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# Central Baffin electromagnetic experiment (CBEX): Mapping the North American Central Plains (NACP) conductivity anomaly in the Canadian arctic

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## Abstract

Over the summers of 2001 and 2002, a 45 station, 500-km-long regional magnetotelluric (MT) profile was acquired on central Baffin Island in the eastern Canadian arctic. This Central Baffin electromagnetic experiment (CBEX) profile traverses the northern margin of the Paleoproterozoic Trans-Hudson Orogen (THO). In its southern segment, within the juvenile rocks of the orogen, the profile lies on Paleoproterozoic meta-sedimentary strata known as the Piling Group, and the profile extends northwards onto the Archean Rae craton. The primary goal of the experiment was to determine the subsurface geometry of major geological boundaries and to define regional electrical structures. Field observations and laboratory analyses show that one particular horizon within the Piling Group, the sulphidic–graphitic Astarte River formation, is highly conductive and can be mapped and used as structural proxy for the base of the Piling Group. The laboratory results imply that the source of the enhanced conductivity in the Astarte River formation is the high content of interconnected graphite, and that the host rocks are highly anisotropic due to bedding. Mapping this formation in depth images the base of the Piling Group basin well. There is high contrast in electrical conductivity between the Piling Group meta-sedimentary rocks and the Archean granites and gneissic complexes of the Rae craton to the north. The lower crust of the Rae craton in this area is moderately conductive (some 100 s Ω m), in contrast to Rae lower crust observed elsewhere in Canada, and this observation is not readily explained. The lithospheric mantle beneath

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the profile exhibits a strong north-to-south gradient in decreasing resistivity, suggesting resistive Archean mantle (>3000 Ω m) subducted beneath moderately resistive Proterozoic mantle (300 Ω m).

*Keywords:* Trans-Hudson orogen; Paleoproterozoic orogeny; North American Central Plains conductivity anomaly (NACP); Electromagnetic induction; Magnetotelluric technique; Petrophysical conductivity measurements

## 1. Introduction

During the summers of 2001 and 2002, magnetotelluric (MT) measurements were made on Baffin Island in northern Canada as part of the Geological Survey of Canada's multi-disciplinary Central Baffin project to study the northern margin of the north-eastern segment of the Trans-Hudson Orogen (THO, Corrigan et al., 2001; Scott et al., 2002, 2003). The primary goal of this Central Baffin electromagnetic experiment (CBEX) was to determine the subsurface geometry of major crustal and mantle boundaries, particularly between rocks of the Archean Rae Craton to the north and Paleoproterozoic continental margin units, the Piling Group, to the south (Jones et al., 2002b; Evans, 2003; Evans et al., 2003). Within the Piling Group lies a black shale and sulphide-facies iron-formation unit—the Astarte River formation—and, given its likely high electrical conductivity, this formation was a particular target for electromagnetic imaging of crustal-scale structural geometries.

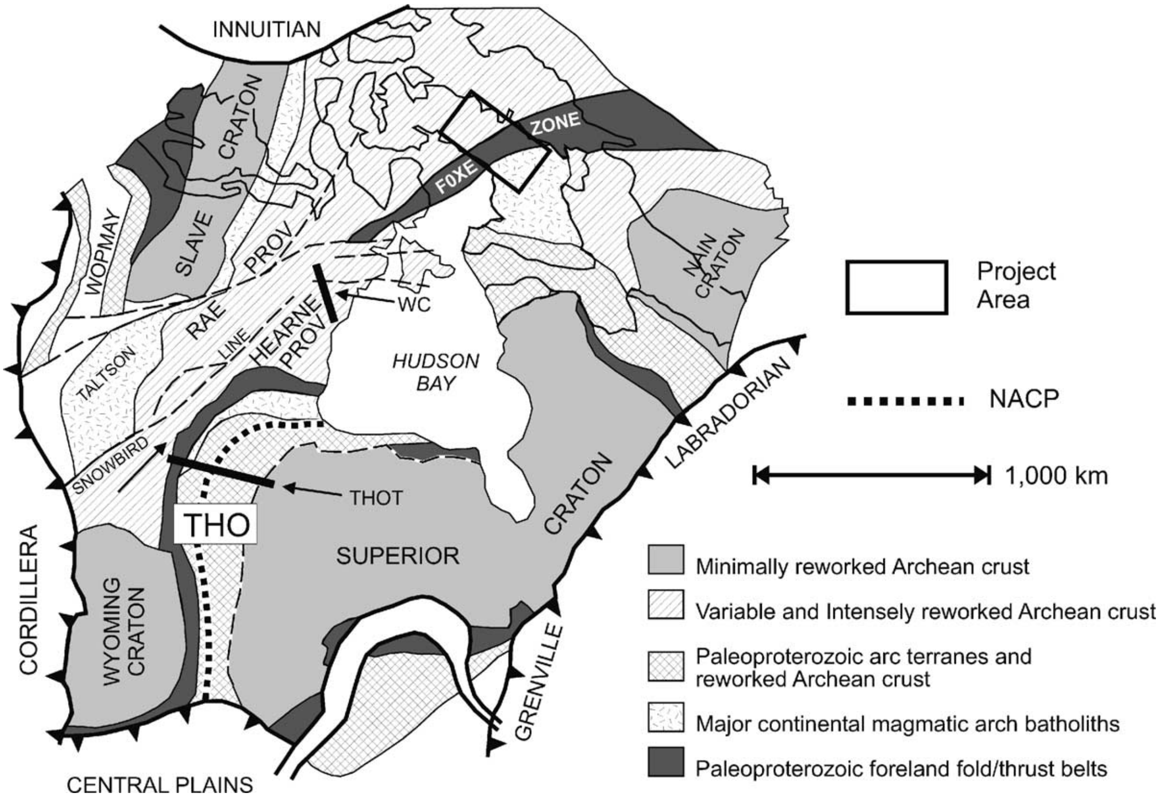

Fig. 1. Tectonic cartoon of Eastern Canada based on Hoffman (1988) and modified by Evans (2003). NACP: North American Central Plains conductivity anomaly. Also shown are the locations of the Lithoprobe Trans-Hudson Orogen Transect MT profile (THOT), the Western Churchill MT profile (WC), and the location of the CBEX project area.

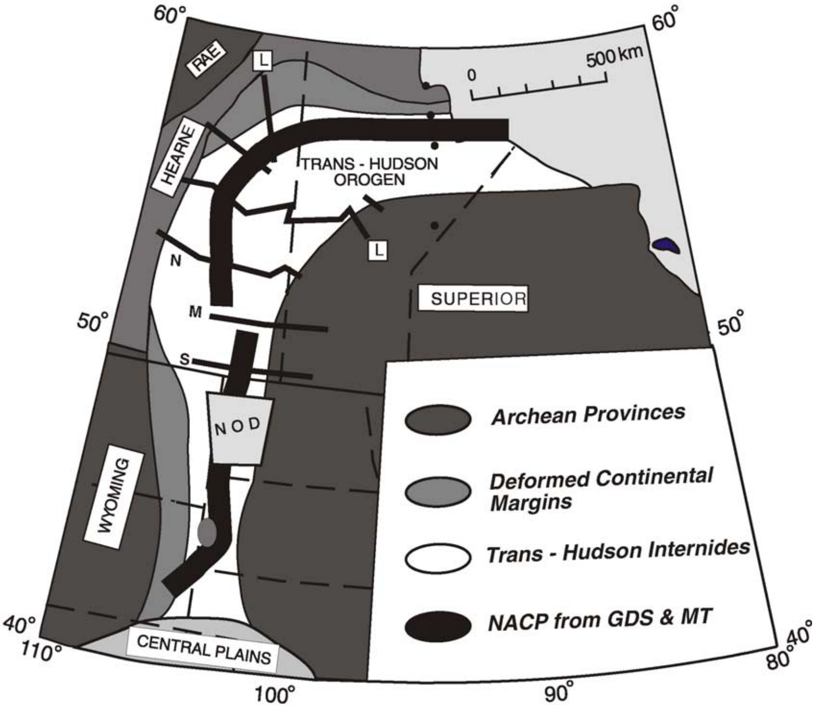

Fig. 2. The previously mapped extent of the NACP within the southern segment of the Trans-Hudson Orogen and the locations of previous MT studies. The profiles and projects are: NOD, North Dakota project; S, south profile; M, middle profile; N, north profile; L, Lithoprobe profiles.

