Three dimensional geoelectrical structure delineated from Magnetotelluric data recorded along Roorkee-Gangotri profile, India

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Keywords

3D modeling, magnetotelluric, Tipper

Summary

Geoelectric structure obtained from 2D inversion of magnetotelluric (MT) along Roorkee- Gangotri (RKG) profile has been extended into three dimensional geoelectrical structures by incorporating and interpreting induction vector response. Induction vector is sensitive to the lateral conductivity variations. Induction vector (Weise convention) points away from the lateral conductive structure. This property of induction vector has been used in the present work to add three dimensional features in the 2D geoelectrical model delineated from MT data along RKG profile. It has been observed that induction vector plotted (Weise convention) along the profile consistently pointing towards northwest directions. This indicated elongated conductive structure in the southeast direction almost parallel to the profile. Geometry, depth, thickness and resistivity of this structure have been adjusted on the basis of intensive 3D forward modelling. Amplitude and direction of observed induction vector has been matched with the computed response at selected periods. It has been found that induction vector responses closely matched with a 3D geoelectrical model consisting a conductive structure along the southeast of the RKG profile extending from the 15 to 30 km depth with resistivity of 10 Ohm-m. The conductive body is extending from southern end of the profile to almost MCT zone. Magnetotelluric impedance decomposition indicates one of the dominant geoelectrical strike direction is N 13^0 E. This strike direction supports the existence of transverse tectonics in the Garhwal Himalayan region. Such transverse structure could be the extension of Aravalli trend into Himalaya, indicated as Trans-Himalayan Conductor (THC) given earlier (Arora and Adam 1992).

Introduction

The Himalaya is one of the youngest and highest mountain range, which originated from continental collision tectonics and underthrusting 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 Himalayan system is normally considered as laterally continuous and its geological subdivisions have been viewed as uninterrupted along its entire length (Le Fort 1975), despite significant along-strike variations in topography and relief (Duncan et al. 2003) and convergence and shortening rates (Larsons et al. 1999; Banerjee et al. 2008; Burgess et al. 2012). It is consequently possible to divide the orogen along poorly characterized transverse zones that separate the mountain range into sectors with distinct thicknesses of major sedimentary units, deformation style and present day seismicity (Yin 2006). Recently Godin and Harris (2014) discussed basement cross-strike discontinuities in the Indian crust beneath the Himalayan orogen using gravity data and their relationship to upper crustal faults. Mitra et al. (2011) speculated that the Delhi-Haridwar basement ridge divide lateral variations in the felsic component of the upper-middle Indian crust under the Gange Basin. Manglik et al. (2013) inferred transverse tectonics in the Sikkim Himalaya on the basis of magnetotelluric studies. Transverse Magnetotelluric geoelectric strike directions has been delineated in the MT data which

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is consistent with the seismotectonic model of the Sikkim Himalaya based on the focal mechanisms of moderate earthquakes and composite fault plane solutions of microearthquaks. Existence of transverse tectonic in Garhwal Himalayan region has been discussed by Khattri and Tyagi (1983). Continuation of Aravalli trend in NE-SW direction in Himalaya is an example of transverse tectonics in Garhwal Himalayan region. Existence of transverse conductor has been explained on the basis of geomagnetic induction response. This structure is referred as Trans-Himalayan Conductor (THC), which follow the strike of the Aravalli range of the Indian shield (Arora and Adam 1992). In the present paper we have analysed magnetotelluric Tipper response (also referred as induction vector) to test whether magnetotelluric data could explain the transverse tectonics and existence of Trans Himalayan Conductor in Garhwal Himalayan region.

