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The North American Central Plains Conductivity Anomaly*

A. O. Alabi, P. A. Camfield and D. I. Gough

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Summary

An array of 41 three-component magnetometers recorded geomagnetic disturbances during August and September 1972, between latitudes 42° and 54° N and longitudes 98° and 109° W. The objective was a detailed study of the North American Central Plains (NACP) conductive body earlier discovered striking northward from the Black Hills roughly along longitude 104° W in the United States. Source fields were provided by polar magnetic substorms and by other events with incident fields more uniform over the array. Northward mapping of the conductor was carried to within 90 km of the exposed Canadian Shield of north central Saskatchewan. Between latitudes 43° N and 48° N maximum depth estimates place the conductor within the lithosphere; the currents probably flow at smaller depths, i.e. within the crust. At the Shield edge the axis of the conductor is parallel to the strike of fold belts and fault zones in metamorphic rocks, including mylonites, characteristic of intense grinding and crushing. Graphitic conductors are known in many fracture zones. The conductivity anomaly links these structural elements in the Churchill Province Shield to the metamorphic belt mapped by Lidiak in the South Dakota basement, and to the Black Hills. South of the Black Hills the conductor turns southwest to the northern end of the Southern Rockies. There is evidence which suggests, but does not demonstrate, a conductive link there between the mantle conductor under the Southern Rockies and the NACP crustal conductor. It is postulated that the linear crustal structure may be a major continental fracture zone now mapped over a total length of 1800 km, of which 300 km is exposed in the Shield. Two of three earthquakes located in southern Saskatchewan have epicentres close to the axis of the conductive body.

1. Introduction

Large anomalies in the eastward horizontal component Y and in the vertical component Z of polar magnetic substorm fields (period range $\frac{1}{2}$–2 hr) were recorded at stations south of the Black Hills of South Dakota, during a magnetometer array study in 1967 (Reitzel *et al.* 1970; Porath, Oldenburg & Gough 1970). As these stations were near the north-east corner of the array, the 1967 study established only the existence of a strong local increase in conductivity related to the Black Hills thermal area of South Dakota. In an array study in 1969 (Camfield, Gough & Porath 1971) three east–west lines of magnetometers crossed the conductive body, which was shown to be elongated, with strike nearly due north and axis close to the border

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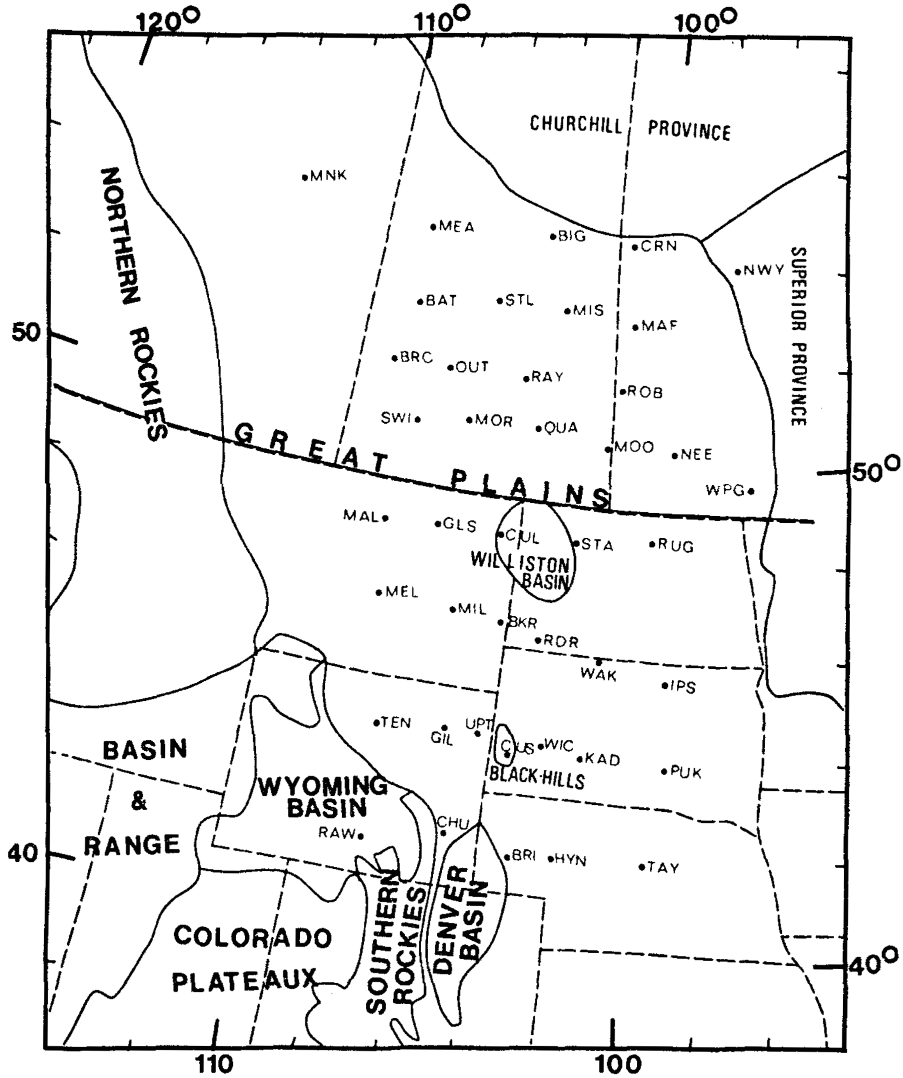

FIG. 1. Magnetometer locations in relation to major tectonic provinces. Some political boundaries are shown.

between Montana and the Dakotas, along longitude 104° W. In South Dakota the small half-width of the anomaly in Y showed the body to be at most 38 km deep and so in the crust. Attempts to model the observed anomalous fields (Porath, Gough & Camfield 1971), by a uniform transverse horizontal field inducing current in a two-dimensional crustal conductor, could produce Y and Z computed fields providing adequate fit to observation at period 50 min, but could not fit either observed frequency response or observed phase relationships. Porath *et al.* (1971) regarded these misfits as evidence that the crustal conductor joins regions, outside the array, in which the induction occurs, and channels the induced current. Since the geometry of such a system is both three-dimensional and unknown it clearly cannot be modelled in two dimensions nor, indeed, in three. Jones (1973) has used a storm sudden commencement recorded on July 26 by the 1969 array to demonstrate, at the shorter periods 3 and 5 min, clear reversals in Z between adjacent stations on lines 5 and 6 in Fig. 1 (line 1 is the northernmost). Rankin & Reddy (1973) have investigated the conductivity structure near the Black Hills, seen by fields in the period range 80–1000 s, using the magnetotelluric method. In their results the local uplift of the Black Hills is the principal feature, rather than the elongated conductor mapped by the magnetometers. At another extreme Camfield and Gough (1975) analysed daily-variation data from the 1969 array to show that strong anomalies persist at periods 8 and 12 h in Z but not in Y. They used phase relationships to indicate that whatever the conductive configuration, induction is largely by Y at periods less than 2 h but that induction by Z is significant at periods 8 and 12 h.

In the first paper on the 1969 array Camfield *et al.* (1971) suggested that a graphite schist body in the basement might provide the necessary high conductivity, linear form and crustal depth for the conductor. Lidiak (1971) independently and by quite different methods (borehole data, static magnetic and gravity anomalies) mapped a metamorphic belt in western South Dakota in exact coincidence with the conductor which causes the anomalous time-varying magnetic fields (Gough & Camfield 1972).

The array of 1969 was located mainly to investigate the Cordillera and their boundary with the Great Plains in the north-western United States and south-western Canada. That array was stretched to cover the Black Hills because of the earlier evidence of anomalous fields there (Reitzel *et al.* 1970) but the anomaly was close to its eastern edge and the stations were widely spaced. For these reasons a new array study was carried out in 1972 with the single objective of extending knowledge of the North American Central Plains (NACP) anomaly. The new study was planned to map the conductive structure northward, if it were found to continue, into Canada and perhaps to the exposed Canadian Shield. Another objective was to investigate the relationship between the southern end of the crustal conductor, south of the Black Hills, and the northern end of the upper mantle conductor underlying the Southern Rockies. A detailed account of the 1972 array study is given by Alabi (1974).

