Electromagnetic sounding and crustal electrical conductivity in the region of the Wopmay Orogen, Northwest Territories, Canada[1]

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AND

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Temporal variations of the three components of the geomagnetic field were recorded at eight sites along a 240 km profile across the Early Proterozoic Wopmay Orogen. After an empirical separation of these data into normal and anomalous parts, horizontal-to-vertical-field transfer functions in the period range 40 − 1200 s display evidence for a minor anomaly spatially located near the allochthonous shelf margin at the eastern edge of the Hepburn Batholith. The observations can be partially simulated by a two-dimensional 20 Ω · m body (30 km wide, 2 km thick) embedded in the surface of a very resistive layered Earth model derived from inversion of magnetotelluric sounding data at a central station. The body correlates spatially with metamorphosed graphitic pelites of the Odjick Formation (Epworth Group), a unit of deep-water facies interpreted as continental slope − rise deposits. Laboratory measurements on samples of the pelite yielded resistivity values of the order of 10^4 Ω · m, so the enhanced conductivity of the body is more likely caused by water filling cracks associated with the pelites' well-developed cleavage and schistosity, rather than by the graphite. A scalar audiomagnetotelluric survey across the Wopmay fault zone, a prominent structure that bisects the orogen, gave results very much distorted by three-dimensional effects. The electric-polarization apparent resistivities of these data indicate a shallow conductor 2 km east of the fault scarp, 1 − 2 km wide. Models of the feature suggest that its vertical extent is at least 1 − 2 km.

Des variations temporelles des trois composantes du champ géomagnétique ont été enregistrées à huit points sur un profil long de 240 km, en travers de l'orogène Wopmay du Protérozoique précoce. Après avoir séparé empiriquement la partie normale de la partie anomale de ces données, on a calculé des fonctions de transfert des champs horizontaux au champ vertical pour des périodes de 40 à 1200 s. Ils montrent, pour de faibles périodes, une anomalie mineure près de la marge de la plate-forme allochtone à extrémité est du batholite Hepburn. On a partiellement modélisé les observations par un corps bi-dimensionnel (30 km de large par 2 km d'épais) de résistivité 20 Ω · m, encastré dans un modèle de la Terre constitué de couches très résistives, modèle qu'on a tiré d'un sondage magnétotellurique effectué à une station centrale. Il y a une corrélation spatiale entre le corps conducteur et les pélites graphitiques métamorphisées de la Formation Odjick (du Groupe Epworth), une unité à faciès d'eau profonde interprétée comme étant des dépôts de talus ou de glacis continental. Des mesures en laboratoire de la résistivité des échantillons des pélites ont donné des valeurs très élevées, de l'ordre de 10^4 Ω · m. Pour cette raison, on ne peut pas associer la haute conductivité du corps à la présence de graphite. Il est plus probable que la cause de la conductivité élevée est l'eau qui remplit les pentes du clivage et de la schistosité bien développés des pélites. Un levé audio-magnétotellurique scalaire réalisé en travers de la zone de faille Wopmay, une structure proéminente divisant l'orogène en deux, a produit des résultats très perturbés par des effets tri-dimensionnels. Les résistivités apparentes de la polarisation électrique indiquent la présence, à faible profondeur, d'un conducteur large de 1 − 2 km situé à 2 km à l'est de l'escarpement de la faille. Des modèles numériques suggèrent que ce conducteur se prolonge verticalement jusqu'à au moins 1 − 2 km sous la surface.

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Introduction

Regional electromagnetic surveys have made extensive contributions in recent years to the investigation of a number of tectonic problems in continental and oceanic areas; see the review by Gough (1983) and an illustrative example by Kurtz *et al.* (1986). As part of its ongoing research in this field, the Earth Physics Branch (now merged with the Geological Survey of Canada) undertook reconnaissance magnetovariational (MV) and magnetotelluric (MT) observations in the region of the Early Proterozoic Wopmay Orogen in the northwestern Canadian Shield (Fig. 1). Hoffman (1980) and others (cited later) have given convincing evidence for episodes of sea-floor creation and consumption in Proterozoic time in the region, although no truly oceanic crust has been recognized to date. Lewry (1981) had postulated the action of analogous plate-tectonic processes in the Proterozoic of north-central Saskatchewan, where electromagnetic induction surveys similar to those reported here detected a massive electrical conductor in the crust, possibly associated with the Rottenstone − La Ronge magmatic belt (Handa and Camfield 1984). The work across the Wopmay Orogen was designed to determine whether an electrical structure similar to that in Saskatchewan was present in the crust of the orogen. It had the additional goal of adapting the Branch's deep-sounding techniques to surveys at latitudes immediately north of the auroral zone, our previous investigations having been considerably farther to the north or south.

In support of a long profile of MV observations at eight sites, wide-band tensor MT recordings were made at a central location. In addition, scalar audio-frequency (8 − 1000 Hz)

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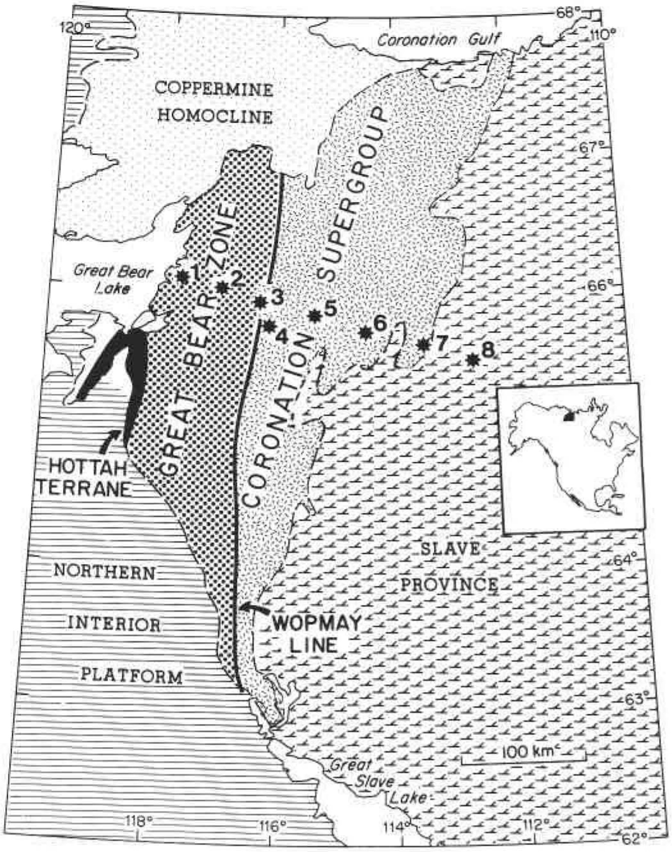

FIG. 1. Major tectonic zones of Wopmay Orogen, whose location within North America is shown in the inset map. Of interest in this study are the Coronation Supergroup, the Great Bear magmatic zone, and the Hottah Terrane. The Wopmay Line (in part the Wopmay fault zone, south of 66°N) marks the boundary between the magmatic zone and the Coronation Supergroup. Stars numbered 1–8 indicate the sites at which temporal variations in the geomagnetic field were recorded. The base camp for the fieldwork was at site 4.

magnetotelluric (AMT) measurements were made along a short line across the Wopmay fault zone in an attempt to estimate its depth extent and attitude. The higher frequencies used in the AMT technique give better structural resolution at smaller depths than do the MV and MT methods.

Geological setting

As detailed most recently by Hoffman and Bowring (1984), Hildebrand and Bowring (1984), Hildebrand *et al.* (1986, 1987), and King (1986) and documented in the references cited therein, the Wopmay Orogen is composed of three major tectonic elements: the Coronation Supergroup, the Great Bear magmatic zone, and the Hottah Terrane (Fig. 1). Hildebrand *et al.* (1986) interpreted the Wopmay Orogen as an autochthonous complex involving both a continental magmatic arc and an oceanic back-arc basin, thereby revising Hoffman's (1980) idea that the orogen reflects a complete Wilson cycle of ocean opening and closing. The following description is modified from King (1986).

