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A geomagnetic induction anomaly from IMS data near Hudson Bay, and its relation to crustal electrical conductivity in central North America

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Summary. Canadian geomagnetic data collected during the International Magnetospheric Study are used to investigate the terrestrial electrical conductivity structure of north-eastern Manitoba and part of the North-west Territories. The computed transfer functions resolve a major conductor trending east–west between the communities of Gillam and Back in Manitoba. Regional trends in the surface geology suggest that this conductor may be linked with the North American Central Plains electrical conductor. Two-dimensional modelling of the data suggests that the conductor dips to the north from a small depth beneath Gillam and may extend to the lowermost crust.

Introduction

In the magnetosphere, where incoming solar particles and energy are temporarily stored, complex energy transfers and interactions between plasmas, fields, waves and particles are continuously taking place. The influence of these phenomena on the delicate balance of upper atmospheric dynamics and hence on weather systems and climate, on short-wave radio propagation, and on power transmission lines, requires much study. Thus, the International Magnetospheric Study (IMS) was proposed in the early 1970s as a concerted effort to acquire ground-based, balloon, rocket and satellite data to improve our understanding of the behaviour of the plasma environment of the Earth.

The Earth Physics Branch established an array of magnetometers along the Churchill magnetic meridian as part of the Canadian participation in IMS, in order to study the ionospheric and magnetospheric current systems. The present investigation, using transfer functions, was undertaken to identify any distortions of the ground magnetic observations by subsurface electric currents in the region. The influence of the internal currents, if present, needs to be taken into account (1) to obtain meaningful ionospheric current models from the IMS data both during the quiet and magnetically disturbed times and (2) to help in the selection of appropriate sites for future magnetic observations for CANOPUS (Canadian Auroral Network For The OPEN Program Unified Study), in which the magnetometer and riometer array (MARIA) is a significant element. While the investigation thus had a space-physics motivation, the results have important geological and tectonic implications.

Data

Digital data at 10 s intervals were collected at the IMS magnetometer stations between 1976 September and 1980 June. A detailed discussion of the data acquisition and of the derivation of values at 1 min intervals from the recorded data has been given by Plet & Jansen van Beek (1982). The description of the stations may be found in Table 1 and their locations are shown in Fig. 1. One-minute data for Fort Churchill and Igloolik had been analysed previously by Kurtz (unpublished).

Fort Severn (FSV) (refer to Table 1 for the code names of other stations) had the smallest number of days with usable IMS data. Magnetograms of the data available from FSV were examined with the intention of obtaining simultaneous records from the other stations of the Churchill array. Thirty-five days during 1976–80 at FSV were selected during which

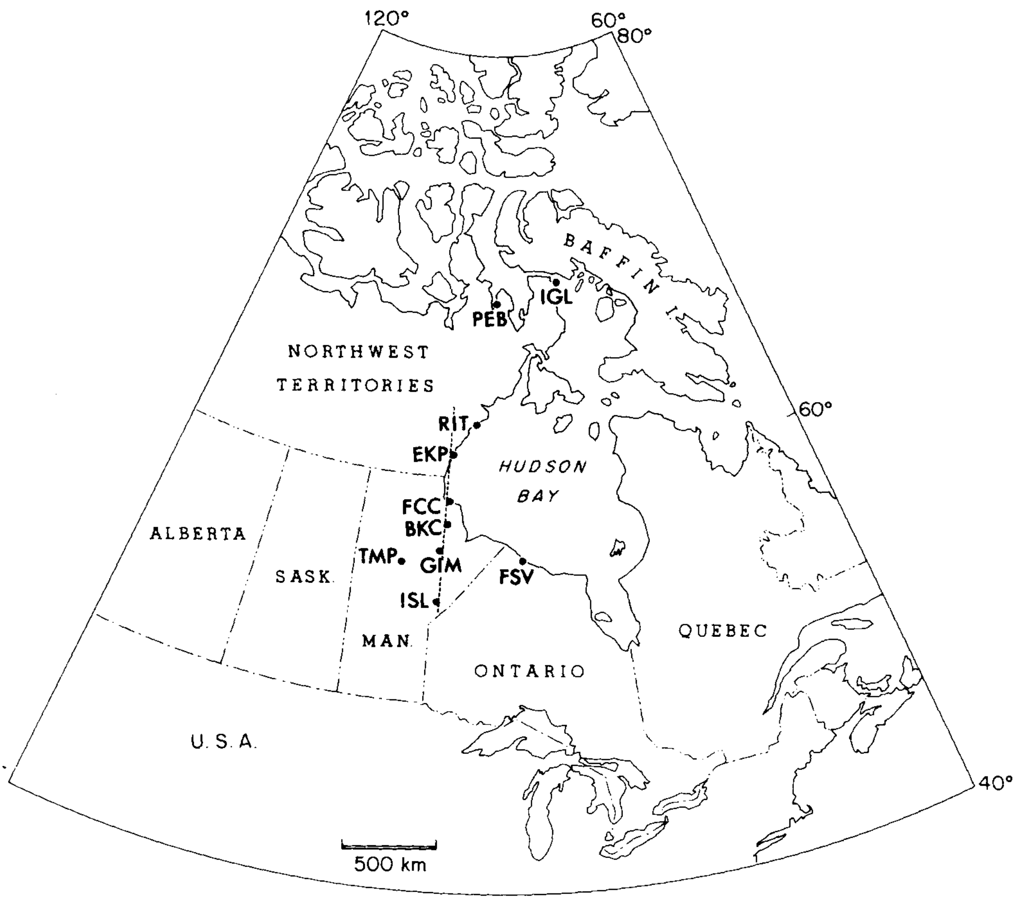

Figure 1. Map of Canada showing the location of the stations from which IMS data are used for the present investigation. For the majority of events analysed in this paper the auroral oval was likely located to the north of FCC. The N–S broken line between RIT and ISL represents the profile discussed in Figs 4 and 5.

