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Electromagnetic images of modern and ancient subduction zones

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ABSTRACT

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One question frequently posed since the advent of plate tectonic theory is "When did it begin?". Correlations of zones of enhanced electrical conductivity with orogenic belts dated to half the age of the Earth support the suggestion that plate tectonic processes have been in operation since at least the Early Proterozoic. The causes for such zones are examined, and, whereas anomalies associated with modern and recent subduction/collision systems can be readily explained, an explanation for Palaeozoic and Proterozoic ones is more difficult.

Correlation of geophysical characteristics associated with the Trans-Hudson (North America) and Svecofennian (Fennoscandia) orogenic zones, and consideration of the paleopole positions of those zones and the Superior and Slave provinces during the period 1.900–1.825 Ga, lead to the suggestion that a Pan-Scandamerican orogenic zone was in existence at that time.

Introduction

Using deep-probing seismic and electromagnetic profiling, it is possible to obtain images of "scars" within the crust that are a consequence of processes associated with the subduction of oceanic material and the subsequent continent–ocean–continent collision. Over the last two decades, such images have been obtained over both active subduction systems and fossil ones dated to half the age of the Earth. As such, these images add to the testimony that plate tectonic theory can be applied back to at least the Early Proterozoic.

In this paper, I will review results from natural-source electromagnetic studies, using principally the magnetotelluric method (MT), over some modern and ancient subduction/collision zones and propose that the enhanced conductivity zones observed are related to the subduction processes. Such a relationship was previously suggested by Law and Riddihough (1971) and examined by Drury and Niblett (1980), but data collected during the 1980s provide a firmer foundation for the spatial and geometric correlations. The cause of the observed enhanced conductivity zones is still an open question, but the very high values associated with ancient orogens precludes fluids, which are too mobile to remain in place for 2 billion years and for which replacement from the mantle is too speculative. A preferable explanation is in terms of some highly conducting mineral phases, such as graphite or various sulphides, in underplated metasediments.

It should be noted that the zones to be discussed are anomalous regions of enhanced electrical conductivity within the middle and lower crust. A well-known observation for the continental lower crust is that it is generally higher in conductivity, by one to two orders of magnitude, than laboratory observations on comparable dry rock samples (see, e.g., Jones, 1992). However,

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the zones associated with subduction/collision are far more conducting, by one to two orders of magnitude, than the "host" middle to lower crustal material.

The parameter being sensed: electrical conductivity (resistivity)

Electromagnetic methods (EM) are sensitive to changes in electrical conductivity both laterally and vertically. Although EM methods are sensing enhancement of conductivity σ, for historical reasons — and for reasons associated with the magnitudes of the values themselves — it is common to discuss and display the reciprocal of conductivity, which is electrical resistivity ρ. This parameter varies by over seven orders of magnitude within the continental crust (Fig. 1), having values of greater than 100,000 Ω.m for competent crystalline upper crust, to values lower than 0.01 Ω.m for mineralized zones such as graphitic schists. Although EM methods are sensitive to changes of conductivity within a volume of the earth — and as such are integrating techniques — this very large variation in resistivity ensures a higher resolution, particularly laterally, compared to other integrating geophysical methods such as gravity, thermal or surface wave studies. Also, EM studies suffer far less from the intrinsic nonuniqueness inherent in potential field data interpretations because the potential functions involved are vector (Hertz) potentials and not scalar potentials. For one-dimensional (1D) models of the earth, there is a theoretical uniqueness proof that, given perfect MT data at all frequencies, only one model will satisfy the data (Bailey, 1970). Whilst we may never obtain perfect data, modern high-quality data are better for constraining the interpretations than older data.

The method being used: the magnetotelluric technique (MT)

The magnetotelluric technique uses the naturally-occurring time-varying electromagnetic fields as a source. A useful collation of MT papers describing the method to the early 1980s can be found in Vozoff (1986). At periods greater than about 0.1 s these variations are due mainly to emissions of ejected solar plasma interacting with the Earth's magnetosphere (aurora is one prominent and visual display of this phenomenon). At shorter periods the energy originates from distant electrical storms (up to half the globe away)

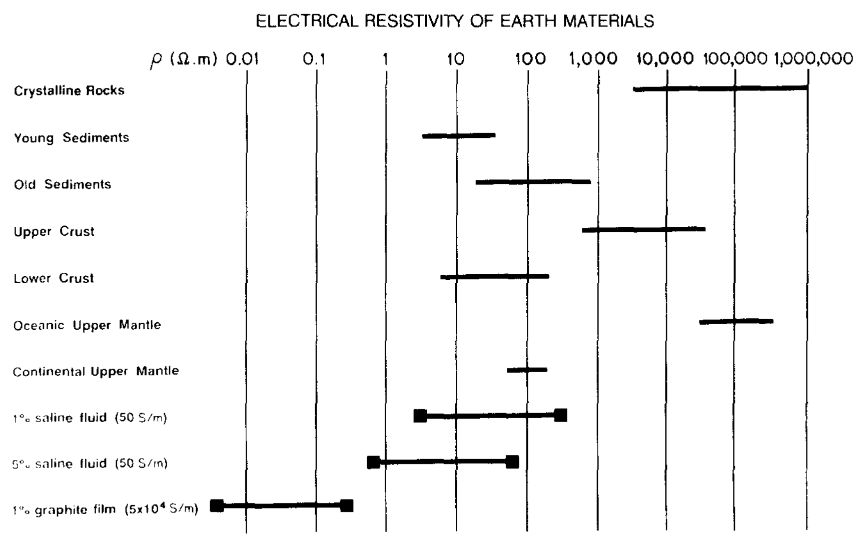

Fig. 1. Variation of electrical resistivity in the continental crust (redrawn from Haak and Hutton, 1986). The lower bars represent the ranges of resistivity for a resistive matrix with 1% and 5% of saline waters (50 S/m conductivity) and 1% graphite film, with varying pore geometry. The upper and lower bounds on these bars are for assumptions of Archie's Law with exponents of 2 and 1, respectively.

trapped in the Earth's ionospheric waveguide. The magnetic field external to the earth interacts with the conductivity structure of the earth, inducing electric fields and secondary magnetic fields. An observer on the earth's surface measures the total electric and magnetic fields as a function of period (inverse of frequency) and computes the ratio of these two fields and the phase difference between them.