The northeastern segment of the THO is flanked to the north by the reworked Rae Craton, and to the south and southeast by the Superior and Nain Cratons, respectively (Figs. 1 and 2). The southern segment of the THO is host to one of the world longest conductors, known as the North American Central Plains (NACP) conductor (Figs. 1 and 2), which extends from South Dakota in the United States, north through central Saskatchewan and then east through northern Manitoba where it disappears beneath Hudson Bay (see Jones, 1993, for a historical review). Given the mapped northeastern segment of the THO onto Baffin Island (Fig. 1), another objective of this project was to investigate whether the NACP anomaly also extends into the Baffin segment.

## 2. Regional geology and tectonic setting

The Central Baffin project area (Fig. 3) straddles the northern margin of the northeastern segment of the ca. 1.8 Ga Trans-Hudson Orogen (Lewry and Collerson, 1990), a Himalayan-scale collisional mountain belt that is exposed from Greenland in the east, across Baffin Island and beneath Hudson Bay, to Manitoba and Saskatchewan in the west. The southern segment of the THO is well understood, especially where exposed in northern Saskatchewan and northern Manitoba. Its internides are commonly referred to as the Reindeer Zone, with the Hearne craton to the west and the Superior craton to the east. In contrast, the northeastern segment is far less understood, and the geometrical and tectonic relationships between these two segments is contentious (e.g., Hoffman, 1990; Lewry and Collerson, 1990), given the existence of the Paleozoic Hudson Bay. Zhao et al. (2002), in their recent review, follow Hoffman (1990) and refer to this orogen as the Foxe Orogen, after Henderson and Parrish (1992) who themselves took the nomenclature from Jackson and Taylor's (1972) mapping of what they termed the Foxe Fold Belt. However, there are multiple problems with Hoffman's (1990) interpretation of a limited, southern extension of the THO. Principally, it was based on interpreting the Archean Rae craton extending from Melville peninsula southeastward towards northeastern

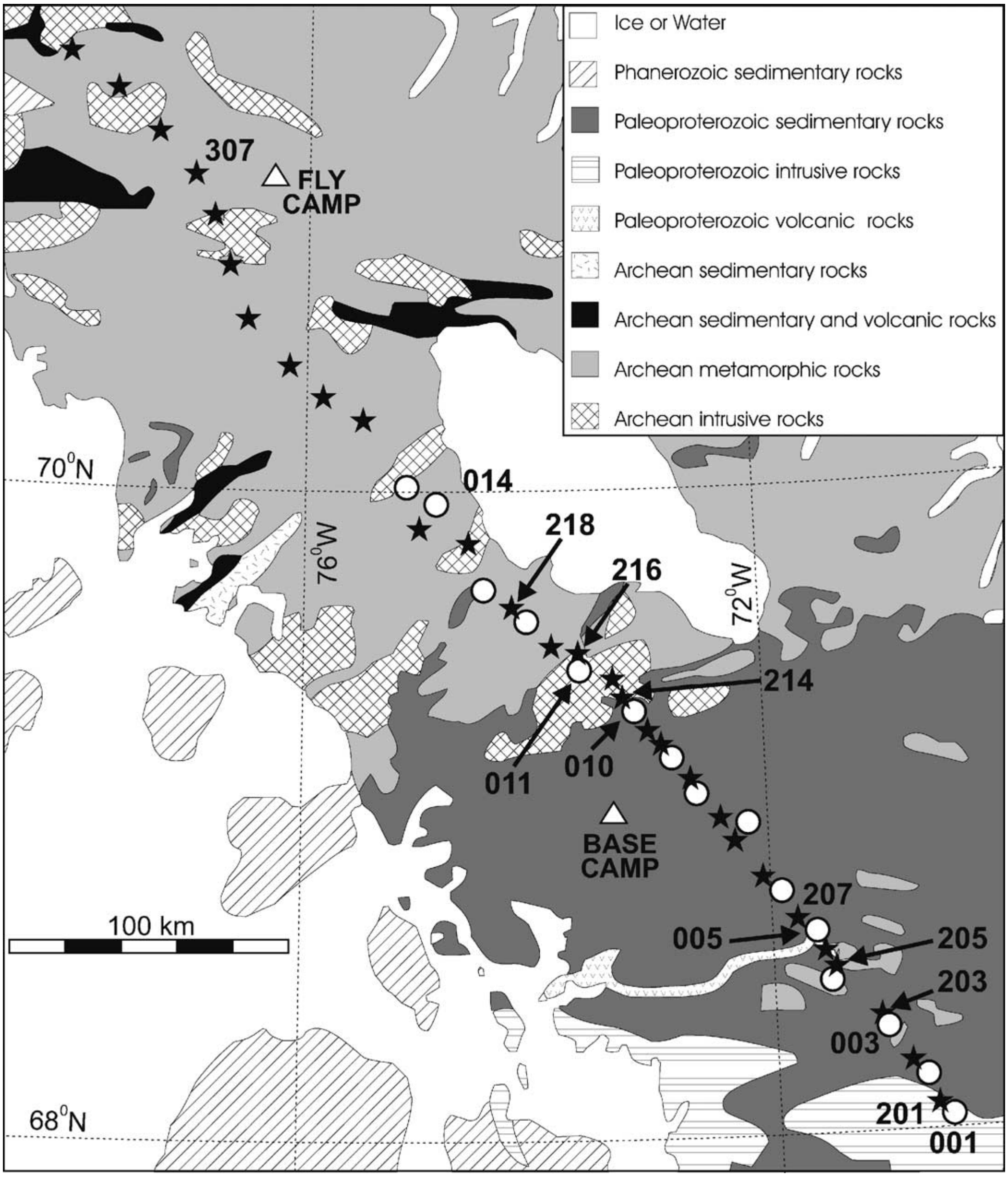

Fig. 3. Geological map of the Central Baffin project area with MT station locations marked. White circles denote BBMT+LMT sites recorded in 2001, and black stars denote BBMT sites recorded in 2002. Base and fly camps also shown.

Quebec and western Labrador (i.e., the hinterland of the New Quebec and Torngat Orogens), an extension which isolated the THO in the west from the Paleoproterozoic belts of Baffin Island in the east. This purported extension was demonstrated not to exist by St-Onge et al. (2002a,b) in their mapping of the Ungava Peninsula and southern Baffin Island.

Herein, we follow the interpretation of this orogen of Lewry and Collerson (1990), and ascribe it to the Trans-Hudson Orogen. This interpretation is more consistent with the thermo-metamorphic data that have been acquired, principally since 1990, on Baffin Island (D. Corrigan, pers. comm., 2003; M. St-Onge, pers. comm., 2003).

The northern part of the project area is underlain by various orthogneisses, metamorphosed sedimentary and volcanic rocks of the Mary River Group, and younger felsic plutonic rocks, all of Archean age and ascribed to the Rae craton (Jackson, 1969; Bethune and Scammell, 1997; Corrigan et al., 2001; Scott et al., 2002, 2003). The central part of the area, known as the Foxe Fold Belt (marked as Foxe Zone in Fig. 1), includes highly remobilized Archean basement and inboard miogeoclinal foredeep Paleoproterozoic supracrustal rocks incorporating siliciclastic, carbonaceous, and mafic volcanic rocks of the Piling Group (Morgan et al., 1975, 1976; Morgan, 1983; Henderson et al., 1988, 1989; Henderson and Henderson, 1994; St-Onge et al., 2001, 2002a,b). The southern segment of the project area is dominated by a suite of felsic plutonic rocks that ranges from rare tonalite, to granodiorite, monzogranite, and monzogranite grading into syenogranite and has been interpreted as the northern margin of the Cumberland batholith (Jackson and Taylor, 1972; Corrigan et al., 2001).

