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# MAGNETOMETER ARRAY STUDIES IN INDIA AND THE LITHOSPHERE

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ABSTRACT

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Two magnetometer array experiments were conducted in India during 1978–1980, under an Indo-Australian collaboration project, using 21 Australian three-component magnetometers of the Gough-Reitzel type. The first array study was made in the northwestern region covering the Aravallis, the Punjab, and the lesser Himalaya, while the second experiment was carried out in the southern peninsular shield area. Both these sets of geomagnetic deep sounding (GDS) observations yielded valuable results on the crustal and upper mantle structure in the two geologically and geophysically important regions of India.

Geomagnetic induction patterns observed in northwest India have revealed a variety of electrical conductivity structures. The primary conductivity structure providing paths for induced currents is found to be striking at right-angles to the Himalayan Mountains. The conductivity structure is indicated to be a northward continuation of the Aravalli belt and, thus, suggesting the continuation of the Indian shield at depth into the base of the Himalayan foothills under the Ganga basin.

The induction effects observed in the southern tip of peninsular India are by far the most complex geophysical phenomenon due to the simultaneous occurrence of the sea coast, the crustal and upper mantle conductivity anomalies between India and Sri Lanka under the sea, and the day-time equatorial electrojet as part of the external heterogeneous inducing field. It is further complicated by the existence of a conductive step, structure along the coastline at the Moho boundary and a "graben" structure in the Palk Strait, as revealed by the array observations.

## INTRODUCTION

### *Electromagnetic induction in the earth and magnetic observatories*

Geophysics may be defined as the study of physical phenomena, both natural and applied, to seek knowledge regarding the evolution, structure and composition of the earth. One major physical phenomenon is that of electromagnetic induction, which takes place on global scales at the surface of the earth, and penetrates inwards

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(according to the skin-depth rules of electromagnetic induction) as far as the upper mantle.

The source fields for such natural electromagnetic induction are electric currents flowing external to the solid earth, in the earth's ionosphere and beyond in the magnetosphere. The transient variations in geomagnetic field which these currents cause at the earth's surface have been a subject for research since they were first observed, more than two centuries ago (see, for example, Chapman, 1967). The observed variations are partly of external and partly of internal origin. The external component is the primary source field originating from electric currents in and beyond the ionosphere, generated by a complex interaction of radiation and plasma flux from the sun with the earth's magnetosphere and ionosphere. The internal part, on the other hand, is the magnetic field of the currents induced electromagnetically in the solid earth by the external field. Since the magnetosphere and ionosphere produce source fields of a few seconds to a few days, the induction process provides us with a probe to study the interior of the earth from a few kilometres to about 1000 km. depth.

The electrical conductivity of sub-surface layers is a parameter of special importance as an indicator of temperature distribution in the earth's interior, as well as of other physical characteristics of the materials inside the earth.

From the time of the last century it was realized that the magnetic fluctuations at the earth's surface are controlled by the electrical conductivity of the earth, and so might be analysed to give information on the earth's interior. A global network of magnetic observatories was required for the separation of the transient variations into their internal and external parts, using spherical harmonic analysis (Schuster, 1889; Chapman, 1919; Chapman and Whitehead, 1922; Lahiri and Price, 1939).

However, as more magnetic observatories were added to the global network it became apparent that strong departures were present in the real earth from the model of it which assumed radial symmetry in electrical conductivity structure, and which traditionally formed the basis for interpreting global observatory data. Firstly, near coastlines the effects of the ocean water and possibly of different geological structure between continent and ocean were identified; and secondly, within continents, some places exhibited anomalous transient variations interpreted in terms of geological "conductivity anomalies" (Schmucker, 1959; Rikitake, 1959; Parkinson, 1959).

The study of magnetic transient fluctuations thus developed as a method of regional geophysical research. Portable magnetic observatories, set up temporarily at field stations either individually, in lines, or in two-dimensional arrays, detected electric currents flowing in the earth in a non-uniform manner. Important theoretical developments occurred regarding electromagnetic induction taking place in horizontally-layered (or "one-dimensional") electrical conductivity structure, and also in "two-dimensional" and "three-dimensional" structures involving departures from such horizontal layering.

The subject became known as "geomagnetic deep sounding", because of the depths (some hundreds of kilometres) to which the magnetic fluctuations penetrated. The electrical conductivity at such depths affected the surface observations, the interpretation of which thus gave information on the deep electrical conductivity.

It was almost half a century after the monumental work of Chapman (1919) and Chapman and Whitehead (1922), that geomagnetic deep sounding (GDS) attained credibility and became one of the modern methods of lithospheric investigations. It became possible thanks to the development of a special type of portable, inexpensive magnetometer (Gough-Reitzel, 3-component). The method consists in collecting simultaneous records of transient geomagnetic variations from a two-dimensional array of magnetometers deployed in a regular grid pattern, and their analysis and interpretation using modern computers (Reitzel et al., 1970; Porath et al., 1970), over regions of geological interest.

