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THE GEOPHYSICAL SIGNIFICANCE OF GEOMAGNETIC VARIATION ANOMALIES

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Analytic procedures in classical geomagnetic deep sounding and in two-dimensional magnetometer array studies are outlined. Three types of magnetic variation anomaly are considered, and anomalies of one geographical area. *Continental-edge* anomalies remain somewhat ambiguous as to the contribution of structure in the upper mantle; the geophysical significance in geothermal terms is understood, if the effect exists. *Subduction-zone* anomalies in the Peruvian Andes and in central Japan are considered in relation to the ascent of an andesitic melt fraction from the lithosphere slab, a process which accounts also for uplift and support of the mountains. In *western North America* anomalies are closely related to heat flow and indicate complex tectonic activity with considerable fine structure in general agreement with seismological parameters. The Basin and Range Province has a highly conductive upper mantle and still higher conductivities are found under the Wasatch fault belt and under the southern Rockies. Under the northern Rockies the evidence is for only a thin conductive layer in the upper mantle and in general for much lower heating than in mid-latitudes of the United States. *Crustal anomalies* are discussed in relation to the current concentration effect. It is suggested that some of them may mark metamorphic belts in crystalline basement rocks. This association has been demonstrated for the North American Central Plains anomaly.

1. Introduction

In recent years many studies have been made with linear or two-dimensional arrays of three-component recording magnetometers, of geomagnetic disturbance fields in the period range from a few minutes to one day. Many local anomalies in these fields have been found, with spatial wavelengths typically between 100 and 1000 km; closer spacing of instruments would probably extend the spectrum to shorter wavelengths. Except near the equatorial and auroral electrojets, such anomalies are in general associated with concentrations of induced currents in the solid earth, and so with variations in electrical conductivity at depths less than 700 km.

The significance of anomalies of any sort can be assessed only with some understanding of the processes of measurement and calculation which produce them. Before discussing the magnetic variation anomalies and their implications I therefore give brief attention to existing methods of investigation.

2. Methods of observation and interpretation

Classical *geomagnetic deep sounding* (G.D.S.) methods were developed, largely by Schmucker (1964, 1970), to make use of observations from a small number of magnetometers, usually less than ten, recording simultaneously. In most cases the best arrangement of six or eight magnetometers will be along a straight line, so that G.D.S. methods are often associated with small linear arrays. In regions far from local anomalies the smoothness of the observed fields indicates that the electrical conductivity varies approximately with depth alone, and so is one-dimensional. In this case one can compute the ratio Z/H of vertical to horizontal components for an incident field of given period T and spatial wave-number k, at the surface of a layered conductive half-space. Computed Z/H is compared with the observed ratio for each T at which data are available. Models are non-unique and the estimation of k is a major difficulty.

In anomalous regions the station-to-station changes in amplitude and phase of the field components indicate the presence of internal conductive structure; in general this will be three-dimensional but in some cases it may approximate two-dimensional form. To allow the use of different variation events, and thus to allow the anomaly to be mapped by placing the magnetometers in different positions successively, one requires a measure of the response of the earth to the incident field, normalized to that field. Parkinson (1959, 1962) and Wiese (1962) took a first step with their arrow representations of response. Schmucker (1970) introduced the use of a matrix of transfer functions, each of which gives the response of the earth in one component of the anomalous field, to one component of the normal field. Since each transfer function is complex, phase relationships are represented. If the structure appears to be elongated, transfer functions for a given two-dimensional model can be computed numerically and compared with observation. The estimation of the transfer functions requires computation of powers and cross-products between normal and anomalous field components. Therefore the first step is to make a separation into normal and anomalous parts; this may be very difficult and it may be necessary arbitrarily to declare one station to be 'normal'.

Recently large two-dimensional arrays of magnetometers have come into use, as a result of the development of an inexpensive three-component magnetometer by Gough and Reitzel (1967). Arrays of forty or more of these instruments have recorded simultaneously in array studies, the earliest of which were conducted jointly by the University of Alberta and the University of Texas at Dallas. Large two-dimensional arrays have characteristic advantages and problems and have led to the development of new interpretative techniques. In this paper array will mean a large two-dimensional 'array' unless the word 'linear' is added.

