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MAGNETOMETER ARRAY STUDIES: A REVIEW OF THE INTERPRETATION OF OBSERVED FIELDS

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A magnetometer array study consists of a number of variometers recording simultaneously across a two-dimensional area. Data recorded by an array should satisfy certain criteria, showing that transient magnetic events have been thoroughly monitored on the plane of observation. Interpretation of such data in terms of solid-earth geophysics involves two separate classes of problem. In the first the local geoelectric structure changes over a shorter lateral distance than does the inducing field. The observed response of the local structure is modelled numerically, taking the inducing field to be uniform. The parameters modelled are relationships between regional and anomalous horizontal and vertical field components. Operation of many instruments in an array should give better estimates of these parameters than operation of instruments singly, or in small groups. Numerical models constructed to fit observed data are non-unique, though the wide frequency range of geomagnetic events may perhaps be used to greater advantage in distinguishing between conductors in the upper crust, lower crust, and upper mantle. In constructing models a further complication arises in distinguishing between conductors simply concentrating current induced elsewhere, and conductors in which the induction is itself taking place.

The second class of problem comprises determination of conductivity as a function of depth, utilizing non-uniformity in inducing fields. Here a large array of instruments should enable estimation of field gradients more accurately than is possible with fewer instruments. Interpretations published to date have perhaps not exploited this aspect of array information as fully as might prove possible.

Some miscellaneous comments are: (1) daily-variation data in particular could resolve some depth ambiguity problems; (2) there is confusion in the literature between two possible definitions of phase; (3) ideas on optimum station spacing are still evolving; (4) it is not easy to decide an optimum ratio for time spent collecting data to time spent interpreting data; (5) array data have relevance to the study of electric currents in the ionosphere.

1. Introduction

1.1 Historical note

Magnetic observatories have been in existence for several centuries, as a consequence of early interest in the phenomenon of the earth's magnetic field. A network of permanent observatories around the earth has gradually grown during this time, and has occasionally been augmented by temporary observing stations. For example, a special effort was made during the 1957–1958 International Geophysical Year to obtain improved information on transient magnetic variations, and on the electric currents external to the earth which cause them.

Such global observatory data also hold information on electromagnetic induction occurring in the earth, and the first analyses of this process assumed spherical symmetry in the earth's electrical conductivity. However careful inspection of records from some permanent observatories, and from some densely-spaced temporary ones like those of the International Geophysical Year, demonstrated the extent to which local electrical-conductivity structure can affect the vertical component of a transient magnetic event. This realization led to the operation of further temporary observatories for the specific purpose of exploring local crustal and

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upper-mantle conductivity. Initially stations were operated either singly, or in pairs or small groups laid out along a line. From these experiments large array operations developed, involving some twenty to forty variometers recording simultaneously over areas of order 100,000 km^2.

This review will concentrate on aspects of interpretation which are peculiar to the data produced by such large arrays. As in other geomagnetic depth-sounding exercises, there is valuable information in the surface electric fields at recording sites, should these be measured also. Array data were used for magnetotelluric purposes by Tammemagi and Lilley (1973), and a joint interpretation of magnetotelluric and magnetometer array data was given by Lilley and Tammemagi (1972).

1.2 World activity

Fig. 1 shows a map of world activity in magnetometer array studies, up to the present time. The map has been compiled by tracing the use of those sets of variometers which are known to the author to have been assembled for the specific purpose of large array operation. In the nineteen operations shown, some 100 variometers have occupied a total of some 500 sites. Most of these variometers are of the economical Gough and Reitzel (1967) type.