In the continental regions, the conductivity at first drops rapidly from $10^{-1}$ s/m with increasing depth as the influence of the conductive sediments, moist sub-surface rocks, etc. decreases. The average conductivity of the remaining upper 400 km of the earth is rather low, in the range of $10^{-3}$–$10^{-2}$ s/m. At a depth of about 500 km, it starts rising very rapidly attaining a value of $10^{-1}$ s/m at 700 km. At about 2000 km depth, this quantity has been estimated as $10^{2}$ s/m. Results of many GDS and Magneto Telluric Sounding (MTS) surveys have suggested the existence of extensive localized layers of materials having conductivities greater than $10^{-1}$ s/m even in the upper 400 km of the earth. Such high conductivity values are very often caused by electrolytic conduction in saline solutions in zones of mineralization or by partial melting in the mantle. The frequency of occurrence of such conductive regions is relatively high, and it no longer seems possible to consider the upper 400 km of the earth as a region of generally uniform and low conductivity (Hutton, 1976).

### *Magnetic observations and array studies in India*

Observations of the magnetic field in India date back to the establishment of the Colaba Magnetic Observatory at Bombay in 1846. Moos (1910) gave a detailed analysis and an excellent discussion of the 60 years of the Colaba magnetic data (1846–1905), and the geomagnetic phenomena. Subsequently, a network of permanent magnetic observatories was developed, operated by the Indian Meteorological Department, the Indian Institute of Geomagnetism (IIG), the Survey of India, the Indian Institute of Astrophysics and the National Geophysical Research Institute (NGRI). The number of such permanent observatories in India is now eleven, extending from Gulmarg in the Kashmir Himalaya in the north to Trivandrum at the southern tip of India.

Srivastava (1966, 1970) found that the large quiet-day ranges in the vertical component $Z$ at Alibag were almost double that of Hyderabad while the $H$ and $D$ ranges were comparable, and attributed this to a coast effect at Alibag. Again, Srivastava and Sanker Narayan (1967, 1969, 1970) identified and delineated for the first time the induction anomalies in short-period variations (SSCs and bays) as well as long-period variations (Sq and Dst) from the records of the existing permanent observatories located in peninsular India. They interpreted them in terms of the coast effect due to oceanic induced currents in the Arabian Sea, the Indian Ocean and the Bay of Bengal, and upper mantle conductivity structure, the anomaly being most severe at Trivandrum. Srivastava and Sanker Narayan (1969) and Nityananda et al. (1977) also noted that not only the $Z$ variations for short period events during night hours were anomalously large near the peninsular tip, but also the $H$ and $D$ variations were anomalous at Annamalainagar and Trivandrum, due to oceanic induction effect.

To explore for geological information in addition to that available from the records of the permanent observatories, records from two lines of temporary observing stations in peninsular India were obtained and discussed by Srivastava et al. (1947a, b). For the same reason two arrays of magnetometers were operated between 1978 and 1980, in collaborative studies between the Indian Institute of Geomagnetism, the National Geophysical Research Institute, and the Australian National University. These two array studies will now be described individually along with their geological and geophysical implications.

## THE MAGNETOMETER ARRAY STUDY IN NORTHWEST INDIA

### *Sites*

The station sites for the instruments of the northwest Indian magnetometer array are shown in Fig. 1. The network includes three permanent magnetic observatories, and 21 installations of Gough-Reitzel magnetic variometers, as constructed at the Australian National University and described by Lilley et al. (1975).

Installations of the temporary observatories took place between December 1978 and April 1979, and the instruments operated, with various starting and finishing times, between March and June 1979. While operating, each instrument made observations at 1 min. intervals of the three magnetic variation components, $H$ (magnetic north), $D$ (magnetic east), and $Z$ (vertically downwards). We now summarize some of the important results of the array operation, as described in more detail by Lilley et al. (1981) and Arora et al. (1982).

### *Stacked profiles of magnetic fluctuation events*

Consistent with an observation period of several months, the northwest Indian array recorded a variety of quiet-day and magnetic disturbance events. One substorm is shown in Fig. 2, as recorded by fifteen stations. To produce stacked profiles such as in Fig. 2, original film records from the Gough-Reitzel instruments are

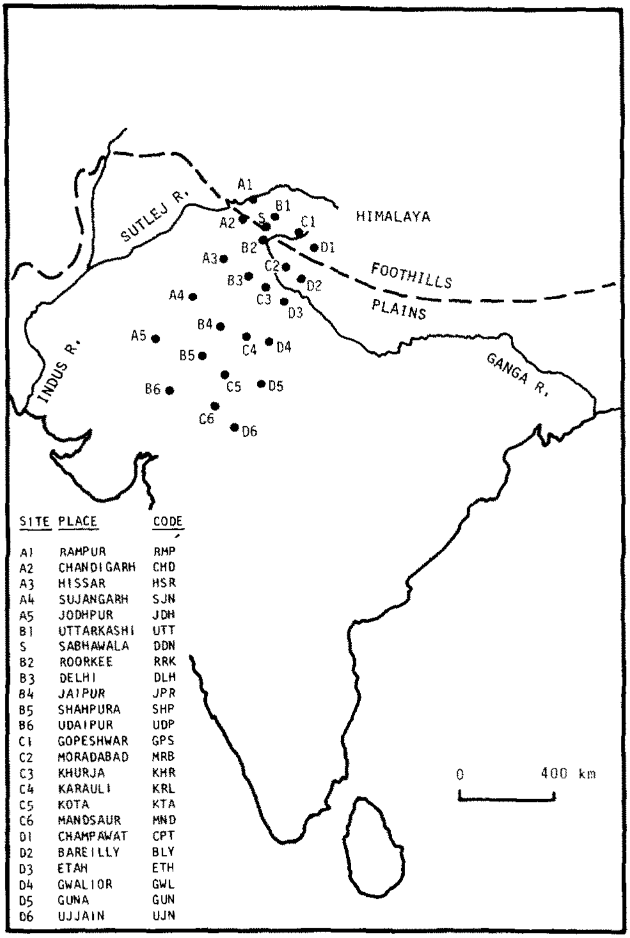


Fig. 1. The observation sites of the 1979 magnetometer array study in northwest India.

