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Magnetometer Array Studies in the North-Western United States and South-Western Canada

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Summary

Time-varying magnetic fields were recorded during the summer of 1969 with a two-dimensional array of 46 variometers in the north-western United States and south-western Canada between latitudes 44° and 51° N and longitudes 100° and 121° W. Magnetograms and maps of Fourier spectral components of three magnetic events are used to describe conductive structures in the upper mantle and crust. The most prominent of the anomalies are found in the North American Central Plains and over the Northern Rockies. The Central Plains anomaly runs from the eastern edge of the Black Hills northward along the boundary between Montana and the Dakotas to the Williston Basin. Its large magnitude, with anomalous fields larger than the normal fields, and its small half-width indicate a crustal conductor which concentrates current induced in a large region. In the western part of the array, attenuation of the vertical variation fields is attributed to a westward rise in the highly-conducting mantle. Two small anomalies in the vertical and horizontal fields, over the eastern front of the Northern Rockies and the Rocky Mountain Trench, may be associated with ridges or steps on the upper-mantle conductor or with crustal features.

1. Introduction

During the summer of 1969 the University of Alberta and the University of Texas at Dallas operated 43 magnetic variometers (Gough & Reitzel 1967) along four east–west profiles across the north-western United States and south-western Canada. With three stations operated by others (named in the Acknowledgments) the total array included 46 variometers. This array study completed the reconnaissance survey of magnetic variation anomalies in western North America from the U.S.–Mexico border to the Trans-Canada Highway. Our survey, therefore, linked the variometer profiles by Schmucker (1964) across southern New Mexico and Arizona to those by Hyndman (1963) and by Caner, Cannon & Livingstone (1967) across southern British Columbia.

In previous years variometer array studies had been made in the central Rocky Mountain States (Reitzel *et al.* 1970) and in the south-western United States (Porath & Gough 1970). It was shown that the observed magnetic variation anomalies could be related to lateral changes in the electrical conductivity of the upper mantle of the Earth, probably caused by regional variations in mantle temperature. The results were consistent with high conductivities under the Southern Rockies and the Basin and Range Province, and with low conductivities in the mantle under the Colorado Plateau and the Great Plains Province. Additional increases in conductivity above the average for the Basin and Range Province were found at its limit under the Rio Grande Rift Valley in southern New Mexico. The anomalous fields in the vertical and horizontal variation components were then approximated by induction in simple conductivity models (Porath, Oldenburg & Gough 1970; Porath & Gough 1970).

The electrical conductivity structure of the upper mantle in the western United States seems to be in excellent agreement with structure in other geophysical parameters, such as heat flow and seismic data for the upper mantle. Regions of low mantle conductivity show normal heat flow (Great Plains, Colorado Plateau); regions of high mantle conductivity are characterized by high heat flow (Basin and Range, Southern Rockies) (Roy *et al.* 1968; Blackwell 1969). Variations in the depth and thickness of the seismic low-velocity zone in the upper mantle, which probably arise from regional differences in the temperature-depth relations, also correlate with the electrical conductivity structure. Where the low-velocity zone is thick and shallow one observes high conductivity; low electrical conductivity is associated with a thinner and deeper low-velocity zone under the Great Plains and the Colorado Plateau (Julian 1970). It is not, however, suggested that the highly-conductive structures studied by our method are at the same depth as the seismic low-velocity layer. Other seismological studies (Herrin & Taggart 1962, 1968; Cleary & Hales 1966; Doyle & Hales 1967; Archambeau, Flinn & Lambert 1969) distinguish the Basin and Range Province from the Great Plains but do not resolve the Colorado Plateau from the Southern Rockies.

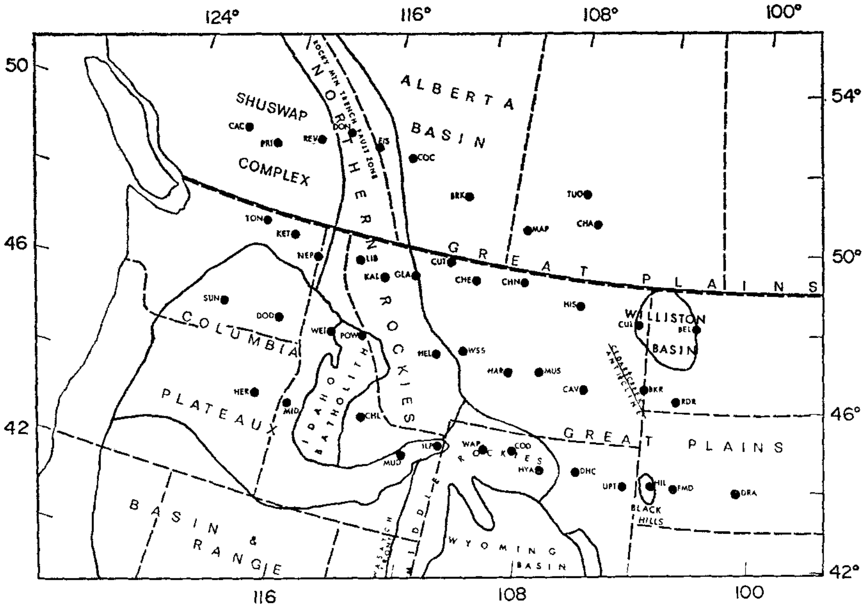

Fig. 1. Variometer array of 1969 on a simplified tectonic map of the north-western United States and south-western Canada.

The station arrangement for the summer of 1969 is shown in Fig. 1 with respect to large-scale tectonic features. The two southern lines were operated by the University of Texas, the northern lines by the University of Alberta. Stations were concentrated close to the boundaries of tectonic provinces, where maximum anomalous vertical fields were expected. Results from our 1967 array showed a large variation anomaly centred at Crawford, Nebraska, just south of the Black Hills area of South Dakota. The 1969 array was therefore extended eastward to cover the Black Hills uplift.

2. Magnetograms

Of numerous disturbances observed by the array, we present magnetograms of three which were recorded by 90 per cent or more of the instruments. Figs 2, 3 and 4 show disturbances recorded on August 10, August 12 and August 20, 1969 respectively. Times are marked in G.M.T. The lines of variometers are numbered 1–4 from north to south. Downward Z, northward H and eastward D are positive. Each variation anomaly will be discussed with reference to the three sets of magnetograms.

The most prominent variation anomaly occurs near the eastern edge of our array and strikes approximately northward from the eastern edge of the Black Hills to the Canadian border. The vertical variation field reverses its sign over less than 70 km on the two southern lines between FMD and HIL (Figs 2(b) and 3(b)) and between BKR and RDR (Fig. 4(b)). On Line 2 the anomaly is located between BEL and CUL (Figs 2(a) and 4(a)). CUL shows no reversal in Z, but has very much reduced amplitudes. Because of the narrow width of the anomaly the zone of reversed Z may have been missed with the station spacing on Line 2. The maximum concentration of current is close to the stations HIL, BKR and CUL, as is evident from the increased amplitudes of the horizontal components at these stations, particularly the east–west component D. The internal currents must be of very high intensity as shown by the large vertical fields of opposite sign on either side and the large horizontal field anomaly above the current. It is immediately obvious from the magnetograms that the Z variation field is closely in phase with D.

Small anomalies appear in the variation fields in the western half of the array. Before interpreting these in terms of mantle structure it is necessary to recall some general features of the vertical variation fields which become more relevant to geomagnetic deep-sounding studies as one approaches the auroral zones. Two types of vertical fields must be distinguished, the *normal* and the *anomalous* fields. The source field in general has a vertical component which induces internal currents whose field opposes the external vertical field. The *normal* vertical field is defined as the resultant of the external and internal fields. It increases towards the auroral zone (Figs 2, 3 and 4) and decreases where the conducting part of the Earth rises to smaller depths. *Anomalous* vertical fields appear close to current concentrations associated with lateral variations of conductivity (Reitzel *et al.* 1970). The anomalous fields are easily identified in mid-latitudes, where normal Z is small. Towards the auroral zone any anomalous Z has to be observed in the presence of large and rapidly changing normal Z.

The principal feature of the Z variograms is a general decrease in amplitude towards the west (Figs 2, 3 and 4). This is a general change in the normal Z field attributed to a rise of conducting material to shallower depths in the west. Our three array studies show it as a general feature of the continent. This westward change in normal Z has been recognized and studied by Hyndman (1963), by Caner *et al.* (1967) and by Caner (1970).

