, 1988) into Greenland (Lewry and Staffer, 1990). and is a component of a global network of coeval Paleoproterozoic orogens that welded together Archean provinces.

Tbe early studies used only natural time variations of the magnetic field, and had widely spaced observation sites. The nature of the anomaly sparked curiosity in PanCanadian Oil Company, who were interested in the control of sedimentary structures within the Williston Basin by basement structures. Accordingly. PanCanadian contracted magnetotelluric surveys over the NACP anomaly in 1984 and 1985 just north of the U.S./Canadian border in southern Saskatchewan (line S in Fig. 1). Initial modelling of these data illustrated that the anomaly indeed lay within the crust. and its top was at around 10 km (Jones and Savage, 1986). More complete modelling of the MT data with static shifts removed (Jones, 1988) confirmed this, and illustrated that the anomaly was arcuate in form, with a wavelength of approx. 80 km (Jones and Craven, 1990). One enigmatic aspect about the behaviour of the NACP anomaly in these data is that *it* has virtually no effect on the TM mode response, only on the TE mode. This was explained as being due to lack of connection between multiple conducting bodies (Jones, 1993b). Two other profiles in the middle of Saskatchewan illustrated that the NACP anomaly is not a continuous linear feature, as suggested by the early magnetometer array studies, but is, in fact, a series of en echelon linear bodies with a major break in south-central Saskatchewan (Jones and Craven, 1990).

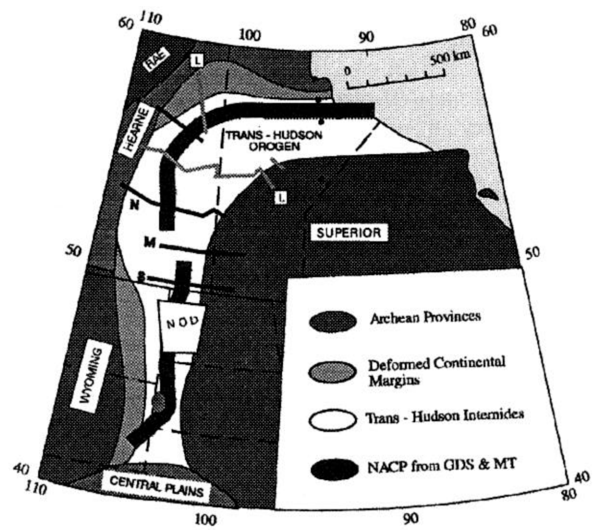

Figure 1: Trace of the NACP anomaly from GDS and MT studies. L: LITHOPROBE lines; NOD: North Dakota MT survey; S, M. N: South, Mid- and North MT lines of Jones and Craven (1990).

An intimate geometrical relationship was demonstrated between this arcurate anomaly and tectonic units lying within the Trans.Hudson orogen by COCORP seismic reflection studies in the Williston Basin just south of the U.S./Canadian border (Nelson et al.. 1993). Tbe conductive bodies were shown to be reflective, and overlying a non-reflective region interpreted as representing an Archean body of unknown affinity.

As part of LITHOPROBE's Trans.Hudson orogen transect investigations. magnetotelluric (MT) data were acquired along two profiles in 1992 and 1994 (Fig. 2). The 1992 EW pmfile extended over 700 km, from the Superior Province on the East to the Hearne Province on the west, just on the Paleozoic cover sequences (Jones et al., 1993). The 1994 NS profile was directly on basement, and extended from the first are domain in the internides of the THO to the Rae bounding craton. Additionally, in 1994 samples were acquired of rocks believed to be the host of the enhanced conductivity.

This paper will present the available data over the NACP struture, concentrating on the recent LITHOPROBE datasets, and corresponding models derived from them. Also. the results of the laboratory analyses on the rock samples will be shown.

LITHOPROBE MT Data and Tectonic Setting

The MT data along the two profiles crossing the NACP (Fig. 2) were acquired on contract by Phoenix Geophysics Ltd. Five components of the time-varying electromagnetic fields were recorded in the frequency bandwidth of 0.0005-10,000 Hz. On the 1992 survey, two additional measurements were made of the horizontal magnetic field components at a site some l-2 km distant by using a cable to permit remote-reference processing. In contrast, cm the ,994 survey all 5 components were recorded at two sites simultaneously some 5-10 km apart with accurate clock-syncing of the data. In-field processing indicated whether the responses were of sufficient quality to permit the site to be moved. On both surveys there was a minimum of 40 hours (over 2 nights) observation time at each site, with the 1994 survey operating in “leap-frog” mode.