For a highly *conductive* body, there is only a small electric field induced so that the magnitude of the ratio between it and the magnetic field is small and the two fields are totally out of phase (i.e., 90° phase difference). In contrast, for a highly *resistive* body there is a large induced electric field leading to a large ratio and the fields are totally in phase (i.e., 0° phase difference). This electric field to magnetic field ratio is scaled so that for a uniform half space it gives the correct resistivity of the medium, and is hence an "apparent resistivity" akin to the equivalent parameter in D.C. resistivity methods. At high frequencies (alternatively called "short periods"), the fields are influenced by structures close to the receiver site, whereas at long periods (low frequencies) because of the skin depth effect the fields respond to more distant structures. Hence, analysis of the ratios between the fields and the corresponding phase differences as functions of period gives an "image" (depth and lateral distance) of the earth's conductivity structure.

One important point with the MT method (which is true of most geophysical methods) is that a "natural" parameterization of the earth model, in terms of lengths (depths and distances) and resistivities, is often not the correct parameterization for the model parameters to be independent (or "orthogonal") of each other. For example, in a situation where a conducting zone is sandwiched between two resistive ones, the orthogonal parameterization of the conducting zone is not in terms of its layer thickness h and resistivity ϱ, but in terms of its *conductance* S and *resistance* T; the conductivity–thickness product and resistivity–thickness product respectively. Typically, S (in units of Siemens, S) will be well resolved, but T (units of ohms, Ω) will be virtually unresolved unless the data are of very high

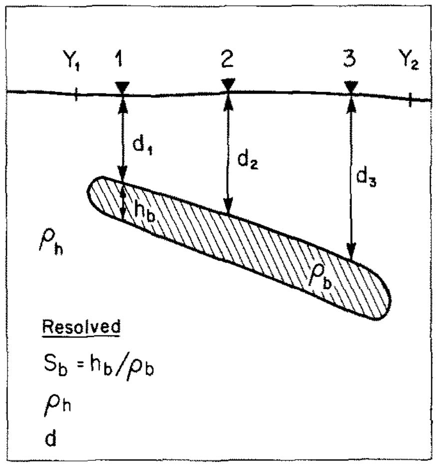

Fig. 2. Generalized model of a dipping conductive slab showing model parameters and their resolution.

quality (standard errors smaller than a few percent). Generally, it is difficult to image a structure of conductance less than the total conductance from the surface down to that depth, and it is difficult to image a structure having lateral dimensions far less than its depth.

For the problem of imaging a dipping zone of enhanced conductivity (Fig. 2), the parameters that are well-resolved in a properly designed EM study are:

(1) the resistivity of the host rock, ϱ_h;

(2) the depths to the top of the body (which gives its geometry), d;

(3) the locations of the "edges" of the body, y_1 and y_2; and

(4) the vertically-integrated conductance of the body (from which can be deduced any lateral variation), S_b (assuming that $S_b > \sigma_h d$ $(= d/\varrho_h)$, and that sufficiently long-period measurements are made that penetration through the body is assured).

Marginally resolved, or more usually unresolved, is the actual resistivity and thickness of the body, ϱ_b and h_b, respectively. This means that the geometry of the base of the zone cannot be imaged. At best, a first-order approximation can be obtained by assuming that the resistivity remains constant and accordingly that lateral variation in S_b can be attributed to variation in h_b alone. This can be a very restrictive assumption given that the resistivity is so critically dependent on the interconnectivity (see, e.g., Waff, 1974; Honkura, 1975; Schmeling, 1986; Hyndman and Shearer, 1989; Jones, 1992). In two-dimensional (2D) models, the mode in which currents are flowing perpendicular to strike (B-polarization) is sensitive to the electrical continuity of the zone, whereas the other mode, in which currents flow parallel to strike (E-polarization) gives a measure of the magnitude of enhanced conductivity.

Some of the EM work to be discussed is the result of Geomagnetic Depth Sounding (GDS) experiments, which involve synoptic observations at a number of sites of the three components of the magnetic field only. GDS profiles and arrays are very useful mapping tools (see, e.g., Gough, 1989), but have limited resolving power compared to MT.

Images of modern subducting plates

Juan de Fuca plate

The subduction of the Juan de Fuca plate off the northwest coast of North America has been the subject of two MT induction studies during the 1980s. The 1984 MT survey of Vancouver Island by Kurtz et al. (1986, 1990) was able to image a conducting zone of some 200 S (Fig. 3) that correlated in depth with a zone of enhanced reflectivity ("E"-reflector, Green et al. 1986, 1987). It was originally suggested that this zone was near the boundary between the top of the downgoing Juan de Fuca plate and the overriding North American plate (Green et al., 1986). However, earthquake foci from the seismic network on Vancouver Island, and marine seismic reflection studies offshore, show that this conductive/reflective zone is not the top of the oceanic plate (Hyndman, 1988). Instead, it has been suggested that this zone represents a thermal/metamorphic boundary below which fluids, originating either from the downgoing sediments themselves or from devolatization reactions, are trapped (Jones, 1987; Hyndman, 1988). Recent analyses of teleseismic shear wave arrivals support the suggestion that the top of the downgoing oceanic plate is some 10 km below the "E"-reflector (Cassidy and Ellis, 1991, 1992).

The 1986 EMSLAB (ElectroMagnetic Study of the Lithosphere and Asthenosphere Beneath the Juan de Fuca plate) experiment (EMSLAB group, 1988; Booker and Chave, 1989) was the largest EM experiment conducted to date, and involved some fifty scientists from ten institutions (six countries) simultaneously making observations of the EM fields on the Juan de Fuca plate from its birthplace along the ridge to the site of its consumption under the Cascades. The final model produced (Wannamaker et al., 1989) is virtually identical in all major features to that of Kurtz et al. (1986, 1990) with the successful imaging of a horizon which is intimately related to the downgoing slab, but is probably not the slab itself. Again, this zone has a conductance of the order of 100 S beneath the continent, but is higher

