GEOPHYSICAL INVESTIGATIONS IN THE JANUARY 26, 2001 BHUJ EARTHQUAKE AFFECTED REGION

IIG Working Group*, @ for Bhuj Earthquake Related Studies,
Indian Institute of Geomagnetism,
Colaba, Mumbai 400 005

@ Corresponding Member: Prof B.R. Arora, bra@iig.iigm.res.in

ABSTRACT

Number of geophysical investigations were conducted, as a part of the DST sponsored project, to study the seismotectonics of the Bhuj earthquakes affected region. Magnetic total field and vertical field values were collected over the Kutch region with an average station spacing of 5 km. The total field anomaly map reflects NW-SE to WNW-ESE trends with several high amplitude short wavelength anomalies. The analytical signal map of the region has helped in identifying the magnetic sources. They are related to the exposed volcanic and they delineate the subsurface extension of the trap flows.

The flow path of induced currents inferred from the nature of transient geomagnetic variations recorded by 10-station magnetometer array suggests presence of blocked crustal structures within the Kutch main land, marked by large lateral conductivity contrast. The long period magnetotelluric measurements in the period range of 10s – 16000s have shown evidence of a crustal conductor in the depth range of 10-17 km, and a possible lithosphere-asthenosphere boundary at 150 km. It is interesting to note that recent Bhuj earthquake with focus at 17 km depth was seated at the base of this high conductivity layer.

First look on the GPS data do not suggest any significant short-term post seismic deformation, following the Bhuj earthquake of 26th January, 2001. GPS repeat measurements are in progress to monitor long-term crustal movements.

INTRODUCTION

The catastrophic Bhuj earthquake of 26 January 2001 with magnitude Mw 7.7 (Ms 8) was the most damaging in the last 50 years and was felt in nearly in all parts of India. The Kutch region has witnessed many high magnitude destructive earthquakes in the past. Of these the 1819 earthquake with a magnitude of 7.8 that occurred in the northwestern part of the Great Rann of Kutch and the Anjar earthquake of 1956 with a magnitude of 6.1 are well documented. Apart from these major ones, the region has experienced several earthquakes in the magnitude range of 4-5. The repeated earthquake activities have challenged the Earth scientists to explore the area with a view to understand the seismotectonic complexities of the region. The Department of Science and Technology has funded several projects to enable the Earth Science Community to accomplish this mammoth task.

----

* -IIG Working Group includes following members:
-GDS and LMT Studies: B.R. Arora, P.B.V. Subba Rao, A.K. Singh, R.N. Maurya, Gautam Rawat, and B.H. Dawalappa
-Geopotential Studies: Mita Rajaram, Vinit Erram, S.P. Anand, P.B. Gawli and A.P. Bhingare
-GPS Studies: C.D. Reddy, P.S. Sunil, M Poonraj, S. Amrithraj and B.D Kadam

The present geophysical studies, initiated by the Indian Institute of Geomagnetism, are primarily aimed at delineating the sub-surface structures in and around the Bhuj earthquake-affected area. Two complimentary studies are being undertaken (i) Magnetic surveys and (ii) Electrical conductivity imaging. Given the thick sedimentary (non-magnetic) sequence at surface, the spatial variations in magnetic fields can be effectively used to map the basement configuration as well as deep-seated structures. On this physical consideration, ground magnetic surveys are undertaken. The Bhuj earthquake caused widespread appearance of water bodies and channels. At number of places water came out in the form of spiral fountains and had very high temperature. This may be the simple case of water brought to the surface from greater depths by seismic pumping (Sibson et al., 1975) or may emphasize the role of high-pressure fluids in triggering earthquake (Blanpied et al.,1992; Kellar and Loaiciga,1993). Given the sensitivity of electrical conductivity of rocks to the presence of fluids, the techniques of magnetotelluric (MT) and geomagnetic deep sounding (GDS) are used to image the radial (depth) and lateral (spatial) distribution in electrical conductivity. The GDS with widely spaced magnetometers offers effective way to map first order regional structures marked by large electrical contrast (Arora,1997), whereas MT with better depth resolution is used to map the structure in greater details (Singh and Gokarn, 1997). Given this complementary character, GDS and MT studies were planned to cover the regions in and around the earthquake-affected regions. In order to map structures for the full thickness of the lithosphere, both broadband (300 Hz to 2000S) and Long period Magnetotelluric (LMT) measurements (105 – DC) were envisaged.

Global Positioning System (GPS) is fast growing as a major tool to monitor crustal dynamics, a basic input for the integrated earthquake research. Following the Latur earthquake of 1993 in the Peninsular India, Department of Science and Technology (DST) has taken the initiative to establish a coordinated programme for crustal dynamic studies in India. Under this programme, the Indian Institute of Geomagnetism has established a regional scale GPS network of about 73 stations in western Maharashtra. Repeated measurements in all the stations have been carried out during the last four years. Given this expertise and infra-structural facilities, GPS measurements are undertaken in the Bhuj region to monitor post seismic deformations.

The present paper presents preliminary results of the magnetic survey, GDS, LMT and GPS studies conducted over the Bhuj region. The results from this study, integrated with other geophysical studies will pave way for better understanding of the structural configuration of the earthquake prone Kutch region.