The immediate advantage of an array is that it allows one to map each component of a single variation event over the whole array, which may cover 10^5–10^6 km^2. Because a Fourier transform refers to a precise period, and sums the energy of the whole event at that period, the Fourier transform amplitudes and phases of variation components have proved good parameters to map (Reitzel et al., 1970). Fig. 5 provides an example of an amplitude map. Two other amplitude maps and three phase maps are needed to describe the disturbance field at one period. Surface integration of components, mapped in either the time or period domain, can be used to separate the variation fields into parts of external and internal origins (Porath et al., 1970). This technique separates only fields of spatial wavelength smaller than the array, and for this reason simple smoothing procedures are almost as effective in separation as formal surface integration (Porath et al., 1971). If Fourier transform maps show consistency in the anomalies for several events, a set of maps at various periods from one or two events can be used to estimate the normal and anomalous fields and to normalize the latter with respect to the former. If the anomaly is elongated, numerical methods (Jones, 1973) can be used to calculate anomaly fields for two-dimensional models for comparison with the observed anomaly. First-order models of two-dimensional conductive structures can in this way be fitted to the observations. They are, of course, not unique.

If different variation events show reasonable agreement in the positions and magnitudes of anomalies, the structure can be modelled in the above manner in terms of the fields of one or two of the events. There is then no special reason to use transfer functions. If, however, the anomaly pattern changes from event to event, one may have strongly three-dimensional structure which makes the polarization of the normal field, and the phase difference between its horizontal components, important in determining the anomaly pattern (Gough et al., 1972). In such a case transfer functions may be very helpful in dealing with results of an array study.

The principal difficulties, which are severe, are common to classical G.D.S. and array studies. They are the problem of separation of the anomalous field from the normal field, and the problem of dealing with three-dimensional anomalies. Model computations in such cases (Jones, 1973) are still almost prohibitively expensive.

3. Types of magnetic variation anomalies

Anomalies have been found virtually wherever a magnetometer array has been operated. This need not cause surprise. It means, simply, that the crust and upper mantle are electrically heterogeneous. But the profusion of anomalies does mean that they cannot all be included in a short review paper. Instead three types and one geographical area have been chosen for discussion. Anomalies associated with *continental edges* and with *subduction zones* will be considered, followed by the anomalies of *western North America* and *crustal anomalies.*

3.1. Continental-edge anomalies

It is well known that the vertical component of variation fields is enhanced on the continent side of a continental edge. Parkinson (1959, 1962) showed that variation-field vectors recorded at Australian and other observatories tended to be confined to a characteristic plane for each observatory, inclined upward toward the nearest continental edge. He pointed out that this could be a result of induction in the ocean water or in both the water and the conductive upper mantle, expected to rise on the ocean side. This ambiguity, which thus entered the interpretation of the continental-edge effect at its discovery, remains today after much observational and theoretical labour. Observatories near the southeast coast of Japan and near the coast of Peru show strongly abnormal behaviour which appears to be related more to the nearby subduction zones than to the continental edges: these anomalies are considered in section 3.2. Excluding these, the most intensively studied continental-edge anomaly is that of the California coast. Schmucker (1964, 1970) has used records from stations along four profiles at right angles to the coast, to show that both vertical and horizontal anomalous fields can be interpreted, within the precision of the data, as effects of induction in the ocean water alone, above a conductive mantle with a plane surface. Schmucker points out, however, that his data could alternatively be explained by induction both in an upward step in the conductive mantle at the continental edge and in the ocean water. The two conductors would interact, the mantle conductor tending to reduce induction in the ocean. In the light of Schmucker's results it may be doubted whether the ambiguity can be resolved by means of variation-field observations on the land only.

The study of the California continental-edge anomaly was extended across the shelf to the ocean floor by Cox, Filloux and Larsen (Filloux, 1967; Cox et al., 1970), who used a linear array of six three-component magnetometers on land, three telluric stations across the shelf to 150 km off-shore, and a magnetotelluric station on the ocean floor 630 km offshore. Their data were interpreted in terms of a rapid rise of the conductive mantle offshore. Laterally the surfaces of equal conductivity rise sharply between 80 and 140 km from the coast. Under the ocean their conductivity structure is layered and rises to 0.5 $(\Omega m)^{-1}$ at a depth of about 50 km. Though this model is not unique, the results of Cox et al. (1970) strongly support a rise in the conductive mantle off the Californian coast.

Recently Greenhouse (1972) has reported a study with twelve three-component fluxgate magnetometers placed on the sea floor off southern California. His results indicate lower conductivities in the oceanic lithosphere than those found by Cox et al. (1970) and are inconsistent with any sharp lateral change in conductivity in the upper mantle from land to sea. Greenhouse suggests that the conductive mantle rises gradually beneath the outer borderland. Thus the best-studied continental edge, that off California, still provides no definite answer to the question whether upper-mantle conductive structure contributes to the anomaly fields.

