International Journal of Applied
and Natural Sciences (IJANS)
ISSN(P): 2319-4014; ISSN(E): 2319-4022
Vol. 7, Issue 6, Oct - Nov 2018; 43-52

International Academy of Science, Engineering and Technology
Connecting Researchers; Nurturing Innovations

A DEEP CRUSTAL STRUCTURE OF BHUJ EARTHQUAKE REGION (INDIA) USING MAGNETOTELLURIC STUDIES AND ITS RELATION WITH SEISMICITY

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ABSTRACT

Kutch region is well known for high seismicity with the reported occurrence of atleast three major earthquakes. Although various geological and geophysical studies have been carried out, the deep crustal structure is poorly understood. In order to understand the physical processes related to seismicity of the Bhuj earthquake, a wide-band (1000-0.001Hz) magneto telluric survey has been carried out along three profiles with 21 stations. The profiles cut across the major structural features such as Kutch Mainland Fault (KMF), Wagad Fault and Katrol fault. In the present study, deep geoelectric structure along a profile oriented in SW-NE direction i.e. Mundra-Rapar is presented. Results indicated the presence of thick sediments (1-4km) dipping towards south underlain by high resistive basement. From detailed 2-Danalysis of the data, it is observed that the resistivity of the basement shows distinct variation for the stations located towards the South compared to the north. It is interesting to observe that the well-known KMF is spatially located near the sharp variation in the basement resistivity. The deeper electrical structure shows a north-eastward dipping electrical conductor (25-50 ohm). Interestingly, the numbers of hypocenters are located in the transition zone of the resistor (brittle) and conductor (ductile) at depths of around 10-40 km. The results suggest an ongoing tectonic activity across the area with a blocked structure embedded between the North Wagad Fault and South Wagad Fault. The relative movement of these crustal blocks might be the reason for the continuous development of stresses that led to major earthquakes in the region. This deformation may be related to the present neo-tectonic compressive stress regime of the Indian Plate due to its NNE movement against the collision front in the north and its proximity to the triple junction in the western continental margin of the study area

KEYWORDS: *Magnetotellurics, Apparent Resistivity, Sediments, Seismicity, Bhuj Earthquake, Basement Depth, Dipping Conductor, Transition Zone*

Article History

Received: 24 Sep 2018 | Revised: 29 Sep2018 | Accepted: 12 Oct 2018

INTRODUCTION

In this study the geoelectric section derived from magneto telluric investigation in the Bhujearthquake epicentral zone of Kutch region is presented along Mundra-Rapar profile.

The Bhuj earthquake (M 7.9) of 26th Jan.2001 a rare event over the past 50 years that has killed more than 20,000 people and rendered thousands of people homeless. This region located in the high seismic zone (Zone-V) has a past history of great earthquakes. Major faults in the region are Kutch Mainland Fault, Katrol Fault and North and South Wagad Fault. The region is covered by Tertiary sediments and Deccan traps. The region has attracted many earth scientists owing to large magnitude and severe damage caused by it. Several geophysical and geological studies were initiated to understand the lithology and structure and also to study the physical processes related to seismicity of the region (Gupta et al., 2001a,b; Kayal et al., 2002, KareemunnisaBegum,2003, Sastry et al 2008, Naganjaneyulu *et al*., 2010, Kapil et al., 2018). As a part of such an investigation, magnetotellurics - being one of the important geophysical techniques to tackle a wide variety of geological problems is also initiated. With the objective to understand thebasement features and also to study the deep crustal structure in the region. A wide band (1000-0.001 Hz) magnetotelluric study has been made in the Bhujearthquakeepicentral zone during March – April2001 and 21 sites have been occupied along three profiles to understand the deep structure of the region. Earlier during 1998-99, five profiles have been occupied with 35 stations in the Kutch basin as a part of integrated geo physical study for hydrocarbon exploration(Harinarayana et al 2000). Thus the region surrounding Bhuj has been covered with a number of profiles and the information about the upper crust (5 km) is known. The subsurface structure is well constrained from the hydrocarbon exploration point of view and also for seismotectonic studies. A few additional stations are occupied in addition to the repetition of earlier stations after the Bhuj earthquake. In the present study, the results obtained along 140 km long profile with 13 stations from Mundra-Rapar oriented in SW-NE direction passing through the epicenter of Bhuj earthquake are presented considering the two databases covering both pre (MB1, MB3, MB2, MB4, MB5, MB6) and post-earthquake events (KB8, KB15, MR10, MR3, MR4, MR11, MR12) are presented in the Figure 1which shows few old MT sites in red color and new MT sites in blue color (Kareemunnisa Begum, 2003).

