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A Magnetometer Array Study Across Southern Victoria and the Bass Strait Area, Australia

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Summary

A second magnetometer array study in south-east Australia has clarified anomalous effects discovered earlier, and revealed a linear conductor striking south-west–north-east under or nearby the Otway Ranges. The anomalous effects are most strongly present in variation fields of period about one hour, but persist to the longer periods of the quiet daily variation. At the shortest periods studied, of order several minutes, the anomalous effects are weak. The conductor is approximately coincidental with a zone of continental seismicity, and may be due to rock fracture and dilation or to the presence of a diapir of magma beneath the seismic zone. The existence of an upper mantle hotspot in the area has been speculated.

In interpreting the observed array data, use is made of a method for separating anomalous fields from regional fields, based on inspection of polar diagrams. The anomalous components of horizontal field are especially diagnostic, and for one station it is possible to construct special polarization ellipses for them.

This paper covers the full frequency range possible with simple variometers, from pulsation events, through substorms, to quiet days.

1. Introduction

In 1973–1974 the Australian National University conducted a magnetometer array study across southern Victoria and the Bass Strait area of Australia, overlapping and south of the 1971 array described by Bennett (1972), Lilley & Bennett (1972), and Bennett & Lilley (1974).

The sites of both array operations are shown in Fig. 1 and more information concerning the 1973–74 sites is given in Table 1. The purpose of the second array study was to clarify anomalous effects which had been discovered by the first array near the southern edge of its area of operation.

The instruments used in 1973–74 were the ANU set of 21 Gough–Reitzel magnetic variometers, newly constructed and tested as described by Lilley *et al.* (1975). Installation sites were at country airstrips, and servicing runs were made by light aircraft. The sites were occupied from October 1973 to April 1974, this period comprising two recording periods of three weeks each during which readings were taken at 10-s

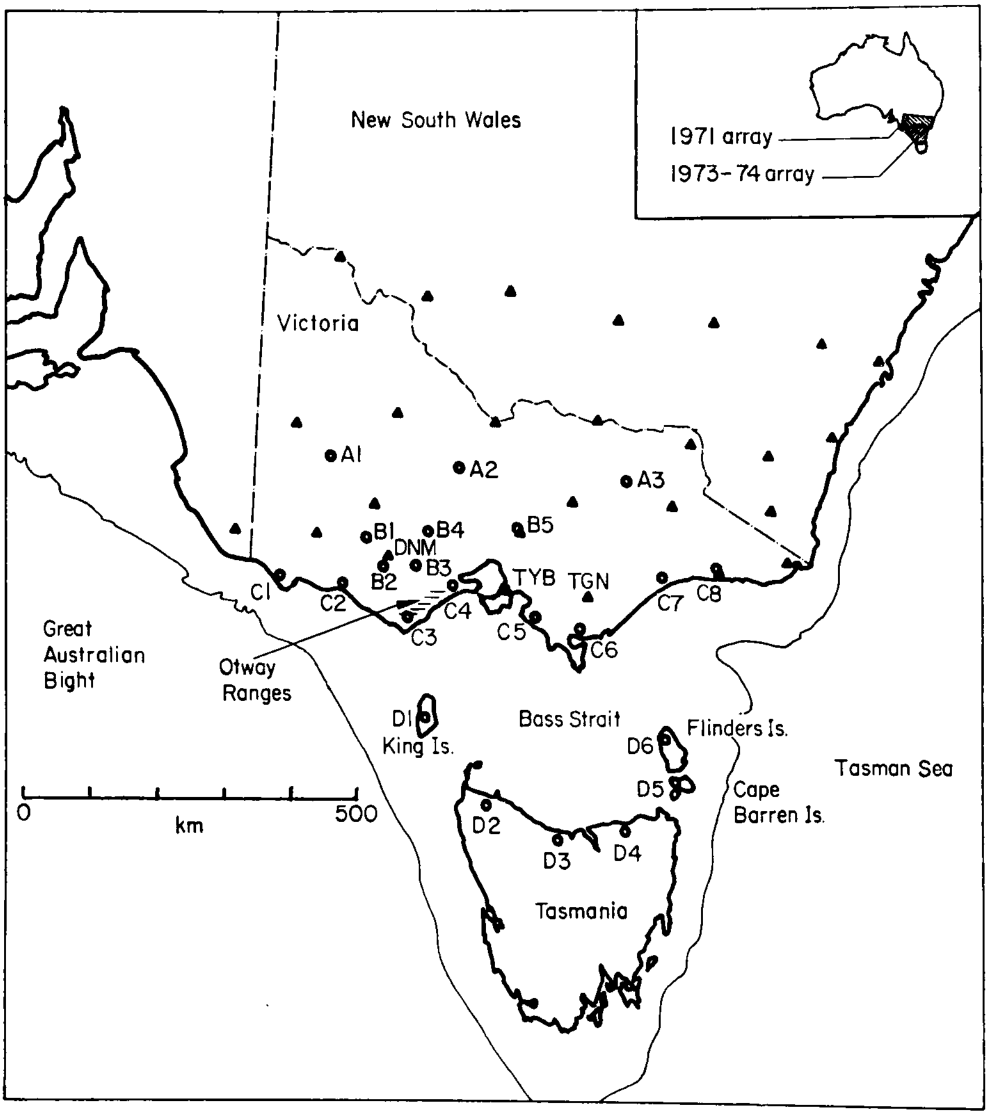

FIG. 1. Map of south-east Australia; ▲, sites of 1971 stations; o, sites of 1973–74 stations.

intervals, one recording period of 8 weeks at 60-s intervals, and a final period of 8 weeks at 30-s intervals. A great variety of natural magnetic variation events were recorded.

2. Data

2.1 *Simple vertical-field response arrows*

Using the basic film records from the instruments, arrows which show the response in the vertical field to variations in the local horizontal field have been constructed for all stations of the array. The method used is that of Wiese (1962), in which plots are

Table 1

Observing sites, 1973–74 *array*

Code	Station	Abbreviation	Latitude	Longitude
A1	Horsham	HRM	36° 40′ S	142° 10′ E
A2	Bendigo	BND	36 45	144 19
A3	Bright	BGT	36 43	146 54
B1	Lake Bolac	LBC	37 41	142 53
B2	Kurweeton	KTN	38 05	143 08
B3	Cressy	CSY	38 03	143 39
B4	Ballarat	BLT	37 31	143 47
B5	Toolangi	TLG	37 33	145 29
C1	Portland	PLD	38 23	141 37
C2	Warrnambool	WBL	38 17	142 26
C3	Apollo Bay	APB	38 46	143 38
C4	Grovedale	GRV	38 13	144 19
C5	Wonthaggi	WGI	38 37	145 34
C6	Welshpool	WPL	38 41	146 26
C7	Bairnsdale	BRN	37 53	147 33
C8	Orbost	ORB	37 47	148 36
D1	Currie	CRR	39 53	143 53
D2	Smithton	SMN	40 49	145 05
D3	Devonport	DPT	41 10	146 26
D4	Bridport	BPT	41 01	147 24
D5	Cape Barren Island	CBI	40 24	148 00
D6	Killiecrankie	KCK	39 50	147 52

made on a map polar diagram of $\Delta D/\Delta Z$ (plotted east) against $\Delta H/\Delta Z$ (plotted north), using simultaneous changes in the east, north and downwards field components of ΔD, ΔH and ΔZ respectively for a particular station. Given several such sets of simultaneous changes, an estimate of the in-phase response arrow for the station results, and an estimate of its error can be made from how good a straight line is defined by the $\Delta D/\Delta Z$ versus $\Delta H/\Delta Z$ plot. It is straightforward to account for different instrument sensitivities, and for inter-sensor interactions.

The arrows thus produced are given in Fig. 2, together with the in-phase arrows for nearby stations from Lilley & Bennett (1972). A disparity exists in that the newly-determined arrows (all shown with error circles) result from the examination of events in a period range of 5–20 min, whereas the Lilley and Bennett arrows shown are for period 80 min; however the patterns of the two different sets of arrows match reasonably well, and are thus something of a check on the polar plot method. Fig. 2 will be referred to again below.