A review of the interpretation of the array studies shown in Fig. 1 is limited by the fact that most of them have taken place relatively recently, and interpretations have not yet been published. This is a reflection partly of the work involved in reducing the

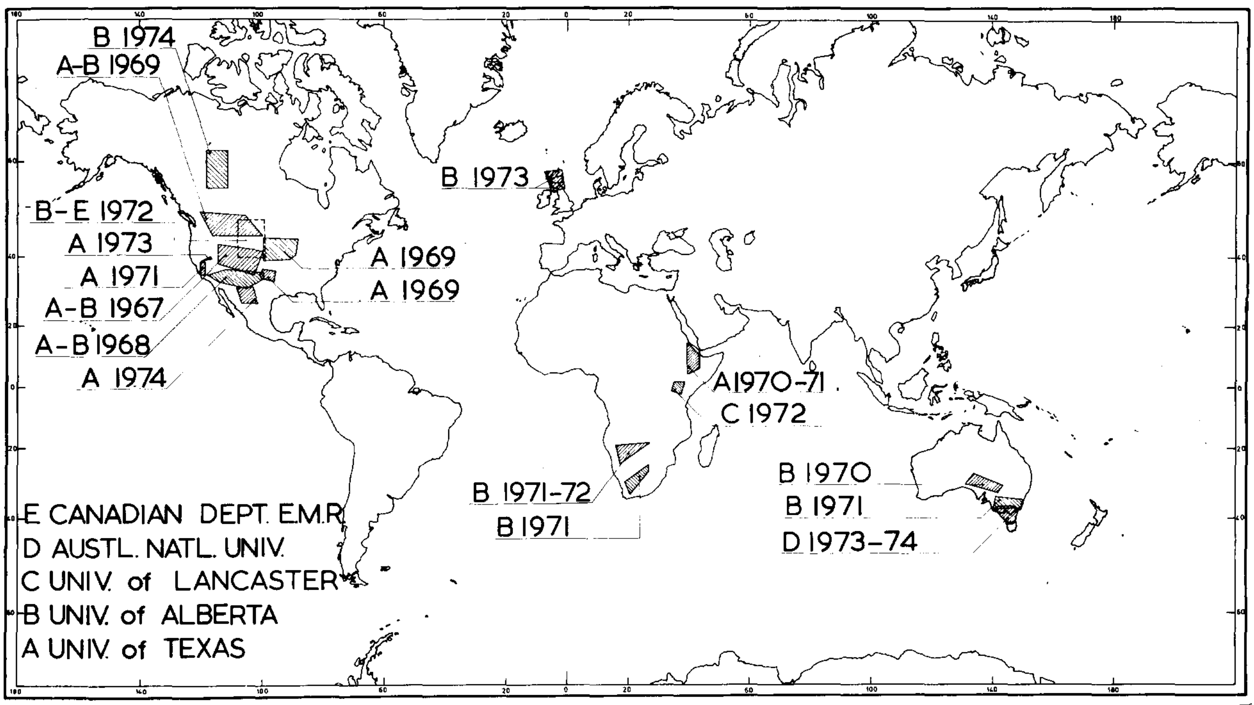

Fig. 1. World activity of magnetic variometers built specifically to operate in large arrays. Identifying letters refer to the home bases of instruments, rather than to the scientific groups operating them. Thus the Scottish arrays (*B 1973* marks two distinct operations) were run in collaboration with the University of Edinburgh, the South African arrays in collaboration with the S.A. National Physical Research Laboratories, and the Australian *B 1970* and *B 1971* arrays in collaboration with the Australian National University. (After Reitzel et al., 1970; Camfield et al., 1971; Porath and Gough, 1971; Porath and Dziewonski, 1971b; Gough et al., 1972; Lilley and Bennett, 1972; Gough et al., 1973; and R.J. Banks, J.H. De Beer, D.J. Bennett, D.I. Gough, and V.R.S. Hutton private communications, all 1974.)

great volume of observed data to the stage where interpretations can proceed, and it is also a reflection of the fact that interpretation techniques are by no means routine, but often have to be developed (and are still being developed) to deal with particular data. The major frontiers of present interpretation effort are probably those concerning the conduction and induction effects of three-dimensional inhomogeneities.