DATA ACQUISITION AND ANALYSIS

The data consist of the record of variations of natural electric and magnetic fields of the earth, measured with wide band (1000-0.001Hz) digital magnetotelluric data acquisitionsystem (GMS05, Germany). A dipole length of 80m has been used for telluric field measurements (Ex and Ey). Three components of the magnetic field (Hx, Hy and Hz)were measured using induction coil magnetometers. The entire system is computer controlled with on-line processing to monitor the data and the processed results for quality check. The data were acquired for sufficiently long time, at an average of about 3-4 days and in four different frequency bands in the range 1000-0.001Hz. The frequency range of signals is large enough to scan the earth from shallow to deeper levels (5 to 10 km and more). The data acquired data 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 is removed from further processing. Linear trend removal is used conventionally in MT data processing and the same has been applied by fitting a straight line. Similarly, the data from time domain is converted to the frequency domain. Thus we obtain auto and cross spectra for the five components of the signals, namely Ex, Ey, Hx, Hy and Hz. These parameters further processed to obtain impedance, apparent resistivity, phase, coherency, skew etc. We used weighted coherency criteria to derive these parameters. The same procedure is adopted for all windows of the data and a smoothed spectrum is derived for each site to compute the above MT parameters.

The PROCMT software of M/S Metronix, Germany is used for processing the data. A consistent regional strike for the data set is obtained from the plot of Swift (Swift, 1967) angle for all the sites. Towards the longer period the average strike angle of aboutN45°E (i.e., N45°W with 90° ambiguity) is obtained and thus regional strike direction is considered as N45°W. From the tectonic map of the Kutch region the eastern half is fully dominated by nearly East-West oriented geological faults. However, in the western half of Kutch, the fault (KMF) orientation is nearly N45°W. This is consistent with the regional strike direction obtained in the present study. To deal with the galvanic distortion and to reduce the effect of local in homogeneities, the Groom-Bailey tensorde composition method has been applied for all sites (Groom and Bailey, 1989). The dataare also corrected for static shift based on the geology of the local area.

The profile from Mundra to Rapar crosses different geological formations ranging from Recent to Jurassic. From the study of the high frequency data it is obtained that at frequencies > 100 Hz the data is reasonably good. Moreover, due to high conducting sediments the data at 100 Hz senses the shallow depths and serve the purpose for static shift correction. For this purpose, the sites falling on each formation are grouped together and the apparent resistivity values obtained after Groom-Bailey Decomposition in both XY and YX components at 100 Hz are averaged and the resultant value is assigned to the individual Rho-XY and Rho-YX components. The result antapparent resistivity is used for modelling.