Closer inspection of the magnetograms shows anomalous Z fields associated with boundaries of conductive structures. In Line 4, the southernmost of the array, anomalous Z associated with D appears at COD and ILP but not at MUD at 05 G.M.T. in Fig. 3(b). The same anomaly is less strongly seen at WAP and ILP in Fig. 4(b). This is believed to be the northward continuation of the Wasatch Front anomaly (Reitzel *et al.* 1970; Porath & Gough 1970) at much smaller amplitude

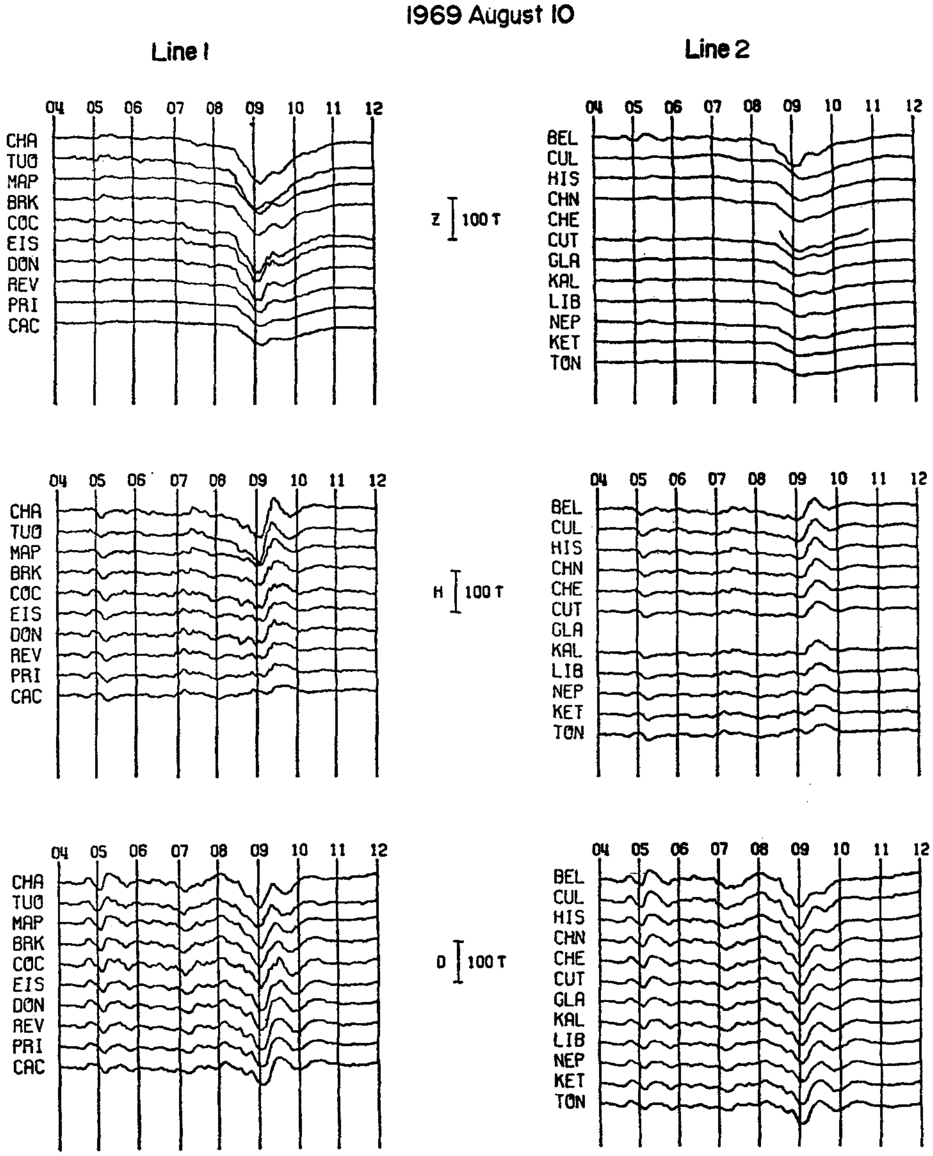

FIG. 2. (a) Magnetograms for disturbance of 1969 August 10. Northern lines.

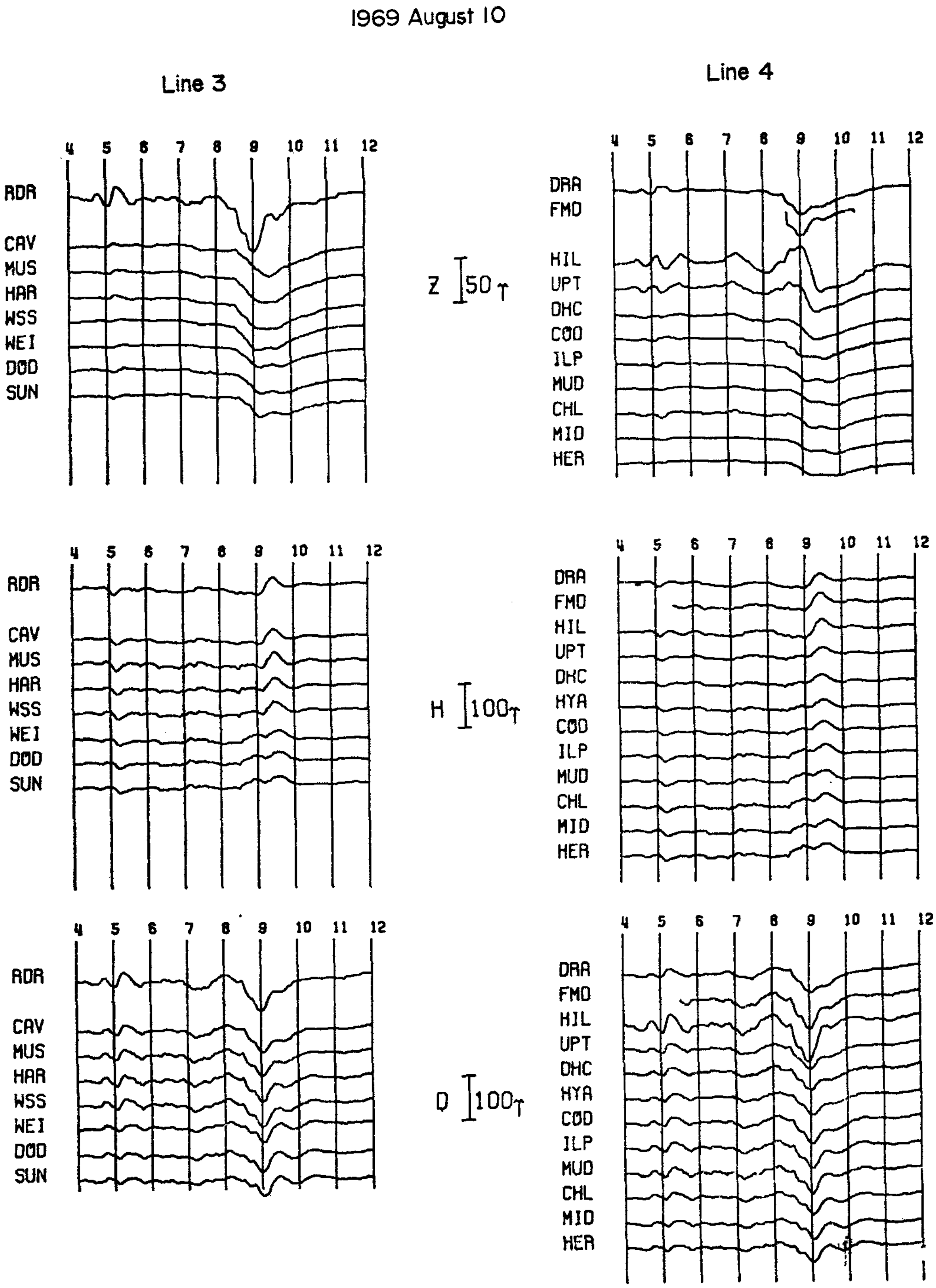

FIG. 2 (b) Magnetograms for disturbance of 1969 August 10. Southern lines.