digitized, correction is made for a known interaction between the $H$ and $Z$ sensors, and the calibration factors of the different instruments are taken into account. The geographic north and east magnetic components of the variations are calculated by resolving the observed magnetic $H$ and $D$ components (for northwest India the magnetic declination is very small, and $H$ and $D$ approximate $X$ and $Y$ very closely). Figure 2 also shows an extra set of fluctuation profiles, for the total field $T$. These total field fluctuation profiles have been produced by resolving the component data $H$ and $Z$ in the direction of the steady ambient geomagnetic field $T$ (the $D$ fluctuation component contributes negligibly to the total-field fluctuation). Computation and presentation of such total-field data have not been customary in previous geomagnetic deep sounding studies. However, the profiles are presented here both for their own interest, and also for their relevance to a reduction process for aeromagnetic data, as discussed below.

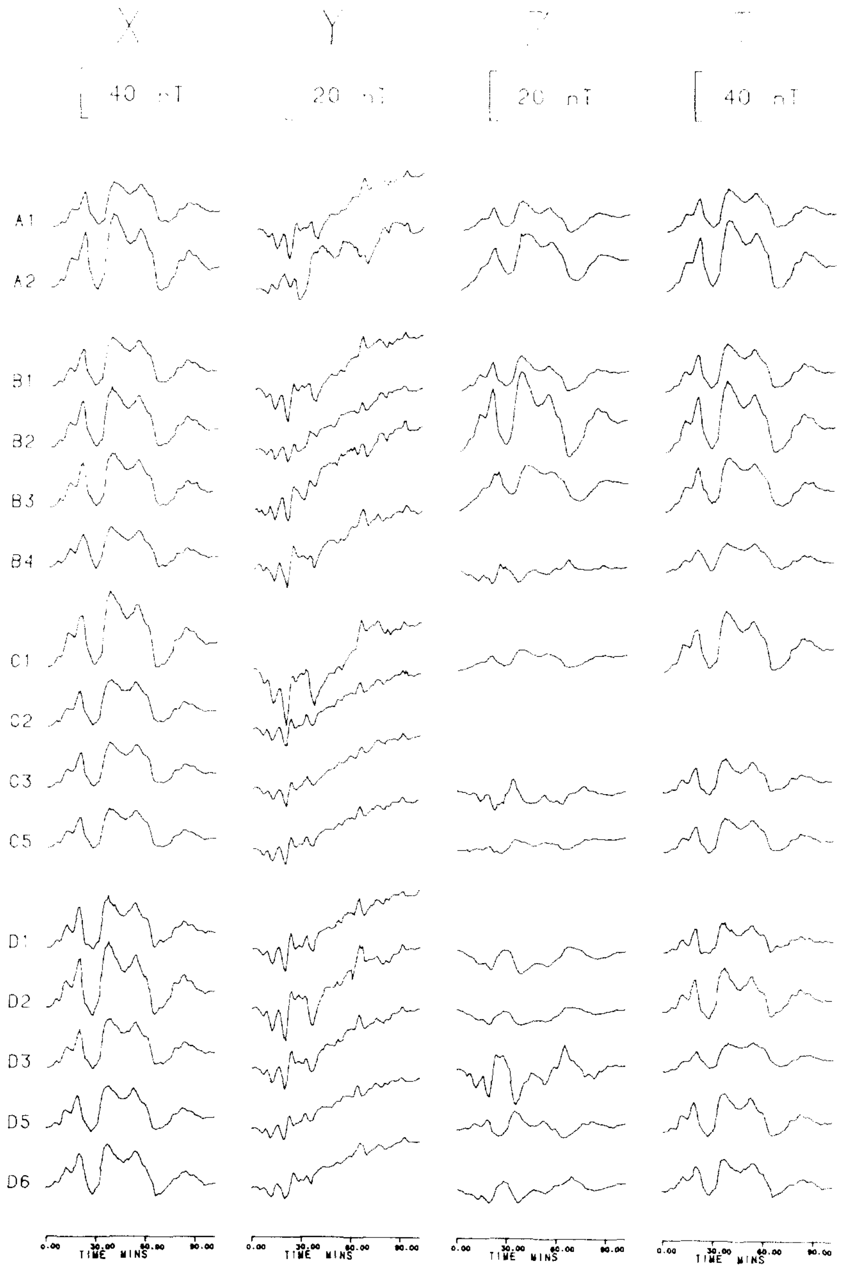


Fig. 2. Stacked variometer profiles for the substorm event of 5 April 1979, starting at 1559 U.T. approximately, and of 102 min. duration. The notations $X$, $Y$ and $Z$ denote the magnetic fluctuation components in the directions of geographic north, east and vertically downwards. The notation $T$ denotes the magnetic fluctuation component resolved in the direction of the local ambient main geomagnetic field, as would be measured by a total-field magnetometer. Note that the components are not all plotted to the same vertical scale.