MODELING RESULTS

In Figure 2 the MT sounding data for two sites namely, KB8 and MR11 are presented. These data earlier subjected to Groom-Bailey decomposition and static shift correction. It may be seen that the site KB8 is located south of Kutch Mainland Fault (KMF). As can be seen, the apparent resistivity at the high frequency end shows about 5 Ohm.m and increases to nearly 20 Ohm.m at 2 Hz frequency. This indicates the shallow conductive layer is underlain by a more resistive formation. This is as expected from a geological point of view as well. It may be noted that at this location, Alluvium is underlain by Deccan Traps. Further the apparent resistivity reduces to 6 Ohm.m at 0.1 Hz. This indicates that a thick layer of sediments corresponding to Bhuj sedimentary formation. Again the apparent resistivity increases to 100 Ohm.m towards lower frequencies beyond 0.1 Hz. This indicates the presence of resisitive basement below the sediments. In contrast to the pattern shown in KB8 data set, the data at MR11 exhibits a near horizontal pattern upto 5 Hz and then increases gradually with a gentle gradient. This is an indication that sediments are lying just above the basement.

Geoelectric section derived by 1-D inversion (Marquardt, 1963, Constables al, 1987) along the profile Mundra-Raparis shown in Figure 3, it shows the basement undulation and shown correlation with the surface deformations recently mapped in the region. (Kareemunnisa Begum and Harinarayana, 2016). From geoelectric section it is obtained that the basement depth is around 5 km at Mundratowards the southwest end of the profile and becomes shallow in the north (1-1.5 Km) nearRapar. The basement topography although gentle, exhibits undulations at places along the profile. These undulations near the Katrol fault, KMU Fault and South Wagad Faultare quite evident (Kareemunnisa Begum and Harinarayana, 2016).

To understand the structure further, detailed 2D analysis of the data has been done by using Rapid Relaxation Inversion (Smith & Booker, 1991). Figure 4 shows a 2D model showing the shallow section (0-10km) along Mundra-Rapar profile. Figure 5 shows2D deeper geo electric section (0-40 km) along this profile. The basement shape is closely agreed with that of 1-D result and shows a dipping conducting slab (25-50 ohm.m) at adepth starting from 10 to 40 km towards the NE direction at site MR12 near Rapar, and site KB8 as the boundary and indicates a dipping fault. Local anomalous conductive zone (<10 ohm.m) at depths of 10-13 km is also observed at site MB2. The 2-D model presented in Figure 5 from Mundra –Raparhas exhibited a sharp lateral variation in the electrical resistivity structure located at site KB8. It is interesting to see the concentration of aftershock activity (Rastogi et al., 2001) falls in this region as shown in Figure 5. The hypocenters are located from 20 to 30 km as shown in the Figure 5.

Figure6 shows the fit between the observed and computed GB apparent resistivity responses for TE and TM mode data for all the sites along this profile. Figure 7 shows the fit between the observed and computed GB phase responses for TE and TM mode data for all the sites along this profile. Although, detailed 2D modelling using different inversion schemes need to confirm, the model shows an indication of a dipping conductor at 5-15 km towards south to 25-35 km towards north. Such a dipping signature is seen usually in subduction environments.