Table 1. Description of the IMS stations analysed in this study.

Station No.	Station Name	Code	Geographic Coordinates		Geomagnetic Coordinates*		Declination (°)
			Lat. (°N)	Long. (°W)	Lat. (°N)	Long. (°E)	
1	IGLOOLIK	IGL	69.4	81.8	77.4	353.9	-48.0
2	PELLY BAY	PEB	68.5	89.8	76.6	340.6	-27.5
3	RANKIN INLET	RIT	62.6	91.9	70.9	337.8	-5.0
4	ESKIMO POINT	EKP	61.1	94.1	69.2	335.3	2.0
5	FORT CHURCHILL	FCC	58.8	94.1	66.9	335.5	0.0
6	BACK	BKC	57.7	94.2	65.8	335.7	2.9
7	GILLAM	GIM	56.4	94.7	64.5	335.1	3.3
8	FORT SEVERN	FSV	56.0	87.6	64.4	344.2	-8.0
9	THOMPSON	TMP	55.7	97.9	63.8	331.0	9.8
10	ISLAND LAKE	ISL	53.9	94.7	62.1	335.4	3.8

*Wallis & Hughes (1982).

Z-variations were moderate ($\Sigma Kp \simeq 23$) when compared with the observed general level of activity in this component and also in the H- and D-components. Data simultaneous with the selected FSV series were available for 11 of the 35 days from PEB, 26 days from RIT, 25 days from EKP, 26 days from BKC, 14 days from GIM, 28 days from TMP and 30 days from ISL. Kurtz (unpublished) used nine days in 1978 from FCC and 12 days in 1981 from IGL.

All stations included in the study are strongly affected by auroral-zone and polar-cap currents. Large-amplitude magnetic variations exist even under moderately disturbed conditions. The orientation of the source and its distance from the point of observation determine the variation in any component. Since these parameters change radically with time, variations may differ significantly from event to event. The stacked plots of a particular event may sometimes indicate the presence of additional currents flowing in an underlying conductor. Such indications may not be consistent from one event to another, however, because the internal contributions depend on the frequency content and the polarization of the source field. Another important point is that the stations in the Churchill array, although on nearly the same geomagnetic meridian, are quite far apart. Therefore, subjective inspections of the data will provide only a very general view of induction anomalies in the vicinity of the stations.

The influence of the external sources at these high latitudes is minimized by careful selection of day-time events to eliminate the influence of the substorms, and by taking ensemble averages of the calculated transfer functions. Here, the assumption is that the external currents vary in position, sometimes drastically, but that the internal currents do not. Any effect left after averaging should then be due primarily to the internal currents. Thus, for the present investigation the following criteria adopted by Handa & Camfield (1984) in the analysis of similar data collected in nearby Saskatchewan have been closely followed:

(1) Z-variations should have small amplitudes relative to the horizontal variations.

(2) Day-time events are preferable. In the present case parts of magnetograms showing relatively low magnetic activity were generally taken.

(3) Degree of polarization of the horizontal fields should be less than 0.7. This parameter is defined as the ratio of polarized power to total power (Bailey *et al.* 1974, p. 137).

For each day (00–24 hr UT), stacked plots of individual components *H, D* and *Z* for all stations allow a convenient inspection of the data. Due to the compact form and the low sensitivity at which these plots were made, induction effects, especially at shorter periods, were not obvious. Fig. 2(a) gives a plot of the magnetic variations for 6 hr at some of the stations for 1979 September 4. Evidence for the existence of terrestrial conductors is difficult to discern from these figures. Strong vertical source fields change rapidly along this north–south line of stations and obscure the reversals in *Z* phase which would be due to internal currents. At these latitudes, it would indeed be fortuitous to find clear reversals. However, on the plot of the 10 s data in Fig. 2(b), which is an enlarged portion of Fig. 2(a), obvious large phase shifts or even reversals of the *Z*-component are observed between BKC and GIM. Such phase shifts of the *Z*-component indicate flow of current between these stations, either overhead or under the surface. If such phase changes occur consistently for many day-time events, the currents can be assumed to be internal. Unambiguous evidence for internal currents emerged only after transfer function analysis of many data sets, which averaged out the source effects.

In other stacked plots (not shown), the influence of the longer duration substorms is quite clear at all stations. At times, an enhancement of the *H*-component is recorded at BKC and GIM. Sometimes differences in the variation of the *Z*-component at BKC relative to other stations may also be seen. In one plot, a large phase difference or even a reversal in *Z* was noted at BKC and higher latitude stations, when compared to those stations to the south. Pulsational activity superimposed on the longer duration substorms tends to have maximum amplitude at different stations during different events. These latter effects almost certainly are related to the changing location of the external current sources.

Relative to *H*-component variations, those seen in the *D*-component are generally small for the majority of the events chosen. This implies that the relevant ionospheric current systems tend to flow east–west.

Following the criteria noted above, suitable 12 hr intervals at each station were selected