1.3 Definition

A magnetometer array study consists of a number of variometers recording simultaneously across a two-dimensional area. The instruments record fluctuations in the earth's magnetic field, resolved along three components. The smallest number of instruments which could comprise an array might be three arranged in a triangle, but to be fully effective the minimum number is probably between five and ten. All the operations mentioned in this paper involved more than fifteen instruments, and several involved more than forty.

Simultaneous observations from a network of recording sites offer additional and more accurate information than non-simultaneous observations from the same sites, and it was to exploit this fundamental improvement in information that array operations were developed. The extra information has three main characteristics:

(1) Array data should give a direct demonstration of whether the conductivity structure beneath a surveyed area varies in one, two, or three dimensions. A range of horizontal-field polarizations will usually be important in this analysis. If the structure is two-dimensional, the strike direction will be shown.

(2) In the vicinity of local conductivity structure, array data should give estimates of regional fields and anomalous fields, in all three horizontal and vertical components.

(3) Above one-dimensional structure (where the electrical conductivity of the earth is taken to be laterally uniform and to vary with depth alone) array data should give direct estimates of the spatial gradients of the field components, across the plane of observation.

While a noticeable aspect of array operation is the speed and efficiency with which a continent can be explored with temporary variometer stations, definition of an array study should not be in terms of the number of stations occupied so much as in terms of whether the observations satisfy criteria 1–3 above.

The use of this information in interpreting electrical conductivity structure will be discussed in Sections 2 and 3. In those sections a basic subdivision of the tractable parts of the subject is made, according to whether the spatial wavelength of an inducing field is greater or less than the horizontal scale-length of a conductivity structure.

1.4 An example

Fig. 2 shows a diagram from Reitzel et al. (1970).

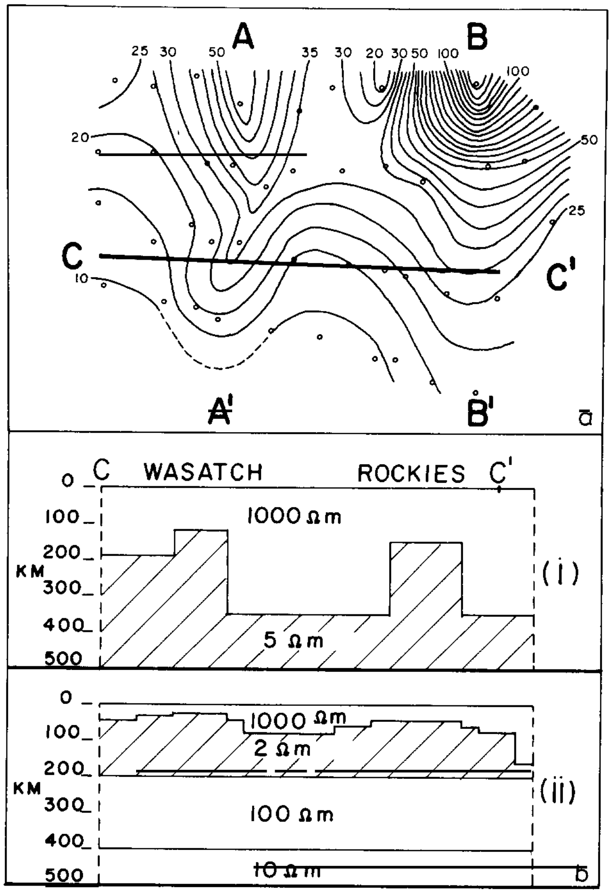

Fig. 2. a. An example of reduced array data, from the operation marked *A–B 1967* in Fig. 1 after Reitzel et al. (1970). The magnetic variation contours are controlled by data values at the different observing sites, shown by dots. The data values (in this case for the amplitude of the vertical field component) have been obtained by Fourier analysis of the vertical signals for a particular event, as recorded at the different stations of the array.
b. Two of many possible models constructed to fit data recorded along line *C–C'* (after Porath and Gough, 1971; Porath, 1971).

Data representation in this way requires a set of six such maps, to show amplitude and phase patterns of all three field components. Different sets of maps then compare the response of the array area to variation fields of different horizontal polarization, and of different frequency. For the present example, the polarization of the horizontal field is approximately northeast–southwest.

