GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L04307, doi:10.1029/2006GL029165, 2007

Deep resistivity structure of the northwest Indian Himalaya and its tectonic implications

B. R. Arora,[1] Martyn J. Unsworth,[2] and Gautam Rawat[1]

Received 21 December 2006; accepted 16 January 2007; published 23 February 2007.

[1] Long-period magnetotelluric (MT) data were collected at 15 stations on a 250 km long profile in the northwest Indian Himalaya to study the structure of this continent-continent collision zone. Two-dimensional MT inversion was used to find a resistivity model that fit the data. In the upper crust low resistivity was imaged on the limbs of the Tso-Morari dome and may originate in serpentenization or zones of graphite. The Indus Tsangpo Suture was imaged as a sub-vertical conductive structure that dips northeast and merges with a mid-crustal conductor. A north dipping zone of low resistivity is imaged at the top of the underthrust Indian Plate and is likely due to fluids expelled from the underthrust sedimentary rocks. North of the Indus Suture zone this layer is located at 20–25 km depth with a conductance around 3000 S. The resistivity of 5–10 Ωm can be attributed to the presence of fluids, likely partial melt or aqueous fluids. This layer is underlain by a relatively resistive Indian crust that extends from the High Himalaya to north of the Indus suture. A decrease in deep resistivity was observed at the northern end of the profile, and is similar to the structures observed further east in the region of the INDEPTH study, despite the smaller north-south extent of the orogen in the Indian Himalaya. **Citation:** Arora, B. R., M. J. Unsworth, and G. Rawat (2007), Deep resistivity structure of the northwest Indian Himalaya and its tectonic implications, *Geophys. Res. Lett.*, *34*, L04307, doi:10.1029/2006GL029165.

1. Introduction

[2] The Himalaya and Tibetan Plateau are the spectacular result of the Cenozoic collision between India and Asia. Recent studies have advanced understanding of this continent-continent collision. Magnetotelluric (MT) data revealed a low resistivity layer at mid crustal depths which suggested the presence of crustal fluids [*Nelson et al.*, 1996; *Unsworth et al.*, 2005]. This is significant since fluids such as melt or water can significantly change the rheology of the crust and control the style of deformation [*Beaumont et al.*, 2001; *Klemperer*, 2006]. However, to fully understand the tectonic processes associated with the collision, and compare with previous results, it is necessary to study other parts of the orogen such as the northwest Himalaya of India where slower convergence is occurring [*Klootwijk et al.*, 1985]. The HIMPROBE project was initiated to study the northwest Indian Himalaya and has combined passive seismic, MT and geological observations [*Jain et al.*, 2003]. Broadband MT data showed that low resistivity characterized the mid-crust [*Gokarn et al.*, 2002] but the long period signals needed to image the lower crust and upper mantle were not recorded. Long period magnetotelluric (LMT) data were collected in 2002 and 2003 on the same profile as *Gokarn et al.* [2002]. In this paper, these new LMT data are described and their tectonic implications discussed.

2. Geological Setting

[3] The LMT profile (Figure 1) crosses the four major litho-tectonic belts that extend the entire length of the Himalaya. In the south of the study area are the high-grade gneisses of the High Himalaya. These rocks are bounded on their upper surface by the north dipping Southern Tibet Detachment and are interpreted as a thrust sheet of India continental basement displaced southward along the Main Central thrust. To the north the profile crosses the Tethyan Himalaya, a low-grade meta-sedimentary sequence deposited on the passive Indian continental margin of the Tethys Ocean prior to collision. The Tso-Morari crystalline complex is located in the northern part of the Tethyan Himalaya and is an exhumed section of high-grade metamorphic basement [*Thakur*, 1983], similar to the Kangmar dome in southern Tibet [*Lee et al.*, 2000]. Ultra-high pressure rocks are also exposed in the Tso-Morari dome and are related to deep subduction process [*Sachan et al.*, 2004]. The Tethyan Himalaya is bounded to the north by the Indus Tsangpo Suture Zone (ITSZ) that separates rocks of Indian and Asian origin. This narrow zone is bounded to the south by the steeply south-dipping Main Zanskar Backthrust, and is composed of remnant ophiolitic mélange, forearc flysch, volcanic rocks and post-collision Indus molasses [*Thakur*, 1981]. To the north of the ITSZ, the Ladakh batholith complex is the product of the island arc magmatism during the pre-collision subduction and is dominated by granitoid and calk alkaline intrusives [*Rai*, 1980]. Significant strike-slip movement occurs in this area, dominantly along the Karakoram fault system [*Murphy et al.*, 2000].