Methodology

Magnetotelluric data along the Roorkee-Gangotri (RKG) profile in the Garhwal Himalayan region was recorded in two phases. In the first phase MT data from 27 sites were used to generate a 2D geoelectrical model of the crustal structure along the profile (Israil *et al.* 2008). Subsequently, in the second phase, ten MT sites are added to the profile during 2010-2012, out of which four sites extended the profile about 20 km in southern direction and six MT sites are added within the profile length. By reprocessing of entire data stable impedance tensor is estimated for 37 sites in the period range of 0.01 to 2048 s. Using these data 2D geoelectrical model is presented by Miglani et al. (2014). Computation of induction vectors requires vertical magnetic field component, which was recorded by induction coil. Vertical magnetic field (Hz) coil was not buried fully at many MT sites due to hard Himalayan terrain and the estimated tipper values are noisy at those MT sites. As a result we could only obtain stable tipper responses at 26 sites. In the present paper we used Tipper responses at the selected sites to laterally extend 2D geoelectrical model to the 3D geoelectrical model. Figure 1 shows the location map of the study area along with the locations of Tipper responses sites used. Tipper response in magnetotelluric also known as induction vector in geomagnetic induction studies were introduced by Parkinson (1962) and Weise (1962) independently to explain anomalous geomagnetic variations.

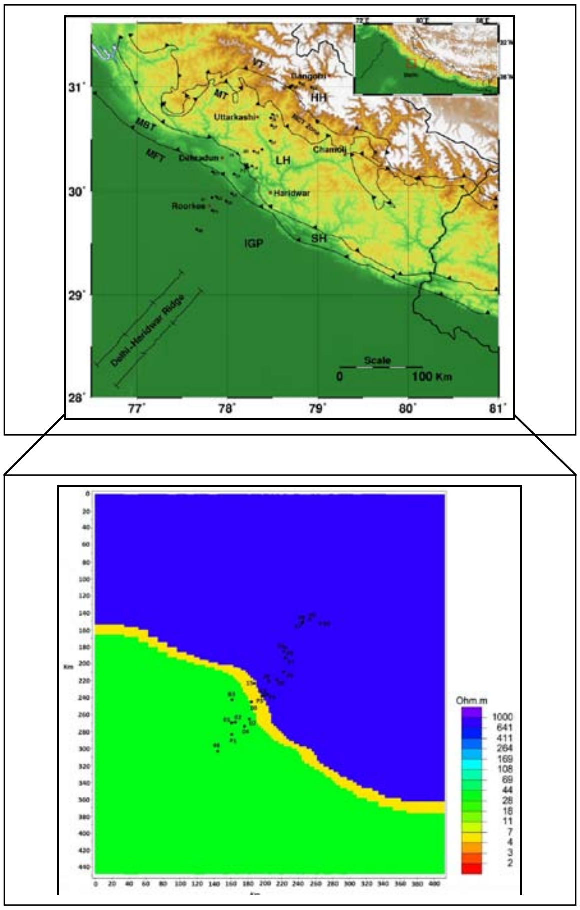

Figure 1. Simplified tectonic map of the study area, projected over topography, top panel showing major Garhwal Himalayan thrusts: VT Vaikrita thrust; MT Munsiari thrust; MBT Main Boundary thrust; MFT Main Frontal thrust, IGP Indo-Gangetic plain, SH Sub Himalaya; LH Lesser Himalaya, HH Higher Himalaya (reproduced from Miglani et al. 2014). Bottom panel z-plane (0-185m) of 3D electrical model with Magnetotelluric sites used in present study.

In horizontal plane induction vector is defined in terms of linear relationship between horizontal and vertical magnetic field components as:

$$H_z = T_{zx} H_x + T_{zy} H_y \qquad (1)$$

Where T_{zx} and T_{zy} are Tipper (induction vector) and H_x, H_y and H_z are magnetic field components. In frequency domain these are complex quantities and represented in terms of real and imaginary components.

When real induction vectors are plotted in Parkinson (1962) Convention, they points toward the zone of higher conductivity whereas in Weise Convention Real induction vector points away from the zone of higher conductivity. Amplitude and direction of the induction vector can be defined by equations (2 & 3)

$$|\,\mathrm{Re}\ T\,| = \mathrm{sqrt}\left((\mathrm{Re}\ T_{zx})^2 + (\mathrm{Re}\ T_{zy})^2\right) \qquad (2)$$

$$\mathrm{T\_angle} = \left(\frac{180}{\mathrm{pi}}\right) * \mathrm{phase}\ (\mathrm{Re}\ T) \qquad (3)$$

