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Electrical structure across the Indus Tsangpo suture and Shyok suture zones in NW Himalaya using magnetotelluric studies

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[1] Magnetotelluric studies in the NW Himalayan region have shown anomalously high conductance of about 20,000 siemens in the crust beneath the Indus Tsangpo suture (ITS) and the adjoining Tso-Morari dome in the depth range of 1–20 km. High heat flow and high attenuation of the seismic waves in the Himalayan crust, together with the observed high conductance indicate presence of wide spread partial melt generated from the subducted Indian crust. The Ladakh batholith appears as a resistive block to the north of ITS. A moderately conductive zone demarcates the Ladakh batholith from Karakoram batholith to the north. The similarity in the resistive structure with the results reported from the Tibetan region by *Wei et al.* [2001] about 1500 km to the east is rather significant, indicative of a two dimensional nature of the Himalayan collision belt, at least to the first order. *INDEX TERMS:* 0905 Exploration Geophysics: Continental structures (8109, 8110); 9320 Information Related to Geographic Region: Asia; 1515 Geomagnetism and Paleomagnetism: Geomagnetic induction; 8102 Tectonophysics: Continental contractional orogenic belts

1. Introduction

[2] Indus Tsangpo suture (ITS) is a prominent feature extending over the entire 2500 km length of the Himalayan range and is generally believed to be the line along which the Indian and Tibetan blocks are sutured together subsequent to the intercontinental collision. This suture forms the line of divide between the Ladakh-Gangdese plutonic belt to the north and the higher Himalayan crystallines to the south [*Gansser*, 1964]. The Shyok suture zone (SSZ) is a prominent feature in the NW Himalaya located to the north of ITS and demarcates the Karakoram batholith to the north from the Ladakh batholith to the south. The possible eastward extension of SSZ is not known at present due to the lack of geological data. The purpose of this paper is to identify the deep electrical resistivity associations in the ITS and SSZ regions at deeper strata.

2. Structural Setting

[3] In the NW Himalayan region, the ITS forms about 20 km wide zone bounded on either sides by steep south-dipping thrusts and comprises of Ophiolites, Ophiolitic melanges and several sequences of acid and basic volcanics resulting from the calc-alkaline magmatism which accompanied the Himalayan collision [*Thakur*, 1983].

[4] Ladakh batholith occurs as a 600 km long and 20–80 km wide linear belt to the north of ITS [*Sharma and Choubey*, 1983] exhumed into the thick pile of unmetamorphosed volcanics [*Brookfield and Reynolds*, 1981; *Sharma et al.*, 1978]. The Shyok suture (SSZ) located between the Ladakh and Karakoram ranges is about 10 km wide in the present study area. This region comprises of the granitoids exposed on the northern and southern borders of the Shyok valley, the acid and basic volcanics, together known as the Shyok volcanics, Ophiolites and Ophiolitic melanges, and metasediments [*Rai*, 1983]. The Karakoram batholith is an elongated NW-SE trending feature parallel to Ladakh batholith located to the NE of SSZ. Both the Ladakh and Karakoram batholiths were emplaced during the Eocene to Oligocene concurrent with the Himalayan orogeny and share a common emplacement history but the radiometric ages indicate that the emplacement of the Karakoram batholith is a younger event [*Rai*, 1983]. The higher Himalayan Tso - Morari crystallines are exposed to the south of the ITS. These formations show prominent NE dips on the north and SW dips on the south, giving a domal appearance to them and hence this region is also referred to as the Tso- Morari dome. The MT survey profile passes through the Taglang la sub-group of the Tso - Morari crystallines, consisting of the metamorphosed calcerous, marly and argillaceous sediments together with concordant bands of amphibolites. Based on the fossil evidence, *Virdi et al.* [1978] propose that the Taglang la formations may be of the lower Carboniferous to lower Triassic age.