2. Observations

The 41 stations of the array are shown in Fig. 1. Twenty-four instruments, those in the United States and at SWI, were of Gough–Reitzel type (Gough & Reitzel 1967) and were operated by two of us (AOA and DIG) from the University of Alberta; 15 were three-component fluxgate magnetometers (Trigg, Serson & Camfield 1971) operated by PAC from Earth Physics Branch, Ottawa; and two (NWY and WPG) were fluxgate instruments operated for a magnetospheric study by Dr J. K. Walker, from which he kindly supplied data. The standard magnetic observatory at Meanook, Alberta (MNK) provided digital magnetograms. The magnetometers lie along eight roughly east–west lines, four in Canada and four in the United States. We shall number these 1–8 from north to south. Major tectonic provinces as well as some political boundaries are shown in Fig. 1.

The observation period of nine weeks ran from early August to late September, 1972. Six magnetic disturbance events were selected for analysis. The times and types

Table 1

The dates, times of occurrence and types of disturbance events. The K_p indices refer to eight 3-hour periods through the day.

Date	Time (UT)	Type of event	K_p indices
August 28–72	0930–1230	Substorm	1o1o1o3 – 3 – 3o3 – 3 +
August 30–72	0830–1330	Substorm	3o1 – 0 + 2o2o1 + 2o2 –
August 31–72	0400–1000	Substorm	3 – 2 + 3 – 1 – 1o1 + 1o1o
September 8–72	0200–0400	Pulsation	2 + 2 + 2o2 + 2 + 2o2o3 –
September 12–72	0330–0530	Substorm	1 + 3 – 2o2 – 1o1 – 1 – 0 +
September 13–72	1600–1800	Part of storm	1o2 – 3 – 1 + 7 – 6 – 7 + 6 –

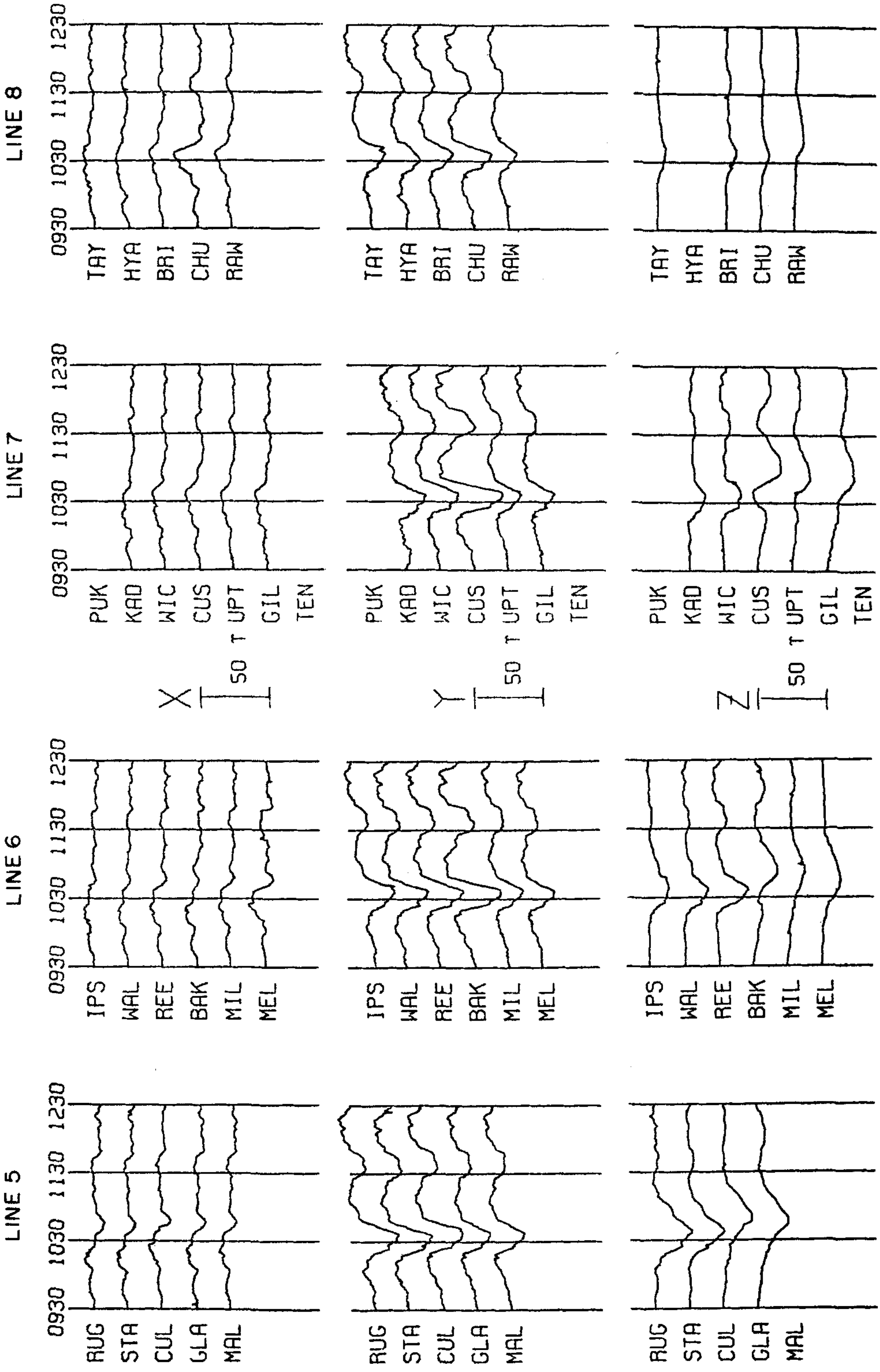

FIG. 2. Magnetograms for a substorm of 1972 August 28, from the southern half of the array.

of these events are listed in Table 1. Four were polar magnetic substorms, which provide convenient transient fields of large amplitudes in the period range 30–170 min but have the disadvantage of complicated source-current geometry near the array (Rostoker 1972). One was a pulsation event (September 8) which provided a rather uniform input field over the array with good amplitude in the 10–40 min period range. The last (September 13) was part of a magnetic storm providing an input field rather less uniform over the array than that of the pulsation at similar periods. Magnetograms from 14 standard observatories in North America, distributed in latitude from 32° N to 73° N and in longitude from 78° W to 155° W, were examined to establish that the events of September 8 and 13 provided fields which could be considered uniform over our array. For brevity these will be called 'world-wide' events but uniformity over the array is the relevant point.

Magnetograms for all six events are given by Alabi (1974). Here we show (Fig. 2) only magnetograms for one substorm as recorded by the southern half of the array (lines 5–8). Magnetograms are stacked with the easternmost station of each line at the top. In Fig. 2 the geographic northward component X is small and becomes smaller southward, except at Chugwater and Rawlins, Wyoming (CHU and RAW), where it increases again. This anomaly in X could be related to a downturn in the NACP conductor (see Section 7). In lines 4–1 (not shown) X increases steeply northward as the auroral electrojet is approached. By contrast, the eastward component Y falls more slowly in amplitude from north to south of the array. This suggests that field-aligned Birkeland currents at the ends of the ionospheric segment of the substorm current system (Rostoker 1972) contribute much of the Y field, whereas the ionospheric east–west current should be the main source for X. The very different northward gradients for X and Y can be seen in the amplitude maps of these components in Fig. 6.

Currents in the NACP conductive body produce large phase shifts in Z, even phase reversals, at stations on either side of the current, and increased amplitude of Y near the current (Fig. 2). Thus in line 5 the current passes between STA and CUL, and produces a large phase shift in Z between these stations and enhancement of Y at both. In line 6 a Z reversal and Y enhancement locate the current just east of BKR, in line 7 the form of both components indicate a current between WIC and CUS but nearer to CUS, and in line 8 a clear reversal in Z places the current betweeen CHU and RAW and Y reports it close to CHU. The enhanced amplitude of X at these last stations has been mentioned already.

Phase reversals and phase shifts in the vertical component Z, and amplitude maxima in Y can be used to map the axis of the conductive body on the assumption that it approximates a line current. Fig. 3 shows the position of the North American Central Plains conductor inferred from magnetograms in this simple-minded way. Both substorm and world-wide events agree with the placing of the conductor in the position shown as it passes through lines 5, 6, 7 and 8 in the United States. North of 50° N the substorm magnetograms do not show the currents in the NACP conductor, presumably because the source fields are too large and swamp those of the NACP current. However both world-wide events show clear reversals in Z and agree as to the location of the current (Alabi 1974).