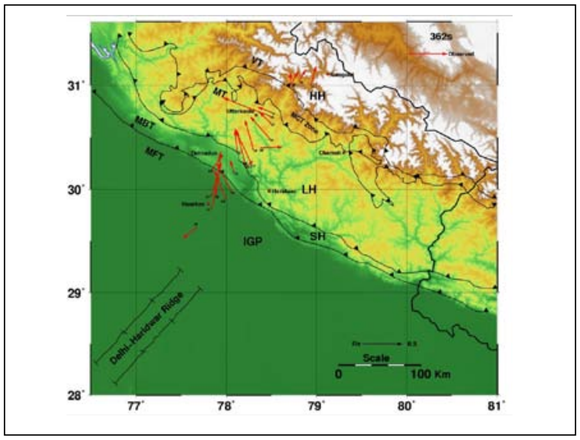

Figure 2(a) Observed Tipper at 362 s period.

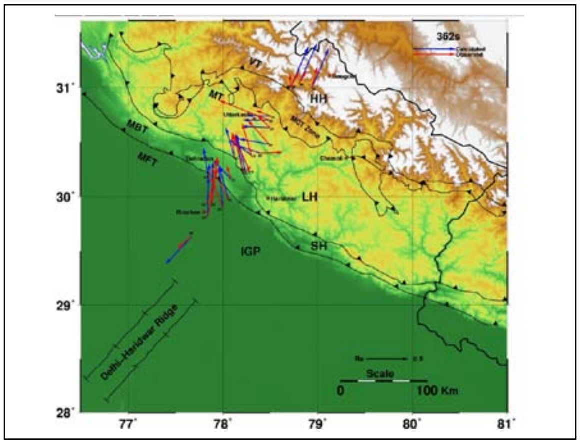

Figure 2(b) Comparison of Observed and computed Tipper at 362 s period.

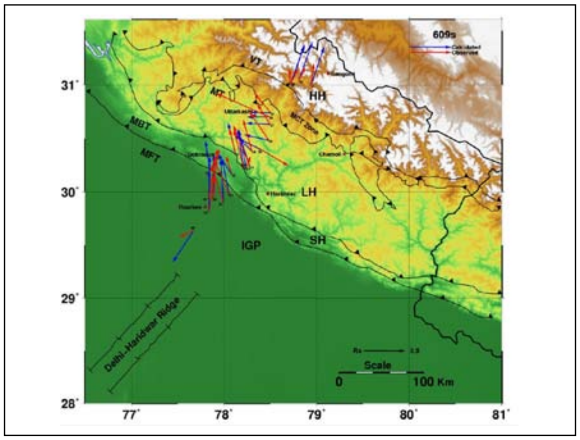

Figure 2(c) Comparison of Observed and computed Tipper at 609 s period.

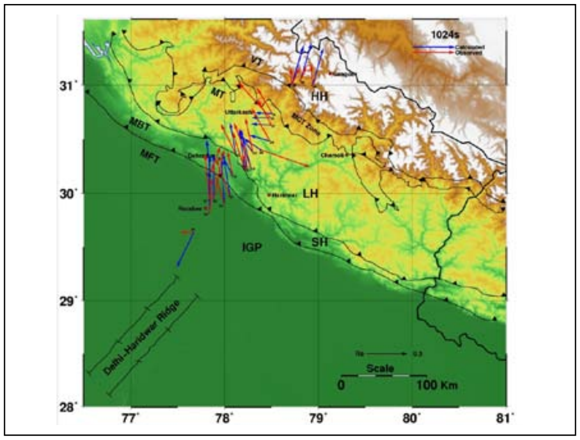

Figure 2(d) Comparison of Observed and computed Tipper at 1024 s period.

The orientation of observed and computed tipper are matched manually as well as through the Similarity index defined as

$$C_n = \cos\Theta = \left(\frac{x.y}{|x|\,|y|}\right) \qquad (4)$$

Where x and y are observed and computed tipper respectively at given frequency and C_n = similarity index which lies between – 1 to + 1.
If observed and computed induction vectors (x and y) are in the same direction then the similarity index, C_n = 1.