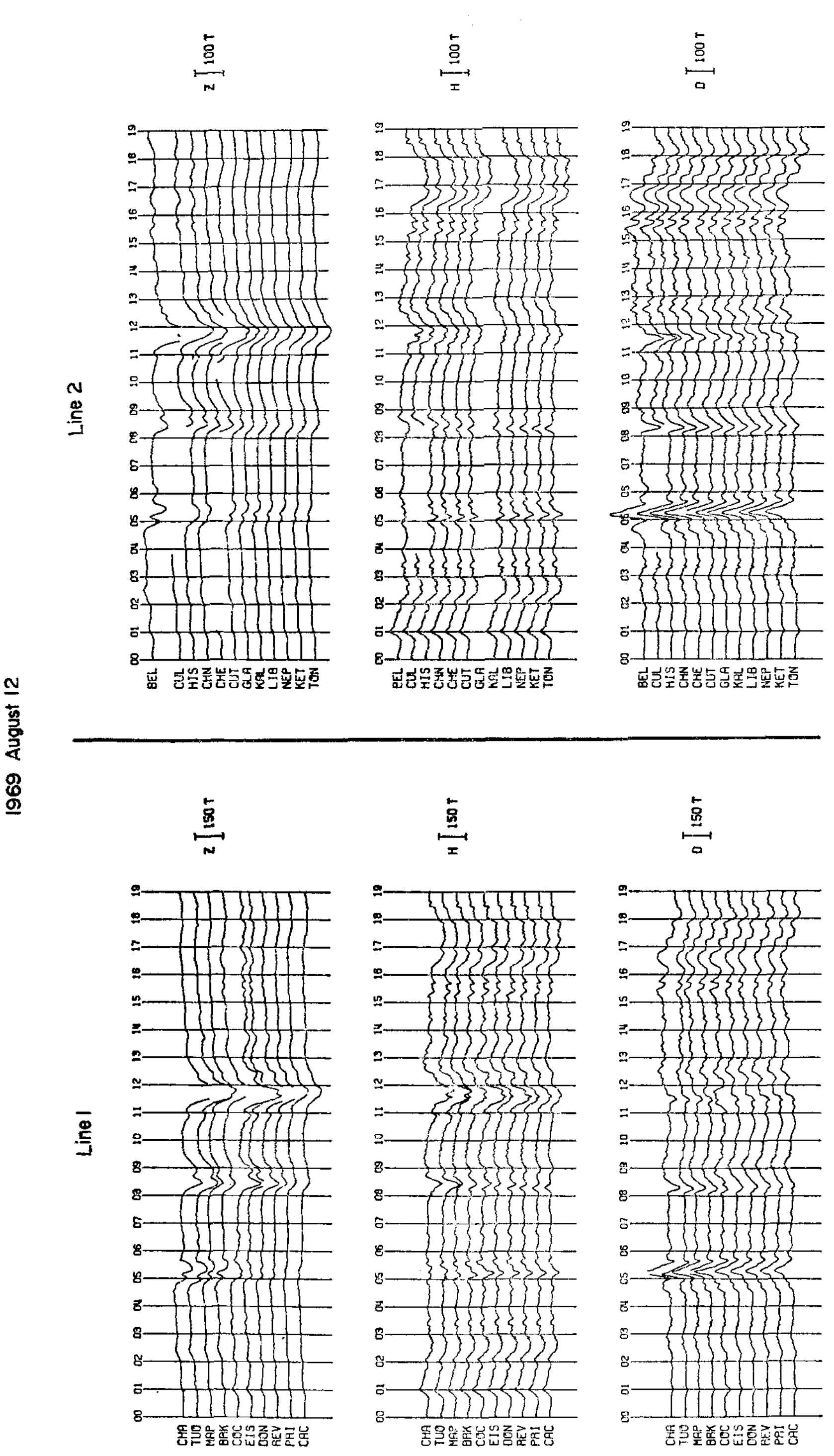

FIG. 3. (a) Magnetograms for storm of 1969 August 12. Northern lines.

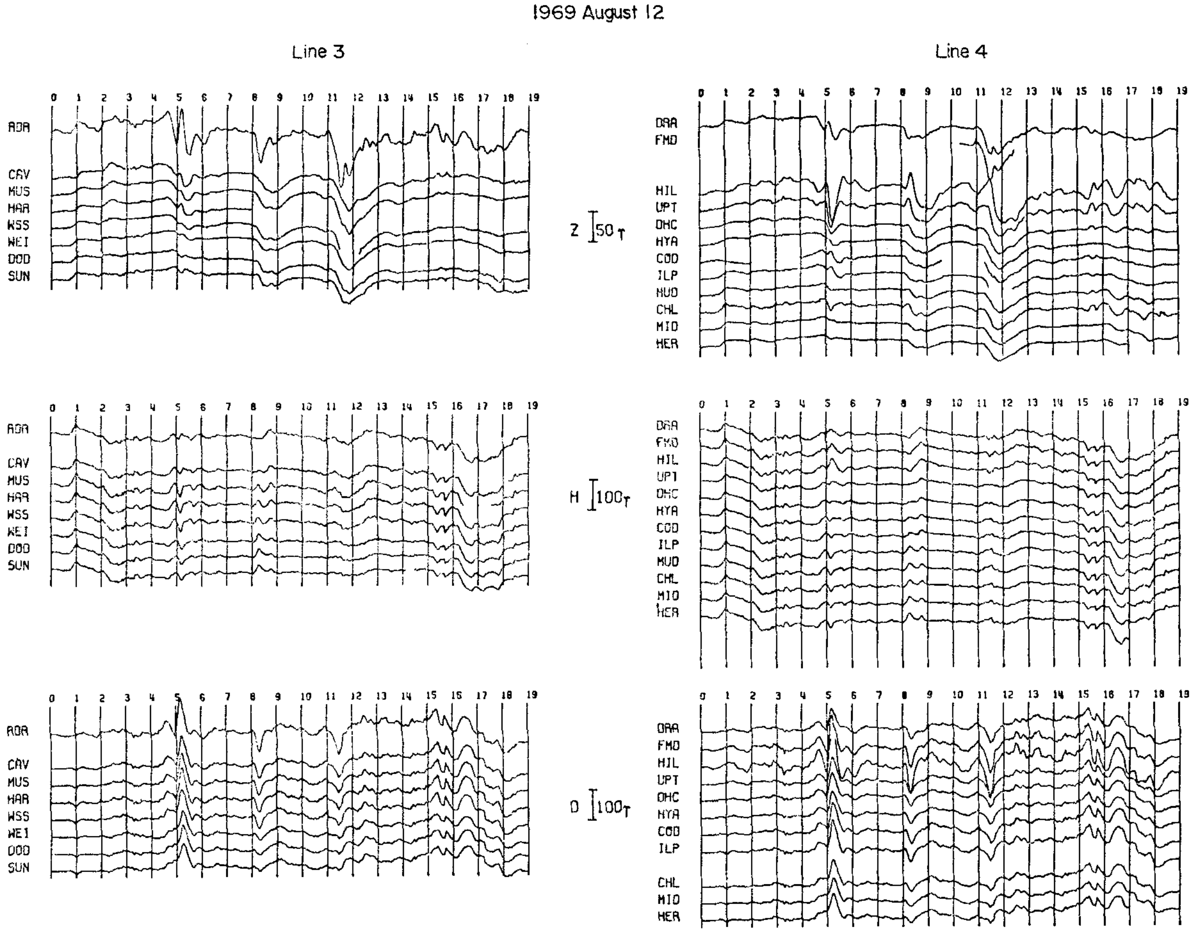

FIG. 3 (b) Magnetograms for storm of 1969 August 12. Southern lines.

