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A magnetometer array study in northwest India

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A magnetometer array study has been carried out in northwest India, from Rajasthan across the Indo-Gangetic Plain into the Himalayan foothills. Over the three months of operation, a wide variety of natural geomagnetic events has been recorded. The analysis of a simple substorm, polarized just west of north, shows a strong anomaly in the form of a reversal of the vertical component of the fluctuation, both in the Himalayan foothills and on the Ganga Plain.

The magnetic fluctuations pattern observed is most directly interpreted in terms of a path of concentrated current flow in the Earth, striking across the Himalaya. It is evidently aligned with the Aravalli belt which outcrops further south, and may indicate that some geological structure in the sub-basement is of abnormally high electrical conductivity. The path of such a current concentration across the foothills raises the question whether some transverse structure in the Himalaya is not acting as a bridge to Peninsular India for current induced in the Tibetan plateau to the northeast.

1. Introduction

A magnetometer array study was carried out in northwest India in 1979 as a collaborative exercise by the Indian Institute of Geomagnetism (IIG), the National Geophysical Research Institute of India (NGRI) and the Australian National University. The area investigated is shown in Fig. 1, and more details of site positions and codes are given in Table I, including the three regular observatories of Sabhawala, Jaipur and Ujjain, which formed part of the array. The area was selected because of the classic nature of the Himalaya mountains in the study of global geology and geophysics. The response of such a type area to global geomagnetic induction may greatly assist in the interpretation of electrical conductivity anomalies found elsewhere in the world, besides contributing to the fundamental understanding of Himalayan geology.

Observations of the geomagnetic field on a regular basis first began in India in 1846 when the Colaba Observatory was established at Bombay. There are now eleven magnetic observatories distributed over the Indian subcontinent. Magnetic fluctuations at some of these observatories have been analysed for information on geomagnetic induction by Srivastava and Prasad (1974), Nityananda et al. (1977), Singh et al. (1977), Srivastava (1977), Jain and Sastri (1978), Agarwal et al. (1979) and Rajaram et al. (1979). Magnetic fluctuation studies based particularly on temporary observatories have been carried out on two traverses across the Indian Peninsula by Srivastava et al. (1974a, b).

The northern observatory of Sabhawala is situated just in the Himalayan foothills, and determinations of Parkinson arrows have been made for it by groups at both the NGRI and the IIG (see Srivastava and Abbas, 1980; Nityananda et al.

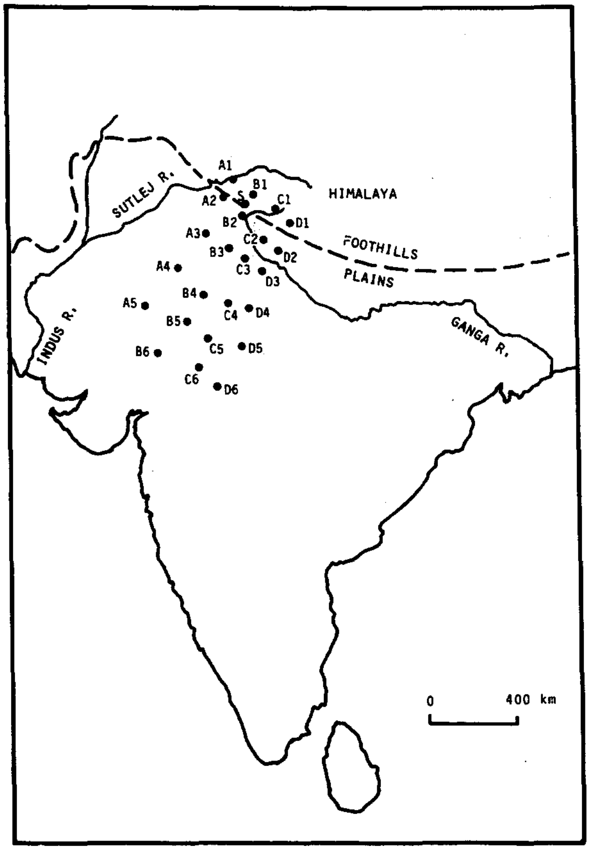

Fig. 1. Sites occupied in magnetometer array study in northwest India. Codes are according to the key in Table I. Sites S, B4 and D6 are the permanent observatories of Sabhawala, Jaipur and Ujjain respectively.