GEOLOGY AND TECTONICS

The Kutch rift basin is considered to be a major seismogenic domain due to occurrence of four earthquake of high intensity and forms a crucial geodynamic part of the western continental margin of Indian sub-continent. Seismically this region is categorized under active zone V outside the Himalayan seismic belt. It extends for approximately 250 km in east-west direction and about 150km in the north-south. Figure 1 shows the major tectonic elements against the geological background of the region. The two major E-W trending faults of relevance to our study include the Katrol Hill fault and Kutch Mainland Fault (KMF) (Merh, 1995) and NW-SE trending Vigodi fault. Apart from these major faults numerous oblique cutting subordinate faults trending N-S, NNE-SSW, ENE-WSW and WNW-ESE, have developed during various tectonic events. These faults have controlled the trends of the major drainage network. Structural configuration of the Kutch basin is characterized by highlands, which are the areas of uplifts and the plains are the basins in the form of half graben between the uplifts. The region between the southern coastline and the KMF is the Kutch main Land divided into central portion of rocky upland, northern hill range and coastal plains. Kutch rifting took place in the late Triassic – Early Jurassic (Biswas, 1987) and this basin has the longest record of the Mesozoic in western India with thick accumulation of late Triassic to lower Cretaceous sediments.

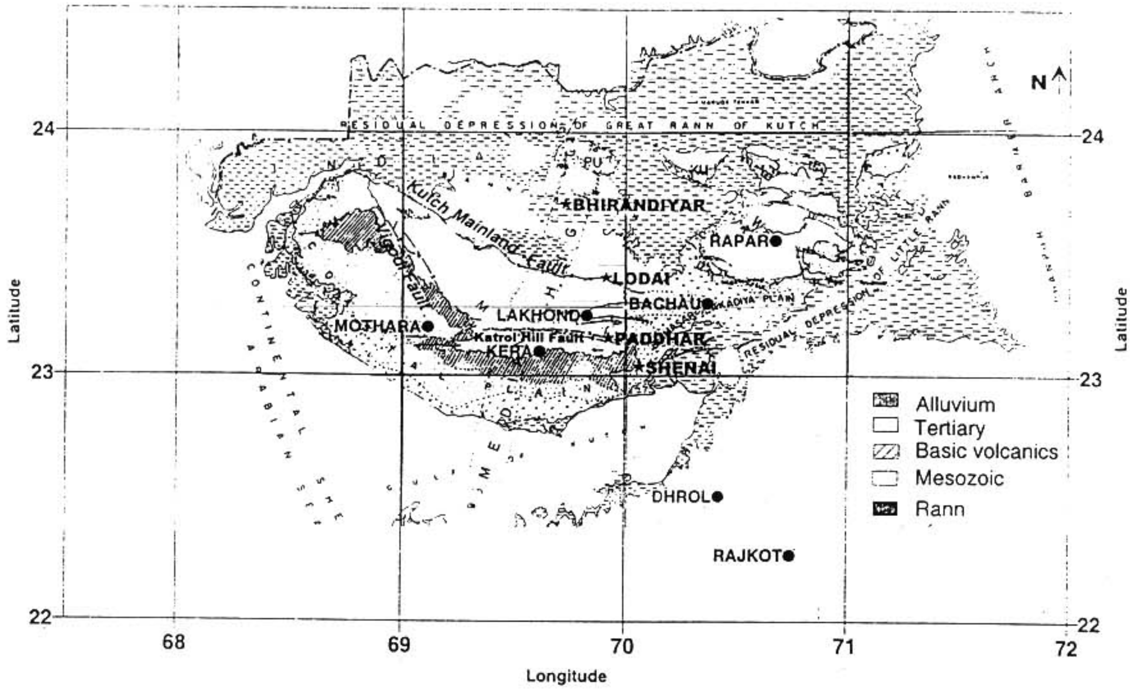


Fig. 1. Geology and Structural framework of Kutch (After Biswas and Deshpande, 1970). Location of GDS (•) and Long Period Magnetotelluric (LMT) (⋆) sites superposed.

The present study is mainly limited to the south of the Kutch Mainland Fault, including the central high land, the northern hill range with an intervening low ground and a southern coastal plain. Lithologically, the central high land is made up of Mesozoic rocks. The Deccan trap flows lie between the Mesozoic rocks and the Tertiary rocks and coastal plains to the south. The northern hill range forms a chain of domes of Jurassic and Cretaceous rocks, and is flanked to the north by E-W trending Kutch mainland Fault. The southern coastal plains that boarder the mainland and overlooks the Gulf of Kutch in the south are made up of Tertiary and Quarternary sediments.