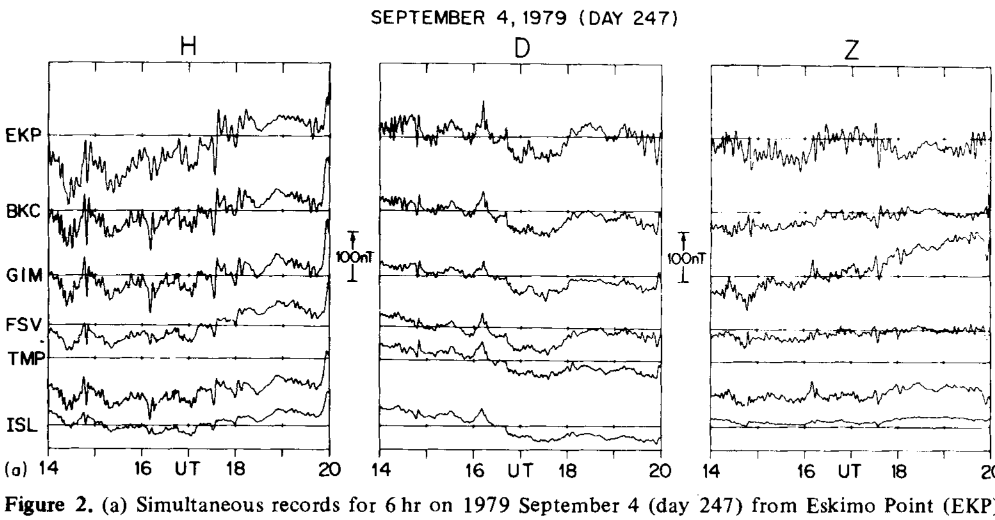

Figure 2. (a) Simultaneous records for 6 hr on 1979 September 4 (day 247) from Eskimo Point (EKP), Back (BKC), Gillam (GIM), Fort Severn (FSV), Thompson (TMP) and Island Lake (ISL). Sampling interval was 1 min. (b) Magnetograms between 1700 and 1800 UT on 1979 September 4, prepared from 10 s data from Back (BKC) and Gillam (GIM). A large phase shift may be noted easily in the vertical component variations. Such reversals are first indications of an induction anomaly.

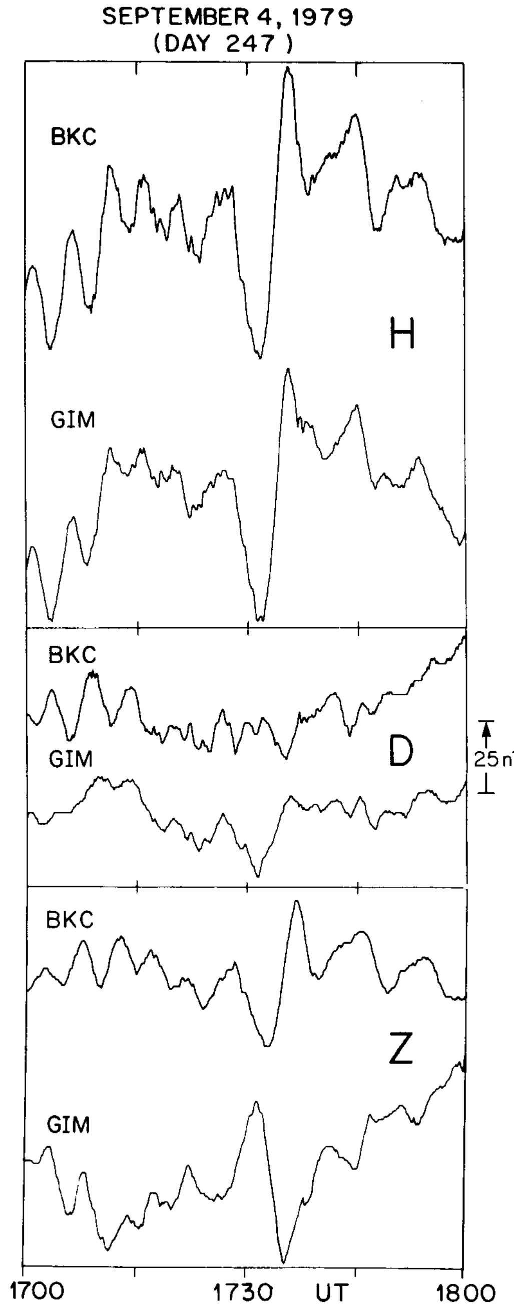

Figure 2 – *continued*

(in a few cases a shorter interval was taken) and average horizontal-to-vertical transfer functions were calculated following Edwards, Law & White (1971) and Bailey *et al.* (1974) at 22 periods ranging from 122 to 30 720 s ($\simeq$ 2–512 min). A detailed discussion of the method of analysis is given elsewhere (Gupta, Kurtz & Camfield 1983) along with plots of the frequency response of the transfer functions.

Response arrows

At periods of 2.5, 4, 5, 10, 20, 40, 80 and 162 min, response arrows (induction arrows) derived from the transfer functions are displayed in Fig. 3. Following the usual convention, the direction of the arrow shows the azimuth of horizontal variations which best correlate with vertical variations, and the length gives the ratio of the correlated vertical and horizontal fields. Here the upper diagram gives the in-phase (real) and the lower diagram gives the quadrature phase (imaginary) response arrows. The arrows for the in-phase transfer functions have been reversed in direction so as to point towards the internal currents and away from the external currents.

