MAGNETOMETER ARRAY STUDIES

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Abstract. A review of experiments in which arrays of recording magnetometers deployed over an area of land to study induction problems is presented. Intensive array activities take place on a continual basis in North America, Australia, Scotland and Africa and array studies have been conducted in India, Scandinavia, and Russia. The main results are summarised. Analysis, presentation and interpretation of array data have also enjoyed significant developments which are discussed with illustrations. The use of multi-techniques in the analysis of array data has improved the reliability of the interpretational inferences. One-dimensional conductivity profiles can now be deduced by the simple inversion of the inductive response function $C(w, t)$ estimated from the vertical field Z and spatial gradient of the horizontal field components $(\partial X/\partial x + \partial Y/\partial y)$ of magnetometer array data with large gradient. Bounds can be placed on accepted profiles using the Monte Carlo process just as it is done in magnetotelluric data inversion. The results from array studies continue to improve our understanding of the synthesis of realistic tectonic models of the continents. The structure under some geothermal zones are now known through a number of recent studies.

1. Introduction

In recent years, magnetometer array studies have enjoyed widespread popularity among earth-scientists who are interested in the Earth's interior and its relation to geological features observed on the Earth's surface and the space physicists seeking information regarding electric currents in the ionosphere or beyond it, in the magnetosphere. We are concerned here with magnetometer array experiments conducted for the purpose of studying the Earth's inner structures and processes.

A magnetometer array consists of a number of recording magnetometers operated simultaneously along a profile to form a *linear array* or over a two-dimensional area to form a *two-dimensional array*. In a linear array, a set of magnetometers (ten or less in number) are operated simultaneously along a line transverse to the conductive body being studied. The effectiveness of magnetometer study depends very much on the number of instruments used. J. Bartels in Germany and T. Rikitake in Japan and their colleagues in the early 1950's pioneered the use of magnetometer arrays in mapping lateral variations in the subsurface conductivity distribution (Meyer, 1951; Rikitake, *et al.*, 1952; Bartels, 1954). Schmucker (1964), and later Caner *et al.*, (1967) employed linear arrays to locate some conductive anomalies in the mid-western United States. In two-dimensional arrays from twenty to over forty magnetometers are usually arranged along two or more lines perpendicular to the strike of the suspected conductive structures. The optimum spacing depends on the type of anomaly being investigated.

A flurry of activity in two-dimensional array experiments was generated by the introduction of the inexpensive torque-type magnetometer by Gough and Reitzel (1967). It has been in a continuous state of improvement and development and has been constructed by other research groups at the University of Lancaster in United Kingdom, at the Institüt für Geophysik, Münster, Western Germany (Küpper and

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Post, 1981); at the Australian National University (ANU) Australia (Lilley, 1975a); at the National Physical Research Laboratories in South Africa; in South America by Aldrich and co-workers. A number of small arrays have been run using electronics recording magnetometers (fluxgate magnetometers) owned by government agencies such as the Earth Physics Branch of the Canadian Department of Energy, Mines and Resources.

Schmucker (1964) classified conductive anomalies into three classes as follows:

(1) surface anomalies which may be due to saline water in the first few kilometers of the porous rocks.

(2) intermediate anomalies which can penetrate through the conductive surface layer of the earth.

(3) deep anomalies associated with thermal states and/or melting effect in the upper mantle.

In recent years several studies have discussed a fourth class of anomaly which is due to the concentration and channelling of currents from a large area elsewhere through a long narrow conductor under the area of a magnetometer array. This type of anomaly has been reported in almost all regions of the world through array studies and was extensively discussed in the review by Jones (1982a).

Geomagnetic depth sounding (GDS) is the method of investigating electrical conductivity structures using the three orthogonal components X (true north), Y (true east) and Z (downward vertical) of the time-varying geomagnetic field. Depending on the nation where the study is carried out, GDS is referred to by some other descriptive names such as 'magneto-variational sounding or profiling' and 'geomagnetic variation method'. GDS often refers to observations from a set of single stations or a small number of magnetometers that may form a linear array. The methods of analysis and interpretation of GDS data are in many respects similar to those for multi-station array data. This review will be confined to the treatment of large (two-dimensional) array data analysis, interpretation and results. The theories relevant to GDS studies have been reviewed (Rokityanski, 1975; Schmucker 1973). In reviewing GDS works, Singh (1978) at the fourth induction workshop in Murnau and Hutton (1976b) discussed results of a number of regional geomagnetic surveys with 2-demensional arrays of magnetometers.

A number of excellent review works on magnetometer array studies have appeared in the literature (Porath and Dziewonski, 1971a; Gough, 1973a; Frazer, 1974; Lilley 1975a). The present review is to supplement these with more emphasis on the recent studies and the advances made in the area of data analysis and interpretation.

