PICASSO Phase II – TopoMed
MT investigations over the Atlas Mountains of Morocco: preliminary results

Duygu Kiyan[1,2], Alan G. Jones[1], Colin Hogg[1], Juanjo Ledo[3], Agata Siniscalchi[4], and the PICASSO Phase II Team

[1] Dublin Institute for Advanced Studies, School of Cosmic Physics, Dublin, Ireland
[2] National University of Ireland, Galway, Department of Earth and Ocean Science, Galway, Ireland
[3] University of Barcelona, Department of Geodynamics & Geophysics, Barcelona, Spain
[4] University of Bari, Department of Geology & Geophysics, Bari, Italy

SUMMARY

The overarching objective of the second phase of the PICASSO (Program to Investigate Convective Alboran Sea System Overturn) project, and the concomitant TopoMed (Plate re-organization in the western Mediterranean: Lithospheric causes and topographic consequences) project, is to develop a better understanding of the internal structure of the crust and the lithosphere of the Atlas Mountains of Morocco. The magnetotelluric (MT) experiment across the Atlas Mountains region started in September, 2009 and ended in February, 2010. The experiment comprised acquisition of broadband and long period MT data along two profiles: a N-S oriented profile through Meknes to the east and a NE-SW profile through Marrakesh to the west. Since completion of fieldwork all MT data have been processed with robust remote reference methods. The data will be submitted to comprehensive strike and dimensionality analysis, and modelled using 2-D smooth inversion. The paper will show the resulting lithospheric model across the complex Atlas region.

Keywords: Magnetotellurics, Atlas Mountains, Lithospheric Structure, Morocco

INTRODUCTION

The Atlas System is an intracontinental mountain belt extending for more than 2000 km along the NW African plate with a predominant NE-SW trend. The System comprises three main branches: the High Atlas with summits of 4000 m, the Middle Atlas, which reaches 3000 m, and the Anti Atlas.

Numerous geophysical studies have been carried out in the Atlas region. Crustal studies using seismic refraction data suggest that the crust beneath the most elevated parts of the High Atlas (south of Marrakesh) is 34-38 km thick (Makris et al., 1985) and 38-39 km thick near Midelt, reducing to 35 km to south and to north (Tadili et al., 1986, Wigger et al., 1992). The results from receiver function studies resulted in Moho depth estimates of 36 km (Sandvol et al., 1998) and 39 km (van der Meijde et al., 2003) near Midelt in the High Atlas to the east (see Fig. 1). Interpretation of gravity data resulted in crustal thickness estimates of between 38-41 km in the Central High Atlas (Ayarza et al., 2005). Furthermore, the tectonic shortening estimated for the Atlas Mountains is relatively low (value range from 15% to 24%, Teixell et al., 2005) suggesting moderate crustal compression. The fact that the Moho depth required to isostatically compensate the high topography at a crustal scale should be more than 45 km infers significant variations in the topography of the lithosphere-asthenosphere boundary (LAB) beneath the Atlas Mountain range. Peculiarly, lithospheric thinning beneath the Atlas has been proposed by several authors on the basis of elevation, geoid and gravity anomalies, surface heat flow, and seismic data modelling (Zeyen et al., 2005, Teixell et al., 2005, Missenard et al., 2006, Fullea et al., 2007, and Fullea et al., 2010). The relatively low Pn velocities, ranging between 7.7 and 7.9 km/s, in the Middle and High Atlas (Makris et al., 1995; Wigger et al., 1992) and the negative velocity anomalies depicted by seismic tomography studies (e.g. Boschi et al., 2009; Spakman and Wortel 2004) are also suggestive of a relatively hot upper mantle in the study region.

The magnetotelluric method is particularly suited for imaging the LAB, as the electrical conductivity is highly sensitive to temperature and the onset of even small fractions of partial melt (Jones, 1999). Schwarz et al. (1992) conducted the only previous MT survey in the region of interest. MT data were collected by those authors along three profiles: two main profiles start from the Rif Mountains and that go through the Anti-Atlas (coincides with the MEK profile shown in the Fig. 1), where the E-W oriented third one runs from High Atlas towards Moroccan Meseta. They concluded that a high conductivity zone existed at crustal depths beneath the High and Middle Atlas.

In this study, we present the preliminary results of a recent MT experiment carried out in the Atlas Mountains during September 2009 - February 2010. The experiment comprised two profiles across the Middle and High Atlas, as shown in Fig. 1. The MT project is a component of two overarching projects, PICASSO (Program to Investigate Convective Alboran Sea System Overturn) project, and the concomitant TopoMed (Plate re-organization in the western Mediterranean: Lithospheric causes and topographic consequences). Our results will give new constraints on the lithospheric structure of the Atlas Mountains, and will aid discrimination between competing models describing the tectonics of the region.