The Cumberland batholith, first mapped by Jackson and Taylor (1972), is a ca. 1.86–1.85 Ga (Scott, 1997) plutonic intrusion that covers much of south-central Baffin Island. The batholith is interpreted to have been intruded during the 1.86–1.82 Ga interval when there existed at least two distinct north-dipping subduction zones at the southern end of the orogen (Thériault et al., 2001).

From the centre of the Piling Group belt, mineral assemblages in pelitic rocks progress southward toward the plutonic rocks from biotite–muscovite, to biotite–muscovite–cordierite ± andalusite, sillimanite–K-feldspar ± melt, and ultimately garnet–cordierite–K-feldspar ± melt. The volume of melt present in individual outcrops increases toward the plutonic rocks, from increasingly large pods through to dykes and sills. In proximity to the batholith, accumulations of locally generated melt material can be mapped as plutons of distinctive white, garnetiferous monzogranite. This regional thermal metamorphic zonation is interpreted as the result of tectonic thickening loading to relaxation of crustal isotherms during Trans-Hudson orogeny, in addition to heat advection through the emplacement of the plutonic rocks (St-Onge et al., 2003).

## 3. The North American Central Plains (NACP) conductivity anomaly

The North American Central Plains (NACP) conductivity anomaly was first discovered, completely serendipitously, by Ian Gough and colleagues in the mid-1960s from the anomalous response at one site in western Nebraska in the corner of a magnetometer array across the western United States (Reitzel et al., 1970). The anomaly was further mapped in the mid-West of the U.S. and into Canada in the late-1960s and early 1970s by Camfield et al. (1970) and Alabi et al. (1975). Camfield et al. (1970) initially suggested that the high conductivity, and the linear form, could be due to a graphitic schist body in the basement, noting that high conductivities had been observed in graphite bodies in western South Dakota (Mathisrud and Sumner, 1967). In a later highly perceptive but sadly little appreciated paper, Camfield and Gough (1977) proposed that the NACP anomaly was a marker that traced a Proterozoic plate boundary, of 1800 km length extent, lying beneath the thick sedimentary strata of the Williston Basin and which separated the Superior from the Wyoming cratons. Their suggestion ran counter to prevailing opinion at that time (Peterman, 1979; and references in Dutch, 1983), but has been since proven correct primarily from basement samples in drill core (Peterman, 1981; Van Schmus and Bickford, 1981; Klasner and King, 1986; Sims and Peterman, 1986). They reiterated their earlier interpretation that the NACP structure was likely due to graphitic sheets in highly metamorphosed and folded basement rocks.

The northern extension and continuity of the NACP within the southern segment of the THO was confirmed through the 1980s using Geomagnetic Deep Sounding profiles by Handa and Camfield (1984) and Gupta et al. (1985), and using MT by Pan Canadian (Jones and Savage, 1986), Maidens and Paulson (1988), Jones and Craven (1990), Rankin and Pascal (1990) and Jones et al. (1993). The NACP is hosted by meta-sedimentary rocks, and it has been suggested by Jones et al. (1993) that the supracrustal rocks were deposited between the Hearne Archean hinterland and the first, in a geographic sense, of a series of Paleoproterozoic island arc terranes. Laboratory rock property studies by Jones et al. (1997) demonstrated that, where exposed in northern Saskatchewan, the mechanism for enhanced conductivity of the NACP is interconnected sulphides (pyrite) not graphite.

## 4. MT data acquisition and quality

In 2001, broadband (BBMT) and long period (LMT) magnetotelluric data were recorded at 15 locations, sites 001–015, approximately equi-spaced along a 300-km-long northwest–southeast profile (Fig. 3, locations marked by white circles). In 2002, BBMT measurements at a further 30 locations, sites 201–220 and 301–310, were made, both infilling the 2001 stations and also extending the profile 200 km northwards onto the Archean Rae craton and outside of the Central Baffin bedrock project area (Fig. 3, locations marked by black stars). The survey line thus comprises 15 LMT stations and 45 BBMT stations with a total profile length of approximately 500 km. Fieldwork was accomplished in this isolated area using helicopters based out of the main base camp and, in 2002, also out of a fly camp (for the northern extension).

Fifteen GSC-designed LiMS systems acquired the LMT data simultaneously with a digitizing interval of 5 s, giving responses at periods of 20–10,000 s probing the mid-crust to upper mantle. The systems remained at each site for 4–5 weeks from July to mid-August, 2001. At each site, the five components of the time varying electromagnetic field, the two horizontal components of the electric field ($E_x$, $E_y$) and all three components of the magnetic field ($H_x$, $H_y$ and $H_z$), were recorded. The sites were visited whenever helicopters were available, to minimize data loss due to local wildlife. Data loss was an issue at sites 003 and 013 (Fig. 3), where wolves repeatedly chewed through electrode lines.

Broadband (BBMT) measurements, in the period band of 0.001–1000 s, were made using Phoenix MTU V5-2000 systems. With these systems, the depth of investigation is typically from a few kilometres to the lower crust and, within resistive regions, the upper mantle. For the BBMT sites, the shallow occurrence of permafrost prevented the installation of the vertical magnetic field sensor, and accordingly only four components of the electromagnetic field were measured ($E_x$, $E_y$, $H_x$ and $H_y$). The MTU systems recorded for a period of 3 days (two nights) at each site. During the 2002 field campaign, the four systems were powered using solar cells, with an RF filter in the power supply circuit to reduce EM noise that could contaminate the observations.

Data quality was generally good, due to lack of any cultural EM noise and high signal levels, with over 100 active sunspots for both field campaigns. This resulted in high quality response function estimates at most sites. Typical examples are from sites 005 and 307 (Fig. 4).

One problem encountered on these surveys was very high contact electrode resistance, especially at sites with little surficial cover due the recent retreat of the Barnes Ice Cap, one of the last remaining glaciers from the Laurentide ice sheet which covered all of northern North America and Greenland 16,000 years ago. Typically, in MT one strives to have resistance between the electrodes below 10 kΩ to ensure good ground contact. The worst site, 001 (Fig. 3), was situated in a boulder field, where resistances were measured at greater than 2 MΩ. Such high contact resistances result in capacitive coupling with the ground becoming important, with the consequence that the ground responds in a manner characteristic of a low pass RC filter to the electric signals. This can be seen in the data from sites 001 and 201 where there is a significant decrease in the apparent resistivity and phase at period less than 0.1 s (Fig. 4).

Electric field distortions due to local heterogeneities were strong at some sites and can be attributed to current channelling. The most severe distortions are seen at the sites located in river valleys (003 and 205) and result in phases shifting into the wrong quadrant for two-dimensional modelling. In severe cases of distortion, it may only be possible to extract information in one mode.

## 5. Processing and analysis

The first step in processing raw MT data is spectral analysis of the time series data using appropriate processing codes. Both the LMT and BBMT data were processed with the Jones–Jödicke robust code (Jones and Jödicke, 1984; method 6 in Jones et al., 1989). The remote reference technique (Gamble et al., 1979) was