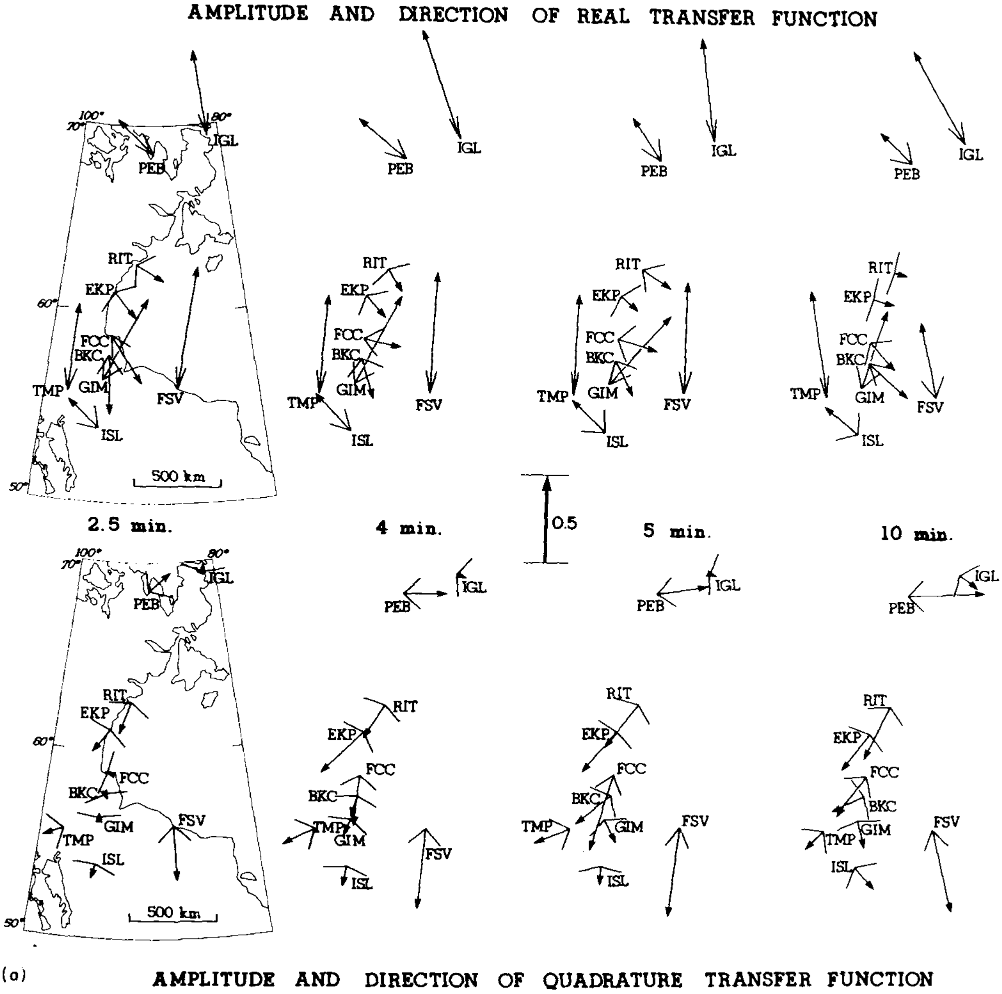

Figure 3. The vertical-field response arrows giving the amplitude and direction of the transfer functions at all the nine stations at eight different periods ranging from 2.5 to 162 min. The in-phase arrows shown in the upper part of the diagram have been reversed to point towards the internal currents and away from the external currents. The quadrature-phase arrows are shown in the lower part of the diagram. A half-unit scale arrow is in the centre of the diagram. Plus or minus one standard deviation of azimuthal uncertainty in each arrow is marked by the short lines drawn from the foot of the arrow. Since the directions of the arrows are the principal focus of this figure, uncertainties in the lengths are not shown, for clarity. An appreciation of these uncertainties may be gained from the error bars in Fig. 5.

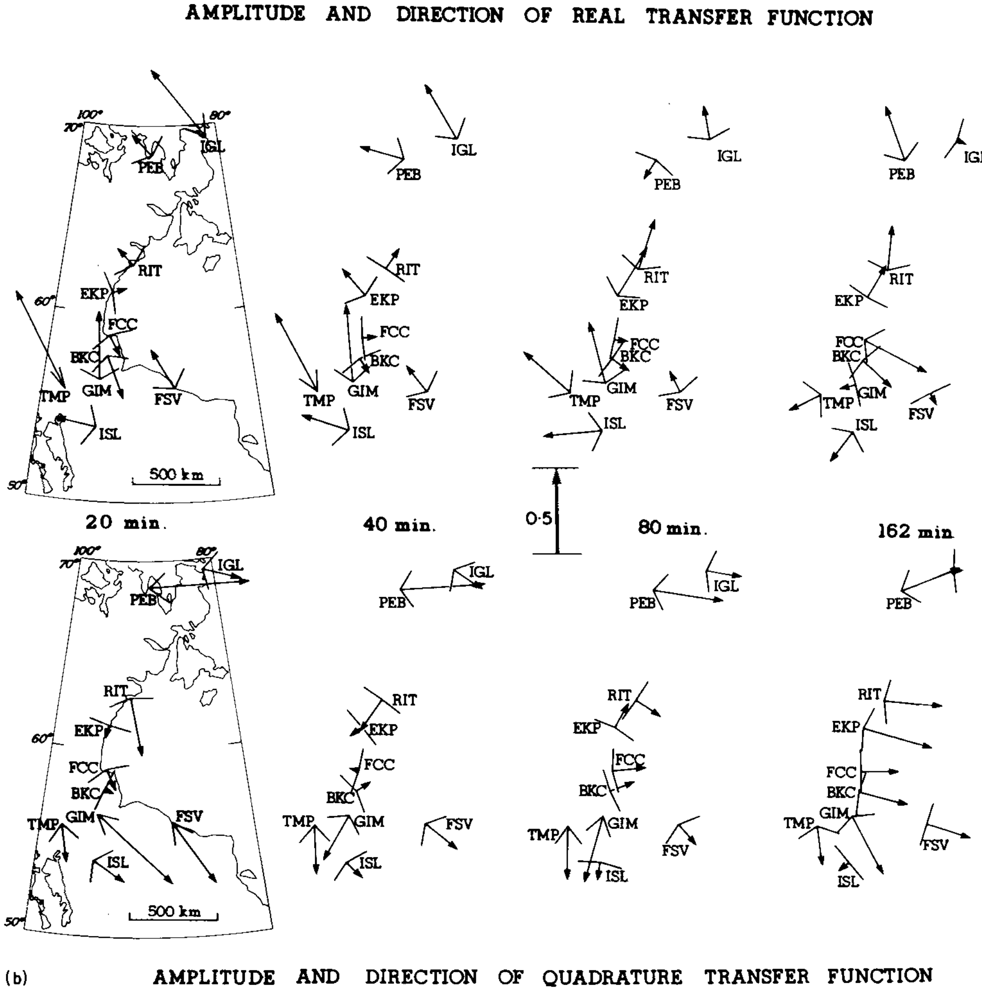

Figure 3 – *continued*

In general, the in-phase arrows at PEB and IGL have large amplitudes and point NW. Those at RIT and EKP have smaller amplitudes and point SE for periods of up to 10 min. Such a situation may arise if uniform external currents are flowing close to PEB and IGL but far away from the rest of the stations (Loomer & Gupta 1980) consistent with the assumed position of the auroral oval for the events analysed. This would partially satisfy the condition that vertical variations due to external sources, at the stations of interest for induction investigations, be very small (condition 2). However, magnetic variations at PEB and IGL would also be influenced by electric currents flowing in the conducting salt water to the north.

