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A Wideband Magnetotelluric Study in the Chamoli Earthquake Region, Uttaranchal India : Preliminary Results

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Abstract : A wideband magnetotelluric (MT) study was carried out to evaluate the nature of subsurface lithology and structure in the epicentral region of Chamoli earthquake. A total of 23 sites were occupied traversing important features, viz., the Munsiari thrust and other minor expressions of the Main Central Thrust (MCT). The sites covered the region between Joshimath, Pipalkoti, Gopeshwar, Mandal, Pokhri, Nandprayag and Karnaprayag. The MT coverage includes a few NE-SW traverses in the region of maximum damage, viz., in the vicinity of Gopeshwar and a long traverse, over 100 km long, from Joshimath to Karnaprayag (Gaucher).

The results of modeling the high frequency part of the data (1000 Hz - 1 Hz) show a more resistive basement overlain by moderately conductive formations near Gaucher (Site 23). On the other hand, near Joshimath (Site 20), close to MCT, the results indicate a conductive layer sandwiched between resistive layers which could be the typical manifestation of a thrust zone in this area, that could be correlated with the Vaikrita thrust (MCT). The longer period data at some of these sites have been modeled to bring out a broad image of the deeper regional crustal structure of this sector of the Lesser Himalayas. These results are interpreted and discussed along with the results of previous geophysical studies in this area in order to assess the subsurface structure, to delineate significant structural features and also to understand the subsurface conditions of the crust in this region.

INTRODUCTION

The 6.3 mb Chamoli earthquake of March 29[th] 1999 is yet another event in the well-known Himalayan Seismic belt region. The other recent major earthquake around this region is the Uttarkashi earthquake of 19[th] Oct. 1991 and other seven major earthquake (mb≥6.0) occurred from the past 35 years of record (Mandal *et al.*, 1999; Kayal *et al.,* 1999). In order to understand the subsurface features, geological and geophysical investigations have been initiated around Chamoli epicentral zone by various organizations. As a part of this programme, NGRI has carried out magnetotelluric (MT) studies in addition to seismological and GPS investigations.

It is well known that the entire Himalayan region is geodynamically active and prone to earthquakes, along the existing thrusts and faults. The epicenter of Chamoli earthquake is located north of Chamoli (USGS) as shown in Figure 1 at about 2000-3000 m altitude, where the Munsiari thrust (MCT zone) is exposed. The MT traverses covered the region in the Chamoli district, are in the inner lesser Himalayas characterized by Nappe, Klippe and schuppen zones, bounded by faults. The main lithological units in this region are: Vaikrita group, Munsiari, Tejam, Berinag and Damtha formations. The Vaikrita group of rocks are part of higher Himalayas and consist of high grade metamorphic rocks of granite gneisses. Precambrian sediments are exposed in the area North of Chamoli. The Ramgarh group consists of crystalline rocks of predominantly Quartzites and sediments exposed southwest of Chamoli. The crystalline rocks of metasediments and acidic intrusives are exposed near Siraupani and north of Chamoli. The Klippen zones of Almora are medium grade metamorphics covering large part of the area and form a border located south of Vaikrita group of rocks (Fig. 1), (Valdiya, 1980 and references therein).

The boundary between the high grade metamorphic rocks of Vaikrita group and low grade metamorphic rocks of Almora group is the Vaikrita Thrust, defined by Valdiya (1980) as the Main Central Thrust (MCT). The MCT has also been identified as a zone of ductile shearing and thrusting, dipping about 30^0, northward manifested essentially in abrupt change in structures and grade of metamorphism (Gansser, 1964) is a major tectonic boundary and traceable all along the Himalayan region. The Munsiari thrust form the base of this zone, and defines the lower boundary of the MCT zone and most of the epicenters in the lesser Himalaya lie near the zone (Ni and Barazangi, 1984). The well-mapped faults in the region are the Alaknanda fault near Karnaprayag and