1981, this issue; Srivastava, 1981, this issue). Parkinson arrows summarize the vertical-field fluctuations likely to occur with particular horizontal-field fluctuations of given direction, and the existence of such arrows for Sabhawala indicates that the geology of the region must somewhere depart from simple one-dimensionality in its electrical conductivity structure. Therefore, somewhere electrical conductivity must vary laterally, and the directions determined for the Sabhawala arrows indicate that the better electrical conductor of such a conductivity contrast lies on the southern (plains) side of the observatory.

This result may be due to a variety of geological factors, perhaps in combination. On the basis of the geological structure of the area as presently understood, such factors include the possibility of high electrical conductivity in the deep sediments of the trough below the Indo-Gangetic Plain; the possibility of a step upwards in a well-conducting asthenosphere where the crust thins south of the Himalaya in accordance with isostatic models; and some effect associated with a possible asthenospheric upwelling beneath the Aravalli belt, a major geological structure of the Indian shield.

This paper presents the first results from the 1979 array, intended to expand greatly the information held on the magnetic fluctuation patterns of northwest India. Operational details of the array are recorded, and the geomagnetic induction behaviour of the area for a particular simple substorm event is analysed. A strong anomalous effect is evident which is interpreted directly in terms of electric current concentration in the Earth along some geological structure of high electrical conductivity. In the present case the result obtained is, perhaps surprisingly, current flow perpendicular to, rather than parallel with, the strike of the Himalaya mountains. The current pattern directly traverses the foothills to the plains and may map as a crustal basement or upper mantle structure some extension of the Aravalli belt. Such an extension would be northeast from the area of outcrop of the Aravalli belt, under the Ganga sediments, and into the base of the Himalaya foothills.

2. Operational details

The array study was carried out under the India–Australia Science and Technology Agreement. Twenty-one Gough–Reitzel variometers of the Australian National University (described by Lilley et al., 1975) were taken to India in November 1978 for the array study described here, and also for a second array study carried out subsequently in southern India. The instruments were installed at the sites shown in Fig. 1 between December 1978 and April 1979 and operated, with various starting and finishing times, between March and June 1979. While operating, each instrument made observations of three magnetic fluctuation components at 1 min. intervals.

TABLE I
Observing sites, 1979, Northwest India array

Site	Place	Abbreviation	Latitude (° ′) (north)	Longitude (° ′) (east)
A1	Rampur	RMP	31 28	77 43
A2	Chandigarh	CHD	30 43	76 54
A3	Hissar	HSR	29 16	75 48
A4	Sujangarh	SJN	27 43	74 30
A5	Jodhpur	JDH	26 18	73 07
B1	Uttarkashi	UTT	30 45	78 26
S	Sabhawala	DDN	30 22	77 48
B2	Roorkee	RRK	29 54	77 56
B3	Delhi	DLH	28 38	77 16
B4	Jaipur	JPR	26 55	75 48
B5	Shahpura	SHP	25 39	74 56
B6	Udaipur	UDP	24 37	73 46
C1	Gopeshwar	GPS	30 22	79 23
C2	Moradabad	MRB	28 49	78 49
C3	Khurja	KHR	28 13	77 56
C4	Karauli	KRL	26 27	77 06
C5	Kota	KTA	25 12	75 58
C6	Mandsaur	MND	24 05	75 09
D1	Champawat	CPT	29 21	80 07
D2	Bareilly	BLY	28 22	79 27
D3	Etah	ETH	27 32	78 40
D4	Gwalior	GWL	26 16	78 10
D5	Guna	GUN	24 40	77 17
D6	Ujjain	UJN	23 11	75 47

3. Data recorded

A great variety of magnetic activity, from quiet days to strong storms, was recorded by the array over the three months of operation. As has often been the case with previous array studies, the electrical conductivity characteristics of the area covered are most clearly seen in simple substorm events, and with a wide range of activity recorded it is possible to choose such events for analysis. Thus Fig. 2 shows records for a simple magnetic event, collected from all the variometers in operation at that time. The variometer film records have been digitized, normalized for their respective calibration constants, and corrected for (known) interaction between the H and Z sensors in the usual manner (Lilley et al., 1975). Figure 2 is supplemented by Fig. 3, which shows vertical-field records for most of the stations missing them in Fig. 2, for other events of similar characteristics and polarization.

