Electromagnetic studies of the central Tibetan Plateau from INDEPTH magnetotelluric profiles and magnetovariational data

Jan Vozar[1], Alan G. Jones[1], Florian Le Pape[1], Martyn J. Unsworth[2], Wei Wenbo[3],Jin Sheng[3], Gaofeng Ye[3], and the INDEPTH MT Team
[1] Dublin Institute for Advanced Studies, Dublin, Ireland
[2] Department of Physics, University of Alberta, Edmonton, Canada
[3] China University of Geosciences Beijing, 29 Xueyuan Road, Beijing, China

SUMMARY

During the last 15 years, broadband and long period magnetotelluric data were collected and interpreted in Tibet as a part of InterNational DEep Profiling of Tibet and the Himalaya project (INDEPTH). The study presented herein is focused on two profiles acquired during Phase III crossing the Banggong-Nujiang Suture, which separate the Qiangtang and Lhasa terranes, along approximately longitudes of 89°E (longer “500 line”) and 92°E (shorter “400 line”). The long period magnetotelluric data have been combined with available magnetovariational data from permanent geomagnetic observatories situated within or close to the investigated area. Both magnetotelluric TE and TM modes with the vertical field geomagnetic transfer functions have been derived for the defined regional azimuth angle oriented approximately in an east-west direction, and modeled using smooth inversion. The local geomagnetic depth soundings responses, and responses from generalized horizontal spatial gradient method for mid-latitude INDEPTH region, have been derived.
The preferred model of the 500 profile confirms the previous observations that the region is – to first-order - characterized by a resistive upper crust and a conductive middle to lower crust that extends from the Lhasa terrane to the Qiangtang terrane with varying depth. The conductive layer is relatively uniform along whole profile, except for two breaks in the region of the Banggong-Nujiang suture and 50 km south of it. Absence of high conductive crustal layers in these short parts of the 500 line profile, and combination of long period magnetotelluric and magnetovariational responses, allow us to obtain information about deeper structures and reveals the possible existence of a high conductive layer localized at upper mantle depths.
The same conductive structure setting is also present on the shorter 400 line. Other models show focused information about the Banggong-Nujiang suture and its changes in geoelectrical structure between the longitudes of 89°E and 92°E. The eastern profile (400 line) exhibits a shallower crustal conductive layer and a sharp horizontal jump in conductivity just below the surface trace of the Banggong-Nujiang suture, in comparison with western 500 line. These along-strike differences represent varying conditions, such as temperature, partial melt content and connectivity, and fluid content and connectivity, and/or varying rock types.

Keywords: electromagnetic soundings, Tibet, Banggong-Nujiang suture, geomagnetic data

INTRODUCTION

Since 1995 broadband (BBMT) and long period (LMT) magnetotelluric data have been collected and interpreted within the framework of the InterNational DEep Profiling of Tibet and the Himalaya (INDEPTH) project. The overarching objectives of the MT part of INDEPTH are to describe the geoelectrical properties of the crust and uppermost mantle as a product of the ongoing continent-continent collision between India and Asia. The currently-active processes in the Tibetan Plateau, like its thickening and flow in the lower crust, are consequences of this continental collision (Bai et al., 2010).

The tectonics of Tibet are a prolonged history of terrane accretion lasting over 250 Myr, with four major terranes identified, namely from north to south Songpan-Ganzi, Qiangtang, Lhasa and Himalaya, all separated by major sutures. Each of these can be subdivided into subterranes. Terrane accretion initiated in the late Permian with the northernmost subterrane of the Songpan-Ganzi accreting to the Kunlun (Tarim) terrane of southern Asia along the Kun-Qinling Suture. Songpan-Ganzi terrane accretion was completed in the late Triassic/Jurrasic period. The Qingtang terrane is bounded to the north by the late-Triassic/Jurrasic Jinsha Suture and the south by the Banggong-Nujiang

Suture. Late-Jurrasic Banggong-Nujiang Suture (BNS) separates the Qiangtang and Lhasa terranes and trends approximately east-west across the interior of the Tibetian Plateau. Finally, the Himalaya terrane sutured against the Lhasa terrane along the Yarlung-Indus-Zangbo suture, which initiated about 50-30 Ma.