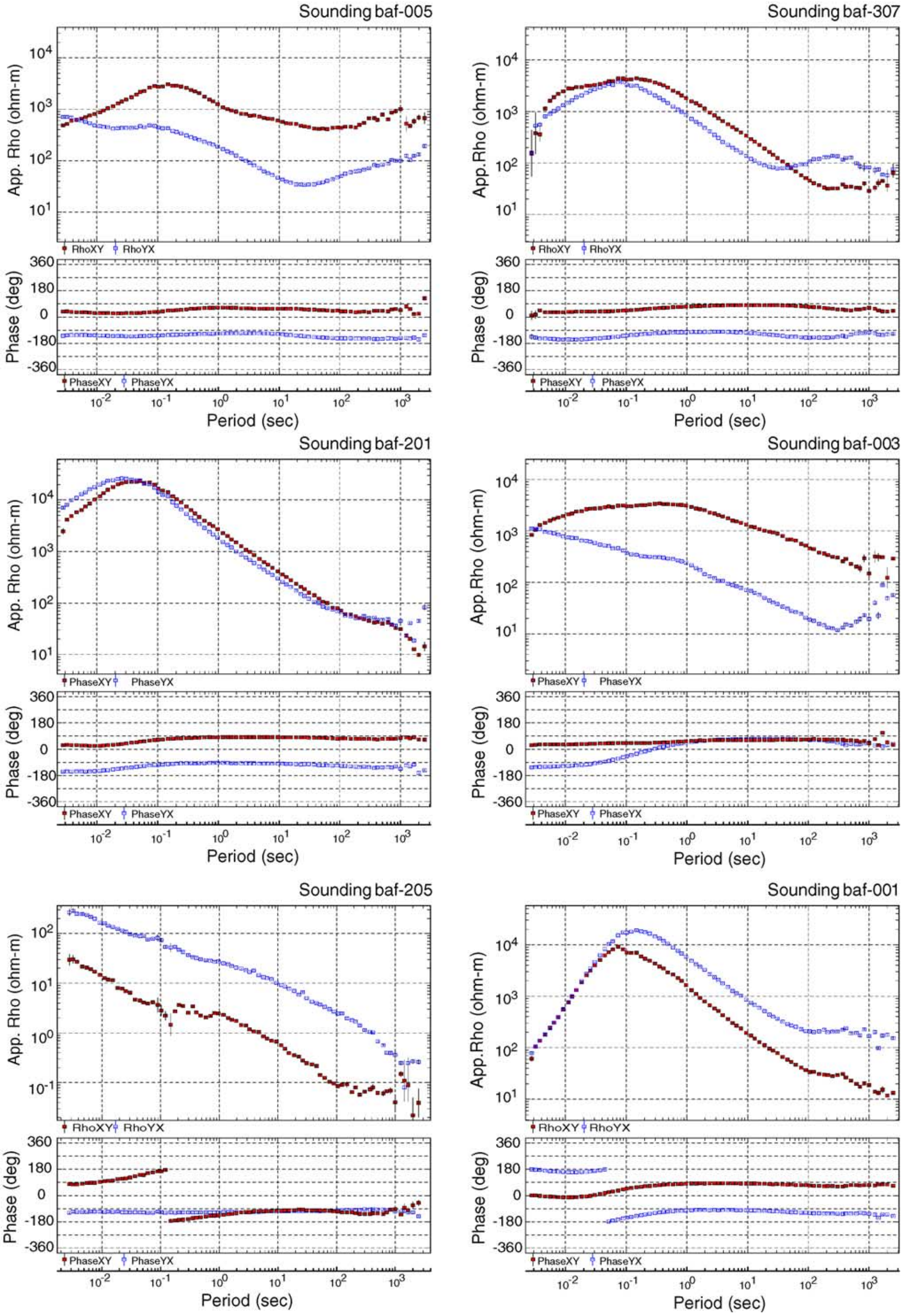

Fig. 4. Magnetotelluric response curves derived from data acquired at representative site baf005, baf307 and distorted sites baf201, baf003, baf205 and baf001 (see Fig. 3 for locations). Red curves are the responses for currents flowing perpendicular to the profile, and the blue profiles are the responses for current flowing along the profile.

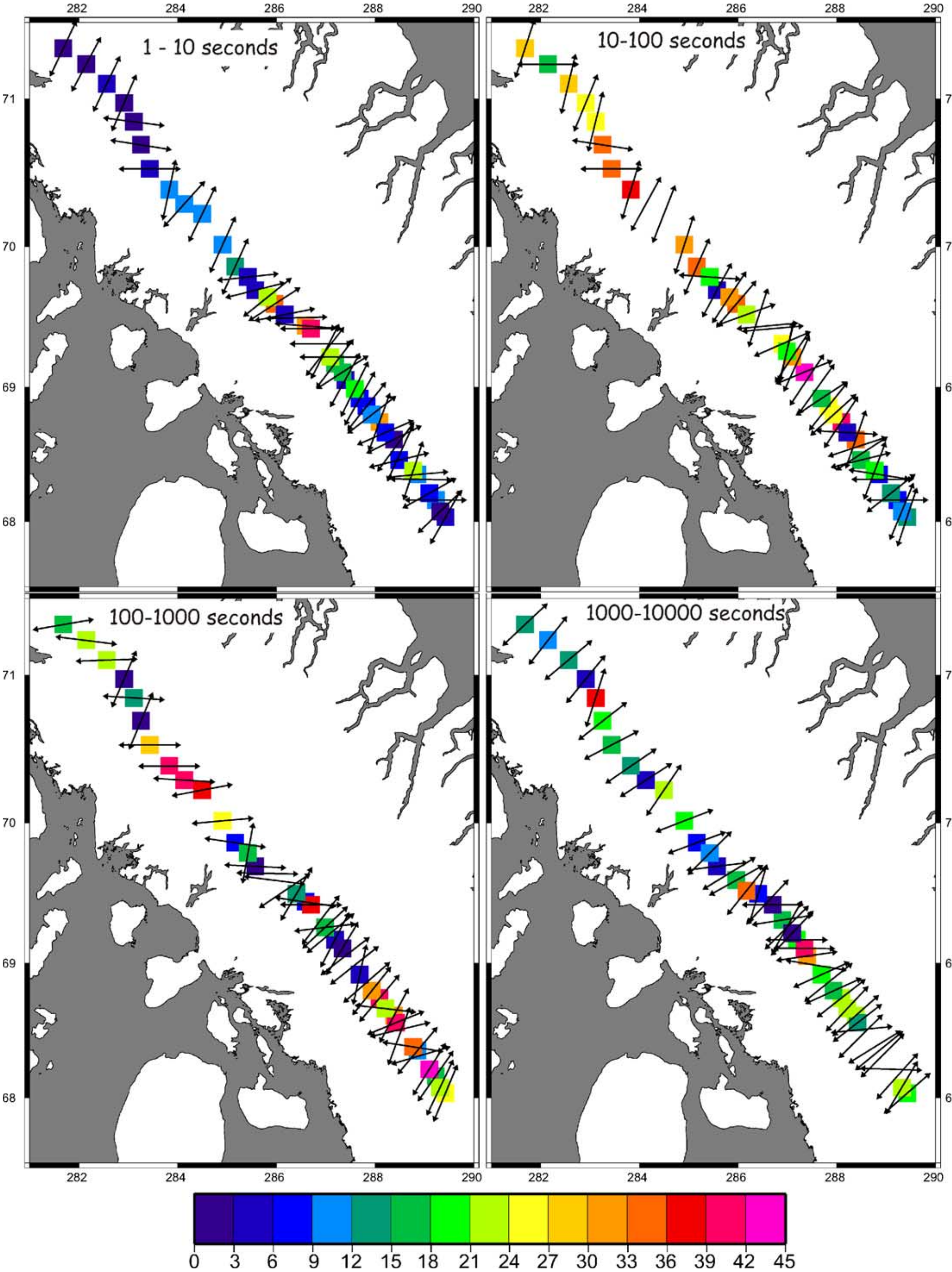

Fig. 5. Single site strike angles calculated at decade wide bands between 1 and 10,000 s. Coloured blocks centred on the arrows show the phase differences between the two orthogonal directions.

employed to reduce the biasing effects of noise in the data. In the case of the LMT data, given that all 15 sites recorded simultaneously, multi-remote processing was undertaken. In addition, the LMT data were analyzed for potential non-uniform source field contamination effects. The survey lies at high geomagnetic latitude, 77–80°N corrected geomagnetic coordinates (CGM), and is north of the auroral oval within the polar cap where current flow is dominantly sheet-like and uniform from local magnetic midnight to local magnetic midday. To ensure that the MT response estimates were not adversely affected by non-uniform source field contributions, the approach of Jones and Spratt (2002) was applied. Apart from a few exceptions, the responses were not affected by the choice of data, indicating that either the source field effects were negligible, or that the robust processing scheme successfully identified and removed problem sections.