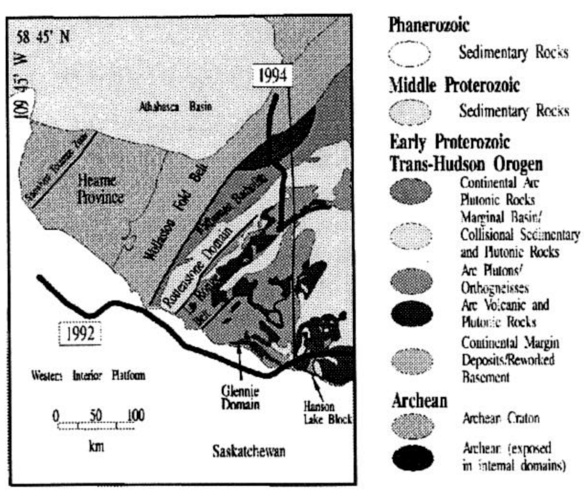

Figure 2: Locations of the 1992 and 1994 MT profiles and the lithotectonic elements of the Trans-Hudson orogen within northern Saskatchewan. Canada

There were a total of 80 MT sites in Saskatchewan along the 1992 profile, and 23 sites along the 1994 profile. Time series at each site were recorded onto optical disk, and were subsequently m-processed using the robust scheme method 6 in Jones et al. (1990). Data errors are typically less than 1%. especially in the frequency range of 0.01 - 100 Hz.

The tectonic elements of the western boundary of the Trans-Hudson orogen are illustrated in Fig. 2. The Heame province is the Archean hinterland, against which Wollaston Fold belt comprises deformed continental margin assemblages. The La Range belt comprises oceanic volcano-sedimentary sequences associated with the La Range arc, which was the first arc to collide with the Heame craton. The Rottenstone domain rocks are likely shelf and sloper-rise sequences. The Wathaman batholith is thought to be a stitching batholith emplaced subsequent to La Range-Heame terminal collision. Within the Glennie Domain and Hanson Lake Blocks are Archean windows, which led to the interpretation of an Archean microcontinent of unknown affinity, termed the *Sask craton,* underlying much of the internides (Reindeer zone) of the THO (Lucas et al., 1993). The Needle Falls Shear Zone is interpreted as a very late strike-slip fault.

MT Tensor Decomposition and Regional Responses

The data from each location were analyzed for distortion effects using a decomposition of the MT impedances tensor following the McNeice and Jones (1996) extended version of Groom and Bailey (1989) for simultaneous solutions at multiple sites and multiple frequencies.

The data from the 1992 profile (Fig. 2) showed that the regional strike angle for the sites sensitive to the anomaly is virtually frequency-independent, and at a direction of N22E, which is the surface strike direction of the geological structures. Electrically, the entire crust, from the surface to the Moho, displays this strike direction. The regional responses in this co-ordinate system display the same phenomenon as on the S line of a very strong TE anomaly but no TM anomaly.

In contrast, the data from the 1994 survey display frequency dependent strike directions (Fig. 3). with frequencies that sample the uppermost and lower crust giving essentially a direction of around N50E - N60E. which is the surficial structural strike. Frequencies sampling the middle of the crust, around 5-20 km, display a strike direction of around N35E - N40E. This suggests that the tectonic elements vary their strike with depth, and indicates that dips on the co-located seismic data must he interpreted with care.

For the purposes of determining a preliminary model that fits the 1994 data, a frequency-independent strike angle of N50E was assumed.