3. Maps of geomagnetic disturbance fields

The polarization of the horizontal field incident upon a structure is of significance in relation both to the source currents and to induction by the incident field (Lilley & Bennett 1972; Gough, Lilley & McElhinny 1972; Gough, McElhinny & Lilley 1974). In places far from concentrated parts of ionospheric currents, such as southern Australia to which the papers just cited refer, the incident-field polarization changes little across an array and that at one normal station is relevant to the array in general. The present array is close to the ionospheric parts of polar magnetic substorm currents

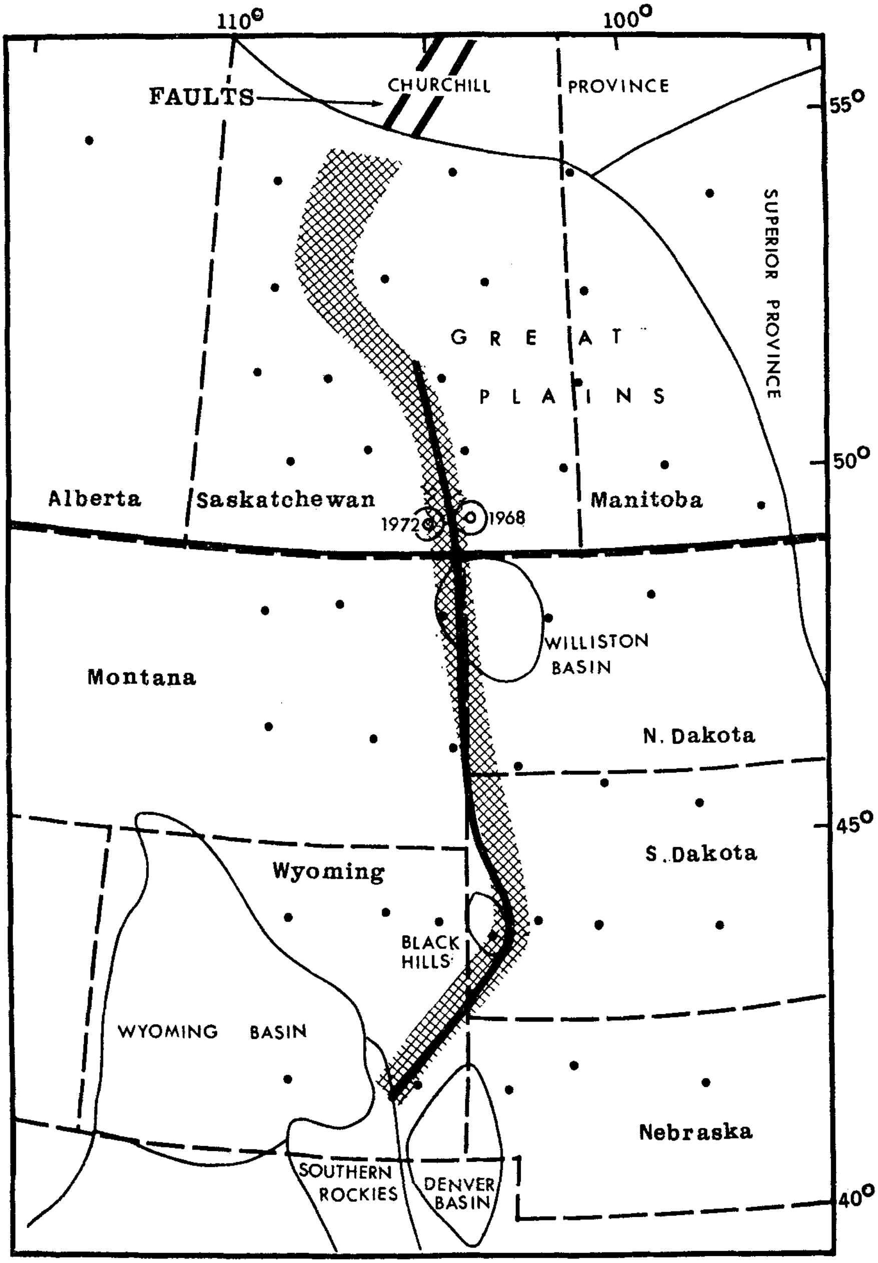

FIG. 3. Location of the North American Central Plains conductive body. The broad shaded strip represents information from magnetograms of 'world-wide' events and from quadrature-phase induction arrows. The black line locates the axis of the conductor more accurately from Fourier coefficient maps discussed in the text. In the Churchill Province Shield, the Wollaston Lake Fold Belt lies north-west of the faults, and the La Ronge–Reindeer Lake Belt, southeast. The double circles mark earthquake epicentres, and the dots show magnetometers.

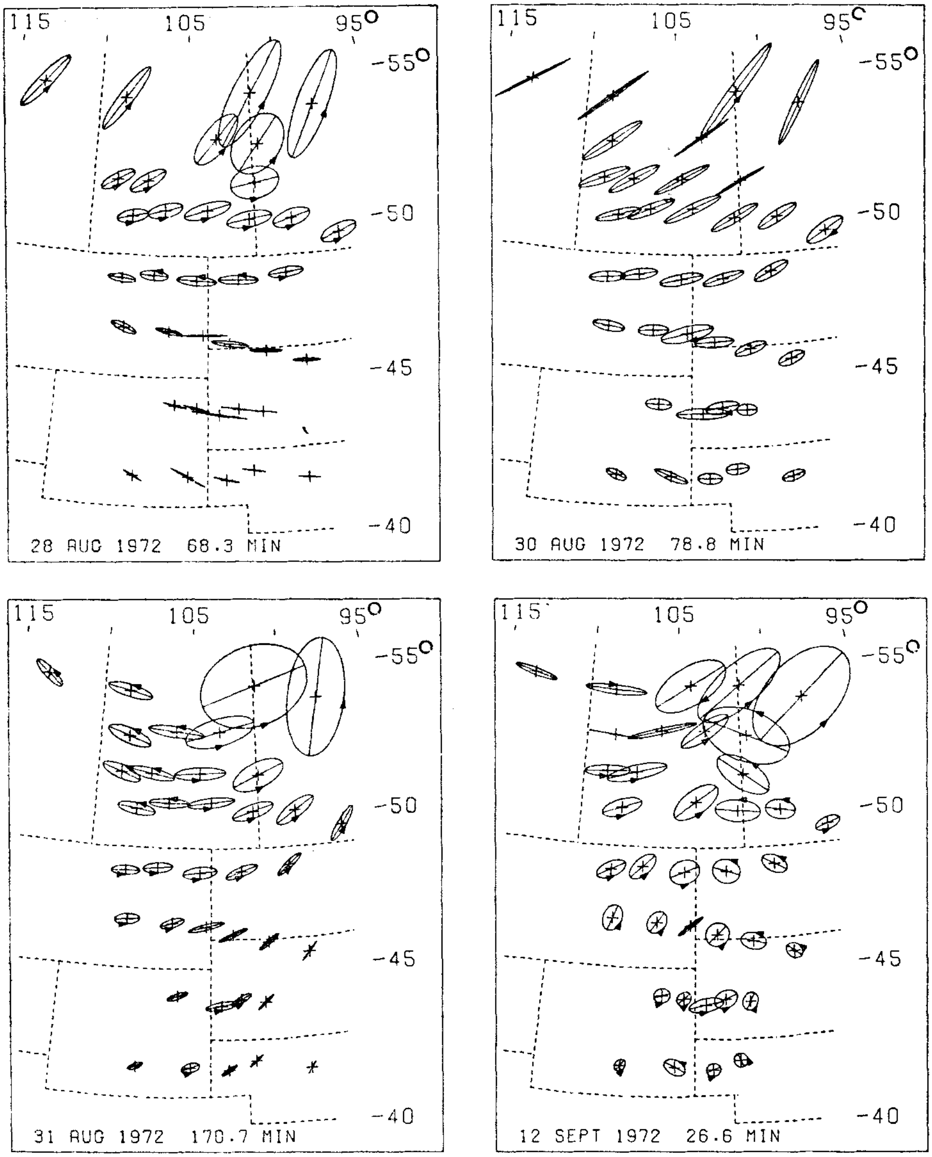

FIG. 4. Horizontal-field polarizations for the Fourier components at the periods shown of four polar magnetic substorms.

and it is of interest to know how the polarization varies through the array. Polarization ellipses have been drawn for the horizontal fields of four substorms, in each with the use of Fourier transforms at a period at which that event had good amplitudes (Fig. 4). It is at once evident that the four events are of the same type. It is also clear that an ionospheric current directed magnetic east–west lies close to the north-east corner of the array and produces very large *H* components there. Further south the ellipses have largely east–west major axes and show the slower southward fall in *Y* amplitude than in *X*, already discussed in Section 2. Along the NACP conductor, near the 104° W meridian, anomalous *Y* turns the ellipses and elongates their east–west dimensions. However the main interest of the polarization ellipses lies in the picture they give of the substorm fields *per se*.