4. Contour maps of Fourier transform parameters

Following the method for array studies developed by Reitzel et al. (1970), the substorm event of Fig. 2 has been analysed in the frequency domain by carrying out Fourier transformations on all the recorded profiles according to

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

after first subtracting, as a linear trend, any difference which may occur in the amplitudes of the first and last points of a particular record. For such estimates of the Fourier transform $g(\omega)$ to be valid it is important that the geomagnetic event

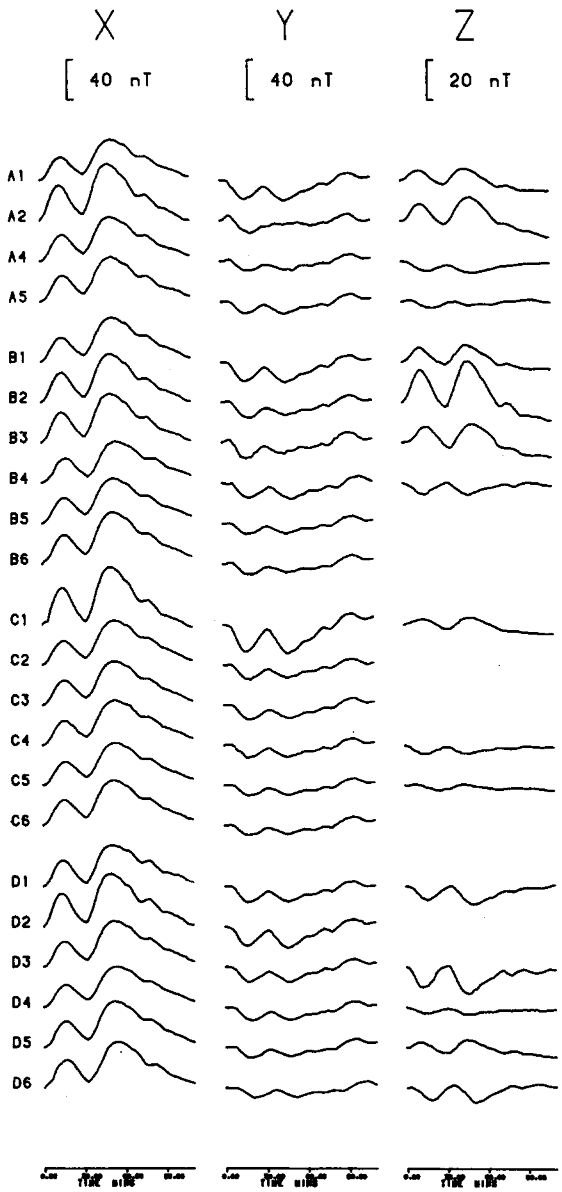

Fig. 2. The geomagnetic substorm event of April 29, 1979 as recorded by the magnetometer array. The records shown are of 110 min. duration, and commence at 20 h 54 min. UT approximately. X, Y and Z represent the variation components in the geographic north, east and vertically downward directions respectively.

