The Longest Conductivity Anomaly in the World Explained: Sulphides in Fold Hinges Causing Very High Electrical Anisotropy

Alan G. Jones[1], T. J. Katsube[2], and Pamela Schwann[3]

[1] *Geological Survey of Canada, 1 Observatory Crescent, Ottawa, Ontario, Canada, K1A 0Y3*
[2] *Geological Survey of Canada, 601 Booth St., Ottawa, Ontario, Canada, K1A 0E8*
[3] *Saskatchewan Northern Affairs, Box 5000, La Ronge, Saskatchewan, Canada, S0J 1L0*

After almost three decades of study, from its initial discovery in the 1960s to laboratory analyses of rock samples last year, we can now identify the most probable cause of the North American Central Plains (NACP) conductivity anomaly for much of its 1,500-km strike extent. Tectonic processes operating during Paleoproterozoic Trans-Hudson orogenesis, with closure of the 5,000-km-wide Manikewan ocean, included subduction and compression of sediments deposited during a hiatus in volcanism as the first of the advancing arcs approached the Archean continental margin to the west (Wyoming and Rae/Hearne cratons). These sediments were folded, and syngenetic sulphides within them migrated to concentrate along fold hinges, preferentially along strike, leading to high anisotropy in electrical conductivity (over 2–3 orders of magnitude). Mapping of the anomaly in similar tectonic environments, from the southern Dakotas to northern Manitoba, suggests that these processes were active along the whole western and northern margin of the orogen. However, other processes, possibly invoking graphitic emplacement in a foredeep, more likely account for the southern terminus of the anomaly from the Black Hills to southeastern Wyoming.

1. Introduction

Through electromagnetic (EM) surveys we obtain regional and local images of the lateral and vertical variation of electrical conductivity. With the recent advances in instrumentation, acquisition strategies, analysis and processing methods, modern surveying practices, particularly for magnetotellurics (MT), have improved to the stage where highly precise response estimates (typically better than a percent) give confidence in the features of the images obtained (see, e.g., Jones, 1993a). The challenge is to take these images and determine the causes for the observed conductivity enhancements, and relate these causes to tectonic and geodynamic processes. This is not a simple task, given that many minor constituents to the resistive host rock matrix can dramatically affect the total rock resistivity. There are basically two types of conductive mechanisms that operate within the Earth. Ionic conduction occurs when ions are free to migrate through pore waters or partial melts. Electronic conduction occurs when the electric current is carried by electrons migrating through electronically conductive solids, such as graphite, sulphides, and ilmenite. Discriminating between these two mechanisms requires frequency and conductivity amplitude analysis beside hard evidence from either surface or borehole sampling. It has been suggested that some types of conductive mechanisms can never be observed at the surface due to disconnection of their conducting path during uplift and exposure (Katsube and Mareschal, 1993).

Seldom has an anomalous enhancement in electrical conductivity been definitively associated with a particular conductivity mechanism, and then the mechanism been taken to imply processes leading to its generation. Boerner *et al.* (1996) proposed that anomalies observed beneath the Albertan Basin sediments, and within other Proterozoic orogens, can be associated with

metamorphosed euxinic carbonaceous shales deposited in foredeeps, but lack of bedrock exposure hampers this thesis.

In this paper, we show that the longest mapped conductivity anomaly in the world can be associated with sulphides deposited between the advancing La Ronge arc and the Wyoming and Rae/Hearne Archean cratonic hinterlands, and that these sulphides were mobile during compression resulting in conductivity enhancement along the hinges of folds. We demonstrate this by going from the continental (50 km–500 km) to the regional (10 km–50 km), to the local (1 km), to the hand-sample (1 cm–1 m) scale. The implications are that the anomaly is not a single body, but comprises discrete conductors preferentially aligned along strike, and that the body was emplaced as part of Paleoproterozoic subduction and collision-related processes.