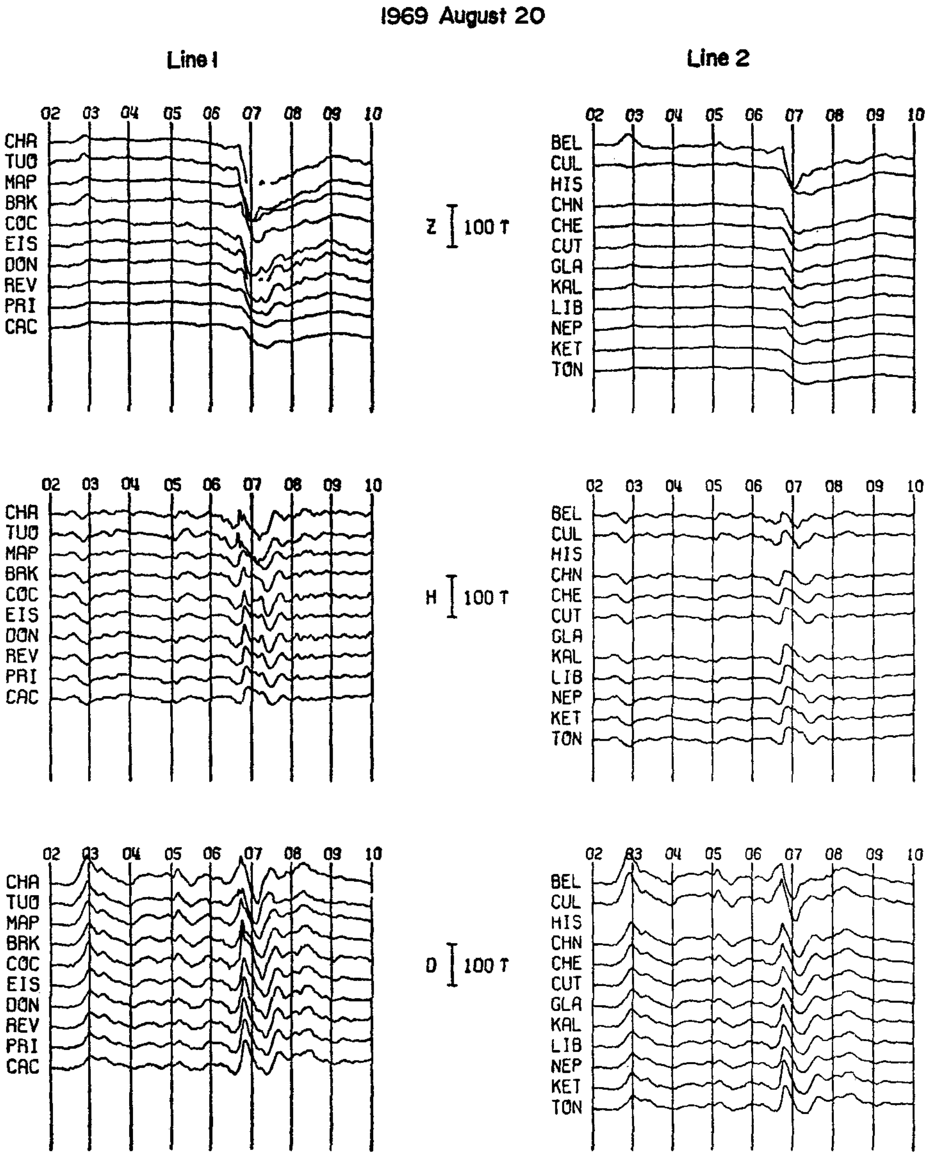

Fig. 4. (a) Magnetograms for disturbance of 1969 August 20. Northern lines.

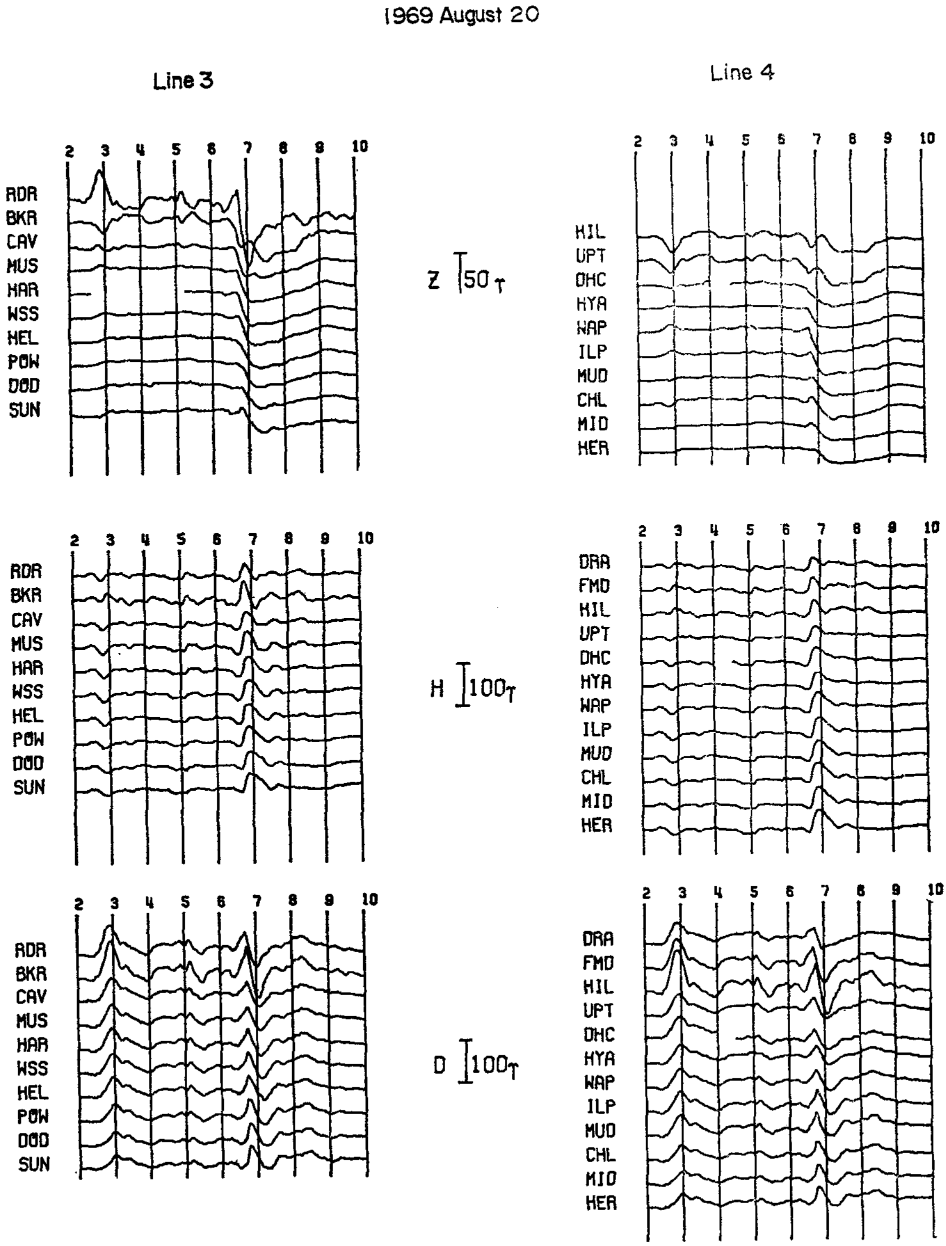

FIG. 4. (b) Magnetograms for disturbance of 1969 August 20. Southern lines.

than in Utah. Anomalous Z fields associated with H, indicating a conductor to the south, are seen strongly at CHL and less strongly at MUD, MID and HER at times at which H variations can be distinguished from D, especially on August 12 at 01 and 08–09 G.M.T. (Fig. 3(b)). This anomaly may be associated with a rise in the conductive mantle southward from the Columbia Plateaux to the Basin and Range Province. It appeared very strongly at Bruneau, just south of the Idaho Batholith, in the 1967 array study (Reitzel *et al.* 1970).

In Line 3 a small Z anomaly appears at CAV, MUS and HAR and is attenuated at WEI, with WSS probably transitional, at 05 G.M.T. on August 12 (Fig. 3(b)) when a large D variation occurred. At other times in all three events these stations show the general westward decrease in normal Z.

Line 2 shows a small, broad Z anomaly associated with large D peaks on August 12 at 05 G.M.T. (Fig. 3(a)) and less clearly before 07 G.M.T. on August 20 (Fig. 4(a)), at stations CUT, GLA, KAL, LIB and NEP. At KET and TON anomalous Z appears to be absent. Once again the main effect on this line is the general westward decrease in the normal Z variation field.

Line 1 is so far north that the normal Z field is very large and varies strongly between stations as a source effect. There is again a strong westward attenuation of the normal Z field, but most of the change occurs rather steeply between DON and PRI, with REV transitional. This is the main effect studied by Caner and his collaborators (Caner 1970). These authors locate a transition closer to DON. Anomalous Z appears at the stations east of DON at times at which the horizontal field lies in the NE–SW quadrants (Figs 2(a) and 4(a)). At 05 G.M.T. on August 12 (Fig. 3(a)) the horizontal field was NW–SE and anomalous Z appears only from BRK eastward. The dependence of anomalous Z at EIS and COC on the azimuth of the horizontal field must reflect complications in the local strike of the edge of a conductor. One possibility is that the edge is inflected so as to strike locally east–west south of COC.