The MT data were analysed for galvanic distortions, caused by small, near-surface inhomogeneities, and to determine the appropriate strike direction for two-dimensional (2-D) interpretation using the McNeice and Jones (2001) multi-site, multi-frequency galvanic distortion decomposition code based on the approach of Groom and Bailey (1989). Galvanic distortions observed were related to local site conditions, not to any particular geological horizon. Perversely, the most distorted sites were the most picturesque; on terraces in the deep river valleys especially where a second river joined the main one. Single-site strike angles, and the phase differences between the two modes (electric field parallel and perpendicular to strike, TE and TM modes, respectively), are shown in Fig. 5 for four decade-wide bands of data from 1 to 10,000 s. Strike angles can be observed to vary along the profile, but regions with consistent strike angles are distinguishable throughout. Generally, geoelectric strike direction correlates well with surface observation of geological strike. A strike angle of N33E was determined to be most appropriate for the decomposition when all sites at all periods are analysed simultaneously. Misfits to this single strike direction occur particularly at high frequencies (>1 Hz), due to geological variation along the profile.

Having defined the most appropriate coordinate system for interpretation, the MT data were fit to a distortion model with an assumed strike of N33E and with frequency-independent galvanic distortion (twist and shear in Groom-Bailey parlance). It should be noted that the data were not rotated into the interpretation reference frame, as this yields inferior estimates of the regional 2-D MT impedance tensor estimates (Jones and Groom, 1993; McNeice and Jones, 2001), but fit with a model of galvanic distortion that includes rotation. The difference between rotation and model fitting for high quality data with little distortion is small, but for noisy data suffering a high level of distortion the superiority of fitting over rotation is evident, as shown in both Jones and Groom (1993) and McNeice and Jones (2001). After correction for Groom-Bailey's *anisotropy* term, by coalescing the high frequency asymptotes of the two modes, the regional 2-D responses were imported into both WinGLink and Geotools modelling software packages to derive 2-D resistivity models.

## 6. Laboratory analyses

In the summer of 2001, rock samples were taken from the Astarte River formation for laboratory analysis for electrical properties. Tri-axial electrical resistivities were measured at room temperatures and pressures after immersion in pure $H_2O$ following the techniques outlined in Katsube et al. (1996). Measurements were made perpendicular ($\alpha$) and parallel ($\beta$ and $\gamma$) to the bedding planes, as represented by foliations.

Results of the analyses are listed in Table 1 from the five samples. Samples BAF-1, -2 and -3 were visually graphitic-rich, whereas samples BAF-A and -B were visually sulphide-rich. These analyses indicate that the enhanced conductivity in these samples is likely due to the presence of graphite (samples BAF-1, -2 and -3).

Table 1
Results of electrical resistivity measurements on samples from the Astarte formation, Baffin Island

| Sample | $\rho'$ or $\rho^+$ ($\Omega$ m) | | |
|---|---|---|---|
| | $\alpha$ | $\beta$ | $\gamma$ |
| BAF-1 | 3600 | 13 | 82 |
| BAF-2 | 2100 | 48 | 61 |
| BAF-3 | 390 | 8 | 36 |
| BAF-A | >40000 | >16000 | >8000 |
| BAF-B | >28000 | 2500 | 2300 |

$\rho'$ = Real electrical resistivity measured after 24 h saturation, $\rho^+$ = amplitude of complex electrical resistivity after 24 h saturation, $\alpha$ = measurement made in the direction perpendicular to bedding (foliation), and $\beta$ and $\gamma$ = measurements made in directions parallel with bedding (foliation).

Although there was a significantly high pyrite sulphide content observed visually in samples BAF-A and -B, it is disconnected in these surface samples, and contributes little to the conductivity of the samples. The graphite samples also show high anisotropy; electrical conductivity is up to two orders of magnitude higher parallel to bedding compared to perpendicular to bedding. Such high anisotropy at the hand sample scale was previously observed by Katsube et al. (1996) and Jones et al. (1997) in rocks from the NACP in northern Saskatchewan, but in that case it was due to pyrite grains connected along strike but disconnected across strike.

The analyses were undertaken at room temperatures and pressures, and so can be considered appropriate for the top 2–5 km of the crust, beyond which the pressures will close microcracks (see, e.g., Christensen and Wepfer, 1989). At deeper depths, there is possibly interconnection of the sulphide grains. However, the model of the responses does not show a marked significant increase of conductivity with depth, thus, we tentatively conclude that indeed the graphite is the primary conduction enhancement mechanism for the anomaly at all depth levels.

## 7. Preliminary model

The effects of distortions due to the coast effect were investigated by generic 2-D and 3-D model studies and inspecting the induction arrows at long periods (∼1000 s, not shown). It should be noted that the profile was chosen to be parallel to the coast, and as far as logistically possible from it. These model studies indicated that there should be little coast effect in our data. In the observations, the induction arrows pointed generally parallel to the profile, further validating the strike direction assumption and demonstrating that the coast effect does not affect the responses observed.

A preliminary 2-D resistivity-depth model to describe the observations is shown in Fig. 6A. The model was obtained with the RLM2DI smooth inversion code of Rodi and Mackie (2001), as implemented in Geosystem's WinGLink package, inverting the responses from both TE and TM modes in the period range 0.1–1000 s. The start model was a uniform half space, and the final model was obtained after hundreds of iterations. Inversions were undertaken with other start models and other inversion parameters chosen, and the same five basic features discussed below always appeared. The final model chosen has an overall RMS misfit of 7.71, with the misfit approximately equal for TE and TM, and is the result of the inversion of both the TE and TM modes from a starting model of a half-space with a resistivity of 100 Ω m. The model mesh consisted of 123 vertical columns and 46 horizontal rows. The inversion was run using the following RLM2DI parameters: $\tau = 8$, $\alpha = 3$, $\beta = 1$, and error floors of 10% for $\rho$ and 5% equivalent for the phase.

Although the RMS misfit is high, visually the theoretical response of the final model fits most of the observations well (Fig. 7); the majority of the misfits occur at the longer periods in the phases (100–1000 s). This inability to fit the observations over broad frequency bandwidths of many decades is not an uncommon occurrence when trying to model a profile with a large number of stations, primarily due to the Earth not being 2-D over the vast scale lengths sensed. Nonetheless, the smooth model procedure ensures low structural complexity, and it is likely that models obtained from subsequent inversions will have improved fit but will still possess the following large scale prominent electrical features:

A conductive layer forms a composite synformal basinal feature between sites 207 and 214 with a maximum depth of approximately 12–15 km. This structure outcrops at sites 010 and 214, where the graphite rich Astarte River formation is exposed on the surface. Thus, MT has imaged the geometry of the structural basin containing the Piling Group meta-sedimentary sequences.

A distinct contrast, to a depth of approximately 10 km, of greater than an order of magnitude in resistivity can be seen moving north from sites 214 to 216. This contrast is indicative of the contact between the Paleoproterozoic meta-sedimentary rocks of the Piling Group to the south, and those of the reworked Archean Rae craton to the north. The highly resistive (>10,000 Ω m) upper crustal Rae craton rocks can be mapped to the northern end of the profile. Such highly resistive values for the Rae craton rocks were also observed in north-central Canada by Jones et al. (2002a) along profile WC (Fig. 1).