2.2 *Stacked profiles*

The range of data chosen for further detailed analysis consisted of one pulsation event (of period about 2 min), five substorm events (periods of order 1 hr), and one quiet day. These events were scaled off the film records using a film reader, scalings being taken every 10 s for the pulsations, every 1, 2 or 4 min for the substorms, and every 0·5 hr for the quiet day. Such variometer data were corrected for *H-Z* sensor interaction (Lilley *et al.* 1975), normalized for different sensitivities, resolved to geographic horizontal axes (X, Y), and then re-plotted mechanically. Representative resulting stacks of variograms are shown in Fig. 3 (pulsations), Fig. 4 (a substorm), and Fig. 5 (a quiet day).

The pulsation profiles (Fig. 3) are sufficiently weak to be near the detection limit of the instruments. Lilley *et al.* (1975) give an estimate of 1·5 nT for the probable error of an individual scaled datum, and though in Fig. 3 the consistency of the X traces

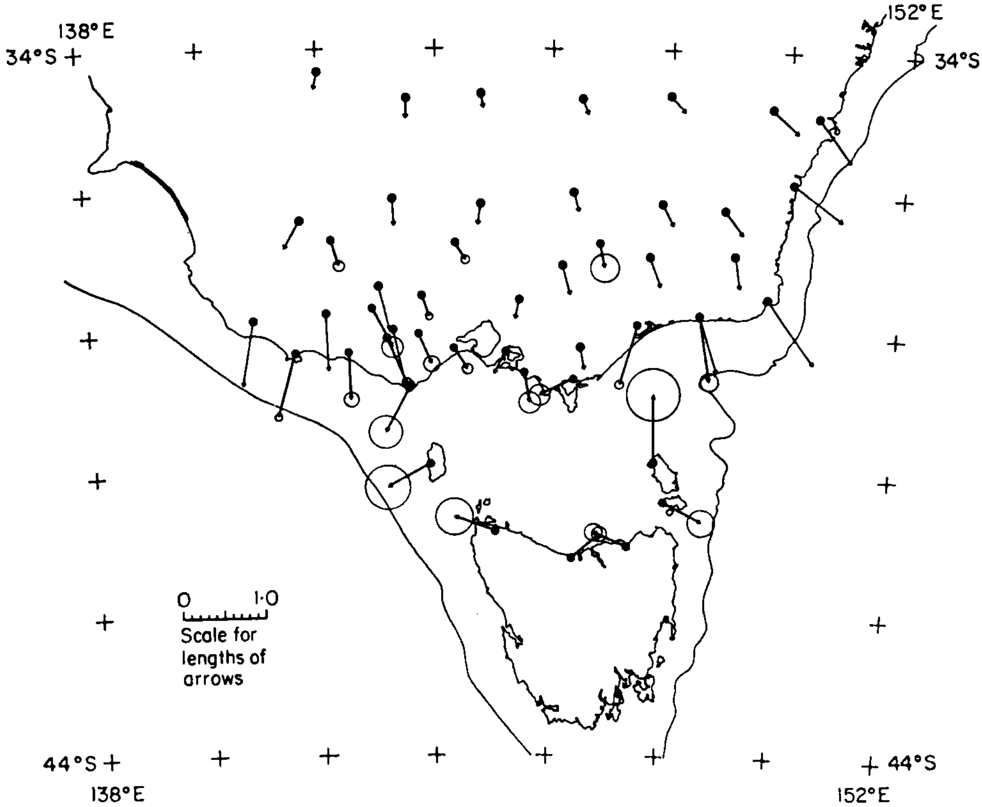

FIG. 2. In-phase vertical-field response arrows (i.e. Parkinson vectors, or induction arrows), for south-east Australia. Lighter arrows without error circles are for the 1971 stations from Lilley & Bennett (1972). Heavier arrows with error circles are for the 1973–74 stations.

implies that their error is considerably less, consistency is not evidence against systematic error such as may be present due to calibration imperfection. The stack of X variograms shows variation in amplitude from place to place, and in the Y and Z stacks the pulsations recorded vary considerably, with Z-reversals evident across the Bass Strait.

The substorm profiles (Fig. 4) indicate much in the enhanced horizontal variations at C3, and the enhanced vertical variations at B1, B2, C1, and C2. They also show sea-water effects, especially at stations on the D-line.

The quiet-day profiles (Fig. 5) show slightly enhanced X and Y signals at C3; they are, however, perhaps most remarkable for their generally featureless Z fields. Because such long-period variations are commonly expected to have substantial regional Z components this is at first sight surprising; however as shown by Bennett & Lilley (1973) for the 1971 daily-variation data, the weak Z fields are consistent with destructive interference occurring between a substantial regional Z component (which is indeed present), and a widespread anomalous Z component caused by the coast-effect of south-east Australia and the adjoining Tasman Sea.

2.3 *Transformation to the frequency domain*

For further analysis the variograms have been transformed to the frequency

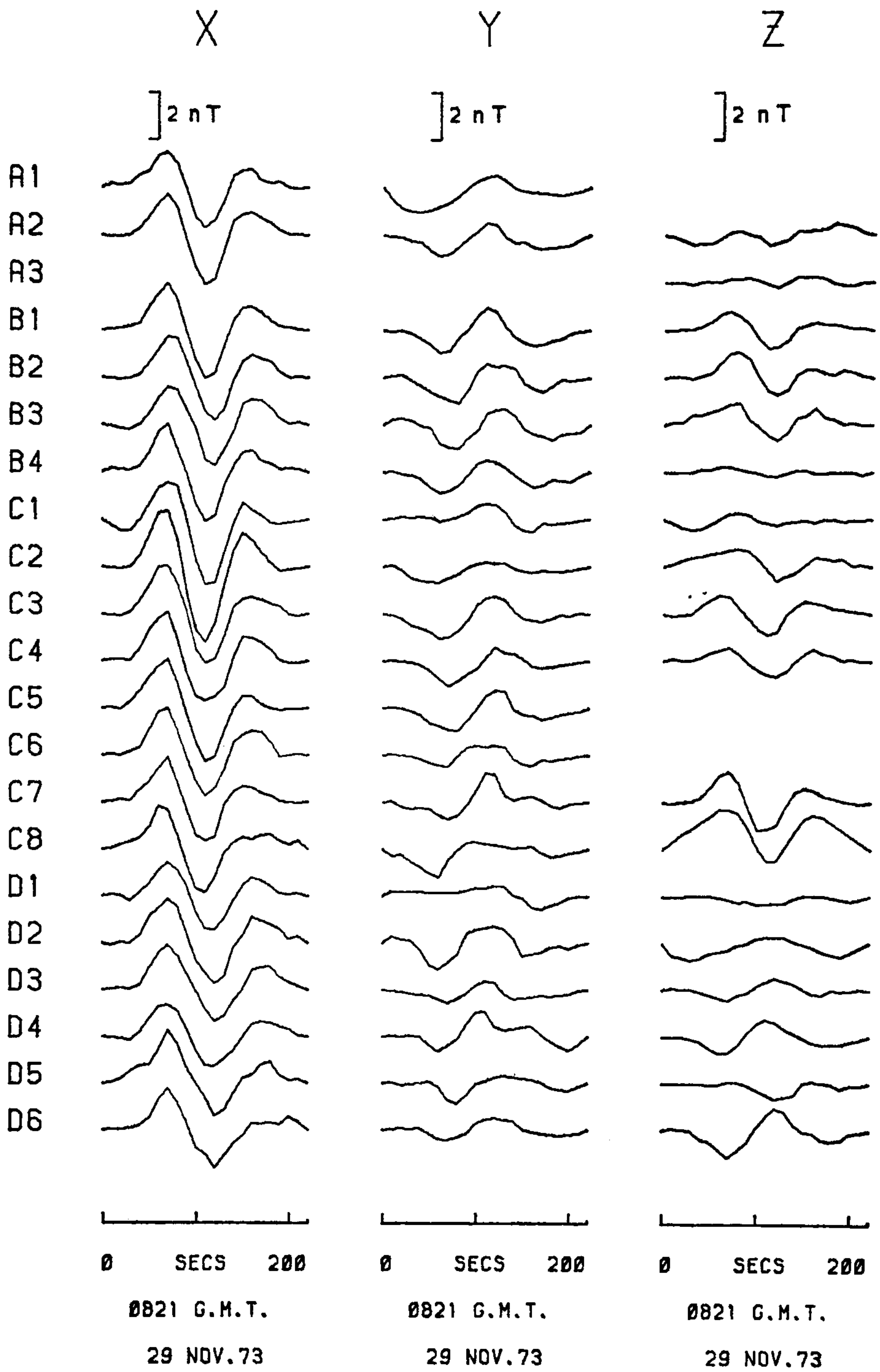

FIG. 3. A pulsation event of several minutes duration recorded by the 1973–74 array. Linear trends between the first and last points of each profile have been subtracted before the plotting of this figure.