On the east is the Coronation Supergroup, a marginal (back-arc) depositional prism. To the west is the Hottah Terrane, a metamorphic complex that was intruded by calc-alkaline plutons in the time range 1914–1902 Ma. Between the Coronation Supergroup and the Hottah Terrane is the Great Bear magmatic zone, a volcano-plutonic depression dated at 1875–1840 Ma that uncomformably overlies the Hottah Terrane. The Great Bear Zone resembles Cenozoic continental-margin magmatic arcs and is interpreted as being the result of eastward subduction of oceanic lithosphere beneath the Hottah Terrane.

At its base, the Coronation Supergroup includes volcanic and sedimentary rocks of the Akaitcho Group, which filled a rift that developed in the Slave Craton. These rocks are overlain by siliciclastics and carbonates of the Epworth Group. Among the clastics (shed across the Slave Craton and onto the subsiding margin from an uplift to the east), St-Onge (1984) noted graphitic pelites of the Odjick Formation, interpreted as slope–rise facies deposits. Among the carbonates are those of the Rocknest Formation, deposited by chemical precipitation on the shelf. Overlying these units are the foredeep flysch deposits of the Recluse Group, formed subsequently on the subsided shelf.

The Coronation Supergroup was deformed during three episodes of regional subhorizontal shortening. The first two episodes predate the development of the Great Bear magmatic zone, and the third postdates it. The first episode included the emplacement of syntectonic intrusions (among them the Hepburn Batholith; see Fig. 6) with resultant metamorphism of part of the Supergroup (including the Odjick pelites and quartzites). Zircon geochronology shows that the three deformations occurred in rapid succession between 1.89 and 1.69 Ga.

The Wopmay Line (Hoffman 1984*a*; King 1983) is a prominent structural feature in the area (Fig. 1). This fundamental discontinuity trends north–south for over 600 km and corresponds in part to the boundary between the Coronation Supergroup and the Great Bear Magmatic Zone. It includes the Wopmay fault zone, a band of mylonitic rocks broken by a brittle fault system confined in a belt up to 20 km wide but often narrower. Hoffman (1984*a*) noted that the unique role of the Wopmay fault zone during the evolution of the orogen stems from its position at the western edge of relatively cold and rigid Archean lithosphere capped by buoyant, non-stretched continental crust.

Geophysical setting

Aeromagnetic data over the Wopmay area (Dods *et al.* 1984) show two main features: (*i*) a strong linear positive anomaly coinciding with the Great Bear magmatic zone and (*ii*) generally negative signatures over the Coronation Supergroup. As noted, the Great Bear Zone is geologically similar to Cenozoic continental-margin magmatic arcs such as the western Coast Plutonic Complex of British Columbia, which also has an associated positive magnetic anomaly (Coles and Currie 1977). If this is the case, it is possible that the Great Bear magnetic anomaly arises from magnetic material formed in a hydrous environment like that postulated to have existed under western British Columbia.

Thomas (1984, and personal communication, 1986) undertook detailed gravity measurements across the orogen to supplement the regional gravity coverage. A 23 mGal (1 mGal = 10^{-5} m/s^2) positive anomaly, trending north–south and associated with the Hepburn Batholith, is related to a westward thickening of the wedge of metamorphosed clastic-prism rocks in the Coronation Supergroup. At the latitude of the gravity and electromagnetic profiles, the wedge is interpreted as reaching a maximum depth of about 11 km near the centre of the belt. The deep western margin of the wedge is modelled

TABLE 1. Coordinates of magnetovariational stations

Station	Geographic		Corrected geomagnetic		Declination
	Lat (°N)	Long. (°W)	Lat. (°N)	Long. (°E)	(°E)
1	66.08	117.70	72.6	286.9	36.5
2	66.01	117.01	72.7	287.8	35.8
3	65.92	116.33	72.7	288.6	35.1
4	65.75	116.17	72.6	289.0	34.7
5	65.82	115.41	72.8	289.8	34.4
6	65.71	114.51	72.9	291.0	34.1
7	65.60	113.52	73.1	292.4	33.8
8	65.50	112.65	73.2	293.7	33.2

NOTE: Station 1 is near Echo Bay on Great Bear Lake; station 8 is at Itchen Lake.

as vertical, projecting to the surface at the Wopmay fault zone. A superimposed negative gravity anomaly with smaller amplitude over the ''granitic'' intrusions in the Hepburn Batholith suggests that these rocks now have a tabular geometry and a thickness of about 3 km.

Magnetovariational and tensor magnetotelluric observations

Observations of temporal variations in the Earth's magnetic field were made across the Wopmay Orogen for three weeks in May and June 1982, at eight sites along an east−west profile 240 km long (Fig. 1; Table 1). The profile was chosen to be perpendicular to the generally north-south structural trends of the orogen for optimum detection of electrical currents induced within, or channelled into, the structure. The stations were located within half a degree of a constant parallel of corrected geomagnetic latitude (72.8°N, Gustafsson 1970) with the hope that the spatial nonuniformity in the external source fields would be minimized along the profile, facilitating the recognition of internal currents.

Magnetic time variations were sensed by three-component fluxgate magnetometers (Trigg *et al.* 1971) aligned in geomagnetic north (H), east (D), and vertically downwards (Z), respectively. As a supplement to the MV data, the corresponding horizontal electric variations were measured at station 4 with 200 m lines to provide MT data in overlapping period bands of 4−300 and 40−30 000 s (Trigg 1972). All signals were recorded digitally on cassette tape (Trigg 1974) with a sampling interval of 2 s for the short-period band (MT) and 20 s for the long-period band (MT and MV) and a resolution (least-significant bit) of 0.25 nT and 0.5−2.5 mV/km, depending on the telluric gains. Scalar AMT information in the range 8−1000 Hz was added to the tensor MT data.

Permafrost and sparse overburden in this area prevented us from burying the instruments, our usual practice to ensure stability and security. Instead, the battery-powered electronics were housed in foam-lined aluminum cases left on the ground surface. The magnetic detectors were mounted on 30 cm × 30 cm concrete slabs cast with a protruding piece of aluminum pipe, placed on smooth exposed bedrock chosen from the air.

After unpacking and editing, we plotted the variation data in the form of stacked magnetograms for initial interpretation and for the selection of events for further analysis. An example is given in Fig. 2. Clearly, the variations in all three components either were uniform or changed very slowly from stations 1 to 8. This indicates source fields virtually homogeneous in the east−west direction and a lack of any obvious concentration of internal currents. These currents would be evident as shifts or reversals in the phase of the Z-component waveforms if their fields are not masked by those of external currents.

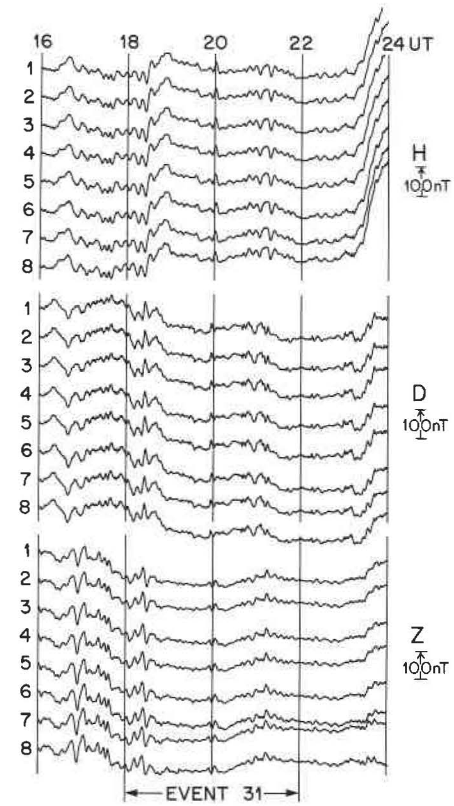

FIG. 2. Stacked magnetograms for 8 h of recordings on day 157 (June 5), 1982. H is the variation component taken as positive towards magnetic north; D, towards magnetic east; and Z, vertically downwards. Declinations are about 35°E; see Table 1. The uniformity of the records along the profile suggests the absence of major anomalies in crustal electrical conductivity.