The stacked profiles in Fig. 2 summarize much information. The strongest geophysical effect is perhaps in the contrasts between the vertical component ($Z$) signals at certain stations, for example where a complete reversal of the fluctuation characteristic is seen between sites $B2$ (Roorkee) and $D3$ (Etah). This phenomenon, occurring consistently as it does for a number of substorms, indicates a concentration of induced current flow inside the ground along a path running through between these two stations.

The horizontal components in Fig. 2 also show departures from uniformity, and are marked by their surplus strength where anomalously strong ground currents are flowing beneath some of the recording stations.

*Response arrows determined*

Following a widely used procedure for the analysis of magnetic fluctuation data (Schmucker, 1964, 1970; Everett and Hyndman, 1967), anomalous vertical-component ($Z$) signals apparent at many of the stations in Fig. 2 are found to be related to the horizontal-component signals $X$ and $Y$ by the simple equation:

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

where $A$ and $B$ are functions of geographical position and $A$, $B$, $X$, $Y$ and $Z$ are all functions of the frequency of magnetic fluctuations, and are complex with real and quadrature parts. The functions $A$ and $B$ ideally are determined by earth electrical conductivity structure. While particular theoretical models predict that eq. 1 will be obeyed, its application to general data is an empirical approach. Substorm events of different polarization characteristics are needed to make good determinations of the $A$ and $B$ functions, and if $A$ and $B$ are to be interpreted in terms of geological structure, care must be taken to minimize any biassing effect on their determination that non-uniform source field effects might have.

Values of $A$ and $B$ thus determined may be combined to form arrows which, plotted on a map, indicate regions of anomalously high electrical conductivity by pointing towards paths of current concentration in the ground. In the present work, separate arrows are constructed for both the real and quadrature parts of $A$ and $B$, and following the convention of Parkinson (1962) such arrows are plotted with components $A$ south and $B$ west.

Such a set of arrows, for a period of 91 min, is shown for the northwest Indian array in Fig. 3 (from Arora et al. 1982), superimposed on a sketch map of some main tectonic features of India. In the determination of the arrows shown in Fig. 3, the horizontal fields $X$ and $Y$ in eq. 1 above have been taken as those at Karauli (C4); if Karauli records were not available then those at Khurja (C3) or Kota (C5) were used.

*Interpretation in terms of conductive structures*

Conductive structures marked $I$–$VI$ are shown in Fig. 3. These structures have been interpreted not only from the arrows shown, but also from arrow patterns at

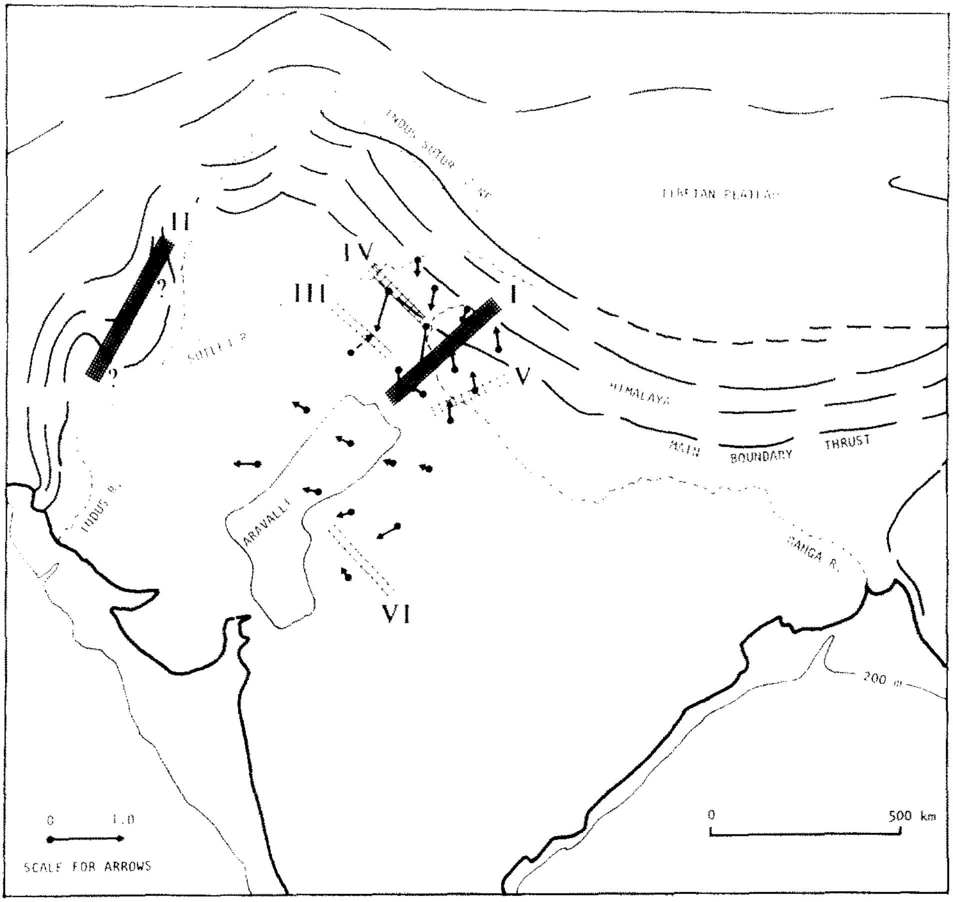


Fig. 3. Map of India, showing real Parkinson arrows determined for magnetic fluctuations of 91-min period, with superimposed the interpreted conductive structures *I–VI*. The positioning of structure *II* is provisional. Structures *I* and *II* are classed as "first order", and structures *III–VI* are classed as "second order".

shorter periods, and particularly from maps of Fourier transform parameters obtained from the response of different stations to substorms such as that shown in Fig. 2. More arrow patterns, and several sets of such Fourier transform parameter maps, are given in Arora et al. (1982).