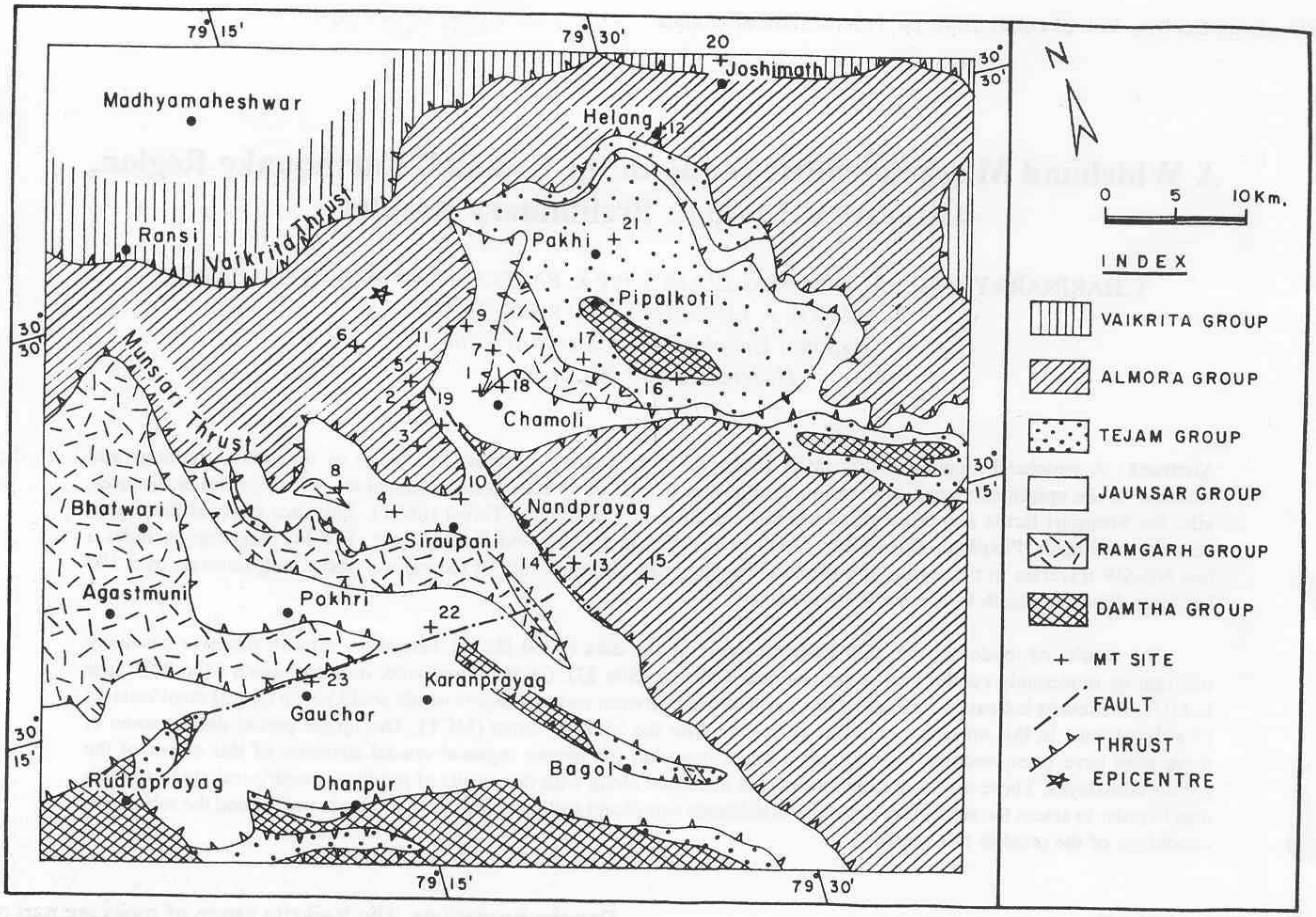


Fig. 1. Location of MT sites on a regional geological map of Chamoli earthquake region (modified from Valdiya, 1980).

the Gopeshwar fault extending NNW-SSE direction from Nandprayag to Gopeswar (Valdiya, 1980).

While detailed geological studies were carried out by various workers (Valdiya, 1980 and other references therein) in the regions of lesser Himalayas to understand the surface geological features and near surface structural features, geophysical studies to understand the subsurface structures carried out are very few (Cotton *et al.,* 1996 and Lemonnier *et al.*, 1999). The results of a magnetovariational study (Arora *et al.*, 1992) indicated the presence of a crustal conductor transverse to the strike of the Himalaya (NE-SW) extending from Haridwar through Pauri upto Gopeshwar.

Subsequent to the Chamoli earthquake of March 29, wide-band digital magnetotelluric investigations were carried out in order to understand the subsurface geoelectric structure and correlate with tectonic features of the region. A total number of 23 stations could be occupied along Karnaprayag, Nandprayag, Chamoli, Pipalkoti, Joshimath areas and also Gopeshwar-Pokhri, Chamoli-Mandal roads. Highly undulating topography and the proximity of power lines are some of the factors that laid restrictctions on the number of sites that could be occupied. Figure 1 shows the location of MT sites on a regional geological map of Chamoli region. The MT sites located at different locations can be projected along two profiles: 1. Gaucher - Joshimath extending from site No. 23 towards SW to near North of Joshimath (site 20) in NE direction and 2. Nijmula (site 16) to Mandal (stie 6) in ESE-WNW direction.

DATA ACQUISITION

State-of-the art wide band (8192 Hz - 4096 Sec) magnetotelluric system (GMS 05 of M/S Metronix, Germany) was used and this data enables probing of the earth from a few tens of meters to few tens of kilometers. Magnetic induction coils were used in order to measure the three components of magnetic field, Hx (NS), Hy (EW), Hz (vertical) and two orthogonal electric dipoles for Ex (NS), Ey (EW). The MT equipment along with accessories was vehicle mounted and typical example of sensor setup is shown in Figure 2. The system is a portable unit with computer - controlled hardware and software for data acquisition & data processing. Data were recorded with a minimum of 3-5 sessions for all the four frequency bands, one band at a time.

At each site the total duration of recording of signal is about 15-20 hrs on an average. The bands and their frequency range are listed in Table 1.

Table 1. *The Bands and their frequency range.*

Band No.	Frequency range
1.	8192 Hz ... 256 Hz
2.	256 Hz ... 8 Hz
3.	8 Hz ... 0.25 Hz
4.	0.25 Hz ... 0.008 Hz

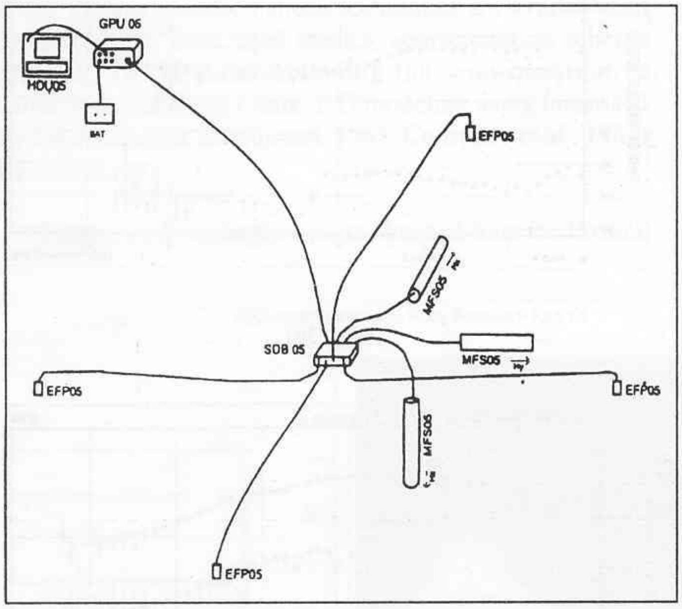


Fig. 2. Field layout of MT equipment.