It will be noted that the stations showing anomalous Z associated with D are further west in Line 2 than in the other three lines.

3. Spectra

Fourier transforms of variation events have been computed for preparation of anomaly maps and for study of the frequency-dependence of anomalies. A data set which includes more than one substorm gives a complex spectrum with many maxima for which it is difficult to find periods at which the energy is large at all stations (Porath & Gough 1970). For this reason only parts of the events shown in Figs 2, 3 and 4 have been transformed. The event of August 10 has been transformed between 06.30 and 12.00 G.M.T. and the storm of August 12 between 03.30 and 07.30 G.M.T. The event of August 20 was transformed over the time interval 06.00 to 10.00 G.M.T. and also between 02.00 and 10.00 G.M.T., and gave essentially similar spectra. As in previous work each event was treated as a transient (Reitzel *et al.* 1970).

Amplitude spectra from part of the storm of August 12 are shown for three stations in Fig. 5. This complex event gives quite different spectra for H and D for reasons discussed elsewhere (Porath & Gough 1970). Where the vertical field is anomalous its spectrum may have peaks which coincide with peaks in the spectrum of the horizontal field in some azimuth. At CHL the magnetograms show correlation of anomalous Z with H (Section 2). The spectra of Fig. 5(a) show this correlation but no relation between the Z and D spectra. At the station SUN in Line 3 (Fig. 5(b)) the same correlation of Z and H peaks is present, though it is difficult to see in the magnetograms except at 01 G.M.T. on August 12 (Fig. 3(b)). The station MUS in Line 3, on the other hand, shows anomalous Z related to D

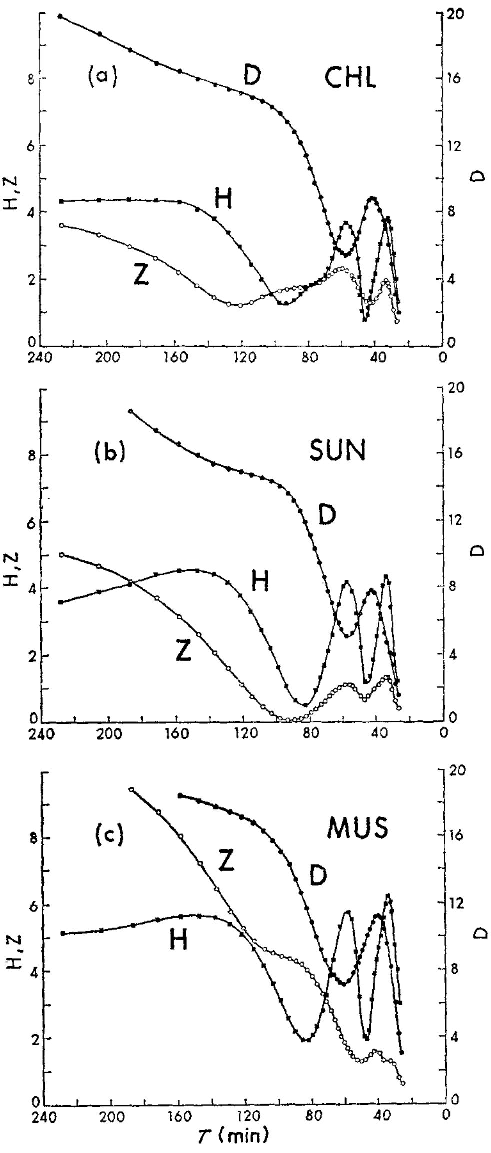

Fig. 5. Amplitude spectra of the storm of 1969 August 12 (03.30–07.30 G.M.T.) at (a) Challis, Idaho (CHL), (b) Sunnyside, Washington (SUN), and (c) Musselshell, Montana (MUS).

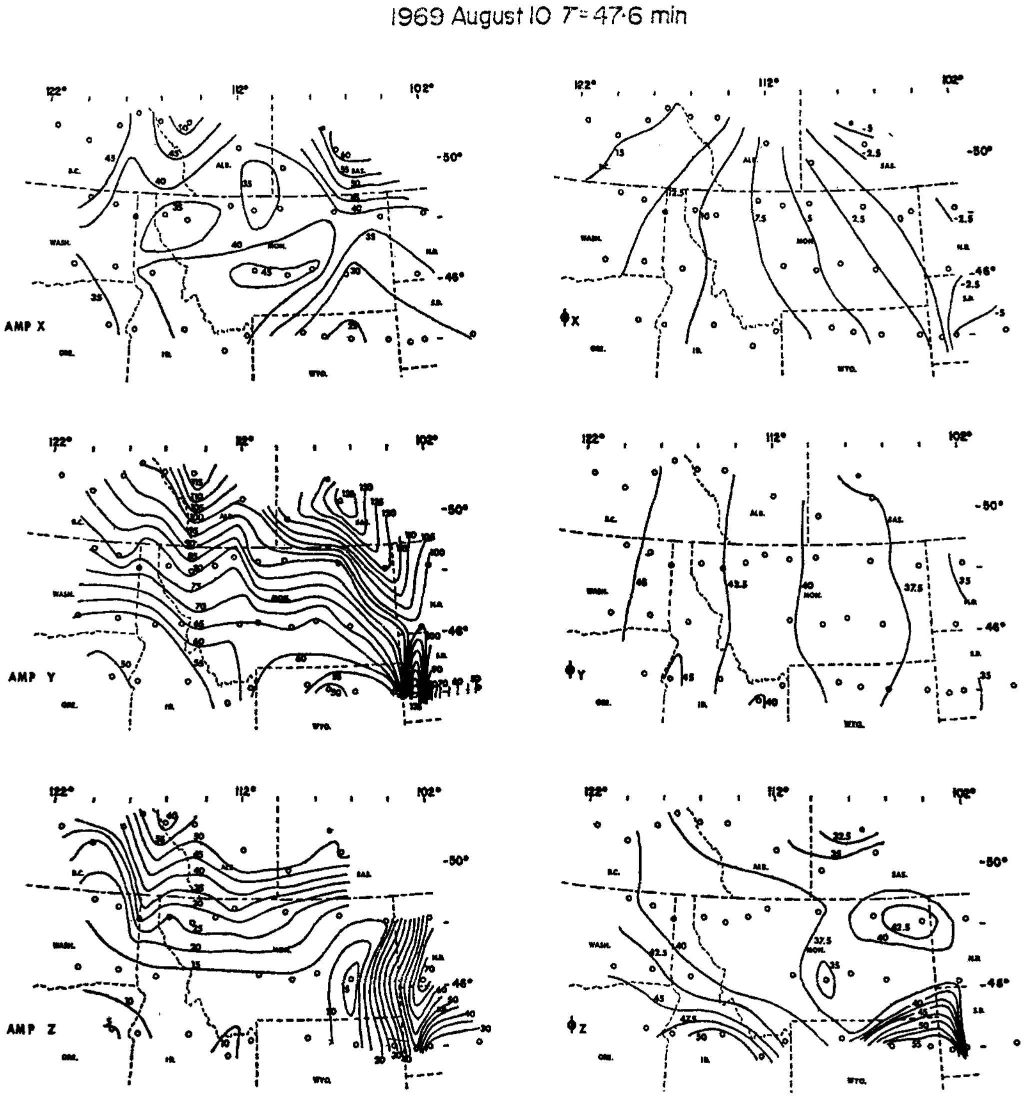

FIG. 6. Amplitudes (in arbitrary units) and phases (in min) at period 47·6 min for the disturbance of 1969 August 10.