Since the geology of the orogen is not uniform, the lack of any visual indication in the plots allows (to the resolution of the plots) the initial conclusion that electrical conductors in the Wopmay crust do not have the intensity of the North American Central Plains (NACP) conductor mapped with similar methods in Saskatchewan and Manitoba (Alabi *et al.* 1975; Handa and Camfield 1984, Gupta *et al.* 1985) or in the Ameri-

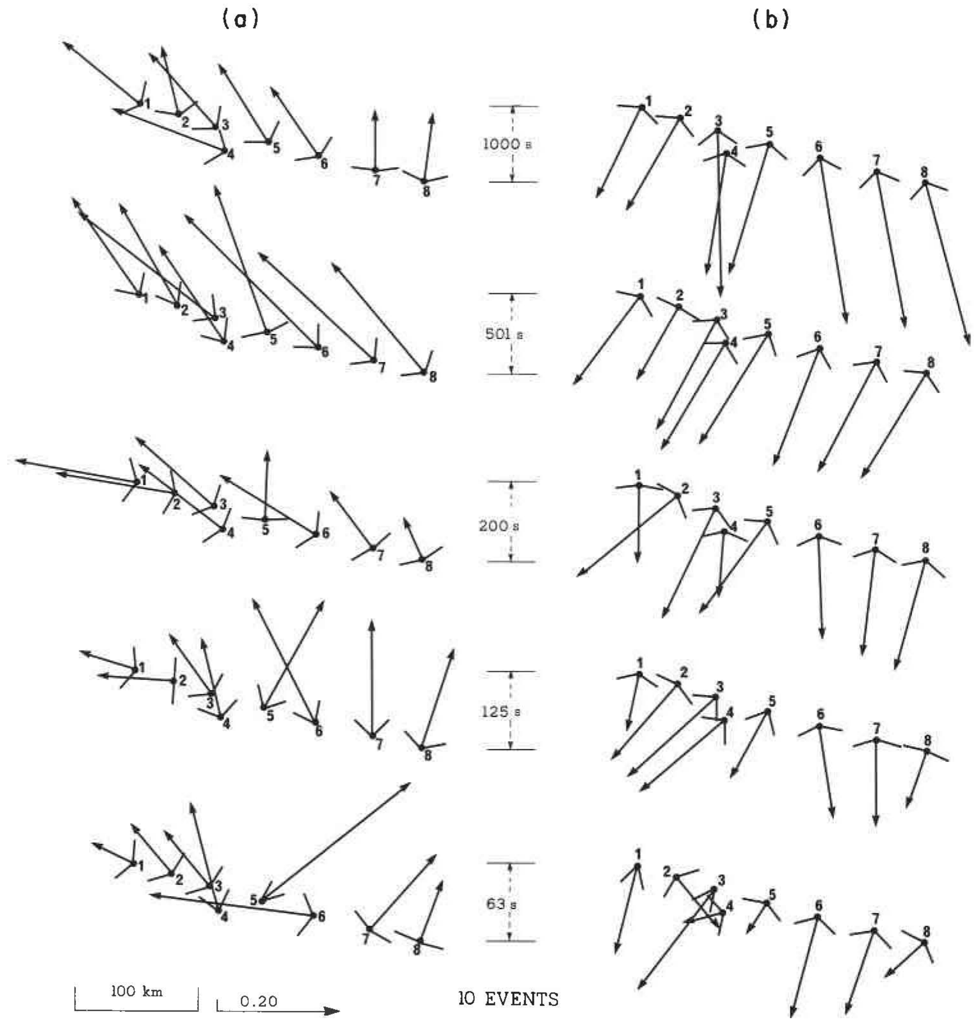

FIG. 3. (*a*) In-phase and (*b*) quadrature vertical-field response or induction arrows representing single-station transfer functions calculated from 10 selected events analyzed at each station. In-phase arrows have been reversed to point towards internal currents. Plus or minus 1 SD of azimuthal uncertainty in each arrow is given by the short lines drawn from the foot of the arrow, marked by the black dot. Since the directions of the arrows are the focus of the figure, uncertainties in the lengths are not shown for clarity. (For the quadrature arrows at 501 s, the scale arrow has length 0.50, not 0.20).

can states to the south. In these areas, variation fields had very clear Z reversals. Green *et al.* (1985) showed evidence for associating the enhanced conductivity responsible for the NACP anomaly with rocks they interpret as ancient oceanic crust. If this is the case, then the absence of such an anomaly in the Wopmay Orogen allows the further conclusion either that truly oceanic crust never formed there or that it has been consumed by subduction or otherwise lost during uplift and erosion of the orogen.

Transfer functions and response arrows

The relationship among the components H, D, and Z of the variation field was investigated statistically through the computation of single-station transfer functions and their display in the form of response arrows. Under certain conditions (Schmucker 1970, reviewed in Gupta *et al.* 1983) a linear relation between the components may be assumed in the frequency domain, of the form

$$Z_a = A \cdot H + B \cdot D$$

where Z_a represents the anomalous vertical field of current flow in a laterally inhomogeneous Earth, and A and B are the transfer functions. It is usual to assume further that the vertical component of the source field is small, so that Z_a may be replaced by the total recorded Z. This assumption is adequate at low and middle geomagnetic latitudes but may be a major source of error at these high latitudes (Beamish 1979). Methods used to reduce source effects, including an empirical separation of the normal and anomalous Z fields, are discussed below.

The in-phase and quadrature parts of the transfer functions A and B may be expressed in terms of amplitudes and phases defined as $(A_k^2 + B_k^2)^{1/2}$ and $\tan^{-1}(B_k/A_k)$, respectively, where k represents either the in-phase or quadrature component. By reversing the azimuth of the real part, we define conventional in-phase response arrows so that they usually point towards concentrations of internal current (Schmucker 1970; Jones 1986).

Standard single-station transfer functions were calculated according to the method outlined by Bailey *et al.* (1974) and described in detail by Gupta *et al.* (1983). Auto- and cross-power estimates from events 240 min long were averaged over