DATA ANALYSIS

Using processing software, the data acquired have been evaluated for its quality by visually inspecting the time series on a screen. The bad data segments i.e., the data corrupted by spikes as well as from 50 Hz electrical noise are deselected for further processing. A linear trend removal for each data window is carried out by fitting a straight line using trend removal technique. The time series data converted into frequency domain and complex Fourier spectra are obtained, from which auto and cross spectra are computed. From the auto and cross spectra of five components Ex, Ey, Hx, Hy and Hz, the MT parameters such as impedance, apparent resistivity, phase, coherency, skew, etc., are obtained using classical tensorial techniques (Swift, 1971). The procedure is repeated for all sessions of data and a final set of smoothed spectra are obtained for each site. A few examples of apparent resistivity and phase curves obtained are shown in Figure 3.

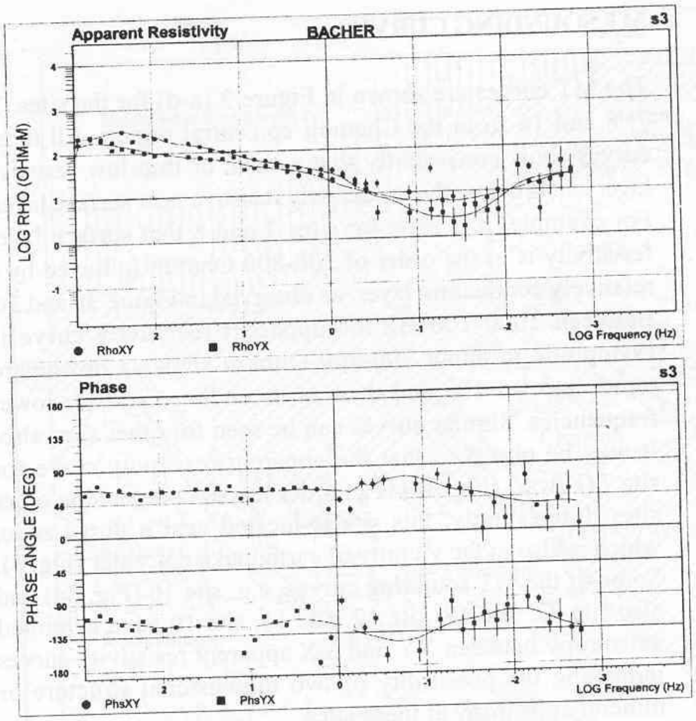
MT SOUNDING CURVES

The MT curves are shown in Figure 3 (a-d) for the sites, 3, 7, 8 and 16 from the Chamoli epicentral region. All these curves show consistently that a thick or thin low resistive layer exists below the moderately resistive near surface layer. For example, it is seen for sites 3 and 8 that surface layer resistivity is of the order of 200-800 Ohm/m followed by a relatively conducting layer, as observed in Figure 3a and 3c. Between 1000-100 Hz the apparent resistivity curve is asymptotic to about 200-800 Ohm/m shows a downward trend upto 0.1 Hz. and then an ascending trend for lower frequencies. Similar curves can be seen for other sites also. It may be observed that the apparent resistivity curve for site 7 (Diwar) (Fig. 3b) is an order less as compared to other sites. Interestingly, this site is located near a thrust zone, which is also in the vicinity of earthquake epicenter (Fig. 1). Some of the MT sounding curves, e.g. site 16 (Fig. 3d) and also site 22, site 18, site 12, site 11, site 10 have exhibited anisotropy between XY and YX apparent resistivity curves indicating the possibility of two dimensional structure or mineral anisotropy at these sites.

