Bull. Ind. Soc. Earthq. Tech. Paper No. 295, Vol.27, No.3, Sept. 1990, pp.105-112

GEOMAGNETIC DEPTH SOUNDING OVER SEISMICALLY ACTIVE AREA OF SOUTH GUJARAT

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ABSTRACT

Paper presents the results of geomagnetic depth sounding (GDS) experiment carried out over restricted area of Valsad district, South Gujarat, which is experiencing swarm type of seismic activity since early 1986. The GDS experiment was designed to probe the sub-surface structures in and around the seismically active area which may prove helpful in identifying the likely cause of seismic activity. In this experiment an array of 12 fluxgate magnetometers were operated simultaneously to evaluate the pattern of induced currents associated with lateral discontinuities of electrical conductivity. Separation of observed transient geomagnetic variations into normal and anomalous parts and their examination in frequency-space domain suggests anomalous enhancement of east-west (Y) component of magnetic field at stations bounding the seismically active area. Consistent with overall induction pattern, it is suggested that this anomalous behaviour is related to the channelling of induced currents through a pair of roughly NNW-SSE aligned conductive zones which may represent elongated fracture zones saturated with saline hot water. The role of these mapped structures in triggering earthquake swarm is not clear, but it is interesting that the seismic activity appears to be aligned along a line joining the diagonal ends of mapped elongated conductive zones. This geometric relations between structural features and epicentral distribution pattern is similar to those observed in many volcanic regions prone to earthquake swarms. To account the observation that anomalies in Y-component are not accompanied by any distinct anomaly in vertical component, it is suggested that the channelled currents complete their path by flowing vertically downward to conducting mantle. The vertical dikes which might have provided passage to the lava flows during Deccan trap activity provide the right kind of structural configuration for vertical leakage of currents. Following the hypothesis of Agrawal and Gaur (1970), it is conjectured that the present seismic activity may probably be related to the tectonic reorientation of dikes by shearing.

INTRODUCTION

A limited area of Valsad district of South Gujarat is experiencing swarm-type of seismic activity since early 1986. The thick pile of horizontally disposed basaltic lava has blanketed the structural architecture of the region and has, thus, prevented easy speculation on the cause of seismic activity. In an attempt to explore the sub-surface structural configuration, which might provide certain clues on the likely source of seismic activity, geomagnetic depth sounding (GDS) experiment has been carried out to delineate the sub-surface structures by investigating the distribution of electrical conductivity in and around the seismically active region of Valsad district. In its principle, GDS study utilises the time-variations of the natural external geomagnetic field variations as the energy source, and penetration of these variations into the earth is assumed because of the skin-depth phenomenon of electromagnetic fields. These variations diffuse into the earth and induce electric currents. Physical entities measured in the GDS are three orthogonal components of the time-varying geomagnetic field at discrete points over the earth's surface. At each site, observed magnetic field variations can be considered as the sum of a normal field variation consisting of external source field and its electromagnetic response in layered medium and an anomaleous field which exists only if the medium has lateral inhomogeneities of conductivity. Anomalous conductive zones perturb the flow of induced currents which manifest at the earth's surface in geomagnetic field components. Because the information is contained as a change in patterns, structures are revealed by correlating data from a number of sites obtained by operating simultaneously an array of magnetometers.

EXPERIMENTAL DESIGN AND ANALYSIS OF DATA

In the present experiment, an array of 12 fluxgate magnetometers, acquired for Himalayan seismicity work under Department of Science and Technology Project, were operated simultaneously to evaluate the pattern of induced current. Figure 1a shows the location of study area on the tectonic map of western India. The layout of the magnetometer sites occupied during present array in relation to the seismically active area is shown in Fig. 1b. The study area is bounded to the north by the Tapti-Narmada lineament, generally interpreted as rift zone, and to the west lies the western coast fault (WCF) which hosts number of hot springs. Conducting water in the Arabian sea provides a natural boundary of large conductivity contrast aligned with the coast line. Concentration of induced current along this electrical discontinuity is expected to influence the nature of transient variations over the array area.