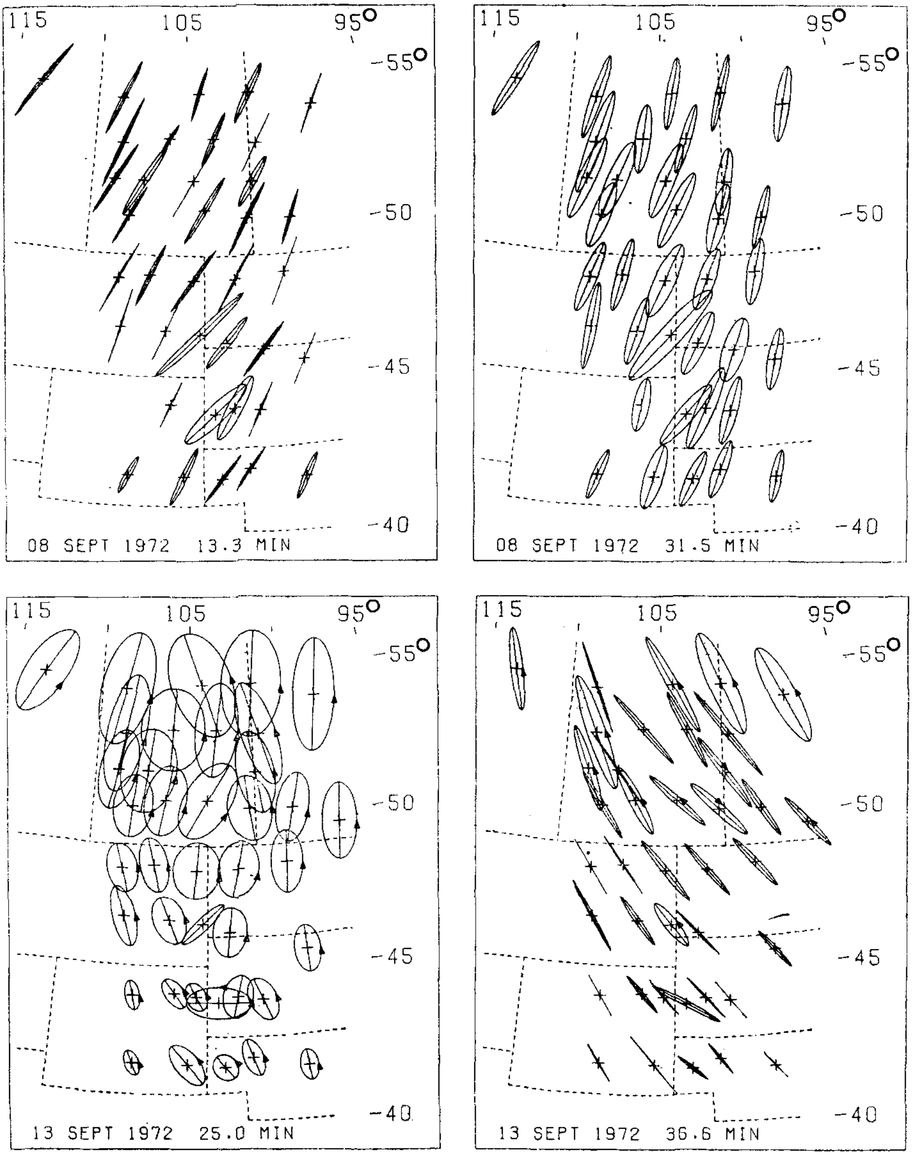

FIG. 5. Horizontal-field polarizations for a pulsation event of September 8 and for an event during a storm of 1972 September 13, each at two periods.

Corresponding polarization maps for the two world-wide events, each at two periods, are very unlike those of the substorms (Fig. 5). There is no sign of a local ionospheric currrent near the array. The storm fields (September 13) show a smooth northward increase of amplitudes with X and Y remaining in the same ratio, so that the ellipses become larger northward without rotation or change of shape. The pulsation event of September 8 shows remarkable uniformity over the array apart from the effects of the NACP anomaly, which therefore stand out prominently. The polarization of this event is nearly linear and directed geomagnetic north–south.

Contoured maps of Fourier amplitudes and phases have been drawn for four periods in the range 25–171 min from solar substorm fields, for periods 13 and 32 min from the world-wide pulsation event and for periods 25 and 37 min from the storm

28 August 1972 T = 68.3 min

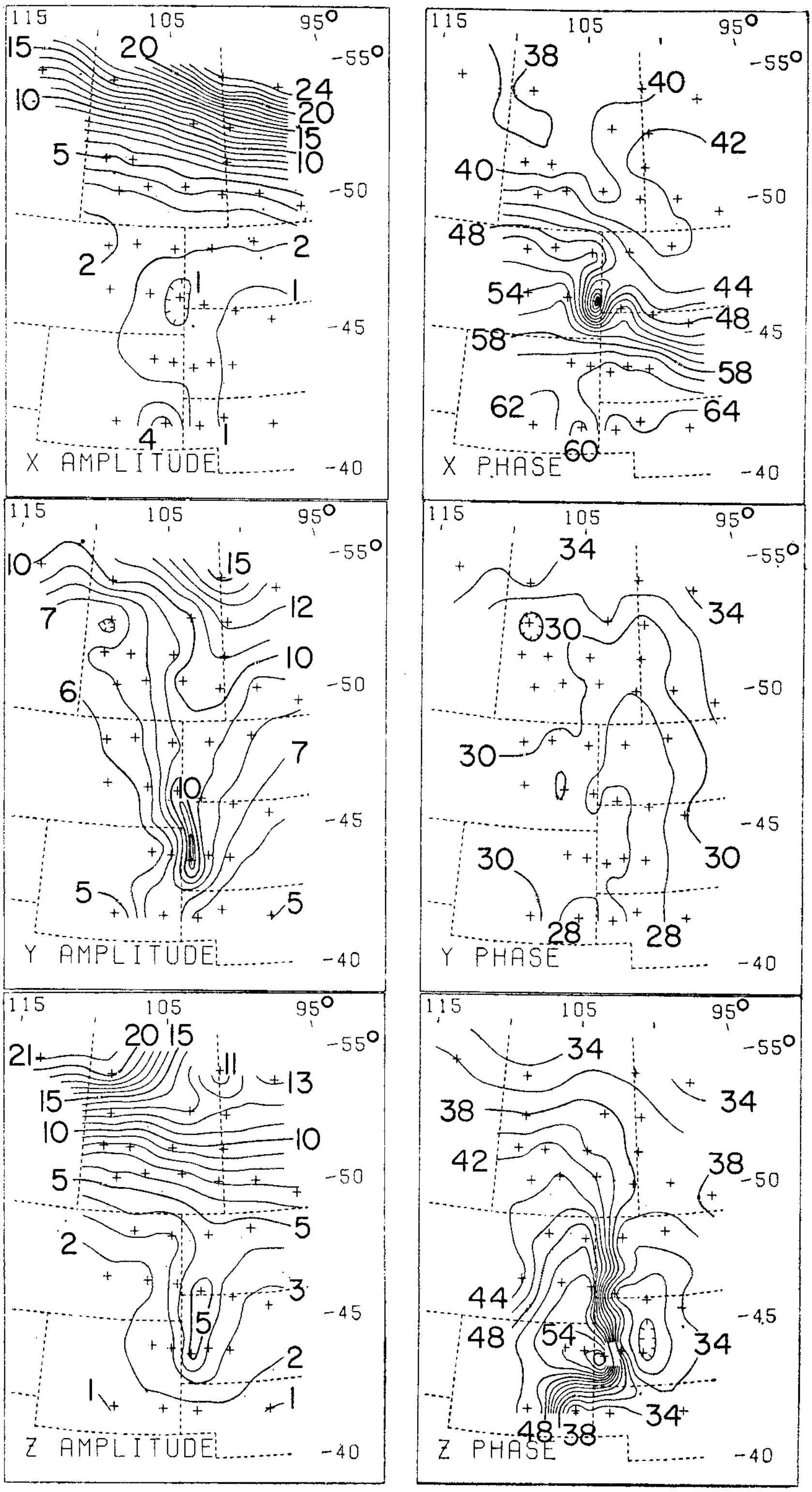

FIG. 6. Fourier transform amplitudes (nanoteslas) and phases (minutes) at period 68·3 min from a substorm of 1972 August 28. Polarizations are shown in Fig. 4, upper left, and magnetograms for half of the array in Fig. 2.