Fig. 3 shows that the in-phase arrows at GIM point northwards and at BKC southwards. The arrows to the west of GIM at TMP and to the east at FSV closely follow the direction of the arrow at GIM, up to a period of about 80 min. In contrast, arrows at FCC, EKP and RIT follow the direction of the arrow at BKC up to a period of at least 10 min. At longer periods the observed directions of the arrows at FCC, EKP and RIT are most probably influenced by the auroral electrojet currents. At short periods the azimuths of the arrows at ISL, TMP, GIM, FSV, BKC and FCC are reasonably well defined, and oppositely-directed arrows seem to be related to phase reversals in the Z-component between BKC and GIM such as shown in Fig. 2(b). The oppositely directed arrows are probably related to anomalous internal currents flowing in an internal electrical conductor that trends E–W to the north of TMP, passes between BKC and GIM, and most likely extends to the north of FSV. From skin depth considerations one would expect the conductor to be a body with a base sufficiently deep in the Earth to affect response arrows of periods up to 80 min and more.

North–south profiles

To look further at the fields associated with current flow in an E–W internal conductor, the N–S component of the transfer function amplitude was calculated using the equation

$$L_{\mathrm{re,qu}} = l_{\mathrm{re,qu}} \cos(\theta_{\mathrm{re,qu}} + D^{\circ})$$

where $l_{\mathrm{re,qu}}$ is the amplitude of the real (quadrature) transfer function and $\theta_{\mathrm{re,qu}}$ lie between $\pm 180^{\circ}$ and are the angles made by the response arrows with the local geomagnetic meridian. D° is the declination at a station. The N–S profiles given in Fig. 4 are drawn using the calculated values of L. The procedure is equivalent to a hypothetical event analysis using a unit N–S inducing field.

Except at FSV the profiles of the projected transfer function amplitudes are quite smooth and similar at all periods. Any changes are gradual from short to long periods. In general form the profiles represent the vertical magnetic field (normalized by the horizontal field) which would arise from E–W currents flowing within the Earth between the latitudes of BKC and GIM/FSV.

FSV is east of the main N–S line of stations and may be affected by electric currents flowing in the saline water of Hudson Bay. Such an effect is supported by the eastward tendency of the response arrows at RIT, EKP and FCC. These currents may enhance the amplitude of the FSV real transfer function at short periods (2.5–5 min) and that of the quadrature transfer function at periods from 2.5 to 20 min. The dotted lines in Fig. 4 suggest possible distortions of the amplitude profiles at FSV. At longer periods (from 10 to 162 min) the amplitude of the real transfer function is below that at GIM and TMP, as is the quadrature transfer function from periods of about 40–162 min. At FSC, the fields of currents in the water of Hudson Bay should add to those in an E–W crustal conductor north of this station. The reduction in the amplitude of the FSV transfer functions at the long periods suggests that the depth extent of the conductor may be limited.

Conductive structure

To study the structure of the internal conductor evident in the transfer functions, the E-polarization responses of 2-D inhomogeneous earth models were calculated following Ku, Hsieh & Lim (1973). For the model calculations it was assumed that a conductor (resistivity = 10–50 Ωm) lies within a resistive crust and upper mantle (2500–25 000 Ωm) that extends to a depth of about 130 km. Underneath is a conducting aesthenosphere (200 Ωm). For the model of the area under consideration, high crustal resistivities have been assumed, similar to those reported elsewhere for the Canadian Shield (Strangway, Redman & Macklin 1980). The computed transfer functions obtained from the ratio of the vertical to the horizontal fields at periods of 2.5 and 20 min were compared to the profiles described in Fig. 4, which were considered to be transverse to the strike of the E–W conductor. Various models were computed, i.e. conducting bodies with rectangular cross-section and several widths and depths, conductors dipping towards higher or lower latitudes, etc. The