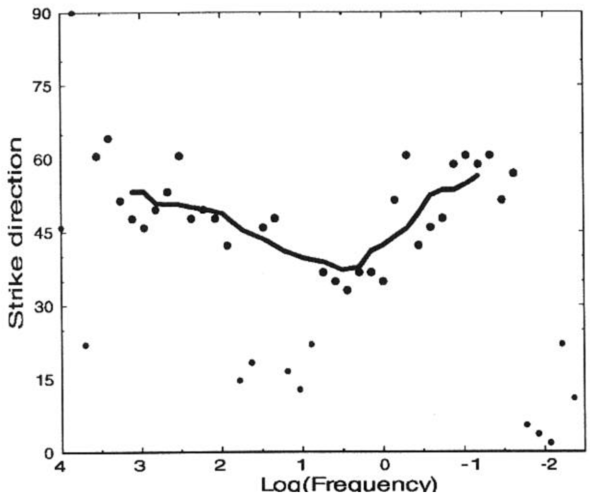

Figure 3: Regional strike direction versus frequency for all sites along the 1994 profile

Inversion

The MT data from the two profiles have been inverted using the RRI least-structure code of Smith and Booker (1991).

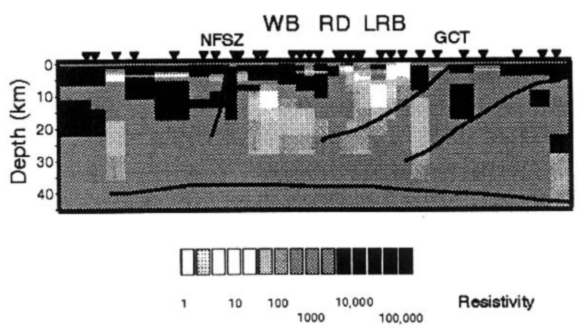

Figure 4: Resistivity model for the data along the portion of the 1992 profile crossing the NACP. The inverted triangles show the locations of the MT sites. White represents resistivity <30 Ω.m, whereas black represents resistivity >1,000 Ω.m. NFSZ: Needle Falls Shear Zone; WB: Wathaman batholith; RD: Rottenstone domain; LRB: La Range Belt; GCT: Guncoat thrust

The model fitting the 1992 data over the NACP is illustrated in Fig. 4. This model tits the data in the frequency range 0.1 100 Hz with an average misfit of 1.5” in phase, and an equivalent level in apparent resistivity. The zone of high conductivity (low resistivity) can be associated with the western part of the La Range Belt. The conductive bodies lie structurally above the Guncoat thrust, which is interpreted as a late compressional feature, and extend beneath the Rottenstone Domain and Wathaman batholith to be truncated almost directly below the surface trace of the Needle Falls Shear Zone.

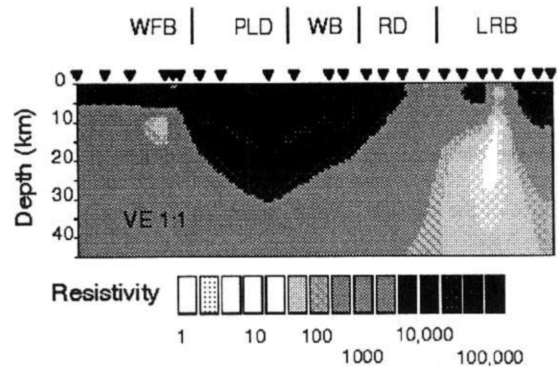

Figure 5: Preliminary resistivity model for the MT data along the 1994 profile. The inverted triangles show the locations of the sites. Grey scale as Fig. 4.

The preliminary model for the 1994 data is illustrated in Fig. 5. This model does not fit as well as the 1992 model, with misfits averaging around 10° in phase. Static shifts have not been accounted for, and also the regional strike varies with depth, whereas this model assumes a constant strike. This misfit level is sufficient for the gross features portrayed. but more subtle features require further analyses This model demonstrates that there is a significant conductive anomaly in the mid-crust beneath the La Range belt, but, in contrast to the model of Fig. 4 for the line further to the south, this anomaly does not penetrate beneath the Rottenstone domain and Wathaman batholith. The Peter Lake domain, an Archean inlier, is highly resistive (>100,000 Ω.m) within the resistive Wathaman batholith (10,000 - 100,000 Ω.m, which is suggested to be of far greater thickness (up to 20 km) compared to further south. There does not appear to be a strong contrast in resistivity between the deep crustal units beneath the Wollaston Fold belt and those of the adjacent THO intemides.

Rock Property Studies

Spatial correlation of airborne EM anomalies with bedrock geology (Lewry and Slimmon, 1985) shows that rocks within the western La Range metasedimentary unit “Lsn” are highly conducting. The EM anomalies are curvi-linear features that follow the structural trend of the orogen.