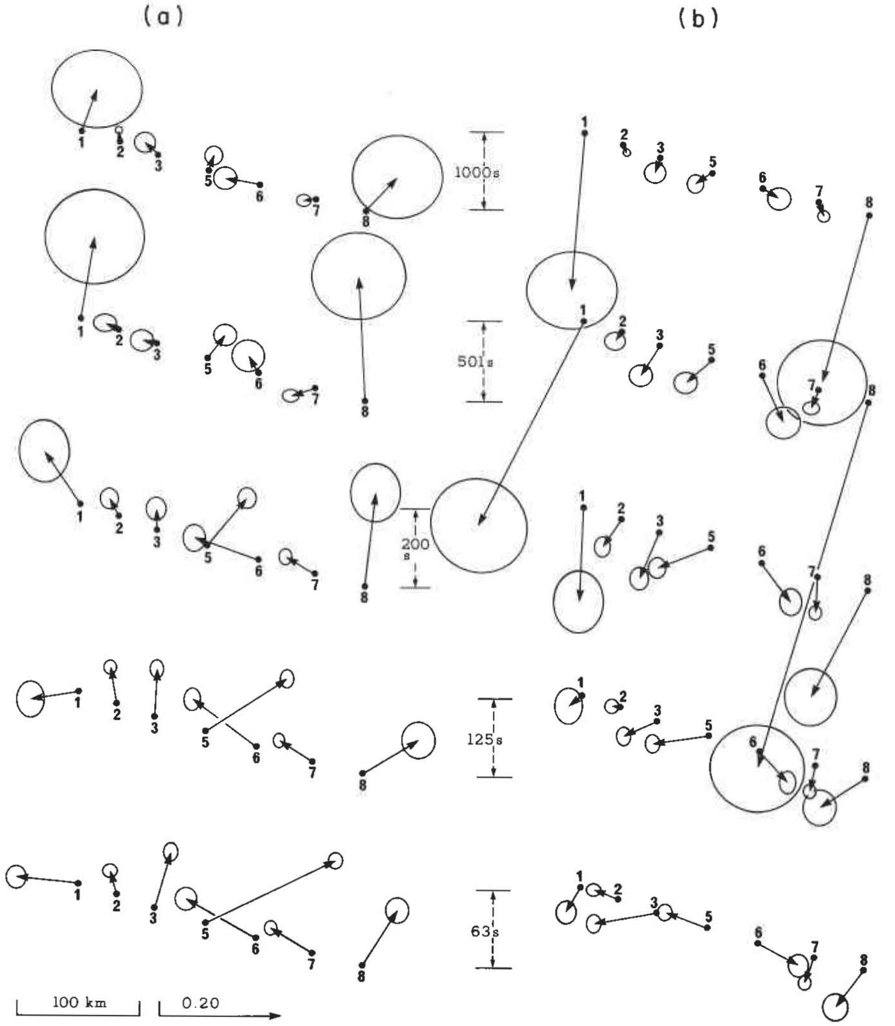

FIG. 4. (*a*) In-phase and (*b*) quadrature arrows calculated at stations 2–7 from normal fields defined by linear trends between the end stations 1 and 8 and anomalous fields that are the difference between total and normal fields. The error ellipses represent 1 SD in length and azimuth. The arrows at stations 1 and 8 represent single-station transfer functions. The more refined processing has reduced the uncertainties substantially. The anomaly between stations 5 and 6 can be seen clearly in both the reversed in-phase and unreversed quadrature arrows.

period bands; transfer functions calculated from these means were further averaged across ensembles of series. The standard deviations of the ensemble averages were taken as an estimate of the errors. Although about 40 events with medium levels of magnetic activity were initially chosen as suitable for analysis, the selection was further refined in an attempt to minimize source effects, following Kurtz (1982) and Handa and Camfield (1984). Magnetograms were reexamined, and events with smallest variations were retained. Of these, only 10 events were found with power in the vertical component less than the total power in the horizontal components. The 10 events were analyzed with the expectation that the effect of the vertical component of the source field would be reduced.

Response arrows representing the transfer functions from the restricted data set are given in Fig. 3; they have appreciable errors. The observed reversal in the direction of the real arrows at 63 and 125 s at stations 5 and 6 and the shorter northward arrow at station 5 at 200 s show the evidence for a conducting structure between stations 5 and 6. The general northwestward direction of the in-phase arrows could be attributed to the combined effect of external (ionospheric) source currents lying to the south and remote internal currents to the west. All quadrature-phase arrows (unreversed) have a predominant southward component. Although it is not easy to understand how a significant part of the external vertical field could be consistently 90° out of phase with the external horizontal fields over the period range considered here, Jones (1981) noted similar source effects in magnetometer-array data from Scandinavia.

The data were reprocessed in an empirical attempt to separate normal and anomalous fields and to improve the definition of the anomaly between stations 5 and 6. The stations at each end of the line, clearly remote from the anomaly, were used to define the normal fields as had been done by Alabi *et al.* (1975), but here we subtracted the normal fields in the time domain before the Fourier transforms were calculated, rather than afterwards as did Alabi *et al.*, in order to avoid complications that arise in the transformation. Since the Fourier transform is a linear operation, normal and anomalous fields will add in the time domain as in the frequency domain.

A time-domain scheme requires precise timing. This was checked by cross-correlating the H components at adjacent stations. The maximum cross correlations were always found at zero lag, showing that the data were simultaneous within one sampling interval (20 s).

Following high-pass filtering with a cutoff period of 2000 s to remove long-term drifts, we defined the three normal components D_n, H_n, and Z_n at each station within the line using a linear trend calculated at each instant in time between the recorded fields at the end stations 1 and 8. Z_n was subtracted from the recorded Z at each station, and transfer functions were formed between Z_a and the specific H_n and D_n. Between 30 and 40 data series, each 170 minutes long, were used for all stations except station 2, where the curiosity of a grizzly bear had resulted in only 18 series being available. Station 4 was omitted because it lay significantly to the south of the line.

The response arrows for these calculations are shown in Fig. 4 for comparison with the single-station arrows in Fig. 3. In Fig. 4, the arrows at stations 2−7 (excluding 4) are based on the separated fields. The arrows at stations 1 and 8 represent single-station transfer functions; they differ from those in Fig. 3 because of the different data sets used. The first point to note in Fig. 4 is that the errors in the transfer functions for stations 2−7 have been substantially reduced; the error ellipses representing 1 SD (standard deviation) in length and azimuth of the response arrows are substantially smaller at stations 2−7 (separated fields) than at the end stations (total fields). Secondly, the arrows at stations 2−7 in Fig. 4 are considerably shorter than those in Fig. 3, reflecting the subtraction of the large, normal, vertical fields. The reversal of the in-phase arrows between stations 5 and 6 becomes increasingly clear from longer periods to shorter; the small but persistent divergence of the quadrature arrows at stations 5 and 6 in Fig. 3 has become a well-defined opposition in Fig. 4. Some inconsistencies in the behaviour of the arrows in Fig. 3 have disappeared in Fig. 4; for example, the in-phase arrow at 63 s for station 7 now has the same sense as that at station 6 and is shorter, appropriate since station 7 is farther from the internal conductor.

Modelling of the conductor between stations 5 and 6

The conductive body most evident in our observations is that between stations 5 and 6. We sought information on its lateral extent, thickness, depth, and conductivity using two-dimensional modelling. We began by considering the MT data recorded at station 4. For a review of magnetotellurics, see Vozoff (1985). From the MV data, we judged station 4 as being sufficiently distant from anomalous stations 5 and 6 to provide a reasonable estimate of the regional resistivity. As is evident below, MT data at this station are unfortunately affected by closer structures.

Tensor estimates of apparent resistivity and phase were calculated following Kurtz (1982) over the period range 4−1500 s. These estimates are clearly anisotropic (Fig. 5). The electric field was strongly polarized at an azimuth of N65°E. The results in the minor axis of anisotropy are poorly defined compared with those in the major axis. As well, the skew is greater than one, and the minor-axis phase increases dramatically with increasing period; this latter effect is occasionally observed in MT measurements at sites with strong three-dimensional characteristics, for example, those observed on the Nelson Batholith in southeastern British Columbia (Jones *et al.* 1988).

Since the major axis of anisotropy had a well-defined azimuth of N30°E, it was reasonable to extend the tensor apparent resistivities in the direction of major and minor axes of anisotropy with scalar AMT data measured at the station in the geomagnetic north−south (N35°E) and east-west directions. As shown in Fig. 5, these data are relatively isotropic and have considerably higher values than the longer period values in the direction of maximum anistropy.

We applied Fischer's inversion algorithm (Fischer *et al.* 1981; Fischer and LeQuang 1982) to the wide-band apparent resistivities and long-period phases in the major axis of anisotropy to derive a one-dimensional model with the minimum number of layers required to fit the data within their errors. The ill-behaved phases at long periods in the minor axis suggest that the minor-axis data are unsuitable for one-dimensional inversion. The best model for the major-axis data and the fit of its response are shown in Fig. 5. The model has a thin, moderately resistive top layer above a very resistive thick layer. Below these two, the resistivity falls initially to 2200 Ω · m and then to 200 Ω · m below 12 km. We acknowledge the limitations on this interpretation, which comes from a one-dimensional analysis of single-station data that clearly show three-dimensional effects. The high cost of logistics precluded further MT measurements that might have permitted a better interpretation. Given the limitations, we have made no attempt to relate this model to the regional geology.

Into this plane-layered Earth model we inserted a two-dimensional conductive body with northward trend (parallel to geological trends) to simulate the cause of the geomagnetic variation anomaly between stations 5 and 6. Since the anomaly is most evident at the shortest periods recorded (Fig. 4), the body must be at small depths. Two major geological units have been mapped on the surface between stations 5 and 6: the granitic Hepburn Batholith and the metamorphosed slope−rise and foredeep rocks of the Coronation marginal prism (Fig. 6). Since granites are generally resistive (Table 5.4 of Telford *et al.* 1976), we identified the conductor with the metamorphosed rise-prism rocks.