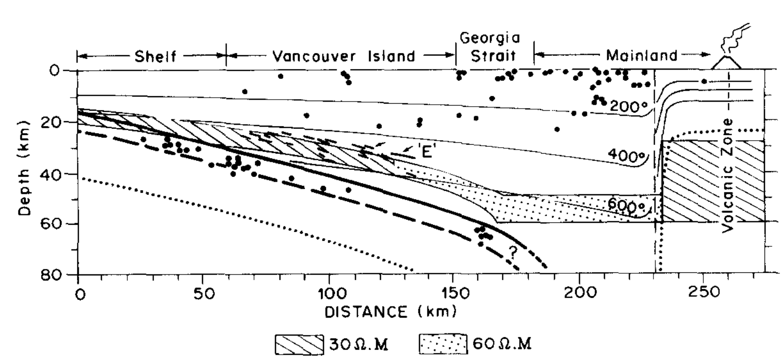

Fig. 3. Model of the geophysical structure beneath Vancouver Island (redrawn from Hyndman, 1988). The shaded zone is the region of high electrical conductivity, the top of which spatially correlates with the "E"-reflector. The interpreted location of the dipping oceanic plate is shown in the solid and dashed lines; the earthquake epicentres are given by the dots. Thermal modelling indicates that the top of the conductor, and the "E"-reflector, are at 400°C.

beneath the coast; this decreasing eastward conductance was also a feature of Kurtz et al.'s (1990) model. Imaging this feature was more difficult for Wannamaker et al. (1989) than for Kurtz et al. (1990) because the upper crust is far less resistive beneath the Coast Range of Oregon (some 100 Ω.m) than beneath Vancouver Island (some 1000s Ω.m). Hence, the total conductance of the Coast Range material above the enhanced conducting zone is of the same order as the conductance of the zone itself, whereas for Vancouver Island the conducting zone dominated the response.

Kurtz et al. (1990) and Wannamaker et al. (1989) interpret the enhanced conductivity as due to 1–2% saline fluids in an interconnected network. Jones (1987) proposed a generic crustal model of fluids becoming trapped beneath an impermeable layer at a temperature of 400°C, and mentioned the correlation of the electrical and seismic reflection boundaries with a 400°C isotherm beneath Vancouver Island. Hyndman (1988) extended Jones's model to consider the possible sources of water from dehydration reactions. Analyses by Calvert and Clowes (1990) of the high reflectivity observed for some reflections from the "E" horizon led them to infer the presence of a shear zone, because fluids alone could not provide the geometries and amplitudes observed for those reflectors (reflection coefficients of up to 20%). Calvert and Clowes (1990) considered that the zone was caused by shearing of subcreted metasediments as they reached 400°C temperature, and suggested that the shear zone trapped the fluids expelled from the plate. In a recent study of teleseismic shear wave arrivals with almost vertical ray paths beneath Vancouver Island, Cassidy and Ellis (1991) concluded that the "E" zone is a low-velocity zone in V_s (low by more than 1 km/s) as well as in V_p, and showed that the zone has an anomalously high Poisson ratio of greater than 0.34. Poisson's ratio was found to be more normal (0.25) throughout the rest of the crustal section, including the region associated with the Juan de Fuca plate itself. The seismic information can be explained by fluids in rocks of porosities of 0.1–1% and pore aspect ratios of 0.001–0.01, which are consistent with the porosities required for the interpretation of the enhanced conductivity zone in terms of interconnected saline fluids. Further studies by Cassidy and Ellis (1992) have imaged this zone as deepening beneath Georgia Strait and the B.C. mainland, as suggested by the MT model of Kurtz et al. (1986, 1990; Fig. 3). Thus, the electromagnetic and seismic observations can be explained by saline fluids alone, with reasonable values of salinity and porosities.

However, mineralized metasediments could be adding to the conductivity. This is discussed below with regard to the North American Central Plains (NACP) conductivity anomaly. It is worth noting that the two models for the dipping conducting zone of Kurtz et al. (1990) and Wannamaker et al. (1989) require an electrical connection between the conducting sediments of the accretionary wedge and the conductive and reflective zones observed at depth. This connection is required for modelling the B-polarization data.

Phillipine Sea plate

Scientists in Japan have been using MT and GDS methods for over two decades to study the subduction of the Phillipine Sea plate underneath southwestern Japan. The development of seafloor instrumentation during the early 1980s has enhanced this program. Recent GDS ocean-bottom studies from the Ryukyu Trench to the Okinawa Trough (Shimakawa and Honkura, 1991) have been interpreted in terms of two zones of enhanced conductivity; a relatively shallow one beneath the forearc and a much deeper one beneath the trough (Fig. 4). The authors acknowledge that their model resolution permits lateral variation in the positions of both blocks by up to 20 km, and that the resistivities of the blocks can be changed within the bounds 1–10 Ω.m. The data preclude combining the two blocks into a single anomalous zone. Of particular interest is the spatial correlation of the upper block with the principal zone of earthquakes (Fig. 4), which clearly identifies the block as associated with the downgoing slab. In contrast, there is no such correlation between the deeper conducting block and the top of the slab as defined by the seismic-

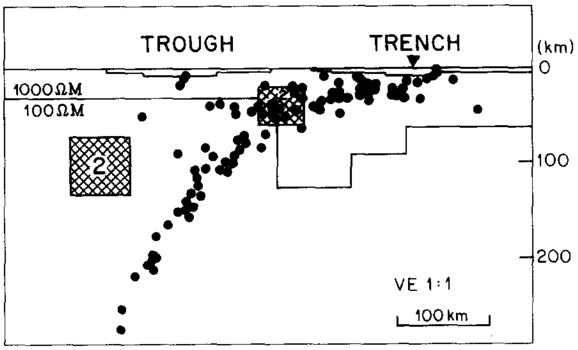

Fig. 4. Conductivity model for the region of subduction of the Phillipine plate beneath Japan (redrawn from Shimakawa and Honkura, 1991). Note that the shallower zone of enhanced conductivity spatially correlates with the earthquake epicentres (circles), whereas the deeper zone lies above the earthquakes.

ity. Note that only a small fraction of the downgoing slab, as defined by the epicentres, is conductive, which infers that certain conditions must be met.

Shimakawa and Honkura (1991) interpret the enhanced conductance of the shallow block as being due to water released through a dehydration process, whereas the deeper conductor is believed to be a zone of partial melt possibly triggered by water released from another dehydration reaction. These two blocks have very high vertical conductances of 22,500 S and 35,000 S for the shallow and deep blocks respectively. For the shallow block it is difficult to understand how such a large zone (50 × 45 km in section) of pervasively high porosity could exist.