2.   Continental Scale

An anomalous observation on one station of a magnetometer array study in 1967, by Ian Gough and his colleagues (Reitzel *et al.*, 1970), 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, mostly in the deep crust, has been tracked from Wyoming through the Dakotas and Saskatchewan over to northern Manitoba (Alabi *et al.*, 1975; Handa and Camfield, 1984; Gupta *et al.*, 1985), and possibly has a counterpart in Scandinavia
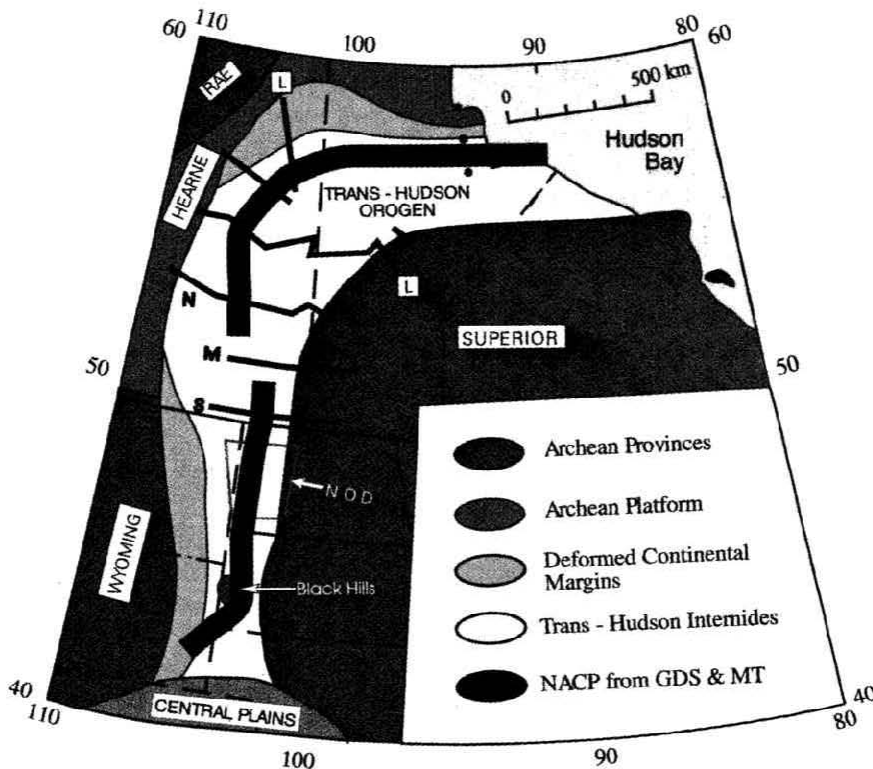

Fig. 1.   A generalized map of the North American Central Plains conductivity anomaly and the internides of the Trans-Hudson orogen and its bounding Archean cratons.

(Jones, 1993a). Camfield and Gough (1977), in an insightful paper, suggested that the conductivity anomaly is the geophysical marker for a Proterozoic collision zone from the southern Rockies to northern Canada—a proposal that conflicted with the then prevailing view that the Wyoming and Superior cratons were contiguous. Basement core sampling proved their idea to be essentially correct, and the NACP anomaly lies wholly within what is now termed the Trans-Hudson orogen (THO), a Paleoproterozoic orogen extending over 3,000 km from South Dakota through Hudson Bay (Hoffman, 1988) into Greenland (Lewry and Stauffer, 1990), and is a component of a global network of coeval Paleoproterozoic orogens that welded together Archean provinces. These early studies used only natural time variations of the magnetic field, and had widely spaced observation sites (typically 25–50 km), and consequently although they detected the existence of the anomaly, the data were insufficient for detailed resolution of its geometry.