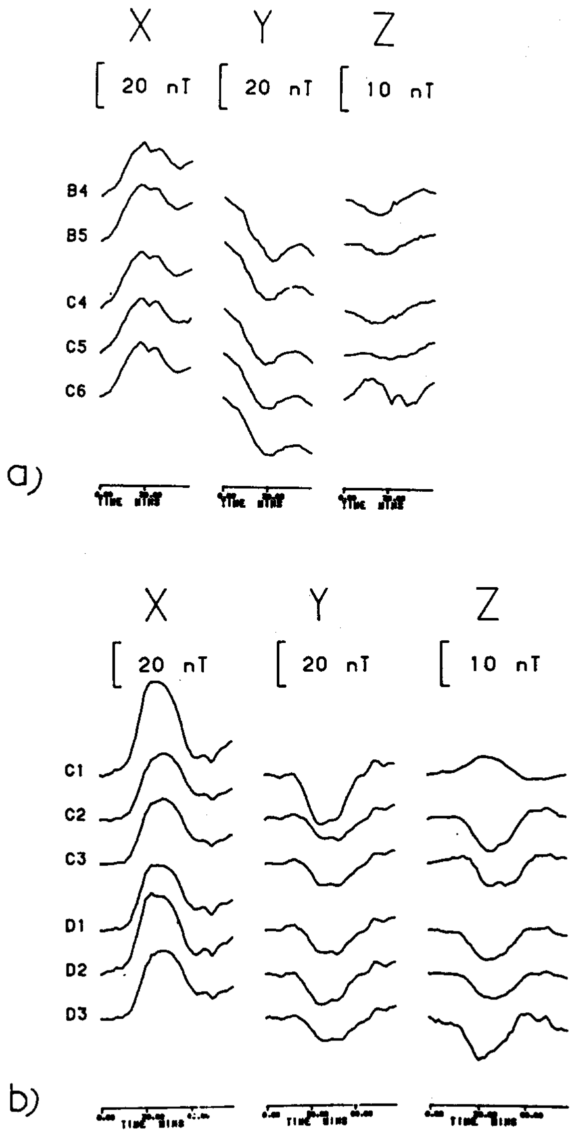

Fig. 3. Supplementary events showing Z traces for stations missing from Fig. 2, for substorm events of similar horizontal polarization. (a) The event of April 22, 1979. The records are of 60 min. duration and commence at 6 h 5 min. UT approximately. This daytime event can be seen to have the background trend of quiet daily variation. (b) The event of April 2, 1979. The records are of 88 min. duration and commence at 15 h 48 min. UT approximately.

has been recorded essentially complete, so that the time series of it, $f(t)$, can be transformed without truncation. At each particular frequency in the Fourier transform spectra for a given station there will then be a particular horizontal polarization ellipse (Lilley and Bennett, 1972). Figure 4 presents results obtained thus for the event of Fig. 2