Below the Rae craton, the lower crust is reasonably conductive, exhibiting resistivities of 30–300 Ω m

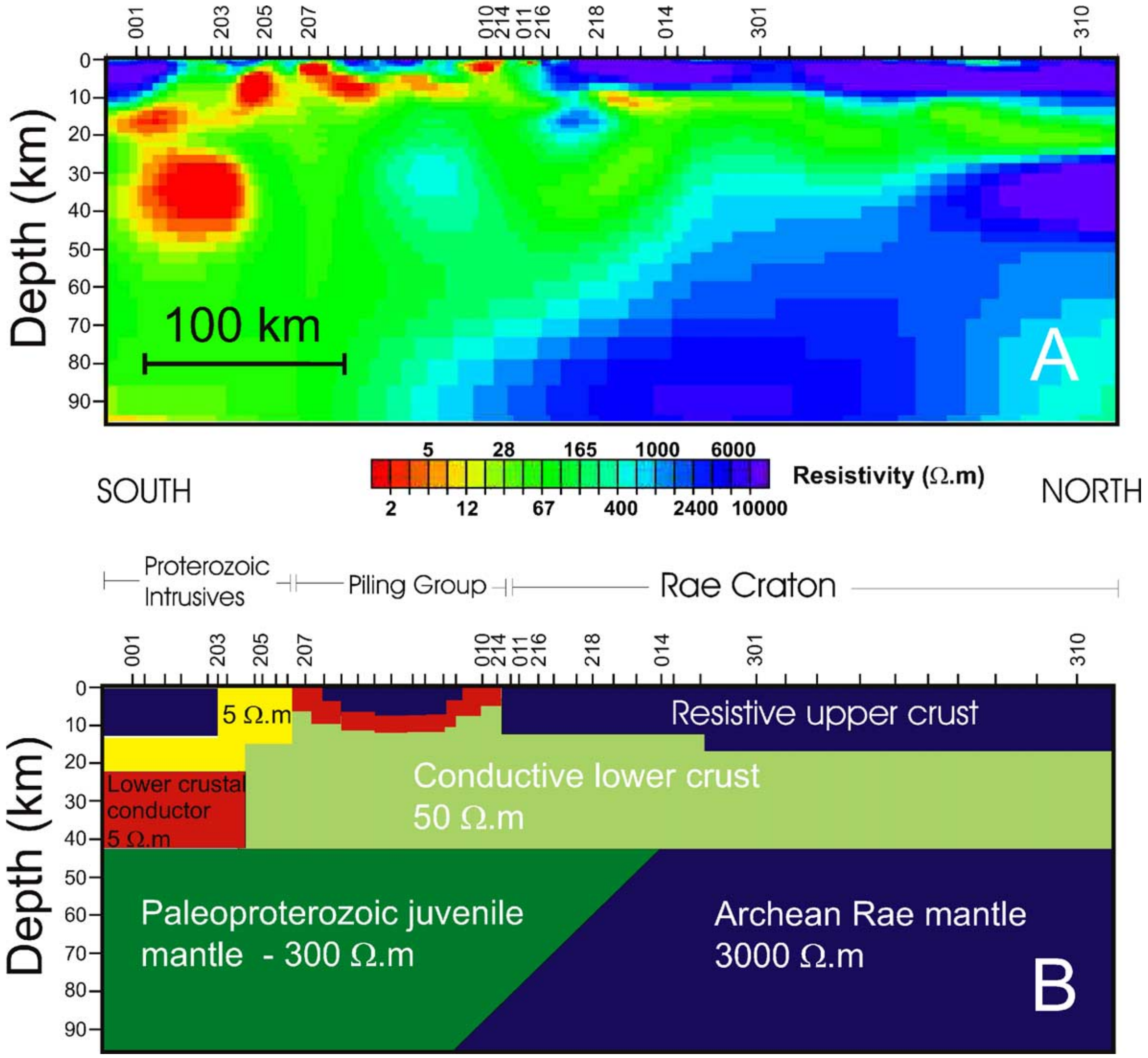

Fig. 6. (A) Final resistivity model obtained using both TE and TM modes and (B) cartoon interpretation.

and a total conductance of around 100 S. There appears to be some geometrical complexity within the lower crust, such as beneath sites 218–014, but those features require further verification. The model appears to imply a continuity of lower crustal rocks from beneath the Rae craton to beneath the Piling group sequences. Such lower crustal conductors have been observed pervasively around the world (Jones, 1992), although such high values of total conductance have been observed more predominantly in Phanerozoic regions (Jones, 1992). The lower crust of the Rae craton here is markedly different in its electrical properties from lower crust observed in the other location on the Rae craton where MT measurements have been made, namely in the Western Churchill province of Canada (Jones et al., 2002a); that MT profile is marked as WC in Fig. 1. Although the cause of the enhanced conductivity of the lower continental crust is still contentious, it is clear that different processes of formation and deformation must have occurred here compared to the Western Churchill province.

To the south of site 205 (Fig. 3), there are closely associated resistive and conductive bodies possibly related to the southern plutonic rocks,

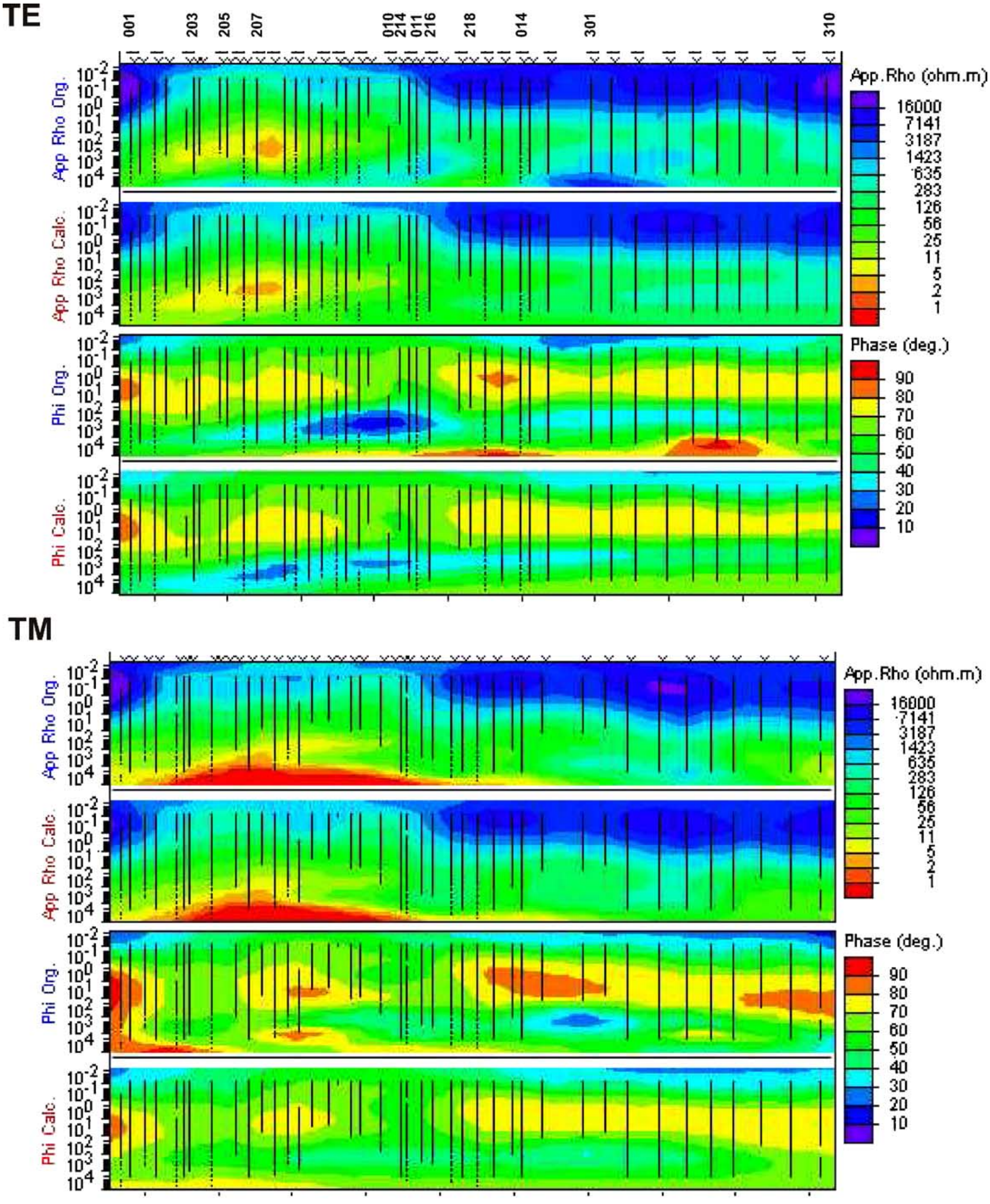

Fig. 7. Pseudosections for both TE and TM modes with original data and data calculated from the model shown in Fig. 6A.

including the Cumberland batholith, and a sequence of mafic–ultramafic intrusions. The lower crust here is anomalously highly conductive, and requires explanation.