3. Magnetotelluric Data Collection and Analysis

[4] Long period MT data were collected at 15 stations using the University of Gottingen LMT system [*Steveling and Leven*, 1992]. The time series data were processed to give estimates of the impedance tensor and induction vectors using statistically robust processing in the period range 10–10000 s. The geoelectric strike was investigated using the tensor decomposition algorithm of *McNeice and Jones* [2001]. Single site decomposition revealed a strike direction that was parallel to the major geological features

[1]Geophysics Group, Wadia Institute of Himalayan Geology, Dehradun, India.
[2]Department of Physics, University of Alberta, Edmonton, Alberta, Canada.

0094-8276/07/2006GL029165$05.00

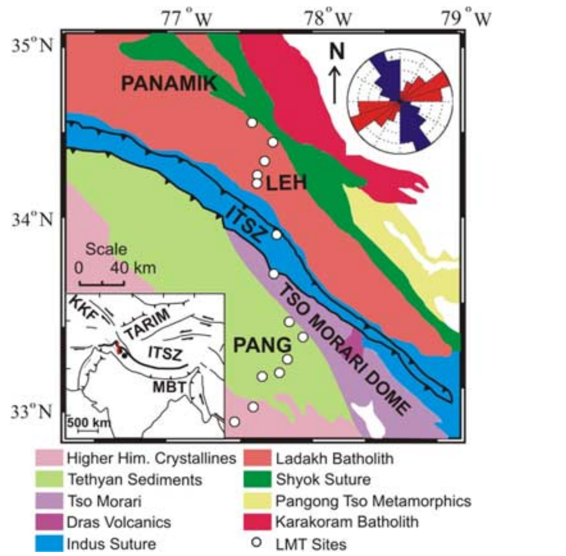

Figure 1. Locations of the long-period MT stations and the regional geology of the NW Himalaya. Rose diagram shows strike direction from single site tensor decomposition. Radial scale shows number of stations with each strike.

(Figure 1, inset) for the period range 10–3000 s. Multi-site tensor decomposition was found to give acceptable fits to the measured impedance data by analyzing the impedance data in two groups. Stations north of the Indus suture gave a strike N 38°W while the southern group has a strike is N 52°W. The magnetic field transfer functions (T_{zy}) are of high quality and the induction vectors generally point across strike supporting the results of the tensor decomposition. The MT data are displayed in a N45°W co-ordinate system that represents an average geoelectric strike (Figure 2). High phases are observed at short periods (10–100 s) at most stations, indicating the presence of a crustal conductor. Data at a typical station are shown in Figure 3.

[5] The MT data were inverted using the algorithm of *Rodi and Mackie* [2001]. It was found that both the transverse magnetic (TM) mode and vertical magnetic field data could be fit with the resistivity model in Figure 4. This fits the measured data with a normalized root-mean-square (r.m.s.) misfit of 1.60. Static shift coefficients were estimated directly by the inversion algorithm and also by down

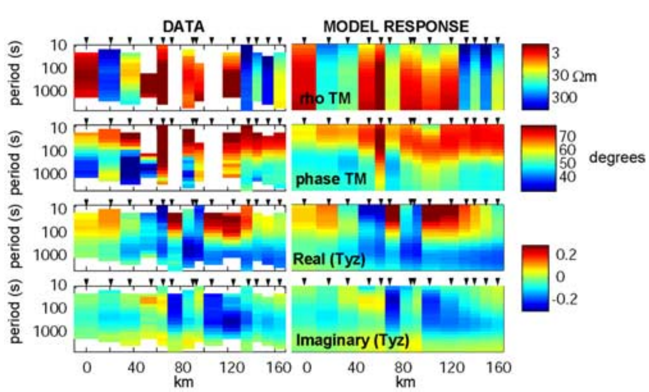

Figure 2. (left) Measured data displayed in a N45°W coordinate frame. (right) The predicted response of the resistivity model shown in Figure 3.