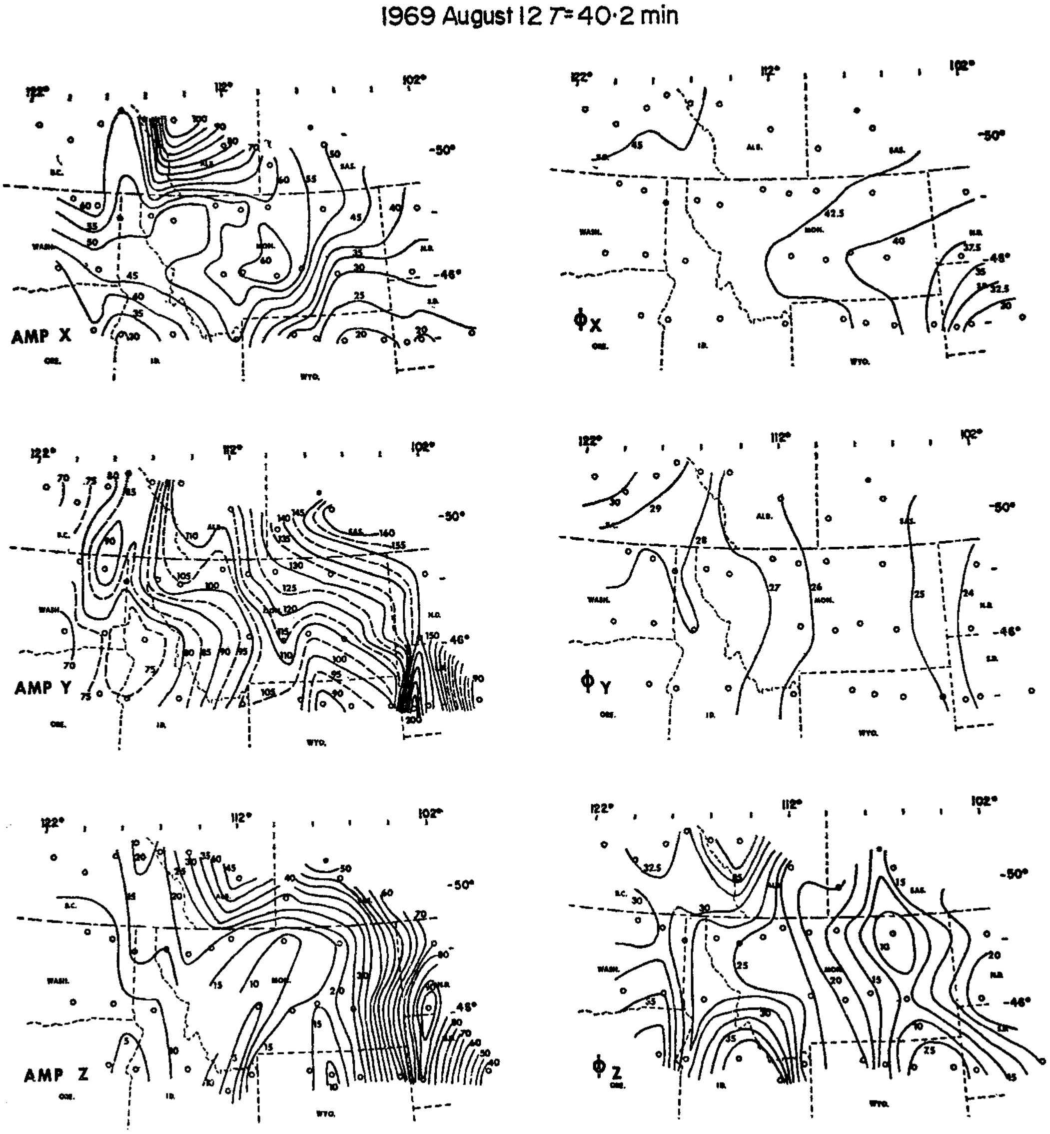

FIG. 7. Amplitudes (in arbitrary units) and phases (in min) at period 40·2 min for the storm of 1969 August 12.

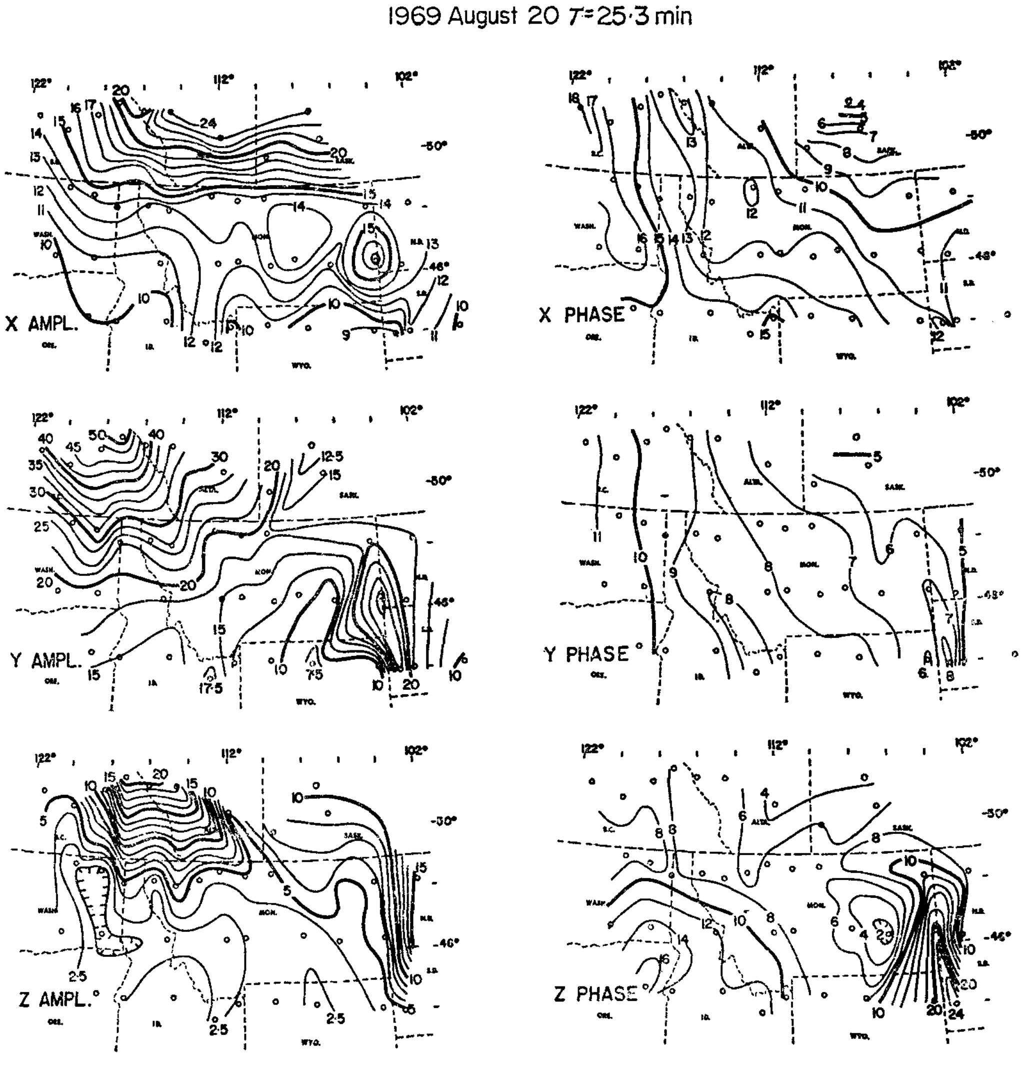

Fig. 8. Amplitudes (in arbitrary units) and phases (in min) at period 25·3 min for the disturbance of 1969 August 20.