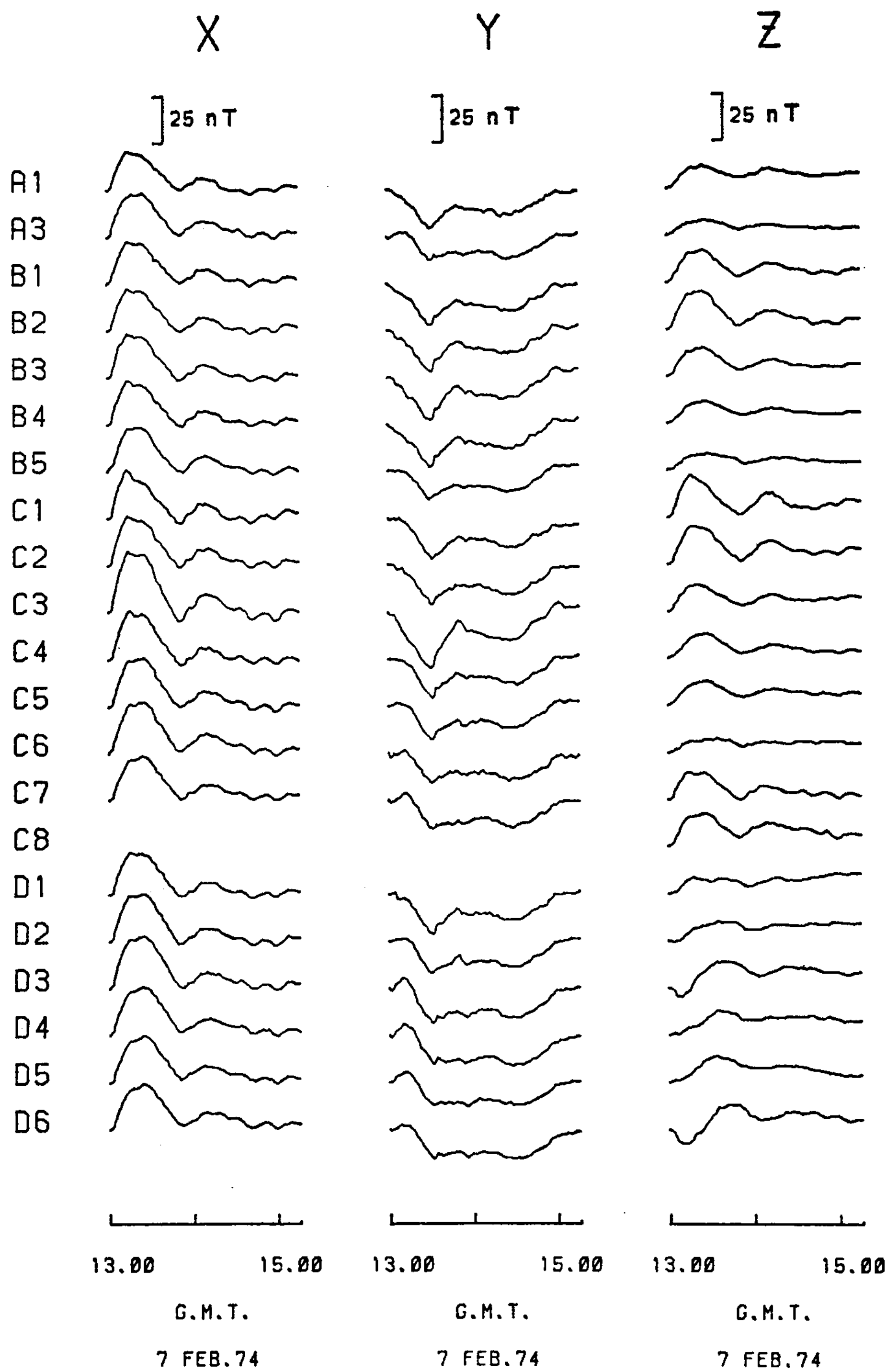

FIG. 4. A sub-storm event of 2-hr duration recorded by the 1973–74 array.

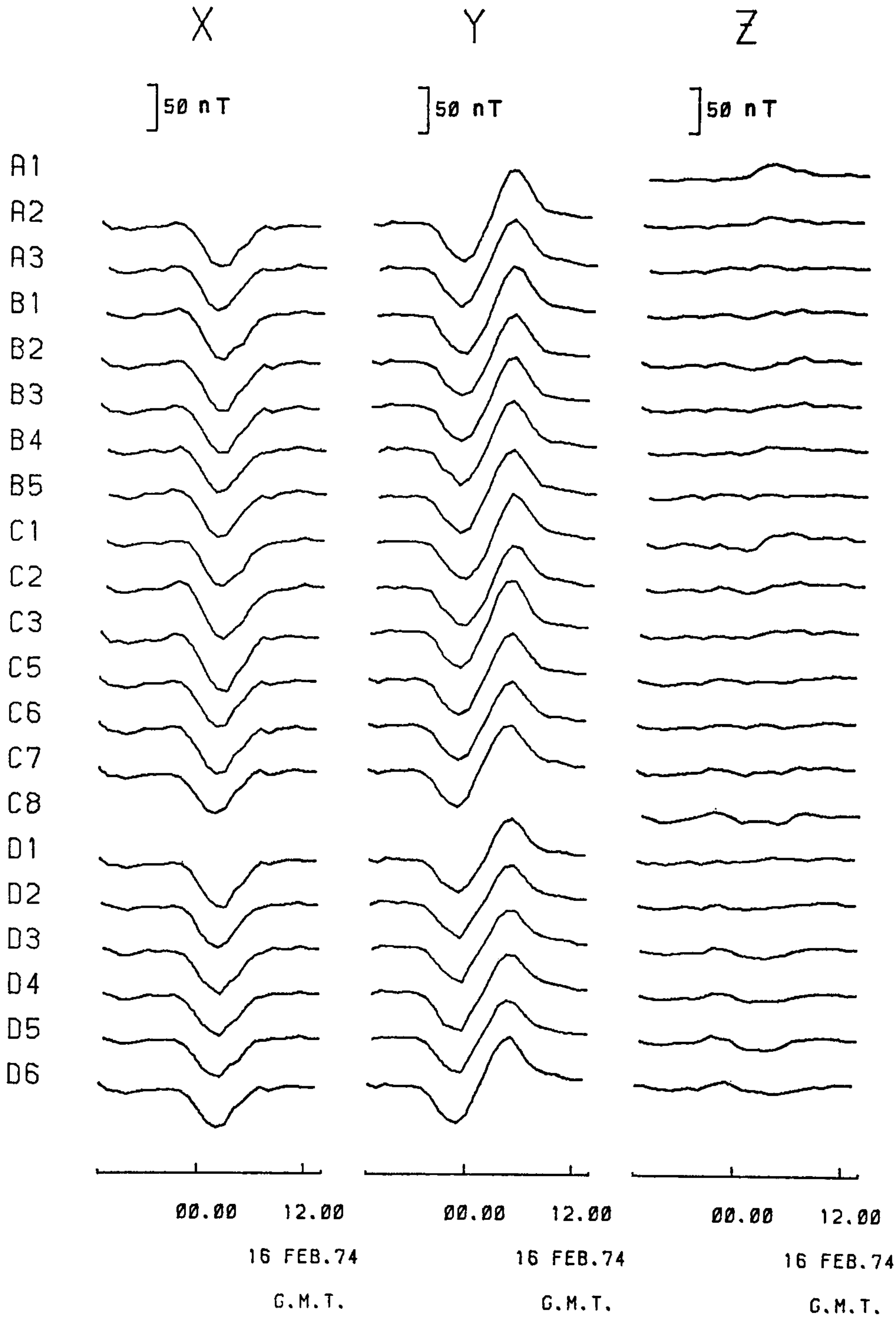

FIG. 5. A quiet day recorded by the 1973–74 array.

domain, estimates being made of the Fourier transform of each event according to the formula

$$g(\omega) = \int_{-\infty}^{\infty} f(t)\, e^{-i\omega t}\, dt$$

with any trend existing between the first and last points of a variogram being subtracted linearly first. As discussed by Lilley & Bennett (1972), the validity of such spectral estimates at all frequencies depends on the event being recorded complete, so that the signal of the event in question is indeed zero over all time up to the start of the variogram, and zero again after the end of the variogram. The pulsation and substorm events were chosen for the clarity of their starts and ends, and a justification of such a procedure for an individual quiet day is given by Lilley (1975a). Resulting Fourier transform values have units of the form nT-minutes (equivalent to nT/radian/minute). Phases given in this paper are phase lags according to the convention that an event occurring at a later real time has a more positive phase. All times referred to in this paper are GMT.