MAGNETIC SURVEY AND ANOMALIES

A ground magnetic survey was conducted over the earthquake affected Bhuj region with the magnetic total field and vertical field data collected using Proton Precession and Flux gate magnetometers. The area is bounded by latitude 22.8° to 23.9° N and longitude 68.5° to 70.9° E. Data was collected at an average station spacing of 5 km. The data interval is large in places where there was accumulation of debris. Some of the data gaps are due to inaccessible roads. The latitude and longitude of the stations were determined using the hand held Global Positioning System with average precision of 100 m. At each observation point, 8 to 10 readings are taken to check the consistency and the average value computed. A total of 277 magnetic observation points covered the area and their distribution is superposed on Figure 2. For the preparation of the anomaly map, normal and diurnal corrections were applied to the observed data. Diurnal corrections were applied based on the geomagnetic elements (H,D and Z) recorded by the Geomagnetic Observatory at Ujjain. IGRF-1995 was used to represent the main field at each observation point. The total filed anomaly map thus prepared applying these corrections is shown in Figure 2

The magnetic total field anomaly map (Figure 2) is represented as iso-anomaly lines. The anomaly contours are extrapolated into regions that were inaccessible during survey based on general trend. The observed anomaly ranges from –850 to +1000 nT. The anomaly map is characterized by several high amplitude short wavelength anomalies superposed on few long wavelength anomalies. Many well defined 3D and 2D anomalies can be observed in the anomaly map. The anomaly trend

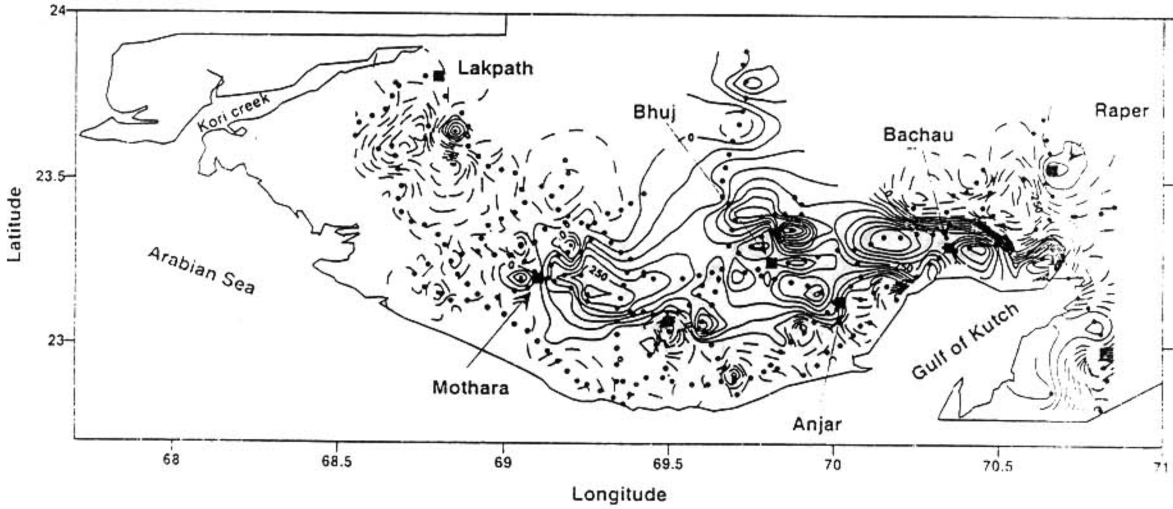


Fig.2. Total magnetic field anomaly map of Bhuj. Contour interval 50 nT. Solid lines represent highs and dashed lines lows. Data points (•) superposed.

swerves from NW-SE in the western part to WNW-ESE in the eastern part through E-W in the central part. The NW-SE trending anomalies, in the western part of the map, fall to the southwest of Vigodi fault and appear to be controlled by it. The Katrol hill fault is limiting the E-W trending anomalies in the south central part of the basin from WNW-ESE anomalies to the northeast. The WNW-ESE trending high gradient anomalies can be a lithologic contact. A glance at the geological and tectonic map of the region indicates that most of the region, under study, is occupied by Mesozoic and Tertiary rocks and alluvium with patches of trap flows as detached patches. The Mesozoic and Tertiary rocks include mainly limestones, conglomerates, sandstone etc, which cannot give rise to such high anomalies. Hence the observed anomalies may possibly reflect the subsurface flows, intrusive bodies or mantle materials that came up as a result of rifting.

To have a better understanding of the distribution of magnetic sources, an analytical signal map of the region is prepared form the total field map.

Magnetic Analytical Signal Map

To define the distribution of magnetic sources in the study area an analytical signal map is prepared. Analytical signal map aids in the delineation of source body irrespective of the inclination parameter. The analytical signal of total magnetic field reduces magnetic data to anomalies whose maxima mark the edges of the magnetized bodies regardless of the direction of magnetization and whose shape can be used to determine the depths of those edges (MacLeod et al, 2000). The amplitude of 3-D analytical signal at location (x,y) can be derived from the three orthogonal gradients of the total magnetic field using the relation (Roest et al, 1992)

$$A(x,y) = \sqrt{(dT/dx) + (dT/dy) + (dT/dz)}$$

The analytical signal map obtained from the total filed map is shown as Figure 3, The analytical signal peaks (sources) directly overlies the exposed deccan traps in region west of Anjar and this is in conformity with the mapping done by Biswas et al. (1970). According to Biswas et al. (1970) as reported by Mehr (1995), the Deccn trap is restricted only to the Kutch Mainland extending from Lakpath to the west to Anjar in the east. The analytical signal map reveals magnetic sources to the east of Anjar. We believe that these are related to subsurface extension of trap flows.