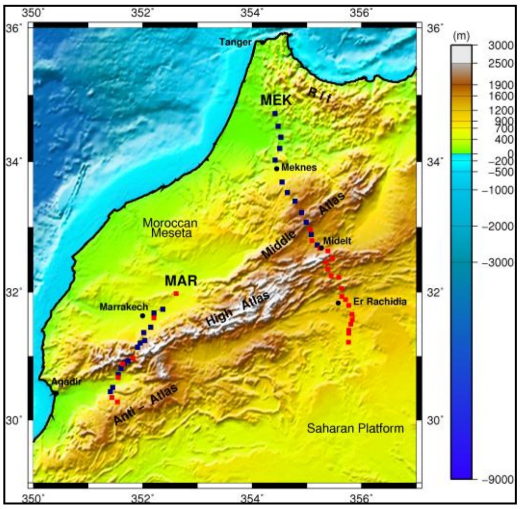

Figure 1. Topographic map (ETOPO2 Global Data Base; Smith and Sandwell 1994; Sandwell and Smith, 1997) of the study area showing the MT site locations across the Atlas Mountains. The red squares represent broad-band only sites and the blue ones represent both broadband and long period sites.

MAGNETOTELLURICS

Data acquisition and processing

The first phase of magnetotelluric measurements, on profile MAR and the southern half of profile MEK, was carried out from end-September to mid-December, 2009. The instrumentation consisted of Ukrainian Lviv long-period called LEMI, Phoenix MTU5 broad-band and EMIs MT-24LF units (used by University of Bari). The data at the long-period (LEMI) MT stations were recorded with a 1 second sampling rate and resulted in the period range of ~15 – 10,000+ s. The total period range for each merged site is between 0.003 and 10,000+ s.

The MAR profile runs in a NE-SW direction, is approximately 300 km long, and consists of 20 broad-band MT (BBMT) stations and 13 LEMI stations merged with every second BBMT station. These stations were deployed at approximately 10 km intervals along the MAR profile. The recording of LEMI data was extended for approximately 2 months, from a planned deployment time of 4 weeks to 8 weeks, due to the very low solar activity in 2009 – there were no sunspots observed on 260 days (71%) of the year (NASA Report). During the first phase of the field campaign, BBMT data were collected at 22 stations along the southern portion of the MEK profile which extends for approximately 500 km from the Rif to the Sahara Platform (Fig. 1).

In mid-December, the LEMI acquisition started at 12 sites (blue squares along the MEK profile in Fig. 1) on the northern part of the MEK profile. These stations were left to record in place for approximately three months (December, 2009-February 2010). The second phase of the field campaign took place in February 2010 to retrieve LEMI stations and to continue BBMT data collection along the northern part of the profile. The BBMT and LEMI stations were deployed approximately at 10 and 20 km, respectively.

Two different robust remote referencing methods (those of Chave and Smirnov, see Smirnov, 2003, and Chave and Thomson, 2004) were tested to obtain optimum MT response for each LEMI site. The BBMT data were processed using remote referencing Phoenix processing software (based on Jones and Jödicke, 1984) and Egbert's (Egbert 1997) robust remote reference method. At most of the sites (BBMT alone) along the MAR profile, data are of good quality to at least 1,000 s and for merged (BBMT+LEMI) sites apparent resistivity and phase estimates in the period range of ~ 0.003–10,000+ s. The sites located over the Middle Atlas and further south have good quality data to periods of 3,000-5,000 s and at merged sites even up to 15,000 s (examples in Fig. 2).

The next steps will be (i) to test dimensionality of the data, and (ii) to define the 2-D geoelectric strike direction using the program STRIKE by McNeice and Jones (2001) based on Groom-Bailey decomposition (Groom and Bailey, 1989). The resulting distortion-free responses will be modelled using 2-D smooth inversion method of Rodi and Mackie (2001) and also that of

Siripunvaraporn and Egbert (2000). Three-dimensional forward modeling will be used to test the effects of the ocean-continent boundary on the data, particularly for MAR and the northern end of MEK.

CONCLUSIONS

An MT experiment was performed over the Atlas Mountains of Morocco. The first results of this MT survey shed light onto the origin of the Atlas Mountains system and test hypotheses for its missing mantle root constructed from surface heat flow, gravity and geoid anomalies, elevation and seismic data modelling (Zeyen et al., 2005, Teixell et al., 2005, Missenard et al., 2006, Fullea et al., 2010).