There is a distinct north-to-south variation in the resistivity of the upper mantle beneath the region, with highly resistive mantle to the north (>3000 Ω m) and moderately conductive mantle to the south (∼300 Ω m). There is the suggestion of a southward dip to the transition, similar to that observed at the Rae-Hearne boundary to the west (Jones et al., 2002a).

## 8. Interpretation and conclusion

These preliminary observations give insight into the geometry of the regional structures along the profile, both within the crust and within the mantle lithosphere. The Astarte River formation is of particular interest as it is exposed over a large area and our laboratory analysis implies that the dominant conducting phase is interconnected graphite. The Astarte River formation is mapped between sites 207 and 010 and can be used as proxy for the base of the Piling Group, as the Piling Group formations that lie beneath the Astarte River formation are at most 2 km thick (Scott et al., 2002, 2003). To the north, a high conductivity contrast between the Piling Group meta-sedimentary rocks and the northern Archean Rae craton places the contact at approximately site 010–214.

The Astarte River formation marks the foundering of the passive margin and the initiation of turbidite deposition, which can be equated with the formation, and subsequent accretion, of arc terranes (M. St-Onge, pers. comm., 2003). Thus, the tectonic setting of the Astarte formation is the same as that for the meta-sedimentary rocks within the La Ronge arc which host the NACP (Jones et al., 1993, 1997). Geometrically, the NACP in the southern segment of the THO is limited to the western (in the Dakotas and Saskatchewan) or northern (in Manitoba) part of the internides, and on central Baffin Island the anomaly we have identified lies on the northern margin of the internides. Given the similarity in both geometry and tectonic setting and environment, we therefore conclude that the conducting feature we have mapped is, by inference, an extension of the NACP anomaly.

We recognise and appreciate that our interpretation of our anomaly being related to the NACP sensu stricto is, by its nature, tenuous and that there are other processes for generating conductivity anomalies within Paleoproterozoic orogens and other conductivity anomalies within the THO. Korja (1992), in his review of electromagnetic studies on the Fennoscandian shield, discusses various conductors and concludes that several are due to graphite-bearing rock layers within meta-sedimentary politic rocks whereas others are caused by black schist layers. Similarly, Boerner et al. (1996) also discuss mechanisms for the generation of conductivity anomalies within Paleoproterozoic orogens in Canada, and suggest that many are caused by euxinic-flysch foredeep successions of graphitic–sulphidic shale sequences were graphitized by metamorphism above 400 °C. Specifically for the THO the Attapaspuskow Lake conductivity anomaly (ALCA) of Ferguson et al. (1999), in the central part of the internides of the southern segment of the THOT profile (Fig. 1) in northern Saskatchewan, is also caused by graphitic and sulphidic rocks within pelitic and psammitic gneisses. The eastern margin of the THO at the U.S./Canadian border exhibits a strong anomaly, named the TOBE anomaly by Jones and Craven (1990) for its interpreted location in the Thompson Belt. However, notwithstanding these arguments, we consider that the evidence is in favour of our interpretation.

Below sites 001–203, is a resistive body that is spatially associated with the Cumberland Batholith. Beneath, and to the north of, this resistive body is an upper crustal conductor. Sulphides associated with the Bravo Lake formation (Stacey and Pattison, 2003) may be the source of the conducting phase within this body. The continuity of the structures observed suggest that these sulphides penetrate deeply within the crust and lie below the Cumberland Batholith.

We do not have a ready tectonic/geological explanation for the lower crustal conducting layer beneath the Rae craton in the northern part of the profile. Candidates for enhancing the conductivity of the lower crust were reviewed by Jones (1992), and basically are of two types; ionic conduction in fluids or electronic conduction in metasediments. A fluid hypothesis would require either implausible residence times or unlikely continuous recharge. Thus, we conclude that Paleoproterozoic orogenic processes resulted in emplacing meta-sedimentary rocks deep into the crustal column for over 200 km laterally, but the appropriate tectonic scenario model needs to be developed.

Finally, the mantle lithospheric geometry suggested by the resistivity model is one of a south-dipping structure, suggestive of southward-directed (present-day coordinates) subduction, or possibly imbrication, or northward-directed overthrusting during THO convergence.

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## References

Alabi, A.O., Camfield, P.A., Gough, D.I., 1975. The North American Central Plains anomaly. Geophys. J. Roy. Astron. Soc. 43, 815–834.

Bethune, K.M., Scammell, R.J., 1997. Geology, Koch Island Area, District of Franklin, Northwest Territories (Part of NTS 37 C), Geological Survey of Canada, Open File 3391.

Boerner, D.E., Kurtz, R.D., Craven, J.A., 1996. Electrical conductivity and Paleoproterozoic foredeeps. J. Geophys. Res. 101 (13), 775–13, 789.

Camfield, P.A., Gough, D.I., 1977. A possible Proterozoic plate boundary in North America. Can. J. Earth Sci. 14, 1229–1238.

Camfield, P.A., Gough, D.I., Porath, H., 1970. Magnetometer array studies in the northwestern United States and southwestern Canada. Geophys. J.R. Astron. Soc. 22, 201–222.

Christensen, N.I., Wepfer, W.W., 1989. Laboratory techniques for determining seismic velocities and attenuations, with applications to the continental lithosphere. In: Pakiser, L.C., Mooney, W.D. (Eds.), Geophysical Framework of the Continental United States, vol. 172. Geological Society of America, Memoir, pp. 91–102.

Corrigan, D., Scott, D.J., St-Onge, M.R., 2001. Geology of the Northern Margin of the Trans-Hudson Orogen (Foxe Fold Belt), central Baffin Island, Nunavut, Geological Survey of Canada, Current Research 2001, C23, 17 p.

Dutch, S.I., 1983. Proterozoic structural provinces in the north-central United States. Geology 11, 478–481.

Evans, S., 2003. A Magnetotelluric Investigation of the Northern Margin of the Trans-Hudson Orogen on Baffin Island, Nunavut, Canada. Unpubl. M.Sc. thesis, Queen's Univ. Ontario, Canada.

Evans, S., Jones, A.G. Spratt, J., Katsube, J., 2003. Central Baffin electromagnetic experiment (CBEX): Phase 2. Geological Survey of Canada Current Research, 2003-C24.

Ferguson, I.J., Jones, A.G., Sheng, Y., Wu, X., Shiozali, I., 1999. Geoelectric response and crustal electrical-conductivity structure of the Flin Flon Belt, Trans-Hudson Orogen, Canada. Can. J. Earth Sci. 36, 1917–1938.

Gamble, T.D., Goubau, W.M., Clarke, J., 1979. Magnetotellurics with remote reference. Geophysics 44, 53–68.

Groom, R.W., Bailey, R.C., 1989. Decomposition of magnetotelluric impedance tensors in the presence of local three-dimensional galvanic distortion. J. Geophys. Res. 94, 1913–1925.

Gupta, J.C., Kurtz, R.D., Camfield, P.A., 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. Geophys. J.R. Astron. Soc. 81, 33–46.

Handa, S., 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. Can. J. Earth Sci. 21, 533–543.

Henderson, J.R., Henderson, M.N., 1994. Geology of the Dewar Lakes area, central Baffin Island, District of Franklin, N.W.T. (Parts of 27 B and 37 A), Geological Survey of Canada, Open File 2924 (scale 1:100 000).

Henderson, J.R., Grocott, J., Henderson, M.N., Falardeau, F., Heijke, P., 1988. Results of Field Work near Dewar Lakes, Baffin Island, N.W.T., in Current Research, Part C, Geological Survey of Canada, Paper 88-1C, pp. 101–108.

Henderson, J.R., Grocott, J., Henderson, M.N., Perreault, S., 1989. Tectonic History of the Lower Proterozoic Foxe-Rinkian Belt in central Baffin Island, N.W.T., in Current Research, Part C, Geological Survey of Canada, Paper 89-1C, pp. 186–187.

Henderson, J.R., Parrish, R.R., 1992. Geochronology and structural geology of the early Proterozoic Foxe-Rinkian Orogen, Baffin Island, NWT. In: Mining, exploration and geological investigations. In: Brophy, J.A. (Ed.), Exploration Overview, Northwest Territories. Mining, Exploration and Geological Investigations, p. 25.