An interesting extension of work on the land side has been made by Lilley and Bennett (1972), who used an array of magnetometers covering southeast Australia and extended the graphical representation of Parkinson's arrow by calculating a two-dimensional response surface for the area of their array.

As to the geophysical significance of continental-edge anomalies the position seems to be that the significance is well enough understood, since the isotherms should rise and the composition become more basic on the ocean side: if only the upper-mantle *effect* is there!

A final point is that continental edges differ, so that there may be species within the genus, continental-edge anomalies. The abnormality of the Peruvian and Japanese coasts has been remarked already. But California is widely believed to be a region of recent subduction and is now near a transform fault. Inactive continental edges such as those of Africa and Australia may have very different electrical properties.

3.2. Subduction-zone anomalies

Geomagnetic variation anomalies are known to exist in two areas above active descending lithosphere plates. The Japanese anomaly has been studied for twenty years by Rikitake (1966) and his students and collaborators. The Andean anomaly of Peru has been under study since 1964 by a group drawn from the U.S.A., Peru and Bolivia and led initially by Schmucker and later by Aldrich (Schmucker et al., 1967). As the equatorial electrojet crosses the Peruvian Andes, day-time incident fields of short spatial wavelength are available in addition to night-time substorm fields of very long normal-field wavelength. Stations on both sides of the Andes show the effects of currents in a conductive body under the mountains. Reversals of Z and maxima in the horizontal perturbation field transverse to the currents locate these under the crest of the Andes or somewhat east of the crest, as shown in Fig.1. A preliminary model (Schmucker et al., 1967) showed that, to first order, the substorm-field effects could be modelled by a semi-elliptic ridge on the surface of a perfectly conductive half-space. The width (major axis) was 470 km and the ridge height (semiminor axis) 180 km, bringing the 'perfectly' conducting mantle to depth 60 km under the mountain crest. A later model (Schmucker, 1973) makes use of the equatorial electrojet fields as well as

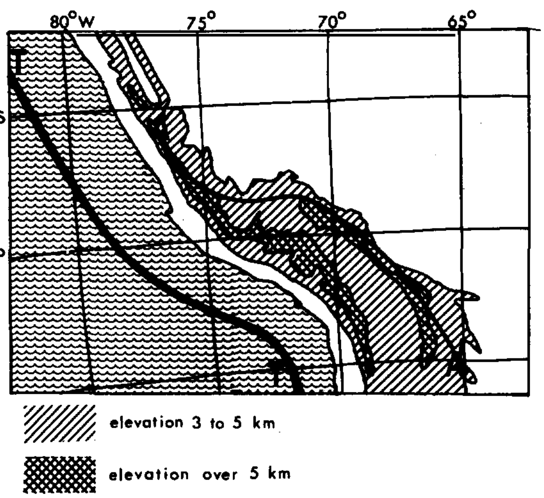

Fig. 1. Location of the conductivity anomaly of the Peruvian Andes. $A-A$ = centre of conductive body after Schmucker et al. (1967). $T-T$ = axis of Peru–Chile Trench.

the substorm fields. The former require the conductor to be still nearer the surface, and a ridge of rectangular section and of conductivity 0.1 $(\Omega\mathrm{m})^{-1}$, 400 km wide and rising to a depth of only 20 km, is indicated by fig.5 of the paper cited.

Nothing is at present known of the heat flow in the Peruvian Andes. However a thermal cause of the conductivity anomaly is strongly supported by the seismological evidence of abnormal absorption and delay of seismic waves passing through the upper mantle under the Andes (Sacks et al., 1967). If the conductivity is raised because the temperature is high, one requires rock at temperatures in excess of 1000°C at a depth of 40 km or less under the mountain crest. Further, the isotherms must fall steeply under each flank of the Andes. These requirements strongly suggest heat transport by bodily movement of magma into the upper mantle and perhaps the crust under the range. At some depth, which cannot be defined on present information, mass transport will cease and conduction take over.

Ringwood and Green (Ringwood, 1969) have suggested that basalt of the oceanic crust may undergo alteration, near the top of a descending slab, to eclogite, which may then yield andesitic magma by partial melting, the andesite rising to the overlying island arc or Andean range. This hypothesis provides a reasonable explanation of the sub-Andean conductivity anomaly (Fig.2). Not only the basalt–eclogite–andesite sequence but any partial melting of slab material with ascent of an acid fraction will serve. The mechanism provides gravitational forces to raise the mountains and to support them, once raised. The deep earthquake foci indicate that the slab has inclination 35–40° under Peru and the mountain crest is about 400 km from the trench. The descending slab should therefore be about 300 km below the crest. If a strip of upper mantle down to the slab is contaminated with a fraction f of andesite (Fig.2) we have compensation by a column 300 km deep which will support a mountain 300 $(3.3-2.8)f/2.7$ km high. For a 5-km mountain one needs $f = 9\%$, which is plausible. If the Andes are raised in this way the situation is dynamic, as the slab adds magma continuously to the root. The mountains will be rising, in dynamic equilibrium or diminishing as erosion is less than, equals or exceeds the replenishment from the slab (Gough, 1973).