[5] The entire Himalayan range is characterised by a negative Bouguer anomaly of about −500 mGal. This has been attributed by several workers to the thickening of the crust in the central Himalaya and Tibetan block. *Choudhury* [1975] has inferred that the crustal thickness increases from 46 km beneath the Himalayan frontal thrust to about 72 km in the higher Himalaya, which is associated with isostatic imbalance by *Qureshy and Kumar* [1992]. From the modeling of the gravity data, *Lyon-Caen and Molnar* [1983] have inferred that the dip of the subducting Indian plate is about 7–8° in the sub Himalayan region, which increases to about 15° further NE. *Banerjee and Satyaprakash* [2001] have reported a positive Bouguer anomaly of about 30 mGal over the Ladakh batholith.

[6] Although there are no reports on deep seismic sounding (DSS) studies in the present study area, studies in several other parts of the Himalaya and Tibet conducted (see *Brown et al.* [1996] and references there in) indicate a high attenuation of the seismic energy and presence of bright spots in the seismic reflections in several parts of the Himalayan orogen, which have been interpreted in terms of fluid phase, probably caused by the magmatic emplacement. These studies also report a flat Moho discontinuity at depths of 70–80 km beneath the ITS and surroundings. From the inversion of the Rayleigh and Love waves generated by the earthquakes in the Himalaya and Indian peninsular region, *Singh* [1991] have observed low Q values (high attenuation of the seismic energy) beneath the Central Himalaya at depths of 20–80 km. He attributes the observed high seismic wave attenuation to the possibility of partial melting of rocks at these depths.

3. Data Collection and Analysis

[7] Magnetotelluric studies were conducted at 15 locations over a 200 km long profile between Bara-la-Cha-la and Panamik. The location map of the stations is shown in Figure 1. Also shown here

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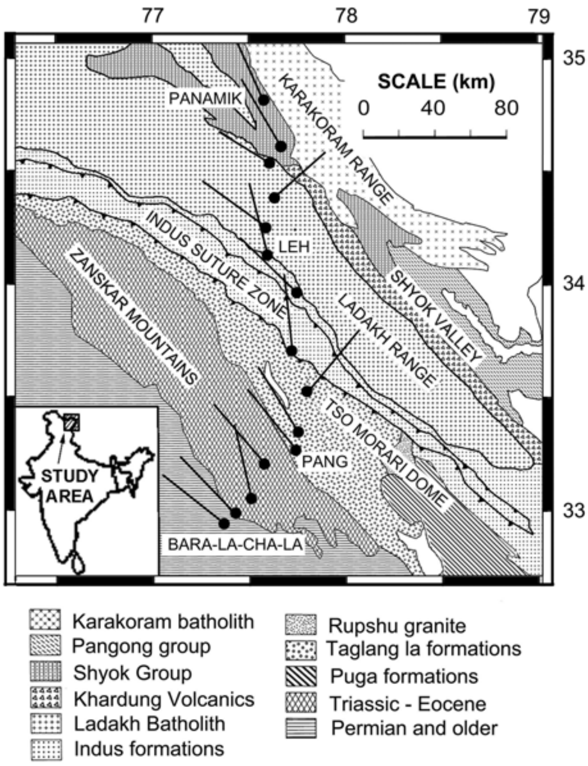

Figure 1. Geology of the NW Himalaya showing the location of the MT survey profile. Thick lines at the stations indicate the average Groom Bailey strike directions at low frequencies (0.01–0.001 Hz).