2. Summary of the Worldwide Array Activities

The early days of two dimensional array activities witnessed a great volume of data and results from North America, United Kingdom, Australia, and South Africa. Most of the results have been published and have been the subject of several reviews. Through joint programmes and equipment loans, array observations have been conducted in some other regions of the world in recent years. The data from the more recent studies are still being analyzed and thus full discussions are not possible at this time. It suffices, therefore, to list in Table I the known array studies with some notes on the conductive structures mapped. The details and location maps of these arrays can be found in the references cited and in the previous reviews mentioned.

TABLE I

Summary of the Worldwide array activities

Region of Study	References	Notes
(A.) Australia		
(1) Southern Australia	(a) Gough (1972) (b) Gough *et al.* (1974)	The array operated in 1970 discovered a north-south conductor close to the Flinders Ranges.
(2) South-east Australia	(a) Lilley and Bennett (1972) (b) Bennett and Lilley (1973) (c) Bennett and Lilley (1974)	Variation field data from a 26-station array operated in 1971 reveal anomalies due to two coast lines at right angles.
(3) Southern Victoria and the Bass strait area	Lilley and Sloane (1976)	This second array of 1973/74 in the south-east Australia delineates the 'Otway' conductor.
(4) Central Australia	Woods and Lilley (1979)	The 1976 array of 21 (ANU) magnetometers at sites in Central Australia located conductivity anomalies which are associated with the conductive sedimentary rocks of the great basin.
(5) South-east	Woods and Lilley (1980)	A closely spaced array of 1977 was designed to examine the details of the anomaly discovered in the S.E. edge of the 1976 array. A current channelling conductor was mapped.
(B) New Zealand		
North Island	Bennett *et al.* (1978)	Twenty magnetometers and 5 magnetotellurics (MT) stations were operated across the central North Island geothermal zone in New Zealand. Signatures of coast effect and induced current flowing along the geothermal zones manifest in the observed variation fields.
(C) United states and Canada		
(1) Western North	Reitzel *et al.* (1970)	2-dimensional array of 42 G-R magnetometers operated in 1967 located an upper mantle conductive structure under the Rockies.

TABLE I (continued)

Region of Study	References	Notes
(2) Central United	Porath and Dziewonski (1971b)	The array of 1968 located anomalies in the Southern Great Plains (Anadarko basin, Tucumcari basin) and in the coastal plain sediments in the south and east Mexico.
(3) South-Western	Porath and Gough (1971)	The 1968 array established the continuation of the southern Rockies anomalies in the Basin and Range province.
(4) North-Western	(a) Camfield *et al.* (1971) (b) Gough and Camfield (1972)	With 46-station array of 1969, a current channelling conductor was found in the central Great Plains (i.e. the NACP Anomaly).
(5) North American Central Plains	(a) Alabi *et al.* (1975) (b) Camfield and Gough (1975)	With the array of 1972, the NACP anomaly was traced southwards from the Black Hills and northward into Canada over a distance of 1400 km.
(6) Quebec, Canada	Camfield (1976)	In 1975, an array of 23 G-R magnetometers was operated in the tectonically active region of Quebec. Preliminary results indicate a medium scale anomaly.
(7) Southwestern	Mäki-López *et al.* (1978)	An array was operated in the goethermal zone in Southwestern New Mexico. The preliminary results indicate marked conductivity increase towards the Basin and Range and local conductive zones in the Mogollen Plateau.
(D) South America		
Chile-Argentina	Aldrich *et al.* (1978)	A 2-Dimensional array of magnetometers operated between Chile-Argentina border mapped a conductive anomaly in Central Chile.
(E) United Kingdom		
Scotland	(a) Sik and Hutton (1977) (b) Sik *et al.* (1981) (c) Kirkwood *et al.* (1981)	From the two arrays of G-R magnetometers operated in 1972, complex conductive structures were mapped (these include the 'Eskdalemuir anomaly').
(F) Europe		
Scandinavia	(a) Küpper *et al.* (1979) (b) Jones (1980, 1981)	An array was jointly operated to study the ionospheric current system and the induced field. Large coastal effects were found at all the coastal stations.

TABLE I (continued)