The Japanese anomaly is perhaps the most inten-

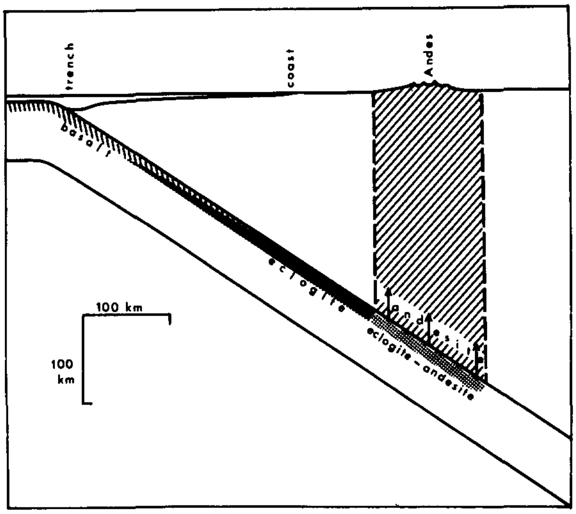

Fig.2. A model based on the basalt–eclogite–andesite sequence of Ringwood and Green, which accounts for heating under the mountains by ascent of andesite in the shaded column. This column has reduced density through the andesite contamination, and accounts for dynamic uplift of the mountains.

sively studied of all anomalies in variation fields (Rikitake, 1966). A well-defined maximum in the vertical component of substorm fields occurs in southeastern Honshu, and there is a pronounced phase anomaly in Z for the daily variation. A conductivity model which accounts for the main features of the anomaly, in terms of topography on the surface of the highly conducting mantle, shows (Fig.3) a steep dip in this surface from the Philippine Sea at the southeast coast of central Japan and a more gradual ascent across Honshu and into the Japan Sea (Rikitake, 1969; Uyeda and Rikitake, 1970). The region is among the most densely observed on the planet, in terms of heat flow; the pattern is complicated (Fig.3) but does show values between 1 and 2 H.F.U. in the southern half of Honshu and values above 2 H.F.U. both southeast and northwest of the island. There is, therefore, a qualitative correspondence between the electrical conductivity and the heat flow. In a general way the heat flow and conductivity support the hypothesis that magma is rising from above the lithosphere slab which is underthrusting the southern half of Honshu.

The tectonics are much more complicated here than in Peru. The distribution of shallow, medium and deep earthquake foci shows that there are three subducted slabs close to Honshu and considerable variation in