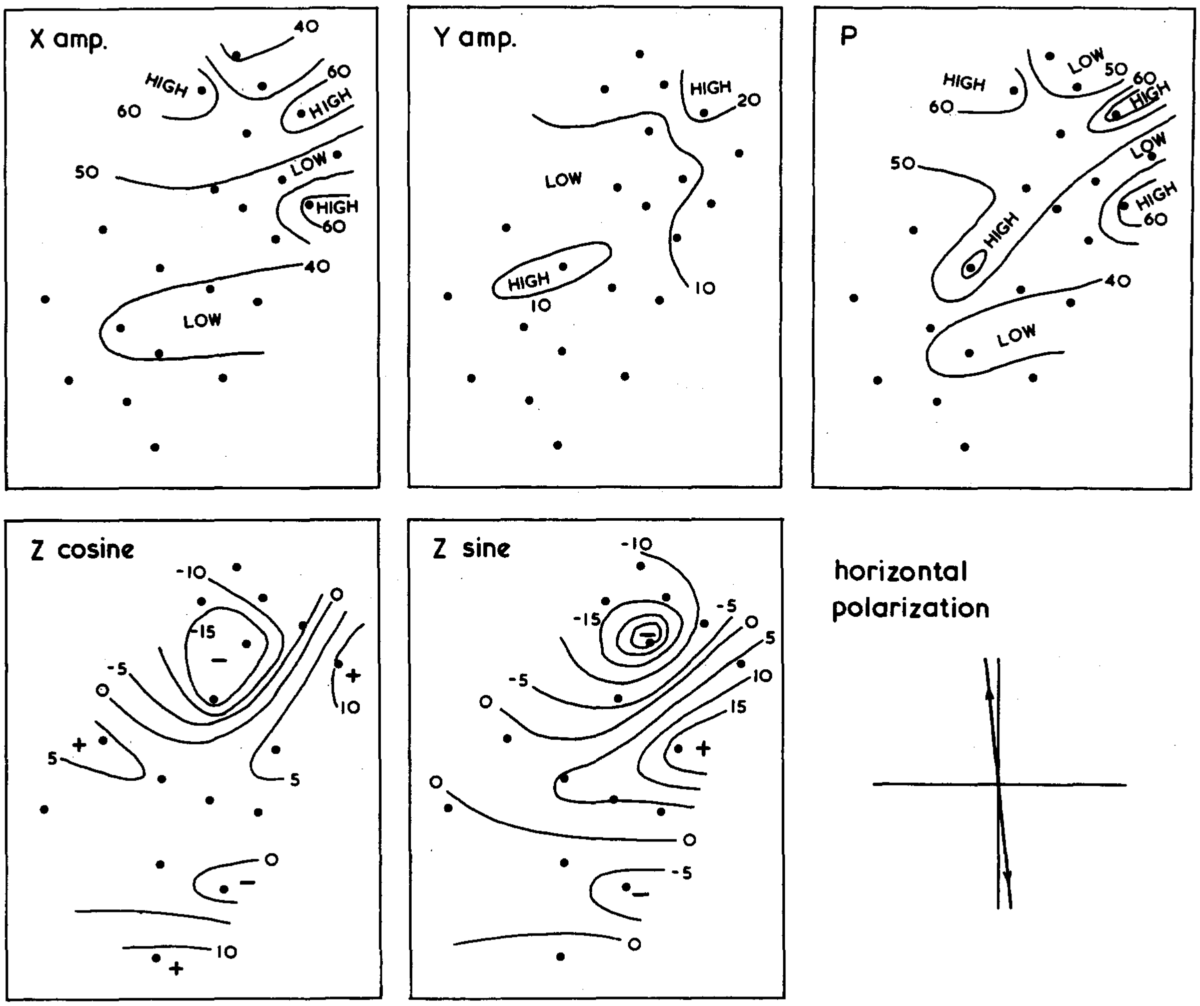

Fig. 4. Contour maps of Fourier transform parameters obtained for the event of Fig. 2 at the period of 38 min. Also shown is the horizontal polarization for station D5, which is linear and of bearing 6° west of north. Units of the contours are tens of nT rad^{-1} min.

at the Fourier transform period of 38 min., chosen for the direction and linearity of the horizontal polarization ellipse at this period. The various Fourier transform parameters have been plotted on maps of the array area, and contoured.

It has been most common in such Fourier transform map presentations to give sets of six maps, one for each of the X, Y and Z components, in both amplitude and phase. This time, however, several alternative maps have been found to suit better the purpose of synthesizing and emphasizing the features of the fluctuation patterns. The particular advantages these alternatives have been found to offer are now noted.

4.1. Mapping the vertical fluctuation field in terms of the real (Z-cosine) and imaginary (Z-sine) parts of its Fourier transform, rather than in terms of the amplitude and phase of its transform

(1) Using the cosine and sine Fourier transform values for the vertical component (Z) avoids the danger (which may occur with a Z amplitude map) of contouring across a line of Z reversal to join

areas of reversed Z to areas of normal Z. For cosine and sine maps the normal and reversed areas are of different sign.

(2) On a map of Z phase a weak Z reversal has a phase pattern as obvious as that of a strong Z reversal, which perhaps thus gives the weak Z reversal undue significance. However, on maps of cosine and sine transform patterns, the strength of a contour pattern will correspond to the strength of the Z reversal which it is mapping.

4.2. *The horizontal-field parameter,* P

For horizontal-field fluctuations, the phenomenon of reversals does not occur; also phase patterns are usually less significant, so contour maps of amplitude values are appropriate. In the present case, however, a map which has been found useful has been formed by contouring values of a parameter $|P|$, where

$$P^2 = X^2 + Y^2$$

and X and Y are the amplitudes of the north and east components respectively (at the period in question). P thus corresponds to a strength parameter for horizontal-field fluctuations, and since it is independent of the direction and polarization of these fluctuations, it may be effective in tracing currents locally perturbed from a common regional path. That is, above a continuous current path P may be constant even though the direction of the current path varies.

5. Interpretation

5.1. *Physical*

The interpretation here is restricted to the main feature evident in Figs. 2, 3 and 4: the reversal of the vertical variation fields in the northwest part of the array, in particular between stations A1, A2, B1, B2, B3, C1 to the northwest, and stations C2, C3, D1, D2, D3 to the southeast. The reversal is evident in the record profiles in Figs. 2 and 3, and also in the Z-cosine and Z-sine maps of Fig. 4, as a zero-level contour between peaks of opposite sign.