Region of Study	References	Notes
(G.) Africa		
(1) Kenya	(a) Beamish (1976) (b) Beamish (1977)	A 23-station array in Kenya located a crustal conductor along the axis of the Kenya Rift valley terminating at about latitude 1°S. and a second crustal conductor NE of Nairobi together with an upper mantle conductive structure east of the main fault.
(2) Southern Africa	(a) Gough *et al.* (1973) (b) de Beer and Gough (1980)	The 24-station G-R magnetometer array of 1971 discovered a conductive body elongated along east-west under Cape Karoo Basin.
(3) South-West Africa	de Beer *et al.* (1975)	An array of 25 G-R magnetometer array was run in 1972. It located a lithospheric conductor which is a south-west continuation of the African rift valley.
(4) Southern Africa	Gough and de Beer (1980)	The 1977 fifty-three station magnetometer array, the second one in southern Africa was employed to map the south cape conductive belt in detail. This study also sheds further light on source bias in geomagnetic transfer functions.
(H) India		
(1) North-west India	Lilley *et al.* (1981)	In 1979 an array was operated by the collaborative efforts of the India Institute of Geomagnetism, the National Geophysical Research Insitute of India and the Australian National University (ANU). The conductivity anomaly discovered is associated with continuation of the India shield as a subcrustal conducting zone under the Himalayan foothills.
(2) Peninsular India	Thakur *et al.* (1981)	In 1979/80, twenty-one G-R type magnetometers loaned from Australia National University were employed in the Peninsular India near Palk Strait. Current channelling conductor was found along the Palk strait between Sri Lanka Island and India.
(I) Russia		
Central part of Russian Platform	Rokityanski *et al.* (1977)	An array of 17 Bobrov type magnetometers was placed in the central part of the Russian platform. The variation fields reveal a strong induced current system near Moscow.

3. Array Data Analysis and Interpretation

The procedures for analysis of array data have become more or less standardized. Previous reviews especially Frazer (1974), Gough and Ingham (1983), treated the subject in detail. Considerable progress has been made in analysing each array data using many techniques, the goal being to improve the surface response resolution due to conductivity structures. In the discussion that follows aspects of analysis that are now receiving more attention are highlighted.

3.1. DATA SOURCES

In the mid-latitudes, the source fields commonly used are magnetic storms and polar magnetic substorms. These are the major parts of the perturbations associated with the complicated series of processes in the magnetosphere. Excellent treatments of the magnetospheric source fields are given by Rostoker (1972) and Kisabeth (1975). In the auroral zone rapid movement of electric current systems in the ionospere produces a non-uniform source field. Two dimensional array observations have led to an improved knowledge of the polar magnetic substorm fields and the behaviour of auroral electrojets. Notable among such are the works of Bannister (1977), Bannister and Gough (1977, 1978) Küpper *et al.* (1979).

The daily variation field observed during magnetically quiet days (Sq-field) provides long-period fields with which greater depths can be probed. They are due to electric current systems in the ionosphere with two vortices (north and south respectively) in the sunlit side of the earth. The amplitude of the Sq. variation depends on the latitude (Matsushita, 1967). In the equatorial region an enhanced ionospheric current density results in a non-uniform source field of small spatial wavelength. Onwumechilli (1967), Carlo *et al.* (1981) and Hesse (1982) are a few examples of the geomagnetic studies in the equatorial electrojet regions. Array studies using the daily variation of the quiet time magnetic fields have been found to provide additional information of the very deep structures (Camfield and Gough, 1975) and oceanic induction problems (Bennett and Lilley, 1973).

Geomagnetic micropulsations are the variation fields in the period band of between 0.2 and 600 s (Troitskaya, 1967). They are magnetic effects of hydrodynamic waves trapped in the magnetosphere. They are employed in probing the very shallow depths especially in magnetotelluric work.

3.2. MAGNETOGRAMS INSPECTION

In the mid-latitudes where most of the array studies have been undertaken, systematic variabilities in the amplitudes and phases of the three orthogonal components (X, Y, Z or H, D, Z) of the variation fields plotted in stacks usually reveal the presence of internal conductive structures. Numerous examples have been given in publications and in the previous reviews of array studies.

3.3 SPECTRAL ANALYSIS AND FOURIER ANOMALY MAPS

Digitized magnetic variation data are decomposed into frequency components very often using the fast-fourier transform (FFT) programmes of Cooley and Tukey (1965). The data can be filtered to select sections with statistically significant energy content and smoothed by averaging or by the use of smoothing windows. These procedures are more or less standard. Usefull textbooks and articles on the subject include Jenkins and Watts (1968), Kanasewich (1973), Thomson *et al.* (1976) and Blackman and Tukey (1959).

The Fourier anomaly maps were introduced by Reitzel *et al.* (1970) in making semiquantitative interpretations of array data. Frazer (1974) provides a review of the conventional method of producing Fourier maps. Jones (1981) stressed the importance of smoothed Fourier maps. These maps show the combined effects of the external and internal fields and ususally local conductivity anomalies appear consistently in approximately the same position for different variation fields.

3.4. POLARIZATION OF THE HORIZONTAL FIELD

Bennett and Lilley (1972) introduced the use of horizontal polarization based on monochromatic wave optics (Born and Wolf, 1959; Fowler *et al.*, 1967), into the scheme of presentation of array data. Examples of invaluable use of the polarization ellipse can be found in the array studies reported by Bennett and Lilley (1972); Gough (1972) and Gough *et al.* (1974). The results of the array experiments by Rokityanski *et al.* (1977) in the central part of the Russian platform point out that when several conductive structures can explain a variation field anomaly, consideration of fields of different periods and polarization sometimes eliminates some of the options.