Samples were collected of this unit from seven localities. Laboratory analyses of these samples for electrical conductivity included measurements along three axis to determine anisotropy. Most of the samples were biotitic gneiss, and yielded resistivities well in excess of 1,000 Ω.m up to 20,000 Ω.m. One sample however. of a carbonaceous sulpbidic argillite, displayed zones of concentrated sulpbides along the fold axes. Sub-samples of this specimen showed highly anisotropic behaviour with values of 0.3-10 Ω.m for sub-samples from within the concentrated sulphides, and 100s- 1,000s of Ω.m for those from outside the zone. Individual sub-samples could be cut from the specimen that displayed over two orders of magnitude anisotropy in electrical conductivity.

Conclusions

Studies of the world's longest and most enigmatic anomaly in electrical conductivity, from the continental to the hand sample scale, illustrate that the North American Central Plains (NACP) anomaly is caused by sulphides concentrated along the limbs of folds. This causes a high anisotropy to be observed, with resistivities along the structural strike direction two to three orders of magnitude lower than perpendicular to it.

The sulphides are syngenetic, and were deposited between the advancing La Ronge arc and the Hearne craton with a low rate of sedimentation during a hiatus in volcanism. Their current position on the 1992 line, lying structurally above the Guncoat thrust, implies that subduction during arc-craton collision must have been directed towards the craton, and that the Guncoat thrust is a re-activated subduction-related feature. The metasedimentary sequences stop beneath the surface trace of the Needle Falls Shear Zone, which suggests that the Heame cratonic edge lies at this position.

Further north, the metasediments do not penetrate beneath the Rottenstone domain and Wathaman batholith, attesting to the along-strike variability of the NACP anomaly and subduction processes.

References

Alabi, A.O., Camfield, P.A., and Gough, D.I., 1975, The North American Central Plains anomaly: Royal Astronomical Society Geophysical Journal, v. 43, p. 815-834.

Camfield, P.A., and Gough, D.I., 1977, A possible Proterozoic plate boundary in North America: Canadian Journal of Earth Sciences, v. 14, p. 1229-1238.

Groom, R.W., and Bailey, R.C., 1989, Decomposition of magnetotelluric impedance tensor in the presence of local three-dimensional galvanic distortion; Journal of Geophysical Research, v. 94, p. 1913-1925.

Gupta, J.C., Kurtz, R.D., Camfield, P.A., and Niblett, E.R., 1985, A geomagnetic induction anomaly from IMS data near Hudson Bay, and its relation to crustal electrical conductivity in central North America: Royal Astronomical Society Geophysical Journal, v. 81, p. 33-46.

Handa, S., and Camfield, P.A., 1984, Crustal electrical conductivity in north-central Saskatchewan: The North American Central Plains anomaly and its relation to a Proterozoic plate margin: Canadian Journal of Earth Sciences, v. 21, 533-543.

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

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

Jones, A.G., 1993a, Electromagnetic images of modem and ancient subduction zones: Tectonophysics, v. 219, p. 29-45.

Jones, A.G., 1993b, The COPROD dataset: tectonic setting, recorded MT data, and comparison of models: Journal of Geomagnetism and Geoelectricity, v. 45, p. 933-955.

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

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

Jones, A.G., Chave, A.D., Egbert, G., Auld, D. and Bahr, K., 1989, A comparison of techniques for magnetotelluric response function estimation: Journal of Geophysical Research, v. 94, p. 14, 201-14, 213.

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

Lewry, J.F., and Slimmon, W.L., 1985, Compilation bedrock geology, Lac La Ronge NTS area 73P/73I: Saskatchewan Energy and Mines, Report 225 (1:250 000 scale map with marginal notes).

Lewry , J.F., and Stauffer, M.R., editors, 1990, The Early Proterozoic Trans-Hudson Orogen of North America: Geological Association of Canada Special Paper 37, pp. 505.

Lucas, S.B., Green, A.G., Hajnal, Z., White, D., Lewry, J., Ashton, IS., Weber, W., and Clowes, R., 1993. Crustal architecture of a paleoproterozoic orogen: Implications for continental growth: Nature, v. 363, p. 339-342.

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

McNeice, G., and Jones, A.G., 1996, Multi-site, multi-frequency MT tensor decomposition. In poreparation.

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