3. Regional Scale

Determining the structure of the anomaly on a regional scale has been accomplished with magnetotelluric profiles across it, with typical station spacing of 10–15 km, as part of a number
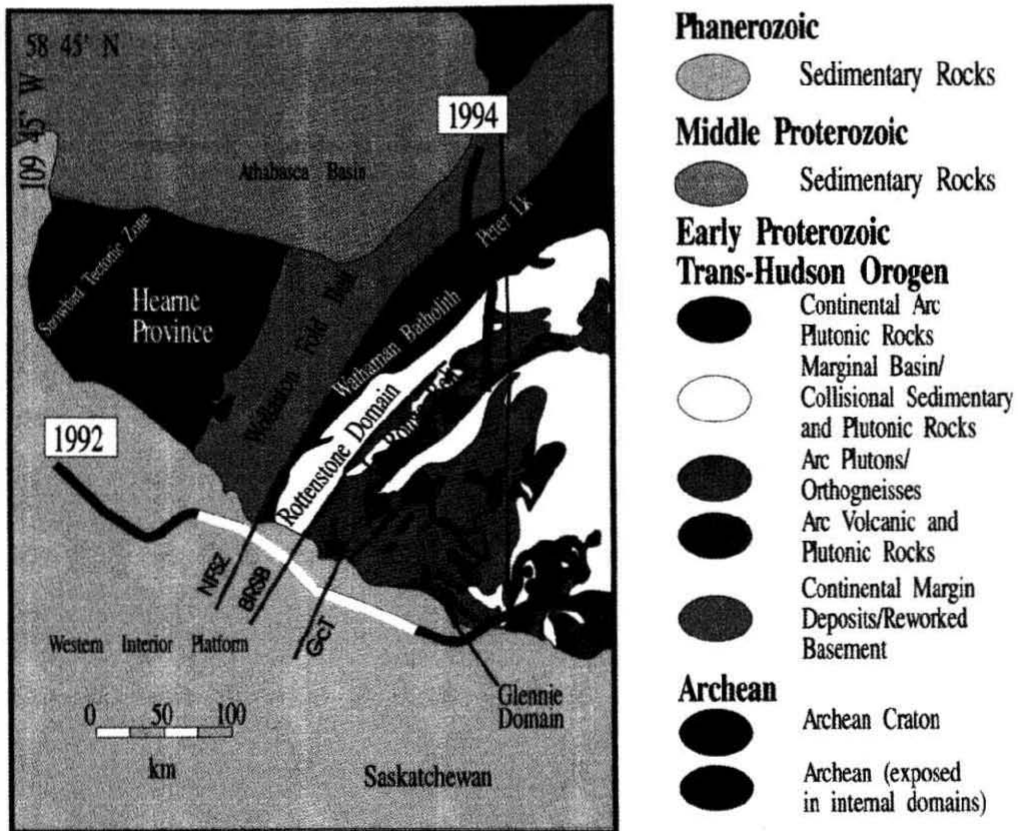

Fig. 2. Exposed units of the Trans-Hudson Orogen and its western boundary in northern Saskatchewan. The black line shows the location of the MT profile, and the white portion gives the location of the model of Fig. 3. NFSZ: Needle Falls shear zone; BRSB: Birch Rapids Straight Belt; GcT: Guncoat thrust. The location of the rock sampling is indicated by the star.

of projects. The first of these was conducted by PanCanadian Oil Company, who were interested in the control of sedimentary structures within the Williston Basin by basement structures. Pan-Canadian contracted magnetotelluric surveys over the 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 lay within the crust, and its top was at around 10 km (Jones and Savage, 1986). More complete modelling confirmed this, and showed that the anomaly was arcuate in form, with a wavelength of approx. 80 km (Jones and Craven, 1990). One formerly enigmatic aspect about the behaviour of the anomaly in these data is that it has virtually no effect on the MT responses for across-strike (East-West) travelling currents, only on the responses for along-strike (North-South) travelling currents. 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 at least one major break in south-central Saskatchewan (Jones and Craven, 1990). MT profiles in North Dakota (NOD, Fig. 1) gave essentially the same result as that for line S of a number of discrete bodies with an overall arcuate shape within the mid-crust (Wu, 1994; Booker *et al.*, 1997).