Mesozoic subduction: the Alaskan Range

MT studies across the Alaskan Range were performed by Stanley et al. (1990), principally as part of the U.S. Geological Survey's Trans Alaskan Crustal Transect (TACT). The Alaskan Range was formed during the Late Jurassic to Mid-Cretaceous as the Talkeetna superterrane, riding on the Farallon plate, docked against Proto-Alaska with attendant subduction of the Farallon plate to the north beneath Proto-Alaska (Csejtey et al. 1988; reported in Stanley et al. 1990).

The MT models produced for three profiles crossing the Denali fault system all included extensive zones of enhanced conductivity, with resistivities in the range of 1–3 Ω.m, which, in places, are modelled as constituting 20–50% of the entire crust. The conductances of these zones are thus well in excess of 6,000 S and extend up to 18,000 S. The conductive body in the MT model for the central profile in the eastern Alaskan Range correlates with bands of major reflections (Fig. 5). Given our knowledge of the sensitivity of MT data to various model parameters, the correlation of the lower interface of the conductive body with a seismic horizon is not well substantiated; once the EM fields have entered the highly conducting body resolution is lost. However, the coincidence of the top of the body and a major reflector is significant.

Stanley et al. (1990) suggest that these anomalous conducting zones are due to mildly-meta-

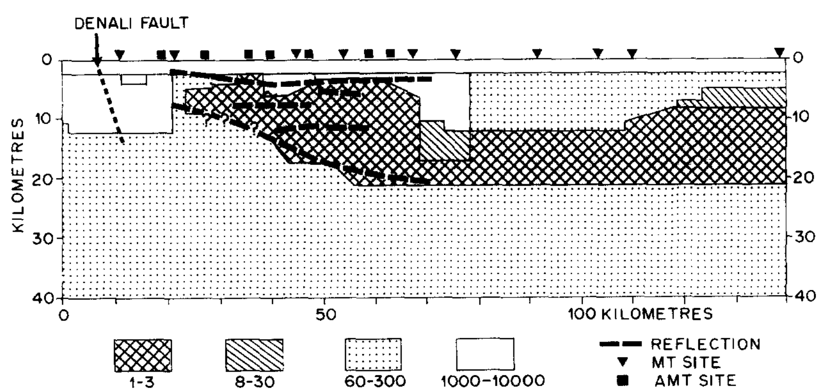

Fig. 5. Conductivity model for the eastern Alaskan Range showing the coincidence of a zone of enhanced electrical conductivity with major seismic reflectors (heavy dashed lines) (redrawn from Stanley et al., 1990).

morphosed underplated Mesozoic shale flysch that was formed in the collapsed oceanic basin between the converging Talkeetna superterrane and the Yukon–Tanana terrane, which formed the continental margin block of Proto-Alaska. It is further suggested that the deep marine basin was subject to anoxic conditions, leading to the development of black shales in the flysch; large volumes of black shale are present in various terranes and belts. The very high conductivities of black shales had been observed in laboratory studies by Duba et al. (1989).

Stanley (1989) has suggested that underplated black shale flysch is also responsible for a conducting region beneath the Carpathian Mountains, which were formed during Mesozoic closure of Europe and microplates in front of the converging African plate. The conductance of the Carpathian zone was modelled to be in the range of 2,000–3,000 S by Picha et al. (1984).

Early Palaeozoic subduction: the Iapetus suture in Scotland and Ireland

The Iapetus suture (Wilson, 1966) has been studied in southern Scotland using EM methods since the early 1960s (Jain, 1964; Jain and Wilson, 1967). The landmark magnetometer study of Edwards et al. (1971) identified the "Eskdalemuir anomaly". V.R.S. Hutton and her students (Jones and Hutton, 1979a,b; Ingham and Hutton, 1982; Sule and Hutton, 1986) and Beamish (Beamish and Smythe, 1986) have made extensive MT measurements of this anomaly, and recently an MT profile was recorded across the same tectonic structure in Ireland (Whelan et al., 1990). All interpretations show a north-dipping zone of enhanced conductivity (Fig. 6), the top of which correlates with the suture imaged seismically by the BIRPS group in both the Irish and North Seas (Beamish and Smythe, 1986; Klemperer and Matthews, 1987). The conductance of this zone is estimated at 650–850 S (Beamish and Smythe, 1986). From an MT study in northern England, it has been tentatively inferred that there may also be a southward-dipping conductive zone beneath that region which also correlates with a seismic horizon (V.R.S. Hutton, pers. commun., 1986). Although the Southern Uplands fault is thought to be associated with the Iapetus suture, the conductivity anomalies mapped in southern Scotland and Ireland trend at an angle of some 20° to the fault (Whelan et al., 1990), which may suggest oblique subduction as proposed by Phillips et al. (1976). Various models have been suggested for the tectonic history of the closure of the Iapetus, and certainly the information provided by the MT studies is proving to be an important geophysical result which may aid in discriminating between competing geometries.

Early Proterozoic subduction

The Trans-Hudson Orogen

The longest, and perhaps most enigmatic, conductivity anomaly discovered to date is the North American Central Plains (NACP) structure imaged by magnetometer array studies in the U.S. and southern Canada by Gough and his col-

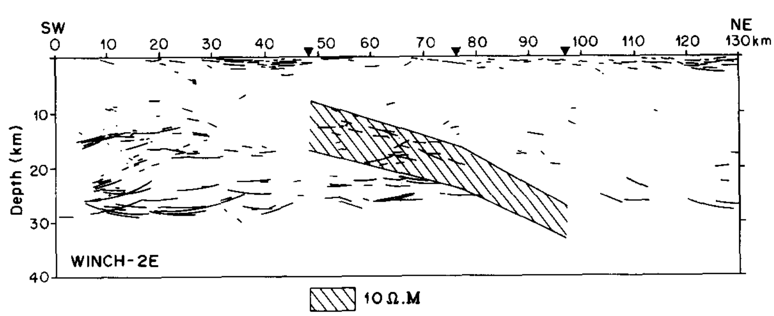

Fig. 6. Conductivity model of the Iapetus suture (redrawn from Beamish and Smythe, 1986).