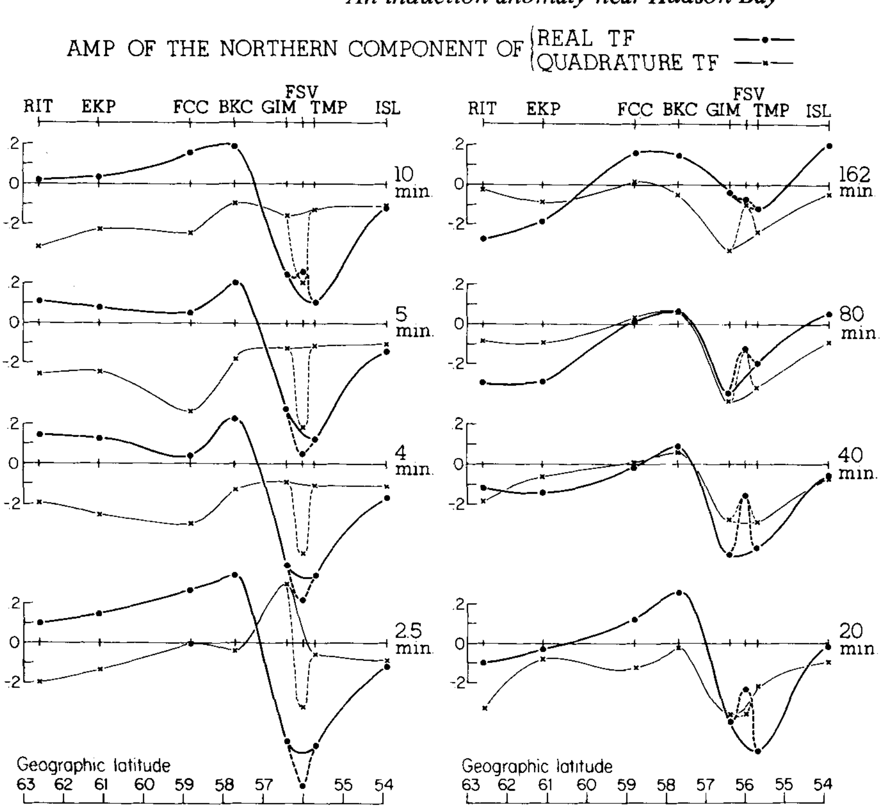

Figure 4. Amplitude of the real and quadrature transfer functions projected on a N–S profile. Note the anomalous behaviour of the curves at station FSV.

model that provides the best fit to the observed real and quadrature transfer functions at both the short (2.5 min) and long (20 min) periods is shown in Fig. 5 and is henceforth called the 'selected model'. Results are given in Table 2 for some experiments in which parameters of the host medium and of the conductor were varied. The model transfer functions are graded A, B or C for decreasing quality of fit to the measured transfer functions on the N–S profiles. The selected model is the reference with uniform A grades.

It is obvious from Table 2 that the fit remains unchanged whether the conductor comes to the surface of the Earth or is buried 5 km deep. A narrower conductor improves the fit to the short-period profiles but some deterioration is noted in the fit of the long-period in-phase transfer functions. On the other hand, a wider conductor improves the fit to the real transfer function profile at long periods but the fit deteriorates for shorter periods and so on. Based on the information given in Table 2, the following may be said about the conductor under western Hudson Bay:

(1) The conductor influences the observations at BKC and GIM most, to give oppositely directed response arrows at these two stations. TMP and FSV are also strongly influenced.

(2) It is buried in an environment of high resistivity (5000 Ωm). There was little change in the quality of fit when the resistivity was lowered to 2500 Ωm or raised to 25 000 Ωm.

(3) The lateral position of the top of the conductor is constrained reasonably well between GIM and BKC, but is closer to GIM than to BKC.

(4) The depth to the top of the conductor is not well constrained by the data. The top may be at the surface or as deep as 10 km. The conductor may extend to the bottom or

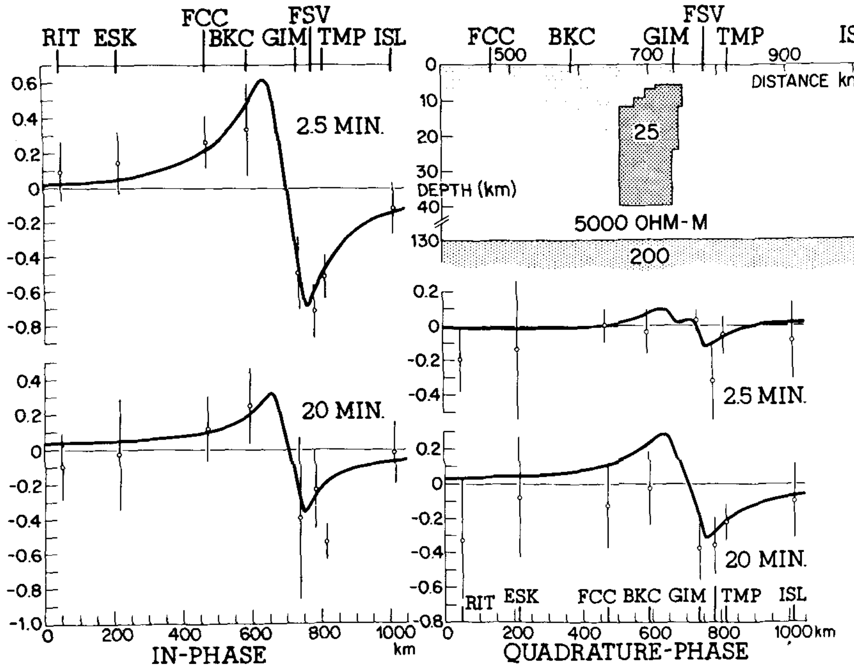

Figure 5. In-phase and quadrature responses (ratios of vertical to horizontal fields) at 2.5 and 20 min periods were computed for the 2-D conductivity structure shown in the upper right. The observed values of the transfer functions projected on to the N–S line in Fig. 1 are shown by circles with error bars representing plus and minus one standard deviation from the average values, and the calculated values are shown by the solid curves.

below the base of the Earth's crust in this region, at a depth of about 40 km (Innes *et al.* 1972).

(5) The top of the conductor appears to be about 40 km wide with the southern end under GIM or possibly slightly south of GIM. The body gradually becomes wider at greater depths and may be 60–80 km wide near its greatest depth. It dips towards higher latitudes.

(6) Its resistivity lies between 10–50 Ωm with the best fit to the observed data being achieved for a value of 25 Ωm.

Despite the above, it needs to be emphasized that the selected model cannot be considered unique. It is only one of many possibilities that may produce similar or better results. In addition it must be noted that the 2-D structure is assumed to strike E–W. This is certainly supported by the transfer functions and by trends in the regional geology (Manitona Department of Energy and Mines 1979) and in magnetic and gravity anomalies (McGrath, Hood & Darnley 1977; Earth Physics Branch 1980). However, further induction studies would be required to confirm this contention. More serious, perhaps, is the projection of two of the stations on to the N–S profile. While EKP, FCC, BKC, GIM and ISL are on the profile, TMP and FSV are not. However, if the data from TMP and FSV were omitted from Fig. 5 the final model would still be constrained to have the same general configuration.