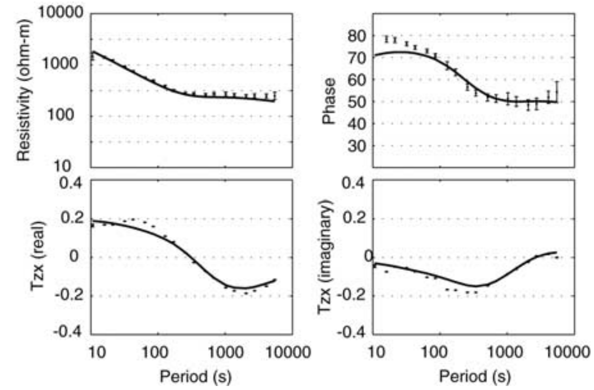

Figure 3. MT sounding curves at station 11. Solid line shows the response of the model in Figure 4.

weighting the apparent resistivity data. Both approaches gave similar results. The stability of the model was investigated through additional inversions with a range of control parameters and constrained inversions that began with edited versions of the model. This analysis showed that the major features in Figure 4 were required by the MT data. The model in Figure 4 shows some differences from that reported by *Gokarn et al.* [2002], who collected higher frequency MT data on the same profile. The most significant difference is that the very low resistivity zone in the upper crust beneath the Tso-Morari dome is absent. Such a low resistivity zone would produce a large anomaly in the vertical magnetic field, and this is not observed in Figure 2. *Gokarn et al.* [2002] did not use vertical magnetic field data and this limited the resolution of their study.

4. Interpretation

4.1. Indian Upper Crustal Features (ITSZ and TMD)

[6] The relatively low frequencies and station spacing of the LMT data is not ideal for detailed imaging of upper

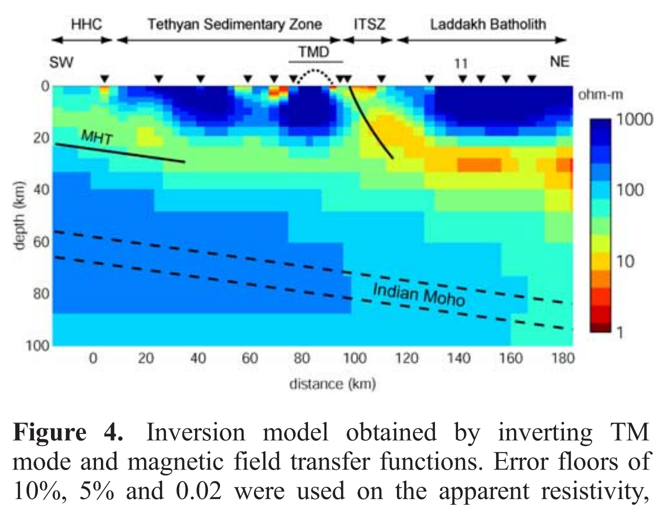

Figure 4. Inversion model obtained by inverting TM mode and magnetic field transfer functions. Error floors of 10%, 5% and 0.02 were used on the apparent resistivity, phase and transfer functions respectively. Inversion began from a 100 ohm-m halfspace. The location of the Indian Moho is taken from *Rai et al.* [2006], and the location of the Main Himalayan Thrust (MHT) is inferred. HHC, High Himalayan Crystalline units; TMD, Tso Morari Dome; ITSZ, Indus Tsangpo suture zone.

crustal structure. However, the shallow part of the model is consistent with the known geology, giving an important validation of the data analysis. The upper crust is generally resistive (>300 Ωm) along most of the profile to a depth of 15 km. This is compatible with the exposed lithology of granitic rocks in the Ladakh Batholith and the crystalline gneisses in the Tethyan Himalaya. The Indus suture is imaged as a northeast dipping low resistivity zone that merges with the low resistivity mid-crustal layer. The low resistivity at least in the upper section may be attributed to underthrust sedimentary rocks [*Thakur*, 1981]. Note that the ITSZ suture in Southern Tibet was not imaged as a low resistivity zone [*Unsworth et al.*, 2005]. New GPS data suggests that deformation along the southern margin of Tibet is accommodated by southward extrusion whereas deformation in the NW Himalaya is dominated by strike-slip movements along the Karakorum Fault [*Zhang et al.*, 2004]. The weak post-collision deformation along the ITSZ in western Himalaya coupled with relatively slower convergence may have preserved the near sub-vertical structure of the ITSZ, which is lost by extrusion along the southern margin of the Tibet.