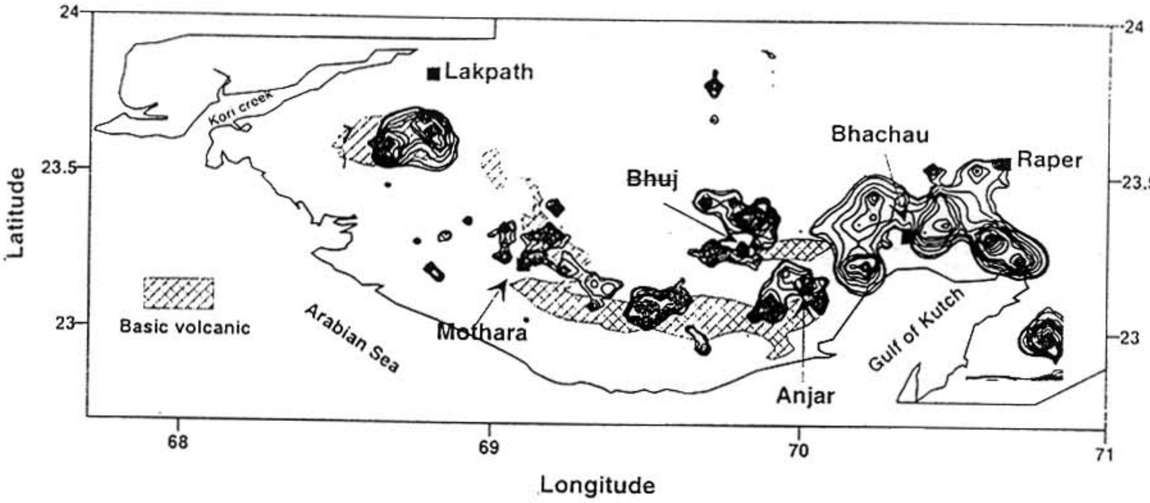


Fig.3. Analytical signal map of the magnetic field representing the distribution of magnetic sources, superposed on the basic volcanic outcrops (from GSI 2000).

Interpretation of Magnetic Sources

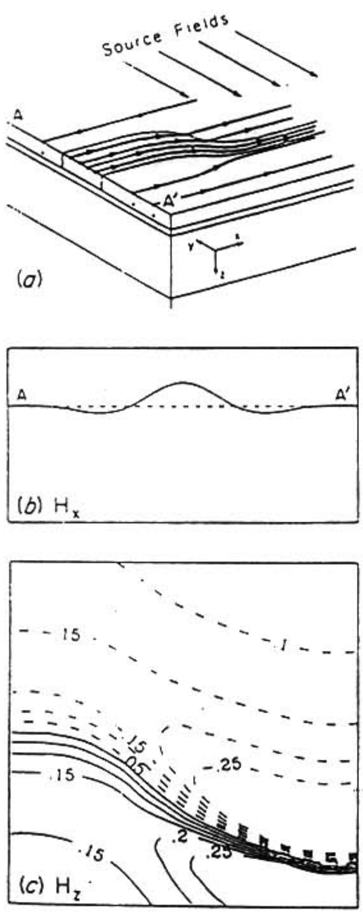
From the present study we were able to isolate the magnetic sources in and around the Bhuj. The western part of the study area depicts NW-SE trends while the central part shows E-W trend and are in accordance with the major tectonic grain in this region. Most of the magnetic sources are found to be restricted to the southwest of Vigodi fault and south of the Katrol Hill fault. The Katorl hill fault and the Vigodi fault forms the limit of the trap flows to the north and thus it can be inferred that most of the anomalies reflect the exposed and subsurface trap flows in the region. The WNW-ESE trending high gradient anomaly in the east of Lodai may possibly be the limit of the sub-surface extension of traps, where the trap comes into contact with the Mesosoic rocks exposed south of Raper. It appears that the basic flows exposed towards the east of Bhuj (GSI, 2000), northeast of the Katrol hill fault, may be extending further east underneath the Tertiary cover and possibly thins out to the northeast. Thin trap cover is reported near Bhachau (Biswas and Deshpande, 1973). The present study suggests that the magnetic sources (probably the traps) occur as separate micro-blocks, which might have resulted from the neo-tectonic activity.

ELECTRICAL CONDUCTIVITY IMAGING

Electromagnetic fields are induced in the earth by external time-varying ionospheric and magnetospheric current systems. They undergo attenuation and induce eddy currents, which set up their own electric field and also contribute to the magnetic field variations observed at the earth's surface. The depth δ to which incident electromagnetic wave penetrates the sub-surface is dependent on the frequency (period –T, sec) of the wave and the conductivity (resistivity- ρ,Ωm) in the earth's interior ($\delta = 0.5\sqrt{\rho T}$). Thus, the frequency-dependent response functions can be used to investigate the electrical conductivity distribution of the earth by Magnetotelluric (MT) or Geomagnetic depth sounding (GDS) methods.

