Geothermal inferences drawn from 3D inversion of Magnetotelluric Data recorded from Chamoli region, Uttarakhand, India

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SUMMARY

Broadband Magnetotelluric (MT) data were recorded at 28 sites in Chamoli region, Uttarakhand, India to image the geoelectrical structure and its correlation with possible geothermal system in the area. MT data were processed using MAPROS software to obtain impedance tensor for each site. After processing, for 3D inversion, we have chosen impedance responses of 23 sites. MATLAB based 3D MT inversion code (AP3DMT 2017) has been used for the inversion of impedance tensor. Different inversion experiments were performed using initial guess model of homogeneous half space with varying resistivity values. Effect of regularization parameters was also studied by varying smoothness in x, y and z-direction. For the off diagonal impedance tensor a normalized Root mean square (nRMS) misfit of 2.3 was obtained; however, it was reduced to 1.7 after removing two sites having high nRMS values. The inverted geoelectrical model indicates an intra-crustal high conductive feature (< 10 ohm-m) around Chamoli region at a depth of 10-18 km. This conductive feature is moving upward and it seems to flow in multiple channels which reach upto the depth of one km from surface. These conductive channels appear to be correlated with the hot water spring in the area. The low resistivity (< 10 ohm-m) of this feature is an evidence of fluid-filled fractured rock with high concentrations of either aqueous fluids or melts or their combination. The meteoric water is flowing from the Higher Himalayan region reaching to these high conductivity zones and is transported to the surface in the form of hot water springs in the study area.

Keywords: 3D Magnetotelluric inversion, Hot springs, Main Central Thrust (MCT)

INTRODUCTION

The Himalaya is one of the youngest and highest mountain range, which originated from continental collision tectonics and under-thrusting of the Indian Plate beneath the Eurasian Plate. Regional N-S compression, resulting from horizontal movement of rock masses along the north dipping thrust planes, caused crustal shortening, horizontal extrusion and lithospheric delamination (Le Fort 1975; Molnar 1990). In this process, leading upper brittle portion of the subducting Indian crust has been sliced and stacked up southwards to form the Himalayan mountain belt. The various regional thrust systems in the area, namely, the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) are the elements of this geodynamical process. Magnetotelluric investigations were carried out in the Garhwal corridor along Roorkee to Gangotri (RKG) profile of the Uttarakhand Himalaya and Geoelectrical model presented earlier by Israil et al. (2008). In the present study we have recorded MT data at 28 sites in the east of the Roorkee-Gangotri profile and around the Chamoli region. 3D inversion is performed from the processed MT responses using AP3DMT a MATLAB based inversion code (Singh et al. 2017).

GEOLOGICAL SETTING

The study area falls in MCT zone. The zone is characterized by dual strands. The upper and lower strands of the MCT are Vaikrita thrust (VT) and Munsiari thrust (MT) respectively (Valdiya 1980; Gupta et al. 2012). Together they form the MCT zone, a ductile zone where Higher Himalayan Crystalline (HHC) complex is placed over Lesser Himalayan Sequence (LHS). The metamorphic pressure and temperature across the MCT increase from 5 kbar and 550°C in the LHS to 14 kbar and 850°C in about 3 km zone of the MCT in the Higher Himalaya (Spencer et al. 2012). The zone is characterized as geothermally anomalous and high temperatures, high heat flow and hot springs (GSI 1991). The cluster of hot water springs are emerging in the area. The hot springs in the area have a temperature gradient of 60±20°C/km and the heat flow of 130±30mW/m² (GSI 1991). The hot springs in MCT zone shows high temperature in the range of 55°C to 94°C. Most of the thermal springs emerge through joints and are controlled by interface of lithological units.
DATA ACQUISITION AND PROCESSING

Broadband MT data was acquired, at 28 sites, using Metronix ADU06 system in and around the Chamoli region. Locations of these sites are shown in Figure 1. MAPROs software (Friedrichs 2003) was used to estimate impedance tensor (Z) from the recorded time series. Out of 28 MT sites, 5 sites were discarded due to very high noise in the estimated MT response. Thus stable impedance tensor at 23 sites, derived in the period range 0.001-100 s, are used in further processing and inversion. The response curves were smoothed using the numerical techniques and consistency test, a procedure available in WingLink, Geosystem code (WinGLink User’s Guide). Smoothed responses, off diagonal impedance and full impedance tensor were used for 3D inversion.

3D INVERSION OF MT DATA

We used MATLAB based 3D inversion code, AP3DMT (Singh et al., 2017) for the inversion of MT data. This code uses non-linear conjugate (NLCG) gradient algorithm for minimization of penalty functional \( \Psi = \Psi_d + \lambda \Psi_m \) composed of data misfit \( \Psi_d \) and model regularization term \( \Psi_m \) weighted by \( \lambda \), the trade-off parameter. We have taken several inversion runs with different data selection, off-diagonal impedance tensor rotated in regional strike direction (N80°W) and full impedance tensor. We also vary smoothness in x, y and z- direction keeping in view the regional geological strike. 3D geoelectrical model with robust features are presented in Figure 2 and 3. The prior and initial guess models were set as homogeneous half space of resistivity 100 ohm-m.