The two most basic models to consider when interpreting a magnetic variations anomaly are those of a line current and the edge of a sheet current. These models have a diagnostic difference in that the former causes a reversal of the vertical magnetic fluctuation field across it, whereas the latter causes a maximum in the strength of the vertical magnetic fluctuation field, but no reversal. With this criterion, the phenomena of Figs. 2, 3 and 4 are most directly interpreted by a line current in the ground, striking approximately northeast–southwest between the two groups of stations mentioned. Independent support for this interpretation comes from the horizontal-field data, which in Fig. 2 show anomalously strong variations at some stations, and in Fig. 4 show a high-P region along the line of reversal. From basic theory, horizontal fields should be enhanced above anomalously strong current flows.

The width and depth of the postulated line current flow are not determined. A limit of maximum depth can be estimated if the strongest vertical variation field is taken to occur at Roorkee, of the order of 100 km offset from the current path: then the depth of a single direct current filament to cause the Roorkee field would also be of the order of 100 km (and the filament would be of strength 20000 A at the peak of the event in Fig. 2). A physically more realistic current path of finite width and thickness will have its upper surface at a lesser depth, anywhere up to the Earth's surface: thus this simple line current analysis does not resolve the depth of the anomalous conductor.

Other events inspected on the array records show reversal characteristics similar to those of Figs. 2 and 3, so there is little cause for doubt that the patterns of Fig. 4 are due to internal current in the ground and not some current concentration in the ionosphere. Nevertheless, it is relevant to note that the enhanced horizontal fields (most notably at C1) are of the correct sign for a current flow below (and not above) the station to be supporting the observed anomalous vertical fields.

5.2. *Geological*

Figure 5 shows the line of current flow interpre-

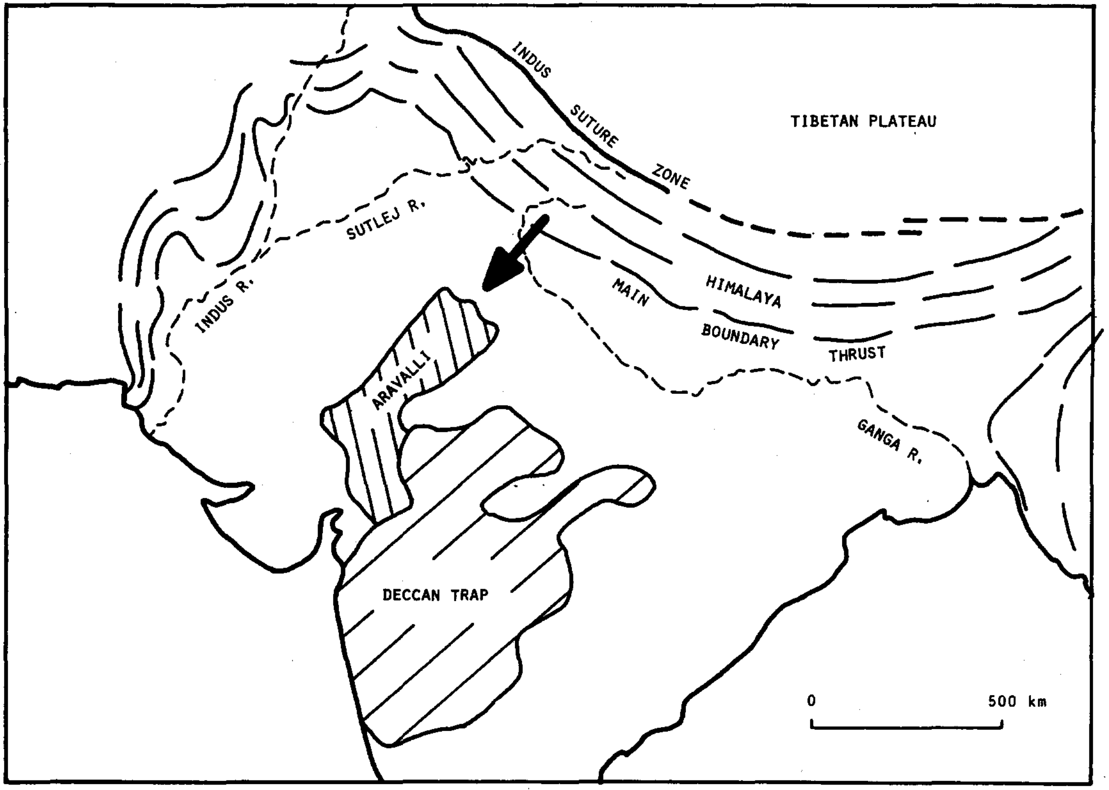

Fig. 5. A sketch map of northern India (after Wadia, 1961; Gansser, 1964) showing as a heavy arrow the line of current flow interpreted for the event of Fig. 2, and its relationship to the Himalaya and the Aravalli belt.