leagues (Alabi et al., 1975, and references therein), and in northern Canada by Handa and Camfield (1984) and Gupta et al. (1985). As shown by Jones and Craven (1990; see also Gupta et al., 1985, and Green et al., 1985), when the trace of this anomaly is drawn onto the tectonic assembly map of North America proposed by Hoffman (1988), the NACP lies totally within the 1.9–1.85 Ga Trans-Hudson orogen (fig. 9, Hoffman, 1981) from its southern end to at least Hudson Bay. Accordingly, the NACP is intimately related to the orogen itself and is a "marker horizon" for the Early Proterozoic orogen as suggested initially by Camfield and Gough (1977) and later by Green et al. (1985). EM studies prior to Jones and Savage (1986) and Jones and Craven (1990) were too coarse to image the geometry of the structure in any detail, but they did show that the character of the structure varies along its strike and appears to be closer to the surface and/or of greater conductance in the U.S. than in Canada. The 2D model (Fig. 7) developed by Jones and Craven (1990) to explain the MT observations is a conductive zone of some 2,000–4,000 S with its upper surface at about 10 km depth at a longitude of 103°W, just north of the U.S./Canada border in southeastern Saskatchewan. The zone dips markedly to the west for about 50 km at an angle of approximately 12.5°. The zone must be relatively thin and must have a resistivity of much less than 5 Ω.m (modelled at 0.1–0.5 Ω.m). First results from a COCORP seismic reflection experiment across the Williston Basin, just south of the international border, have imaged an arcuate band of reflectors dipping to the west at 5 s — or 15 km — which correlates geometrically and spatially with the NACP model of Figure 7 (Nelson et al., 1993).

In northern Saskatchewan, the anomaly has been modelled as having a conductance in the range 2,000–2,500 S by Handa and Camfield (1984), and near Hudson Bay, Gupta et al. (1985) modelled their data in terms of a north-dipping structure of 500–3,500 S.

For such a zone of high conductivity to be explained by saline fluids, the porosity would have to be implausibly high — of the order of 12–20% depending on the geometry of the pore spaces and the degree of salinity. Also, given the age of the structure (1.85 Ga) one would have to propose a continual recharge mechanism as it is highly unlikely that fluids from obducted sediments or from devolatization would remain in the crust for such a long time. Thus, alternative causes have to be proposed to explain the observed enhancement in electrical conductivity, together with the other geophysically observed phenomena such as a gravity high, a magnetic quiet zone, and high heat flow. Camfield and Gough (1977) noted that the southern end of the NACP in Wyoming correlates spatially with major fault zones known to contain graphite, although graphite is not always conducting (Camfield et al., 1989). Jones and Craven (1990) dwell on various speculative interpretations for the enhanced conductivity of the NACP, but none are completely satisfactory.

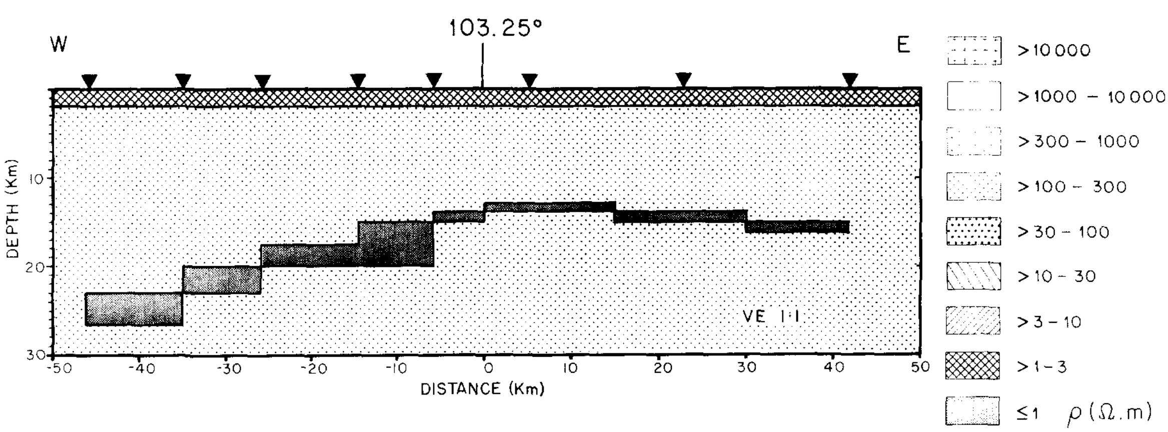

Fig. 7. Conductivity model of the Trans-Hudson orogen (redrawn from Jones and Craven, 1990).

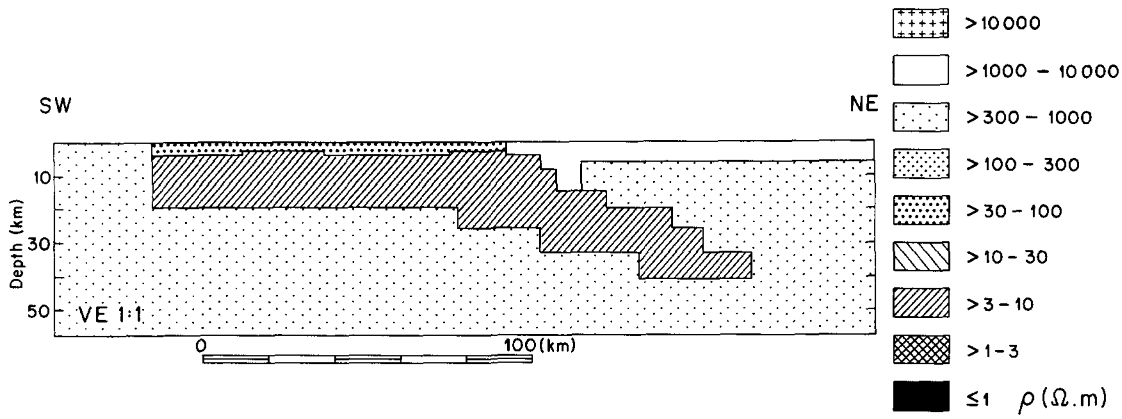

Fig. 8. Conductivity model of the Skellefteå conductor (redrawn from Rasmussen et al., 1990).

Ladoga–Bothnian Bay–Skellefteå zone

A northwest-striking lineament from Lake Ladoga (northeast of St. Petersburg) through Finland to Bothnian Bay then across to the Skellefteå zone in northern Sweden is the boundary between Archean-age Karelian rocks to the northeast and Early Proterozoic Svecofennian rocks to the southwest (Park, 1985, 1991; Gaál and Gorbatschev, 1987; Gaál, 1990). Geological models of the zone include a northeast-directed subduction zone of 1.85 Ga age.