Fig. 2 shows three features, best described by imagining the contour lines to define a topographic surface:

(1) The general slope from north to south is a regional variation in field amplitude.

(2) Superimposed upon the regional slope are two ridges, A–A' and B–B', which are taken to be two-dimensional because of their extended linear strike.

(3) Near point B, the eastern ridge appears to drop from a pinnacle. The evidence of this map, and of subsequent investigations in the area, (arrays *A–B 1969* and *B–E 1972* in Fig. 1), show this feature to be a case of three-dimensional "current channelling", in which current induced over a much larger and ill-defined area is channelled conductively through a linear conductor of limited extent, simply according to Ohm's law.

The array having thus outlined the response of the area, a line C–C' is taken across the two-dimensional ridges, and subsequent interpretation consists of fitting models to the various response parameters observed along this line. No information enters this further part of the analysis other than what would have been obtained with just ten (say) variometers operating along the line C–C', but the considerable contribution from the rest of the array has been to provide the freedom with which line C–C' can be selected, and then to indicate the confidence with which two-dimensional modelling can be applied. Models fitted to line C–C' will be discussed in Section 2.4.

1.5 The two-stage process of interpretation

Interpretation of electromagnetic observations to give geologic information is a process of two distinct stages. The first stage involves interpretation of observed data in terms of electrical conductivity structure, and the second involves interpretation of electrical conductivity structure in terms of parameters such as composition, phase and temperature.

This paper deals only with the first stage of interpretation of array data. For recent review of aspects of the second stage, the reader is referred to Shankland (1975) and Garland (1975).

1.6 Bibliography

To conclude this introduction reference should be made to other recent and comprehensive reviews on the subject. On geomagnetic variations in general these include Rikitake (1966, 1971), Schmucker (1970a, 1970b, 1973), Schmucker and Jankowski (1972), and Rokityansky (1975). On magnetometer array studies in particular, recent reviews are by Porath and Dziewonski (1971a), Gough (1973a, b), and Frazer (1974). The present author has attempted to complement, rather than duplicate, these reviews.

2. Departures from layered structure in the earth, and the assumption of uniform source fields

2.1 Basic principles

This section covers those cases where the geologic structure changes more rapidly with lateral distance than does the regional magnetic variation field. Departures from horizontal layering in the electrical conductivity of the earth will be evident as anomalies in the observed magnetic variation components. As described in Section 1.3, an ideal array operation will map both anomalous fields and regional fields, in all horizontal and vertical components. A conductivity structure can then be modelled which causes a uniform horizontal field to induce appropriate horizontal and vertical anomalous fields. For variation periods of order one hour, upon which most array interpretations so far have concentrated, the regional vertical variation fields will be small and have little effect.

2.2 Two-dimensional geometry

Most published modelling of actual field data has so far been for two-dimensional geometry, in which case the response of an anomalous structure at a particular frequency can be represented by four profiles drawn across its strike. These profiles are the in-phase and out-of-phase parts of the vertical and horizontal anomalous fields, divided by the amplitude of the horizontal regional field resolved across the strike direction and taken to be entirely in phase. Such profiles are compiled using data which have been transformed from the time domain to the frequency domain, like those in Fig. 2, and the frequency dependence of an anomaly can be a strong criterion in its modelling. Should the regional field be not uniform but have a smooth gradient, one pragmatic way to proceed is simply to normalize the estimates of the anomalous fields at each measurement point by the value of the regional field at the same point, as done by Porath et al. (1970), and others since. This procedure seems reasonable, but the fact that most modelling techniques assume a uniform regional field should be remembered. Some recent modelling techniques now take non-uniformity of the source-field into account, for example Hibbs and Jones (1973a, b).