3.5. TRANSFER FUNCTIONS AND ARRAY DATA

'Induction arrows' or 'induction vectors' first used by Parkinson (1959, 1962) and Wiese (1962) give the response of a geomagnetic variation. They are pictorial representations of transfer functions which describe the linear relationship between the components of the variation field. The procedures for their calculation by a least square analysis using the smoothed auto- and cross-power of the field have been clearly set out by Schmucker (1964, 1970); Everett and Hyndman (1967), Cochrane and Hyndman (1970) and reviewed by Gregori and Lanzerotti (1980). The generalized vertical transfer functions obtained by matrix inversion of the 3×3 matrix formed by auto- and cross-spectra have been used to deduce further qualitative information from array data (for examples, Ingham *et al.*, 1982; Booker and Hensel, 1982).

A quantitative measure of the statistical significance of the estimated transfer function is determined from estimates of the circles of confidence at specified confidence level. An illustration can be found in Jones (1981).

Lilley and Bennett (1972) calculated transfer functions from their 1971 array data and fitted n-th degree polynomial surfaces to their values. Figure 1 is an example of a fitted surface and the Parkinson vectors to a variation field event from Lilley and

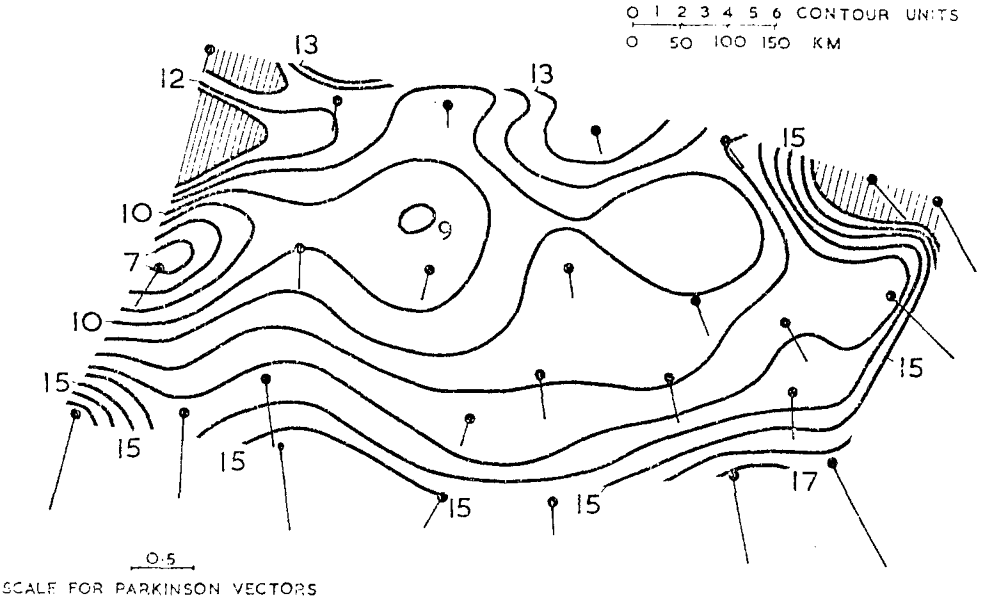

Fig. 1. The fitted response surface and the Parkinson vectors at period 30 min. Units of contour are relative to an arbitrary zero (after Lilley and Bennett, 1972).

Bennett (1972). In general the steepness of the slope of the response function is directly related to the length of the Parkinson vectors. This type of response surface is a smoothed anomaly map and is therefore able to give a clearer picture of the conductive anomalous structures.

Hypothetical event analysis based on the assumption of uniform source field first proposed by Bailey *et al.* (1974) has now become another form of depicting transfer functions. Hutton *et al.* (1977, 1981), Sik *et al.* (1981) and Kirkwood *et al.* (1981) calculated transfer functions from their Scottish array data and contoured hypothetical values of the *Z*-field as anomaly maps. The advantage of this approach is that the direction of polarization of the field can be chosen and hence responses of conductive bodies striking in different directions can be studied.

The use of transfer functions and induction arrows have posed a number of problems. Gough and de Beer (1980) found that the induction arrows deduced from their 1971 array data are in conflict with those from their 1977 array (both arrays in the same area, see Table I). They concluded that there must be some selection criteria if transfer functions are to give unique information at all times. Meyer in a paper presented at the Istanbul workshop in 1980 and through personal communication (1982) questioned the validity of the use of complex induction arrows to delineate conductive structures since such arrows depend on the polarization of the source field. Anderson *et al* (1978) demonstrated that the induction vectors for VLF field (period 37 to 1380 s) vary with local time and therefore can give an incorrect location of the internal current system. Current channelling bodies cause distortion of the variation field and consequently affect the estimates of the transfer function. However, the theoretical work of Hibbs and Jones (1976) confirmed that induction arrows can be used in the usual manner to diagnose anomalous current concentration and to indicate the direction of the conductive body. More recently, Lam, *et al.* (1982) demonstrated theoretically the features of induction arrows for three-dimensional conductive anomalies. They caution that induction arrows must be used with extreme care near current channelling anomalies.