Geological and tectonic implications

Recently, Lewry (1981), Lewry, Sibbald & Schledewitz (1984) and Green, Hajnal & Weber (1985) have summarized the known geological features of the Precambrian Shield in the

Table 2. Quality of fit between observations and calculated response, as affected by changing the parameters of the model in Fig. 6.

CONDUCTOR	PERIOD = 2.5 MIN REAL TF	PERIOD = 2.5 MIN QUAD. TF	PERIOD = 20 MIN REAL TF	PERIOD = 20 MIN QUAD. TF
Top at the surface	A	A	A	A
Top 5 km deep	A	A	A	A
Displaced 16 km to north (both cases above)	C	C+	C	C
8 km narrower	A+	A+	B+	A+
8 km wider	C	A	A+	B
extending deeper (94 km)	A-	A	B-	B
shallower (14 km)	A	B-	B-	A-
Resistivity = 50 ohm.m	B+	C+	C+	A
Resistivity = 10 ohm.m	C	B+	A	B-
R=15 ohm.m below 10 km	A	B+	A-	B+
Same, but also 8 km narrower	A+	A	A-	A-
Dipping towards lower latitudes	B	B+	A-	A
Vertical	C	C	C	C

TF: transfer function.
A: indicates highest quality of fit.

Saskatchewan–Manitoba area. It may be seen from Fig. 6 (from Green *et al.* 1985) that the area may be subdivided into a number of tectonic/geological zones. The conductor between GIM and BKC is in the vicinity of the easterly extensions of the Wathaman–Chipewyan (W–C) batholith and the La Ronge–Lynn Lake (LR–LL), Reindeer–South Indian Lakes (R–SI) and Kisseynew (KG) belts. North and west of these terrains lies the Cree Lake zone (Wollaston and Seal River domains) and to the south lies the Glennie Lake domain, the Tabbernor fault/fold zone and the Flin Flon–Snow Lake, Thompson and Fox River belts. According to Green *et al.* (1985) the La Ronge–Lynn Lake and Flin Flon–Snow Lake belts are granite/greenstone terrains of Proterozoic age and are composed of volcanic island-arc assemblages. However, the geology is poorly known in the vicinity of our magnetometer stations because of lack of outcrop. The Wathaman–Chipewyan batholith is a composite of granitic to monzonitic to granodioritic intrusive rocks and is exposed for a length exceeding 800 km between the cover rocks of the Williston and Hudson Bay basins. Rocks in the Kisseynew and Reindeer–South Indian Lakes belts are mainly greywackes, siltstones and mudstones that have been subjected to high grades of metamorphism to form paragneisses, migmatites and, in the central regions of the belt, anatectic granitic bodies. These rocks likely originated as volcanic detritus from the nearby volcanic island arcs, transported in part by turbidity currents.

The 'Gillam–Back' conductor found in this study trends E–W and appears to have its southern edge beneath GIM or slightly to the south and its northern edge 60–80 km towards

BKC (distance between BK and GIM is about 145km). This suggests that the conductor lies beneath geological units identified tentatively as cordillerian-type arc massifs and highly reworked oceanic material (former fore-arc or back-arc basins north of the Fox River belt).

Handa & Camfield (1984) have shown that the North American Central Plains (NACP) conductivity anomaly extends into Saskatchewan where it lies beneath the Rottenstone–La Ronge magmatic belt at about longitude 150°W. This belt in Fig. 6 consists of the Wathaman–Chipewyan batholith, the Reindeer–South Indian Lakes and La Ronge–Lynn Lake belts. However, the Gillam–Back conductor relates most closely to the surface exposure of the Kisseynew belt, whereas the NACP is related to the more northerly structures. It is likely however that the Gillam–Back feature passes beneath the Reindeer–South Indian Lakes belt and/or the La Ronge–Lynn Lake belt as suggested by Green *et al.* (1985).

Both the NACP conductor in Saskatchewan and the Gillam–Back conductor in Manitoba are major structures. Surface geological trends suggest that the NE–SW structure in Saskatchewan turns E–W in Manitoba. In general terms this is the basis for speculating that the NACP structure links with the Gillam–Back structure. In detail it is hard to correlate this claim with surface geology, since the station spacing is too sparse in both areas, especially in Manitoba. Fig. 7 shows the NACP conductor and a possible link with the Manitoba part of the Gillam–Back conductor. The transfer functions at FSV suggest that the conductor extends further eastward under Hudson Bay.