Hoffman, P., 1988. United plates of America, the birth of a craton: early Proterozoic assembly and growth of Proto-Laurentia. Ann. Rev. Earth Planet. Sci. 16, 543–603.

Hoffman, P.F., 1990. In: Lewry, J.F., Stauffer, M.R. (Eds.), Subdivision of the Churchill Province and the Extent of the Trans Hudson Orogen. Geol. Assoc. Can. Spec. Pap. 37: Geol. Assoc. Can., pp. 15–39.

Jackson, G.D., 1969. Reconnaissance of north-central Baffin Island: in Report of Activities, Part A, April to October 1968, Geological Survey of Canada, Paper 69-01 A, pp. 186–187.

Jackson, G.D., Taylor, F.C., 1972. Correlation of major Aphebian rock units in the northeastern Canadian shield. Can. J. Earth Sci. 9, 1650–1669.

Jones, A.G., 1992. Electrical conductivity of the continental lower crust. In: Fountain, D.M., Arculus, R.J., Kay, R.W. (Eds.), Continental Lower Crust. Elsevier, Amsterdam, pp. 81–143 (Chapter 3).

Jones, A.G., 1993. The COPROD2 dataset: Tectonic setting, recorded MT data and comparison of models. J. Geomagn. Geoelectr. 45, 933–955.

Jones, A.G., Chave, A.D., Egbert, G., Auld, D., Bahr, K., 1989. A comparison of techniques for magnetotelluric response function estimation. J. Geophys. Res. 94, 201–14, 213.

Jones, A.G., 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. Phys. Earth Planet. Inter. 60, 169–194.

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

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

Jones, A.G., Jödicke, H., 1984. Magnetotelluric transfer function estimation improvement by a coherence-based rejection technique. In: Proceedings of the 54th Society of Exploration Geophysics Annual General Meeting, Atlanta, Georgia, USA, December 2–6, Abstract volume pages 51–55.

Jones, A.G., Katsube, J., Schwann, P., 1997. The longest conductivity anomaly in the world explained: sulphides in fold hinges causing very high electrical anisotropy. J. Geomagn. Geoelectr. 49, 1619–1629.

Jones, A.G., Savage, P.J., 1986. North American Central Plains conductivity anomaly goes east. Geophys. Res. Lett. 13, 685–688.

Jones, A.G., Snyder, D., Hanmer, S., Asudeh, I., White, D. Eaton, D., Clarke, G., 2002a. Magnetotelluric and teleseismic study across the Snowbird Tectonic Zone, Canadian Shield: a NeoArchean mantle suture? Geophys. Res. Lett. 29 (17), doi: 10.1029/2002GL015359.

Jones, A.G., Spratt, J., 2002. A simple method for deriving the uniform field MT responses in auroral zones. Earth, Planets and Space 54, 443–450.

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

Katsube, T.J., Jones, A.G., Scromeda, N., Schwann, P., 1996. Electrical characteristics of rock samples from the La Ronge domain of the Trans-Hudson orogen, northern Saskatchewan. Geological Survey of Canada Current Research, 1996-E, 159–169.

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

Korja, T., 1992. Electrical conductivity distribution of the lithosphere in the central Fennoscandian Shield. Precambrian Res. 64, 85–108.

Lewry, J.F., Collerson, K.D., 1990. The Trans-Hudson Orogen: extent, subdivision, and problems. In: Lewry, J.F., Stauffer, M.R. (Eds.), The Early Proterozoic Trans-Hudson Orogen of North America, Geol. Assoc. Can. Sp. Pap., vol. 37. Geol. Assoc. Can., pp. 1–14.

Maidens, J.M., Paulson, K.V., 1988. A magnetotelluric investigation under the Williston Basin of south-eastern Saskatchewan. Can. J. Earth Sci. 25, 60–67.

Mathisrud, G.C., Sumner, J.S., 1967. Underground induced polarisation survey surveying at the Homestake mine. Min. Cong. J. 53, 66–69.

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

Morgan, W.C., 1983. Lake Gillian, District of Franklin, Northwest Territories, Geological Survey of Canada, Map 1560A, scale 1:250 000. of the Foxe Fold Belt, Baffin Island, in Report of Activities, Part A, Geological Survey of Canada, Paper 76-1A, pp. 387–391.

Morgan, W.C., Bourne, J., Herd, R.K., Pickett, J.W., Tippett, C.R., 1975. Geology of the Foxe Fold Belt, Baffin Island, District of Franklin, in Report of Activities, Part A, Geological Survey of Canada, Paper 75-1A, pp. 343–347.

Morgan, W.C., Okulitch, A.V., Thompson, P.H., 1976. Stratigraphy, Structure and Metamorphism of the west half of the Foxe Fold Belt, Baffin Island, in Report of Activities, Part A, Geological Survey of Canada, Paper 76-1A, pp. 387–391.

Peterman, Z.E., 1979. Geochronology and the Archean of the United States. Econ. Geol. 74, 1544–1562.

Peterman, Z.E., 1981. Dating the Archean basement in northeastern Wyoming and southern Manitoba. GSA Bull. 92, 139–146.

Rankin, D., Pascal, F., 1990. A gap in the North American Central Plains conductivity anomaly. Phys. Earth Planet. Inter. 60, 132–137.

Reitzel, J.S., Gough, D.I., Porath, D.I., Anderson III, C.W., 1970. Geomagnetic deep sounding and upper mantle structure in the western United States. Geophys. J.R. Astron. Soc. 19, 213–235.

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

Scott, D.J., 1997. Geology, U–Pb, and Pb–Pb geochronology of the Lake Harbour area, southern Baffin Island: implications for the Paleoproterozoic tectonic evolution of northeastern Laurentia. Can. J. Earth Sci. 34, 140–155.

Scott, D.J., St-Onge, M.R., Corrigan, D., 2002. Geology of the Paleoproterozoic Piling Group and underlying Archean gneiss, central Baffin Island, Nunavut, Geological Survey of Canada, Current Research, 2002-C17, 12 pp.

Scott, D.J., St-Onge, M.R., Corrigan, D., 2003. Geology of the Archean Rae craton and Mary River group, and of the Paleoproterozoic Piling group, central Baffin Island, Nunavut, Geological Survey of Canada, Current Research, 2003-C26.

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

Stacey, J., Pattison, D.R.M., 2003. The Stratigraphy, Structure, and Petrology of a Representative Klippe of the Bravo Lake formation, Central Baffin Island, Nunavut, Geological Survey of Canada Current Research, 2003-C13.

St-Onge, M.R., Scott D.J, Corrigan, D., 2001. Geology, Central Baffin Island Area, Nunavut, Geological Survey of Canada, Open File D3996, 1 CD-ROM, scale 1:250000.

St-Onge, M.R., Scott, D.J., Corrigan, D., 2002a. Geology, Unuksulik Lake, Nunavut, Geological Survey of Canada, Open File 4317, 1 CD-ROM, scale 1:250 000.

St-Onge, M.R., Scott, D.J., Wodicka, N., 2002b. Review of crustal architecture and evolution in the Ungava Peninsula–Baffin Island area: connection to the Lithoprobe ECSOOT transect. Can. J. Earth Sci. 39, 589–610.

St-Onge, M.R., Wodicka, N., Scott, D.J., Corrigan, D., Carmichael, D.M., Dubach, K., Berniolles, F., Monday, P., Russel, I., Begin, N.J., Allan, M., Pattison, D.R., 2003. Thermal architecture of the Trans-Hudson Orogen from the Superior to Rae cratons (Quebec–Baffin segment). Geol. Assoc. Canada, Program with abstracts.

Thériault, R.J., St-Onge, M.R., Scott, D.J., 2001. Nd isotopic and geochemical signature of thePaleoproterozoic Trans-Hudson Orogen, southern Baffin Island, Canada: implications for the evolution of eastern Laurentia, Precambrian Res., 108, 113–138.

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

Zhao, G., Cawood, P.A., Wilde, S.A., Sun, M., 2002. Review of global 2.1–1.8 Ga orogens: implications for a pre-Rodinia supercontinent. Earth Sci. Rev. 59, 125–162.