3. Maps of amplitude and phase

From such transformed data many sets of maps have been drawn. The method of Reitzel *et al.* (1970) has been followed, so that each set shows the distribution across the array area of a particular frequency component of a particular event. As previously, the horizontal polarization ellipse (Lilley & Bennett 1972) is found to hold crucial information for the interpretation of such data maps.

Representative sets of maps are shown in Figs 6–9, together with their ellipses of horizontal polarization plotted between the X and Y amplitudes and phases. Polar plots of the same data are also given on the right-hand sides of the figures, and some of these are used in Section 4 below.

3.1 *Substorm event, south-east–north-west polarization, Fig.* 6

This set of maps is typical of many with similar horizontal polarizations constructed for different (substorm) periods, and forms the most important basis of the interpretation to follow. The polarization is such as to emphasize the anomaly found in south-west Victoria by the 1971 array, and to reduce the coast effect due to the boundary between continent and deep ocean on the western side of the array area.

The dominant feature of all such maps at substorm periods with south-east–north-west polarization is the strong horizontal fields above station C3, and the offset enhancement of vertical fields to the north-west; in some cases there is also reduction of the vertical component to the south-east at station D1. The existence of the Victorian anomaly detected by the earlier array is thus confirmed, and to localize it more within the state of Victoria it will henceforth be referred to as the Otway anomaly, as it occurs near or under the Otway Ranges.

The vertical-field response arrows of Fig. 2 (which could have been obtained by single-station operation) show some of the features of the Otway anomaly now evident on Fig. 6, but only those features due to anomalous vertical fields rather than to anomalous horizontal fields. The strongest features of Fig. 6 are in fact the anomalous horizontal fields, the mapping of which can result only from array operation.

Further information, especially about the anomalous conductivity structure near station C3, results from estimates separating regional from locally-anomalous fields, to be made in Section 4.

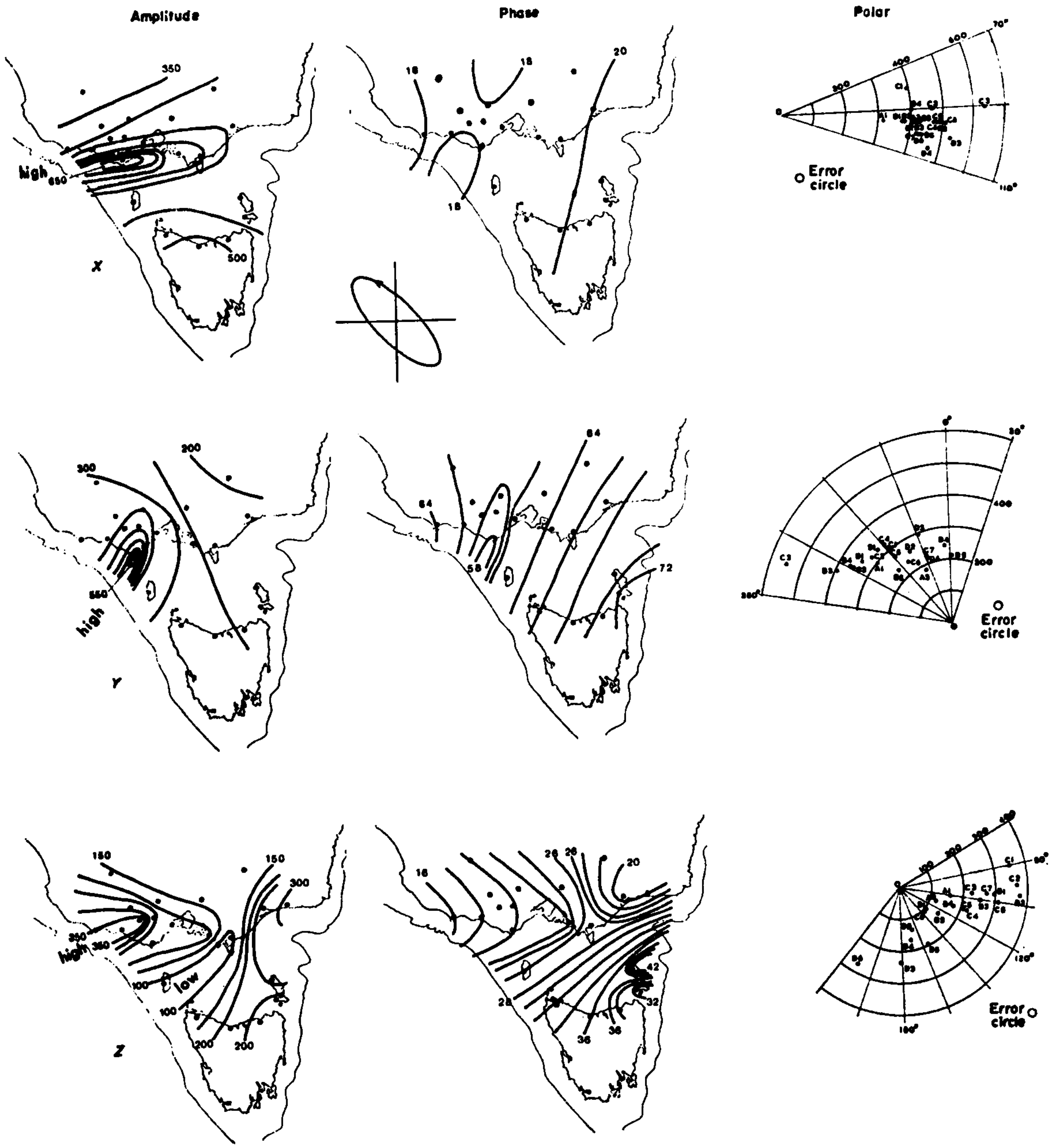

FIG. 6. Data for period 72 min obtained by transforming the array observations of the substorm event of 1974 February 7. Amplitude units are nT-min. Phase units are min.