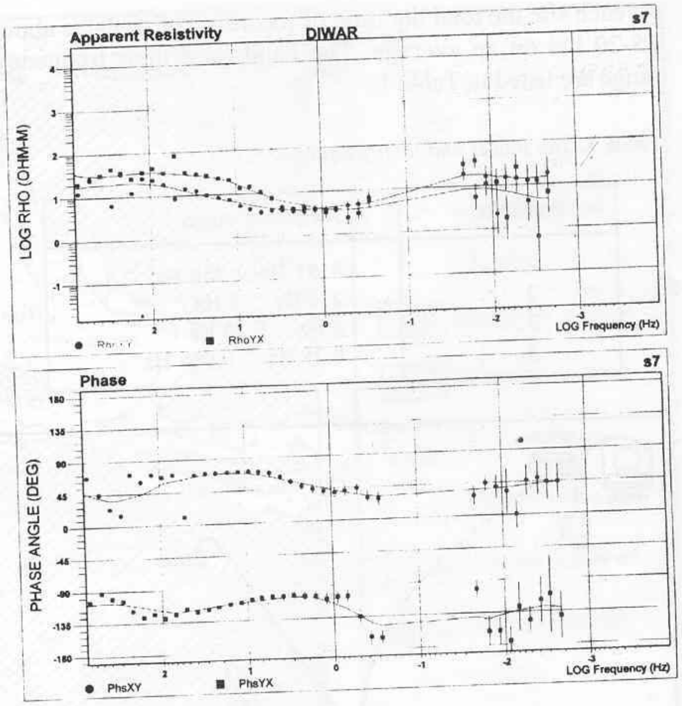
PSEUDO-SECTIONS

One of the useful ways of qualitatively studying the MT data is by representing any one of the response functions, say resistivity, phase, etc., along a profile and contour it. In this representation the X-axis represents the profile, on which the nearest MT sites are projected and the Y-axis represents the frequency on a log scale. In Figure 4 (a & b) such pseudo-sections for two profiles, Gaucher - Joshimath in NE-SW direction, and Nijmula - Mandal in a near EW direction are shown. As can be seen in the first profile (Fig. 4a), the NE-SW apparent resistivity - frequency pseudo section at higher frequency towards NE part of the profile i.e., near sites 20, 12 and 21 moderately high resistivity of 100-560 Ohm/m upto 1 Hz followed by relatively conductive section upto 0.001Hz is obtained. On the other hand the resistive sub-surface for sites 17, 18 and 10 exhibits high resistivity upto 0.01 Hz followed by relatively conductive sections for low frequencies. Site 22 exhibits the similar nature as of sites 21, 12 and 20. Such variation indicates resistive near-surface layers in the vicinity of sites 21, 12 and 20 followed by a relatively conductive crust at deeper levels. The deeper conductor at the SW end appears to rise near site 22.

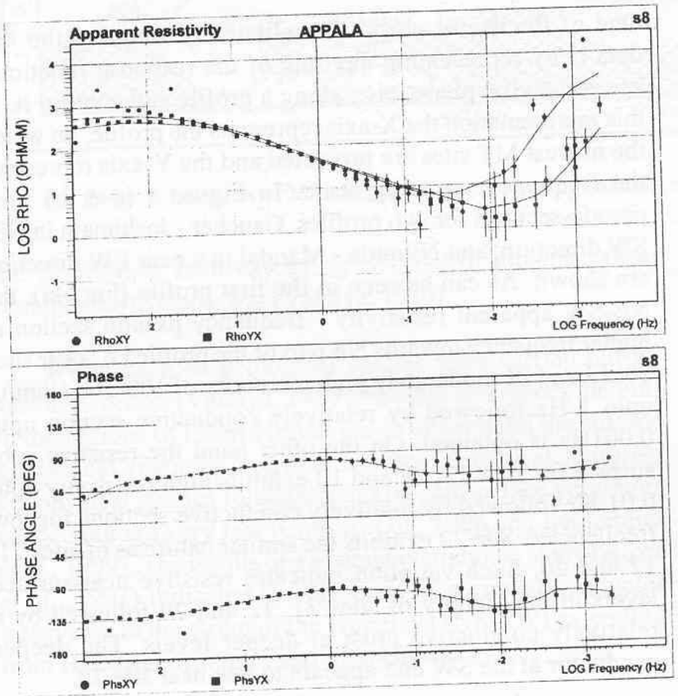
Along Nijmula - Mandal profile similar resistivity section is seen i.e. high apparent resistivity at higher frequencies (1,000-1) Hz and low apparent resistivity at lower frequencies, except for site 7. Near site 7, moderately resistive subsurface section can be seen for 1000 - 10 Hz followed by relatively low resistivity section for 10-0.001 Hz indicating that the subsurface section near this location is anomalous as compared to other sites on this profile. Interestingly the



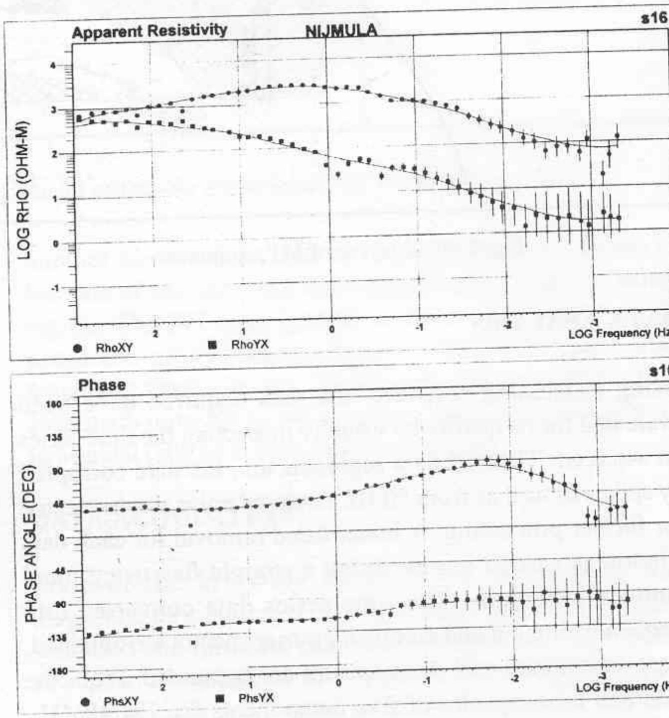
(Fig. 3a)



(Fig. 3b)



(Fig. 3c)



(Fig. 3d)

Fig. 3. Magnetotelluric sounding curves: Apparent resistivity and phase as a function of period at the stations (a) Bacher (site 3); (b) Diwar (site 7) in the vicinity of earthquake epicentre (c) Appala (site 8) (d) Nijmula (site 16).

site 7 is located near a known geological thrust oriented in NS direction (Fig. 1) and is one of the sites in the vicinity of the epicentral region.