Station 6 is located very close to the boundary between slope−rise-facies rocks and shelf-facies rocks (Fig. 6). The boundary, continuous over the length of the orogen, is marked by a fault that has placed metasediments of the Epworth Group (specifically, Odjick Formation members of the slope−rise facies) against Rocknest carbonate rocks (shelf facies). The juxtaposition of metasediments (assumed conductive) against carbonates (generally resistive) suggests that the eastern limit of the conductor is the fault contact.

To the west, the surface contact between the conductive metasediments and the resistive Hepburn intrusives lies two thirds of the way from station 6 to station 5. This contact, which also trends north−south, was taken as the western surface limit of the conductor. Since the gravity studies of Thomas (1984) and the composite down-plunge cross section of King (1986) show that the rise-prism rocks thicken westwardly beneath the Hepburn intrusives, we chose to make the western edge of the conductor dip or step down to the west, as shown in Fig. 7.

Southward extension of the conducting body is limited by the pinching out of the metasediments against the uplifted Slave basement 40 km south of the profile (Fig. 6). Northward, the currents probably follow the metasediments as they disappear under the postorogenic sedimentary cover. The body is not infinitely long in the north−south direction, but to first approximation, it can be taken as two dimensional.

The observations that the model must predict are the transfer functions from separated fields, shown in arrow form in Fig. 4. In-phase and quadrature components were projected onto the line of the profile to approximate the response of currents flowing in the geological structure, which trends north–south, perpendicular to the profile. The north–south components of the transfer functions, relatively small, are of course not accounted for by the two-dimensional model; they are presumed to arise from an incomplete suppression of external Z fields and from currents in minor internal conductors that are not resolved by the line of stations.

To calculate the electric-polarization response of the model we used a numerical method that employs the network solution of Ku *et al.* (1973). Fig. 7 shows the fit between observations and model responses at representative short (63 s) and long (501 s) periods. In a statistical sense the fit is poor, and hence we judged that model computations at other periods were unjustified. However, the agreement at 63 and 501 s is reasonable in view of the assumptions made in deriving the model.

On the surface the body is some 30 km wide, the distance between station 6 and the surface contact between the metamorphosed rise-prism rocks and the Hepburn granites. The body has a thickness of 2 km and a resistivity of 20 Ω · m. These parameters are obviously not unique, but a number of trials in which they were varied suggested that a model with the values given here provides a reasonable fit to the data for this style of model. For a body 2 km thick, the average resistivity is probably not as small as 10 Ω · m or as large as 40 Ω · m. For a resistivity of 20 Ω · m, a thickness of 5 km results in a response at long periods that is significantly greater than the observations. In an earlier analysis, Camfield *et al.* (1987) modelled the single-station transfer functions shown in arrow form in Fig. 3, with results similar to those from the more rigorous transfer functions from separated fields.

King's (1986) cross section indicates that the metasediments are now no more than 5 km thick at the location of the profile. Our modelling has suggested that the thickness of the conductive body is somewhat smaller. Unlike Handa and Camfield (1984) in Saskatchewan, we do not need to invoke a thicker, deep-seated basement structure here (e.g., buried oceanic crust) to explain the anomaly. It is reasonable to assume that the conductor is restricted to the relatively thin metasediments.

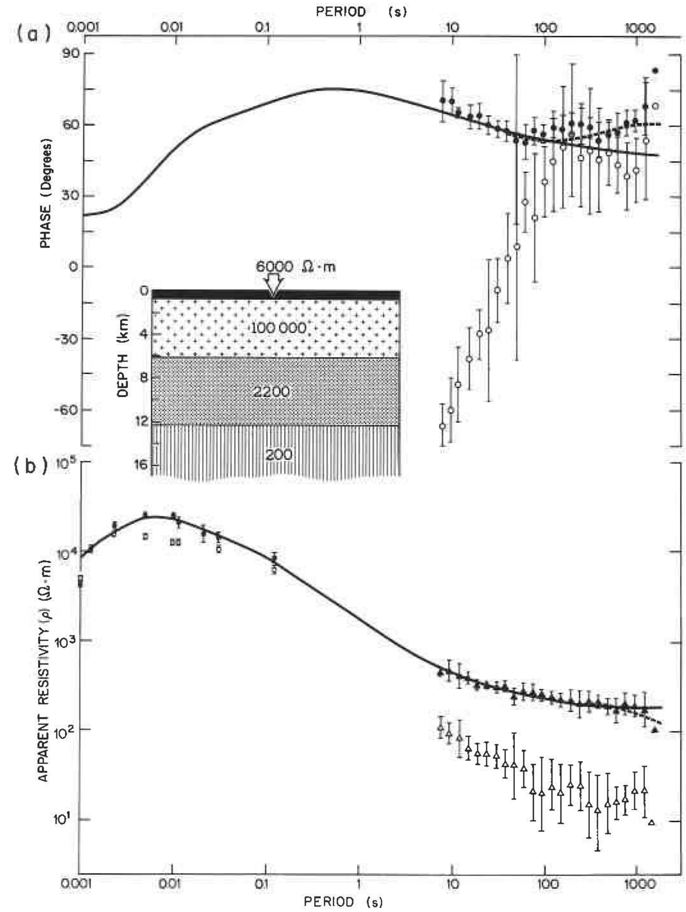

FIG. 5. Magnetotelluric observations at station 4. (*a*) Phases and (*b*) apparent resistivities at long periods in the direction of the major and minor anisotropies are given by the filled and open symbols, respectively. The major-axis direction is assumed to be the electric-polarization (i.e., E-parallel) direction. At long periods, error bars represent ±1 SD about the mean determined from an ensemble of 10 series each 4 h long sampled at 20 s intervals and 10 series each 0.4 h long at 2 s. At short periods, scalar apparent resistivities in the geomagnetic north–south and east–west directions are shown by the filled and open squares, respectively. Error bars are ±1 SD of 5–10 repeated observations. The solid line is the response of the one-dimensional resistivity model shown, derived using Fischer's inversion scheme. The dashed line shows how the response changes when an ultimate layer of 40 Ω · m is added below a depth of 100 km.

Origin of the enhanced electrical conductivity

St-Onge (1984) and Hoffman (1984*b*) reported graphitic and other pelitic schists and gneisses throughout the slope–rise metasediments marked in Fig. 6, particularly among the Odjick metasediments to the east of the Hepburn Batholith. The pelites contain sufficient graphite to give them a black colour, although the graphite content varies across individual pelite beds (thicknesses up to 30 cm), giving the units a banded appearance. The graphite likely originated from organic material transported from the continent, deposited on the slope and rise, and subsequently metamorphosed. The graphite content decreases with increasing metamorphic grade towards the contact with the Hepburn intrusives, the carbon having been driven off by the heat of the intrusion.

Carbon, in either graphitic or elemental form, has long been considered a likely contributor to enhanced electrical conductivity in crustal rocks (Duba *et al.* 1988); certainly, on the smaller scale of mineral exploration surveys, it yields abundant anomalies in electromagnetic data (Palacky 1986). Its role in causing anomalies of much larger scale in geomagnetic variations has been proposed along with other possibilities such as saline water in fractured rock or hydrated minerals such as serpentine produced at ridge crests and amphiboles created when sediments or oceanic crust is subducted. Here it appeared reasonable to assume initially that the enhanced conductivity detected by the magnetic-variation survey was related to the presence of graphite. However, laboratory resistivity measurements of cubes with sides of 2–3 cm, cut from seven representative surface samples of the graphitic pelites, showed very high resistivities (greater than 10 000 Ω · m). The difference between the field and laboratory measurements suggests that the surface samples either are too small to characterize the bulk behaviour of the pelites or are not representative of the material at depth.