[7] Immediately south of the Indus suture, the two narrow zones of low resistivity dominate the near surface geoelectric structure and are coincident with the northern and southern limbs of the Tso-Morari dome. The presence of two closely spaced but distinct conductors is revealed by reversals in the sign of the magnetic field transfer functions at short period (Figure 2). On the basis of seismic reflection data, it has been inferred that the ITSZ in Southern Tibet is underlain by an ophiolitic slab that was emplaced onto the passive continental margin of India prior to the collision [*Makovsky et al.*, 1999]. Scattered outcrops of ophiolite are present west and east of the MT profile in the NW Himalaya of India (inset in Figure 1) and are considered to be the exposed segment of an ophiolite slab [*Searle et al.*, 1997]. According to this hypothesis, during the post collision period the obducted ophiolite slab has undergone extensive folding and structural reorganization and along with underlying carbonate rich shelf sediments were restacked to surface. A narrow surface outcrop of ophiolite between the Tso-Morari dome and the ITSZ could be the remnant of this obducted ophiolite slab along the Main Zanskar backthrust The transformation of organic material to graphite during deformation [*Makovsky and Klemperer*, 1999] and/or the serpentization of the ultramafic rocks [*Makovsky et al.*, 1999] may have produced the observed low resistivity zones.

4.2. Mid-Crustal Layer

[8] The geoelectric structure south of the Indus suture is characterized by a northeast dipping low resistivity zone (∼30 Ωm). The receiver function analysis of the HIMPROBE data identified the Moho of the underthrusting Indian Plate as shown in Figure 4 [*Rai et al.*, 2006]. The depth of the Main Himalayan Thrust (MHT) is inferred from a uniform crustal thickness and denotes the top of the Indian Plate. The dipping low resistivity zone delineates the MHT and likely represents accreted sedimentary rocks overlying the underthrust Indian plate. The geoelectric structure in this region is significantly different to that observed in Southern Tibet, where the dipping zone of low resistivity above the MHT was much less conspicuous [*Unsworth et al.*, 2005]. One possible explanation is that the volume of granitic intrusives formed by continental magmatism is less in the Indian Himalaya than in Southern Tibet [*Burg et al.*, 1984; *Yin*, 2006, Figure 2]. Reduced magmatism and slower convergence may facilitate more direct underthrusting of sediments. These rocks produce the dipping low resistivity layer imaged in this study.

[9] North of the Indus Suture zone, the dipping low resistivity zone flattens out at 20–25 km depth and the resistivity decreases to around 5–10 Ωm. The low resistivity may indicate the presence of fluids, either partial melt, aqueous fluids or a combination [*Unsworth et al.*, 2005]. The presence of fluids is significant since it implies a reduced viscosity and supports the hypothesis that channel flow and extrusion, as envisioned by *Beaumont et al.* [2001] could be occurring in the Indian Himalaya, in addition to Southern Tibet at 90–92°E. The resistivity in this layer is a 2–3 times higher than in Southern Tibet, and implies a lower fluid fraction around 5% [*Unsworth et al.*, 2005]. The southern edge of the low resistivity layer is located beneath the ITSZ, in contrast to southern Tibet where the layer extended at least 100 km to the south [*Unsworth et al.*, 2005]. This may be a consequence of the slower convergence in the Indian Himalaya, which could result in slower flow in a mid-crustal layer [*Klootwijk et al.*, 1985]. This hypothesis is supported by smaller volumes of granitic extrusives in the Indian Himalaya compared to Southern Tibet [*Burg et al.*, 1984]. It is also be possible that the overall conductance and extent of the mid-crustal layer in southern Tibet may be affected by east-west extension, as expressed by the north-south rift zones. This hypothesis is supported by the seismic surveys that showed that bright spots, providing strong evidence for the presence of partial melt, are not mapped outside the rift zone [*Haines et al.*, 2003].