Electromagnetic data from a study by Rokityansky et al. (1981) to the northeast of St. Petersburg were interpreted as imaging a northeast-dipping zone of some 2,000–4,000 S with its top at 10 km. The existence of a significant zone of enhanced conductivity in north-central Sweden was first noted in data recorded on a widely-spaced GDS array covering the whole of Scandinavia (Jones, 1981). The anomaly, called the "Storavan" anomaly because of its proximity to the GDS station with that name, was manifest in strong induction effects, such as attenuation of the horizontal magnetic fields and a reversal in the induction vectors on either side of it. The data showed that the anomaly runs from the Gulf of Bothnia striking in a north west direction across the Skellefteå mining region. Modelling of data from an MT study across the Skellefteå zone by Rasmussen et al. (1987) gave a northeast-dipping conducting zone of the same conductance as the Ladoga anomaly, i.e., 2,000–4,000 S (Fig. 8). Studies by Korja (1992, Korja et al., 1993-this issue) also discovered an anomaly of 2,000–4,000 S at depths of 14–20 km on the Finnish side of the Gulf of Bothnia along strike from the Storavan–Skellefteå anomaly. Recent seismic reflection data acquired across the same structure in the Gulf of Bothnia (BABEL experiment, BABEL Working Group 1990) reveal northeast-dipping bands of reflectivity that correlate with the top of the Skellefteå conductivity model of Rasmussen et al. (1987).

The Wopmay orogen

The Wopmay orogen (Hoffman, 1980) of northwestern Canada (Fig. 9) represents the remnants of the active western margin of the Slave province, which is a late Archean (2.7–2.5 Ga) granite-greenstone terrain. West-dipping subduction of oceanic lithosphere in the period 1.885–1.865 Ga ended with the collision of a microcontinent with the Wopmay continental margin of the Slave province (Hoffman, 1980, 1988). An EM survey was conducted in 1982 to determine if there was a significant conductivity anomaly similar to the NACP (Camfield et al., 1989). It consisted of a 250-km east–west profile of eight GDS stations and a single tensor MT station located on the Wopmay fault in the centre of the profile. In addition, scalar high-frequency MT measurements were made at 12 sites, with a 1-km spacing, across the Wopmay fault itself.

The main conclusion from this experiment is

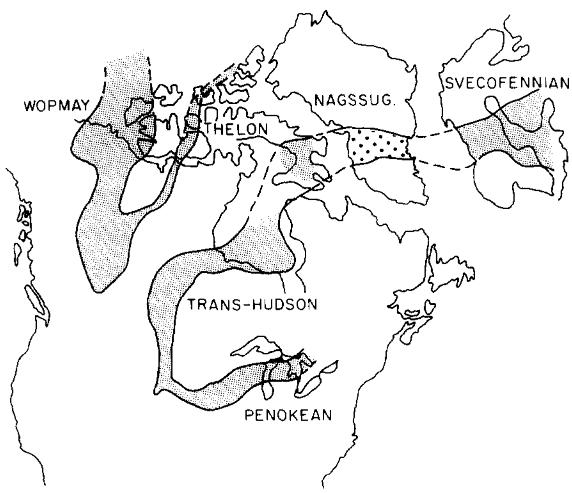

Fig. 9. Proposed "Pan-Scandamerican" orogenic belt connecting the Trans-Hudson and Svecofennian orogenies through the Baffin and Nagssugtoqidian belts. Also shown are the locations of the coeval Penokean and Wopmay orogens (modified from Condie, 1990).

that there are no significant zones of enhanced electrical conductivity associated with the Wopmay orogen. A small surficial body, modelled as a 2-km-thick and 30-km-wide block of 20 Ω.m (conductance of 100 S) material, was identified. This block correlates spatially with metamorphosed graphitic pelites contained in a unit of deep-water facies continental slope-rise deposits. Except for this body, the upper crust in the region is highly resistive (> 2,000 Ω.m), and the lithosphere below 12 km is of moderate resistivity (200 Ω.m). Laboratory measurements on samples of the graphitic pelite yielded resistivity values in excess of 10,000 Ω.m, which leads to the conclusion that the enhanced conductivity is more likely caused by brine-filled cracks associated with the pelite's well-developed cleavage and schistosity, rather than by the graphite.

Correlation between Early Proterozoic conductivity anomalies: a possible Pan-Scandamerican orogenic zone?

The period 2.0–1.85 Ga in the Early Proterozoic represents one of only two well-documented global orogenic episodes of continental growth (Condie, 1990). Accretion of Laurentia during this episode, in which Archean microcontinents collided and welded together (Hoffman, 1988), is estimated to have been ≈ 2.0 km^3/yr, which is three to four times greater than at other times in the Archean or Late Proterozoic (0.5–0.7 km^3/yr) (Condie, 1990). Four major orogenies were active during this time, and are representative of a major episode of continental margin magmatism 1.9–1.83 Ga (Van Schmus et al., 1987). These are the Trans-Hudson (Hoffman, 1981), Svecofennian (Park, 1985), Wopmay (Hoffman, 1980) and Penokean (Van Schmus, 1980) orogenies (Fig. 9).

Table 1 lists various geophysical characteristics of three of the conductivity anomalies of Early Proterozoic age. It is clear from the table that all three have similar geometrical and geophysical characteristics, which leads to the suggestion that all three may be a manifestation of the same tectonic process, and may be "markers" of a single mega-continental-scale "Pan-Scandamerican" orogenic belt (Fig. 9). Condie (1990) prefers a connection between the Penokean and Svecofennian orogenic belts (Fig. 9), but notes that this connection is uncertain. The predominantly westward-dipping geometry of the Trans-Hudson orogen and northeastward-dipping geometry of the Svecofennian orogen is consistent with the two orogens having once been connected. No significant anomalous zone in electrical conductivity has been found in the Penokean orogen (Dowling, 1970; Sternberg, 1979; Young and Rogers, 1985). Note that in the proposed reconstruction of Figure 9, the Svecofennian orogeny is related to the Nagssugtoqidian orogeny of Greenland, rather than the Ketilidian mobile belt as suggested by Gower and Owen (1984) and adopted by Condie (1990).