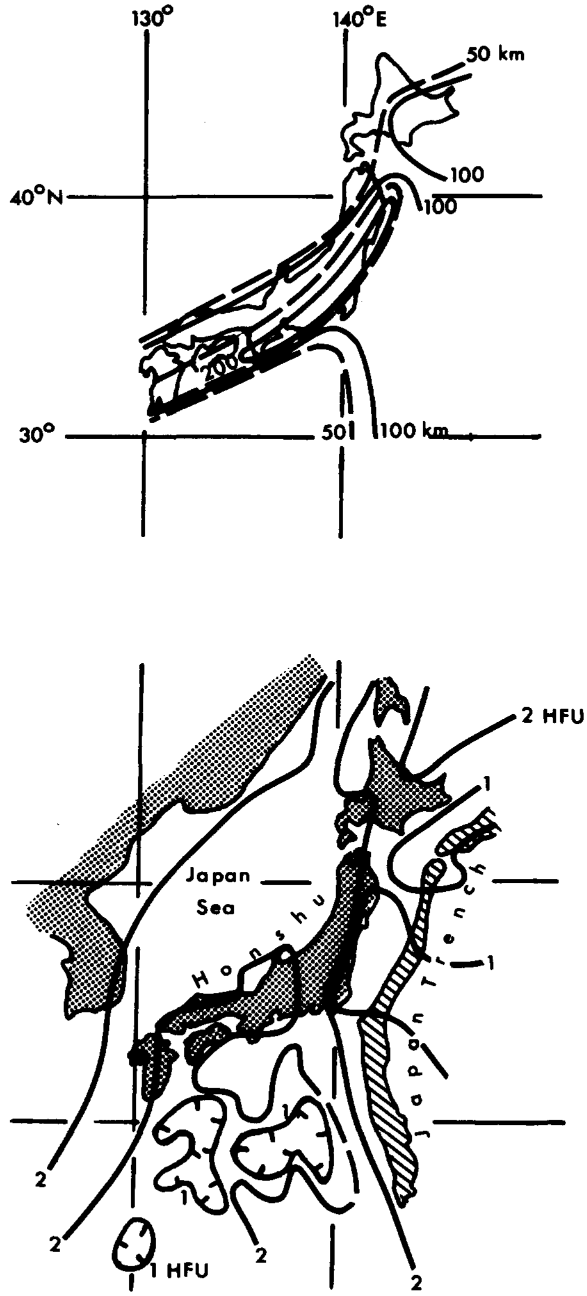

Fig.3. Heat-flow (lower map) and conductive-mantle topography (upper map) near Japan, after Rikitake (1969) and Uyeda and Rikitake (1970).

their dips. In terms of plate kinematics, there is a triple junction of three subduction zones just southeast of central Honshu (McKenzie and Parker, 1967). This makes the region one of extreme tectonic complication. Simplicity is not to be expected, nor is it found, in the conductive structure or in the induction anomaly, as Rikitake and his colleagues have shown. The anomaly is, however, qualitatively accountable in terms of the mechanism of magma ascent from partial melting of subducted slab constituents.

The uplift and isostatic compensation of island arcs may be provided quite generally by the mechanism of ascent of an acid melt from the underlying subducted lithosphere plate. The basalt of many of the islands may well be derivable from partial melting of acid-contaminated ultrabasic material from the upper mantle above the plate. Since the compensation is produced almost entirely by the compositional density difference in the contaminated column, an island