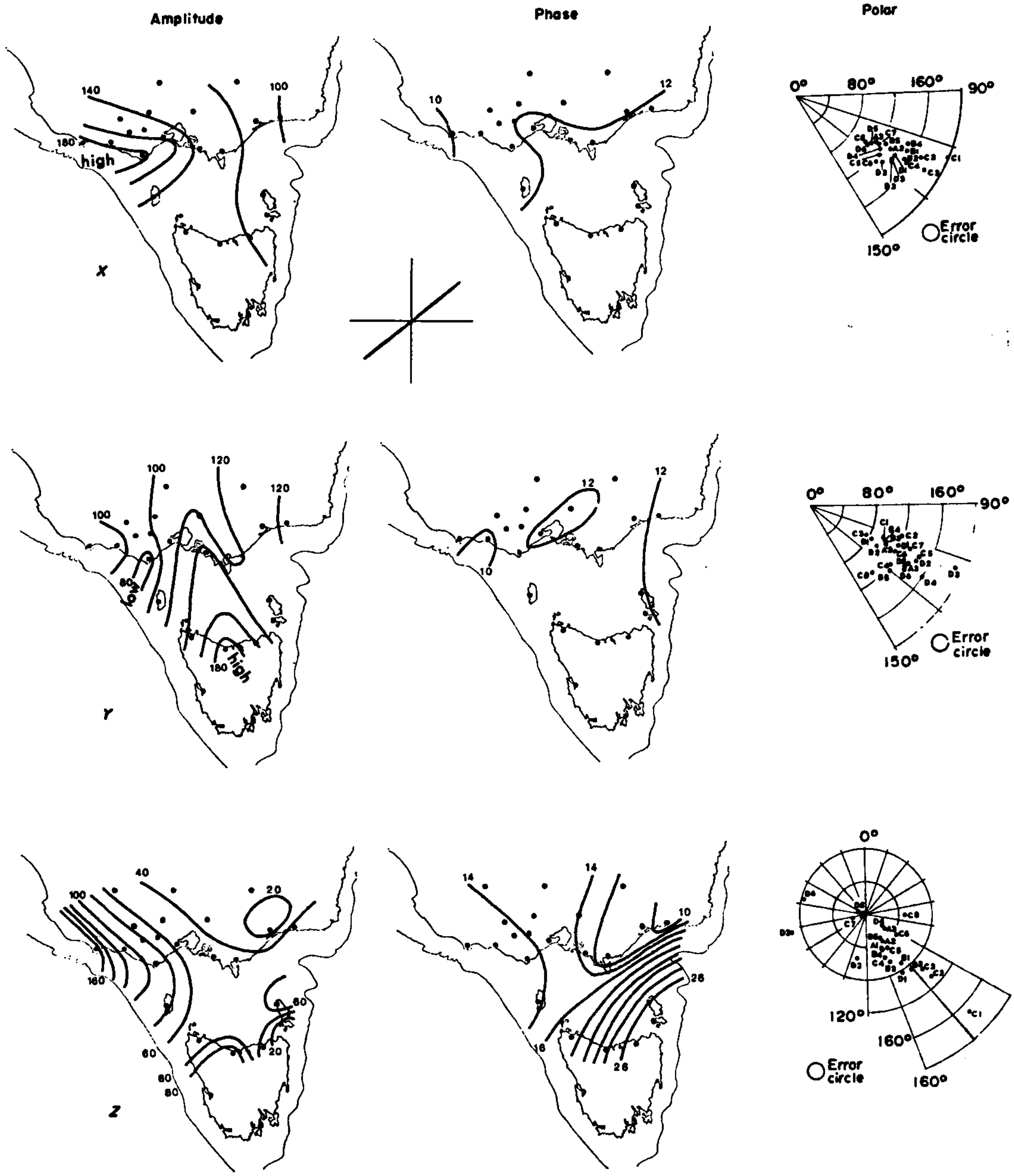

FIG. 7. Data for period 34 min obtained by transforming the array observations of the substorm event of 1974 February 8. Amplitude units are nT-min. Phase units are min.

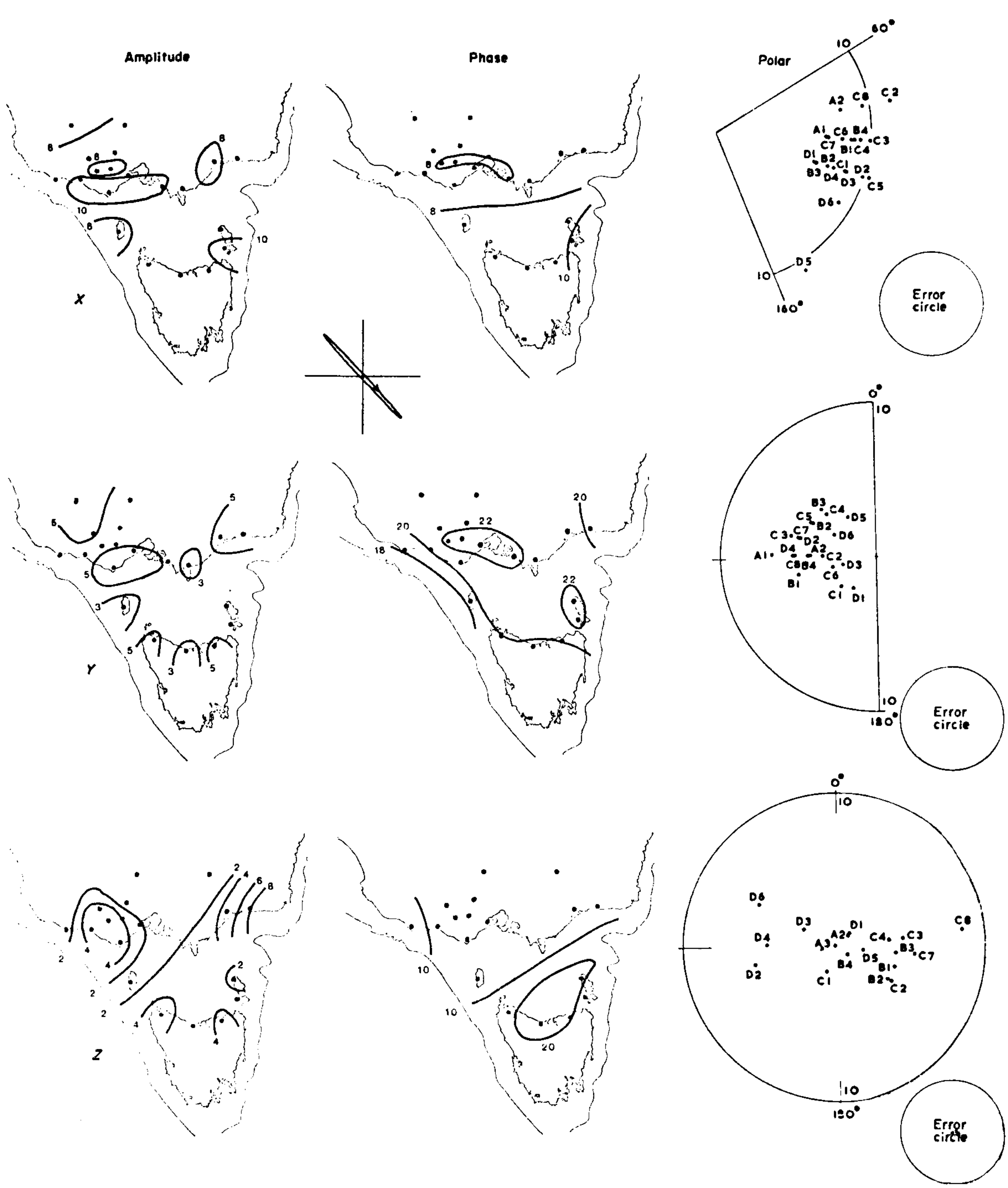

FIG. 8. Data for period 2·7 min obtained by transforming the array observations of the pulsation event of 1973 November 29. Amplitude units are tens of nT-sec. Phase units are tenths of minutes.