There are two "first-order" structures, marked *I* and *II*. The position of structure *I* is relatively well-controlled by the array stations. The structure strikes across the Ganga Basin, at a depth of the order of 50 km, and is interpreted as a continuation of the Aravalli Belt being thrust down by the collision of India and Asia, and made highly conductive by the conditions of stress and temperature which it is experiencing.

The presence of structure *II* to the west of the array area is indicated by the consistent westward-pointing arrow pattern for stations in the southern half of the array. The position of structure *II* is uncertain. The closest line of "good conductor" to the west may be the sediments of the Indus Valley; however, the arrows have a weaker quadrature component than would be expected for induction in sediments. In Fig. 3 therefore the conductor has been placed at the boundary of the Indian and Asian plates where strong shearing is known to have occurred at the time of collision of India with Asia (Molnar and Tapponnier, 1975). Such an interpretation for the western conductor remains provisional, pending further observations.

Structures *III–VI* are classed as second order and are interpreted from a range of characteristics of the reduced data. Structures *III* and *IV* have been placed at the boundaries of the Ganga Basin, the sediments of which may be expected to be highly conducting and to influence magnetic fluctuation patterns. Structure *V* follows a trough in the Ganga Basin bounded by the Delhi–Hardwar Ridge on the west and the Moradabad Fault to the east. Structure *VI* is thought to be correlated with an extension of the sediments of the Godavari Valley.

### *Difference profiles and relevance to aeromagnetic surveying*

It is also sometimes of interest, given a set of stacked profiles as shown in Fig. 2, to construct difference profiles by subtracting the signals observed at some reference station from the signals observed at all other stations. Such a set of difference profiles is shown in Fig. 4, where the reference station has been taken as Kota (*C5*).

The difference profiles show again many aspects of the conductive structures already discussed; especially where the main anomalies occur. The total-field differences, however, may have an extra relevance to magnetic surveying (and particularly to aeromagnetic surveying) as is now to be described.

In regular magnetic survey practice, substorms such as shown in Fig. 2 are an undesirable cause of difficulty, as the intention of the survey is to measure spatial changes in the magnetic field of the earth, relative to some reference level which is steady with time. Changes in the magnetic field which occur with time during the survey process are thus a source of possible error, and the best conditions for magnetic surveying are magnetic "quiet days". Even so careful survey reduction procedures are necessary to correct for time-dependent magnetic variations which also occur during a survey, and especially as some surveying inevitably takes place during more disturbed magnetic conditions. A further reduction procedure made feasible since the development of absolute measuring magnetometers (such as the proton-precession magnetometer) involves operating a temporary observatory at a fixed base station to monitor changes of the magnetic field with time, and then to subtract this base station record point-by-point from the simultaneously observed record from the survey aircraft. Such a reduction procedure depends for its effectiveness on the temporal variation of substorm fluctuations being the same at the moving aircraft as at the base station. An array study like that described above for