An intimate geometrical relationship was demonstrated between this arcuate 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). The conductive bodies were shown to be associated with reflective packages, and overlying a non-reflective region interpreted to represent 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 the western part of the orogen in 1992 and 1994 (Fig. 2). The Hearne province is the Archean hinterland, against which the Wollaston Fold belt comprises deformed continental margin assemblages. The La Ronge belt comprises oceanic volcano- sedimentary sequences associated with the La Ronge arc, which was the first arc to collide with the Rae/Hearne craton. The Rottenstone domain rocks are likely shelf and slope-rise sequences, and
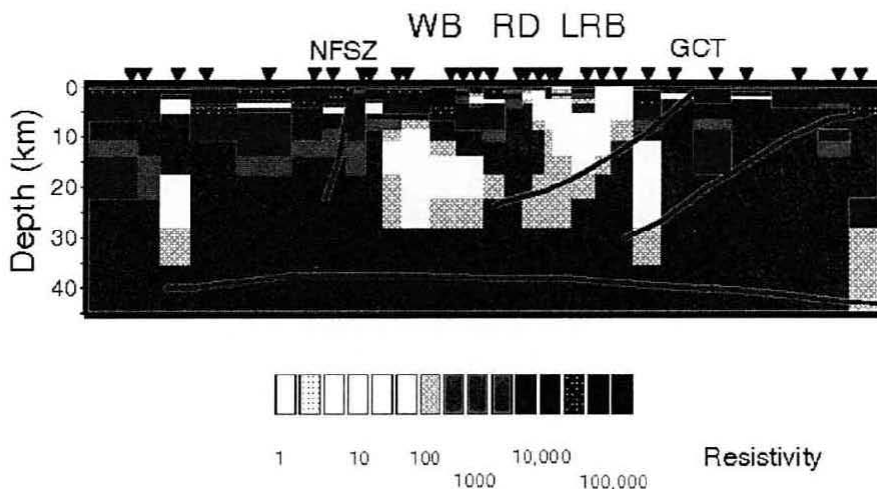

Fig. 3.   Resistivity model obtained from the MT sites along the 1992 profile. Note that the zones of high conductivity lie structurally above the Guncoat thrust mapped by seismic reflection.

the Wathaman batholith is thought to be an Andean-like stitching batholith emplaced subsequent to La Ronge-Hearne terminal collision. The Needle Falls Shear Zone is interpreted as a strike-slip fault which occurred late in the compressional deformation history. Within the Glennie Domain are Archean basement 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 orogen (Lucas *et al.*, 1993). Note the similarity of this interpretation to the one 600 km further south by COCORP.