J. E. King (personal communication, 1988) emphasized that

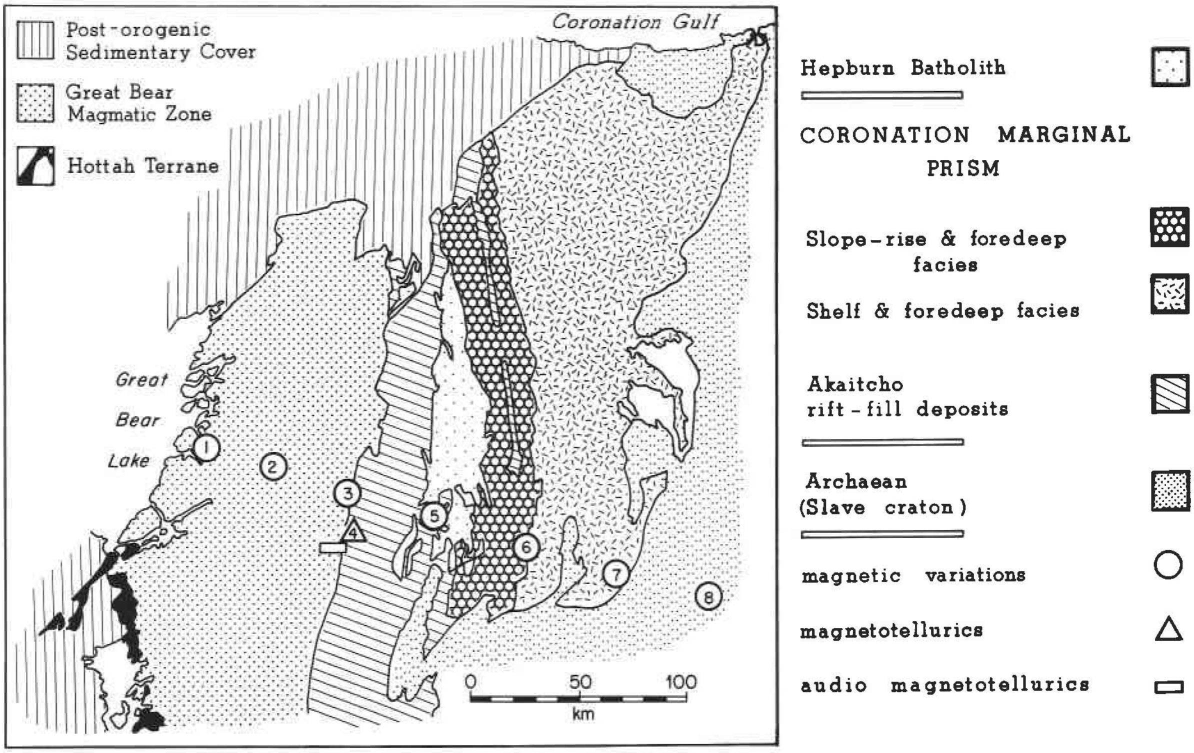

FIG. 6. Simplified geological map of the northern two thirds of Wopmay Orogen, redrawn from Fig. 1 of Hoffman and Bowring (1984). The north–south-trending band of slope–rise graphitic metasediments given by the pattern of embedded open circles between magnetometer stations 5 and 6 is the likely cause of the variation anomaly between these stations. To aid comparison with Fig. 1, note that station 3 is very close to the Wopmay Line.

although the graphite is a first-order characteristic of the pelites, the pelites also possess a metamorphic cleavage and schistosity that are more strongly developed than in the adjacent rock units. In addition, within the pelite belt there is an absence of the less fractured or jointed (i.e., massive) quartzite and carbonate units found to the east. Thus, since the graphite in samples of 2–3 cm does not lead to a high electrical conductivity on that scale, it would appear that the high conductivity could be the result of the connected cracks associated with the cleavage and schistosity, the cracks now being filled with water having sufficient mineral content to make them good conductors.

T. J. Katsube (personal communication, 1985) noted that electric logs in boreholes passing through mafic rocks in Shield areas often show much higher *in situ* conductivities than those measured in the laboratory for core samples of the same rocks. He believed that the bulk electrical properties of such rocks are controlled not by the composition of the competent rock but by networks of connected fractures filled with water, with fracture walls being in addition coated by conducting clays or iron oxides. A similar scenario is reasonable for the Wopmay pelites. A simple calculation suggests that an accumulated thickness of 3–30 m of highly conducting cracks, distributed throughout the otherwise very resistive, 3 km thick unit, could reduce the resistivity of the section to a value of the same order as the 20 $\Omega \cdot$ m derived by modelling the MV data (Fig. 7).

Audio-frequency magnetotelluric survey across the Wopmay fault zone

The location of the Wopmay fault zone is shown on Fig. 7; as can be readily seen, the projected transfer functions do not exhibit any evidence for its presence. In this section we describe a reconnaissance AMT survey across the fault zone that investigated this prominent structural feature. For a review of audio-frequency magnetotellurics, see Strangway (1983).

The scalar AMT data were obtained with a microprocessor-controlled unit built by Sygeq Limited of Montreal. Electric signals from a 20 m telluric line and orthogonal magnetic signals from a ferrite-cored coil were passed through narrow-band filters tunable between 2 and 5000 Hz. The signals were then integrated over time intervals varying from 1 to 30 s, depending on the frequency selected. The corresponding apparent resistivities were calculated in the unit and displayed directly in ohm · metres. Twelve soundings were made at roughly 1 km intervals on an east–west profile that crossed the Wopmay fault scarp near 65.7°N, 117.3°W. The location of the profile is given by the small rectangle south of station 4 in Fig. 6. Two measurement geometries were used at each station to obtain two sets of apparent resistivities: one with the electric field measured parallel to the north–south strike of the fault zone (the E-parallel case) and one with the electric field perpendicular to strike (the E-perpendicular case). Further details of the survey were given by Krentz (1983).

The two sets of apparent resistivities are shown in Fig. 8 and 9 in profile and pseudosection forms. The most prominent features of the E-parallel profiles (Fig. 8) are the low values between the fault scarp (station 7) and the eastern end of the line, which suggest that the fault zone is relatively conducting. The E-perpendicular observations (Fig. 9) show more single-station anomalies than do the E-parallel values, consistent with the discontinuous behaviour of electrical fields transverse to

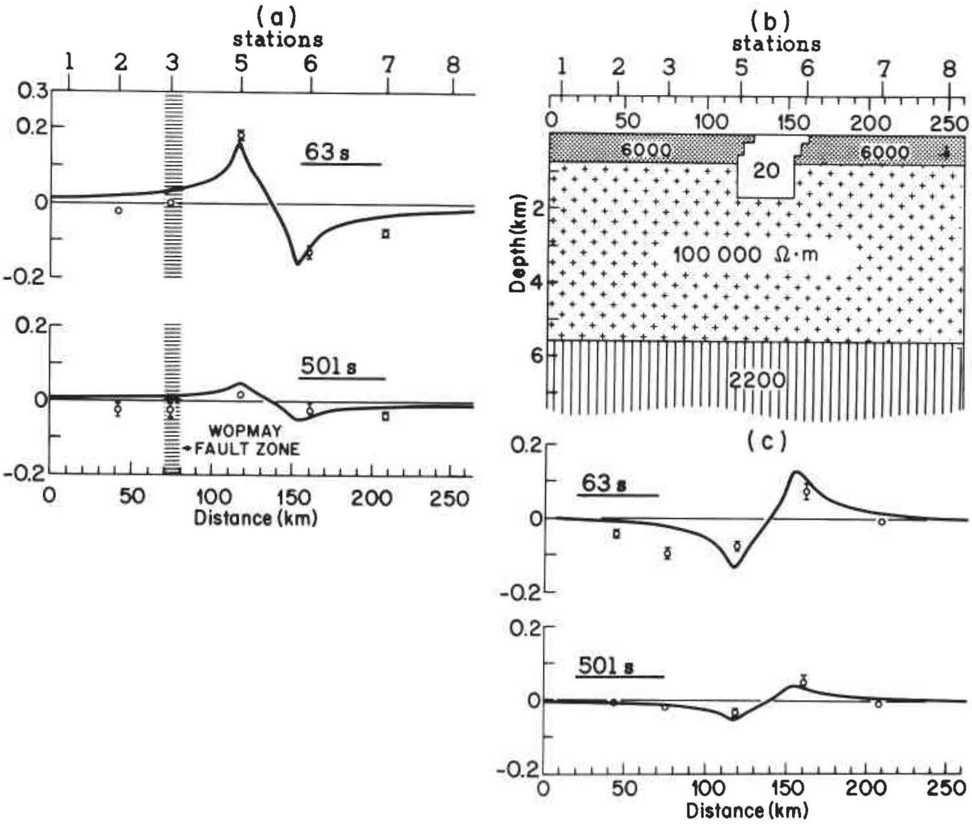

FIG. 7. (*a*) In-phase and (*c*) quadrature responses (ratio of vertical to horizontal fields) of the two-dimensional conductivity structure in (*b*) are given by the solid curves. The model consists of a 20 Ω · m conductive prism between stations 5 and 6 embedded in the one-dimensional model of Fig. 5. The open circles represent the in-phase and quadrature components of the observed transfer functions projected onto the profile. Error bars are plus or minus one standard deviation; where they are not shown, they lie within the symbol. The location of the Wopmay Fault Zone is shown near station 3; as can be seen, the data do not exhibit a corresponding signature.