Figure 2 gives one good example of the natural transient variation recorded during the operation of array. First hand information on the conductivity distribution can be inferred from the examination of such raw data in time domain. However, as the depth penetration of variational field is function of frequency (period), much of the analysis is done in the frequency domain. Figure 3 gives set of real and quadrature induction arrows for three periods. The induction arrows by difinition point at right angles towards the region of internal current concentration, i.e. towards region of high conductivity (Schmucker, 1970). Yet another method to deduce the nature of conductivity distribution is by examining the spatial dependence of fourier amplitude and phases for dominent periodicities of recorded events (Gough and Ingham, 1983). Figure 4 gives the contoured maps of Fourier transform parameters corresponding to period of 37 min.

RESULTS AND DISCUSSIONS

The most prominent features of the transient variation on Fig. 2 is strong variability of east-west (Y) component. The nature of Y component at group of stations located within or in the immediate vicinity of seismically affected area, namely at Ankalach (ANK), Jamanpada (JAM), Wadichonda (WAD) and Nirpan (NIR), are conspicuously different from other stations. Y-amp map on Fig. 4 clearly suggests that the area affected by seismic activity is bounded by anomalously high values. These difference in the amplitude of Y-component are also accompained by distinct phase differences.

The north-south (X) fluctuations are fairly uniform over the array. The vertical (Z) variations though similar in nature show marginal enhancement at selected stations, e.g. Chickli - CHI (Fig. 2) and Valsad - VAL. This behaviour of Z variations as well as the east-west gradient of Z amplitude on Fig. 4 are consistent with the signature of geomagnetic coast effect resulting from the concentration of induced currents along the coast line in the sea water. The Z fluctuation at all stations appear to be correlated better with X than with Y component. Furthermore, their relationship is such that positive Z follows the negative X fluctuation. In terms of internal current concentration, this anti-correlation is indicative of the concentration of induced currents to the north of the array. This interference is in agreement with the induction arrow pattern (Fig. 3) which indicate higher conductive zone of the NW side of the array. In fact, the nature of X and Z variation as well as induction arrow pattern is consistent with the pattern of induced currents that would result from the concentration of induce currents along Tapti-Narmada zone. Magnetometer array studies carried over various rift zones of the world have suggested that the existence of good conductor beneath the rift floor is a more or less universal feature of rift zones (Banks and Beamish, 1979; Hutton, 1976).

The nature of induction anomalies clearly indicate the presence of conductive structures to the north and west of the array but concentrations of induced currents in these structures do not offer any explanation for the anomalous behaviour of Y-component. When the nature of transient variations, recorded by arrays stations are compared with those observed at two distant magnetic observatories, namely Alibag (ABG) and Ujjain (UJJ), it becomes obvious that Y variations at group of stations consisting of Wadichonda, Nirpan, Jamanpada and Ankalach resemble better with observatories record (e.g. Fig. 2). Furthermore, when average pattern corresponding to these stations is taken to represent normal part of variation and substracted from the records of individual stations, anomalous behaviour of Y component becomes much more apparent (Fig. 5). It is rather surprising that such strong anomalies are not accompanied by any variability in the vertical (Z) component. One possible explanation for these anomalous behaviour is that seismically affected zone provides a vertical conducting channel through which current leak vertically to the conducting mantle. Vertical flow of induced current would not produce any Z anomaly and the Y component would be enhanced on all sides of the zone providing path for the vertical diffusion of induced currents. However, the enhanced Y variation on either side of the zone would be expected to have near opposite phase, a feature not borne out by observations. One noteworthy feature of the residual anomalous Y variations (Fig. 5) is that they show almost one-to-one positive correlation with total X variation (Fig. 2). This correspondence indicates that anomalous behaviour of Y component may result from the channelling of currents induced along Tapti-Narmada zone through a pair of roughly NNW-SSE aligned conducting zone, situated on either side of seismically active area. These channelled currents may complete their path by returning to ocean to the south of study area or may terminate against a vertical sink. A possible configuration for the flow path of induced current is shown in Fig. 1.