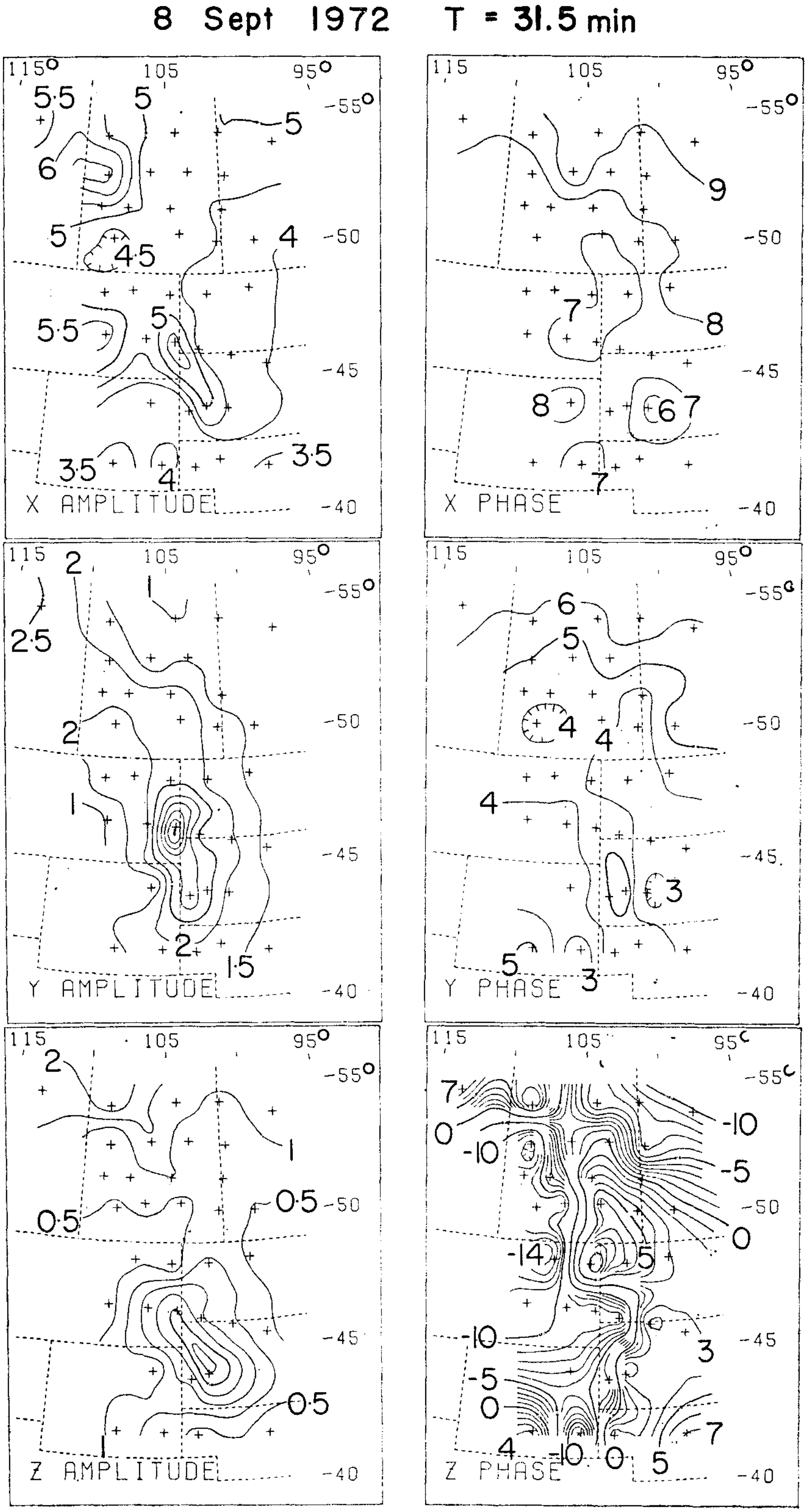

FIG. 7. Fourier transform amplitudes (nanoteslas) and phases (minutes) at period 31·5 min from a pulsation of 1972 September 8. Polarizations are shown in Fig. 5, upper right.

event. The periods were chosen for large amplitudes of the horizontal components. The eight sets, each of six maps, are given by Alabi (1974). Here we show one set at $T = 68$ min from the substorm of 1974 August 28, (Fig. 6), and one set at $T = 31{\cdot}5$ min from the pulsation event of 1972 September 8, (Fig. 7). The corresponding polarization maps are given in Fig. 4 for the substorm and in Fig. 5 for the pulsation. Half of the magnetograms for the substorm are in Fig. 2.

In the substorm field mapped in Fig. 6 the Canadian half of the array, north of 49° N, shows magnetic east–west contours in X and Z which clearly represent the field of the east–west horizontal part of the substorm current system, in the auroral-zone ionosphere. No doubt induced currents in the Earth below the auroral zone contribute. In the United States X becomes rather uniform in amplitude except near Chugwater, Wyoming (CHU) in the southernmost line. The phase of X shows a lead of order 10 min (53°) at Baker, Montana (BKR) relative to adjacent stations; this is probably associated with the NACP conductor. Most of the events mapped show Y and Z anomalies at BKR comparable to those at the Black Hills and suggest that the currents may flow at small depths under BKR. South of 49° N, where the source fields have amplitudes about one-fifth of those in Canada, the Z amplitude map shows the NACP anomaly clearly. However the clearest NACP anomalies are those in Y amplitude and Z phase. Both place the current at or just east of the 104° meridian where it forms the border between Montana and the Dakotas. In the southern half of South Dakota the conductor swings east of due south to pass just east of the Black Hills, and then swings south-west to the northern end of the Southern Rockies (Fig. 3). Every set of maps shows this feature clearly in Y amplitude and in Z phase. Fig. 6 is typical of the four sets of substorm-field maps, in that the conductor cannot be traced northward beyond about 51° N because the rapidly increasing source fields dominate even Y amplitude and Z phase north of that latitude.

The world-wide pulsation event (Fig. 7) shows a much more uniform source field over the whole array, devoid of the east–west contours in X and Z amplitudes characteristic of substorm fields in the northern half of the array. Unfortunately the event provided very little Y component, and in consequence the NACP anomaly cannot be followed north of about 52° N on the Y amplitude map of Fig. 7. The Z phase map traces the conductor northward a little farther but the Z fields are of such small amplitudes in Canada that their phases are clearly unstable. The difficulty is with the source field, which is virtually linearly polarized almost along the length of the conductor (Fig. 5). A world-wide event with east–west polarization would probably be better, but if such events exist our array did not record one. It will be noted, in Fig. 7, that the Y component has larger amplitude at BKR than at the Black Hills.

As the world-wide events were unfavourably polarized the possibility of producing residual anomaly maps from the larger substorm fields was investigated. Various simple models of the source field were deducted from the observed field but without success. The models we tried were too simple and our ignorance of the substorm currents prevented elaboration of them. However, a simple empirical method was surprisingly successful. For each east–west line of stations assume that the end stations represent the source-field or normal field, and deduct the mean of the Fourier cosine coefficients at these two stations from the cosine coefficients at the stations of that line. The sine coefficients are similarly treated. Since common-phase maps are necessary, amplitude maps would be unsuitable. The reader will recall that there is no physical significance in the division of the residuals between sine and cosine coefficient maps or in the sign of either, other than the relation between the signal and the time interval chosen for integration in forming the Fourier transform. This procedure has been applied to cosine and sine coefficients of X and Y transforms from two substorms. All four X residual maps are quite featureless south of 52° N (Alabi 1974), an important verification of the effectiveness of the procedure, in view of the large source fields in X (Fig. 6). Two pairs of Y residual maps are shown in Fig. 8.