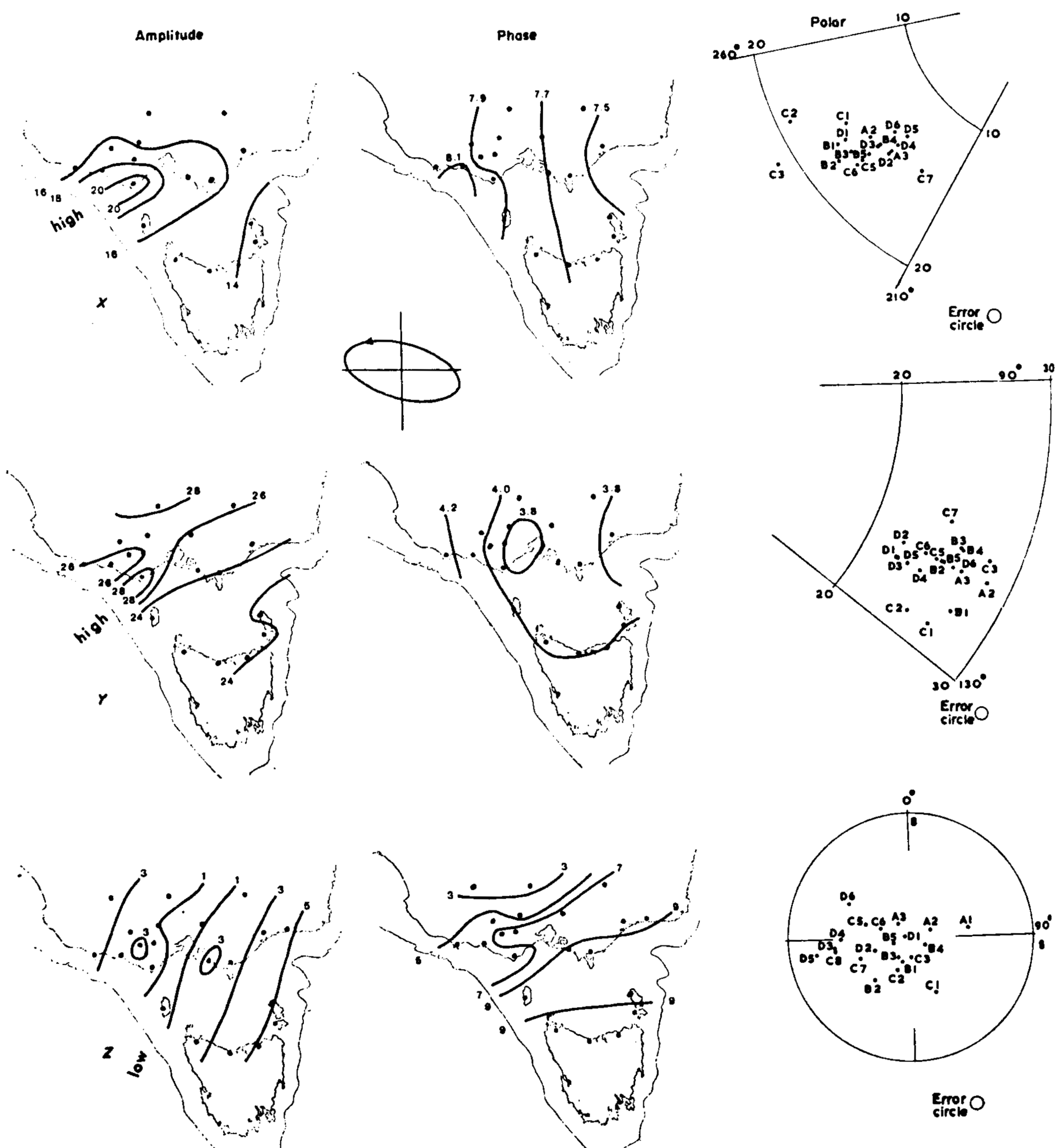

FIG. 9. Data for period 12 hr obtained by transforming the array observations of the quiet day of 1974 February 15–16. Amplitude units are tens of nT-hr. Phase units are hr.

3.2 *Substorm event, south-west–north-east polarization, Fig.* 7

This set of maps is for a horizontal polarization almost at right-angles to the polarization of Fig. 6. The polarization ellipse (in this case near linear) thus lies approximately along the strike of the Otway anomaly; it is therefore consistent that the Otway anomaly is much less evident in this set of maps. The polarization is such as to now produce instead a strong coast effect on the western side of the array, which is evident in the Z-amplitude maps. There is still some disturbance of the horizontal components near station C3, with a high in the X-amplitude and a low in the Y-amplitude. These characteristics will be explained by a regional-anomalous separation in Section 4.

3.3 *Pulsation event, Fig.* 8

The polarization ellipse is approximately south-east–north-west, appropriate to emphasize the Otway anomaly. The large uncertainty of all the data points, resulting from the low amplitude of the pulsation signal, restricts the detail that can be interpreted from Fig. 8.

In all the maps there is a suggestion of anomaly around the stations C3 and C4, but it is not strong. In fact this short-period event appears to show mainly the effect of the shallow Bass Strait seawater, and possible small local anomalies. The station spacing has been too sparse in some places for full confidence that short-period variations over the array area have been fully monitored.

3.4 *Quiet-day variation, Fig.* 9

The quiet-day variation maps, Fig. 9, match quite well with those of Bennett & Lilley (1973) for the 1971 array. The ellipses of horizontal polarization are similar, and though the 1974 quiet day examined occurred in February while the 1971 data were from April, it seems likely that the source fields were approximately the same. Thus the large-scale pattern in the Z field of Fig. 9 is well explained by the interference of a coast effect with a regional Z distribution, as given by Bennett & Lilley (1973).

Fig. 9 also shows distinctly anomalous horizontal fields above station C3. The Otway anomaly is thus observed also at the long periods of the daily variation.

4. Separation of regional and anomalous horizontal fields at station C3

For several of the data sets at substorm periods such as plotted in Figs 6 and 7, separations of regional and anomalous field components have been attempted, as proposed by Lilley (1975a) for quiet daily variations. Thus Fig. 10(a) shows polar plots of the horizontal-field data for stations A1 and C3 for the event of Fig. 6. Inspection of the comprehensive plots on the right-hand side of Fig. 6 shows C3 to be clearly anomalous and on the basis of taking A1 to represent the regional field, (it is the station most removed from both the coasts and the Otway anomaly), a regional-anomalous separation can be carried out, as shown. Fig. 10(b) shows the same exercise for the data of Fig. 7 using stations C3 and A2, (station A1 having been out of operation at that time).

The estimates of anomalous fields thus obtained may be studied in several ways. In addition to a polarization ellipse for the total horizontal variation field, as plotted with the data maps in Figs 6–9, it is now possible for a strongly anomalous station like C3 to construct separate polarization ellipses for the regional and anomalous horizontal components. This is done on the right-hand side of Fig. 10(a) and (b). A significant feature in the present examples is the linearity of the anomalous ellipses for station C3, which results from the anomalous X and Y fields being of the same