MODELING

Magnetotelluric data can be modeled using direct transformation techniques in order to obtain semi-quantitative estimates and then followed by 1-D modeling techniques using inversion schemes. In the transformation techniques both the apparent resistivity and phase data are transformed to get the true resistivity as a function of depth. While various transformations techniques are available, in our studies we have used bostick approximation scheme (Bostick, 1977). After obtaining the semi-quantitative information for the MT data, 1-D modeling using linearised inversion schemes (Marquardt, 1963; Constable *et al.*, 1987) are carried out.

Firstly, we describe the results obtained from the Bostick scheme. As an example, the resistivity-depth profile obtained for sites 3,8,16,10,20 and 23 and 7 for MT data in YX direction are shown in Figure 5(a, b). As can be seen from these figures, for sites 3,8,16, and 20 have consistently exhibited a relatively more resistive near surface section upto a depth of about 1 km and 4 km for site 10 followed by conductive layer. For site 23 the near surface layer exhibited a resistivity of about 150 Ohm/m followed by a more resistive layer from a depth of about 2 kms. Interestingly, the subsurface section at site 7 show an order less resistivity (10-100 Ohm/m) as compared to other sites. It may be noted that the site 7 is located in the vicinity of epicenter and also near the NS oriented thrust zone.

As discussed before, 1-D modeling using linearised schemes have been carried out for all the sites and fit with the observed and computed data for a few sites (20,12 and 7) are presented in Figure 6 a, b and c. From 1-D Modeling results, the shallow depth sections are presented for a few

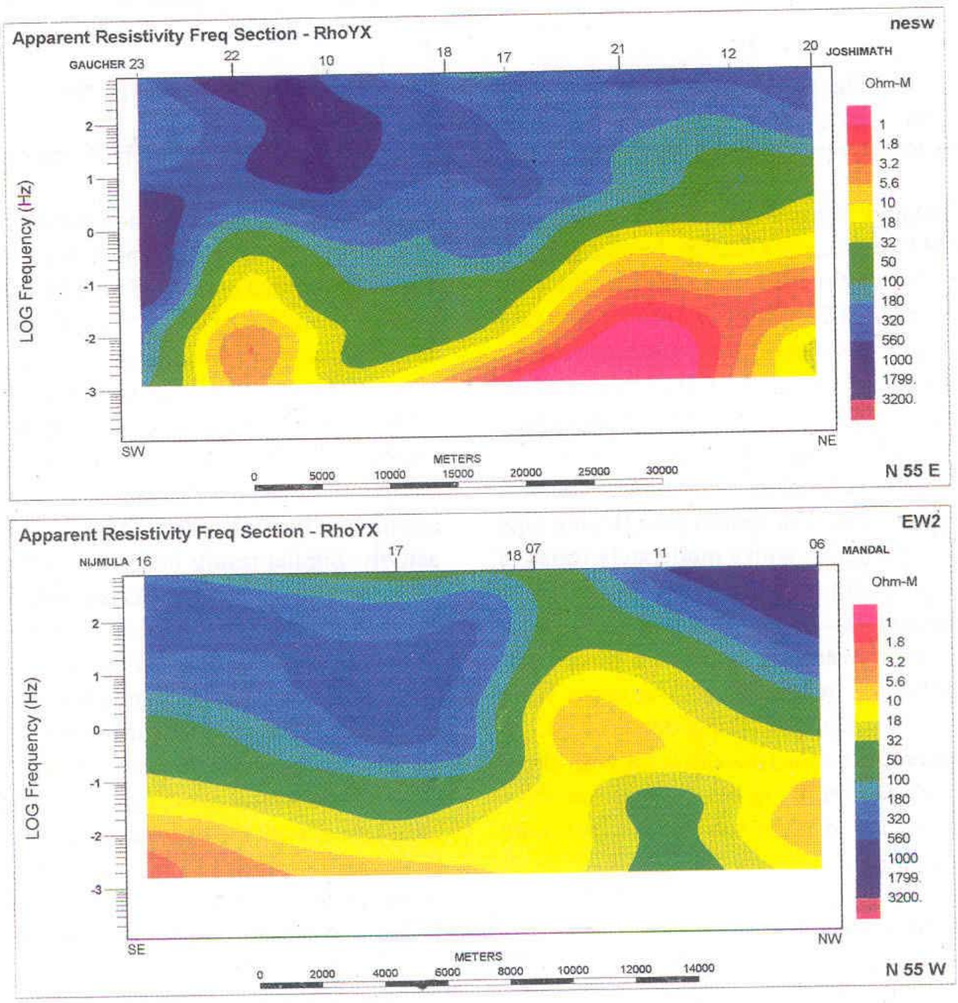
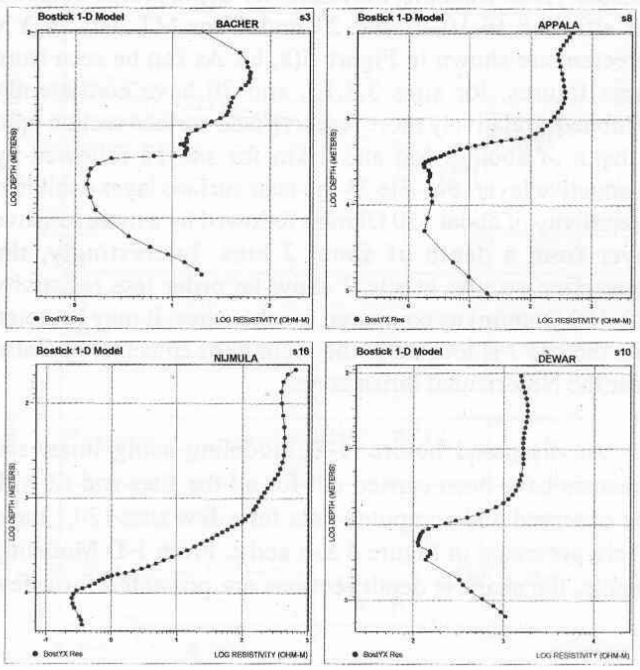
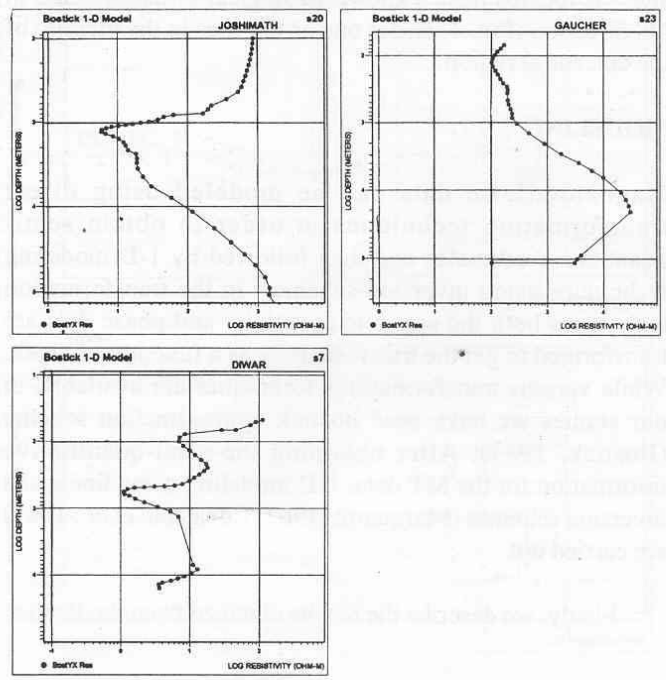


