Short communication

Deep geoelectric structure of the Sikkim Himalayas (NE India) using magnetotelluric studies

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Abstract

Broadband (0.001–1000 s) magnetotelluric soundings were carried out at 18 locations with a station interval of 5–8 km across the Sikkim Himalaya (northern India) along a 120 km long traverse from Siliguri in the south to Yumthang in the north. Magnetotelluric transfer functions were computed after robust processing of single site and remote reference sites. The two-dimensional (2D) model derived from the joint inversion of TE and TM mode data shows distinct electrical signatures of the Main Frontal Thrust (MFT), the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT). The MFT and MBT zones are expressed by a conductive feature of about 10–40 $\mu$m indicating the presence of Siwalik molasse sediments of Gangetic foreland basin. An anomalously high conductive (2–5 $\mu$m) in the crust in the depth range of 3–15 km is observed to the north of MBT. This may indicate the presence of Siwalik molasse sediments together with lesser Himalayan sediments with trapped fluids in the fault zone. These sediments may act as a lubricant accommodating underthrusting of continental crust. The nature of the low resistivity associated with the Main Himalayan Thrust in the higher Himalayas (north of the MCT) might indicate presence of metamorphic fluids released due to under thrusting of the Indian plate.

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1. Introduction

The Himalaya is one of the youngest orogenic belts of the world created by an ongoing collision between India and Eurasia since early Eocene (Molnar and Tapponnier, 1975; Yin and Harrison, 2000). As a result of ongoing subduction, a series of south vergent thrust systems have been developed in the Himalayan fold-thrust belt (Gansser, 1964; Hodges, 2000). The Himalayan structure and the active tectonics are now relatively well understood from recent geophysical and geological studies (Hodges, 2000; Spratt et al., 2005; Unsworth et al., 2005; Arora et al., 2007). Deformation is argued as the main cause for crustal melting and other metamorphic reactions (Beaumont et al., 2001). Low resistivity layers at mid-crustal and upper crustal depths are observed from magnetotelluric (MT) experiments in the Tibetan Plateau, central Nepal and NW Himalaya. These results suggest the presence of crustal fluids such as partial melt, aqueous fluids or metamorphic fluids (Chen et al., 1996; Lemonnier et al., 1999; Unsworth et al., 2005; Arora et al., 2007). The Sikkim Himalaya, lying between Nepal and Bhutan Himalaya, falls in the eastern sector of the Himalaya arc, and is relatively poorly explored as compared to other segments of the Himalaya (Jain et al., 2003). The study area is covered by a few geological and geochemical studies (Acharya and Sastry, 1979; Mohan et al., 1989; Catlos et al., 2004). The latest gravity and magnetic studies (Tiwari et al., 2006) make an attempt to model the crustal structure across Sikkim Himalaya.

Our present study aims at understanding the tectonic process associated with the continent–continent collision in the Sikkim Himalayan segment having a slip rate of 7.8 mm/year (Bilham and Ambraseys, 2005) and to study the deep geoelectric signatures of the important thrust systems, namely the Main Frontal Thrust (MFT), the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT). The present MT profile is positioned to the south of the 100 line of INDEPTH MT studies (Unsworth et al., 2005). Thus, this study also extends the MT studies carried out in Tibet (Pham et al., 1986; Chen et al., 1996; Spratt et al., 2005; Unsworth et al., 2005) that has revealed a zone of high electrical conductivity in the middle crust probably associated with partial melting/aqueous fluids.

2. Geological background

The Sikkim Himalaya (Fig. 1) provides a representative cross section of the eastern Himalaya. The four physiography-based transverse zones (Gansser, 1964) like the Sub, Lower, Higher and Tibetan Himalaya confirm four major tectonic belts namely foothill,
inner, axial and trans axial belts respectively. They are represented by characteristic structural and stratigraphic attributes and are delimited by important dislocations. Geologically the Sikkim Himalaya starts with molasse type deposits of the Siwalik formation in the south. Towards the north, a thin strip of Gondwana rocks, the Buxa formation (carbonate rocks) and Daling group, comprise the lesser Himalayan Domain (LHD). Further north, the higher Himalayan Crystallines (HHC) is known as Higher Himalayan Domain (HHD) (Das Gupta et al., 2004). The different geotectonic domains of the Sikkim Himalaya are separated from one another by thrust faults (Acharya and Sastry, 1979; Sinha-Roy, 1982). The boundary between the Siwaliks and the LHD is marked by Main Boundary Thrust (MBT) and the boundary between the LHD and the HHD is marked by Main Central Thrust (MCT). The MCT takes a sinusoidal turn in the Sikkim Himalaya. Most of the earlier models that were aimed at understanding the evolution of the Himalayas are focused on the MCT, an intra-continental ductile shear zone located at a topographic break in slope (Duncan et al., 2003). The MCT in the study region juxtaposes high-grade gneisses of the HHC and lower-grade slates, phyllites and schists of the lesser Himalaya Formations. The Main Frontal Thrust (MFT) separates Siwalik formation rocks to the north and the Gangetic plain to the south. Neotectonic activity is reported along this fault (Nakata et al., 1990). In this segment of Himalaya, the MFT and MBT are positioned closely. The MFT reaches to the surface and flattens beneath the lesser Himalaya with its roots located along ramp beneath the High Himalaya (Pandey et al., 1995). A major reflector has been identified by seismic investigation (Zhao et al., 1993) beneath southern Tibet and interpreted as the thrust plane along which India is under thrusting Asia today, this thrust plane is known as Main Himalayan Thrust (MHT). The MFT, MBT and MCT all join to this thrust surface at depth. The MHT is locked from the surface to the base of the mid-crustal ramp that leads to stress build up and clustered micro-seismic activity around the ramp (Pandey et al., 1995; Bilham et al., 1997).