4. Quantitative Physical Interpretation

The purpose of quantitative interpretation is to seek the physical models of the conductive body that can explain completely the observed parts of external and internal origin. The normal field consists of both the external field and the field due to internal currents induced in regional conductive structures of dimensions greater than those of the structure being investigated. The anomalous field is the internal current contribution of the structure under investigation. Oldenberg (1969) and Porath *et al.* (1970) used a surface integral to separate fields obtained with a two-dimensional array into external and internal parts. Gregori and Lanzerotti (1982) presented a new approach for separating observed fields based on the fact that at each ground-based observation site, for a given frequency, there is a direction along which the field is of purely external origin. In mid-latitudes the source fields have dimensions that are much larger than the dimensions of the array and therefore field separation can only be based on personal judgement.

Numerical methods which are employed for fitting conductivity models to the anomalous fields include, the finite difference method (see Jones and Price, 1970; Jones and Pascoe, 1972); the transmission line analogue method (see Madden and Swift Jr., 1969 and the reference therein); the finite element method (Coggan, 1971); and the integral equation method (Weidelt, 1975). Reviews and appraisals of the variety of modelling methods have been given by Jones (1973), Praus (1975), and Gough and Ingham (1983). The finite difference and the integral equation methods are more widely used.

Linear conductive structures of long extent are usually represented by two-dimensional bodies, while structures of limited extent are interpreted in terms of three-dimensional models. The computational tasks involved in three dimensional modelling are immense. However progress made in these areas was discussed at the last induction workshop in Istanbul by Tarlowski (1980). Zhdanov *et al.* (1980) discussed developments in the finite difference method for the solution of 2- and 3-dimensional conductivity models. Anomalies due to current concentration have been studied through 3-dimensional numerical models (e.g. Weidelt, 1976). Woods and Lilley (1980) have employed the equivalent current system proposed by Banks (1979) to study current channelling anomalies observed with their 1977 array. Wegner (1982) presents a three-dimensional model of the regional induction in Scotland using thin sheet approximation developed by Dawson and Weaver (1979). Le Mouel and Menvielle (1982), from numerical computation, remarked that the current concentrations responsible for the abnormal fields do not affect their temporal variations. They concluded that the study of the abnormal field due to channelling does not provide any information whatsoever on the structure of the crust in the very area under study and hence under array sites.

The laboratory scale (analogue) models have proved very useful in the physical interpretation of observed magnetic variation field anomalies. Dosso (1973) presented a review of the theory and applications of analogue models. With this method, actual regional structures and complicated conductive bodies can be modelled with the appropriate source field simulated. An example is the analogue modelling of the British Isles by Dosso *et al.* (1980).

5. One-dimensional Earth Models from Array Data

In areas of array experiments where the source field is non-uniform and away from anomalous conductive zones, one-dimensional earth models can be obtained from the spatial gradients of the horizontal field and the vertical field. This type of quantitative interpretation was in the past possible only with magnetotelluric sounding. Its practice and examples of results are now discussed. Berdichevsky *et al.* (1969) and Schmucker (1970) treated the relevant basic equations, Kuckes (1973) and Lilley and Sloane (1976) first applied the method to array data. The frequency dependent inductive response function $C(w, k)$ or ('C-parameter') relates to the vertical field and the gradient of the horizontal field by the expression.

$$C(w, k) = \frac{\partial Z}{(\partial X/\partial x + \partial Y/\partial y} \tag{1}$$

where $k = (k_x^2 + k_y^2)^{1/2}$ is the absolute wave-number.

Weidelt (1972) discussed the inequality constraints on this function. Lilley and Sloane (1976) derived the spatial gradient $[\partial X/\partial x) + (\partial Y/\partial y)]$ from Fourier maps of X and Y. Woods and Lilley (1979) fitted surfaces transforms of the X, Y, and Z-fields. The second order surface for the X-field is of the form

$$X = a_0 + a_1 x + a_2 y + a_3 x^2 + a_4 y^2 + a_5 xy.$$

Jones (1980) imposed the curl-free condition ($\partial X/\partial y = \partial Y/\partial x$) on the fields. Estimates of $C(w, k)$ were made from the horizontal spatial gradient of X- and Y-field surfaces and the smoothed vertical field. The $C(w, k)$ values obtained can be inverted using a simple inversion method such as the substitute conductor scheme discussed by Schmucker (1970) to obtain conductivity (or resistivity) as a function of frequency. Thus

$$\rho_a = w\mu_0 |C(w, k)| 2. \tag{7}$$

At each frequency, w, the real part of $C(w, k)$ relates to the depth value h^* and the imaginary part to half the skin depth ($\delta/2$). Thus the actual depth h is