ACKNOWLEDGEMENTS

We would like to acknowledge the financial support from Irish Research Council for Science Engineering and Technology (IRCSET) and Science Foundation Ireland (SFI grant 2006RFPGEO001). We gratefully thank Prof. Mohamed Rouai (from University of Moulay-Ismail, Morocco) and his PhD students for their help during the fieldwork. Special thanks to the enthusiastic members of PICASSO Phase II team who were involved in the field campaigns.

REFERENCES

Ayarza, P., Alvarez-Lobato, F., Teixell, A., Arboleya, M.L., Teson, E., Julivert, M. and Charroud, M., 2005. Crustal structure under the central High Atlas Mountains (Morocco) from geological and gravity data. Tectonophysics 400 (1-4), 67-84.

Boschi, L., Fry, B., Ekström, G. and Giardani, D., 2009. The European upper mantle as seen by the surface waves. Surveys in Geophysics 30. doi:10.1007/s10712-009-9066-2.

Chave, A. and Thomson, D., 2004, Bounded influence magnetotelluric response function estimation. Geophysical Journal International 157, 988-1006.

Egbert, G., 1997. Robust multiple-station magnetotelluric data processing. Geophysical Journal International 130, p. 475-496.

Fullea, J., Fernandez, M., Zeyen, H. and Verges, J., 2007. A rapid method to map the crustal and lithospheric thickness using elevation, geoid anomaly and thermal analysis. Application to the Gibraltar Arc System and adjacent zones. Tectonophysics 430, 97-117.

Fullea, J., Fernandez, M., Afonso, J. C., Verges, J. and Zeyen, H., 2010. The structure and evolution of the lithosphere-asthenosphere boundary beneath the Atlantic-Mediterranean Transition Region. Lithos, doi: 10.1016/j.lithos.2010.03.003

Groom, R. W. and Bailey, R. C., 1989. Decomposition of magnetotelluric impedance tensors in the presence of local three dimensional galvanic distortion. Journal of Geophysical Research 94, 1913-1925.

Jones, A. G., and Jödicke, H., 1984. Magnetotelluric transfer function estimation improvement by a coherence-based rejection technique, paper presented at the 54th Society of Exploration Geophysics Annual General Meeting, Atlanta, Georgia, 2-6 December, Abstract volume, pp. 51-55.

Jones, A. G., 1999. Imaging the continental upper mantle using electromagnetic methods. Lithos, 48, 57-80.

McNeice, G. W. and Jones, A. G., 2001. Multisite, multi-frequency tensor decomposition of magnetotelluric data. Geophysics 66, 158-173.

Phoenix Geophysics Inc 2003, Data Processing User Guide, version 2.1. Toronto, Canada.

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

Sandvol, E., Seber, D., Calvert, A. and Barazangi, M., 1998. Grid search modeling of receiver functions: implications for crustal structure in the Middle East and North Africa. Journal of Geophysical Research 103 (B11), 26899-26917.

Sandwell, D. T. and Smith, W. H. F., 1997. Global sea floor topography from satellite altimetry and ship depth soundings. Science 227, 1957-1962.

Schwarz, G., Mehi, H. G. and Rath, V., 1992. Eletrical resistivity structure of the eastern Moroccan Atlas System and its tectonic implications. Geologische Rundschau 81, 221-235

Smirnov, M. Y., 2003. Magnetotelluric data processing with a robust statistical procedure having a high breakdown point. Geophysical Journal International 152(1), 1-7.

Smith, W. H. F. and Sandwell, D. T., 1994. Bathymetry prediction from dense satellite altimetry and sparse shipborne bathymetry. Journal of Geophysical Research 99, 21803-21824.

Spakman, W. and Wortel, M.J.R., 2004. A tomographic view on western Mediterranean geodynamics. In: Cavazza, W., Roure, F., Spakman, W., Stampfli, G.M., Ziegler, P. (Eds), The TRANSMED Atlas-The Mediterranean region from crust to mantle. Springer, Berlin Heidelberg, pp. 31-52.

Siripunvaraporn, W. and Egbert, G., 2000. An efficient data-subspace inversion method for 2-D magnetotelluric data. Geophysics 65, 791-803.

Tadili, B., Ramdani, M., Sari, B., Chapochnikov, K. and Bellot, A., 1986. Structure de la croute dans le nord du Maroc. Ann. Geophys. 4 (1), 99-104.

Teixell, A., Ayarza, P., Zeyen, H., Fernandez, M. and Arboleya, M.-L. 2005. Effects of mantle upwelling in a compressional setting: The Atlas Mountains of Morocco. Terra Nova 17, 456-461.

van der Meijde, M., Van der Lee, S. and Giardini, D., 2003. Crustal structure beneath broadband seismic stations in the Mediterranean region. Geophysical Journal International 152 (3), 729-739.

