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# Geomagnetic Induction in Central Australia

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A magnetometer array study in central Australia has revealed a large area over which the vertical-field response-arrows at substorm periods point consistently towards an electrical conductivity anomaly in south-west Queensland. For this area of smooth vertical-field response, estimates of the electrical conductivity profile in the earth have been made by analysis of two magnetically quiet days, using horizontal gradients of the quiet daily variation as measured across the array area. A simple "substitute conductor" method has been used to invert the data. The results indicate that beneath this part of the continent the electrical conductivity is of order 0.1 to 1.0 S m$^{-1}$ at a depth of order 300 to 400 km, confirming the more general results of global analyses, which use data from more widely-separated observatories.

## 1. Introduction

In 1976 a magnetometer array study was carried out in central Australia by the Australian National University using the ANU set of 21 Gough-Reitzel magnetic variometers (described by Lilley *et al.*, 1975). The instruments were installed by road and light aircraft at the sites shown in Fig. 1 and were operated simultaneously during the months of July, August, and September, with readings taken initially every 10 seconds and later every 60 seconds. The operation was part of a plan of basic electromagnetic exploration of the Australian continent, and in particular it sought any possible northern extension of the "Flinders conductor" found in southern Australia by the 1970 magnetometer array study reported by Gough *et al.* (1974).

A reversal of the vertical field fluctuations (characteristic of a linear conductivity anomaly) was located in the extreme south-east corner of the array area and in 1977 a subsequent array study was carried out in this region with the instruments more closely spaced in order to delineate the reversal in detail. This paper, however, presents and interprets only the 1976 data, with particular attention to regional induction away from the anomalous zone. Discussion of the anomaly itself will be left to a subsequent paper, which will also present the observations and interpretations of the 1977 array.

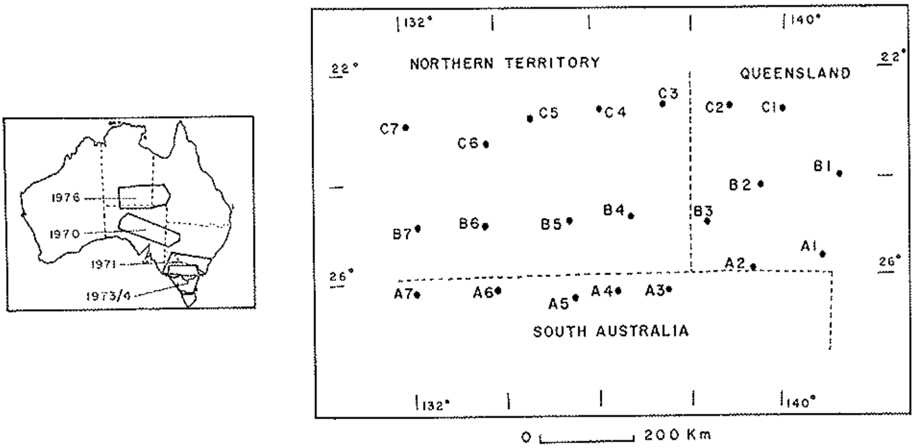

Fig. 1. Map of the central Australia 1976 magnetometer array and its location in Australia with respect to previous array studies.

The strategy to be followed in the present paper is that substorm data, with predominantly anomalous vertical magnetic field fluctuations, will be used to select an area remote from (in fact to the west of) the anomalous current flow in the ground. This western area will then be investigated using daily variation data, the vertical field fluctuations of which are affected less by anomalous current flow and more by source-field non-uniformity over local one-dimensional conductivity structure in the earth.