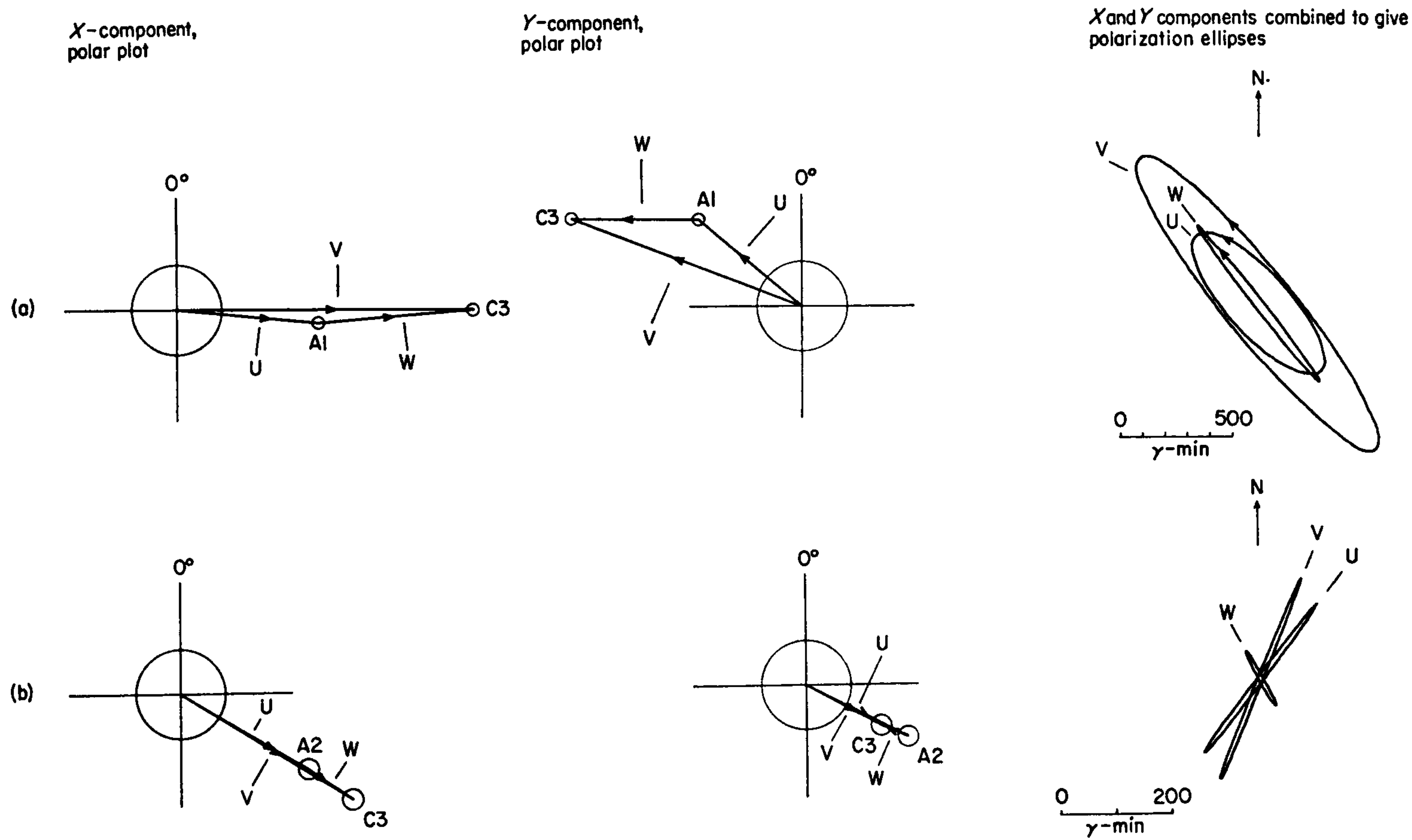

FIG. 10. Separation of anomalous and regional components of horizontal field for station C3. ' u ': field as observed at station A1 (or station A2), taken to be the regional field .' v ': field as observed at station C3, taken to be the regional field plus an anomalous contribution. ' w ': an estimate of the anomalous field at station C3, obtained as the result of subtracting **u** from v. (a) Event of 1974 February 7, period 72 min, (data from Fig. 6). Circles in the *X* and *Y* polar plots are of radius 100 nT-min. (b) Event of 1974 February 8, period 34 min, (data from Fig. 7). Circles in the *X* and *Y* polar plots are of radius 40 nT-min.

phase, (or more precisely being exactly $\frac{1}{2}$ cycle out of phase). This is shown graphically by the pairs of w vectors being antiparallel in Fig. 10(a) and (b).

The anomalous horizontal fields at station C3 have been found in fact to be approximately linear and bearing south-east–north-west for all events thus separated, a result only easily explained in terms of current flow in a linear conductor beneath (or near) station C3. The conductor could be straight or curved, but near station C3 it must be striking about south-west–north-east. Inspection of Fig. 10(b) shows that such quite straightforward current flow will sometimes produce anomalous fields which interfere destructively with the regional fields, to produce amplitude 'lows' like that in the Y-field at station C3 in Fig. 7.

5. Physical interpretation

5.1 *Position of the Otway anomaly*

The data consistently indicate that C3 is the station most nearly above the Otway anomaly. This conclusion, coming largely from anomalous horizontal field data, indicates that the main body of good conductor is indeed south-east from the 1971 station of DNM as concluded by Bennett (1972) and Bennett & Lilley (1974); it is perhaps some 20–30 km further south-east than as placed in their 1974 paper, and it is correspondingly rather stronger than had been surmised. The Otway anomaly is most sensitive to variation fields polarized south-east–north-west, and the previous section presented evidence that the electrical conductivity structure associated with it is of width narrow relative to length, and near station C3 is striking approximately south-west–north-east.

This is a first-order interpretation. Second-order effects have also been observed, and include sometimes considerable differences in the amplitudes recorded at stations B2 and B3, showing that complex local geoelectric structure is present in addition to the first-order model described.

5.2 *Regional effect of the Bass Strait*

Lilley & Bennett (1972) observed a consistent enhancement of X in the central southern stations of the 1971 array especially at TYB and TGN. This enhancement was thought to be a large-scale effect, distinct from what is now called the Otway anomaly, and possibly due either to the electrical conductivity structure of the whole Bass Strait, or to the Tasmanian continental-shelf peninsula jutting into the southern ocean. To explore the effect further, variometers in 1973–74 were placed along the north and south coasts of the Bass Strait and on some intermediate islands.

Inspection of the 1973–74 data now shows the effect to be localized in southern Victoria, with little evidence that it continues across the Bass Strait. Maps of X amplitude like that in Fig. 6 indeed appear to indicate that the effect is an extension of the Otway anomaly.

5.3 *Bass Strait Island measurements*

The data from the Bass Strait Island stations D1, D5 and D6, would be suitable for the study of island effects in shallow water, (the Bass Strait is less than 200 m deep). Such an analysis is not attempted here, except to comment that at medium (substorm) periods (see Figs 6 and 7), induction effects in the shallow water do not appear to perturb the horizontal regional field patterns at all. At the short period of the pulsations (Fig. 8), the Bass Strait may be affecting both the horizontal and vertical variations, whereas at the long periods of the daily variation (Fig. 9), the Bass Strait does not appear to perturb any of the regional fields. Fig. 9 is thus interesting as it appears to indicate that the Bass Strait channels negligible electric current at daily variation periods.

Returning to the substorm periods (Figs 6 and 7) there are some curious effects near stations D3, D5 and D6, but the density of array stations has not been sufficient to map these reliably; in this region the array has operated essentially as a set of single observatories.

5·4 *Depths to the Otway conductor*

Within the limits of the station spacing, the horizontal position of the Otway anomaly has been quite well determined, (as is characteristic in magnetometer array studies), and certain conclusions have been reached about the linearity and strike of the conductor (or conductors) with which it is associated. Less satisfactory is the estimation of depth to the anomalous zone. The observations upon which depth-estimation may be based are as follows:

(i) In Fig. 6 station B2 has the maximum Z response recorded, and station C3 has the maximum X and Y responses, so that an estimate of the half-width of the anomaly is given by the distances B2 to C3, approximately 75 km. Other sites in the neighbourhood of C3 might record even stronger anomalous horizontal fields, but the maximum could not be much further south-east due to the control of station D1 on King Island.

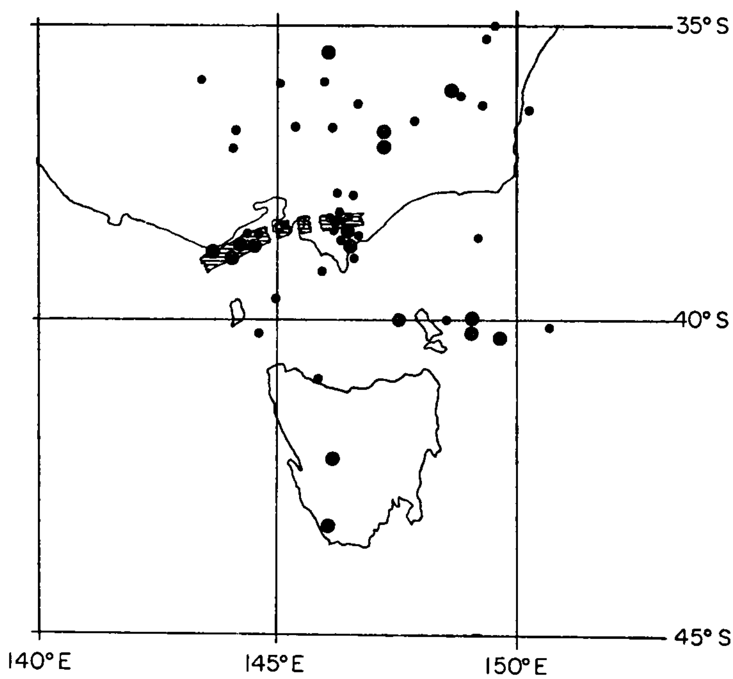

FIG. 11. Earthquake activity in south-east Australia (after Denham *et al.* 1975) with a conductor for the interpretation of the Otway anomaly superimposed. ●, earthquake magnitude between 5 and 6; •, earthquake magnitude less than 5. There is no special significance in the indicated width of the conductor, which is poorly resolved. Due to the difficulty in showing clearly on the diagram two or more earthquakes which have occurred very close to each other, the positions of some earthquakes have been varied from the source reference, sufficiently for each to show as a distinct dot on the map.