Geomagnetic Deep Sounding

Fig. 4 Schematic overview of the principle of Geomagnetic Depth Sounding.



a) Spatially uniform time varying external magnetic field induce electric currents in the Earth, which are generally perpendicular to the inducing magnetic fields and tend to concentrate in the more conductive region (shaded region).

b) Horizontal magnetic field (H_x) which would be observed along the profile AA'. The Horizontal magnetic fields are superposition of external and internal fields. Because of the concentration of induced currents, H_x is enhanced over the conductive zone and slightly reduced to either side.

c) Plan view of vertical magnetic field (Hz). Since for quasi-uniform source, there is no external vertical component, Hz is entirely of internal origin and, thus, clearly locates large-scale variation in conductivity. The sign of the Hz changes as the high conductivity zone is crossed.

d) In case of boundary separating extended blocks of large conductivity contrast e.g. fault zone or coast line, the transverse horizontal component is enhanced over conducting block whereas Hz fluctuating field is enhanced near the edge, but no reversal.

Figure 4 gives the schematic overview of the principle of the GDS. The example clearly brings out how the anomalous horizontal and vertical magnetic fields can be used to image lateral variation of electrical conductivity in the crust and upper mantle. To map structures marked by large electrical conductivity contrast, an array of 10 magnetometers with inter-station spacing of 20-40 km was operated in and around Bhuj affected area. The location of magnetometer sites is shown in Figure 1. During the period of array operation between April 26 and May 15, 2001, variety of magnetovariational fields were recorded.

As an example, Figure 5 shows the nature of magnetovariational fields recorded on 13 April 2001, (15.00 - 23.00 UT). These stacked magnetograms of selected disturbance events in the time domain are useful in identifying the normal and anomalous behaviour of X, Y and Z variations in the study region. Both horizontal components, X and Y, show near identical pattern at all stations, indicating the quasi-uniform character of the external source currents. Given this evidence, the observed large variability of Z variations amongst stations can be considered manifestation of the redistribution of internal currents in association with lateral variation in conductivity.

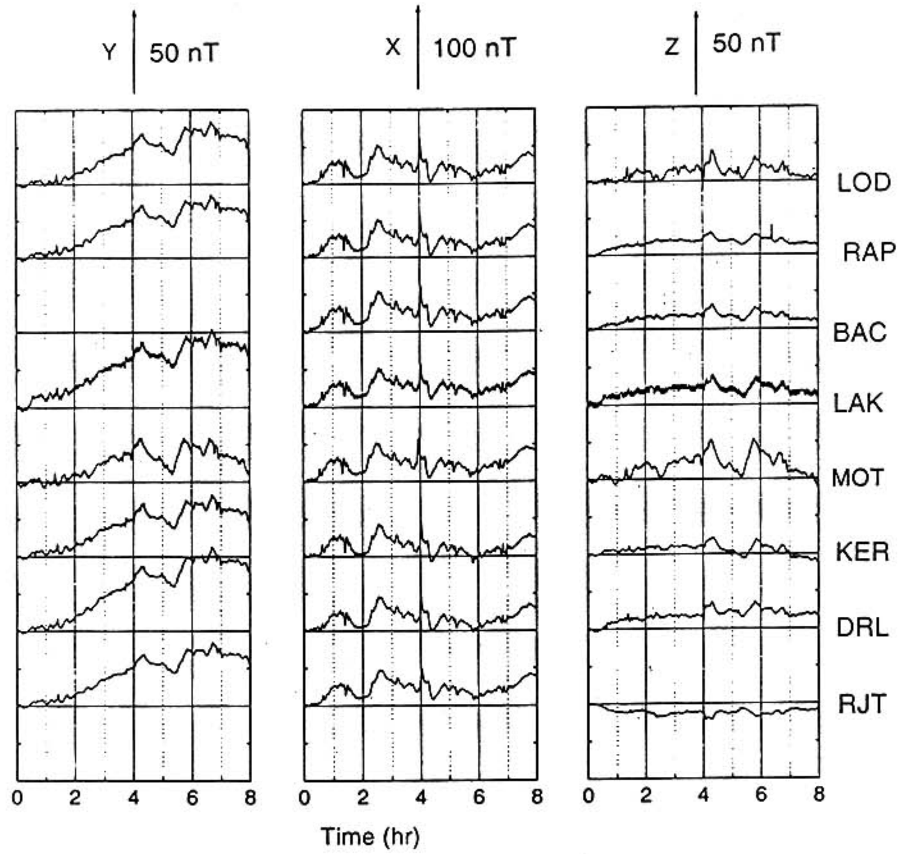


Fig. 5 Magnetovariational event of April 13,2001(1500-2300UT)

A prominent feature of the Figure 5 is that the wave-form of the Z variations closely follow the wave-form of Y variations, albeit in phase opposition. This negative correlation between Y and Z suggests that Z variations are dominantly produced by N-S flowing currents induced by Y component. In the present context, this behaviour can be attributed to the coast-effect resulting from the concentration of induced currents in the conducting sea water in the Arabian sea to the west of Kutch and Saurashtra Peninsula. A net consequence of the coast effect is that amplitude of short-period Z variations would decrease with increasing distance from the continental margin. However, the observed variations in Figure 5 show anomalous enhancement of Z variations at Mothara (MOT), indicating marked perturbation in the flow pattern of induced currents, in addition to the coast effect. It can be traced that even the Y-variations at MOT are marginally enhanced. These signatures of Z and Y-variations indicate that station Mothara defines the boundary between extended sheets of contrasting conductivity. The magnetic anomaly maps have also shown presence of separate blocks in the vicinity of station Mothara.