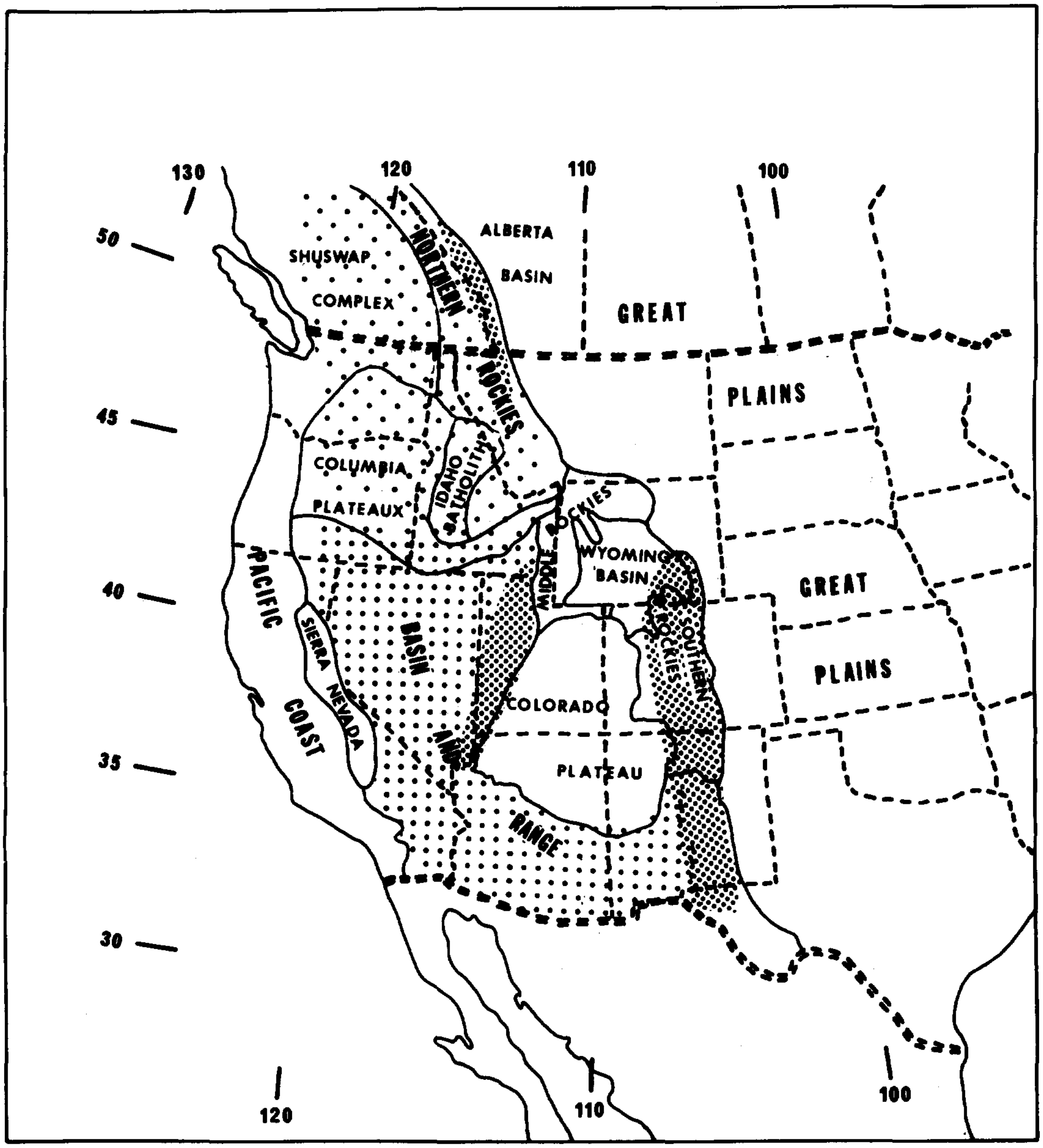

Fig.4. Conductive structure of the upper mantle in western North America.

will be supported statically if the subduction zone moves away. Such statically compensated island arcs must necessarily lose height by erosion, unlike dynamically compensated Andean mountains.

3.3. Western North America

The western part of North America is a tectonically active continental region unique on the planet. Several geophysical disciplines have contributed to the large body of knowledge of the structure of the crust and upper mantle in the western region, in the Great Plains and at their zone of contact near the front ranges of the Rocky Mountains. The magnetic variation anomalies are considered in some detail, with brief mention of other related geophysical results.

Hyndman (1963) was the pioneer of the study of conductivity in western Canada. Schmucker (1964, 1970) made classic studies and Caner et al. (1967), Cochrane and Hyndman (1970) and Caner (1970, 1971) contributed to the description of some of the salient features of the electrical structure of the region, using classical G.D.S. methods and small linear arrays of magnetometers. These discoveries were extended through the development of the magnetometer array techniques outlined in section 2. The results discussed below are derived mainly from the array studies.

Three large arrays were used, in successive years, to cover the continent west of 100°W but excluding the coastal region, and between the United States–Mexico border and the Trans-Canada Highway. Fig.4 gives a schematic representation of the results. East of the front ranges of the Rocky Mountains the crust and mantle are in general resistive (except at the Central Plains crustal anomaly: see section 3.4). In the western region high conductivities prevail in general. The conductive structures are assigned to the upper mantle, partly on evidence of small phase differences between normal and anomalous fields at substorm periods, partly because of excellent correlation between high conductivity and high heat flow (Sass et al., 1971) and, at the latitude of the Colorado Plateau, because the anomalies due to the Wasatch front and Southern Rockies conductive ridges persist in the daily variation fields (Reitzel et al., 1970). Variation in the density of stippling is used, in Fig.4, to attempt to show something of the conductive fine structure.

It is convenient to consider first the southern half of the mapped area (the Southern Region). The mantle below the Colorado Plateau is nearly or fully as resistive as that below the Great Plains, and probably this holds for the Middle Rockies and Wyoming Basin. Low heat flows prevail along a north–south strip through these provinces (Sass et al., 1971, fig.4). Under the Southern Rockies a conductive ridge runs from Wyoming to Mexico: Schmucker (1964) discovered the Rio Grande anomaly on this ridge near the Mexican border. A second ridge on the conductive mantle runs along the boundary between the Basin and Range Province and the Colorado Plateau, under the Wasatch fault belt, which shows large vertical displacements. Finally the Basin and Range Province shows high conductivity in the upper mantle everywhere. Heat flow is high everywhere in this province (Sass et al., 1971) except in south central Nevada where disturbance by groundwater flow is believed to be present. Along a section through Colorado, Utah and Nevada, at 38°N, normalized anomalous fields of substorms are well fitted by induction in two-dimensional structures on the surface of a conductive mantle, with a ridge on this surface under the Southern Rockies and a step with a ridge on it at the Wasatch front. The excellent lateral resolution of a magnetometer array is illustrated by Fig.4. The poor depth discrimination is illustrated by the alternative models, for an east–west section at 38°N, given by Porath and Gough (1971) and by Porath (1971). The first model places the conductive topography in the depth range 120–350 km. The second places the topography in the depth range 27–160 km and suggests an association with the seismic low-velocity zone. The model of Porath is perhaps to be preferred in view of the evidence of partial melting in the seismic low-velocity layer (Hales and Doyle, 1967) and of experimental results by Presnall et al. (1972) showing a rise of two orders of magnitude in the conductivity of an artificial basalt at onset of melting.