The present study area has suffered intense valcanic activity over a long period in the geological past. Fracturing of crust and formation of hot spots in response to the drag effect caused by moving Indian Plate were considered by Chandrasekharam (1985) to be the preparatory steps for magma erruptions during Deccan volcanism. Studying the structural fabric of Deccan province through landsat imagiary, several workers have noted strong correspondance between dyke orientation and fracture pattern. The existence of number of hot springs which appear to be aligned with certain major lineament is another important characteristics of Deccan terrain. Three such springs exist in the study area. The surface temperature of the springs vary from 35°-65°C and show evidence of sea water mixing. Chemical data on the springs indicate that meteoric water is the main source of these springs which at some depth is getting mixed with saline sea water and emerging as hot springs through major lineaments. Base temperature of the springs estimated through Na-K-Ca and Silica thermometry ranges between 137 to 167°C (Chandrasekharam, 1988). Since the electrical conductivity is very sensitive to the presence of conductive fluids in a porous rock mass, it seems plausible to suggest that mapped conductive zones on either side of seismically active area may represent elongated deep fracture zones which may owe their high conductivity to the presence of saline water, an excellent conductor especially at temperatures prevailing at the base of hot springs.

Consistent with evolution model of Deccan Trap, we visualise that vertically upward propagating magma through an elongated fissure zone might have branched off into 'V' shaped segments. The stresses generated by the uprising magma would cause fracturing of host medium near the terminus of Y-shaped erruption zone, which during the subsequent cooling process may be filled with some conducting fluids, e.g. hydrothermal or saline water. The upper fractured edges in the visualised model may provide right kind of structural configuration for channelling of induced currents which may complete their path by flowing vertically downward to conducting mantle through the vertical segment of 'Y' shaped intrusive zone.

CONDUCTIVE ZONES AND SEISMICALLY PATTERN

Earthquake sequences recorded during the onset period of seismicity (February-March, 1986) indicate that the epicentres of events were concentrated and aligned along the NW-SE direction in an area NE of DHA. Such distribution pattern had led Rao et al. (1986) to suggest that a fault oriented in NW-SW direction could be responsible for seismic activity in the region. This inferred position of fault shows good correspondence with the mapped conductive zone running between Dharampur (DHAO) and Jamanapada (JAM).

Figure 6 gives typical example of the distribution pattern of the epicentral/hypocentral locations on various planes in the post April 1986 period. It may be noticed that most of the events are confined in a small zone of about 7 x 5 km^2 with focal depth primarily concentrated between 2-12 km. In space, epicentral locations show definite concentration along a N-S linear following the diagonal ends of the mapped conductive zones. The geomagnetic relations between structural features and alignment pattern of epicentres is similar to those observed in many volconic regions prone to earthquake swarms (Hill, 1977). For example, in the Imperial Valley, California, the swarms occurred within the dextral offset between right lateral strike-slip Imperial and Brawley faults.

Hill (1977) proposed a model for earthquake swarms in active volconic region. The model assumes cluster of dikes within the brittle volume of the crust. The swarms results from a sequence of shear failure along the existing or incipient fractures or faults connecting the adacent tips of offset dikes. Hill noted that although magam has been emphasized as the fluid filling the dikes, other fluids, in particular, water may be important under circumstances. If water under pressure can effectively form a distribution of dikes with long dimensions of the order of tens to hundred meters the model may account for much of the man-made reservoir induced seismicity. Examining the space-time pattern of swarms over present study area, Rao et al. (1986) have suggested that additional fluid pressure due to the impoundment of water in the small Kelia Dam in vicinity may not be a adequate for triggering earthquake swarms. In view of the hot springs in the vicinity (see Fig. 1) these authors suggested that present sequence of earthquake swarms may be of geothermal origin. Earlier, Dutta (1968) had related the seismic activity in Koyna region to the Decay phase of volcanic activity in which strain energy release was considered to be derived from the transfer of thermal energy. Agrawal and Gaur (1970) had proposed yet another source mechanism for Koyna earthquakes which appear more relevant to the present case and is, hence, described below. Their model also associated the source region of seismic activity with the decay phase of volconic activity though the major fraction of the strain energy was assumed to be due to the tectonic processes operative there. The model envisaged that successive extrusions of magma from the magnetic chamber in the form of dikes would cause a rise of the intruded formations. After the volconic activity has subsided, there would be a tendency for region to subside also, thereby creating a void around the dikes at depth. They suggested that tectonic reorientation of dikes in response to tensile field arising due to the creation of void could be possible cause of seismic activity. Their model in addition to explaining the large vertical extent of hypocentres, were able to account the large amplitude ground acceleration, higher frequencies in the ground acceleration record as well as strike-slip movement associated with Koyna earthquakes. It is interesting to note that hypocentres of earthquake swarms in present study area also show alignment on a vertical plane and the nature of transient geomagnetic variation indicate vertical diffusion of induced currents along a vertical N-S elongated dike like structures beneath the area outlined by epicentral distribution of swarms. The data presented here does not resolve the problems. A more detailed discription of frequency characteristic of swarms as well as fault plane solutions will help to evaluate the efficacy of Agrawal and Gaur's model in triggering earthquake swarms in Valsad region.

