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Electrical signature of modern and ancient tectonic processes in the crust of the Atlas mountains of Morocco

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ABSTRACT

The Atlas Mountains in Morocco are considered as type examples of intracontinental mountain chains, with high topography that contrasts with moderate crustal shortening and thickening. Whereas recent geological studies and geodynamic modelling suggest the existence of dynamic topography to explain this apparent contradiction, there is a lack of modern geophysical data at the crustal scale to corroborate this hypothesis. To address this deficiency, magnetotelluric data were recently acquired that image the electrical resistivity distribution of the crust from the Middle Atlas to the Anti-Atlas, crossing the tabular Moulouya plain and the High Atlas. All tectonic units show different, distinct and unique electrical signatures throughout the crust reflecting the tectonic history of development of each one. In the upper crust, electrical resistivity values and geometries can be associated to sediment sequences in the Moulouya and Anti-Atlas and to crustal scale fault systems in the High Atlas developed likely during Cenozoic times. In the lower crust, the low resistivity anomaly found below the Moulouya plain, together with other geophysical (low velocity anomaly, lack of earthquakes and minimum Bouguer anomaly) and geochemical (Neogene-Quaternary intraplate alkaline volcanic fields) evidences, infer the existence of a small degree of partial melt at the base of the crust. Resistivity values suggest a partial melt fraction of the order of 2–8%. The low resistivity anomaly found below the Anti-Atlas may be associated with a relict subduction of Precambrian oceanic sediments, or to precipitated minerals during the release of fluids from the mantle during the accretion of the Anti-Atlas to the West African Supercontinent during the Panafrican orogeny (ca. 685 Ma).

1. Introduction

The Atlas Mountains of Morocco consist of continuous intracontinental mountain chains of different ages; Alpine (Cenozoic) age for the Middle and High Atlas and Late Carboniferous to early Permian for the Anti-Atlas. They are characterized by having high topography that contrasts with moderate crustal tectonic shortening and thickening in the Atlas, and moderate topography and very mild shortening in the Anti-Atlas (Guimerà et al., 2011). Recent geological studies and geodynamic modelling (Teixell et al., 2003, 2005; Zeyen et al., 2005) suggest the role of dynamic topography to explain this apparent contradiction, although there is a lack of modern geophysical data at the crustal scale to corroborate this hypothesis. The High Atlas Mountain chain, located in the foreland of the Mediterranean Alpine belt, is a 100 km wide, ENE–WSW-oriented intracontinental fold-and-thrust belt that extends for 800 km in Morocco, (Fig. 1), and continues eastward into Algeria and Tunisia for a total strike length of approx. 2000 km. The structure of the High Atlas mountain range resulted from tectonic inversion of a Mesozoic extensional basin due to contraction, with an average direction of NNW–SSE, related to the convergence between Africa and Europe from Cenozoic to present times (Mattauer et al., 1977; Beauchamp et al., 1999; Frizon de Lamotte et al., 2000; Teixell et al., 2003; Arboleya et al., 2004). Mesozoic sediments overlie a Precambrian to Paleozoic basement intensely affected by Hercynian (late Paleozoic) orogeny. Cenozoic shortening was mainly achieved by thick-skinned trusting and folding affecting the pre-Mesozoic basement and the Mesozoic–Cenozoic cover. Total shortening during Cenozoic contraction was around 24% in the area of study (Teixell et al., 2003).