## 2. Data and Spectral Analysis

Of the variety of magnetic events recorded by the 1976 array, a range of the most simple, including quiet daily variation, has been chosen for analysis. Simplicity in event morphology is desired for the reason that Fourier transforms of simple isolated events can be computed under the assumption that the events are recorded complete, with negligible truncation. The special case of analysing individual quiet days is discussed by Lilley (1975). The Fourier transform spectra of such simple smooth events are then simple and smooth themselves. Figure 2 presents the array records (reduced and normalized) for a substorm event, and Fig. 3 similarly presents records for two consecutive quiet days. Fourier transforms have been computed according to

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

where $t$ and $\omega$ represent time and angular frequency, and $f(t)$ is an observed signal and $g(\omega)$ its Fourier transform. Phases quoted in this paper are phase

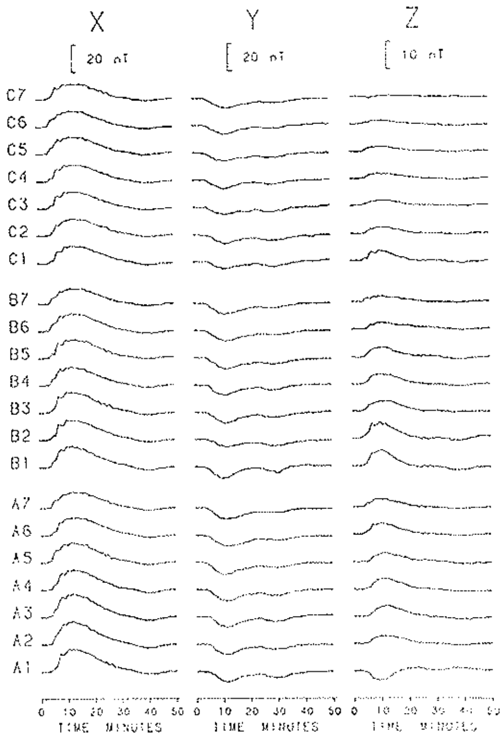

Fig. 2. Stacked profiles of a substorm event commencing at 1245 UT (2145 local time) on 5 August 1976.

lags, in that shifting a waveform to a later real time will uniformly increase the phase values of all Fourier transform components.

## 3. Response Arrows and Their Interpretation

Arrows summarizing the in-phase and quadrature response of the vertical field component $Z$ to substorm fluctuations occurring in the horizontal field components $X$ and $Y$ have been computed for each station by fitting observed data to the usual equation

$$Z = AX + BY \tag{1}$$

where all quantities are complex (see SCHMUCKER, 1964; EVERETT and HYNDMAN, 1967; LILLEY and BENNETT, 1973; for discussion of this relationship). The frequency-dependent constants $A$ and $B$ depend on geoelectrical conductivity structure, and $X$, $Y$, and $Z$ are the Fourier transform values of a particular fluctuation event at a particular frequency. In principle, only two different

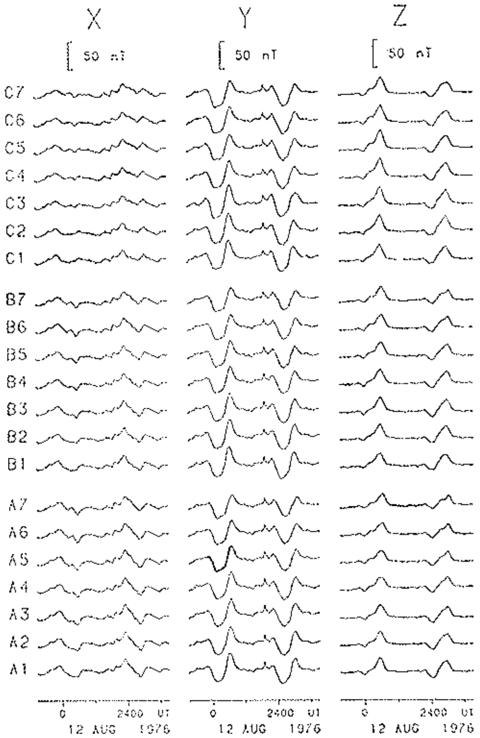

Fig. 3. Stacked profiles of two consecutive quiet days commencing at 1500 UT (2400 local time) on 11 August 1976.

data sets are needed to determine $A$ and $B$; in practice more than two sets are usually used so that the best-fitting $A$ and $B$ values are estimated from an over-determined system.