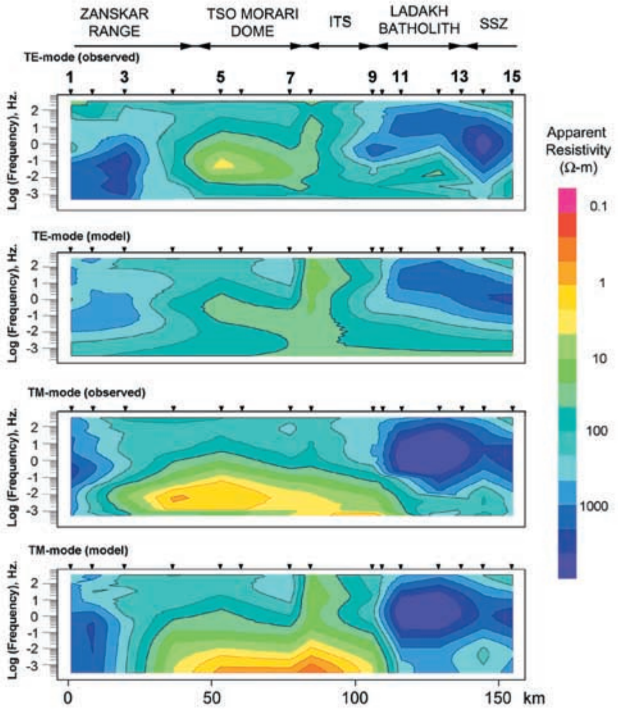

Figure 2. Observed and forward modeled apparent resistivity pseudo-sections.

are the low frequency Groom Bailey (GB) strike directions at each station to be discussed later. A combination of fast Fourier transforms and cascade decimation technique [*Wight and Bostick*, 1980] was used for obtaining the auto and cross power spectra required for computing the frequency variation of the apparent resistivity and phase of impedance.

[8] The impedance tensors at individual frequencies were decomposed using the GB tensor decomposition procedure [*Groom and Bailey*, 1989] at each station. The strike directions averaged at low frequencies (0.01–0.001 Hz) are shown in Figure 1 along with the major tectonic elements in the study area. It may be observed here that most of the strike directions are predominantly oriented either parallel or perpendicular to the N 40°W direction and show a good correspondence with the tectonic elements. Hence this was chosen to be the regional strike direction and the response functions rotated along this direction were assumed to be the TE mode values and those perpendicular, the TM mode values. The apparent resistivity and phase pseudo-sections are shown in Figures 2 and 3 respectively. Also shown here are the pseudo-sections of the forward-modeled responses of the geoelectric cross section to be discussed later. The study area is located in mountainous region, where the selection of the profile and stations are governed largely by the availability of road accesses to the suitable sites. Thus it was not possible to conduct survey along a line perpendicular to the geological strike as is normally desired. All stations were projected on a line perpendicular to the assumed geoelectric strike for the purpose of further analysis.

4. Static Shifts and 2-D Modeling

[9] The static shifts in the apparent resistivities result from the presence of resistivity inhomogenieties in the shallow surface and are normally corrected for by using some a priori assumptions on the expected geoelectric structure or by using the available information on the deep structure from other geophysical studies. In the present study area, no such information is available. The phase of impedance, which is not affected by the static distortion, shows

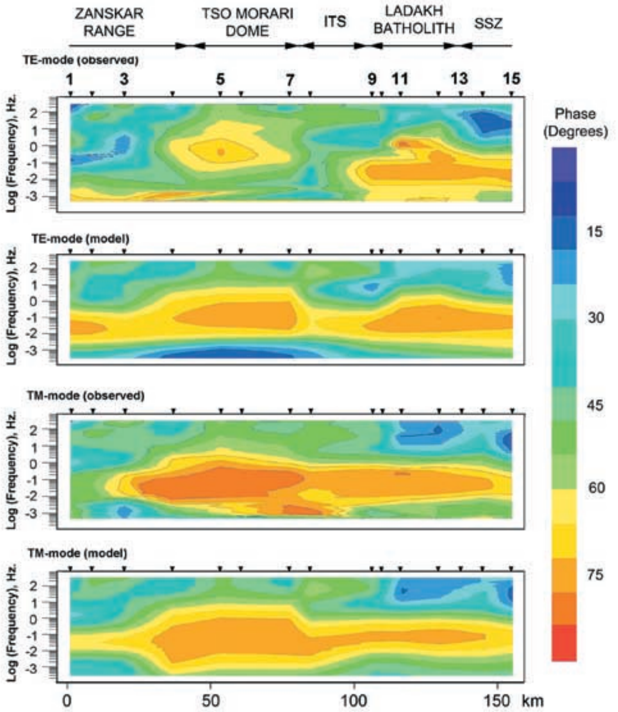

Figure 3. Observed and forward modeled phase pseudo-sections.