Three dimensional modeling of tipper response

Initial 3D geoelectrical model has been constructed from simplified 2D block model obtained through 2D inversion of MT data (Miglani et al. 2014). Taking the clue from literature (Arora and Adam 1992) and behaviour of Weise induction arrow (Fig. 2(a)) we added conducting body in the east nearly parallel to the profile. Parameters (depth, thickness, length, width and resistivity) of this body are iteratively adjusted to obtained best fit between the observed and computed tipper vector. Fitting between observed and computed tipper vectors at 306, 609 and 1024 s are shown in Figure 2(b, c & d) respectively. Similarity index obtained using equation (4) between observed and computed induction vectors is shown in Figure 3(a).

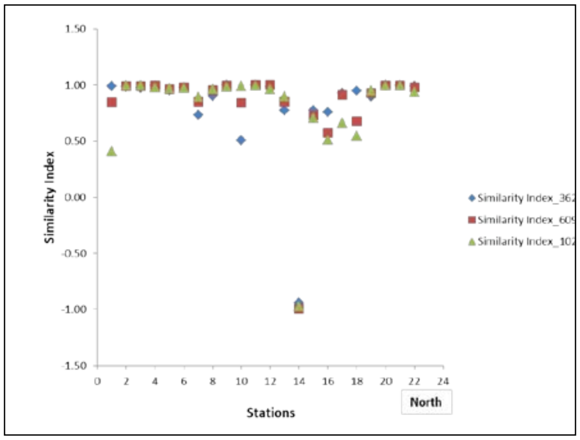

Figure 3 (a) Similarity between observed and computed induction vector Index (equation (6) at 362, 609 and 1024 s periods.

Final 3D geoelectrical model obtained by fitting these induction vectors consists of 2D block model constructed from the model presented by Miglani et al. 2014, along with a 15 km thick conductive body (resistivity 10 Ohm-m) extending from southern end of the profile upto MCT zone. The top of the body is at 15 km depth in the southern end of the profile. In the present 3D model this conducting body lying in the 50 km southeast runs almost parallel to the Roorkee-Gangotri profile. The conducting body is similar to the Trans Himalayan Conductor as indicated by Arora and Adam (1992). Three dimensional geoelectrical model is represented in the form of three z-plane in the depth range of 0-185m, 6-8 km and 20-26 km in Figure 3(b, c & d) respectively.

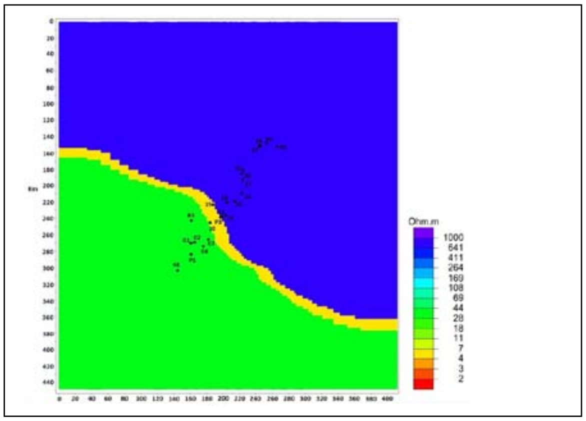

Figure 3(b) Z-plane (0-185m) of final 3D Geoelectrical model.

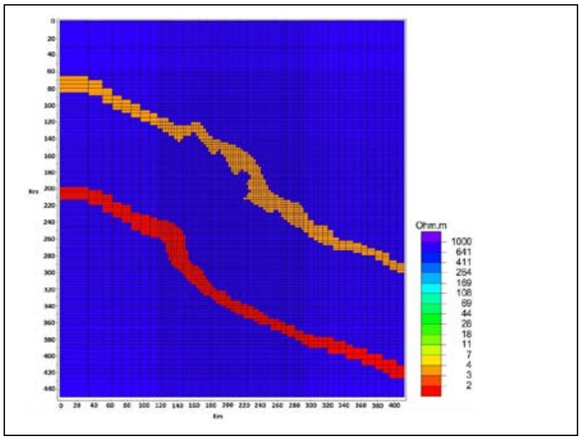

Figure 3(c) Z-plane (6-8 km) of final 3D Geoelectrical model.