4.3. Structure of Lower Crust and Upper Mantle

[10] The Indian lithosphere that underlies the mid-crustal conductor has a relatively high electrical resistivity owing to composition of crystalline rocks. The resistive Indian lithosphere extends significantly north of the Indus suture. MT data have decreased resolution beneath a conductor and sensitivity studies are required to determine if model features can be resolved. A synthetic inversion showed that the MT data are sensitive to the resistivity of the lower Indian crust and upper mantle. Note that mid-crustal layer in the northwest Himalaya has a conductance (integrated conductivity) around 3000 S that is lower than the 10000 S conductance in Southern Tibet. This lower conductance allows imaging of the lower crust that was not possible in Southern Tibet. A decrease in deep resistivity is observed at the northeast end of the profile. The change in deep electrical structure is similar to that observed in central Tibet at 90–92°E where anomalously low resistivities were observed in the upper mantle north of the Banggong-Nuijiang suture [*Unsworth et al.*, 2004]. It is significant that this same north-south transition is also observed in the Indian Himalaya, despite the fact the Tibetan Plateau is much shorter in north-south extent at this location. This may imply that a northward decrease in electrical resistivity due

to a shallowing asthenosphere, is a ubiquitous feature of the Tibetan orogen.

5. Conclusions

[11] The long-period MT data presented in this paper have shown that resistivity structures in the northwest Indian Himalaya are similar to those imaged in Southern Tibet. A broad low resistivity zone is present in the mid-crust beneath the ITSZ and Ladakh and may be due to the presence of a few percent partial melt. The northern end of the profile shows a decrease in the deep resistivity of the lithosphere that is similar to observations further east on the Tibetan Plateau. This deep zone of low resistivity may indicate the presence of shallow asthenosphere. In contrast to Southern Tibet, the Indus suture appears as a low resistivity zone and the Tethyan Himalaya are characterized by a north dipping zone of low resistivity above the Main Himalayan Thrust that may be due to underthrust sedimentary rocks.

[12] **Acknowledgments.** MT data collection and analysis was made possible with funding from Department of Science and Technology, Government of India, through its program 'Deep Continental Studies.' Additional MT data analysis was supported by grants to Martyn Unsworth from NSERC and the Alberta Ingenuity Fund. Authors acknowledge with thanks the constructive comments by George Jiracek and other reviewers.

References

Beaumont, C., R. A. Jamieson, M. H. Nguyen, and B. Lee (2001), Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation, *Nature*, *414*, 738–742.

Burg, J. P., M. Guiraud, G. M. Chen, and G. C. Li (1984), Himalayan metamorphism and deformations in the North Himalayan Belt (southern Tibet, China), *Earth Planet. Sci. Lett.*, *69*, 391–400.

Gokarn, S. G., G. Gupta, C. K. Rao, and C. Selvaraj (2002), Electrical structure across the Indus Tsangpo suture and Shyok suture zones in NW Himalaya using magnetotelluric studies, *Geophys. Res. Lett.*, *29*(8), 1251, doi:10.1029/2001GL014325.

Jain, A. K., S. Singh, R. M. Manickavasagam, M. Joshi, and P. K. Verma (2003), HIMPROBE program: Integrated studies on geology, petrology, geochemistry and geophysics of the Trans-Himalaya and Karakoram, in *Indian Continental Lithosphere: Emerging Research Trend*, edited by T. M. Mahadeven, B. R. Arora, and K. R. Gupta, *Mem. Geol. Soc. India*, *53*, 1–56.

Haines, S. S., S. L. Klemperer, L. Brown, J. Guo, J. Mechie, R. Meissner, A. Ross, and W. Zhao (2003), INDEPTH III seismic data: From surface observations to deep crustal processes in Tibet, *Tectonics*, *22*(1), 1001, doi:10.1029/2001TC001305.

Klemperer, S. L. (2006), Crustal flow in Tibet: Geophysical evidence for the physical state of Tibetan lithosphere and inferred patterns of active flow, *Geol. Soc. Spec. Publ.*, *268*, 39–70.

Klootwijk, C. T., P. J. Conaghan, and C. M. Powell (1985), The Himalayan arc: Large-scale continental subduction, oroclinal bending and back-arc spreading, *Earth Planet. Sci. Lett.*, *75*, 167–183.

Lee, J., B. R. Hacker, W. S. Dinklage, Y. Wang, P. Gans, A. Calvert, J. Wan, W. Chen, A. E. Blythe, and W. McClelland (2000), Evolution of the Kangmar Dome, southern Tibet: Structural, petrologic, and thermochronologic constraints, *Tectonics*, *19*, 872–895.