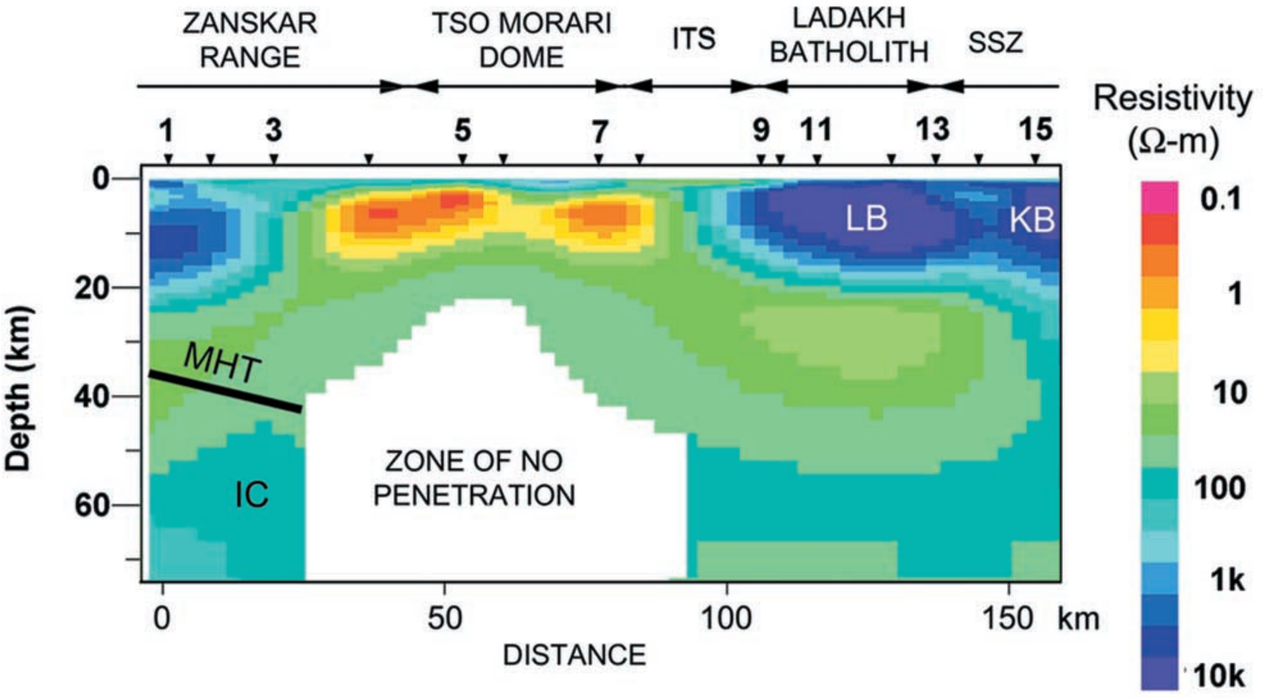

Figure 4. Geoelectric structure across the Indus-Tsangpo suture and Shyok structure zone in NW Himalaya obtained using 2D inversion of the TM-mode data. LB, Ladakh Batholith; KB Karakoram Batholith; MHT, Main Himalayan thrust; IC, Subducting Indian Crust.

some spatial variations at the low frequencies (Figure 3), suggesting the presence of vertical resistivity contrasts at depth.