Previously, Rokityansky (1983) had suggested that an elongated conducting feature ("Trans-

TABLE 1

Comparison of EM anomalies of Hudsonian age

	Age (Ga)	Conductance (S)	Reflective	Depth to top (km)	Lateral extent (km)
NACP	≈ 1.85	3,000–5,000	yes	9	60
Bothnia	≈ 1.85	2,000–4,000	yes	5	90
Ladoga	?	4,500	?	10	40

scandinavian anomaly") extended from northeast of St. Petersburg to northern Sweden. More recent MT measurements in Finland (Korja et al., 1993-this issue, and references therein) suggest that there may be a connection between the two conductors, but that it is not along the Raahe–Ladoga line. Instead, it appears to trend east-west across southern Finland then north at the Finnish coast to a point opposite the Skellefteå conductor. The model of this region (Korja, 1992; Korja et al., 1993-this issue) includes a "Bothnian" conductor on the Finnish side of Bothnian Bay with conductance of some thousands of Siemens in accord with the Ladoga and Skellefteå values.

In North America, the NACP is thought to lie within the Trans-Hudson orogen from its southern end, in the Wyoming Basin, to the western shore of Hudson Bay (Gupta et al., 1985). The Trans-Hudson orogen is known to extend as far east as the Cape Smith belt in northern Ungava, Quebec (St-Onge and Lucas, 1990). Others have suggested that it extends further east to include the Nagssugtoqidian zone of central Greenland (Lewry et al., 1985; Van Schmus et al., 1987; Lewry and Collerson, 1990) in a "Pan-American" orogenic system (Fig. 9).

Paleomagnetic data for Fennoscandia (Pesonen et al., 1989) and for the Superior, Churchill and Slave provinces (Dunsmore and Symons, 1990; Symons, 1991) support the suggestion of a Trans-Hudson – Svecofennian connection. Shown in Figure 10 are the clusters of 1.900–1.825 Ga paleopole positions for rock units from Fennoscandia (FE) and the Trans-Hudson orogen (THO) and similar age mean pole positions from the Slave (SLP) and Superior (SUP) provinces, respectively. It is apparent that Fennoscandia lay on the border of the Superior province during this time interval. Younger paleopole positions show that Fennoscandia and North America subsequently separated. At 1.750 Ga, the Fennoscandian pole moved west and north to a longitudinal position of 150°W (Pesonen et al., 1989), whereas the North American pole moved east and south to a longitudinal position of 15°W (Irving, 1979).

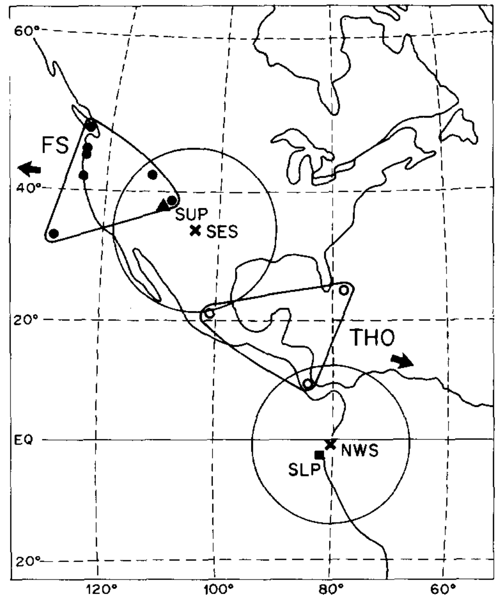

Fig. 10. Pole positions for rock units magnetized between 1.900 and 1.825 Ga in Fennoscandia and North America. The cluster marked *FS* represents the mean pole positions (solid circles) for Fennoscandia (Pesonen et al., 1989). The cluster marked *THO* represents the pole positions (open circles) for rock units within the Trans-Hudson orogen (Dunsmore and Symons, 1990). *SLP* and *SUP* are the mean pole positions of the Slave and Superior provinces respectively, and *NWS* and *SES*, with their 95% cones of confidence, are the poles for rock units to the northwest and southeast of the Trans-Hudson orogen (Dunsmore and Symons, 1990).

One possible objection to this suggestion concerns the age of the north–south-striking Torngat orogen in Labrador, which lies between the Cape Smith belt and Greenland. U. Schärer (reported in Hoffman, 1988) obtained an age of 1.910 Ga from a single zircon extracted from a mylonite zone in the orogen. Such an early age, which predates the collision of the Hearne and Superior cratons, would preclude the proposed connection between the Trans-Hudson and Svecofennian orogens. However, Hoffman (1988) notes, from geological correlations, that the Torngat orogen must be younger than 1.880 Ga, and possibly younger than 1.810 Ga. Given the paleomagnetic evidence (Fig. 10), perhaps the split of Fennoscandia from the North American cratons was related to the Torngat orogen. Hoffman (1990) has raised other objections to the continuity of the Trans-Hudson orogen eastward to Greenland, but these have been challenged, to some extent, by Lewry and Collerson (1990).

Causes of enhanced conductivity

As discussed by a number of authors (e.g., Haak and Hutton, 1986; Jones, 1992), there are many causes for enhanced conductivity. The two most commonly proposed explanations of enhanced conductivity in the continental lower crust are interconnected fluid phases (either brines or partial melts; Hyndman and Hyndman, 1968; Shankland and Ander, 1983; Gough, 1986; Jones, 1987), or carbon on grain boundaries (Duba et al., 1989; Frost et al., 1989; Mareschal, 1990; Haak et al., 1991). However, the anomalous zones associated with oceanic subduction and collisional orogens are regions of greatly enhanced conductivity, by one to two orders of magnitude, compared to the "host" lower crust. These anomalies have been interpreted as possibly due to hydrated minerals, e.g., Green et al. (1985), Gupta et al. (1985). However, hydrated minerals have been shown to be intrinsically resistive — it is the waters released by dehydration reactions that make the rocks have a low resistivity in the laboratory (Olhoeft, 1981).

For modern ocean–continent subduction systems, there are two mechanisms that may produce regions of enhanced conductivity: saline fluids at shallow depths and magma at greater depths. An integrated interpretation of data from the Vancouver Island region suggests that the shallow zone of enhanced conductivity is not actually the top of the plate itself, but is related to it spatially and geometrically. The low resistivity is explained as due to saline fluids, in a matrix of 1–2% porosity (Hyndman, 1988; Kurtz et al., 1990; Calvert and Clowes, 1991; Cassidy and Ellis, 1991). These fluids are either generated by dehydration reactions in the subducting oceanic plate, or are expelled from the subducting sediments (see, e.g., Peacock, 1990). If these fluids are released at sufficient depths in the subduction system, they become trapped beneath an impermeable layer at a temperature of the order of 400°C (Jones, 1987; Hyndman, 1988).