Two INDEPTH profiles cross the BNS along approximately longitudes of 89°E (longer termed "500 line", extending from the centre of Lhasa terrane to the centre of the Qiangtang terrane) and 92°E (shorter "400 line"), see Fig. 1. The modelled MT data collected on 500 line were presented by Wei et al. (2001) with identification of a plateau-wide middle and lower crust conductive zone. A more detailed analysis of a subset of these in the vicinity of the BNS is in Solon et al. (2005), who showed, contrary to Wei et al. (2001), strong lateral variability on either side of the BNS of over an order of magnitude in the conductivity of the middle and lower crust.

The electrical and seismic data across the BNS were jointly-interpreted as indicative of the temperature regime with identification of the alpha-beta quartz transition (Mechie et al., 2004).

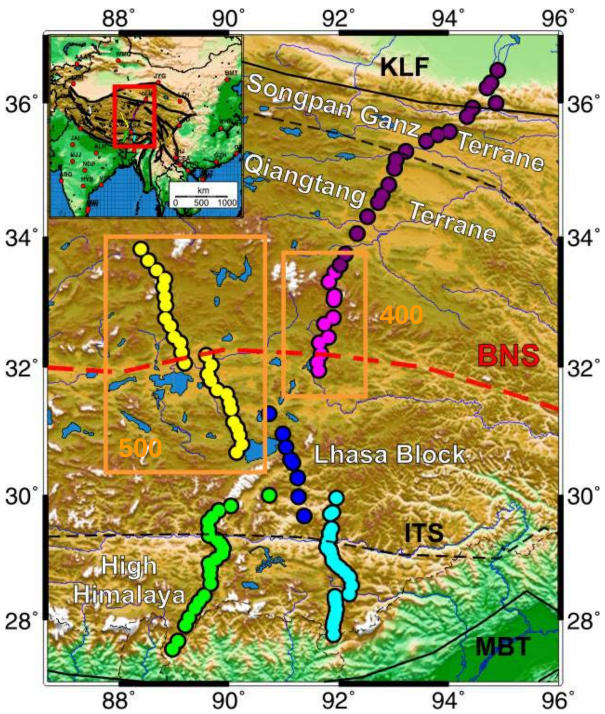

Figure 1. Map with MT INDEPTH's profiles. The yellow dots denote the 500 line and the pink dots show localization of the 400 line.

In this study we re-model and re-interpet the BNS-crossing data and present along-strike and across-strike crustal structures of the BNS using 40 km offset and overlap of northern and southern part of the 500 line modeled in the regional strike direction. Also, the data from the 400 line, is used to describe the BNS some 200 km to the east along strike from the 500 line. For some sites from these profiles we have combined available magnetovariational data from permanent geomagnetic observatories situated within or close to investigated area with MT responses to get information about deeper geoelectrical structures.

ANALYSIS OF THE DATA

All data from the 400 and 500 lines were collected in 1998. The data comprised broad-band MT data at 61 locations (from 250 Hz), used for shallow and middle crustal data acquisition, and 31 sites with long period deep crustal and upper mantle MT data (up to 10,000 s). The time series were processed using remote reference data technique (Egbert, 1997 and Jones et al., 1989) and the long period data were merged and corrected with broadband MT data.

On both profiles we have performed strike and dimensionality analyses, which generally show predominant two-dimensionality of the regional geoelectrical structures with an approximate east-west direction. The multisite and multifrequency MT tensor decomposition technique (McNeice & Jones, 2001) for several Niblett-Bostick depth ranges was used to determine the dominant geoelectric regional strike E10°S (i.e., N100°E), which yielding the lowest global misfit and is consistent with general trend east-west trend of the BNS. Both magnetotelluric TE and TM modes with the vertical field geomagnetic transfer functions (GTF) have been derived in the defined regional azimuth angle in the new resulting coordinate system.

In next step we have been processing available geomagnetic data from mid-latitude INDEPTH region data and adjacent regions. The scalar impedance as function of periods were estimated using local geomagnetic depth soundings (GDS) method and by new generalized horizontal spatial gradient (gHSG) method (Vozar & Semenov, 2010):

$$- H_z \approx \quad (i\omega\mu_0)^{-1}[Z(div\boldsymbol{H}_\tau) + \boldsymbol{H}_\tau\cdot(gradZ)].$$

Reliable new and previously published (Fan et al., 1997) response estimates are combined with the long period MT data. This approach is feasible within the accepted sounding theory where the MT tensor and the MV scalar impedance are physically equivalent functions above laterally uniform structures only (Semenov *et al*., 2007).