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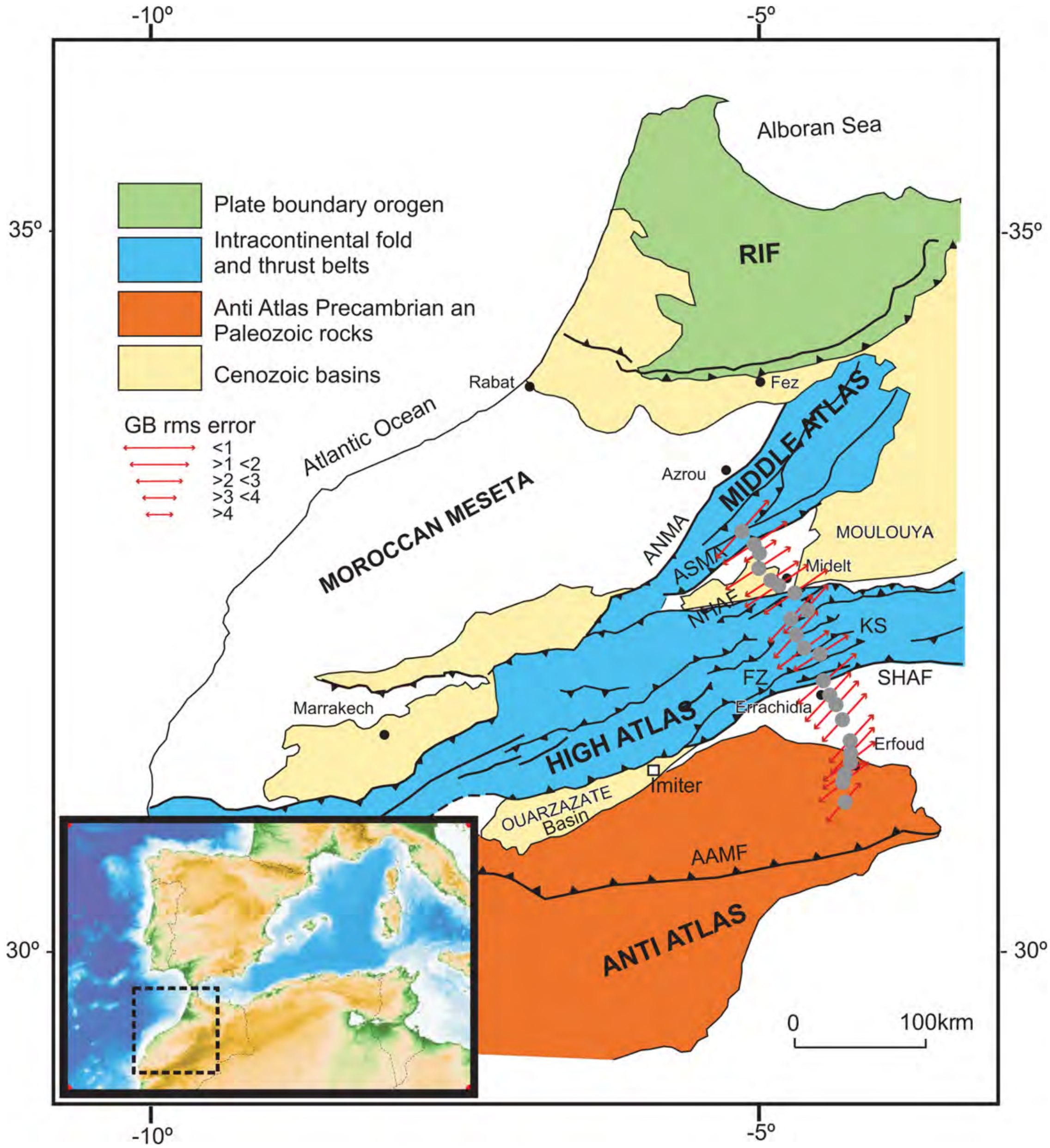

Fig. 1. Geological map of the studied area. Gray circles show the location of the MT stations. Red arrows correspond to the GB strike angle (see text for details). ANMA: North Middle Atlas Fault; ASMA: South Middle Atlas Fault; NHAF: North High Atlas Front; SHAF: South High Atlas Front; AAMF: Anti-Atlas Major Fault; FZ: Forum Zabel thrust; KS: Kerrando syncline.