Examples of both mechanisms of enhanced conductivity are represented in the model for subduction of the Phillipine plate beneath Japan; one of the conducting zones is relatively shallow, whereas the other is deeper and lies further landward. The deeper zone is probably related to a body of partial melt, as suggested by Shimakawa and Honkura (1991) amongst others, which is responsible for back-arc magmatism. This partial melt may be triggered by H_2O and CO_2 released by metamorphic reactions in the subducting oceanic crust. Calculations by Peacock (1990) suggest that only the oceanic crust of young (tens of millions of years) subduction zones partially melts. In cooler subduction zones, the fluids initiate partial melting predominantly in the overlying continental mantle wedge. This is consistent with the earthquake loci and conductivity model of Shimakawa and Honkura (1991) in Figure 4.

For relatively "young" remnant subduction systems (i.e., those active within the last 0.1 Ga) it is possible that the enhanced conductivity is also due to the fluids. Such fluids could be released by devolatization reactions and may be retained within the crustal section beneath an impermeable layer. Fluid residency times after cessation of metamorphic activity are thought to be of the order of 70 Ma (Thompson and Connolly, 1990) or even much longer depending on crustal temperatures (Bailey, 1990). Alternatively, the enhanced conductivity may be caused by the presence of mildly-metamorphosed black shales which are very conductive due to the development of thin carbon films on the grain boundaries (Jödicke, 1985; Duba et al., 1989; Stanley, 1989). However, as discussed by Duba et al. (1989), and illustrated in the thin section in Stanley et al. (1990, fig. 9C), high-grade metashales will have little carbon content, especially in continuous form. In Duba et al.'s (1989) laboratory experiments, temperatures above 417°C were sufficient to oxidize the carbon and break the grain boundary interconnection. Pyrite formed during diagenesis of the shales will not significantly enhance the conductivity because it remains in unconnected nodules (Duba et al., 1989). Thus, Stanley (1989) has proposed a mechanism which may lead to a zone of enhanced conductivity under the restrictions that the metamorphic grade remains low, that the deep marine basin is under anoxic conditions, that sufficient sedimentation occurs, and that appreciable volumes of flysch are underthrust beneath the continental margin.

For subduction systems that are sufficiently ancient that fluid retention is untenable (e.g., the Paleozoic Iapetus suture or the Early Proterozoic orogens) interconnected fluids can probably be excluded as a mechanism for enhancing conductivity, so that other mechanisms must be postulated. In addition, the very high conductivity modelled for the NACP would require implausibly high porosities (greater than 10%) to be explained by fluids alone; Drury and Niblett (1980) had suggested that such anomalies were due to saline fluids in obducted compacted oceanic sediments of 10% porosity.

Of the four Early Proterozoic orogens illustrated in Figure 9, the Trans-Hudson and Svecofennian orogens are known to have significant zones of enhanced conductivity. In contrast, a combined GDS/MT study across the Wopmay orogen (Camfield et al., 1989) did not identify an anomalous conductivity zone, nor has such a zone been identified beneath the Penokean orogen on MT surveys south of Lake Superior (Dowling, 1970; Sternberg, 1979; Young and Rogers, 1985). Obviously, the continent–ocean–continent collision process leads in some cases, but not all, to the emplacement of conducting material at deep levels within the internal zones of the orogens. Such material, which is likely sedimentary in origin, may be deposited on the top of the downgoing oceanic plate and underthrust beneath the overriding continental plate or terrane. The actual nature of the underthrust material is not known at present, but graphitic schists (Camfield and Gough, 1977) and various sulphides are candidates. Care must be taken when suggesting that graphite is ubiquitously responsible for observed high conductivities, as graphite has a number of forms (Ballhaus and Stumpfl, 1985), and a graphitic pelite from northern Canada has been shown to be highly resistive (Camfield et al., 1989). Critical to interpretations of the nature of this material is that in all of the geographical areas discussed in this paper where coincident seismic and EM investigations have been undertaken, there is a good spatial and geometrical correlation between enhanced electrical conductivity and enhanced seismic reflectivity. Whatever is causing one is probably causing the other, effectively eliminating speculations regarding grain-boundary conduction processes that have no seismic signature.

The rates of deposition, convergence and erosion will be key factors that dictate the amount of underthrust material and thereby determine whether a zone of enhanced conductivity will be present or not. In addition, the metamorphic history of the region is important for retention of certain types of conducting material.

Conclusions

MT and GDS studies have successfully imaged anomalies of enhanced electrical conductivity associated with modern, Mesozoic, Paleozoic and Early Proterozoic subduction zones at various locations on the globe. These zones span half the age of the Earth, and lend support to the hypothesis that plate tectonic theory can be applied as far back as the Archean. Where seismic reflection data exist, the conductivity anomalies spatially correlate with regions of enhanced reflectivity.

EM studies can obviously play a significant role in the detection and identification of relic subduction systems. Perhaps the most noteworthy examples are the identification of the Eskdalemuir anomaly (Jain, 1964) prior to Wilson's (1966) proposal, and the suggestion by Camfield and Gough (1977) that the NACP represents a Proterozoic suture zone buried beneath the sedimentary cover, a suggestion that has since been supported by the results of a number of geological and geophysical studies.

For modern and recent subduction systems, explanations of the enhanced conductivity in terms of fluids pose few problems. However, for ancient subduction systems there is more difficulty due to our lack of knowledge about various conditions.

Given the similarity of the geophysical parameters for the Trans-Hudson orogen and the Svecofennian orogen, and given the paleopole positions for the period 1.900–1.825 Ga, it is proposed that they are the expressions of a single pan-Scandamerican orogenic zone which existed at that time.

Two fundamental questions arise from this compilation:

(1) What specific conditions must exist to generate a conducting region? (we know that such zones are not always created, e.g., in the Penokean and Wopmay orogens.)

(2) What is causing both the enhanced conductivity and enhanced reflectivity of the ancient zones?

The answer to the first question obviously lies in further multidisciplinary studies and global comparisons of orogens. In particular, it is suggested that shear wave velocity studies be initiated to determine Poisson's ratio for the depths where there is a significant increase in electrical conductivity. To address the second question, there may be no alternative but to drill one of the anomalies: the Skellefteå zone in Sweden is probably the most accessible, lying at a depth of only 5 km.

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