Following Parkinson (1962), $A$ and $B$ values are traditionally presented as arrows for the stations involved, plotting the $A$-component south and the $B$-component west so that an arrow points towards the higher conductivity side of an electrical conductivity contrast. The in-phase and quadrature $A$ and $B$ values for the 1976 array at the substorm period of 50 minutes are thus presented in Fig. 4. Essentially similar arrow patterns were obtained from the magnetic substorm events taken singly and neglecting the frequency dependence of $A$ and $B$. In this case the several sets of data needed to solve Eq. (1) were taken from the Fourier spectra of a single event over a small frequency range in which the horizontal polarization varies. Initially, the same in-phase arrow pattern had been obtained by direct graphical reduction of the data from analogue form following Wiese's (1962) method.

Figure 4, particularly in the in-phase diagram, shows one antiparallel arrow

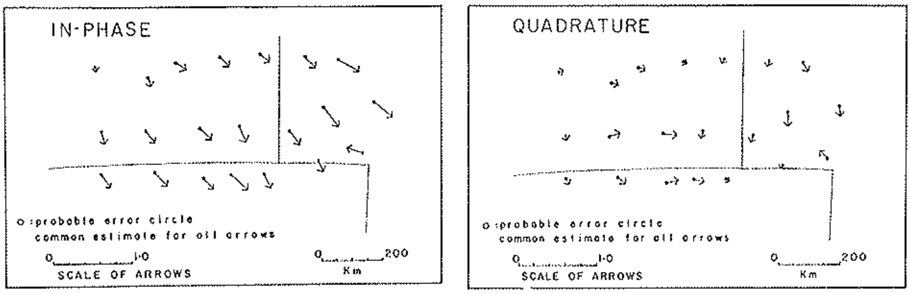

Fig. 4. In-phase (real) and quadrature (imaginary) vertical-field response arrows for central Australia at a period of approximately 50 min.

in the south-east of the array, consistent with the reversed $Z$-record for station A1 in Fig. 2. Over the rest of the array area the response arrows point consistently towards the internal current causing the reversal, with some reduction in amplitude with increasing distance to the north-west. This uniformity of response is taken as evidence that a large area of the array is in fact free from any major horizontal conductivity contrasts, and may thus be suitable for one-dimensional conductivity estimates in which conductivity varies with depth only.

## 4. Horizontal Layering Interpretation

The method followed is that of Schmucker (1970), Kuckes (1973), and Lilley and Sloane (1976) where a parameter $c$, which depends on the horizontally-layered conductivity structure and the frequency and length scale of the magnetic fluctuations, is estimated by means of the equation

$$c = Z/(\partial X/\partial x + \partial Y/\partial y) \qquad (2)$$

where $x$ and $y$ are coordinates of geographic position, north and east respectively. Note that a single station allows an estimate of $Z$, but that a number of stations are needed to give estimates of the spatial derivatives $\partial X/\partial x$ and $\partial Y/\partial y$, and in particular a large array allows the choice of an area where a one-dimensional conductivity structure appears to be most closely approximated. In the present instance, the western half of the array is chosen as such an area.

Data fitted to Eq. (2) for the purposes of determining $c$ values must themselves show the characteristics of having occurred over horizontal layering: this is not so for the substorm data, the vertical fields of which, as discussed in an Appendix below, are dominated by anomalous magnetic effects even away from the zone of anomalous current flow. For the quiet daily variations, however, the vertical components appear to be predominantly due to non-uniform