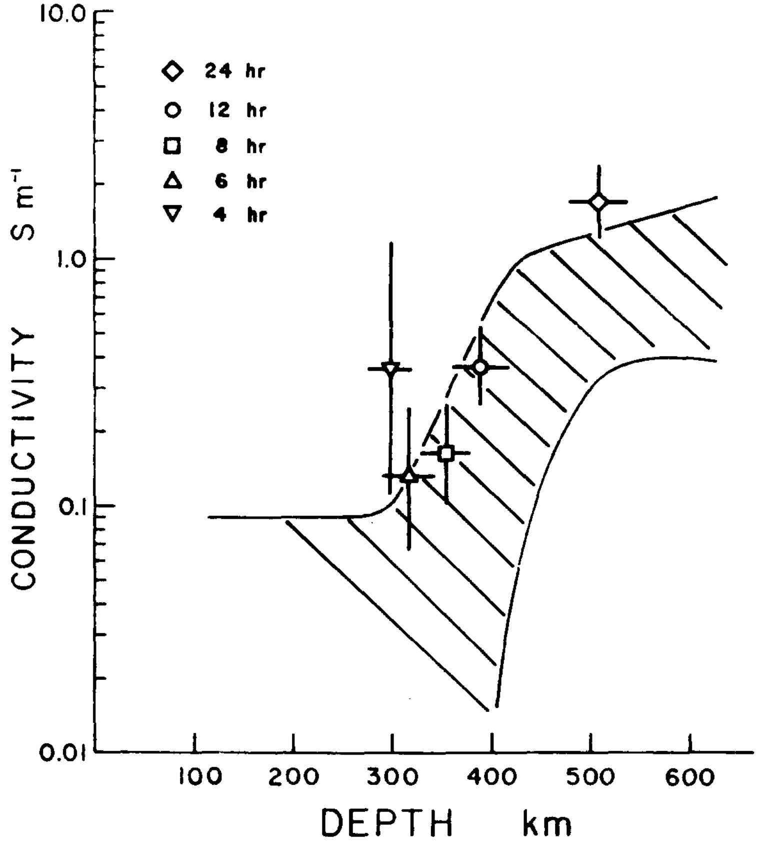

Fig. 2. Conductivity versus depth from inversion of $C(w, k)$ at the principal periods of the Sq. daily variation (from Lilley and Woods, 1979). The envelope encloses the upper and lower Limits of Banks (1969) best fitting model).

$$h = h^* + \delta/2.$$

In Figure 2 an illustration is given of the conductivity-depth profile obtained from the principal harmonics of the Sq. daily variation field from an array experiment of Woods and Lilley (1979).

Lilley *et al.* (1981a) used the Sq. daily variation from a series of array experiments in Australia to secure estimates of $C(w, k)$ at daily variation principal periods. The apparent resistivity obtained agreed with global results, thus lending credence to this form of inversion. By one-dimensional modelling approach, Lilley *et al.* (1981a) fitted layered earth models to the real and imaginary parts of $C(w, k)$ data from central and southeast Australia and found significant differences in the electrical conductivity profiles in the two regions. Figure 3 illustrates the different electrical profiles obtained. Such models are non-unique and thus it is necessary to determine the range of acceptable models. Beginning with a model which has a spread of conductivity at all