[10] In view of the foregoing, we decided to obtain the geoelectric structure by using the GB decomposed apparent resistivities and impedance phases (response functions). In order to accommodate the possibility of the static shifts, the errors on the apparent resistivities in the entire data set were increased by a factor of 10 over those on the impedance phases before inverting the data so as to decrease their weight in the inversion process. A uniform half space with a resistivity of 100 Ω-m was used as the starting model for the 2-D inversion scheme [*Rodi and Mackie*, 2001]. The model obtained using both the TE and TM mode response functions was not geophysically acceptable and showed several lateral resistivity contrasts at deeper levels, which were not reflected in the observed responses in the TM mode. It seems that some weak three dimensional features may be influencing the inversion process. In view of these discrepancies, we decided to use only the TM responses for obtaining the geoelectric model. The smoothing parameter (Tau) for the inversion scheme was set at 5 and the RMS misfit of 1.3 was observed after 20 iterations. The pseudo-sections of the observed and modeled apparent resistivities and phases are shown in Figures 2 and 3 and the geoelectric structure in Figure 4.

5. Results and Discussions

[11] About 70 km wide region beneath the ITS and Tso-Morari dome to the south is characterised by an anomalously low resistivity of less than 10 Ω-m with a conductance of about 20,000 siemens, extending from shallow depth up to about 15 km. The shallow conductive structures here may be due to the Ophiolites and sedimentary sequences of the Tethys ocean as well as the meta-volcanics generated due to the magmatic activity that accompanied the collision. The low resistivity in the deep crust, along with the high attenuation of the seismic waves [*Singh*, 1991], bright spots in the seismic reflections [*Brown et al.*, 1996] and high heat flow values in the excess of 200 mW/m^2 [*Ravishanker*, 1988], suggests a wide spread partial melting in the deep crust beneath ITS and Tso-Morari dome.

[12] The high resistivity block at shallow depth between stations 9 and 14 corresponds to the Ladakh batholith, with a depth extent of about 15 km. Further north, a part of the Karakoram batholith is delineated at station 15, separated from the Ladakh batholith by a south dipping moderately conductive band. A high Bouguer gravity of about 25 mGal is reported over the Ladakh batholith by *Banerjee and Satyaprakash* [2001]. This may be the result of the high density of the Ladakh batholith located over the partially molten rocks which have relatively low densities. The low density sedimentary sequences in the ITS and SSZ region may also be contributing to the observed gravity anomaly.

[13] A high resistivity is observed to the south of station 3, with a depth extent of about 25 km. This region comprises of the Himalayan metamorphics, which underwent prograde metamorphism during the tectonic subsidence to about 25–30 km due to the intra-continental subduction at the leading edge of the Indian plate [*Jain*, 1998]. These were subsequently pushed southwards in the course of the intercontinental collision and exhumed along the main central thrust, located further south of the present study area. A high resistivity block is delineated beneath the higher Himalayan metamorphics, separated by a conductive zone. This seems to be the top part of the subducting Indian plate. The main Himalayan thrust (MHT) observed by *Brown et al.* [1996] in the southern Tibet supports this conjecture. The low resistivity with a conductance of about 200 siemens in the vicinity of the MHT may be partly due to the sediments subducting along with the Indian crust. There may be some contribution to this conductivity from the heat generated by the friction between the Indian plate and overriding supracrustal block of the Himalayan metamorphics.

[14] The geoelectric cross section in the NW Himalaya shows several similarities with the results in the Tibetan block [*Wei et al.*, 2001] although the two profiles are separated by more than 1500 km. In view of the numerous transverse structures cutting across the Himalayan orogen, this is a rather striking observation. It is

also evident from the results of *Wei et al.* [2001] that the lower crustal conductivity extends further northwards over a distance of at least 400 km beneath the Tibetan crust. It seems that the subducting Indian crust acts as a plunger, thus compressing the partial melt. Blocked by the high density mantle material beneath, a part of this melt (subsequent to the fractionation) exhumed in the form of batholithic arc. Subsequently under the force of gravity exerted by the batholiths and the Tso-Morari sequences, the partial melt seems to have emplaced itself beneath the Tibetan crust, fractured and weakened in the process of the collision. A part of this melt may have been emplaced southwards beneath the Himalayan metamorphics at stations 1 and 3 in Figure 4, leading to the high conductivity there. The flat Moho observed in the vicinity of ITS indicates that the depth to which the Indian crust is subducting is limited to 70 km.

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