The 1992 "L"-line MT data showed strong anisotropy in the responses at frequencies greater than 10 Hz for sites on the La Ronge Belt (Fig. 4 of Jones *et al.*, 1993). The TE-mode phases were greater than 50°, whereas the TM-mode phases were all <30°. The model fitting these data is illustrated in Fig. 3 (from Jones *et al.*, 1993). The zone of high conductivity (low resistivity) can be associated with the western part of the La Ronge Belt. The conductive bodies lie structurally above the Guncoat thrust, 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. Preliminary modelling of the 1994 data illustrates that the anomaly lies wholly within the western La Ronge belt.
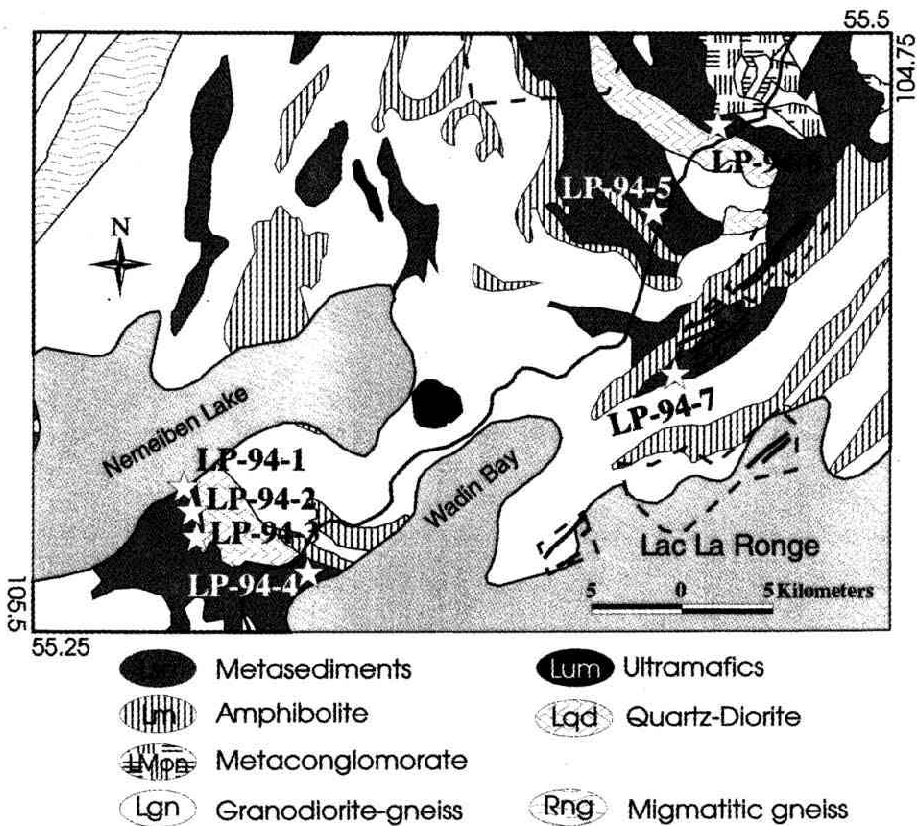

Fig. 4.   Portion of bedrock map sheet 225A (Lewry and Slimmon, 1985 showing the rock sampling localities (stars), the metasediments (unit *Lsn*), and also the airborne EM anomalies (light grey lines within dashed boxes).

4. Local Scale

Local electrical structures, on a <1 km scale, are illuminated efficiently using airborne EM methods. A compilation of the publicly-available data for the 1:250,000 map sheet north of the Lithoprobe line (sheet Lac La Ronge, NTS Area 73P/73I) displays groups of linear conductors (Standing, 1973). Each conductor is of the order of 1–20 km in length, with an aspect ratio of >10:1, and the anomalies are curvi-linear features that follow the structural trend of the orogen. Spatial correlation of these airborne EM anomalies with the bedrock geology map (Lewry and Slimmon, 1985) shows that the only conducting rocks within the western La Ronge belong to a metasedimentary unit (unit *Lsn*) described as biotitic metasediments comprising predominantly psammitic to pelitic gneiss. Within these metasedimentary sequences are economic deposits of gold, nickel, and copper in disjointed vein and disseminated sulphide mineralization (Mineral Resources of Saskatchewan, 1991). No graphite has been observed in the western La Ronge belt (J. F. Lewry, pers. comm., 1993). The correlation of these units with the airborne EM anomalies for the southern portion of the map is illustrated in Fig. 4.