Frequency analysis in the form of transfer functions and elimination of coast effect through thin sheet numerical formulation would help to characterize the true nature subsurface conductivity distribution. Such attempts are in progress.

Long Period Magnetotelluric

Magnetotellurics provide a way to determine the electrical conductivity image of the subsurface by simultaneous measurement of natural electric and magnetic field variations (Vozoff, 1972). For a general three dimensional conductivity variations horizontal electric (E_x, E_y) and magnetic (H_x, H_y) field at a given frequency are related through

$$\begin{pmatrix} E_X \\ E_Y \end{pmatrix} = Z \begin{pmatrix} H_X \\ H_Y \end{pmatrix}$$

Where Z (impedance tensor) is a complex tensor in frequency domain,

$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

Apparent resistivity and phases are computed as

$$\rho_{aij} = \frac{1}{\omega\mu}|Z_{ij}|^2$$

$$\phi_{aij} = \tan^{-1}\left|\frac{\Im(Z_{ij})}{\Re(Z_{ij})}\right| \ldots i = 1,2 \;\; j = 1,2$$

The LMT measurements were made at four sites extending across the meso-seismal zone (locations shown in Figure 1). We present a representative result from the LMT site Lodai (Lat 69.9^0 Long. 23.4^0) Figure 6 shows the nature of apparent resistivities (ρ_{xy} and ρ_{yx}) and phases (Φ_{xy} and Φ_{yx}) at time periods from 10s to 16000s. This also shows the best 1D model fitting curves. The one-dimensional geoelectrical section for the upper 50 kms (shallow) and deeper (> 50 kms) parts is shown in Figure 7. This conductivity-depth profile shows a conductive layer at 10-17 km depth and a possible lithosphere-asthenosphere boundary at 150 km. The presence of a high conductivity layer at mid-crustal depths suggests rheological stratification and marks the onset of ductile behaviour. The ductility and high conductivity layer, coinciding with brittle-ductile boundary, arises due to the presence of fluids trapped beneath the impermeable layer (Muir-Wood and King, 1993; Jones, 1987). It is believed that part of fluids may be produced by thermally controlled metamorphic dehydration process (Fyfe et. al., 1978; Bailey, 1990). It is interesting to note that hypocenter of the recent Bhuj earthquake appears to be rooted in this conducting layer. In that respect, the situation is similar to that observed in the frontal parts of the Himalaya. It was found that the top of the low-dipping underthrusted high conductivity layer at mid-crustal depths correlated well with a plane defined by the alignment of the foci of moderate magnitude earthquakes (Reddy and Arora, 1993). It was shown that while fluid-filled pores were responsible for enhanced conductivity, their lubricating influence could cause softening/stability of faults and thereby producing tectonic focusing of hypocenters on a linear planar zone (Arora, 2000).

The large differences in the conductivity structures at depths below 30 km, obtained by the inversion of electric fields in two orthogonal polarizations, may in parts represent 2D and 3D earth situation and/or a possible anisotropy at depth. Such visualization is consistent with the impedance tensor, Swift skew and Bahr's phase sensitive skew. Ongoing detailed tensor analysis and modeling/ inversion of data from all four sites will provide a detailed and definitive picture of geoelectrical structures.