ACKNOWLEDGEMENTS

Authors wish to thank the Directors of their Institutes for their interest and for providing facilities towards the successful execution of work presented in the paper. Authors are also thankful to Prof. U. Schmucker, Prof. B.P. Singh and Dr. H.N. Srivastava for many useful discussions. Assistance of A. Hunchinal, L.N. Rao, Sanjay Srivastava, N.P. Srivastava, Hameed Sarkar, A.N. Joshi and D.M. Bulsara in the field work is gratefully acknowledged.

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Map showing location of Valsad Array

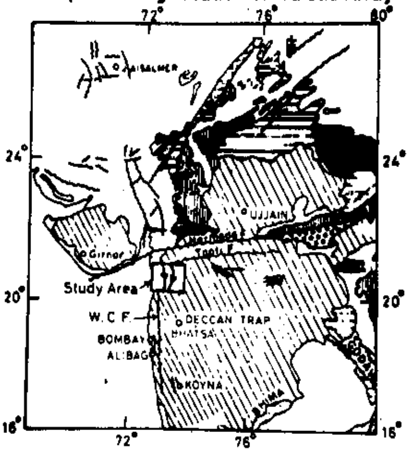

Fig. 1a Tectonic map of Western India showing study area of Valsad Magnetometer Array

LAYOUT OF MAGNETOMETER SITES FOR VALSAD ARRAY

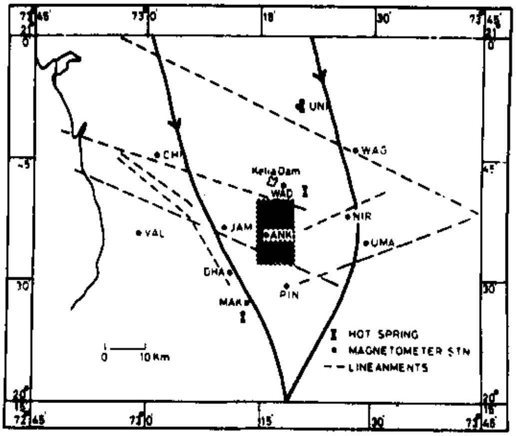

Fig. 1b Map showing layout of magnetometer sites in the study area. Hatched area marks the zone of concentrated epicentres. The thick lines with arrows indicate the flow pattern of induced currents associated with high electrical conductive zone

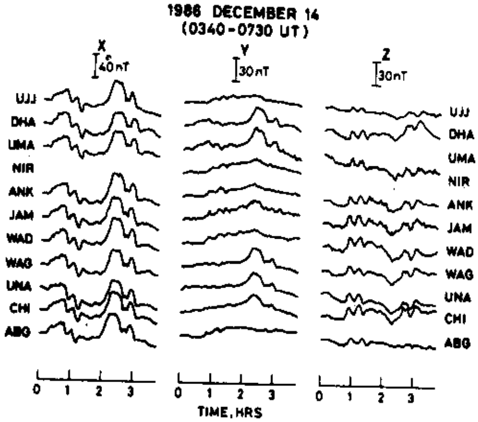

Fig. 2 An example of the geomagnetic disturbance event recorded by the array. Note the anomalous behaviour of Y-component at stations in the vicinity of seismic zone