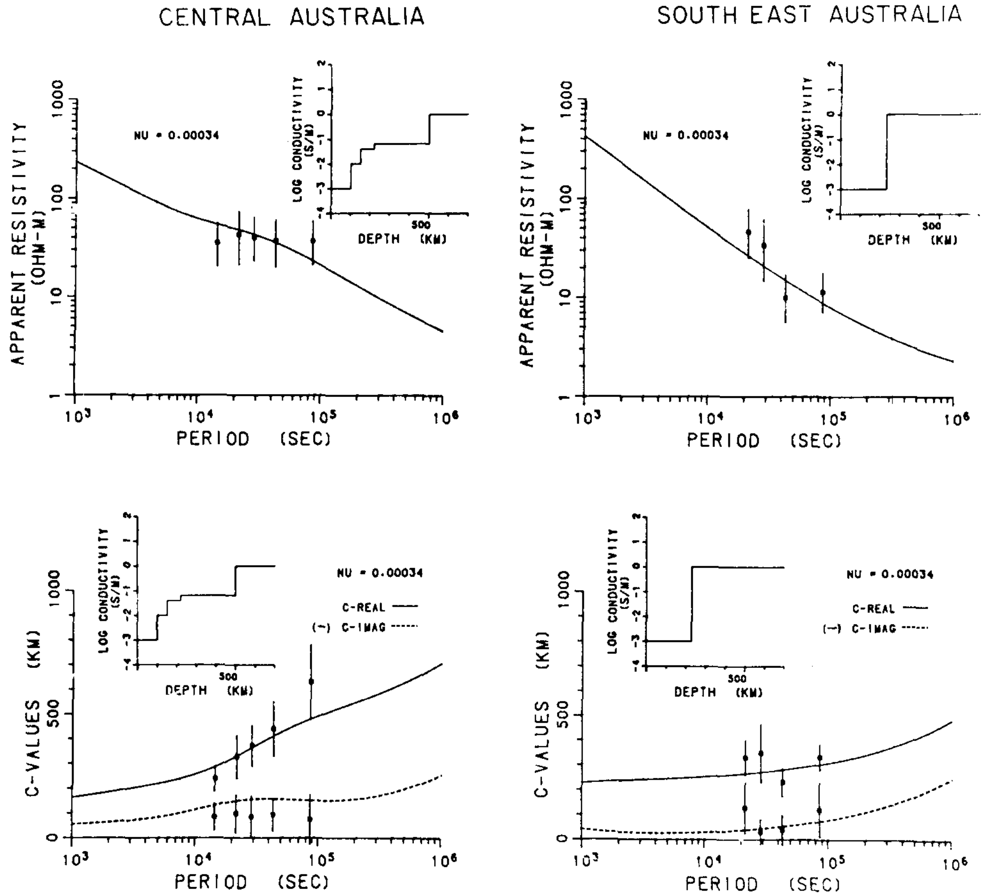

Fig. 3. The conductivity profile obtained for Central and South east Australia by inversion of $C(w, k)$ data (from Lilley *et al.*, 1981b).

depths, the Monte-Carlo method allows one to find a group of models that satisfies the observed data. Lilley *et al.* (1981b) determined acceptable models for central and southeast Australia with accepted bounds as defined by Anderssen (1970). Jones (1980) determined $C(w, k)$ in the periods of 10^2 to 10^4 s by statistical frequency analysis and fitted 3-layer models by the Monte-Carlo inversion process to Scandinavian array data. Jones (1982b) employed the refined version of the Monte-Carlo technique to deduce acceptable models for crust-mantle structure in northern Sweden.

6. Geophysical Implications of Array Anomalies

The majority of the published results of array studies discuss the geophysical implications of the conductive anomalies detected. In addition to reviews already mentioned, others are: Hutton (1976b) for rift regions of the world; Kovtun (1976) for the lower crust structures in different regions of the world. Most of the conductive bodies have been explained in terms of tectonic and geologic features, heat flow and lateral inhomogeneities in the lithosphere. In some cases the conductivity anomalies have been associated with zones with seismic activities. Some examples are the 'Otway' conductor in southeast Australia (Lilley, 1975b) and a conductor in Southern Africa associated with a rift valley (de Beer *et al*., 1975). This review will not concern itself with details of geophysical interpretation which have been extensively dealt with within the references already given.

7. Results from some New Array Studies

In southwestern Canada, Gough and his colleagues have conducted a series of four array experiments between 1980 and 1981. The first in the series (reffered to as 1980A array) was operated in June and July 1980 at an average spacing of 150 km. (Gough *et al*., 1982). The location of this area on a simplified tectonic map is given in Figure 1 in Gough *et al* (1982). Figure 4 reproduced from their work is an illustration of the two local anomalies revealed by this study.

(i) In Figure 4 an enhancement of X and Y components is found in a localized zone around Tête Jaune Cache and along the Rocky Mountain Trench (see Figure 1 in Gough *et al* (1982), for this location). The enhancement is attributed to '... partial melt at depths associated with recent volcanics'.

(ii) An elongated anomaly in X extends from Southern Alberta into the Rocky Mountains. A possible relationship with a buried Precambrian rift in the lower crust is advanced.

The Z phase map and polarization ellipses at the two zones are also indicative of the presence of local conductors.

A second (1980B) array of high resolution (with station spacing of 15 km) was placed over a geothermal zone in the Rocky Mountain foothills of Alberta in Canada. Ingham *et al* (1982) employ the use of contour maps of the response of the anomalous vertical to horizontal hypothetical events and pseudosections of the ratio of the anomalous Z to the normal horizontal field for profiles across the array to reveal the presence of a conductive body beneath the geothermal area. The depth to the top of the conductive body was found to be between 10 and 20 km and it was attributed to partial melt in the crust.

The results of the other two arrays operated one centred over the Tête Jaune Cache and along the Rocky Mountain Trench while the second spread over Southern Alberta and British Columbia are yet to be ready at this time.