5. Hand Sample Scale

To determine the cause of conductivity enhancement at the smallest scale, samples from the unit *Lsn* were collected from the seven localities shown in Fig. 4. One of these samples, sample LP-94-7, was from a location along-strike from a dominant airborne EM anomaly, and is a carbonaceous sulphidic argillite. A sketch of the sample, together with the locations of sub-samples cut from it, is shown in Fig. 5. From each rock sample, cube specimens were cut with
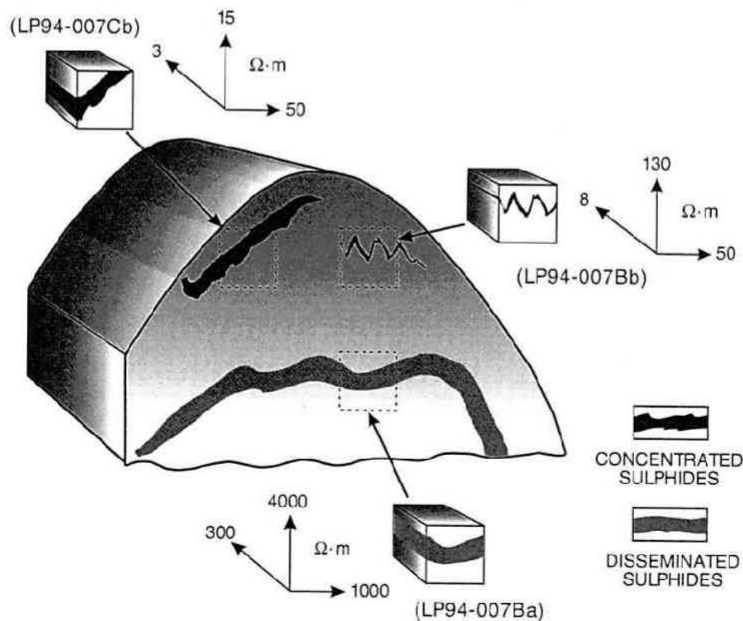

Fig. 5. Schematic representation of a cross-section of sample LP94-007, exemplified by sub-samples LP94-007B and LP94-007C, showing folded layers of sulphide concentrations, and locations from which the second series of sub-samples (LP94-007Cb, LP94-007Bb, LP94-007Ba) were taken. The 3-directional resistivity values of these sub-samples are also displayed. Each sample is a cube with a side length of 1.5 cm.

Table 1. Maximum anisotropy values for rock samples ("Individual" are measured, others are derived).

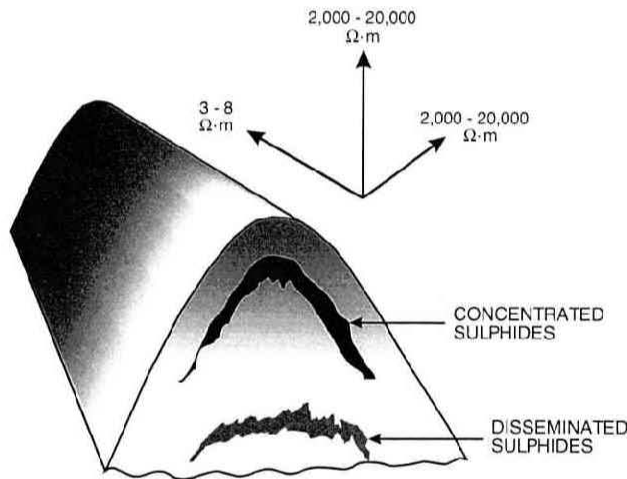| Subsample | ρ_{min} $\Omega \cdot m$ | ρ_{interm} $\Omega \cdot m$ | ρ_{max} $\Omega \cdot m$ | Maximum anisotropy | | |
				Individual	Subsample	Sample
007Aa	19	33	290	15		
007Ab	23	52	320	14	1000	
007Ac	0.3	0.5	1	3		12800
007Ba	330	980	3840	12	490	
007Bb	7.8	48	130	17		
007Ca	8.3	50	79	10	25	
007Cb	3.1	15	54	17		

Fig. 6. Electrical model of the rock, showing folded layers containing highly concentrated sulphides accumulated near the hinge of the fold, and disseminated sulphides in the rock matrix. This suggests resistivities of 3–8 $\Omega \cdot m$ in the direction of the axis, and 2,000–20,000 $\Omega \cdot m$ in the other two directions, for an anisotropy of 200:1 to 7,000:1.

a length of 1.5 cm. Laboratory analyses of these specimens for electrical conductivity included measurements along three axis to determine anisotropy (Katsube *et al.*, 1996).