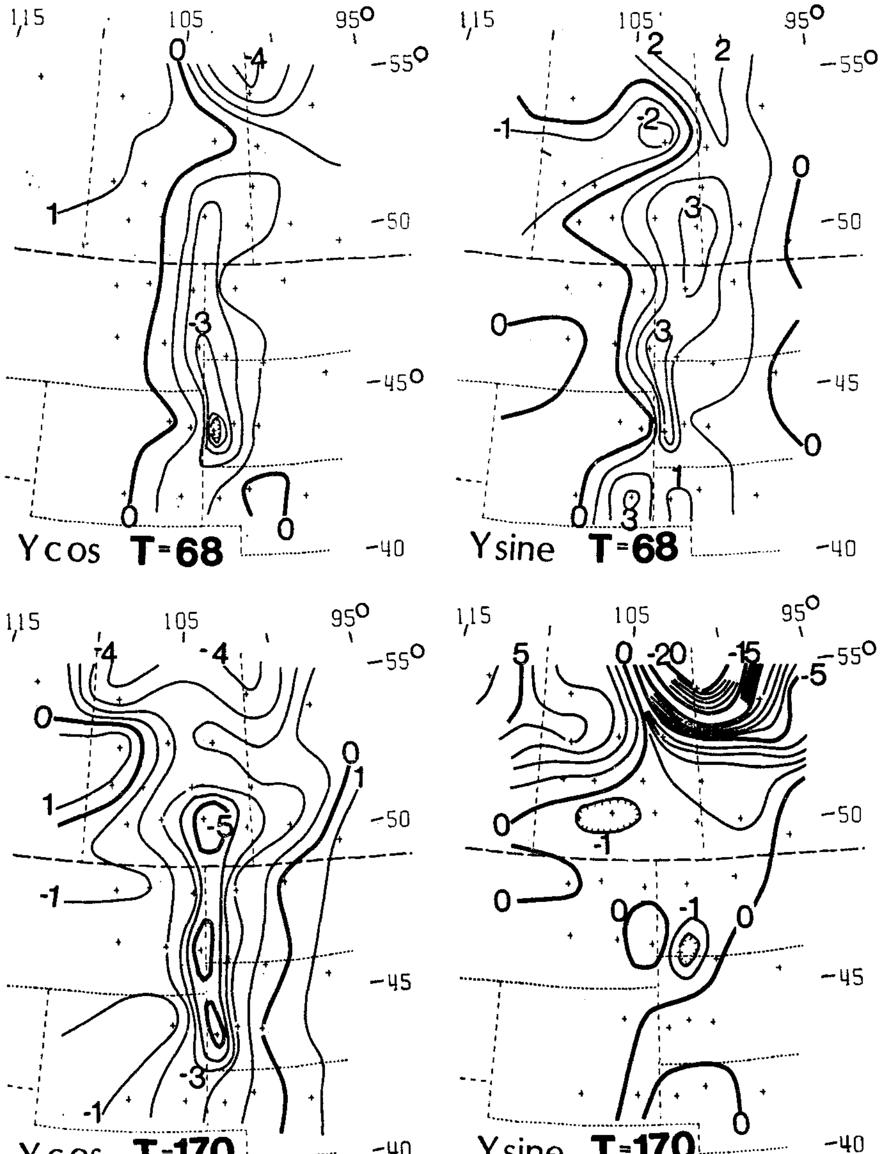

FIG. 8. Maps of residual Fourier sine and cosine coefficients for the eastward horizontal component, *Y*, at periods 68 and 170 min from substorms of August 28 and 31, 1972. The total *Y* component corresponding to the upper maps is mapped in Fig. 6. The method of calculating residuals is given in the text.

One pair is derived from the same transforms as the *Y* amplitude and phase maps of Fig. 6. In the *Y* cosine coefficient maps the north–south elongated closed contours of the NACP continue with axis along the 104° W meridian well into Saskatchewan. There is good agreement of the two *Y* cosine residual anomaly maps with one another and with the pulsation *Y* amplitude map of Fig. 7. The *Y* sine coefficient map for period 68 min serves as a reminder that this agreement is partly fortuitous. The *Y* sine contours show the axis of the anomaly displaced about 2° east of that shown by other maps, no doubt as a result of the crudity of the normal-field estimation.

The best estimate of the position of the NACP conductor, derived from 11 sets of contour maps, is shown in Fig. 3. At latitudes south of 52° N this locus of the conductor is more accurate than that drawn on the same map by inspection of the magnetograms. Within the accuracy of the latter the two loci agree. It is noteworthy that inspection of magnetograms of the world-wide events allows the anomaly to be traced 2° further north than it is shown in the contour maps. The explanation of this may lie in the low signal levels for the world-wide events, together with the reduction in level when a spectral term is isolated and the loss of definition when a finite contour interval must be chosen. Further, the wide spacing between the northern stations prevents the contour maps from showing any steep gradients that may exist in the anomalous fields.

4. Transfer functions

Transfer functions from horizontal to vertical components are often used in geomagnetic depth sounding, especially when only a few instruments are available so that stations must be occupied successively and different events are recorded at these stations. The method has been described by Schmucker (1964, 1970) and by Everett & Hyndman (1967). If the normal and anomalous parts of all three field components were known all nine transfer functions could be found by inverting a matrix.

In practice the simplifying assumption is made that the only transfer functions of importance are z_X and z_Y, which relate anomalous Z to the normal horizontal field which best correlates with it (assumption 1). This amounts to neglecting induction by normal Z, which is often small in mid-latitudes. Induction arrows derived from z_X and z_Y of several variously polarized events should then be directed by currents induced by normal X and Y. It is further assumed that normal Z is not systematically correlated with the normal horizontal fields (assumption 2). This allows cross-spectra between anomalous Z and normal Y to be replaced by those between the total observed Z and the normal fields. On this assumption, separation of total Z into normal and anomalous parts is unnecessary. Under assumptions (1) and (2), the transfer functions z_X and z_Y can be calculated explicitly from auto- and cross-powers of the three components (Schmucker 1970, equations (3.22)).

A third simplifying assumption is often used. This is that X and Y are sufficiently uniform, across the area under study, that z_X and z_Y can be estimated using X, Y and Z recorded at each station separately. Such single-station transfer functions are commonly used in studies with a small number of magnetometers. They will obviously not give the inductive response of the structures of interest if X or Y at the station is anomalous, that is, differs markedly from the regional or normal value of that component at the structures in which it is inducing currents. If stations known not to be strongly anomalous recorded the events, it seems to the authors that transfer functions from X and Y estimates from such 'normal' stations should be used with Z at each station. Alternatively if one has data from a two-dimensional array one can use mean values of X and Y over the array and Z from each station (Gough, de Beer & van Zyl 1973; Gough *et al.* 1974).

A fourth simplifying assumption is usually implicit and sometimes unrealized. It consists in the neglect of current channelling effects, which may mean that Z observed in the area of a survey is related not only to X and Y in that area, but to unknown X, Y and Z fields in undefined regions in which induction occurs outside the area. Near a current-channelling anomaly transfer functions are therefore difficult to interpret in terms of induction, whether they are of the single-station variety or whether other stations are used better to estimate normal X and Y in the area of the survey. Lilley & Bennett (1973) have drawn attention to this difficulty. Nevertheless transfer functions, especially of the single-station type, may still be useful in mapping the location of a channelled current.

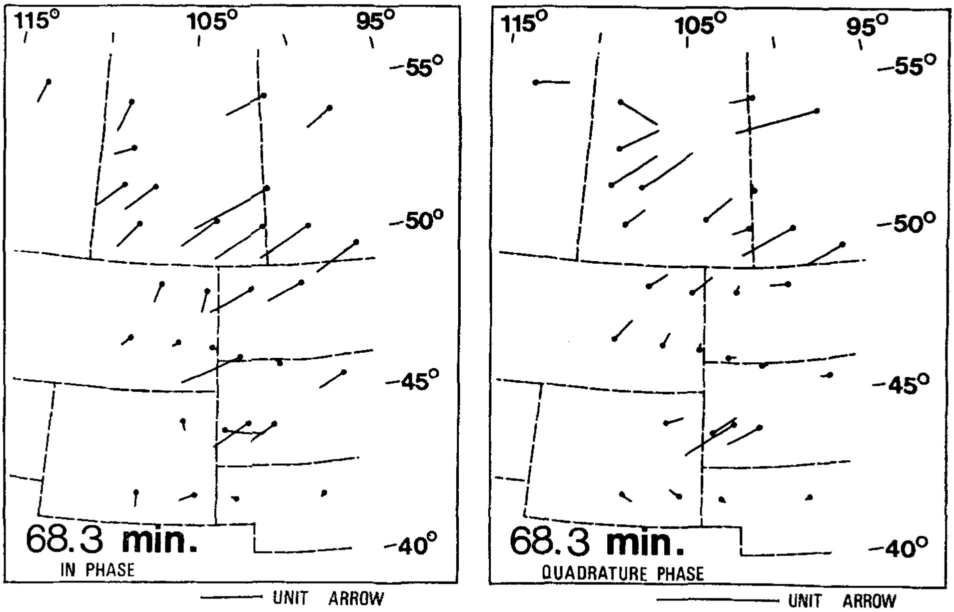

FIG. 9. Induction arrows derived from in-phase and quadrature-phase transfer functions at period 68 min from estimated normal horizontal to station vertical components (see text). Five or six short events were used at each station. The quadrature arrows are plotted on twice the scale used for the in-phase arrows. All arrows are reversed and point towards an induced current.