Early geophysical images of the crustal structure of the Atlas were obtained in the 1980s and early 1990s using seismic refraction data, receiver function and magnetotelluric data (Makris et al., 1985; Tadili et al., 1986; Schwarz and Wigger, 1988; Wigger et al., 1992; Schwarz et al., 1992). Schwarz and Wigger (1988) proposed the existence of small amounts of melt in the middle and lower crust to explain the observed crustal low velocity and low resistivity zones, with the latter determined from one-dimensional (1D) and pseudo two-dimensional (2D) modelling. Sandvol et al. (1998) and van der Meijde et al. (2003), using receiver functions, proposed the existence of multiple velocity jumps at the base of the crust, taken to imply duplication of the Moho discontinuity in the northern part of the High Atlas (35–38 km). Ayarza et al. (2005) combined the previous geophysical results with gravity data and detailed geological cross sections of the area to obtain a crustal-scale density distribution model. In this model, Ayarza et al. (2005) infer crustal-scale thrusting affecting the Moho and penetrating into the mantle. This interpretation differs from previous ones based on seismic refraction and magnetotelluric data (Wigger et al., 1992; Giese and Jacobshagen, 1992) in which the thrusts were rooted at intracrustal detachment level below the Middle and High Atlas, and all the shortening is transferred to the Rif Chain in northern Morocco. All prior studies indicate that below the High Atlas there is no detectable crustal root, and therefore all models require a buoyancy contribution from subcrustal levels to support the topography of the Atlas mountains. The Anti-Atlas region has been impacted by the Pan-African, Hercynian and Alpine orogenies, although the later two only affected it mildly. A slightly folded late Precambrian–Paleozoic sedimentary succession covers Precambrian crystalline basement in the area, which includes ancient subduction zones, marginal basins, magmatic arcs and rift margins juxtaposed on the Eburnian-aged (ca. 2 Ga) West African Craton (Villeneuve and Cornée, 1994; Ennih and Liegeois, 2001). Geophysical data at crustal scale in the Anti-Atlas are scarce and

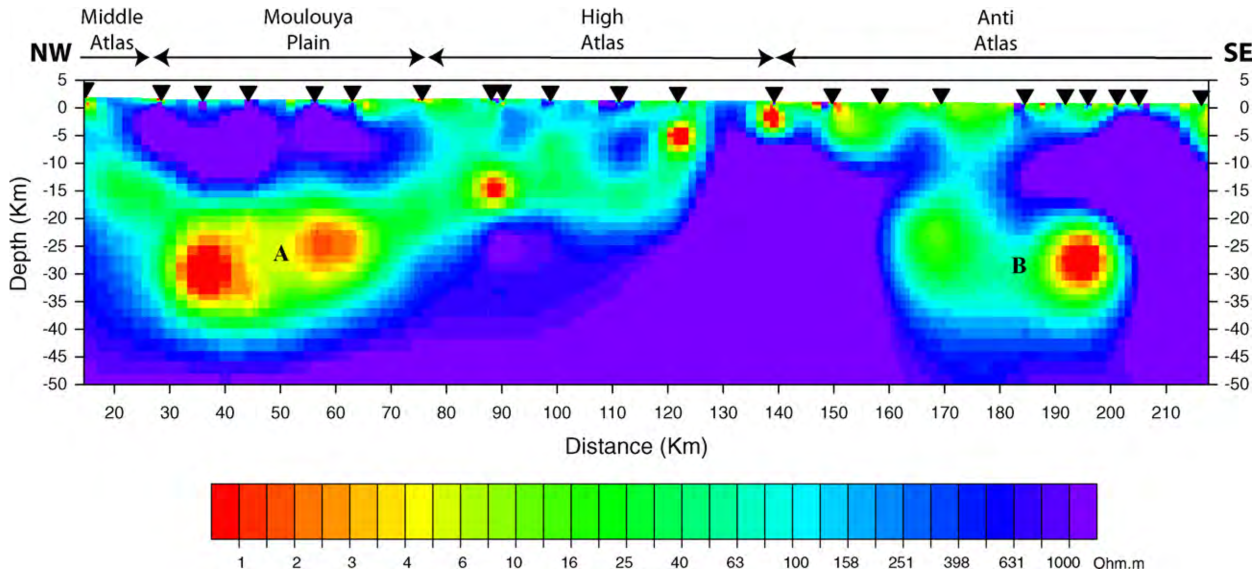

Fig. 2. Two-dimensional MT resistivity model obtained by inversion using both TE and TM mode resistivity and phases.

only gravity data (Bayer and Lesquer, 1978) and a seismic refraction profile (Wigger et al., 1992) have been reported.