Makovsky, Y., and S. L. Klemperer (1999), Measuring the seismic properties of Tibetan bright-spots: Free aqueous fluids in the Tibetan middle crust, *J. Geophys. Res.*, *104*, 10,795–10,825.

Makovsky, Y., S. L. Klemperer, L. Ratschbacher, and D. Alsdrof (1999), Midcrustal reflector on INDEPTH wide angle profiles: An ophiolitic slab beneath India-Asia suture in southern Tibet?, *Tectonics*, *18*, 793–808.

McNeice, G. M., and A. G. Jones (2001), Multi-site, multi-frequency tensor decomposition of magnetotelluric data, *Geophysics*, *66*, 158–173.

Murphy, M. A., A. Yin, P. Kapp, T. M. Harrison, D. Lin, and J. Guo (2000), Southward propagation of the Karakoram fault system into southwest Tibet: Timing and magnitude of slip, *Geology*, *28*, 451–454.

Nelson, K. D., et al. (1996), Partially molten middle crust beneath southern Tibet: Synthesis of Project INDEPTH results, *Science*, *274*, 1684–1687.

Rai, H. (1980), Origin and emplacement of Ladakh batholith, *Himalayan Geol.*, *10*, 77–82.

Rai, S. S., K. Priestley, V. K. Gaur, S. Mitra, M. P. Singh, and M. Searle (2006), Configuration of the Indian Moho beneath the NW Himalaya and Ladakh, *Geophys. Res. Lett.*, *33*, L15308, doi:10.1029/2006GL026076.

Rodi, W., and R. L. Mackie (2001), Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion, *Geophysics*, *66*, 174–187.

Sachan, H. K., B. K. Mukherjee, Y. Ogaswara, S. Maruyama, H. Ishida, A. Muko, and N. Yoshika (2004), Discovery of coesite in the Indian Himalaya: Evidence for deep subduction, *Eur. J. Mineral.*, *16*, 235–240.

Searle, M. P., R. I. Corfield, B. Stephenson, and J. McCarron (1997), Structure of the north Indian continental margin in the Ladakh-Zanskar Himalayas: Implications for the timing of obduction of the Spontang ophiolite, India-Asia collision and deformation events in the Himalaya, *Geol. Mag.*, *134*, 297–316.

Steveling, E., and M. Leven (1992), Ein Datenlogger für niederfrequente geophysikalische Messungen, paper presented at 14th Kolloquium zur elektromagnetischen Tiefenforschung, Dtsch. Geophys. Ges., Borkheide, Germany, 25–29 May.

Thakur, V. C. (1981), Regional framework and geodynamic evolution of the Indus Tsangpo suture zone in the Ladakh Himalaya, *Trans. R. Soc. Edinburgh Earth Sci.*, *72*, 89–97.

Thakur, V. C. (1983), Deformation and metamorphism in the Tso-Morari crystalline complex, in *Geology of the Indus Suture Zone of Ladakh*, edited by V. C. Thakur and K. K. Sharma, pp. 1–8, Wadia Inst. of Himalayan Geol., Dehradun, India.

Unsworth, M., W. Wenbo, A. G. Jones, S. Li, P. Bedrosian, J. Booker, J. Sheng, D. Ming, and T. Handong (2004), Crustal and upper mantle structure of northern Tibet imaged with magnetotelluric data, *J. Geophys. Res.*, *109*, B02403, doi:10.1029/2002JB002305.

Unsworth, M. J., A. G. Jones, W. Wei, G. Marquis, S. G. Gokarn, J. E. Spratt, and the INDEPTH MT Team (2005), Crustal rheology of the Himalaya and southern Tibet inferred from magnetotelluric data, *Nature*, *438*, 78–81.

Yin, A. (2006), Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation, *Earth Sci. Rev.*, *76*, 1–131.

Zhang, P. Z., et al. (2004), Continuous deformation of the Tibetan Plateau from global positioning system data, *Geology*, *32*, 809–812.

B. R. Arora and G. Rawat, Wadia Institute of Himalayan Geology, 33 General Mahadeo Singh Road, Dehradun, Uttaranchal 248001, India. (arorabr@wihg.res.in)

M. Unsworth, Department of Physics, University of Alberta, Edmonton, AB, Canada T6G 2J1. (unsworth@phys.UAlberta.ca)