A large magnetometer array operated in Northwestern United States was reported by Booker and Hensel (1982). From the analysis of matrices of transfer functions, the direction of the currents flowing in the upper crust was found to be induced in the ocean west of the Canadian coastline and chanelled through Puget Sound into the continental crust in Oregon.

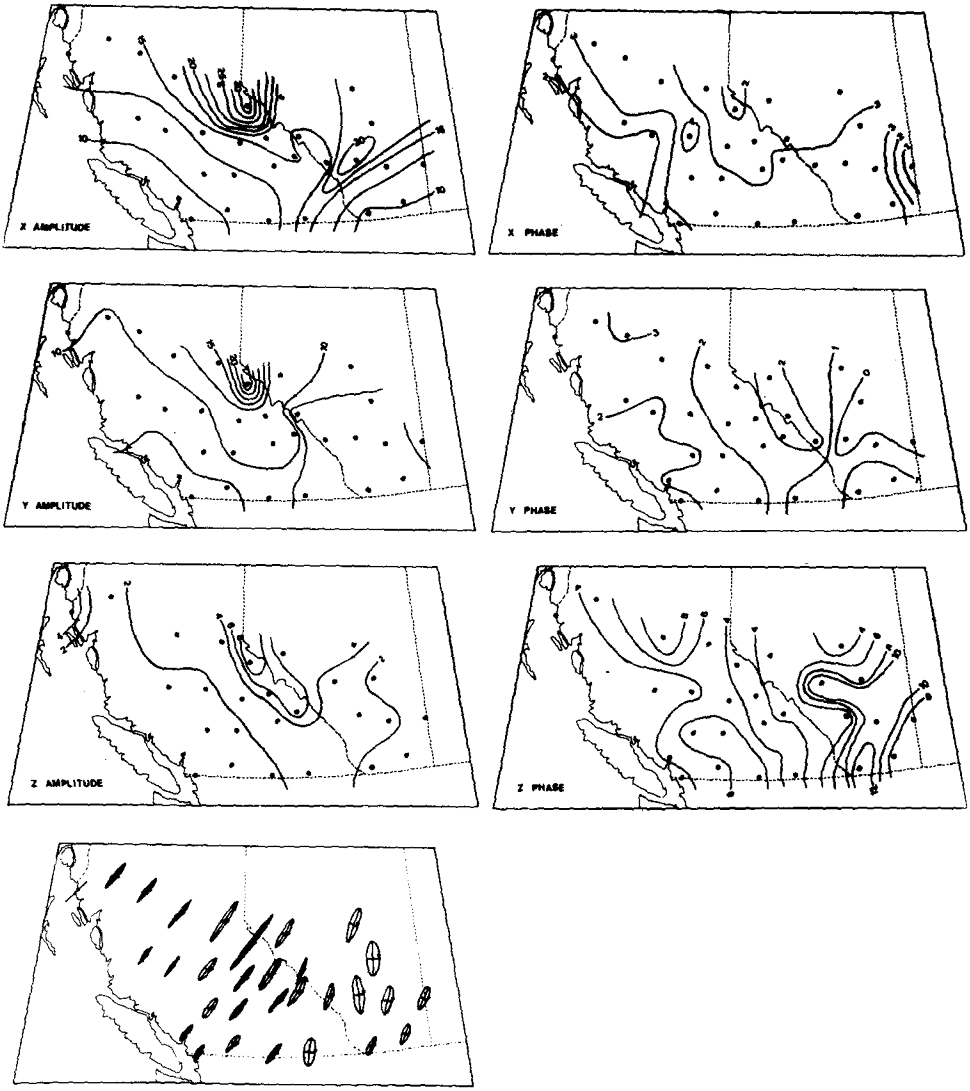

Fig. 4. The Fourier Maps of an event at period 15.5 min from the 1980a Southwestern Canada array (after Gough *et al.*, 1982).

8. Conclusion

It is now almost routine to deploy tens of recording magnetometers in 2-dimensional arrays to map intra-continental geophysical structures in North America, Australia, Europe and South Africa. Our understanding of the important conductive structures and their relation to the tectonics of these continents continue to improve. This increase in array activities exhibits a strong growth trend.

In the area of array data analysis the use of transfer functions, hypothetical event and response surface analyses have been shown to give clear pictures of conductive bodies. However there is a lack of agreement about current channelling anomalies, the view point is held that current channelling in some cases is a physical misrepresentation of elongated 3-dimensional structures. Both numerical and laboratory models can be gainfully undertaken for improved knowledge of this phenomenon very often detected with 2-dimensional array experiments. Future array studies in areas where current channelling conductors have been proposed should extend to remote areas from and to where the currents are suspected to flow. The results may answer some of the questions regarding this phenomenon.

In electrically homogenous regions situated under a non-uniform source field, the array data yields one dimensional layered earth models with bounds placed by the Monte Carlo process. Other inversion schemes such as Backus Gilbert's can be tried as challenging alternatives in the analysis.

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