The close correspondence of heat flow with conductivity in the southern region has been indicated. Various seismological parameters such as P_n-wave velocity, delay times in teleseismic arrivals of P- and S-waves and lateral variation of the low-velocity layer give further support to the general picture of the Basin and Range as having generally a hot upper mantle and the Colorado Plateau less so. The velocity–depth profiles of Archambeau et al. (1969) are informative. Refraction profiles, however, have limited lateral resolution because they must be several hundreds of kilometres long. Mobile seismic arrays observing teleseismic arrivals are coming into use, and will soon provide, for seismology, lateral resolution comparable with that of a magnetometer array.

The structures revealed by the 1969 array study in the northern half of Fig.4 are markedly different from those further south (Camfield et al., 1971). Whereas in the southern region the anomalous fields of the ridge structures dominate the map, only small anomalies are found at the front range of the Northern Rockies and the westward attenuation of the normal Z-field is the main effect distinguishing the region west of the front range from that to the east. This attenuation is limited to periods less than 100 minutes in substorm fields and does not affect daily variation fields at all (Camfield et al., 1971). The conductive layer west of the Northern Rockies is therefore of limited thickness. Caner (1970, 1971) put forward the model of a conductive layer in the lower crust. In work still in hand, on data from the 1969 array over the period range 25 minutes to 24 hours, Camfield and the present writer find that the data are best fitted by a conductive layer 10 – 15 km thick, at a depth between 50 and 100 km, with resistive rock under it to a depth of about 350 km.

Tectonic implications can be considered more usefully when the analysis of the northern structures is complete. It seems possible that processes of underthrusting and subduction of lithosphere plates are involved in both southern and northern regions, but are on a much larger scale and involve greater complications in the south.

3.4. *Crustal anomalies*

Conductive structures in the crust give rise to numerous local anomalies in magnetic variation fields (Porath and Dziewonski, 1971). As part of a survey of crustal anomalies, these authors describe several anomalies in the United States associated with deep basins filled with sedimentary rock. In these the conduction is presumably electrolytic in saline porewater. The celebrated North German anomaly, without which the Göttingen school and a large part of the existing science of electromagnetic induction in the earth might not exist, may be caused by currents flowing in highly conducting sediments (Vozoff and Swift, 1968), though not necessarily induced there. In other cases, however, quasi-linear conductive channels in the crystalline basement rocks are involved. In these it appears probable that the conductive body contains a high concentration of some conductive mineral. In at least one case, the North American Central Plains anomaly, there is strong evidence that this is the case. These crystalline-basement crustal anomalies seem, in most or all cases, to be current concentration anomalies, and it is convenient to discuss this effect before further consideration is given to the anomalies.

A well-known quasi-linear anomaly is that near Alert in Ellesmere Island. The anomaly fields are those of a long, narrow current system which must, from the small half-width, lie at crustal depth. Attempts to model the observed fields, even to first order, in terms of induction in a two-dimensional cylindrical body were unsuccessful (Whitham and Andersen, 1965; Niblett and Whitham, 1970). Whitham and Andersen suggested that the explanation of the effects might require consideration of induction over a wide area, with current distortion by local conductive structure. Dyck and Garland (1969) gave more precise formulation to the concept of a current concentration anomaly. The anomalous fields are those of currents concentrated in a body of high conductivity which joins large, undefined regions of the earth in which the induction occurs. The anomaly is an induction effect, but the induction is not local, in the current channel itself. This concept accounts qualitatively for much larger amplitudes and for quite different phase relationships than those expected in two-dimensional induction models. Quantitative modelling of the channelling conductor, if this proves possible, may have to be based on perturbation of a current field rather than on two-dimensional induction models. The normal field near the anomaly will, in general, not be appropriate for normalizing the anomalous fields. The problem is a difficult one. Present knowledge suggests that in the crust, current concentration anomalies are the rule rather than the exception. While quantitative description of the conductor may prove difficult or impossible, this does not mean that observational study of these features is useless. One can locate the conductor laterally with high precision, and an upper limit can be set to the depth, on the limiting hypothesis of a line current. Comparable returns of information are often accepted as justifying laborious and expensive gravity and static-field magnetic surveys. A question of geophysical interest is how far the induction-current systems in these crustal current-concentration anomalies are confined to the upper crust; put differently, how important is the *conductive* linkage to the mantle?