DATA INVERSIONS

The distortion-corrected responses at a strike angle 100° have been inverted with different 2D inversion algorithms to obtain several two-dimensional geoelectrical models. Both modes of the MT data (TE & TM) were inverted separately and simultaneously, with a combination of inversion parameters. The preferred model of the 500 profile confirms the previous first-order observations of Wei et al. (2001) and Solon et al. (2005) that the region is characterized by a resistive upper crust and a conductive middle to lower crust that extends from the Lhasa terrane to the Qiangtang terrane with varying depth. The conductive zone to the south of the profile, just in the middle between BNS and Yarlung-Zangbo Suture, with highest conductance may be an extension of the conductive channel imaged by Bai, et al. (2010). The conductive layer has a higher conductance/lower resistivity beneath the Qiangtang Terrane than beneath the Lhasa Terrane (Fig. 2), with average conductances of 5,000 Siemens and above for the former, and 2,000 Siemens and below for the latter. This variation has parallels with the newly-defined shallower Moho for the Qiangtang Terrane compared to the Lhasa Terrane (Li et al., 2006). Shallower Moho will mean hotter crust, will mean more partial melt, will mean lower resistivity, will mean higher conductance, for the Qiangtang Terrane.

Towards the southern end of the 500 line the conductance increases rapidly, consistent with previously-imaged anomalously high (partial melt?) bodies in the southern Lhasa Terrane (Nelson et al., 1996; Chen et al., 1996; Li et al., 2003; Spratt et al., 2005).

The northern part of the model provide images of geoelectrical structures of the central Qiangtang metamorphic belt, with Shuanghu suture which represents a distinct and unrelated paleo-Tethyan suture zone that separates Qiangtang terrane to northern and southern part (Kapp et al., 2003, Zhang et al. 2006). This suture is characterized by sharp boundary between conductive northern part and resistive south to depths of 30 km.

The geoelectric images of the BNS from the 400 line MT data confirm the same general conductive structure setting similar to the separate 2D models of northern and southern part of the 500 line with 40 km offset. All these three 2D models show focused information about the BNS and its changes in geoelectrical structure between the longitudes of 89°E and 92°E. The eastern profile (400 line) exhibits a shallower crustal conductive layer and a sharp horizontal jump in conductivity just below the surface trace of the BNS in comparison with western 500 line.

Deep 1D inversions

We merged the available magnetovariational responses from the Lhasa geomagnetic observatory with long period MT data from three sites (520, 524 and 528) which fit a one-dimensional assumption and are localized in part of profile absent of high conductive crustal layers. The final one-dimensional deep resistivity models show the existence of a high conductive layer localized at a depth more than 200 km.

CONCLUSIONS

Deep-probing electromagnetic studies of the central Tibetian Plateau have been presented which focus on the along-strike and across-strike structures of the Banggong-Nujiang Suture and the central Qiangtang metamorphic belt with the Shuanghu suture from re-analyses and re-modelling of the 400 and 500 line MT data. In addition, deep 1-D electromagnetic soundings were derived using magnetovariational responses. In addition to the well-known anomalously conductive middle to lower crust (Wei et al., 2001), we show that the most conductive lower crust anomaly is situated in the lower crust of the southern part of the 500 line, i.e., southern Lhasa Terrane, and estimation of its conductance is similar to that of the conductive channels presented in Bai et al. (2010). The strong bottom boundaries of the conductive layers resulting from 2-D MT inversions are in agreement with the Moho boundary depth for this region (Zhao et al., 2001), although recent Receiver Function estimates suggest that the Moho is some 8 km shallower beneath the Qiangtang Terrane than beneath the Lhasa Terrane (Li et al., 2006), which could explain the far higher conductance of the middle and lower crust beneath that terrane compared to the Lhasa Terrane.