RESULTS ANDCONCLUSIONS

- Bhuj region in Gujarat is located in the well identified high seismic zone-V. The basement undulations are close to the well mapped geological faults indicating the extension of these faults to the basement depths and beyond.
- A major sedimentary basin has been delineated near Mundra-Mandvi on the southern coastal plain of Kutch. In addition to these studies MT has initiated in and around the epicentral zone in order to obtain more details about thesubsurface structure that can throw more light to understand the Seismotectonics of the region.
- A dipping conductor is delineated from the MT study. The northward dipping conductor seems to have a signature of a subduction zone. Although such a signature is not seen from other geophysical studies, from regional tectonic setting, it can be related to the possibility of extension of Makaransubduction zone or the newly created hidden fault between North and South Wagad fault which created the devastating 2001 Bhuj earthquake. The aftershock seismic activity is concentrated more at the bottom of the dipping deep conductor.
- These results suggest an ongoing neo tectonic activity across the area with a blocked structure embedded between the North Wagad Fault and South Wagad Fault. This deformation may be related to the present neo-tectonic compressive stress regime of the Indian Plate due to its NNE movement against the collision front in the north and its proximity to the triple junction in the western continental margin of the study area.
- The 2-D geoelectric section derived along Mundra-Rapar profile in NE-SW direction has clearly indicated the thickening of the sedimentary formationtowards the south and south-west direction, a sharp change in basement depth isobserved near KMF indicative of the importance of the fault in controlling thesedimentation process towards south.
- The deeper thick crustal conductor delineated at a depth of 10 km towards south seems to be dipping towards north is another clinching evidence for the presenceof the seduction process in the complex region. The deeper dipping signature of thecrustal conductor has also been delineated in another adjacent profile oriented inN-S direction.
- Seismic activity also correlates well with the present study in the sense that concentration of hypocenters is restricted to resistor-conductor transition zone and lie just below or within the deeper dipping conductor.
- Present ongoing tectonic activity on Indian plate is so active and no place as such is safe to live, but with good constructions taking the 3D models of magnetotelluricGeoelectric conductivity, seismic velocity, density structures into consideration while preparing seismic hazard maps and constructions we can minimize the damage. Shallow earthquakes are created due to high frequencies and can cause severe damage, whereas intermediate and deep earthquake are created due to low frequencies which generally occurs in the subduction zones cause less damage. In 2001 Bhuj earthquake damage was so high, though the epicentre of the earthquake is at 25 km depth

this damage was mainly due to loose soil present at shallow depths.

- Aftershock activity and electrical conductivity are two independent parameters. Observation of aftershock activity close to the anomalous conductive zones in upper and mid crustal depths as indicated from Chamoli (Kareemunnisa Begum 2017) and Bhuj earthquake regions in India and also noticed in a few cases in Japan and other places is a significant observation. The upper crust of the Indian shield region is believed to be more of brittle in nature similar to any stable continental region. However, presence of anomalous high conductive features in epicentral zones point towards ductile nature of the upper crust at places. The brittle-ductile transition zone is perhaps a favorable location for the concentration of aftershock activity. In other tectonic regions of intense seismic activity such as active subduction zones, intra-plate environment, the correlation of aftershock location with anomalous conductive structure need to be studied with more concerted efforts.
- The magnitude of the aftershocks in the region varies from 3-5 recorded during Feb. and Mar 2001 (Figure 5). The deeper geoelectric section has delineated a major dipping conductor in the upper crust at a depth of about 10 km towards SW part of the profile and dips to mid-lower crustal depths towards NE part with a thickness of about 10 km as shown in figure 4. This is one of the significant findings from the present study. The aftershocks recorded nearer to this profile have been considered and plotted on the geoelectric section. The hypocenters of the aftershocks are located both within the dipping conductor and also outside. The greater density of data can be seen near resistor - conductor (brittle-ductile) transition zone below the stations MR10 and MR3. Interestingly, minimum numbers of hypocenters are located near the anomalous conductive zone at the stations MR4 and MR11. It is also of interest to note that the hypocenter of the mainshock (IMD) is located at a depth of 25 km falls below the dipping crustal conductor. A schematic diagram developed and presented in Figure 8.
- Statistical analysis has been made to relate aftershock activity and electrical conductivity and the results are presented in figure 9. The concentration of hypocenters falls neither at the anomalous conductive zone, nor at high resistive feature, but close to moderately conductive feature. Thus one may conclude that the hypocenters are likely to occur at the brittle-ductile transition zone.

ACKNOWLEDGEMENTS

This work is the part of my Ph.D work. Accordingly, I thank the director NGRI for his permission to publish this paper. Ithank CSIR for providing Senior Research fellowship during my PhD studies at NGRI. I also thank my guide Prof. T Harinarayana, Dr. B. P. K Patro and other members of MT group of NGRI fortheir kind support.