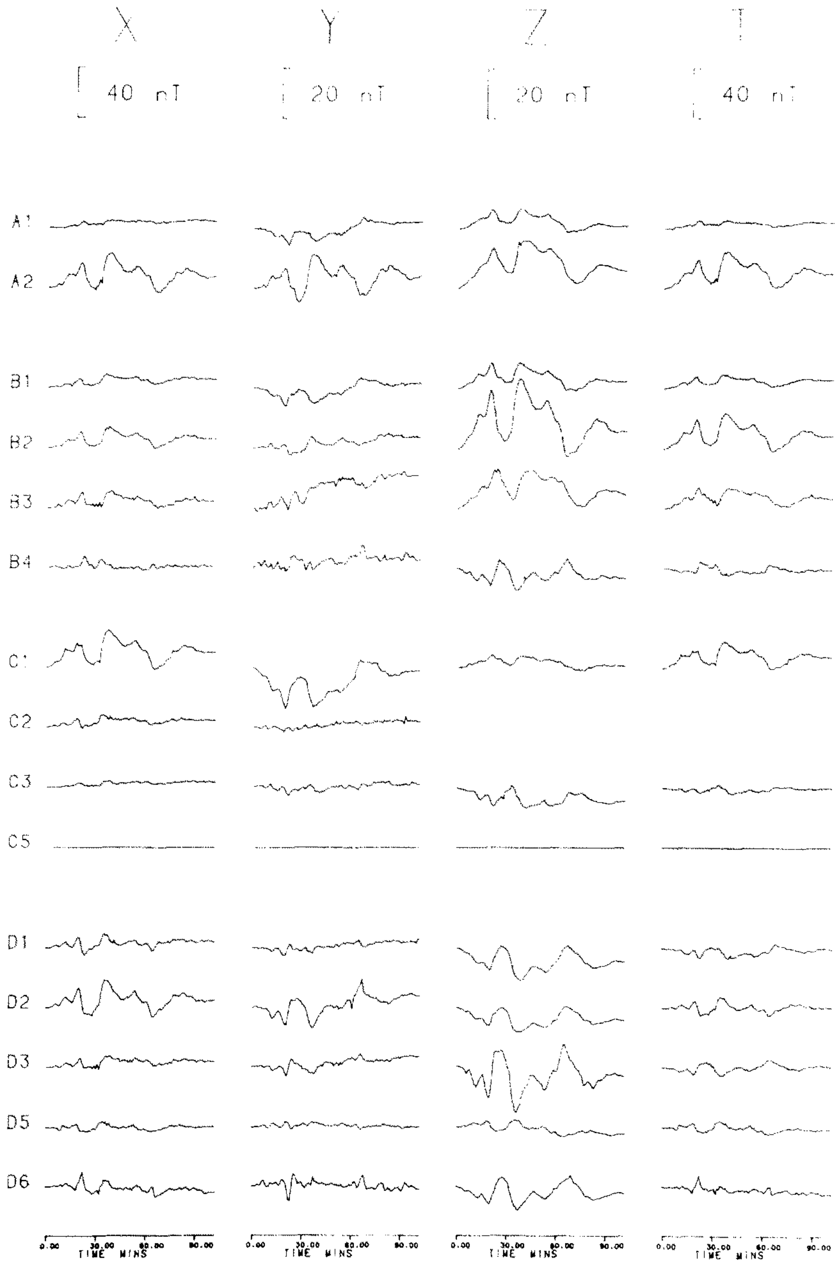


Fig. 4. Stacked difference profiles, obtained from the data of Fig. 2 by subtracting the appropriate component recorded at Kota (*C5*) from the records of every other station. Note that as in Fig. 2 the components are not all plotted to the same vertical scale. Note also particularly some large contrasts in the *T* profiles, for example between *A1* (Rampur) and *A2* (Chandigarh), so that a total-field base station at the former site would give a poor estimate of total-field fluctuations occurring at the latter site.

northwest India shows the extent to which this condition holds over areas of the scale of those covered by an aeromagnetic survey.

In particular, the total-field profiles of Fig. 4 indicate differences relative to a base station at Kota (*C5*). It can be seen that away from the main electrical conductivity anomaly (structure I) the differences are relatively weak, with maxima for the substorm shown of order 5 nT, whereas near the anomaly there are times when differences arise of the order of 30 nT. The point demonstrated is that aeromagnetic surveys in areas of conductivity anomaly (and in the case of northwest India near structure *I*) may require extra care in the data reduction process, especially for data recorded at times other than those of magnetic quiet. Subtracting the record of a fixed base station from a survey record may not be an effective way of correcting for substorm temporal variation in areas of electrical conductivity anomaly.

### *Comments on the results of the northwest India array study*

Although much numerical computation has been necessary in the production of the stacked profiles and arrow patterns presented in this paper, the interpretation given above is basically qualitative: that particular electrical conductivity anomalies have been discovered. Such results are entirely appropriate for a reconnaissance study. Future field observations may well expand the boundaries of the area covered, and also occupy a denser network of stations in the regions now shown to be of interest.

The numerical modelling of such observed field data to derive an interpretation in terms of quantitative electrical conductivity structures is a major frontier in present-day geomagnetic research. Some important theoretical problems are involved, perhaps most notably the extent of the "induction region" for an anomaly such as that associated with structure *I*. Is the current concentrated in structure *I* induced locally, or is it induced much more widely (even globally) and channelled in the structure *I* like a large-scale steady-current flow? For the case of structure *I* there is also the important question of how far into the mountains does the electrical conductivity anomaly extend.

## THE MAGNETOMETER ARRAY STUDY IN SOUTH INDIA

### *Sites*

The station sites for the instruments of the second array experiment in south peninsular India are shown in Fig. 5. The array was operated with the same 21 Gough-Reitzel type magnetometers of the Australian National University, Canberra, as the northwestern array. Installation of the temporary observatories in south India was carried out between September and December 1979, and the instruments