From deep electromagnetic sounding we can be estimated the next conductive layer at depths 200 km and more. The Banggong-Nujiang Suture along strike analysis exhibits that crustal conductive layer become exhibits a shallower in east direction from 500 line. These along-strike differences represent varying conditions, such as temperature, partial melt content and connectivity, and fluid content and connectivity, and/or varying rock types.

REFERENCES

Bai D., Unsworth M. J., Meju M. A., Ma X., Teng J., Kong X, Sun Y., Sun J. Wang L., Jiang C., Zhao C., Xiao P. and M. Liu, 2010, Crustal deformation of the eastern Tibetan plateau revealed by magnetotelluric imaging. Nature Geoscience, Vol. 3, 358-362

Chen, L., J.R. Booker, A.G. Jones, N. Wu, M. Unsworth, W. Wei and H. Tan, 1996. Electrically conductive crust in southern Tibet from INDEPTH magnetotelluric surveying Science, 274, 1694-1696.

Fan G.-H., Yao T., Gu Z.-W., Zhu K.-J., 1997, Investigation of electrical conductivity beneath China using geomagnetic spatial gradient method. Acta Seismologica Sinica, Vol. 10, No.2., 205-216

Kapp P, Yin A, Craig M.E., Harrison M. T. and Taylor M.H., 2003, Tectonic evolution of the Early Mesozoic blueschist-bearing Qiangtang metermorphic belt, central Tibet. Tectonics, 22(4): 1043, doi:10. 1029.

Li, S., M.J. Unsworth, J.R. Booker, W. Wei, H. Tan, and A.G. Jones, 2003. Partial melt or aqueous fluid in the mid-crust of southern Tibet? Constraints from INDEPTH magnetotelluric data. Geophysical Journal International, 153, 289-304.

Li Y, Q. Wu, X. Tian, R. Zeng R. Zhang and H. Li, 2006. Crustal structure beneath Qiangtang and Lhasa terrane from receiver function. Acta Seismologica Sinica, Volume 19, 633-642.

McNeice, G., Jones, A.G., 2001. Multisite, multifrequency tensor decomposition of magnetotelluric data. Geophysics 66, 158–173.

Mechie, J., S.V. Sobolev, L. Ratschbacher, A. Yu. Babeyko, G. Bock, A.G. Jones, K.D. Nelson, K.D. Solon, L.D. Brown, and W. Zhao, 2004. Precise temperature estimation in the Tibetan crust from seismic detection of the alpha-beta quartz transition. Geology, 32, 601-604.

Nelson, K.D., Wenjin Zhao, L.D. Brown, J. Kuo, Jinkai Che, Xianwen Liu, S.L. Klemperer, Y. Makovsky, R. Meissner, J. Mechie, R. Kind, F. Wenzel, J. Ni, J. Nabelek, Leshou Chen, Handong Tan, Wenbo Wei, A.G. Jones, J. Booker, M. Unsworth, W.S.F. Kidd, M. Hauck, D. Alsdorf, A. Ross, M. Cogan, Changde Wu, E. Sandvol, M. Edwards, 1996. Partially molten middle crust beneath southern Tibet: an initial synthesis of Project INDEPTH results. Science, 274, 1684-1688.

Semenov, V.Yu., J. Vozar, and V. Shuman, 2007, A new approach to gradient geomagnetic sounding. *Izv., Phys. Solid Earth* **43**, 7, 592-596,

Solon, K. D., Jones, A.J., Nelson, K.D., Unsworth, M.J., Kidd,W.F.,Wei,W., Tan, H., Jin, S., Deng, M., Booker, J. R., Li, S. and P. Bedrosian, 2005, Structure of the crust in the vicinity of the Banggong-Nujiang suture in central Tibet from INDEPTH magnetotelluric data, J. Geophys. Res., 110, B10102.

Spratt, J., A.G. Jones, K.D. Nelson, M.J. Unsworth, and the INDEPTH MT team, 2005. Crustal structure of the India-Asia collision zone, southern Tibet, from INDEPTH MT investigations. Physics of the Earth and Planetary Interiors, 150, 227-237.

Tapponnier, P., Z. Xu, F. Roger, B. Meyer, N. Arnaud, G. Wittlinger, and J. Yang, Oblique stepwise rise and growth of the Tibet Plateau, Science, 294, 1671 – 1677, 2001.