3. Magnetotelluric experiment

To investigate the electrical conductivity distribution within the collision regime, broadband natural electromagnetic variation measurements were carried out in 2005 at 18 field stations (Fig. 2), deploying ADU06 data acquisition system (Metronix, Germany). The profile was oriented in NNE–SSW direction. Due to the rugged terrain, selection of sites in the profile was mainly governed by road access to the suitable sites. Average station recording time was 36–48 h, the period range of data analysis is 0.001–500 s. The station spacing was about 5–8 km. The two horizontal electric field components were acquired, on two orthogonal dipoles of 80–90 m length, with porous pot electrodes containing CdCl2 electrolyte and Cd core. The horizontal and vertical magnetic field components were measured with induction coil magnetometers.

Single site time series data were processed (Egbert and Booker, 1986; Junge, 1990) to yield estimates of impedance as a function of period. At a few sites, remote reference processing was adopted (Egbert, 1997). The computed magnetotelluric transfer functions were good at most of the sites particularly in the upper Himalayas. However, data quality was not satisfactory at a few stations. This was mainly due to (a) the power lines in the valley and the river terraces and (b) the hydrothermal power generation units that were operating along the Teesta River. The above problems could not be overcome, even by using remote reference technique at few sites, that are severely affected by noise (marked as red stars in Fig. 2); these sites were not considered for further analysis and modeling. Vertical magnetic field data were very often noisy at most of the sites; hence we have not considered them for further analysis. Magnetotelluric transfer functions at site ‘ran’ (site located in the lesser Himalayas) and ‘yum’ (site located in the higher Himalayas) are shown in Fig. 3. Site ‘ran’ displays an amazing drop in apparent resistivity (with a slope $-45^\circ$) and a corresponding phase around or above 90° indicate a very conductive structure at depth.
4. Regional strike analysis

Regional strike determination is often a critical aspect of magnetotelluric data interpretation. Once we get a consistent regional strike estimate for the whole profile then we can apply two-dimensional (2D) interpretation to the whole profile. Frequently the magnetotelluric impedances are distorted by the accumulation of electrical charges along near-surface inhomogeneities. This in turn poses a problem for the determination of true regional strike direction. In this case we have followed two different approaches by Smith (1997) and Becken and Burkhart (2004) for the period range of 0.1–500 s. In the case of Smith's approach, the impedances at each site are fitted for distortion parameters and strikes frequency by frequency, and then a single best strike angle at the site is determined. And then the program calculates a single best strike direction for the whole set of sites. Necessary conditions for the presence of a regional 2D structure (no matter whether galvanically distorted or not) are linear polarization states of the horizontal electromagnetic fields in principal coordinates assuming a linearly polarized primary magnetic field. The fact of a linearly polarized primary magnetic field is used in the analysis of the impedance tensor of Becken and Burkhart (2004). Fig. 4 shows the results from both approaches. The obtained strike direction is approximately N80° E, i.e., almost E–W as one may hope from surface geologic strike; this justifies a 2D interpretation. We rotated the data by −10° (N10° W). The rotated N–S electric field is assigned as TM mode and the E–W electric field is assigned as TE mode.

5. 2D modeling

The nonlinear conjugate gradient algorithm of Rodi and Mackie (2001) was applied to undertake 2D inversion. TE and TM mode data in a period range between 0.002 and 500 s were used as input data and the starting model was a 100 Ω m half-space. For sites ‘sin’ and ‘lem’ we have not considered TE data for inversion, as they were affected by noise. In the algorithm, the regularization param-
The regularization parameter \( \tau \) plays a significant role, controlling the trade-off between data fit and model roughness. In order to find an appropriate \( \tau \), the inversion was carried out several times with different \( \tau \) values. If the resulting RMS errors are plotted against model norm or roughness, a typical L-shaped curve (Hansen, 1998) should be obtained and the preferable \( \tau \) should lie in the knee of the curve. For the magnetotelluric case, however, the L-shape is often not clearly expressed (Fig. 5). For the final model, we have chosen the regularization parameter of 10; the mesh size was 81 (rows) \( \times \) 171 (columns). Topography was included in the inversion scheme. A minimum error floor of 20% was assigned to the apparent resistivities and 1.5° to the phase data. This downweights the apparent resistivities with respect to the phases, which in turn reduces the influence of static shifts. The final RMS obtained was 2.07 (see Fig. 6 for final model). The RMS error for the sites along the profile is shown in Fig. 7. To test the significance and resolution of the conductive features, their resistivity values were systematically varied and the resulting responses were compared with those of the model in Fig. 6, following a procedure proposed by Nolasco et al. (1998). Observed and predicted responses for TE and TM mode data are presented in Fig. 8.