Fig. 4. Pseudo section of 'apparent resistivity' along (a) NE-SW profile from Gaucher to Joshimath (top) and (b) along EW profile from Nijmula to Mandal (bottom).



(Fig. 5a)



(Fig. 5b)

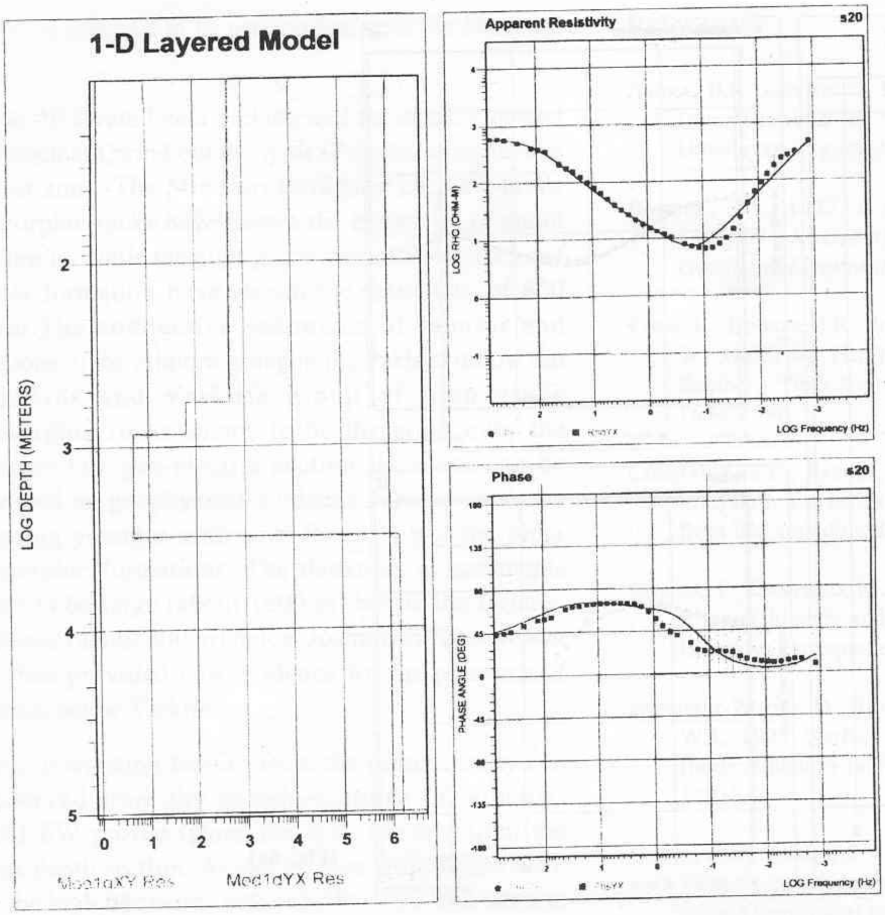
Fig. 5. ID modeling results of Bostick's transformed resistivity at stations - (a) sites 3, 8, 16 and 10 (b) for sites 20, 23, and 7.

sites (sites 20,12,7,10 and 23) in Figure 7. As can be seen from the figure, the MT site 23 near Gaucher, located towards the southern most part of the study area exhibited a moderately resistive layer of 200 Ohm/m upto a depth of 1 km followed by a high resistive layer. The station near Dewar (site 10) exhibits a moderate resistivity of 412 Ohm/m upto a depth of 800 m followed by conductive (30 Ohm/m) layer. The site near Diwar (site 7) has shown the presence of relatively high conductive subsurface section (<50 Ohm/m) as compared to the other sites. The station near Helang (site 12) shows a three layer structure with a moderately resistive (530 Ohm/m) top layer with a thickness of about 250 m underlain by low resistive layers of 60 Ohm/m and 2 Ohm/m. The site no. 20, near Joshimath exhibits a three-layer structure with a conductive middle layer. The upper layer shows a resistivity of 800 Ohm/m upto a depth of 515 m followed by conductive (2 Ohm/m) middle layer with about 1800 m thickness, which inturn lie over a high resistive basement. The significance of these sub-surface layers are discussed in the following.