Wigger, P., Asch, G., Giese, P., Heinsohn, W.-D., El Alami, S.O. and Ramdani, F., 1992. Crustal structure along a traverse across the Middle and High Atlas mountains derived from seismic refraction studies. Geol. Rundsch. 81, 237-248.

Zeyen, H., Ayarza, P., Fernandez, M. and Rimi, A., 2005. Lithospheric structure under the western African-European plate boundary: a transect across the Atlas Mountains and Gulf of Cadiz. Tectonics 24 (TC2001). doi: 10.1029/2004TC001639.

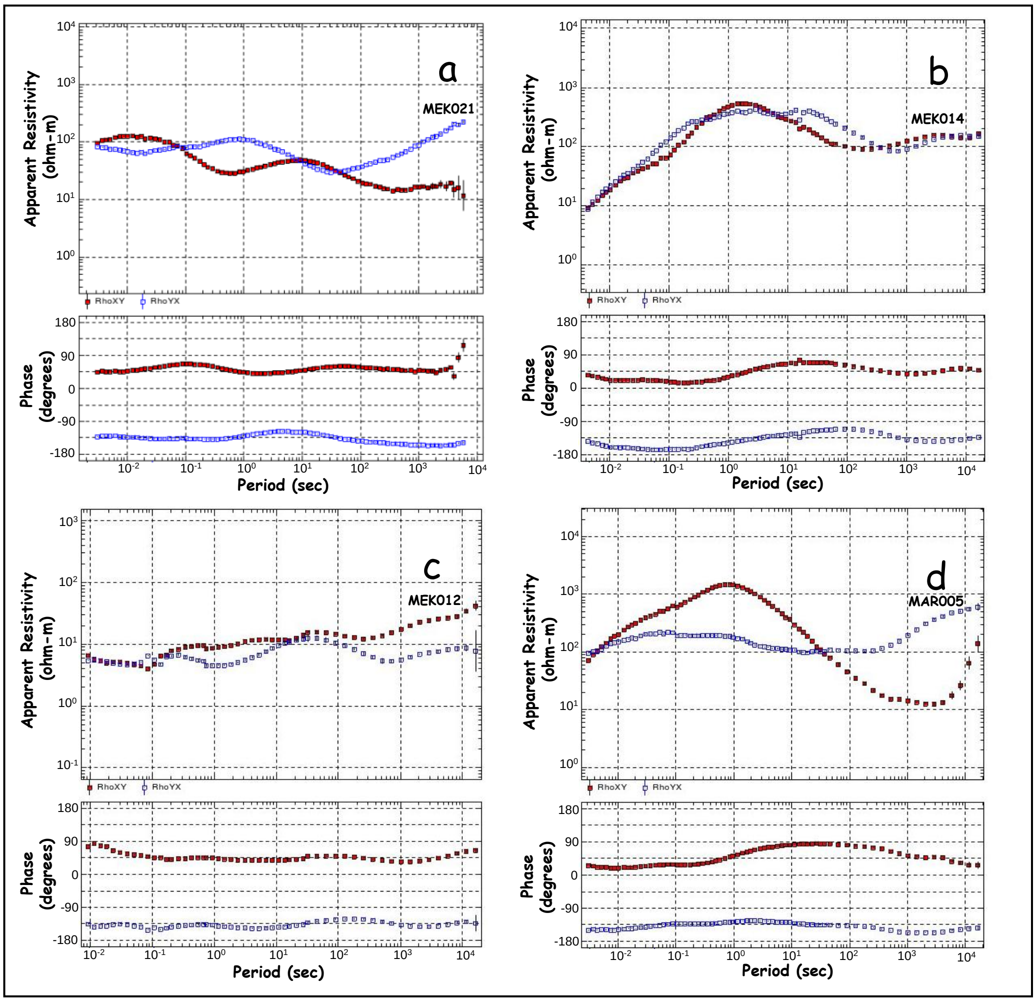

Figure 2. Magnetotelluric apparent resistivity and phase curves for different tectonic units over the Atlas Mountains: (a) BBMT data from MEK profile, located in the eastern part of High Atlas, site MEK021; (b) BBMT+LEMI data from MEK profile, located near Midelt, site MEK014; (c) BBMT+LEMI data from MEK profile, located in the Middle Atlas, site MEK012; (d) BBMT+LEMI data from MAR profile, located in the Anti Atlas, site MAR005. The red squares represent the transverse-electric (TE) mode data, and the blue ones represent the transverse-magnetic (TM) mode data.