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FIGURE CAPTIONS

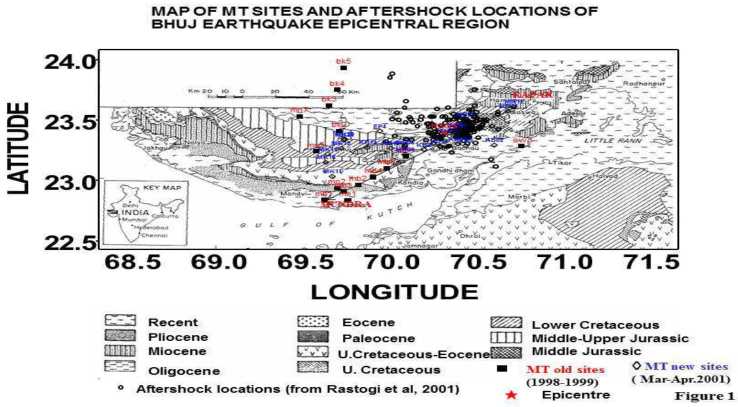

Figure 1: Location map of MT Sites near Bhuj Earthquake Epi Central Region, India along with Regional Geology

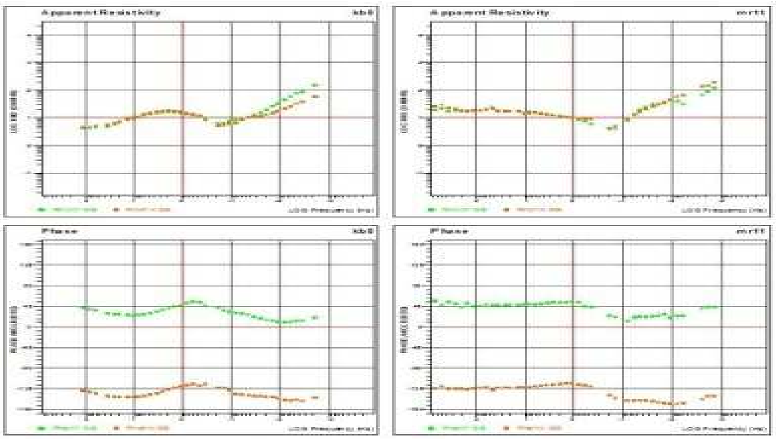

Figure 2: MT Sounding Curves after GB Decomposition and Static Shift Correction for Two Stations KB8 and MR11

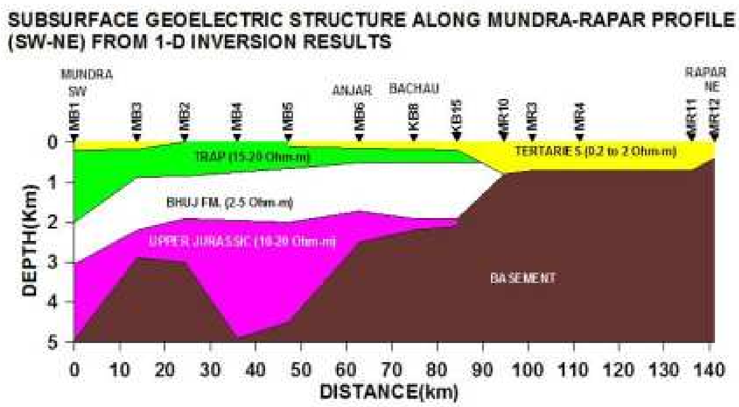

Figure 3: Subsurface Geo Electric Section from 1-D Inversion Results along the Profile