discontinuities in conductivity. Obvious candidates for such discontinuities are the anastomosing brittle faults within the fault zone (King 1983), so readily seen in aerial photos of the region.

Attempts to find a unique, internally consistent two-dimensional model for the AMT data were unsuccessful. We began by placing a buried conducting dyke in the host Earth of Fig. 5, to represent the felsic gneisses between stations 9 and 10 (Krentz 1983). With a resistivity of the order of 100 Ω · m, the model gave apparent resistivities (Ku *et al.* 1973) that were close to the E-parallel minimum observed between stations 8 and 12 (Fig. 8). This value of resistivity is consistent with the fracturing that has taken place in the fault zone. Although the buried dyke gave some idea of the cause of the E-parallel minimum observed to the east of the fault scarp, no reasonable two-dimensional model had a response to the west of the scarp that matched the abrupt rise to greater than 10^4 Ω · m of the E-parallel observations there. Three-dimensional influences must be invoked to suggest an explanation of the observations.

The buried dyke had a response that was also a complete misfit to the E-perpendicular observations. When a thin, laterally inhomogeneous overburden layer was added to the model, the E-perpendicular data could be reasonably matched at higher frequencies without changing the E-parallel fit appreciably, but the E-perpendicular responses at lower frequencies bore little resemblance to the observations.

Modelling the data east of the scarp gave only a limited idea of the depth extent of the Wopmay fault zone as a whole; the response of the models changed very little when the bottom of the conductor was moved from a depth of 1 or 2 km to 16 km. Further numerical modelling suggested that the bulk of the current induced by alternating fields in a conductive dyke flows within considerably less than one skin depth of the surface; the current flow is thus insensitive to conditions at greater depths. The skin depth of 8 Hz signals in 100 Ω · m material is 1.8 km; in 10 000 Ω · m material, 18 km. Hence, even the lowest frequency used here was able to say very little about the possible extension of the Wopmay fault zone to the mid-crust; we can conclude only that it extends to a depth of at least 1–2 km.

Conclusions

These electromagnetic soundings to investigate the electrical structure of the Wopmay Orogen have shown the following:

(1) Simultaneous magnetovariational observations on a profile close to the auroral zone and parallel to it can be separated empirically in the time domain into normal and anomalous parts, permitting the calculations of transfer functions with better definition than single-station analyses.

(2) A relatively shallow, thin conductive structure trending north–south is the likely cause of an anomaly in geomagnetic variations that correlates spatially with graphitic pelites of the Odjick slope–rise-facies metasedimentary unit. The high conductivity is more likely ascribed to fluid-filled cracks

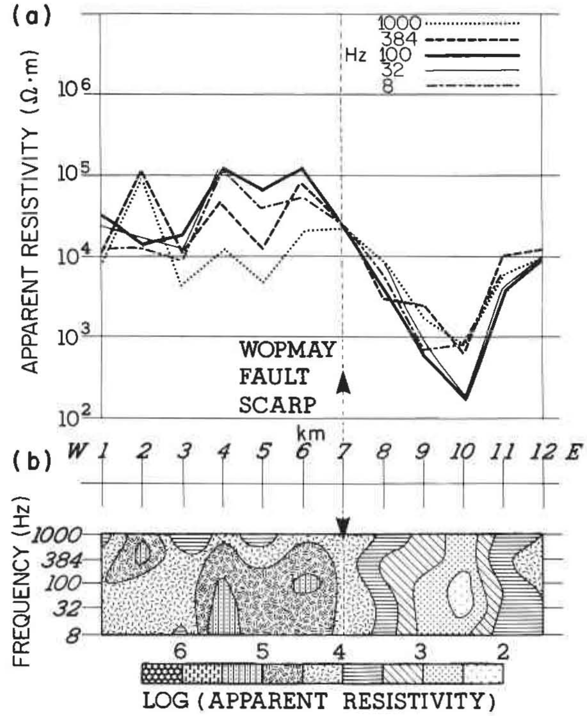

FIG. 8. Scalar audio-frequency magnetotelluric apparent resistivities on an 11 km profile across the Wopmay Fault Line (65.7°N; location marked in Fig. 6 south of MV station 4) for the electric field measured parallel to the strike of the line. The same data are shown in two forms: profiles at constant frequency in (*a*) and a pseudosection in (*b*). Note the low values of resistivity between stations 8 and 12 over the fault zone, which lies to the east of the fault scarp.

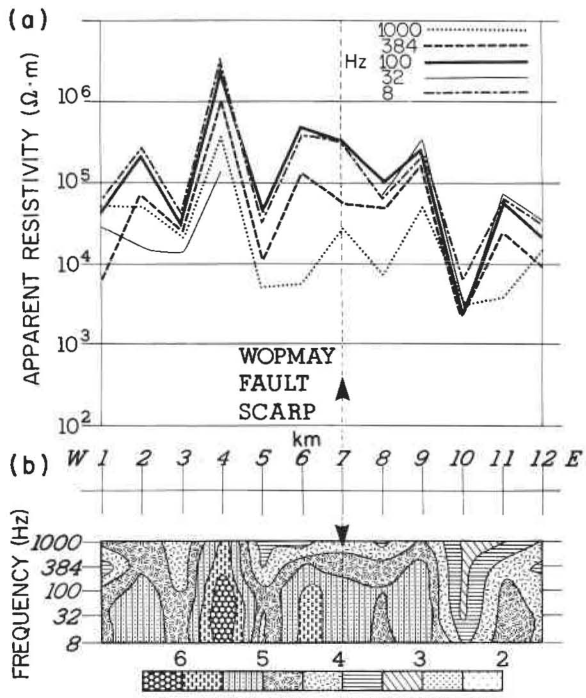

FIG. 9. Same as Fig. 8 but for the electric field measured perpendicular to strike.

associated with the unit's cleavage and schistosity than to the graphite.

(3) The variation anomaly is minor compared with the NACP anomaly mapped in Saskatchewan, Manitoba, and the American states to the south. Since the NACP anomaly may be associated with ancient oceanic crust, one may conclude that such crust is no longer present in the Wopmay Orogen (if it ever existed).

(4) Audio-frequency magnetotellurics is relatively insensitive to the depth extent of narrow two- and three-dimensional conductive units in the Wopmay fault zone. Induced currents are evidently concentrated within a fraction of a skin depth of the top of such narrow features in a resistive host. Hence, the experiment was able to suggest only that the zone extends to a depth of at least 1–2 km.

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ALABI, A. O., CAMFIELD, P. A., and GOUGH, D. I. 1975. The North American Central Plains conductivity anomaly. Geophysical Journal of the Royal Astronomical Society, **43**: 815–833.

BAILEY, R. C., EDWARDS, R. N., GARLAND, G. D., KURTZ, R., and PITCHER, D. 1974. Electrical conductivity studies over a tectonically active area in eastern Canada. Journal of Geomagnetism and Geoelectricity, **26**: 125–146.