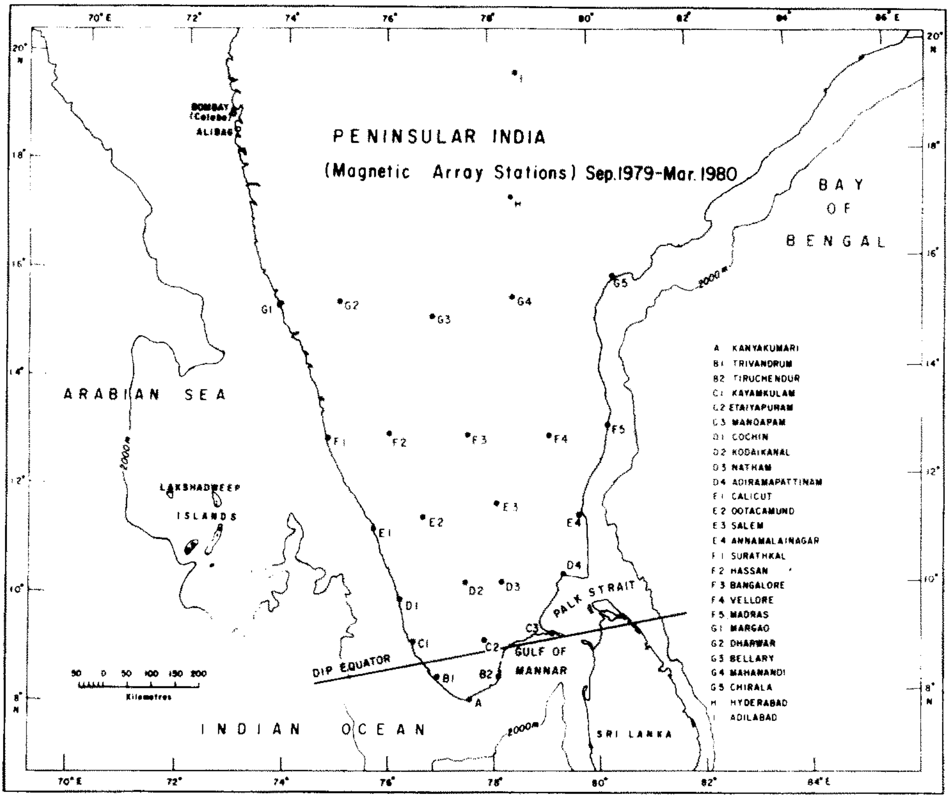


Fig. 5. Magnetic array stations of the second experiment in south peninsular India operated during September 1979–March 1980.

operated simultaneously between December 1979 and March 1980. As before, the instruments made observations at 1-min intervals of the three components $H$, $D$ and $Z$.

The array data were further supplemented with simultaneous records from five permanent magnetic observatories operating in the region.

Some of the important results of this array experiment are described in detail by Thakur et al. (1981) and Srivastava et al. (1982). Analysis and interpretation of the array data are still in progress.

*Stacked profiles of a magnetic substorm event*

In the southern array again, a variety of quiet-day and magnetic disturbance events was recorded. One night-time substorm is reproduced in Fig. 6, and another in Fig. 7.

In the region of southern peninsular India, the source field is highly non-uniform during day hours due to the presence of the equatorial electrojet over the dip

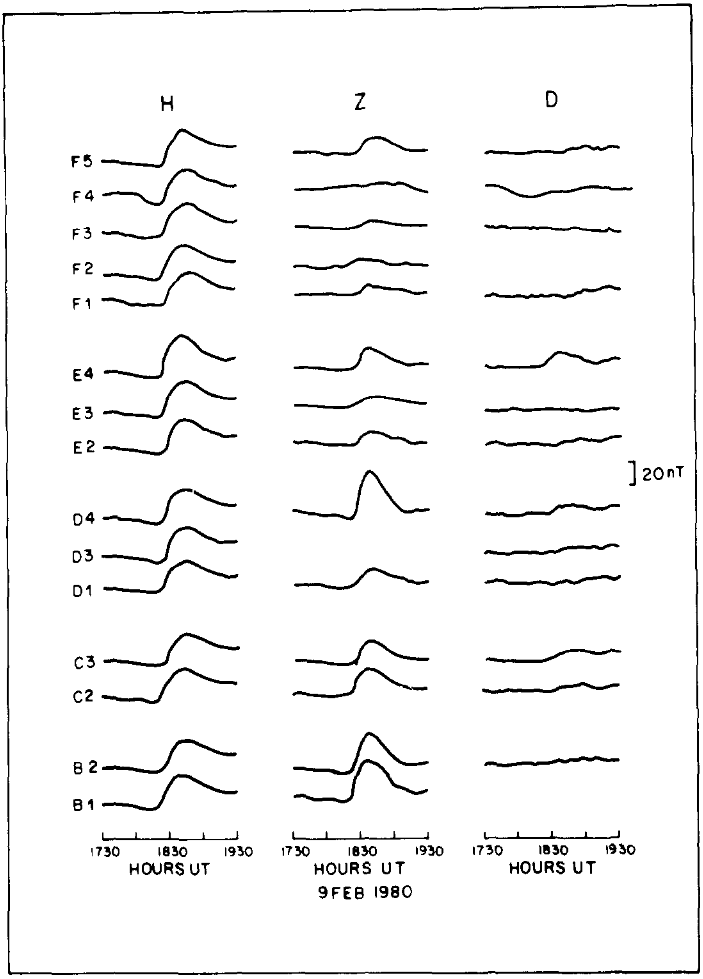


Fig. 6. Stacked variometer profiles (*H*, *Z*, *D* components) for the substorm event of 9 February 1980, starting at 1822 U.T., over a duration of about 1 h, at the array stations in south peninsular India.

equator, at a height of about 100 km in the E-layer of the ionosphere. This makes the detection of local induction anomalies in day-time events rather difficult. However, the night-time events clearly reveal the anomalous induction effects. Anomalies in short-period variations (SSCs and bays) as recorded at the coastal observatories at Trivandrum (*B1*), Annamalainagar (*E4*) and Alibag were identified and delineated and the severity of the *Z*-anomaly at Trivandrum pointed out, a decade ago, by Srivastava (1970). An interpretation of these anomalies in terms of oceanic induced currents and upper mantle conductivity was also given (Srivastava and Sanker Narayan 1967, 1969, 1970). Not only the *Z* variations are anomalously larger in the electrojet region, the *H* and *D* variations are also anomalous at Annamalainagar