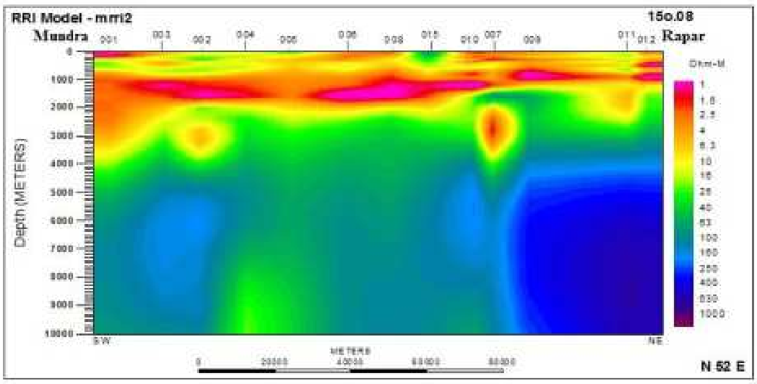

Figure 4: 2-D RRI model along Mundra-Rapar profile, Shallow (0-10 km)

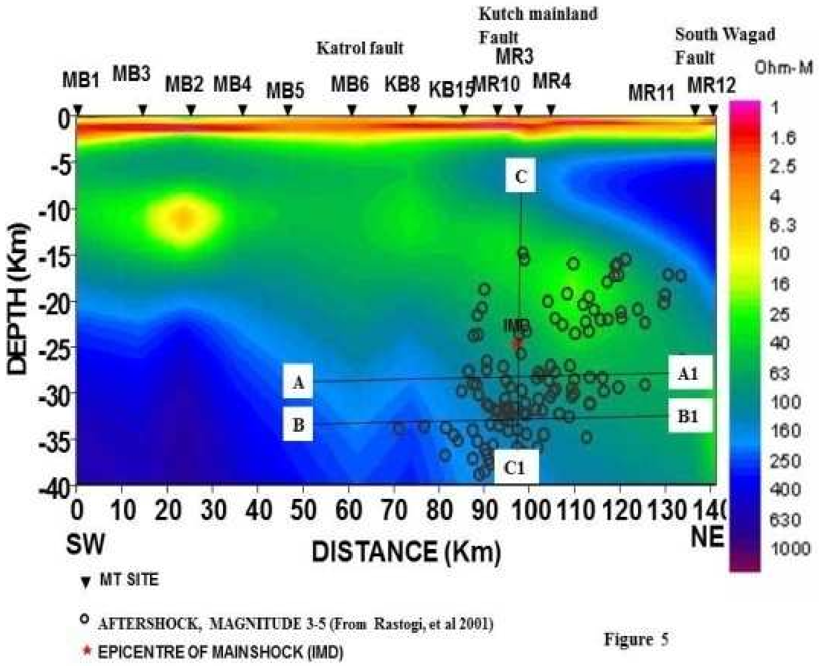

Figure 5: 2-D RRI Model along Mundra-Rapar Profile, Deep (0-40 km) with Hypocentral Locations of Aftershock Data of Magnitude Range 3-5.

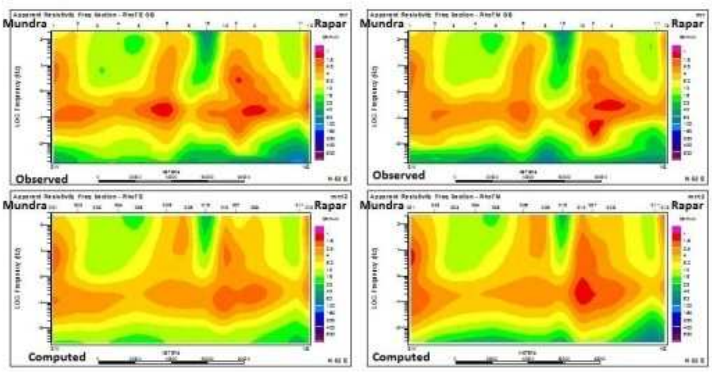

Figure 6: 2-D Fit between Observed and Computed Data for GB Apparent Resistivity Pseudo Section for Both Modes i.e TE and TM Mode