Other prominent crustal anomalies involving current concentration are the British anomaly, the North American Central Plains anomaly and the Ukrainian anomaly.

The conductor responsible for the British anomaly crosses the island at its narrowest part, in southern Scotland. Edwards et al. (1971) discuss several possibilities regarding the geological identity of the local conductor, and the reader is referred to their paper. The induction regions they believe to be the North and Irish Sea. This is one case in which the region of induction can be plausibly defined.

The North American Central Plains anomaly (Fig. 5) runs northward from the Black Hills of South Dakota. Very high conductivity is required in the crustal body, and in describing the anomaly Camfield et al. (1971) suggested that graphite schist might be involved. Independent work by other geophysical and geological methods led Lidiak (1971) to map a metamorphic belt in the basement under the sedimentary cover, in exact coincidence with the magnetic variation anomaly of Fig. 5, leaving little doubt that a metamorphic zone containing graphite schists provides the conductor (Gough and Camfield, 1972). Since metamorphic rocks sometimes contain ore minerals, it is possible that some current concentration anomalies in the basement rocks will be found to have economic significance. The writer and Camfield are working on the daily-variation anomaly of this feature, which appears to indicate a change from D to Z as the main inducing component as the period increases.

The Ukrainian shield anomaly reported by Rokityanskiy et al. (1969) appears also to be of current concentration type, as it shares with the Central Plains anomaly the property of having anomalous fields larger than the normal field.

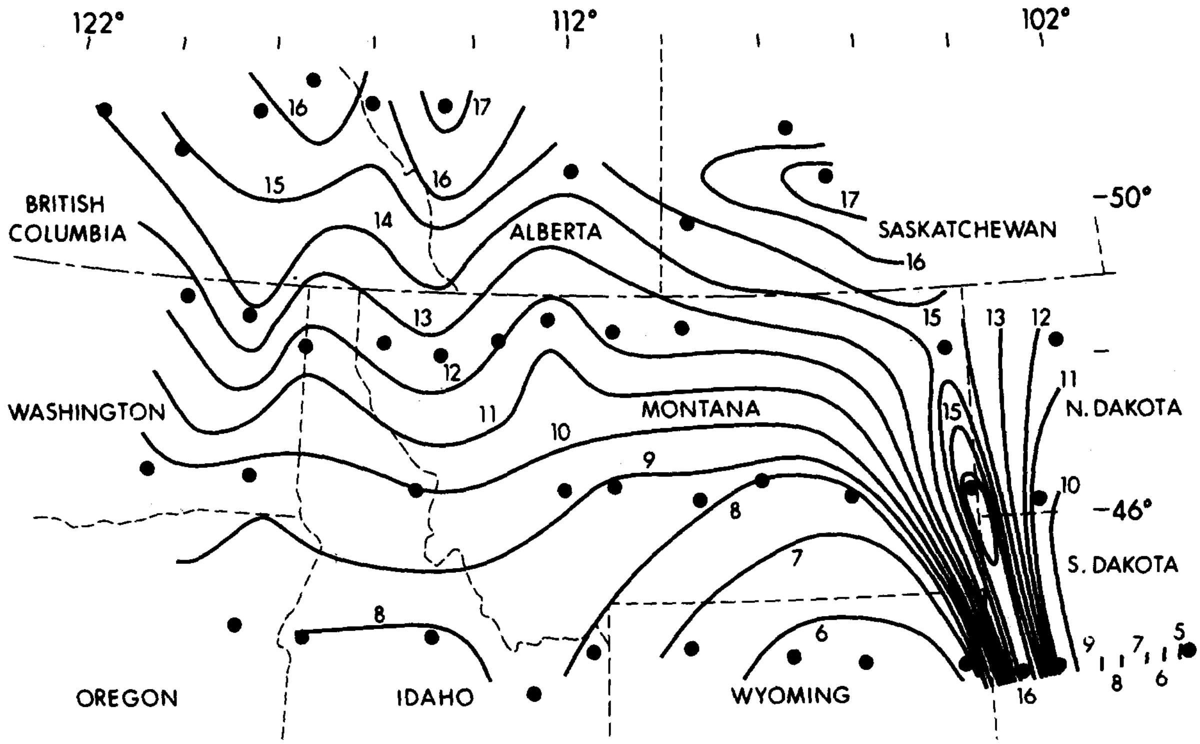

Fig. 5. The Fourier-transform amplitude (in arbitrary units) at $T = 48$ minutes for the eastward horizontal component of a substorm on August 20, 1969. Dots indicate magnetometers. The North American Central Plains anomaly is the elongated feature on the right.

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