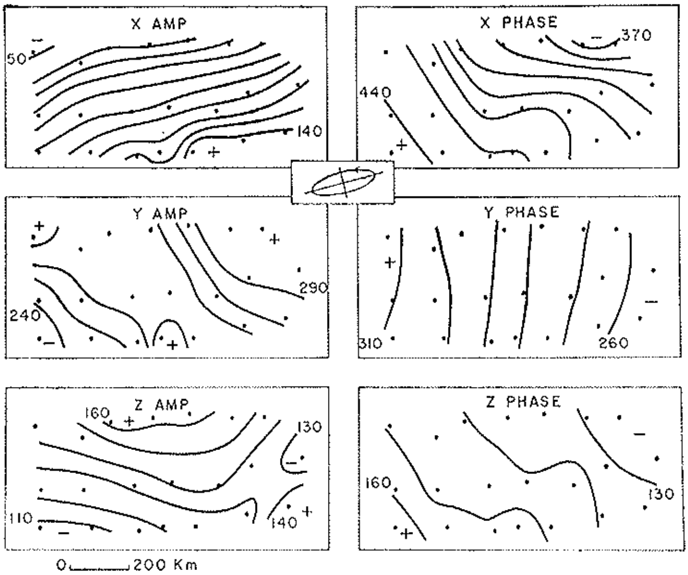

Fig. 5. Fourier transform amplitude and phase maps for the two consecutive quiet days in Fig. 3 at a period of 12 hr. Amplitude units are in nT-hr and phase units are in minutes of time.

structure in the source fields rather than non-uniform structure in the earth. Inspection of the Fourier transform maps for period 12 hr shown in Fig. 5 demonstrates a near-ideal behaviour of the daily-variation field: for any given latitude, the phase advances westward with approximately local solar time, and the strongest amplitude patterns have contours approximately along lines of equal latitude.

Proceeding then with Fourier transform values for the two quiet days of Fig. 3, computations have been carried out at the common periods for daily variation analysis: 24, 12, 8, 6, and 4 hr. For a particular period, in order to have smoothed values of $\partial X/\partial x$, $\partial Y/\partial y$, and $Z$ for use in Eq. (2), simple surfaces have been fitted to the $X$, $Y$, and $Z$ fields over the western half of the array area. The form of the surfaces used is

$$F(x, y)=a_1+a_2x+a_3y+a_4x^2+a_5xy+a_6y^2$$

and as two surfaces are needed to fit the cosine transform and sine transform fields for each component, six surfaces are thus fitted at each period investigated.

Once the surface fits have been carried out and the various coefficients $a_i$ determined, the complex parameter $c$ appropriate to the period in question can be estimated immediately using Eq. (2). The value of $c$ obtained will depend upon the $(x, y)$ position at which the estimation is made, so that computing $c$

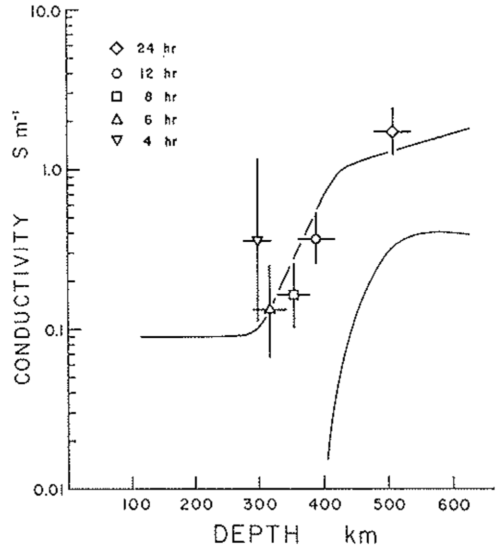

Fig. 6. Plot of conductivity versus depth for the quiet daily variation data in Fig. 3 at periods of 24, 12, 8, 6, and 4 hr. Line profiles represent the upper and lower limit of BANKS (1969) "best-fitting" model.

over an area will give a range of $c$ numbers. In the present work, the average values of $c$ in the west half of the array area have been carried through to produce points on Fig. 6. The ranges in value have also been carried through and plotted as bars on the figure.