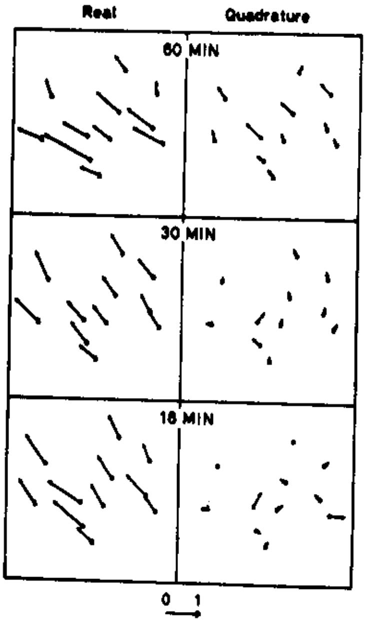

Fig. 3 The set of real and quadrature induction arrows indicating zone of high electrical conductivity to the northwest of study area

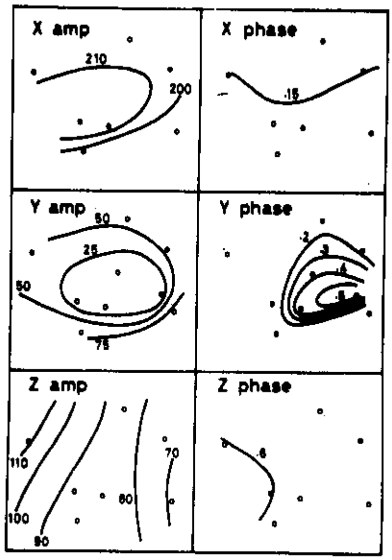

Fig. 4 Contoured maps of Fourier Transform parameters of the magnetic variation at the period of 37 min. Enhancement of Y variation all around the zone of seismic activity is quite conspicuous

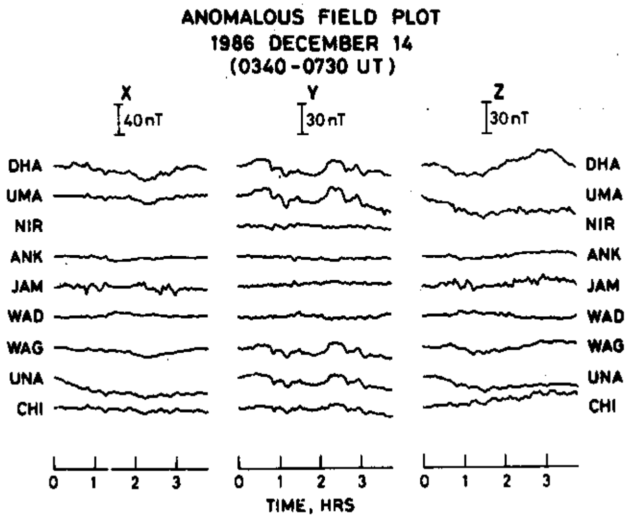

Fig. 5 Plots of anomalous magnetic field variations. The anomalous Y variation, showing positive correlation with total X variation (Fig. 2) are attributed to channelling of induced currents along the path shown in Fig. 1b

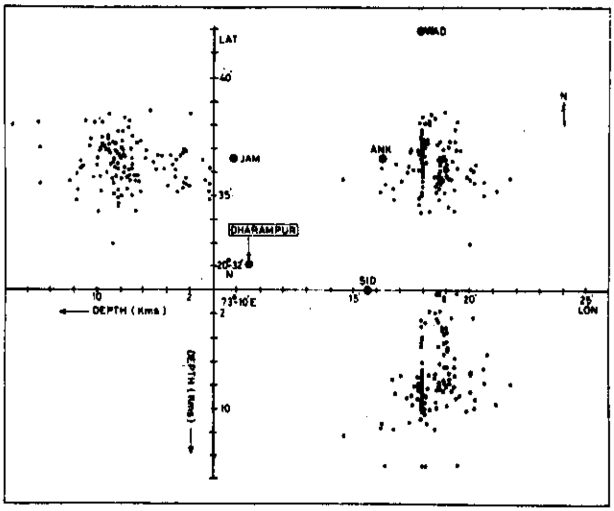

Fig. 6 Projection of Epicentres and Foci of earthquakes recorded during August 20, 1986 to September 10, 1986 on various planes