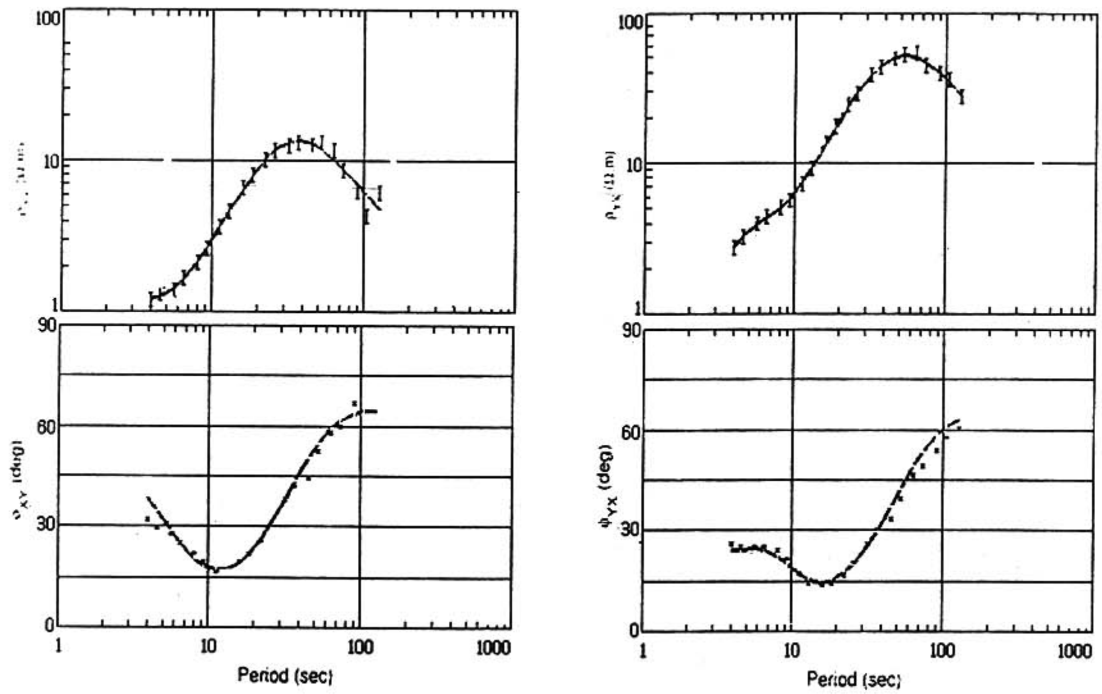


Fig.6 Apparent resistivity (ρ_{xy} and ρ_{yx}) and phase (ϕ_{xy} and ϕ_{yx}) curves for the LMT site Lodai (Bhuj), data is represented by dots and inverted 1D model fitting curves by lines.

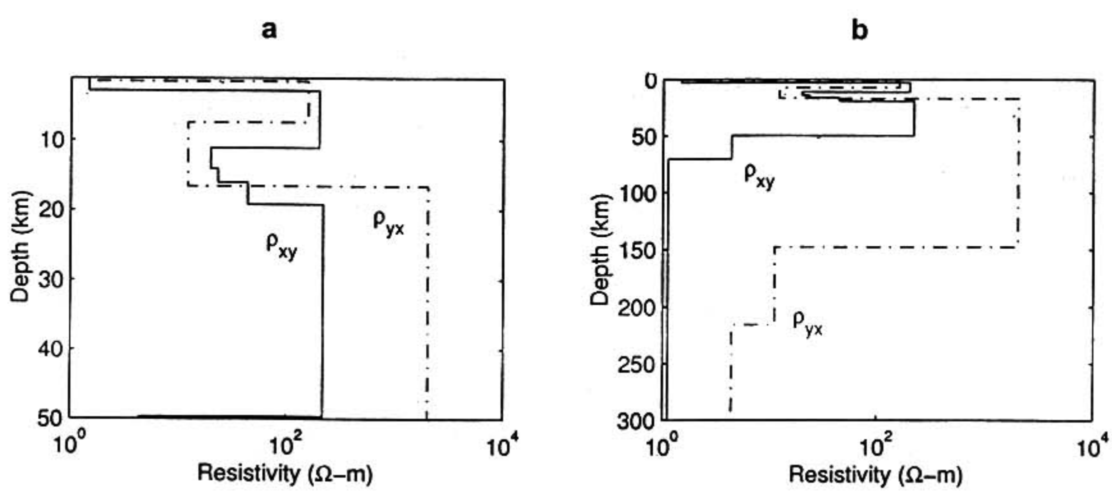


Fig.7 1D resistivity-depth section at LMT site Lodai, showing different resistivity structure along the two measurement directions (N-S and E-W). (a) shows the enlarged section up to a depth of 50 km.

GPS DATA COLLECTION AND RESULTS

To understand the post seismic deformation associated with the Bhuj Earthquake of 26th January 2001, 14 semi-permanent GPS sites were set up and data were collected during the month of February, 2001 using Trimble and Leica receivers. Data were analyzed using Gamit/Globk post processing software. Each 24 hours data covering a UTC day was organized into to four 6 hours segments.

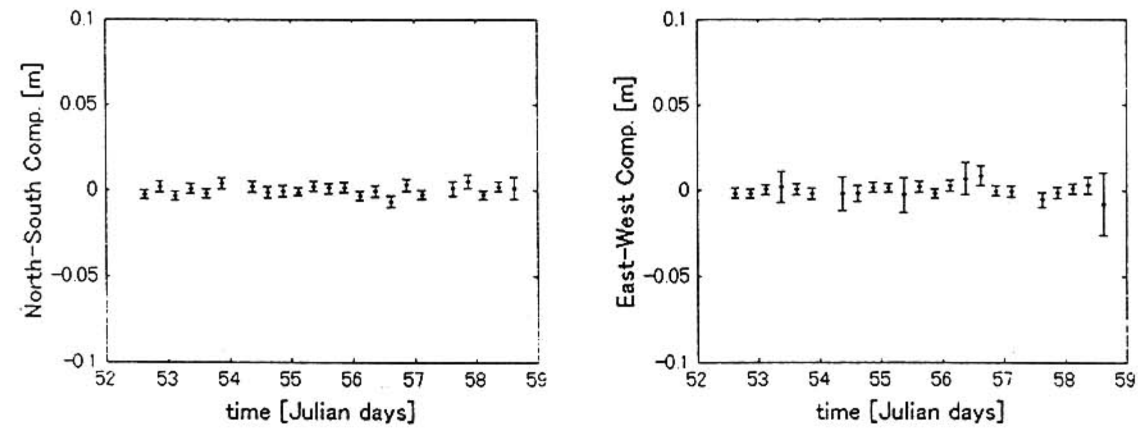


Fig.8 East-west and North-South components of point position of Bhuj site during 21-28 February 20001.