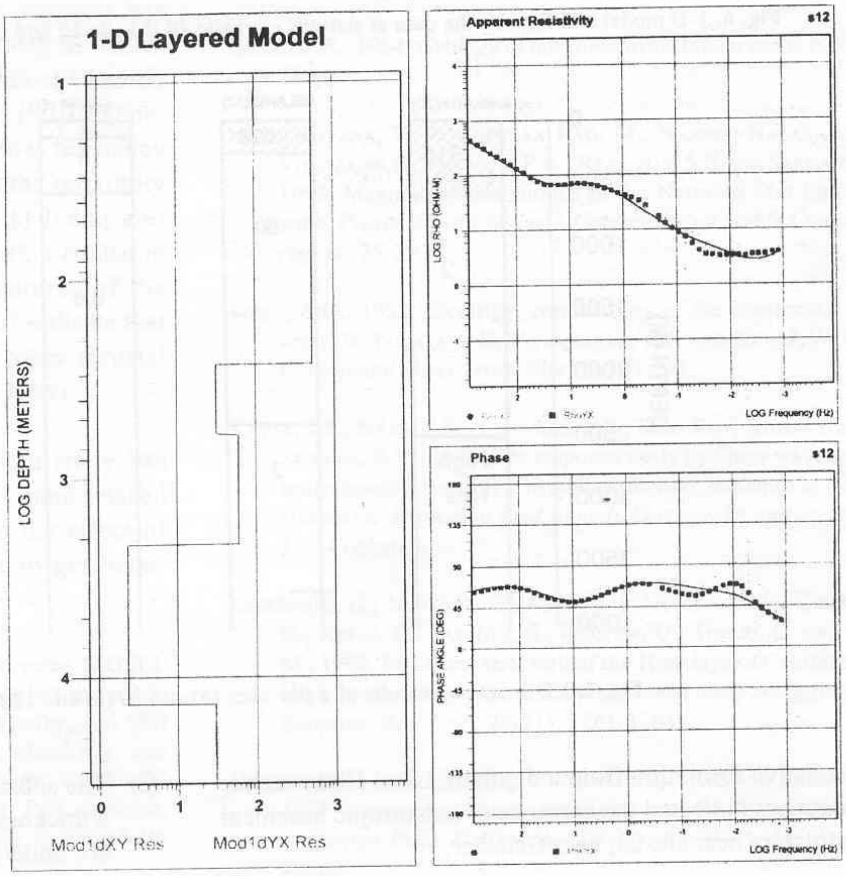
RESULTS AND DISCUSSIONS

Deep electromagnetic methods, particularly the magnetotelluric method is effective in detection and mapping of conductive layers at subsurface levels. Presence of high conductive layers are common in tectonically active regions, fold belt regions, geothermal regions etc. (Jones, 1992; Eberhart-Phillips *et al.,* 1995). These features are known to be the sources of high conductivity owing to their association with mineralized zones, presence of fluids, elevated temperature, etc. Recent MT studies in India, for example near Latur epicentral region (Sarma *et al.*, 1993, Gupta *et al.*, 1996) and also across complex fault zones in central India (Harinarayana *et al.*, 1996) have identified anomalously high conducting zones related to seismic activity. Similar results have also been reported in other parts of the world, for example across San Andreas Fault (Mackie *et al.*, 1997; Park, 1991; Lemonnier *et al.*, 1999; Chen *et al.* 1996). All these studies indicate the significance of subsurface conductors in understanding the physical processes related to seismic activity. The results of the magnetotelluric studies carried out in and around the Chamoli epicentral zone, described in the foregoing section have brought out the geoelectric structure of the region. This helps in understanding the subsurface geology and tectonics of this complex region. Some of the interesting features of present study are as follows.

(i) The conductive sediments of Jaunsar group of rocks in the southern part of the study area exhibits a moderate resistivity of 100-500 Ohm/m and is underlain by a more



(Fig. 6a)



(Fig. 6b)

Fig. 6 contd....