These problems are mentioned not to discourage the use of transfer functions but to encourage their proper use, with recollection of the limited validity imposed by the assumptions made. There are certainly few, if any, known estimates of transfer functions which we would assume to represent the response of the conductive structure in the solid Earth deconvolved from the source-field morphology. Deconvolution of magnetometer array data is in its infancy.

In the present study assumptions (2) and (4) are known to be unsound. Normal Z fields systematically correlated wtih X cover the northern half of the array in substorm fields (Fig. 6). Further, the North American Central Plains anomaly is known to show effects of current channelling (Porath *et al.* 1971). Transfer functions were nevertheless calculated, using the explicit relations quoted by Gough *et al.* (1973), with scepticism as to the significance of the results. Mean cosine and sine transforms for the end stations of each line were adopted as estimates of normal X and Y for that line. Five or six of the events listed in Table 1 were used at each station. In-phase and quadrature-phase induction arrows (both reversed, to point toward induced currents in the Earth) are mapped in Fig. 9 for a period of 68 min at which the events used gave good power. The in-phase induction arrows are dominated by the source-field correlation between Z and the horizontal components, which gives arrows directed away from the ionospheric currents northeast of the array. The NACP anomaly does produce opposed arrows at the Black Hills, at stations CUS and WIC (Fig. 1). Elsewhere it can only shorten the source-field related arrows at stations west of itself. The in-phase map of Fig. 9 serves mainly to demonstrate the falsity, in this instance, of assumption (2).

The quadrature-phase induction arrows proved unexpectedly successful in showing the presence of the NACP conductor along the whole length of the array, by pointing to it from both sides. It is possible that the induced currents dominate the quadrature-phase map because there is little or no normal Z in the source-field 90° out of phase with normal X and Y. However there may be residual source-field effects, and the current-channelling problem remains, so that the transfer functions are as unlikely to give fits to model calculations as the normalized anomalous fields Y_a/Y_n and Z_a/Y_n of single events (Porath *et al.* 1971).

5. Maximum depth estimates

On a simple line-current approximation one can estimate the maximum depth of the centre of the current distribution as half the distance along the surface between the Z extrema, or as half the width of the Y anomaly at half amplitude. In practice the Z extrema give more consistent results. Maximum depth estimates from the separations of Z extrema are given for four latitudes in Table 2, together with the longitude of the axis at each latitude. Very possibly the currents are at smaller depth than those shown and they could be near the basement surface: the usual non-uniqueness exists with regard to depth. The maximum depth at 41·8° N (line 8) is roughly double that between 43·8° N and 48° N.

Table 2

Maximum depths to the line current and the locations of its axis at various latitudes.

Line No.	Latitude °N	Period (Minutes)	Maximum Depth (km)	Longitude of axis (°W) From Y Maximum	From Z Cross-over
8	41·8	36·6	120	104·9	104·8
7	43·8	13·3	43	103·5	103·2
		36·6	37	103·5	103·3
		68·3	60	103·4	103·3
		170·7	45	103·4	103·4
6	46·4	13·3	75	104·1	102·4
		170·7	65	104·1	103·6
5	48·0	170·7	55	104·8	104·6

6. Geological significance of the North American Central Plains conductive body

Evidence was summarized in Section 1 supporting the view that the currents which cause the NACP anomaly flow along a belt of metamorphic rocks in the upper crust, beneath the sediments of the Great Plains. The present study has traced the anomaly in magnetic variation fields northward into Saskatchewan. Magnetograms of worldwide events and quadrature-phase induction arrows indicate that the conductor passes through line 1, near latitude 54° N and just south of the edge of the exposed rocks of the Churchill Province of the Shield. The magnetograms place it between BAT and STL in line 2 (Fig. 1) and between MEA and BIG in line 1, thus inserting a dogleg in the structure (Fig. 3) such that if continued for 90 km beyond line 1, the conductor would reach the Shield at about 55½° N, 106° W on the central meridian of Saskatchewan, striking approximately to the north-east.

The fold belts and regional fault zones exposed in the Shield near this point have the same north-east strike. The faults marked in Fig. 3 have between them an extensive granite and migmatite basement which separates the Wollaston Lake Fold Belt (granites, pelitic schists and gneisses) to the north-west from the La Ronge–Reindeer Lake Belt (metavolcanic and metasedimentary gneisses) to the south-east (Whitaker & Pearson 1972). Rocks in the north-western fault zone are mylonites (L. P. Tremblay, private communication), which, according to Holmes (1965, p. 225) are produced by extensive crushing and grinding near major thrust faults. Garland (in press) remarks that, on the scale of mining exploration, 'shear zones and fractures are well known to result in the development of graphite and to act as conductors. Indeed, in the electromagnetic exploration for ore minerals, graphitic shear zones often produce the most abundant anomalies'.

Byers (1962) calls the south-eastern fault zone the Birch Rapids–Wepusko Bay structure. It extends for more than 300 km from the Shield edge in central Saskatchewan into Manitoba, producing several very straight parallel topographic lineaments. Byers also quotes van Hees (1958) to suggest that faults in pre-Devonian strata beneath the Cretaceous surface, some 90 km south-west of the faults at the Shield edge, belong to the same system. This position lies on the conductor mapped in Fig. 3.

The Wollaston Lake Fold Belt, with its prominent static magnetic anomaly (Geological Survey of Canada 1971) and its weak gravity anomaly (Earth Physics Branch 1974), likewise extends from the Shield edge north-eastwards across Saskatchewan and gradually bends eastwards into Manitoba (Money 1968). Southwards from the Shield edge, above the sediments, the magnetic anomaly continues its arcuate path until the end of the low-level aeromagnetic coverage at the latitude of line 2. At this point the axis of the magnetic high lies between STL and BAT, slightly to the west of the conductor's axis (Fig. 3), and it strikes roughly southwards parallel to the conductor. Between lines 2 and 3, the high-level aeromagnetics of Coles, Haines & Hannaford (1975) shows the magnetic high swinging sharply eastward, although no longer continuously. The axis of the conductor also swings eastward, to pass between RAY and OUT on line 3. In the region where both the magnetic high and the conductor have been mapped, they are roughly coincident.

The continuity of the conductive body demonstrated by our magnetometer array strongly suggests a major structure in the Precambrian basement linking the Wollasston Lake Fold Belt or the fault zone at its south-eastern edge, in the Churchill Province of Saskatchewan and Manitoba, with the metamorphic belt mapped by Lidiak (1971) in South Dakota, the Black Hills uplift and the northern end of the Southern Rockies. If such a structure is a reality it is roughly 1800 km long and is a major tectonic feature of the continent.

In Fig. 3 we have plotted the epicentres of two of the only three earthquakes recorded in southern Saskatchewan (Horner *et al.* 1973). It is interesting to note that they lie very close to the conductive body. An earthquake of magnitude about 5½ in 1909 can be located only from macroseismic information, somewhere in southern Saskatchewan, north-western North Dakota or north-eastern Montana (Horner, Stevens & Hasegawa 1973). Thirty epicentres listed by Coffman & von Hake (1973) in the relevant part of the Dakotas, Nebraska, Montana, Wyoming and Colorado are distributed rather broadly, such that with the exception of seven earthquakes in or southwest of the Black Hills, they cannot be said to cluster along the conductor. As no major faults have been mapped in the Mesozoic sedimentary cover, any major faults which may exist cannot have produced much integrated displacement since the Palaeozoic.

7. Relation between the NACP conductor and that beneath the Southern Rockies

A body of high conductivity under the Southern Rocky Mountains was discovered by Gough & Reitzel (1969) and shown in the first magnetometer array study to be elongated in the north–south direction under the Southern Rockies (Reitzel *et al.* 1970). This conductive region is believed to lie in the upper mantle for two reasons. The first is that its thickness cannot be less than about 100 km, if its conductivity $\leqslant 0{\cdot}2$ (ohm m)$^{-1}$, to account for the small observed phase differences between normal and anomalous parts of a substorm field (Porath *et al.* 1970). The conductor could be thinner with higher conductivity, but the value cited is already high and probably requires partial melting to explain it (Chan, Nyland & Gough 1973).

Whether the conductive region is at seismic low-velocity-layer depths (Porath 1971) or deeper (Porath & Gough 1971) it is too thick to be in the crust. The second reason for assigning the conductor under the Southern Rockies to the upper mantle is that it coincides with a region of high heat flow (Reitzel *et al.* 1970; Sass *et al.* 1971; Roy, Blackwell & Decker 1972; Gough 1974). The United States between the East Front of the Southern Rockies and the Sierra Nevada shows a variety of geophysical evidence of high temperatures and partial melting near the top of the mantle, with the exception of part of the Colorado Plateaux (Gough 1974). There is little doubt that a thick region of anomalously hot upper mantle is the seat of the Southern Rockies conductive anomaly.