2.3 Elementary modelling techniques

Two elementary modelling techniques are:

(1) Matching the "half-width" of an observed anomaly with the theoretical half-width of a line current flowing at some depth in the earth. This method gives the maximum possible depth to a conductor causing an anomaly, and may be most useful in isolating narrow crustal anomalies of the current-concentration type like the American Central Plains anomaly of Camfield et al. (1971), the southern extremity of which is at *B* in Fig. 2. The line-current model was possibly first applied to geomagnetic depth sounding by Bartels (1954). Fig. 3 shows horizontal- and vertical-field profiles across a buried line current of infinite extent.

(2) Calculation of magnetic flux-line distribution above undulations in the upper surface of a perfectly conducting half-space. In this method a two-part model is taken for the earth, of a non-conductor overlying a perfect conductor. The use of this method appears to have been first demonstrated by Cox (1960), and is also discussed by Schmucker (1970a, p. 86).

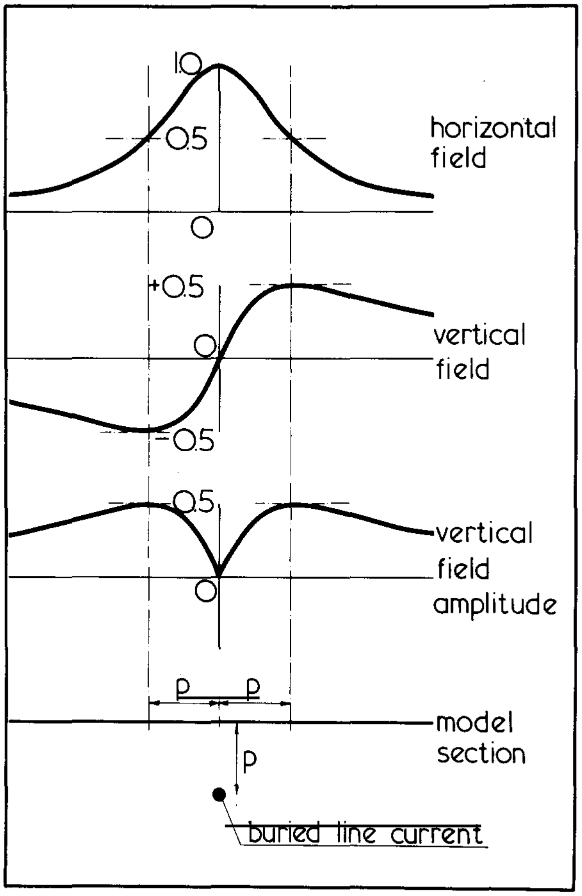

Fig. 3. Profiles of horizontal and vertical magnetic field across a buried line current, which is long in the direction perpendicular to the diagram. Field strengths are scaled in units of $(\mu_0/2\pi)(I/p)$ m.k.s., where I is the strength of the line current and p its depth of burial. Thus a line current of strength 1 A and depth 1 km gives a maximum transverse horizontal field of 0.2 nT, and a current at depth 50 km needs to be of strength 5,000 A to give a maximum horizontal-field anomaly of 20 nT, and an offset maximum vertical-field anomaly of 10 nT.
Note that vertical-field maximum amplitudes occur at horizontal-field half-maxima, where all magnitudes are equal. Note also that spacing of observing sites has to be rather less than depth of burial if the minimum in vertical-field amplitude is to be detected with any certainty.

2.4 General two-dimensional modelling

To calculate the electromagnetic response of more complicated structures numerical methods are generally necessary, as with the exception of but a few cases (Hobbs, 1975), such forward problems have not proved amenable to analytic solution. Various numerical methods in common use have recently been reviewed comprehensively by Jones (1973) and Praus

(1975), who also discuss progress with three-dimensional models. The general lack of forward solutions in the modelling problem greatly restricts application to the subject of certain aspects of modern interpretation theory, such as the resolution estimates possible in global modelling described by Parker (1970). Weidelt (1975) reviews the present state of two-dimensional inversion techniques.

To continue with the example of Section 1.4, Fig. 2 shows two models constructed to fit the data of line C–C'. Both models show the important features of a good conductor at shallow depths beneath the Wasatch Fault Belt and the southern Rocky Mountains, and in the contrasting depths given to the good conductor the models demonstrate the basic non-uniqueness of this type of modelling.