Most of the samples were biotitic gneiss, and yielded resistivities well in excess of 1,000 $\Omega \cdot m$ up to 20,000 $\Omega \cdot m$. Sample LP-94-7 however, a lean sulphide facies iron formation, displayed zones of concentrated sulphides, identified as pyrite, along the fold axis. The sample came from a location along strike from the Sulphide Lake area, named for the obvious exposures of sulphides. Sub-samples of this specimen showed highly anisotropic behaviour, with values of 0.3–10 $\Omega \cdot m$ for sub-samples from within the concentrated sulphides, and 100 s–1,000 s of $\Omega \cdot m$ for those from outside the zone (Fig. 5). Individual sub-samples could be cut from the specimen that displayed more than an order of magnitude anisotropy in electrical conductivity (Fig. 5), and the composite rock displays up to four orders of magnitude electrical anisotropy between the most conductive and most resistive directions (Table 1). Such high anisotropies have not previously been reported in the literature from laboratory analyses of hard rocks. Scanning electron microscope analyses

of the most conducting sub-samples showed that the pyrite grains are in contact along the fold axis, but not in contact perpendicular to it. When pyrite grains are not in contact, then they do not contribute significantly to generally low resistivity (e.g., Duba *et al.*, 1988).

An electrical model of the rock unit is shown in Fig. 6, with 3–8 Ω·m along the fold axis, and 2,000–20,000 Ω·m in the other two directions.

6.   Scaling Between Scales

The physical scaling laws from the observed anisotropy in the hand-specimens to the continental scale for this two-dimensional situation depend on the polarization. The anisotropy is at a scale size which is far smaller than the wavelengths of the fields used in the regional (MT) and continental (GDS) studies, and asymptotic limits of analytical solutions must be considered for a representative model of the resistive host rock matrix containing the concentrated sulphides. One such applicable model is that of multiple conducting dikes.

In the TM mode, Groom and Bailey (1989) have shown that for such a model, the effective DC resistivity of the medium is the spatially averaged resistivity $\rho_{TM,eff}$ given by

$$\rho_{TM,eff} = \frac{d\rho_d + h\rho_h}{d + h} \tag{1}$$

where d and h are the thicknesses of the dike and host respectively, and ρ_d and ρ_h are their resistivities. In an electrical network, this is equivalent to resistances in a series circuit. Thus, for a 1 Ω·m dike of a few centimetres embedded in a host of 10,000 Ω·m, and with a dike separation of greater than ten times the dike thickness, the effective resistivity in the TM-mode asymptotes at the DC limit to close to the host resistivity, in this case it would be 9,091 Ω·m. Also, the electrode line length for MT data acquisition is much greater than the scale-length of the anisotropy, and the effects of the dikes will be further reduced even at the highest frequencies. Accordingly, thin, sub-vertical, repeated layers of sulphides will not be seen in the TM-mode response, as is the case.

The TE-mode response is far more complex to derive analytically, and only the expression for a single dike in a host has been evaluated (Weaver *et al.*, 1986; Weaver, 1994, pp. 123–135). Also, it requires continuity along strike for the currents to flow preferentially in the sulphides rather than the host material. Assuming that such continuity is assured, then, by analogy with network theory, the effective DC resistivity of the medium is likely to be the inverse of the spatially averaged conductivity, i.e., $\rho_{TE,eff}$ is given by

$$\rho_{TE,eff} = \frac{d + h}{d\sigma_d + h\sigma_h} \tag{2}$$

where σ_d and σ_h are the dike and host conductivities. This is the case for resistances being in a parallel circuit. For the 1 Ω·m dike of a few centimetres embedded in a host of 10,000 Ω·m, and with a dike separation of ten times the dike thickness, the effective resistivity in the TE-mode likely asymptotes at the DC limit to 10.99 Ω·m. Accordingly, in the TE-mode response the presence of the sulphides will be sensed, as is the case.