Direct evidence from the small width of the anomaly assigns the North American Central Plains conductor to the crust, at least in South Dakota (Table 2, line 7). It has been shown that consistent features of anomaly maps indicate that the conductor passes east and south of the Black Hills to the northern end of the Southern Rockies (Fig. 3). The question remains whether the two conductors merely overlap by chance, at their different levels, or are joined by a conductive link passing through the lower crust. This question arose from the results of the 1969 array study, and the 1972 array was intended to examine it (Section 1).

The considerable enhancement of X observed in all events at Chugwater, Wyoming (CHU), (Sections 2 and 3) could be related to the westward component of a horizontal current or to the vertical component of a descending current, or both. Qualitatively the small Z amplitudes at CHU and RAW (Fig. 2), with a phase reversal between them, suggest a descending current. There are too few stations between the Black Hills and the Southern Rockies to provide an answer to the question. A dense array in the region might do so, but the present work leaves the question open. *A priori* it may be thought unlikely that two conductors at different depths not only cross but *terminate* one above the other. For this reason the authors believe the probabilities favour a conductive link. A column of magma or a large dyke, rising in the hypothetical fracture zone from the partially molten uppermost mantle, could provide such a link.

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A. O. Alabi and D. I. Gough:
Institute of Earth and Planetary Physics
University of Alberta
Edmonton, Canada

P. A. Camfield
Earth Physics Branch,
Energy, Mines and Resources Canada,
Ottawa, Canada

References

Alabi, A. O., 1974. *A study of the North American Central Plains conductivity anomaly*, PhD Thesis, University of Alberta.

Byers, A. R., 1962. Major faults in western part of Canadian Shield with special reference to Saskatchewan, in *The Tectonics of the Canadian Shield, R. Soc.* Canada, Spec. Publ. 4, 40–59.

Camfield, P. A. & Gough, D. I., 1975. Anomalies in daily variation magnetic fields and structure under northwestern United States and southwestern Canada, *Geophys. J. R. astr. Soc.*, **41,** 193–218.

Camfield, P. A., Gough, D. I. & Porath, H., 1971. Magnetometer array studies in the north-western United States and south-western Canada, *Geophys. J. R. astr. Soc.*, **22,** 201–221.

Chan, T. E., Nyland, E. & Gough, D. I., 1973. Partial melting and conductivity anomalies in the upper mantle, *Nature Phys. Sci.*, **244,** 89–90.

Coffman, J. L. & Hake, C. A. von, 1973. Earthquake history of the United States, *Publication* 41–1, *US Dept. Commerce*, Washington, D.C.

Coles, R. L., Haines, G. V. & Hannaford, W., 1975. Large scale magnetic anomalies over western Canada and the Arctic, *Can. J. Earth Sci.*, to be submitted.

Earth Physics Branch, 1974. Bouger anomaly map of Canada, Gravity map Series 74–1, scale 1:5,000,000.

Everett, J. E. & Hyndman, R. D., 1967. Geomagnetic variations and electrical conductivity structure in south-western Australia, *Phys. Earth Planet. Int.*, **1,** 24–34.

Garland, G. D., 1975. Correlations between electrical conductivity and other geophysical parameters, *Phys. Earth Planet. Int.*, in press.

Geological Survey of Canada, 1971. Carte des anomalies magnetiques du Canada, Map 1255A, 2nd edition, scale 1:5,000,000.

Gough, D. I., 1974. Electrical conductivity under western North America, in relation to heat flow, seismology and structure, *J. Geomag. Geolect.*, **26,** 105–118.

Gough, D. I. & Camfield, P. A., 1972. Convergent geophysical evidence of a metamorphic belt through the Black Hills of South Dakota, *J. geophys. Res.*, **77,** 3168–3170.

Gough, D. I., de Beer, J. H. & van Zijl, J. S. V., 1973. A magnetometer array study in southern Africa, *Geophys. J. R. astr. Soc.*, **34,** 421–433.

Gough, D. I., Lilley, F. E. M. & McElhinny, M. W., 1972. A polarization-sensitive magnetic variation anomaly in South Australia, *Nature Phys. Sci.*, **239,** 88–91.

Gough, D. I., McElhinny, M. W. & Lilley, F. E. M., 1974. A magnetometer array study in Southern Australia, *Geophys, J. R. astr. Soc.*, **36,** 345–362.

Gough, D. I. & Reitzel, J. S., 1967. A portable three-component magnetic variometer, *J. Geomag. Geoelect.*, **19,** 203–215.

Gough, D. I. & Reitzel, J. S., 1969. Magnetic deep sounding and local conductivity anomalies, *The Application of Modern Physics to the Earth and Planetary Interiors*, 139–153, ed S. K. Runcorn, Wiley-Interscience, London.

Holmes, A., 1965. *Principles of physical geology*, 2nd edition, Ronald Press Co., New York.

Horner, R. B., Stevens, A. E. & Hasegawa, H. S., 1973. The Bengough, Saskatchewan, earthquake of July 26, 1972, *Can. J. Earth Sci.*, **10,** 1805–1821.

Jones, R. E., 1973. *Geomagnetic depth-sounding with a sudden commencement in the north central United States*, BSc Thesis, Carleton University, Ottawa.

Lidiak, E. G., 1971. Buried Precambrian rocks of South Dakota, *Bull geol. Soc. Am.*, **82,** 1411–1420.

Lilley, F. E. M. & Bennett, D. J., 1972. An array experiment with magnetic variometers near the coasts of south-east Australia, *Geophys. J. R. astr. Soc.*, **29,** 49–64.

Lilley, F. E. M. & Bennett, D. J., 1973. Linear relationships in geomagnetic variation studies, *Phys. Earth Planet. Int.*, **7,** 9–14.

Money, P. L., 1968. The Wollaston Lake fold-belt system, Saskatchewan–Manitoba, *Can. J. Earth Sci.*, **5**, 1489–1504.

Porath, H., 1971. Magnetic variations anomalies and seismic low-velocity zone in the western United States, *J. geophys. Res.*, **76**, 2643–2648.

Porath, H. & Gough, D. I., 1971. Mantle conductive structures in the western United States from magnetometer array studies, *Geophys. J. R. astr. Soc.*, **22**, 261–275.

Porath, H., Gough, D. I. & Camfield, P. A., 1971. Conductive structures in the northwestern United States and southwestern Canada, *Geophys. J. R. astr. Soc.*, **23**, 387–398.

Porath, H., Oldenburg, D. W. & Gough, D. I., 1970. Separation of magnetic variation fields and conductive structures in the western United States, *Geophys. J. R. astr. Soc.*, **19**, 237–260.

Rankin, D. & Reddy, I. K., 1973. Crustal conductivity anomaly under the Black Hills: a magnetotelluric study, *Earth Planet. Sci. Lett.*, **20**, 275–279.

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

Rostoker, G., 1972. Polar magnetic substorms, *Rev. Geophys. Space Phys.*, **10**, 157–211.

Roy, R. F., Blackwell, D. D. & Decker, E. R., 1972. Continental heat flow, *The nature of the solid Earth*, 506–543, ed. E. C. Robertson, McGraw-Hill.

Sass, J. H., Lachenbruch, A. H., Munroe, R. J., Greene, G. W. & Moses, T. H., 1971. Heat flow in the western United States, *J. geophys. Res.*, **76**, 6376–6413.

Schmucker, U., 1964. Anomalies of geomagnetic variations in the southwestern United States, *J. Geomag. Geolect.*, **15**, 193–221.

Schmucker, U., 1970. Anomalies of geomagnetic variations in the southwestern United States, *Bull. Scripps Inst. Oceanography*, **13**, 1–165.

Trigg. D. F., Serson, P. H. & Camfield, P. A., 1971. A solid-state electrical recording magnetometer, *Publ. Earth Physics Branch*, Ottawa, **41(5)**, 66–80.

van Hees, H., 1958. The Meadow Lake escarpment—its regional significance to Lower Paleozoic stratigraphy, *Second Williston Basin Symposium*, 70–78, Bismarck, North Dakota, Conrad Publ. Co.

Whitaker, S. H. & Pearson, D. E., 1972. *Geological map of Saskatchewan*, scale 1:1,267,200, Dept. of Mineral Resources, Province of Saskatchewan.