Such non-uniqueness might however be reduced by exploiting the full frequency range of natural geomagnetic variations. For example, it is possible that observational data from daily variations could distinguish between models *i* and *ii* in Fig. 2. This point was made in the initial paper describing the array experiment (Reitzel et al., 1970, p. 233).

2.5 *Three-dimensional modelling*

For an obvious case of three-dimensionality, as evident by the dependence of an anomaly pattern upon the polarization of the regional field causing it (Bennett and Lilley, 1972; Gough et al., 1972), the number of profiles characterizing the model becomes much greater, and modelling may need to be in terms of the full transfer matrix of Schmucker (1964, 1970a), evaluated at every observation point. Lilley (1974) analyzed this concept as an "induction tensor", and compared some of its characteristics for two- and three-dimensional cases. The best way of representing three-dimensional data is still being explored. Traditional response arrows of the Parkinson, Wiese or Schmucker types have been used in presenting the results of some array studies, though in fact such response arrows for the anomalous vertical variations at the stations involved could have been computed using non-simultaneous data, with relatively little loss of information. The full advantages of array operation only become apparent when anomalous horizontal fields are also taken into account.

A major class of three-dimensional models is that of the "current-concentration" or "current-channelling" type, already mentioned in Sections 1.4 and 2.3. The best modelling procedures for such cases are still evolving. A feature which may prove diagnostic is that of very strong anomalous horizontal fields, as observed by Camfield et al. (1971) in one region of the North American Central Plains. Lilley and Bennett (1973) pointed out that the fields of current-channelling anomalies, being less strongly correlated with the local inducing field, may give less well-determined response arrows.

2.6 *Separation of external and internal fields*

The exercise of formally separating external and internal fields has been carried out for just one array (that of Fig. 2, Porath et al., 1970). The conclusion from that exercise appears to be that generally the most practical way to proceed is simply to smooth out a regional field and to take residuals as anomalous field (Gough 1973a). This procedure is clearly valid if the anomalous fields are of relatively short scale-length, and are entirely contained within an array area. If these conditions are not met the formal separation procedure also breaks down, and comparably subjective judgements have to be made about where the fields are anomalous and where they are not so.

Because perturbations with scale-lengths shorter than an array are unlikely to occur in mid-latitude fields of external origin, anomalous fields determined by simple smoothing are taken to have their origin in currents within the earth. This assumption gains support if successive and varied magnetic events show anomaly patterns to reappear persistently in the same geographic locations.

Regional fields, with local anomalies removed, will have their origin both external and internal to the earth. The smoothing technique does not separate the external and internal parts of regional fields, but neither would a formal separation process, as regional fields have scale-lengths greater than the dimensions of an array. For the model-fitting techniques described, it does not appear to be necessary or even an advantage to be able to separate regional fields into external and internal parts.

3. Layered structure in the earth, and mildly non-uniform source fields

3.1 The basic inequality regarding scale-length

The inequality at the basis of Section 2 is now reversed, so that Section 3 applies to cases where the electrical conductivity is horizontally layered, over distances on which the source field changes significantly.

3.2 Basic equations

Determination of the electrical conductivity of the earth when it is taken to vary with depth only is a problem which has received much attention in electromagnetic theory. On the scale of magnetometer arrays the earth can be considered as a flat half-space, and the theory for induction in such a region appears to commence with the paper by Price (1950). A recent review of the subject is given by Weaver (1973). For a source field of wave number k, the following formulae, given in many places and taken here from Schmucker (1970a, pp. 63–64), hold:

$$Z/H = ik/K_1G_1(0) \quad (1)$$

$$\partial X/\partial x + \partial Y/\partial y = ikH \quad (2)$$

whence

$$\partial X/\partial x + \partial Y/\partial y = K_1G_1(0)Z \quad (3)$$

where the source field varies with x and y as $e^{ik_x x}$ and $e^{ik_y y}$ respectively; X, Y and Z are the components of variation in the x, y and z (vertically down) directions; $K_1G_1(0)$ is a function of the layered structure and can be computed if the layering is known; and:

$$k = (k_x^2 + k_y^2)^{1/2}$$

$$H = (X^2 + Y^2)^{1/2}$$

The derivation of eqs. 1–3 requires that the scale-length of the source field be much greater than the depth of its penetration into the earth, an assumption which holds for most magnetometer array studies carried out to date in mid-latitudes. The extra complications which can arise with severely non-uniform source fields are discussed (for example) by Schmucker (1973, p. 368).

Schmucker (1970a, p. 68) also shows that for a two-layered model of poor conductor overlying good conductor, (which though simple may approximate an earth with poorly conducting crust overlying highly conducting upper mantle), eq. 3 may be expressed:

$$\partial X/\partial x + \partial Y/\partial y = Z/c \quad (4)$$

where the real part of the complex parameter c reflects the mean depth of the internal eddy currents, called the "depth of a perfect substitute conductor", and from the imaginary part of the parameter c can be calculated quite directly the ambient conductivity at that depth.

3.3 The suitability of array data for one-dimensional inversion

The applications of array data to the equations of Section 3.2 are as follows:

(1) Data can be taken from areas demonstrably free of local anomalies, so that reasonable confidence can be held in the horizontal layering of the medium.

(2) Direct estimates can be made from the array data of $(\partial X/\partial x + \partial Y/\partial y)$ and of Z, giving a value for $K_1G_1(0)$ or c without necessitating an estimate of k.

Though there are many instances in the literature of interpretations of essentially single-station data using eq. 1 above, these have necessitated estimates of k which have not been straightforward. The applications of array data to eq. 3, which does not suffer from the k-estimate disadvantage, seem as yet to have been barely exploited.

Kuckes (1973) derived expressions like eq. 4 above, and demonstrated the possibilities of this very straightforward technique using the array data of Porath and

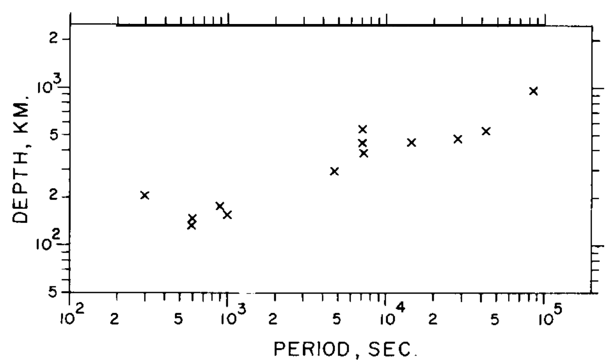

Fig. 4. Kuckes' (1973) estimates of magnitude of penetration depth, (equivalent to the modulus of Schmucker's parameter c), plotted as a function of period of fluctuation.

Dziewonski (1971b, the northern *A 1969* array marked on Fig. 1), combined with some data for longer periods from Chapman and Bartels (1940). Fig. 4 shows Kuckes' estimates of the modulus of the parameter c as a function of period. Addition of phase information to the data would enable a conductivity profile against depth to be plotted on the basis of the simple two-layer model described.

3.4 Possible misapplication of eq. 2

Porath et al. (1971) carried out horizontal layer interpretations, evidently using eq. 1 above rather than eq. 3. Ratios for Z/H were estimated from maps of reduced data, distant from anomalous areas, and k was calculated from a formula:

"$k = \text{grad}\, H/H$"

attributed to Schmucker (1970a, possibly p. 92). To enable this computation for k, grad H and H were also estimated from the data maps, evidently at the same place.

Because eq. 2 above can be expressed:

$$k = (\partial X/\partial x + \partial Y/\partial y)/iH$$

where the "i" has originated from differentiation with respect to horizontal distance, and thus represents a shift of 1/4 of a wavelength from the point of measurement of H to that of measurement of $(\partial X/\partial x + \partial Y/\partial y)$, it is possible that Porath and coworkers applied the equation out of its context on Schmucker's p. 92, and that their results might bear re-examination in the light of estimates of $K_1G_1(0)$ made using eq. 3.