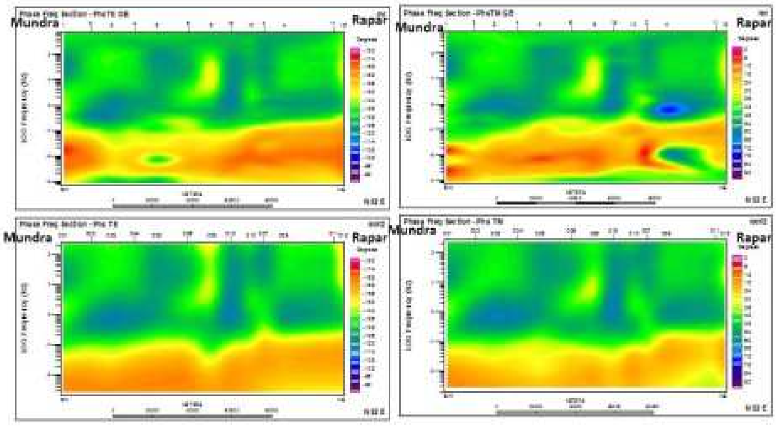

Figure 7: 2-D Fit between Observed and Computed Data for GB Phase Pseudo Section for Both Modes i.e TE and TM Mode.

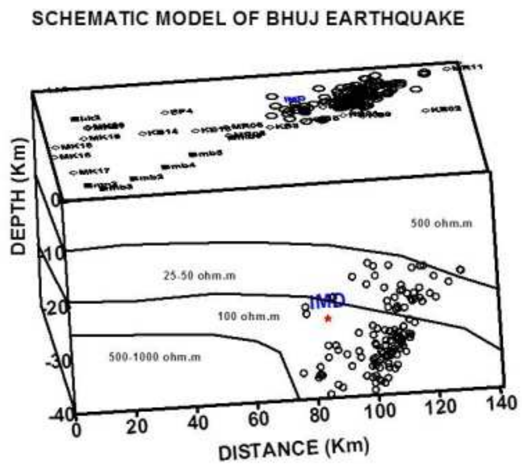

Figure 8: Schematic Model of Bhuj Earthquake

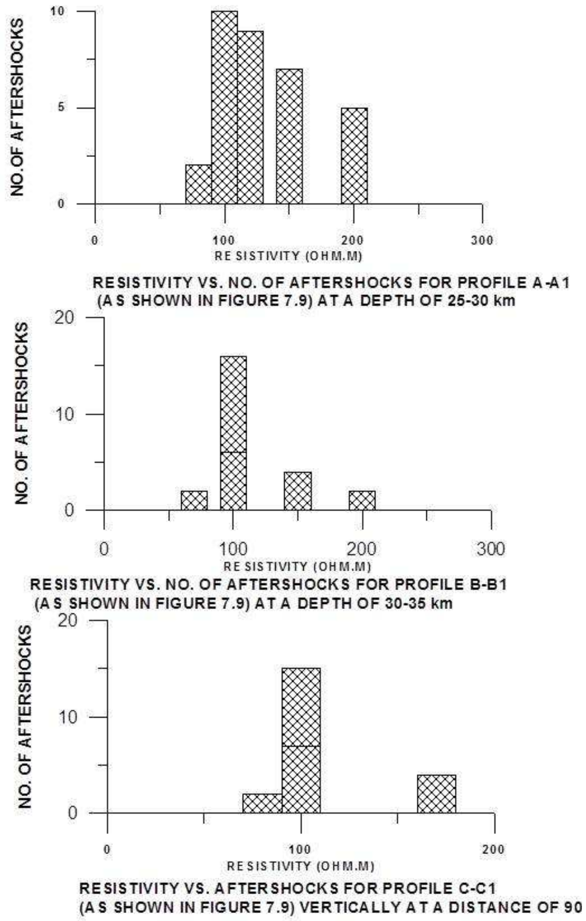

Figure 9: Histogram of Correlation of Electrical Resistivity and Aftershocks along Three Profiles A-A1, B-B1, C-C1 as Indicated in Figure 5 at Different Depths