6. Results and discussion

The geoelectric structure beneath the MFT and MBT zone (C1 in Fig. 6) is characterized by a conducting zone (10–40 \( \Omega \) m) extending from shallow depth to upper crustal depths down to 10 km and beyond. The observed low resistivities (C1) are consistent with the presence of Siwalik sediments in the Gangetic foreland basin (Gupta et al., 1994; Lemonnier et al., 1999). North of MBT, beneath the lesser Himalayan region, anomalous upper crustal conductors C2 and C3 (2–5 \( \Omega \) m) are observed. The upper crustal metamorphic rocks of the lesser Himalaya are characterized as resistive feature (R2, \( \sim \)1000 \( \Omega \) m). The Hi-CLIMB broadband seismological experiment
That, the thrust beneath the Himalayas, which dips at 10–15°, supports an elevation contrast between the Tibetan plateau and plains of India of −5 km, has an average shear stress in the range of 11–17 MPa (Lamb, 2006). In such a low stress system sediments may act as a lubricant accommodating underthrusting of the continental crust. These sediments (possibly Siwalik and metasediments) with trapped aqueous fluids in the fault zone explain the observed conductor C2. Further, an aqueous fluid porosity of 3–4% is sufficient to explain the observed high conductivity feature C2. The northeast dipping low resistive zone delineated along the profile might represent the MHT (see Fig. 6). The resistive features R1 and R3 represent the Indian crust. The region between R1 and R3 is not well resolved due to reduction in the penetration depth of MT signals. This was mainly because the presence of the overburden conductors C2.

Tiwari et al. (2006) suggested from the joint modeling of magnetic and short wave length gravity anomalies that the metasediments of lesser Himalaya extend up to a depth of 12 km, which appears to represent the basement in this region. The conductive sediments observed in the lesser Himalayas coincide with the observation from metamorphic studies of rocks (Mohan et al., 1989). From the present model it is observed that the conductive nature of the metasediments (C2 and C3) is continuing up to the MCT. Geomorphic and space geodetic studies suggest that the MCT may be active today (Hodges et al., 2001). However, considering the regional structure and thermobarometric and geochronologic data, Robinson et al. (2003) suggested that the MCT formed as part of an overall southward progression of thrusting and has not been the site of extraordinary reactivation events.

Another conducting (2–5 Ω m) feature (C4) is observed below the higher Himalayas at a depth of 5 km. This conductive zone coincides with the spatial location of the MHT in the higher Himalayas. The geometry of the crustal ramp along the MHT might induce deformation along the surrounding region. Towards the north the position of MHT is constrained from INDEPTH seismic profiling results (Brown et al., 1996). Such an environment may support fluid circulation in the upper crust. Continuous underthrusting of the Indian plate facilitates availability of metamorphic fluids released by attendant dehydration reactions. Therefore in the present scenario the most likely candidate for the conductivity could be the presence of such metamorphic fluids. Such an interpretation was made earlier by Lemonnier et al. (1999) for MT results from central Nepal, where a deep conductor is delineated to the north of MCT. It may be noted that the modeling results of MT data from INDEPTH 100-line profile by Chen et al. (1996) brought out electrically conductive crust below the depths of 10–40 km in the southern part of the profile, near Yadong. This feature spatially correlates both in amplitude and depth with the present modeled conductor C4. Higher Himalayan crystallines are characterized by resistivities of the order of 1000 Ω m. This is again consistent with the observations made by Chen et al. (1996); in their model a resistive crust was delineated in the southern segment to the north of the conductor.

7. Conclusions

The geoelectric model derived from the broadband MT data brings out the electrical signatures of the MFT, MBT, MCT and MHT. These features show similarity with the electrical characteristics obtained in central Nepal. An anomalously conductive zone obtained in the north of MBT may represent the underthrusting of Siwalik sediments together with lesser Himalayan sediments with trapped fluids in the fault zone. North of MCT, in the higher Himalayas, a conducting feature is observed between depths of 8–30 km. This conductive zone which coincides with the spatial location of the MHT in the higher Himalayas might be due to the presence of metamorphic fluids that has been released during dehydration reaction. The HHC is characterized by high resistivity. Present modeled features in the north are well comparable with that of INDEPTH 100-line results.

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