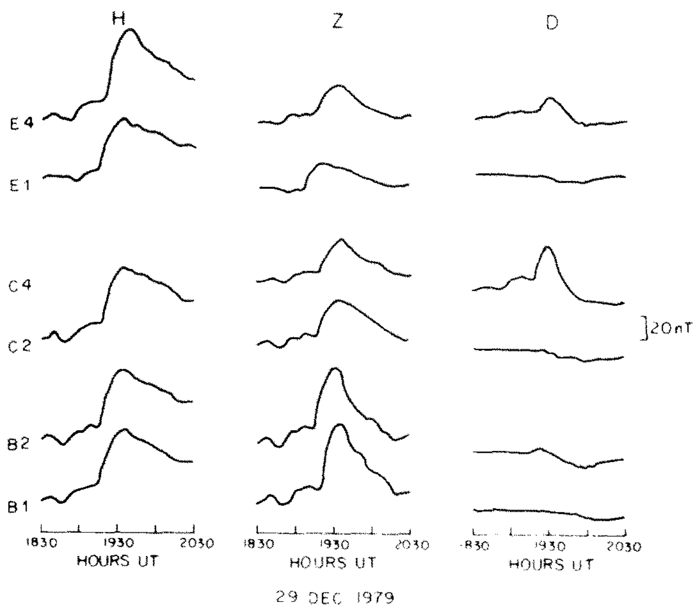


Fig. 7. Stacked variometer profiles ( $H$, $Z$, $D$ components) for the substorm event of 29 December 1979, starting at 1917 U.T., over a duration of about 1 hr, at the southern array stations.

( *E4* ) and Trivandrum ( *B1* ) (Srivastava and Sanker Narayan, 1969; Nityananda et al. 1977). The induction arrows are also very large at the two coastal stations of Annamalainagar ( *E4* ) and Trivandrum ( *B1* ), as well as the inland station Kodaikanal ( *D2* ), indicating higher oceanic conductivity (Nityananda et al., 1975; Srivastava and Habiba Abbas, 1980).

*Interpretation of the records*

It will be readily seen from Figs. 6 and 7, that the anomaly in $Z$ is unusually strong at Adiramapattinam ( *D4* ). The amplitude of $Z$-variation is even greater than the amplitude of $H$-variation at the station, similar to Trivandrum. Figure 7 shows not only an appreciable anomaly in $Z$ at Mandapam (C3) but a very large anomaly in $D$-variation as well. Furthermore, the anomalies in $Z$ are more pronounced on the east coast as against the west coast in the southern peninsular tip of India. The large anomaly in $Z$ at Adiramapattinam ( *D4* ) and Tiruchendur ( *B2* ), coupled with a large anomaly in $D$ at Mandapam, cannot be explained in terms of a normal coast effect. The channelling of internal currents through a conductor in the upper mantle or lower crust between India and Sri Lanka island beneath the Palk Strait alone could give rise to such large induction anomalies (Nityananda et al., 1977; Rajaram et al., 1978). The question of anomalously large $Z$-variations and the suppression of $H$-variations in the equatorial electrojet region of India as compared to the American region can also be resolved partly by assuming induced currents channelling between India and Sri Lanka.

The geological conductor seems to be associated with the India–Sri Lanka graben (a triple junction rift) suggested by Naqvi et al. (1974) and Burke et al. (1978). The geomagnetic observations suggest that the conductor has a north–south trend near Mandapam (*C3*) and is quite close to it since it affects the $D$-variations severely. Larger $Z$-variations on the east coast could be due to its closeness to the Pondicherry rift. A conductive step structure at the Moho boundary along the coast in the southern peninsular region and the associated current concentration therein, along with the induced currents in the sea water, would also make significant contributions to the observed anomalous geomagnetic variations (Srivastava and Habiba Abbas, 1980).

## CONCLUDING REMARKS

The Indian sub-continent contains strong electrical conductivity contrasts, and the unravelling of its electric current path connections with the oceans and with Asia provides an important geophysical challenge. In stimulating the investigation of such problems, the Indian magnetometer array studies complement similar projects taking place in other continents.

There is another point regarding interpretation philosophy which may appropriately be made here. In the trial stages of magnetometer arrays, as of any new development, it is natural to accept results only to the extent that they agree with what is already known of geologic structure. However, for a new development to produce new information it is ultimately necessary for the results of the development to be accepted on their own basis. Magnetometer array studies may now be at this stage, giving information on electrical conductivity structure in the lithosphere and asthenosphere which is not obtainable in any other way.

GDS and MT studies are also desirable in the regions of the Deccan Traps, the Narmada, Godavari and Koyna rifts, the Cuddapah basin, the southern tip of the Indian peninsula together with Sri Lanka, and the syntaxial zones of the Kashmir Himalaya and the Assam Himalaya. The studies in the Himalaya will also bring out the association of induction anomalies with seismicity and plate margins. Analogue and theoretical model studies of the various situations encountered in the induction problem in India are also necessary for better appreciation and interpretation of the observations in terms of lithospheric parameters.

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