BEAMISH, D. 1979. Source field effects on transfer functions at mid-latitudes. Geophysical Journal of the Royal Astronomical Society, **58**: 117–134.

CAMFIELD, P. A., KRENTZ, D. H., GUPTA, J. C., and OSTROWSKI, J. A. 1987. Geomagnetic induction studies in the region of the Wopmay Orogen, Northwest Territories, Canada. *Edited by* W. Mundt. Heinrich Herz Institute (Berlin), Report 21, pp. 125–130.

COLES, R. L., and CURRIE, R. G. 1977. Magnetic anomalies and rock magnetizations in the southern Coast Mountains, British Columbia: possible relation to subduction. Canadian Journal of Earth Sciences, **14**: 1753–1770.

DODS, S.D., HOOD, P. J., TESKEY, D. J., and MCGRATH, P. H. 1984. Magnetic anomaly map of Canada. 4th ed. Geological Survey of Canada, Map 1255A, scale 1 : 5 000 000.

DUBA, A., HUENGES, E., NOVER, G., WILL, G., and JOEDICKE, H. 1988. Impedance of black shale from Muensterland 1 borehole: an anomalously good conductor? Geophysical Journal, **94**: 413–419.

FISCHER, G., and LEQUANG, B. V. 1982. Parameter trade-off in one-dimensional magnetotelluric modelling. Journal of Geophysics, **51**: 206–215.

FISCHER, G., SCHNEGG, P. A., PEGUIRON, M., and LEQUANG, B. V. 1981. An analytic one-dimensional magnetotelluric inversion scheme. Geophysical Journal of the Royal Astronomical Society, **67**: 257–278.

GOUGH, D. I. 1983. Electromagnetic geophysics and global tectonics. Journal of Geophysical Research, **88**: 3367–3377.

GREEN, A. G., HAJNAL, Z., and WEBER, W. 1985. Evolution of the Churchill Province and western margin of the Superior Province in Canada and the north-central United States. Tectonophysics, **116**: 281−322.

GUPTA, J. C., KURTZ, R. D., and CAMFIELD, P. A. 1983. An induction anomaly near the west coast of Hudson Bay, Canada. Energy, Mines and Resources Canada, Earth Physics Branch, Open File 83-19.

GUPTA, J. C., KURTZ, R. D., CAMFIELD, P. A., and NIBLETT, E. R. 1985. A geomagnetic induction anomaly from I.M.S. data near Hudson Bay and its relation to crustal electrical conductivity in central North America. Geophysical Journal of the Royal Astronomical Society, **81**: 33−46.

GUSTAFSSON, G. 1970. A revised corrected geomagnetic coordinate system. Arkiv för Geofysik, **5**: 595−617.

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

HILDEBRAND, R. S., and BOWRING, S. A. 1984. Continental intra-arc depressions: a non-extensional model for their origin, with a Proterozoic example from Wopmay Orogen. Geology, **12**: 73−77.

HILDEBRAND, R. S., HOFFMAN, P. F., and BOWRING, S. A. 1986. Wopmay Orogen as an evolving continental arc: magmatic response to contrasting stress regimes [abstract]. Geological Association of Canada, Program with Abstracts, **11**: 81.

——— 1987. Tectonomagmatic evolution of the 1.9 Ga Great Bear magmatic zone, Wopmay Orogen, northwestern Canada. Journal of Volcanology and Geothermal Research, **32**: 99−118.

HOFFMAN, P. F. 1980. Wopmay Orogen: a Wilson cycle of Early Proterozoic age in the northwest of the Canadian Shield. *In* The continental crust and its mineral deposits. *Edited by* D. W. Strangway. Geological Association of Canada, Special Paper 20, pp. 523−549.

——— 1984*a*. Wopmay fault zone and its role in evolution of Wopmay Orogen [abstract]. Geological Association of Canada, Program with Abstracts, **9**: 74.

——— 1984*b*. Geology, northern internides of Wopmay Orogen, District of Mackenzie, Northwest Territories. Geological Survey of Canada, Map 1576A, scale 1 : 250 000.

HOFFMAN, P. F., and BOWRING, S. A. 1984. Short-lived 1.9 Ga continental margin and its destruction, Wopmay Orogen, northwest Canada. Geology, **12**: 68−72.

JONES, A. G. 1981. Geomagnetic induction studies in Scandinavia, II. Geomagnetic depth sounding, induction vectors and coast effects. Journal of Geophysics, **50**: 23−36.

——— 1986. Parkinson's pointers' potential perfidy. Geophysical Journal of the Royal Astronomical Society, **87**: 1215−1224.

JONES, A. G., KURTZ, R. D., OLDENBURG, D. W., BOERNER, D. E., and ELLIS, R. 1988. Magnetotelluric observations along the Lithoprobe southeastern Canadian Cordilleran transect. Geophysical Research Letters, **15**: 677−680.

KING, J. E. 1983. Wopmay fault zone—a major mylonite and brittle fault belt, internal zone, Wopmay Orogen [abstract]. Geological Association of Canada, Program with Abstracts, **8**: A37.

——— 1986. The metamorphic internal zone of Wopmay Orogen (Early Proterozoic), Canada: 30 km of structural relief in a composite section based on plunge projection. Tectonics, **5**: 973−994.

KRENTZ, D. H. 1983. Interpretation of the Wopmay fault zone using audiomagnetotelluric data. B.Sc. thesis, Queen's University, Kingston, Ont.

KU, C. C., HSIEH, M. S., and LIM, S. H. 1973. The topographic effect in electromagnetic fields. Canadian Journal of Earth Sciences, **10**: 645−656.

KURTZ, R. D. 1982. Magnetotelluric interpretation of crustal and mantle structure in the Grenville Province. Geophysical Journal of the Royal Astronomical Society, **70**: 373−397.

KURTZ, R. D., DELAURIER, J. M., and GUPTA, J. C. 1986. A magnetotelluric sounding across Vancouver Island detects the subducting Juan de Fuca plate. Nature (London), **321**: 596−599.

LEWRY, J. F. 1981. Lower Proterozoic arc−microcontinent collisional tectonics in the western Churchill Province. Nature (London), **294**: 69−72.

PALACKY, G. J. 1986. Geological background to resistivity mapping. *In* Airborne resistivity mapping. *Edited by* G. J. Palacky. Geological Survey of Canada, Paper 86-22, pp. 19−27.

SCHMUCKER, U. 1970. Anomalies of geomagnetic variations in the south-western United States. Scripps Institution of Oceanography, La Jolla, CA, Bulletin 13.

ST-ONGE, M. R. 1984. Geothermometry and geobarometry in pelitic rocks of north-central Wopmay Orogen (Early Proterozoic), Northwest Territories, Canada. Geological Society of America Bulletin, **95**: 196−208.

STRANGWAY, D. W. 1983. Audio-frequency magnetotelluric (AMT) sounding. *In* Developments in geophysical exploration methods. *Edited by* A. A. Fitch. Applied Science Publishers, Barking, Essex, Vol. 5, pp. 107−159.

TELFORD, W. M., GELDART, L. P., SHERIFF, R. E., and KEYS, D. A. 1976. Applied geophysics. Cambridge University Press, Cambridge.

THOMAS, M. D. 1984. Structural significance of some gravity anomalies in Wopmay Orogen [abstract]. Geological Association of Canada, Program with Abstracts, **9**: 111.

TRIGG, D. F. 1972. An amplifier and filter system for telluric signals. Energy, Mines and Resources Canada, Publications of the Earth Physics Branch, No. 44, pp. 1−5.

——— 1974. Operating the Datel data loggers. Energy, Mines and Resources Canada, Earth Physics Branch, Geomagnetic Report 74-2.

TRIGG, D. G., SERSON, P. H., and CAMFIELD, P. A. 1971. A solid-state electrical recording magnetometer. Energy, Mines and Resources Canada, Publications of the Earth Physics Branch, No. 41, pp. 67−80.

VOZOFF, K., *editor*. 1985. Magnetotelluric methods. Society of Exploration Geophysicists, Geophysics Reprint Series, No. 5.