In the first inversion run all 28 sites were used for inversion of off-diagonal impedance tensor for 39 periods, logarithmically spaced between 0.001-100 s. Data errors were set at 10 per cent of \( |Z_{xy} Z_{yx}|^{1/2} \). For inversion, the model was discretized into 50×56×40 cells in X, Y and Z direction respectively. We also added seven cells (layers) in air. The inversion domain comprises a uniform mesh of 44×38×40 having a cell size of 1.7 km with 12 planes padded in each horizontal direction around the central domain. The vertical thickness of first layer is 50 m; the thickness of successively layers increases by a factor of 1.2. In 96 NLCG iterations, the normalized nRMS value reduced from 28.45 to 15.1. By analyzing the nRMS values for each site, we found that nRMS values at five sites were very high. It could be due to high noise level in the responses at these sites. We, therefore, removed these sites in the next stage of inversion run. Inversion was performed with 23 sites responses. In this inversion run we set the initial guess model as the output model obtained from the inversion of 28 sites. It is observed that the nRMS decreases from 5.13 to 3.44 in 73 iterations. Next, the inversion was done on 23 sites for full impedance with initial guess model of homogeneous half-space with resistivity of 100 ohm-m and the nRMS decrease from 20 to 3.4 in 85 iterations. In view of higher noise level, in the next inversion run, the data error floor was increased from 10% to 15%, keeping all the other inversion parameters same. In this inversion run the nRMS decreases from 13 to 2.34 in 68 iterations. In addition to the above, we have also carried out several inversion experiments by varying resistivity of homogeneous half space model used as initial guess model and found that the resistivity of 100 ohm-m is an optimum value. The off-diagonal elements were rotated by N80°W (geological strike direction) and performed another inversion run with rotated off-diagonal elements. For this, the model was discretized into 60×63×44 cells in X, Y and Z direction respectively. The inversion domain comprises a uniform mesh of 42×45×44 having a cell size of 2.0 km with 18 planes padded in each horizontal direction around the central domain. For this the nRMS decreases from 9.4 to 1.83 in 67 iterations. The covariance was changed to study the effect of smoothness for both full impedance and rotated off-diagonal impedance tensor. We have found that, in general, broad features of the model are retained in the final inverted model. 3D inverted model and various depth slices are shown in Figures 2 and 3 respectively.

Figure 1. A simplified map, showing Garhwal Himalayan thrusts: MT: Munsiari thrust; VT: Vaikrita thrust; LH: Lesser Himalaya; HH: Higher Himalaya (compiled from Valdiya 1980) and MT sites.
Figure 2. Model showing only the conductive features (less than 10 ohm-m) at various planes extending from z=0 to z=20 km. The black inverted triangles show the inverted sites and the red circles are known geothermal locations (GSI 1991).

DISCUSSION

A well planned MT survey is very crucial in mapping geothermal areas. In Himalayan tough terrain with limited accessibility, it is not possible to record MT data over a well defined grid. Therefore, MT site locations and their spacings are also guided by the accessibility and noise conditions. We conducted several inversion experiments by changing the control parameters, initial guess model and by choosing different data set. We observed that in general the prominent features of the inverse model obtained are common in most of the run with different final nRMS. The near surface is generally resistive (>500 ohm-m) except at few locations where the subsurface is fractured or influenced by the fluid filled zone Figures 2 and 3. Resistive near surface represents exposed lithology of quartzite rocks. The conducting (< 10 ohm-m) is located at a depth of 10-18 km around Chamoli region. This feature lies in the MCT zone and is an example of mid-crustal conductor. A similar conducting zone was also obtained by (Rawat et al., 2014) through 2D inversion of a profile extending from Bijnaur to Malari. Also, this high Conductive body is observed in MT profiles in various part of Himalayas like, Garhwal Himalaya (Israil et al. 2008), Nepal Himalaya (Lemonnier et al. 1999) located 50-70 km west and 500 east of Chamoli respectively and Sikkim Himalaya (Hannarayana 2009). As evident from Figure 2, the conducting zone appears emerging upward in the form of three channels from this main conducting body. One channel emerges around Chamoli region. In this region, the occurrence of moderate to high temperature springs have been reported (GSI 1991). The second limb terminates at a depth of 2.5-3.0 km while the third limb extends to the surface near the Tapovan hot spring.

Figure 3. The depth slices at different depth for inverted model. The black inverted triangles show the inverted sites and the white circles are known geothermal locations (GSI 1991).

This high conductivity zones may owe their high conductivity to (i) fluids expelled from the underthrusted sediments (Arora et al. 2007) and (ii) fluids released by metamorphic reactions in the down-going plate slab (Hyndman 1988), although nature of fluids, still remains a subject of debate (see Li et al. 2003). At this depth, partial melt alone or in combination with free fluid may be contributing in high conductivity in the MCT zone. Most likely, the conductive phase is fluid, since under-thrusting of the Indian crust can ensure continuous recharge of the hanging wall by fluids released during dehydration reactions (Lemonnier et al. 1999). This zone is associated with high temperatures, high heat flow, and hot springs in the MCT zone.

CONCLUSION

The high conductive feature obtained in the MCT zone, from 3D inversion of MT data, is a coherent feature of MT profiles located to the west and east
of study area. This feature is interpreted as inter-connected fluid filled rock system enhancing electrical conductivity. At a depth of 10-20 km, partial melt is the main contributor to the high conductance. However, the role of free fluids cannot be ruled out. These fluids move upwards through various weak faults and joints resulting in hot water springs in the vicinity of Chamoli. In some case they are trapped by overlaying crystalline rocks.

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