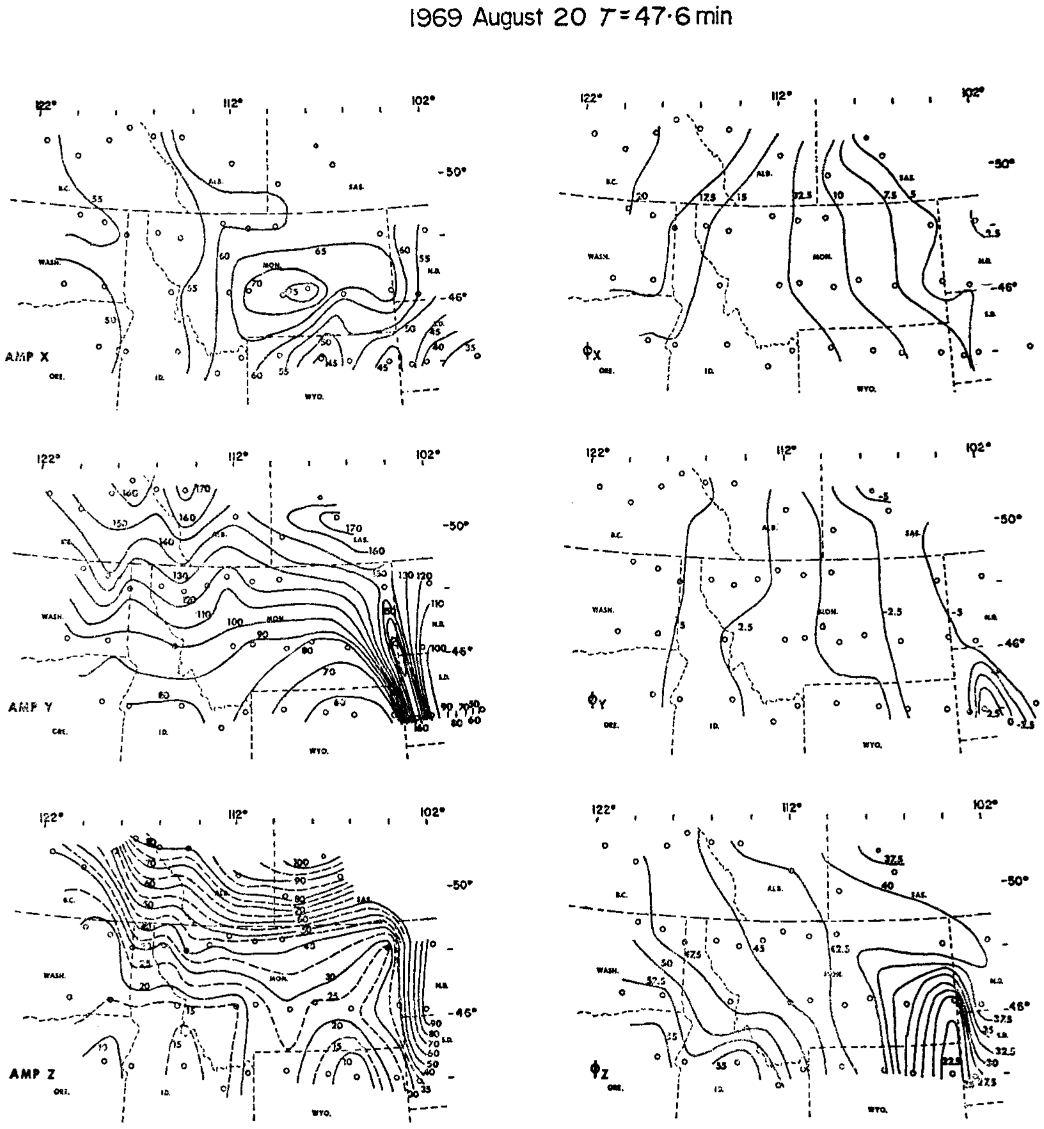

FIG. 9. Amplitudes (in arbitrary units) and phases (in min) at period 47·6 min for the disturbance of 1969 August 20.

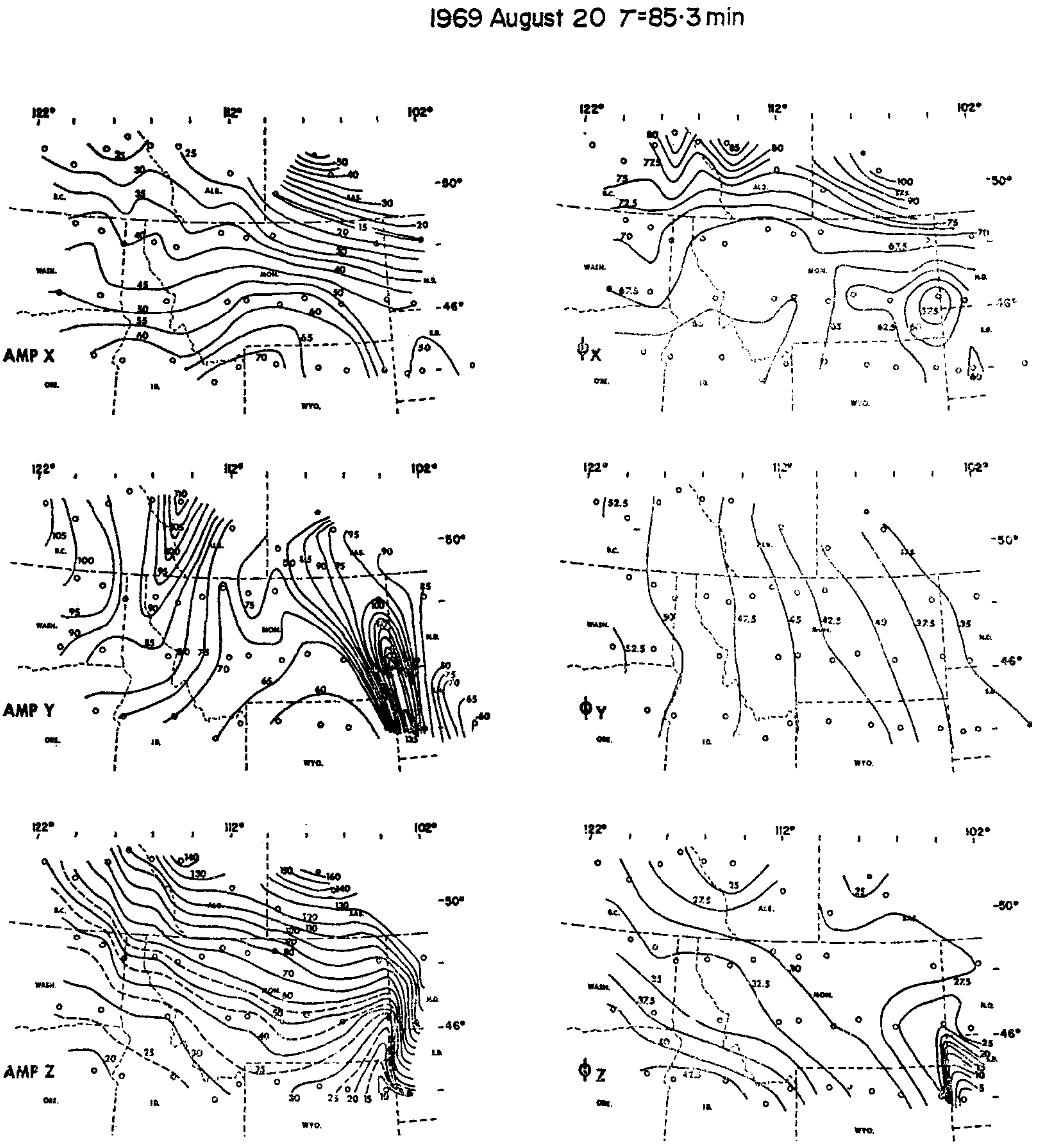

FIG. 10. Amplitudes (in arbitrary units) and phases (in min) at period 85·3 min for the disturbance of 1969 August 20.