Figure 8 shows the horizontal components i.e. East-West and North-South of a point position of Bhuj during 21-28 February, 2001. During this time, though some after shocks occurred, no displacement is seen in both the components. However, a few days of GPS data analysis is inadequate to conclude that no significant deformation is taking place. When sufficient data is collected at all the 14 sites, the data analysis will yield velocity distribution from which strain distribution can be estimated. The efficacy of this approach has been recently demonstrated for Western Maharashtra region by Reddy et al. (2000). The GPS measurements have been repeated in May-June 2001 and another set of repeat measurements are planned for September-October, 2001.

ACKNOWLEDGEMENTS

IIG team wishes to thank Department of Science and Technology, Government of India for encouragement and expeditiously providing funds to launch co-ordinated geophysical investigations. Investigating team also acknowledges with thanks the facilities received from several academic Institutions that enabled operation of field surveys, in particular we thank Prof. K.N. Iyer, University of Saurashtra for providing logistic support to set up base facilities at Rajkot.

REFERENCES

1. Arora, B.R. (1997). "Geomagnetic deep sounding", In: Natural source electromagnetic induction in the Earth, Eds. B.R. Arora and Sriniwas, New Age International (P) Limited, Publishers, New Delhi, pp. 80-128.

2. Arora, B.R. (2000). "Seismotectonics of the Frontal Himalaya through the electrical conductivity imaging", Proc. International Workshop on Seismotectonics at the subduction zone – Towards the breakthrough in the next century, NRIESDP, S&T Agency, Tsukuba, November 29 – December 1, 1999. pp. 275-286.

3. Bailey, R.C. (1990). "Trapping of aqueous fluids in the deep crust", Geophys. Res. Lett., 17, pp. 1129-1132.

4. Blanpied, M.L., Locker, D.A. and Byerler, J.D. (1992). "An earthquake mechanism based on rapid scaling of fluids", Nature, 358, pp. 574-576.

5. Biswas, S.K. (1987). "Regional tectonic framework, structure and evolution of the Western Marginal Basins of India", Tectonophysics, Vol.135, pp. 302-327.

6. Biswas, S.K. and Deshpande, S.V. (1970). "Geological and Tectonic Maps of Kutch", ONGC Bull., Vol.7, No.2, pp. 115-123.

7. Biswas, S.K. and Deshpande, S.V. (1973). "A note on the eruption of Deccan tarp lavas with special reference to Kutch", Jour. Geol. Soc. Ind. Vol.14, no.2, pp. 134 –141.

8. Fyfe, W.S., Price, N.J. and Thompson, A.B. (1978). "Fluids in the Earth's Crust". Elsevier. Amsterdam, pp. 383.

9. GSI. Seismo-Tectonic Atlas of India and its Environs. pp. 39, 2000.

10. Jones, A.G. (1987). "MT and reflection: An essential combination", Geophys., J.R. Astr. Soc., 89, pp. 7-18.

11. Keller, E.A. and Loaiciga, H.A. (1993). "Fluid induced seismicity at regional scale", Geophys. Res. Lett., 20, pp. 1683-1686.

12. MacLeod, I.N, Jones, K and Dai, T.T. (1993). "3D Analytical Signal in the interpretation of Total magnetic Field data at low magnetic latitudes", Explo. Geoph., Vol.24, no.3/4 pp. 679-687.

13. Merh, S.S. (1995). "Geology of Gujrath", Text Book Series. Geol. Soc. India, Bangalore.

14. Muir-Wood, R. and King, G.C.P. (1993). "Hydrological signatures of Earthquake strain", J. Geophys. Res., 98, pp. 22035-22068.

15. Reddy, C.D. and Arora, B.R. (1993). "Quantitative interpretation of Geomagnetic induction response across the thrust zones of the Himalaya along the Ganga-Yamuna valley", J. Geomagn. Geoelectr., 45, pp. 775-785.

16. Reddy, C.D., Gamal El-Fiky, Teruyuki Kato, Seiichi Shimada and Vijay Kumar, K. (2000). "Crustal strain field in the Deccan trap region, Western India, derived from GPS measurements", Earth Planets Space, 52, pp. 965-969.

17. Roest, W.E., Verhoef, J. and Plikington, M. (1992). "Magnetic interpretation using 3D analytical signal", Geophysics. Vol.57, pp. 116-125.

18. Sibson, R.H., Moore, J. McM, Rankin, R.K. (1975). "Seismic pumping – a hydrothermal fluid transport mechanism", J. Geol. Soc. London, 131, pp. 653-659.

19. Singh, B.P., Gokarn, S.G., (1997). "Magnetotelluric techniques", In: Natural source electromagnetic induction in the Earth, Eds. B.R. Arora and Sriniwas, New Age International (P) Limited, Publishers, New Delhi, pp. 80-128.

20. Vozoff, K. (1972). "The magnetotelluric method in the exploration of the sedimentary basins", Geophysics, 37, pp. 98-141.