The real and imaginary parts of a $c$ estimate can be represented directly as a depth value and a conductivity value, using the "substitute conductor" model of SCHMUCKER (1970, p. 68), who shows that for an electrical conductivity profile increasing with depth such a simple inversion method may indeed be usefully accurate. Specifically, for a particular period, the real part of $c$ is interpreted as a depth value, and the imaginary part is interpreted as a "half skin-depth" at that depth, which taking the period into account gives a conductivity value.

The $c$-values determined by analysis of the two quiet days are thus interpreted to give the conductivity-depth points plotted in Fig. 6. An electrical conductivity profile for a part of the mantle is thus obtained from some basic and local magnetic variation measurements.

## 5. Conclusions

The profile in Fig. 6 represents a preliminary deep electrical conductivity profile for central Australia. The values presented lie in a satisfactory manner close to the "global" profiles of Parker (1970) and Banks (1972). The present instance is one of few cases to date in which global results for these depths can be corroborated by local geomagnetic induction results. The high conductivity value at depth of order 300 km, if substantiated, could have profound significance for the electrical state of the Australian upper mantle, but it remains very tentative unless completely cleared of the possibility of being a spurious function of some peculiar aspect of the data. Its similarity with a feature of the Larsen (1975) profile for the Hawaiian Islands might be noted, at the same time remembering the quite disparate geological settings of the Hawaiian Islands and central Australia.

The present exercise has supported the conclusion of Lilley and Sloane (1976) that for continents in mid-latitudes the quiet daily-variation source fields may prove suitable for local geomagnetic depth-sounding, where local is used in the sense of continental as opposed to global. The horizontal length-scale of most magnetometer arrays is several hundred km, which appropriately matches the vertical depth of penetration of the magnetic daily variation into the earth.

With further refinement in smoothing techniques and inversion procedures the analysis of daily variations using magnetometer arrays may enable detailed comparison of the deep electrical conductivity between different continents, and between different tectonic blocks of the same continent.

Many people in central Australia offered help and hospitality during the array observations, particularly the owners and managers of homesteads at which the field operations were based. Our light aircraft pilots, Brian Smith and Jan Styles, enabled a regular array to be set up across the Simpson Desert by establishing landing strips on desert clay pans and other remote places. Merren Sloane assisted with the instrument preparation, data reduction, and drafting of figures. One of us (D.V.W.) is the recipient of an ANU Research Scholarship. The encouragement of A.L. Hales and M.W. McElhinny in the project and the assistance of R.S. Anderssen with the computing is much appreciated. P.A. Camfield is thanked for critically reviewing the manuscript.

## Appendix. A Note on Separating Anomalous Conductivity Effects and Source-Field Effects

Equation (1) in the preceding paper has been fitted by the data of substorm fields, and carries the connotation that the vertical fluctuation component is predominantly due to anomalous induction in the ground and not due to source-field effects. Equation (2), however, has been used for daily variation fields in the western half of the array area, with the connotation that for these events the vertical fluctuation fields and horizontal field gradients are predominantly due to source-field structure, occurring over a horizontally layered earth.

In some circumstances it might in principle be possible to separate the two effects of anomalous geoelectric structure and source-field structure by fitting observed data to an empirical combination of Eqs. (1) and (2), such as

$$Z = AX + BY + c(\partial X/\partial x + \partial Y/\partial y) \tag{3}$$

Equation (3) was thus tried with the data of this paper, but the substorm events produced merely $A$ and $B$ values consistent with those obtained using Eq. (1) above, and $c$-values ill-determined and scattered. This result is taken as further indication that the overhead substorm source-fields are near uniform, so that the observed vertical fluctuations and horizontal fluctuation gradients are due predominantly to anomalous geoelectric structure.

By contrast the daily variation data, when fitted to Eq. (3) by taking the two days as separate events, produced $c$-values similar to those obtained with Eq. (2) alone, and $A$ and $B$ values ill-determined and widely scattered. This result is taken as some confirmation of the deduction made above that for the daily variation data in question, the dominant cause of vertical fluctuations and horizontal fluctuation gradients is the greater non-uniformity of the overhead source field.

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