ted for Figs. 2, 3 and 4 now plotted on a simplified map of the general geological structure of northern India. It is evident that the current line follows the strike of the Aravalli belt of the Indian shield. One straightforward interpretation of the flow is therefore that it follows a conductivity structure which is a northward continuation of the Aravalli belt, underlying the sediments of the Ganga trough and thus indicating the continuation of the Indian shield at depth into the base of the Himalayan foothills.

Such a northward continuation of the Aravalli belt has long been discussed as one of a number of known structures which lie transverse to the general strike of the Himalaya. These structures are described in the basic texts of Krishnan (1953), Wadia (1961) and Gansser (1964). A paper by Valdiya (1976) specifically links structures transverse to the Himalaya with subsurface structures of the north Indian plains, and in introducing the subject attributes to Auden (1935) the first postulate of the extension of the Aravalli belt into the Himalaya. Basement structures along the line include the Great Boundary Fault (of Rajasthan), the Delhi–Hardwar ridge and the Moradabad fault, the last two being seismically active at present, as discussed by Kaila and Narain (1976). On the basis of fault-plane solutions for two earthquakes in Tibet, Chandra (1978) interprets the Aravalli belt to extend subsurface right up to the Indus suture zone, and a portion of it may have underthrust the Eurasian plate along this suture since the continental collision of India with Eurasia.

The line of electric current flow in Fig. 5 may then very reasonably be associated with one of these structures, or something deeper in the crust or upper mantle lying beneath them. At present it is possible only to speculate on the cause of increased electrical conductivity which attracts the current concentration: possibilities include the shearing of a zone into an anisotropic texture of high longitudinal electrical conductivity; mineralization of high electrical conductivity (including high water content); and upwelling of a highly conducting asthenosphere. The surface manifestation of granitic activity in the Aravallis has been geologically attributed to a series of subsurface batholiths.

The anomalous magnetic variation effects are strongest in the northern part of the array, rather than in the southern part where the Aravalli belt actually outcrops at the surface. If the anomaly is to be associated with the belt, then this observation implies that it is some physical effect at depth such as hydration or a consequence of increased temperature and pressure which causes the high electrical conductivity, since where the rocks actually outcrop at the surface the anomaly, as observed, is weaker.

6. Conclusion

The evidence of an electrically conductive structure lying transverse to the strike of the Himalayan mountains and the Ganga trough is remarkable, the more so as the sediments in the trough must remain a region of possible high near-surface conductivity. Further, the strike of the sloping base of the crust according to modern orogenic models must also run parallel to the mountains, and if accompanied by a step in the asthenosphere it might there be expected to form a much deeper conductivity contrast. These expected surface and upper mantle conductors thus form bounds between which the conductor carrying the current arrow in Fig. 5 may be expected to lie, and are consistent with it being some extension of the Aravalli structure in the lower crust.

The current arrow in Fig. 5 is intriguing also in the wider context of large-scale electromagnetic induction taking place in the Himalayan region as a whole. Questions which arise are why does the current concentration evidently weaken away from the foothills on the southern side, and where has it been gathered in from on the northern side? One speculation could be that strong induction takes place beneath the Tibetan plateau, which is understood to have high temperatures at depth (Molnar and Tapponier, 1975) and so may be strongly electrically conducting. For events then polarized west of north as in Fig. 2, any structure of high electrical conductivity across the Himalaya will tend to channel current out of Tibet.

The analysis in this paper has been for a single substorm event of a particular polarization. Experience with other magnetometer arrays has shown that in areas of complicated conductivity structure, events with different polarizations may cause currents along different paths. Indeed an advantage of a magnetometer array study is that a range of horizontal-field polarizations, when available, may be chosen to distinguish the effects of different conductors. Further events from the northwest Indian array, when analysed, may similarly augment the conductivity information presented in this paper.

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