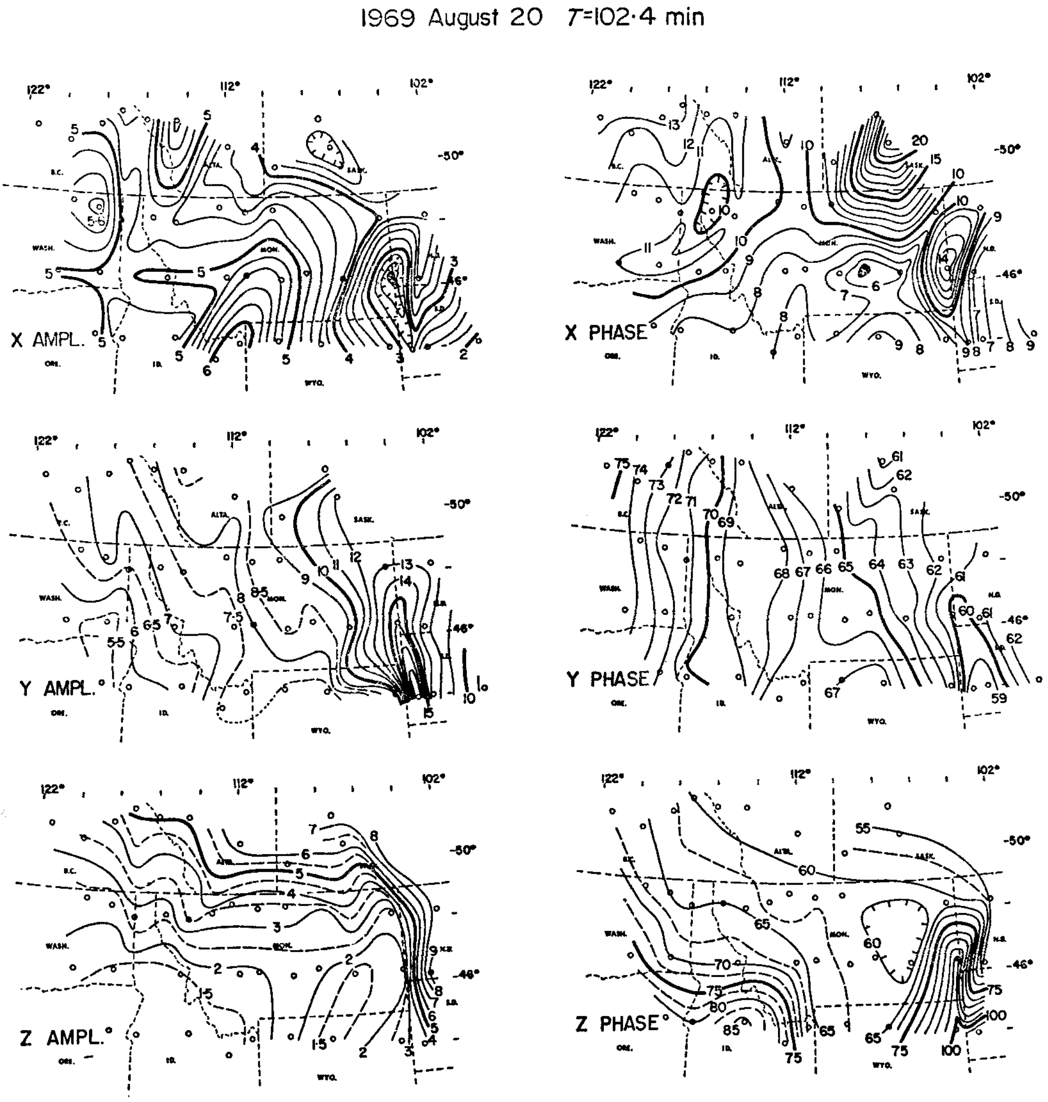

FIG. 11. Amplitudes (in arbitrary units) and phases (in min) at period 102·4 min for the disturbance of 1969 August 20.

associated with the east front of the Northern Rockies. Fig. 5(c) shows correlation of a Z peak with the only D peak and Z is unrelated to H. The same method of defining trends has been applied to a station east of the Southern Rockies by Porath & Gough (1970).

4. Maps of spectral components

Fourier spectral amplitudes and phases have been mapped at periods chosen where the energy in the event was high at all stations. The August 10 event gave only one period of 47·6 minutes (Fig. 6). Transforms of the storm sequence of August 12 have yielded maps for a period of 40·2 min (Fig. 7). The event of August 20, which was recorded at the largest number of stations, has a spectrum with peaks which varied only slightly over the array, and has been mapped for periods 25·3, 47·6, 85·3 and 102·4 min (Figs 8, 9, 10 and 11). Because the penetration of the variation fields and the induction process are frequency-dependent, the differences between maps for various periods contain information concerning the depths of the conductors. The geographical northward (X) and eastward (Y) component are mapped because of the 13° range of declination across the array.

The normal vertical field (defined in Section 2) shows a large northward gradient, especially between Lines 1 and 2 (Figs 6–11). This is a source field effect. A strong attenuation at the western end of the array occurs in all Z maps as a result of a westward decrease in normal Z through induction in the conducting mantle, which is at smaller depths in the west, as discussed in Section 2. A general effect in maps of the phases of X and Y is the westward phase lag associated with the westward surge in the auroral zone current (Rostoker *et al.* 1970). This appears in all X and Y phase maps except the X maps in Figs 10 and 11. The periods mapped in these figures were unavoidably chosen close to minima in the H spectra at eastern stations, as priority was given to securing high energy in Z and Y. Near a spectral minimum the phase is unstable and the X phase maps in Figs 10 and 11 have little significance.

Superimposed on the normal field in each component are the anomalous fields. These will be discussed in relation to the maps.

The largest anomaly runs approximately northward from the eastern edge of the Black Hills along the boundary between Montana and the Dakotas. It may continue into Saskatchewan. It appears prominently on all Y and Z amplitude maps and on the Z phase maps. This anomaly is characterized by very large magnitude and very small width. It is discussed in the next section.

In the western half of the array two anomalies are associated with the Northern Rockies. These are best shown in the maps of the eastward horizontal field amplitude Y but appear also in Z and in some maps in X. The maxima in Z are displaced to the east of those in Y as would be expected for local linear currents. The current maxima should lie under the Y maxima and are located roughly along the eastern front of the Northern Rockies and the Rocky Mountain Trench respectively (Fig. 1). These anomalies are much smaller than those observed by the 1967 array farther south, but occur consistently in maps for various periods and for all three events.

The northern end of the Wasatch Front anomaly is suggested in the Y and Z maps of Figs 8, 9 and 11. Its relation to the two Northern Rockies anomalies does not emerge consistently from the maps here presented.

A phase anomaly in Z appears near the south-west limit of the array. This anomaly is believed to be associated with the northern edge of the highly-conducting mantle under the Basin and Range Province.

For periods less than 50 min a maximum in the X amplitude appears in central Montana (Figs 6, 7, 8 and 9). This anomaly disappears at longer periods and may be related to sediments filling several synclines and mountain basins in this area, as shown in the Tectonic Map of the United States (U.S.G.S. and A.A.P.G., 1962).

An interesting effect appears in the X amplitude maps at periods 85 and 102 min (Figs 10 and 11), which show X increasing southward over most of the array. At shorter periods the other X maps show a general increase northward (i.e. towards the auroral zone) disturbed by local anomalies. A similar reversal of the X north-south gradient was observed with the 1967 array and was interpreted as an effect of a rise in the surface of a good conductor from the Colorado Plateau southward to the Basin and Range Province (Reitzel *et al.* 1970). A similar explanation could apply in the present case in terms of conductive mantle material under the Basin and Range and Middle Rockies provinces near the southern limit of the 1969 array. The effect may, on the other hand, be related to unknown features of the source current system.

5. Discussion

The principal anomalies found in the 1969 array study are the North American Central Plains anomaly which runs from the Black Hills along the boundary between Montana and the Dakotas, and the double anomaly of the Northern Rockies. In another paper we shall make quantitative model studies of these. Certain general features of any acceptable interpretation can, however, be stated at once.

The Central Plains anomaly is both large and very narrow. Where it passes through Line 4 its half-width is no more than 75 km. At Lines 2 and 3 its maximum width is less well defined because the stations are further apart. Such a narrow anomaly cannot be accounted for in terms of current in the upper mantle. Known crustal structures include the Black Hills uplift, the Cedar Creek anticline and the Williston Basin. Conceivably the anomaly could arise from a combination of effects associated with these three structures. However, on present knowledge it appears to be associated with a single structure in the crust.

The magnetograms (Figs 2, 3 and 4) and anomaly maps (Figs 6–11) show that the anomalous Y fields over the structure are more than double the normal Y field. This cannot be accounted for by local induction in an elongated structure. It is therefore necessary to take account of concentration, by a narrow linear conductor, of current induced in the crust in the region. This effect has been discussed in general by Price (1964) and by Dyck & Garland (1969) in relation to the Alert anomaly. It seems extremely unlikely that the sediments of the region could produce such intense channeling of current. The basement structure is essentially unknown. No correlation with gravity or magnetic anomalies is apparent. Combs & Simmons (1970) have reported high heat flow values in the Dakotas, with a regional average of 2·0 H.F.U. which they associate with mantle sources. The Black Hills contain numerous hot springs. It is difficult, however, to see how a narrow linear conductor could be produced in the crust by temperature alone. The required high conductivity and linear form could be provided, for example, by a graphite schist body in the basement. Mathisrud & Sumner (1967) have noted very high conductivities in graphite bodies in the Lead district of western South Dakota.

Across the Northern Rockies the main feature of the variation fields is a westward decrease in normal Z. This is probably associated with a rise of a good conductor in the upper mantle or lower crust to shallower depths in the west. Small local anomalies at the eastern front of the Northern Rockies and Rocky Mountain Trench may be associated with ridges or steps of low relief on the surface of this deep conductor, or with local conductors high in the crust. The attempt to discriminate between these possibilities must await model calculations.

Heat flow data are few in the western part of the 1969 array. However, Blackwell (1969) reports high heat-flow values in the Northern Rockies and Columbia Plateaux.

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