4. Some miscellaneous notes

4.1 Daily variations

Array studies have traditionally concentrated on disturbance fields of magnetic storms, substorms, and bays, and so interpretations have usually been based on data in a period range of one-half to several hours. In seeking to reduce non-uniqueness in such interpretations, analysis of daily variations is a possible discriminant of the depth of an anomaly. One published example of the value of daily-variation analysis is that given by Bennett and Lilley (1974), which demonstrates that highly conducting material, deduced to exist beneath the ocean water off the southeast coast of Australia, only becomes evident in magnetic variations of period six hours and longer.

For the purposes of array interpretation, the analysis of daily-variation data is different from the traditional problem, because arrays are not basically concerned with the daily disturbance for its own sake; they wish only to exploit it as a low-frequency inducing field. Further, instead of the common observatory situation where just one instrument has recorded many quiet days which are to be analyzed according to traditional time-series techniques, an array produces simultaneous data from many instruments, and it is a great advantage in minimizing the data reduction process if only a few quiet days need be analyzed. In other words an array produces data of a few days from many stations, as opposed to data of many days from a few stations. Other complications which arise in array studies of daily variations are:

(1) The presence of a substantial regional Z component, which may itself induce anomalous fields;

(2) the travelling-wave characteristics of the daily variations;

(3) the systematic repeatability of daily variations, which means that the horizontal polarization day after day is much the same, so that the response of the array area to a variety of polarizations is not seen.

Camfield (1973) carried out a thorough analysis of daily variations recorded by an array in North America, and detected an anomaly with unusual frequency-dependence characteristics which he termed a "Vartran" anomaly.

4.2 Confusion in the definition of phase angle

A scan of the literature which is relevant to magnetometer array studies will show, as elsewhere in science, a confusion between definitions of phase angle. There are two possibilities, one the negative of the other, and in some cases it is difficult to know which convention is being followed. This point is discussed more fully in Bennett and Lilley (1973, p. 41). It is clearly desirable for authors using phase values to define which convention they are adopting. A precedent for geomagnetism was set by Chapman and Bartels (1940, p. 605).

4.3 Station spacing

If it is hoped to detect or study local shallow conductors, then the spacing of array stations should be dense, with stations perhaps as close together as 10 km. If, however, the intention is to study regional fields as in Section 3, the spacing should presumably be much greater, to the point of having stations spanning a whole continent. In between these two extremes, with spacings of order 100 km, have fallen the majority of array operations so far; suitable for the detection of conductivity structure in the upper mantle (but vulnerable to spatial aliassing by structures which are shallower, and narrow). There is probably no way of avoiding in advance the common situation of finding an anomaly just beyond the border of an array; or of perhaps detecting it with just one station only (like point *B* in Fig. 2).

4.4 Relative effort in collecting and interpreting data

A long-standing point regarding magnetic observatory practice is the question of optimum balance between effort expended in obtaining data, and effort expended in interpreting the data obtained. Important qualitative results can often be seen in the basic station records of a magnetometer array study, and at this initial stage of the subject once a set of instruments has been commissioned, valuable returns may be gained by operating arrays consecutively and systematically on a reconnaissance basis.

However, it can probably be fairly said that all arrays so far would benefit from review and extension of their data analyses, especially in connection with widening frequency ranges, and where applicable using the equations of Section 3 above.

4.5 Information from array data regarding source currents

The main purpose of array operations is simply to utilize electric currents which flow in the ionosphere (and beyond) as very fortuitous source-fields for studying electromagnetic induction in the earth. A review of the interpretation of magnetometer array studies would not be complete, however, without pointing out that the observations made may be of value in the study of ionospheric currents. The first application of array data in this way appears to have been made by Rostoker et al. (1970), who linked array phase measurement with development of a substorm electrojet.

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