These two circuit analogues explain why such strong anisotropy is seen in the MT observations when the sulphides are sub-vertical. The 1992 L-line TM-mode data from the western La Ronge domain at frequencies above 10 Hz are insensitive to the presence of any conducting bodies, with TM-mode phases of around 30°. In contrast, the TE-mode data show a strong effect due to the presence of conducting anomalies, and have phases >50°(see Fig. 4 of Jones *et al.*, 1993). At lower frequencies, below 3 Hz, both modes sense conducting bodies, which is interpreted as the sulphides becoming sub-horizontal along a listric feature (the Guncoat thrust), consistent with the seismic interpretation.

7. Discussion

The NACP conductor has been continuously mapped on the continental scale and sampled on the hand specimen scale, and we can conclusively identify the enhanced conductivity on the exposed northern Saskatchewan segment with sulphides, concentrated particularly along fold hinges. Sulphides have previously been observed to increase conductivity significantly over large regional areas (e.g., Cook and Jones, 1995; Gupta and Jones, 1995). The high anisotropy in the hand sample explains the observed lack of response for currents crossing the body at this location (Jones et al., 1993). Stratabound relationships of these sulphides within their greywacke host suggest that they are syngenetic (Sibbald, 1984, 1986), not related to post-subduction or post-collisional fluid migration processes, and were developed between the advancing La Ronge arc and the Hearne craton during a hiatus in intermediate-felsic volcanism and sedimentation (Mineral Resources of Saskatchewan, 1991). This hiatus may have been key to the seafloor concentration of the metals. We propose that during compression the sulphides migrated from high stress regions along the limbs of folds to lower stress regions along the fold hinges. Their current position, in the hanging wall of the Guncoat thrust, implies that subduction during arc-craton collision must have been directed towards the craton, and that the Guncoat thrust may be a re-activated subduction-related feature. The metasedimentary sequences stop beneath the surface trace of the Needle Falls Shear Zone, suggesting that the Hearne cratonic edge lies at this position, and that the craton/metasedimentary contact provided a rheological boundary for a zone of weakness leading to localization of stresses for fault genesis.

Whether this cause for the conductivity anomaly is also operating for the whole length of the anomaly is an open question. The along-strike continuity of the orogen, particularly the similarities in tectonic setting from the COCORP work in North Dakota (Nelson et al., 1993) and the Lithoprobe work in northern Saskatchewan (Lucas et al., 1993), would argue for this being the case. Striking for both localities is that the conductivity anomaly is interpreted to be draped over an Archean microcontinent of unknown affinity. Also, the insensitivity of the anomaly to currents travelling across it, rather than along it, is consistent from southern North Dakota to northern Saskatchewan. Accordingly, we conclude that the tectonic environment that led to the development of the sulphides exposed in northern Saskatchewan likely occurred over 1,000+ km extent on the western and northern boundaries of the Trans-Hudson orogen internides.

However, the southern terminus of the conductivity anomaly, from the Black Hills to south-eastern Wyoming (Fig. 1), is likely caused by a different mechanism. Camfield and Gough (1977) noted the spatial correlation of the NACP at that location with the Hartville Arch, which connects the Black Hills to the Laramie uplift. Within the Hartville Arch are mapped exposures of graphite (Osterwald et al., 1959) and major shear zones and fault systems that continue to the Sierra Madre. Modelling of the magnetometer array responses at the Black Hills shows that the anomaly at that location is both very shallow (within 1 km of the surface) and highly conductive (<1 $\Omega \cdot$m) (Jones and Craven, 1990). Such very low resistivities are necessary to explain the observation that the anomalous horizontal EW magnetic field is larger than the normal horizontal EW magnetic field. This part of the conductor also follows the edge of the Wyoming province, rather than lying within the internides of the orogen as does the rest of the anomaly. It is possible that the foredeep hypothesis of Boerner et al. (1996) explains this section of the anomaly. Accordingly, the apparent continuity of the anomaly north and south of the Black Hills could be an artifact of the coarse spatial resolution of the magnetometer array studies. Rather, there could be two anomalies caused by different conducting mechanisms, one due to sulphides for most of the Trans-Hudson orogen, and one due to graphite at its southern terminus.

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