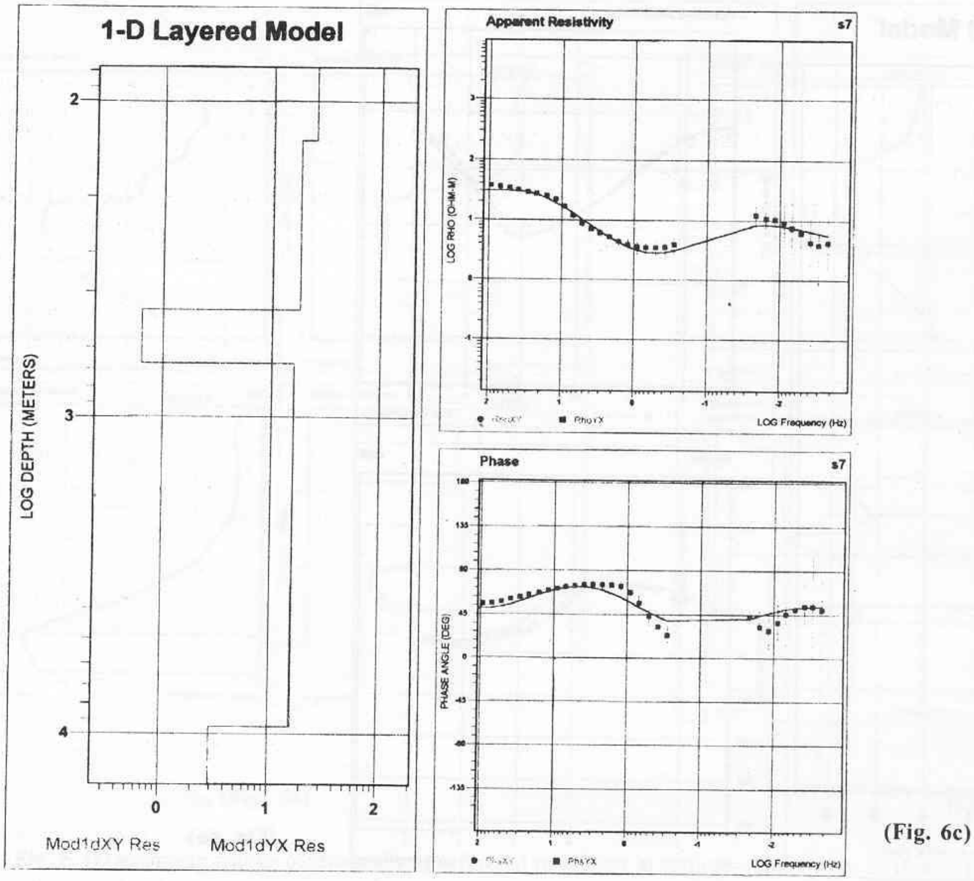


Fig. 6. 1-D model and fit with the data at stations - (a) site 20 (b) site 12 and (c) site 7.

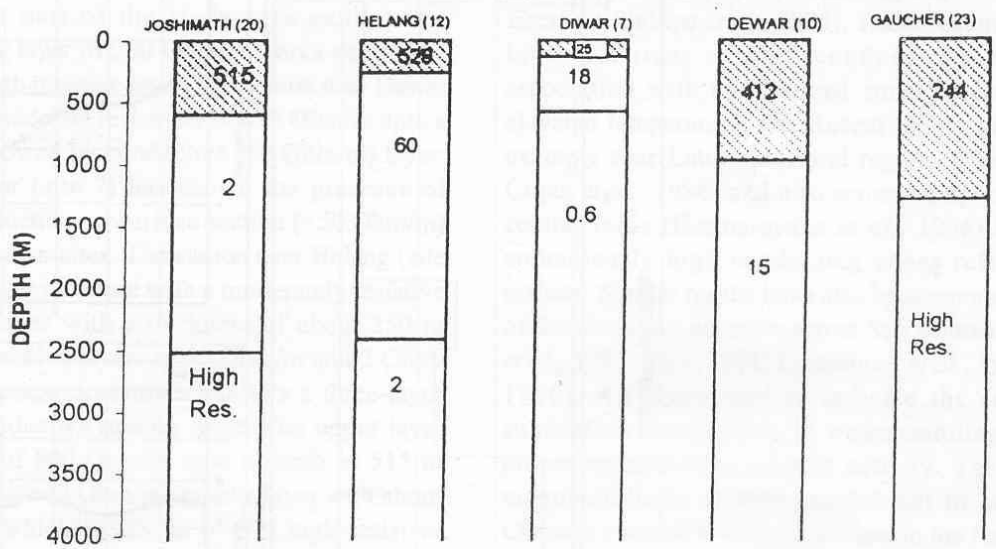


Fig. 7. 1 D Inversion results of a few sites (a) site 20 (b) site 12 (c) site 7 (d) site 10 and (e) site 23.

resistive formation from a depth of 1 km. However the data has indicated the presence of anisotropic basement structure near site 23, near Gaucher.

(ii) The subsurface structure near Dewar (site 10) indicates a thickness of 800 m for Jaunsar group of rocks, which are underlain by more conductive formation (30 Ohm/

m). This is inferred to be association with the Munsiari thrust.

(iii) The site 12 located near Helang and the site 20 located near Joshimath bring out the typical electrical signatures of thrust zone. The Munsiari formation i.e., low-grade metamorphic rocks have shown the resistivity of about 400 Ohm/m, while the high-grade metamorphic rocks of Vaikrita formation have shown the resistivity of 800 Ohm/m.The conductive sediments of Jaunsar and formations of the Almora group in the Pakhi window dip northwards and Vaikrita group of high grade metamorphic rocks seems to be thrusting over the sediments.The geo-electric section therefore can be considered as geophysical evidence for the existence of dipping younger sediments thrust below the older metamorphic formations. The thickness of sediments appears to be large (about 1800 m) below the Helang, but thinner (about 800 m) below Joshimath. The present study thus provided new evidence for the presence of sediments below Vaikrita.

(iv) Another interesting feature from the present study can be observed from the pseudo-sections of Nijmula-Mandal EW profile (from site 6 to 16) and from the Bostick depth section. As can be seen from figure 4(b), while the high frequency data exhibits 1000-180 Ohm/m apparent resistivity, the low frequency segment has apparent resistivity of about 30 Ohm/m along the entire profile. However, at site no. 7, located north of Chamoli shows a relatively conductive subsurface (50-10 Ohm. m) both for high frequency as well as low frequency data. Interestingly, this site is located in the proximity of a known N-S trending thrust zone (Fig. 1). It may also be noted that the Chamoli epicenter location is also in the vicinity of site 7. The above signatures of the conductive subsurface structure near site 7 indicate that this thrust might be more active than other thrustal planes in this area (Ravindran and Philip, 1999).

As described above, although our present study has identified a few significant electrical signature, a more detailed 1-D and 2-D modeling of the data and also the effect of topography need to be considered in order to get better constraints on the derived models.

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