Vozar J. and V. Y. Semenov, 2010, Compatibility of induction methods for mantle soundings, JGR, Vol. 115, B03101

Wei, W., M. Unsworth, A.G. Jones, T. Handong, K.D. Nelson, J.R. Booker, L. Chen, S. Li, K. Solon, P. Bedrosian, S. Jin, M. Deng, J. Ledo, D. Kay and B. Roberts, 2001, Detection of widespread fluids in the Tibetan crust by magnetotelluric studies. Science, 292, 716-718.

Zhang K.-J., Zhang Y.-X., Li B., Zhu Y.-T., Wei R.-Z., 2006, *Geology;* June 2006; v. 34; no. 6; p. 493–496; doi: 10.1130/G22404.1

Zhao, W., et al. (2001), Crustal structure of central Tibet as derived from project INDEPTH wide-angle seismic data, Geophys, J. Inter., 145, 486–498.

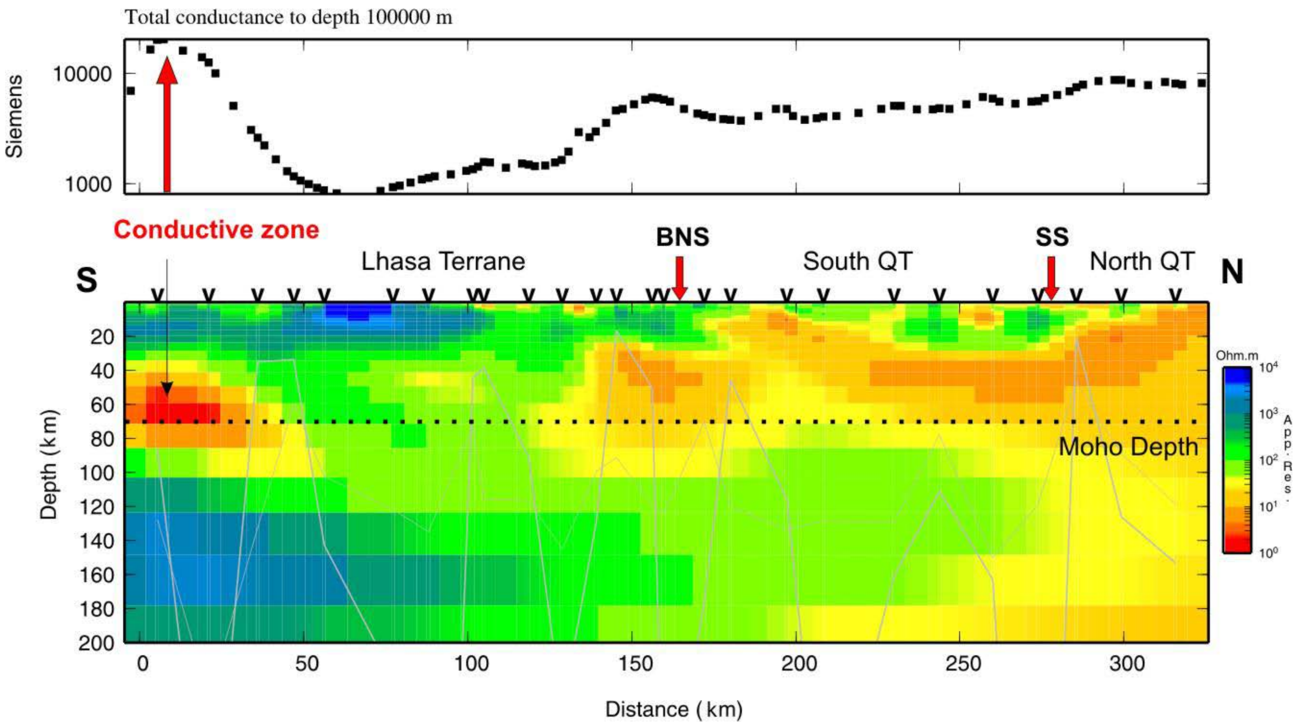

Figure 3. Line 500 final interpretation. BNS - the Banggong-Nujiang Suture, QT - the Qiangtang terrane, horizontal gray lines – Niblett- Bostick depths