Strike and dip of Trans Himalayan Conductor (THC)

Strike directions in Magnetotelluric impedance tensor has been estimated using three approaches: (i) Groom-Bailey (GB), (ii) Bahr's and (iii) Phase tensor decomposition by Miglani et al. (2014). These methods determine geoelectric strike and quantify impedance distortion in term of decomposition parameters.

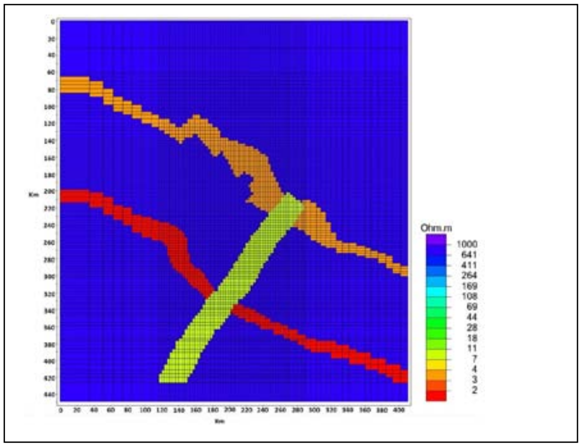

Figure 3(d) Z-plane (20-26 km) of final 3D Geoelectrical model.

The distortion parameters twist (T), shear (S), the geoelectric strike and the regional impedance tensor (Z_{2D}) are estimated using a least square method by fitting the observed impedance tensor with the decomposition model. Limiting values of twist and shear are $\left|60^0\right|$ and $\left|45^0\right|$ respectively, which define validity of decomposition hypothesis. The approach, based on the phase tensor, gives the same strike as Bahr's decomposition for 2D structure (Caldwell *et al.* 2004). The estimated strike has 90^0 ambiguity in the estimated values, which may be removed using geological constraints. In view of general geological strike direction of the Himalayan thrusts system, estimated average geoelectrical strike in the period range from 1 to100 s, are N79^0W, N70^0W, N68^0W and N81^0W in four litho-tectonic zones: IGP Indo-Gangetic plain, SH Sub Himalaya; LH Lesser Himalaya, HH Higher Himalaya respectively. The strike directions in the long period range (100-1000 s) are stabilized to N77^0W for all four litho-tectonic units along the profile (Miglani et al. 2014). However, by careful analysis of the strike directions it has been observed that the strike direction obtained using phase tensor method (Caldwell *et al.* 2004) is N13^0 E at 15 MT sites located in southern direction of the profile. The period band for this strike change from 13 – 1024 s at southern (site 1) to 256-1024s at the northern (site 16) near MCT zone. We interpret this strike as the strike of Trans Himalayan conductor with northward dip of about 10-15^0. It may be mentioned that Miglani et al. (2014) used 90^0 ambiguity to bring N13^0 E strike of THC in agreement with general geological strike (NW-SE) of Himalayan thrusts (Khattri, 1992).

Conclusions

First three dimensional geoelectrical model of Garhwal Himalayan corridor is proposed on the basis of limited magnetotelluric data along the RKG profile. This has been done by translating 2D geoelectrical model into a simplified block model and by adding 3D feature in it using characteristics of Tipper data. Parameters of the additional structure have been adjusted on the basis of intensive 3D tipper modelling and by fitting observed and computed tipper responses at selected periods. The main features of the proposed 3D geoelectrical model are:

Indo Gangetic Plane (IGP) sediments extended from southern most end of the model domain with 6 km thickness and resistivity of 30 Ohm-m. Further north of IGP formation resistivity is 5 Ohm-m. MCT zone ramp structure in depth range from 6 to 30 km is modeled in three steps. The MCT conductor with resistivity 4 ohm-m has been modeled in steps. THC with a resistivity of 10 Ohm-m is extended from Southern end of the model domain to MCT zone in the north, parallel and 50 km east to existing MT profile. The thickness of THC is 15 km which is adjusted in the depth range from 15 to 30 km to fit computed tipper with the observed.

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Acknowledgments

Authors are thankful to Ministry of Earth Sciences, Govt. of India for financial support. Mr Sudhanshu Tyagi recalculated geoelectrical strike used in this paper is thankfully acknowledged.