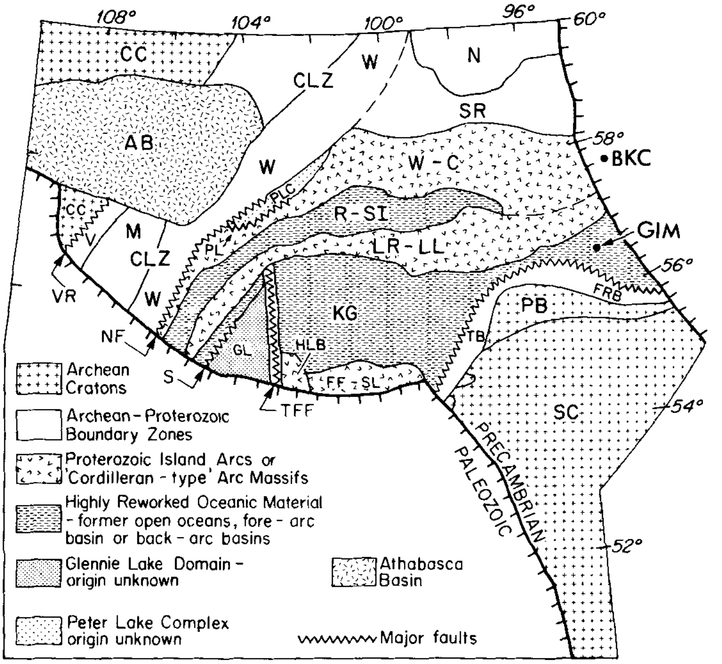

Figure 6. Tectonic units on the exposed Canadian Shield of Manitoba and Saskatchewan from Green *et al.* (1985). TB – Thompson belt; FRB – Fox River belt; KG – Kisseynew gneiss belt; FF–SL – Flin Flon–Snow Lake belt; HLB – Hanson Lake block; GL – Glennie Lake domain; LR–LL – La Ronge–Lynn Lake belt; R–SI – Reindeer–South Indian Lakes belt (includes Lewry's Rottenstone migmatic complex); W–C – Wathaman–Chipewyan batholith; PLC – Peter Lake complex; W – Wollaston domain; SR – Seal River domain; N – Nejanilini domain; M – Mudjatik domain; V – Virgin River domain; CLZ – Cree Lake zone (includes the Wollaston, Seal River, Nejanilini, Mudjatik and Virgin River domains); CC – Churchill craton; TFF – Tabbernor fault/fold zone; S – Stanley Shear zone; NF – Needle Falls shear zone; PL – Parker Lake shear zone; VR – Virgin River shear zone; AB – Athabasca basin.

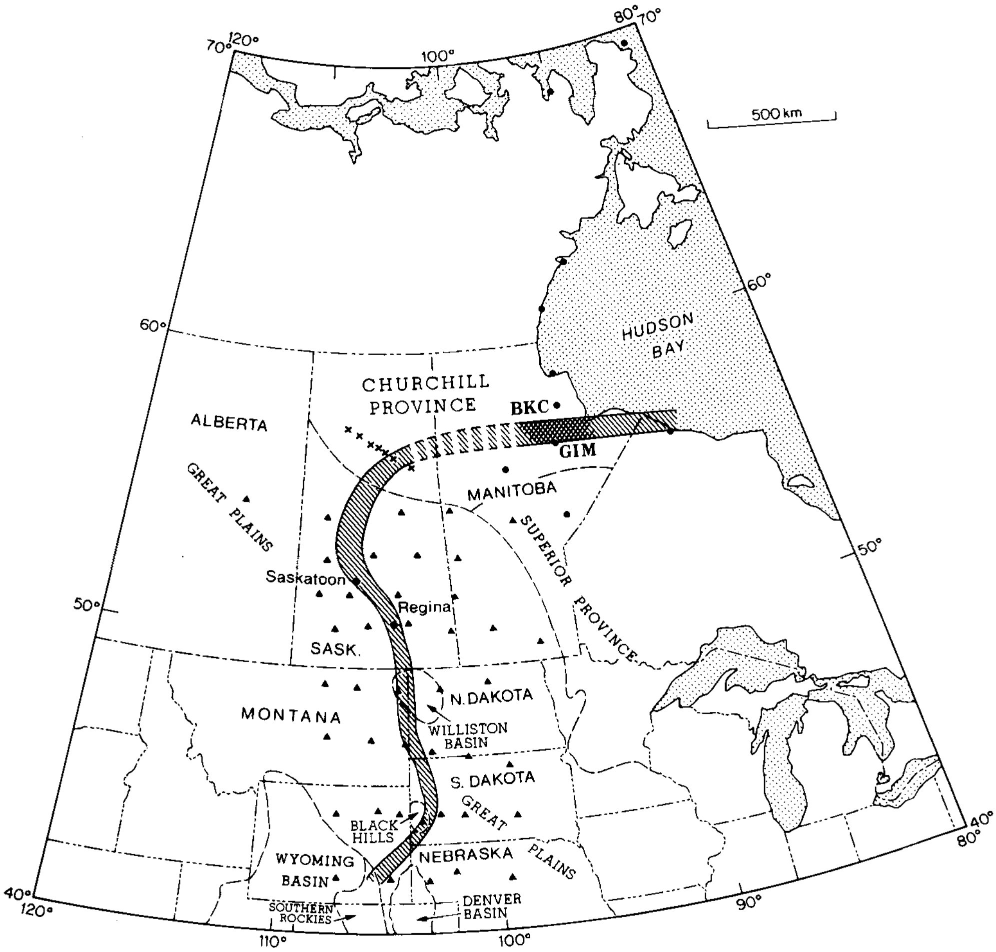

Figure 7. Location of the North American Central Plains conductive body (broad shaded area). In the Churchill Province the Wathaman–Chipewyan Batholith lies to the north and the bulk of the Kisseynew gneiss belt to the south of the conductor. The triangles locate the array of 41 magnetometers from Alabi, Camfield & Gough (1975) and the permanent observatory at Meanook, the crosses locate an array of seven magnetometers established by Handa & Camfield (1984) and dots represents the IMS stations of the present study.

The observations of Handa & Camfield (1984) and of this study require the presence of substantial electrical conductors in the crust. The tectonic or geological processes that have caused the conductors are not clear. Handa & Camfield suggested that conductive mineralization or the presence of saline water in fractured rocks may be the source of the enhanced electrical conductivity. In this connection Camfield & Gough (1977) have noted that 'there are salt-solution features in the Devonian Prairie evaporite formation which lie along the trend of the conductor in southern Saskatchewan. Faults in the basement might have influenced the removal of the salt; the high electrical conductivity could be caused by saline water in the fractures'. On the other hand, the possible association of the conductor with ancient former oceanic crust (Green *et al.* 1985) may indicate that the high conductivity arises from conductive mineralization related to partial serpentinization of oceanic mafic and ultramafic rocks at a ridge crest (de Beer *et al.* 1982).

Acknowledgments

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