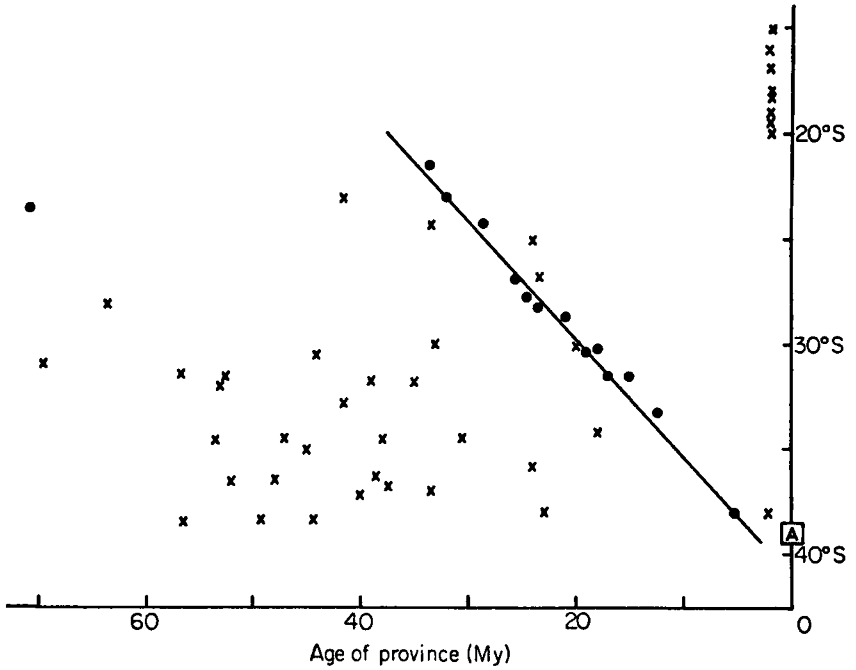

FIG. 12. The Otway anomaly plotted as an ' A ' at its present latitude and time, on data for Cainozoic igenous activity in eastern Australia from Wellman & McDougall (1974). x, lava field province; ●, central volcano province. The trend line demonstrates the southern progression with time of the central volcano provinces.

Interpreting such a half-width in terms of a simple line current would place it at depth of order 75 km below station C3. However the same anomaly half-width would also be given by wider bodies which were more shallow, or by vertical dyke-like bodies with upper and lower edges in a whole range of depths.

(ii) The frequency dependence of the Otway anomaly is such that it is strongest at periods of order 1 hr, it persists to periods of order 1 day, but it is weak at periods of order 1 min.

Schmucker (1970) gives, for a reasonable continental earth model, attenuation depths of order 450 km, 160 km and 40 km for fluctuations of periods 12 hr, 1 hr and 6 min respectively. An attenuation depth of order 30 km might thus be expected for fluctuations of period 2·7 min. An interpretation of the frequency dependence of the Otway anomaly is then that the depth of the conductors causing it is such that the pulsations of Fig. 8 are mostly attenuated before they reach it; i.e. the depth is greater than order 30 km, so that the conductor is in the lower crust or upper mantle. The observed half width of 75 km of the anomaly would be consistent with this interpretation based on frequency characteristics. The present interpretation is complicated, however, by the proximity of both a shallow sea (the Bass Strait) and a deep ocean (the Great Australian Bight). In sea water the attenuation depths are considerably less, and the Otway anomaly occurs near a continent–ocean boundary. The conductive bodies may therefore be more shallow than 30 km, though the weakness of the anomaly at pulsation periods and its strength at daily variation periods are taken as evidence against the anomalous conductors being as shallow as the upper crust.

6. Geological interpretation

6.1 *Coincidence with seismic zones*

The position of the Otway anomaly, as determined from the 1973–74 array data, coincides with a zone of seismic activity as observed over the last century in south-east Australia. This coincidence is demonstrated in Fig. 11, where the model conductor which has been drafted onto the map of continental seismicity is consistent with the physical interpretation of the Otway anomaly given in preceding sections of this paper. As the author has noted (Lilley 1975b), this marks the third coincidence of electrical conductivity anomalies with continental seismicity in Australia, and similar coincidences have been found in eastern Canada (Bailey *et al.* 1974), southern Africa (de Beer, Gough & van Zijl 1975), and certain other places as reviewed by Garland (1975). Such coincidences might have no geophysical significance, or they could reflect a general result that both electrical conductivity anomalies and earthquakes tend to occur in tectonically active areas. In the present instance it seems reasonable to examine possible causal relationships more carefully. There appear to be three:

(i) The fracturing and dilation associated with seismic activity in the crust may have increased the electrical conductivity of the active region by causing an increase of water content and conducting paths along water channels.

(ii) Beneath the seismic zone of mechanical fracturing, motion along fault planes presumably still occurs by some sort of ductile flow. A region undergoing ductile flow may exhibit increased electrical conductivity due to fabric modification and due to the heating the ductile flow process must involve.

(iii) The earthquake activity may be caused by some process involving the intrusion into the lithosphere of a diapir which, being molten or partially molten, would have greatly increased electrical conductivity.

6.2 *Magma-source hypothesis of Wellman and McDougall*

Wellman & McDougall (1974), in reporting on Cainozoic igneous activity in Australia, distinguish on geochemical grounds between ' lava field provinces ' and ' central volcano provinces ', and show the latter to have displayed a remarkable southern progression with time down the eastern side of the Australian continent, at a rate (66 ± 5 mm/year) consistent with that determined for the separation of Australia and Antarctica from independent marine magnetic data (50–74 mm/year, Weissel & Hayes 1971). The Wellman & McDougall data is reproduced in Fig. 12. The position of the Otway anomaly is also given, (that is, its approximate latitude is plotted against the present time), and it is seen to conform with the trend discerned by Wellman & McDougall.

While highly speculative, the possibility is thus established that the Otway anomaly is an expression of the Cainozoic central volcano magma-source.

7. Conclusions

The essential conclusion of this paper is the more accurate delineation of the southern Victorian anomaly, now called the Otway anomaly. It coincides with a zone of seismicity, and may be linked to this directly if mechanical effects have increased rock conductivity, or indirectly if both conductivity anomaly and seismicity are caused by a zone of weakness in the lithosphere in which partially molten magmas are present. The weakness may be the result of failure under continent-wide stress patterns, or more speculatively, due to the migration of the Australian continent over an asthenospheric ' hot spot ' hypothesized as the origin of the eastern Australian ' central volcanoes '.

Local effects are present in the western part of the area covered by the 1973–74 array study, but the major Otway anomaly does not appear to underlie the lava field provinces of western Victoria; (the lava fields appear geochemically distinct from the central volcanoes). This lack of coincidence is resolved by a model in which the lavas have risen up fairly narrow fissures direct from a widespread and approximately 'one-dimensional' layer of partial melt in the asthenosphere, (identified with the low-velocity zone). To cause an effect on geomagnetic variations like the Otway anomaly, a magma chamber would have to be limited in horizontal extent, and so be 'two-' or 'three-dimensional'. Such a model would not be unreasonable for diapirs arising from the (southerly-progressing?) magma source of the central volcanoes.

8. Miscellaneous notes

The following notes may be made generally upon the experience of the 1973–74 array exercise and its interpretation:

(i) Polarization ellipses of anomalous horizontal field, as obtained in Section 4, promise to offer powerful discrimination between alternatives of interpretation in certain cases. For example, the problem posed by Gough, Lilley & McElhinny (1972) of distinguishing between a single-curved conductor and two crossed conductors should be resolved by examining such ellipses. For the curved conductor the anomalous horizontal polarization ellipse would be expected to be always of very high ellipticity and of fixed azimuth, independent of the regional horizontal field. The model of two crossed conductors should in contrast produce a whole variety of anomalous horizontal polarization ellipses, dependent on the regional horizontal field.

(ii) Strong and easily separable anomalous horizontal fields suggest the formation of some response arrow based upon the anomalous horizontal ($\Delta B_A = [\Delta X_A^2 + \Delta Y_A^2]^{\frac{1}{2}}$) and anomalous vertical (ΔZ_A) components only; say $|\Delta Z_A/\Delta B_A|$ plotted on a map in the direction of ΔB_A for ΔZ_A negative, and in the direction of $-\Delta B_A$ for ΔZ_A positive. Such arrows would then point towards current channelling conductors, independent of the effect (Lilley & Bennett 1973) which may cause aberration in traditional response arrows if the distant regional field (causing the current channelling) differs from the local field (upon which estimation of a traditional response arrow is based).

Another possibility would be to scale the arrow with length arctan ($|\Delta B_A/\Delta Z_A|$). This scaling would have the advantage of giving the arrow maximum length directly above a conductor.

A possibly rewarding exercise if anomalous horizontal components have been separated for many stations would also be to plot directly onto a map their respective polarization ellipses of anomalous horizontal field.

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