In this paper we will present and describe a preliminary interpretation of the results of new magnetotelluric data acquired along a profile crossing the High Atlas and the eastern Anti-Atlas that allows defining its electrical crustal structure in finer detail than before. Previous MT data models were based on stitched 1D inversions or in 2D using only the MT phases and induction vector data following a forward trial-and-error approach (Schwarz et al., 1992). Also, none of the modern analysis tools were applied to them. Therefore the overall geoelectrical structure is only partly resolved. From north to south, our new profile (Fig. 1) starts in the Middle Atlas north of the South Middle Atlas Fault (ASMA) crossing the tabular Moulouya plain by Midelt, which is characterized by a reduced Mesozoic and Neogene succession in which a metamorphic and granitic basement outcrops occasionally. The High Atlas is a doubly vergent fold and thrust belt characterized by narrow deformation zones (anticlines and thrust faults) separated by wide synclines and tabular plateaux. Anticlines are tight and form calcareous ridges of Liassic limestones and dolomites separated by open synclines occupied by Upper Lias-Dogger shales. The northern border of the High Atlas is dominated by a north-vergent thrust, the frontal zone of which overrides the Moulouya plain (North High Atlas Front). In the middle part of the section there is large anticlinorium defined by Liassic limestones. This anticlinorium is followed to the south by the Kerrando syncline, a high amplitude structure that contains the thickest Jurassic succession of the transect and is bounded to the south by the Foum Zabel Thrust. The southern part of the High Atlas has again a tabular structure, disrupted by spaced thrust faults. The South High Atlas Front (SHAF) is a south-vergent thrust that overrides a Mesozoic/Cenozoic Plateau. The southernmost MT sites are located on Paleozoic outcrops of the Eastern Anti-Atlas system.

2. Magnetotelluric data

The magnetotelluric method (MT) involves measuring the temporal fluctuations of the horizontal components of the natural electromagnetic field at the Earth's surface to infer the lateral and vertical variations of electrical conductivity of the Earth's interior (see review papers on MTNet – www.mtnet.info). In autumn, 2009 broadband magnetotelluric (BBMT) data were recorded at 22 stations (Fig. 1), from the Middle Atlas to the Anti-Atlas crossing the High Atlas, as a part of the TopoMed Coordinated Research Project within the TOPO-EUROPE EUROCORES (http://www.esf.org/activities/eurocores/running-programmes/topo-europe.html). Remote reference was used to derived MT and geomagnetic transfer function responses in the period range from 0.001 s to 10,000 s, although in this work we are only focused the responses between 0.001 s and 1000 s, as these are the periods sensitive to crustal resistivity variations (Fig. 1 of supplementary material shows the apparent resistivity and phases curves for the soundings). Moreover, due to the middle-low quality of the tipper data it was not included in the inversion procedure. The total length of the profile (Fig. 1) is 220 km with an average site spacing of 10 km.

To retrieve the strike of the regional structures and the regional impedance tensor, we applied the distortion decomposition method of Groom and Bailey (1989, GB) following the scheme of McNeice and Jones (2001). Fig. 1 displays the strike directions estimated from the MT impedance tensors at each site for the period band of 0.001–1000 s. The individual site estimates of strike are weighted by the error misfit to the GB distortion model; misfits with an RMS less than 2.0 are considered reliable, whereas larger misfits are indicative of three-dimensional (3D) effects or of errors that are too small. In general, most sites display a misfit to the distortion model of below 2, so a 2D model is valid and appropriate. The best-fit average multi-site, multi-frequency GB regional strike is N50°E, which is consistent with the strike of the main surface geological structures.

Simultaneous 2D regularized inversions of the TM and TE apparent resistivities and phases were undertaken using the algorithm of Rodi and Mackie (2001). This algorithm simultaneously searches for the model which trades off the lowest overall RMS misfit with the smallest lateral and vertical conductivity gradients in a regularized manner, following the approach pioneered for MT data by Constable et al. (1987). On average, we fit the logarithm of the apparent resistivity data to within 5%, and the phases to within 1.4°. This is a remarkably good level of model fit that few MT data models are able to achieve. During the inversions, neither structural features nor conductivity discontinuities were imposed, and the start model was a uniform half space. The resulting final model, is shown in Fig. 2. Fig. 3A and B compares the phase pseudosections of the data and model responses. We focus on comparing phases given the notorious nature of static shifts in the apparent resistivity curves (e.g., Jones, 1988). As is evident in Fig. 3, the residuals between the observed data and the model responses are random,

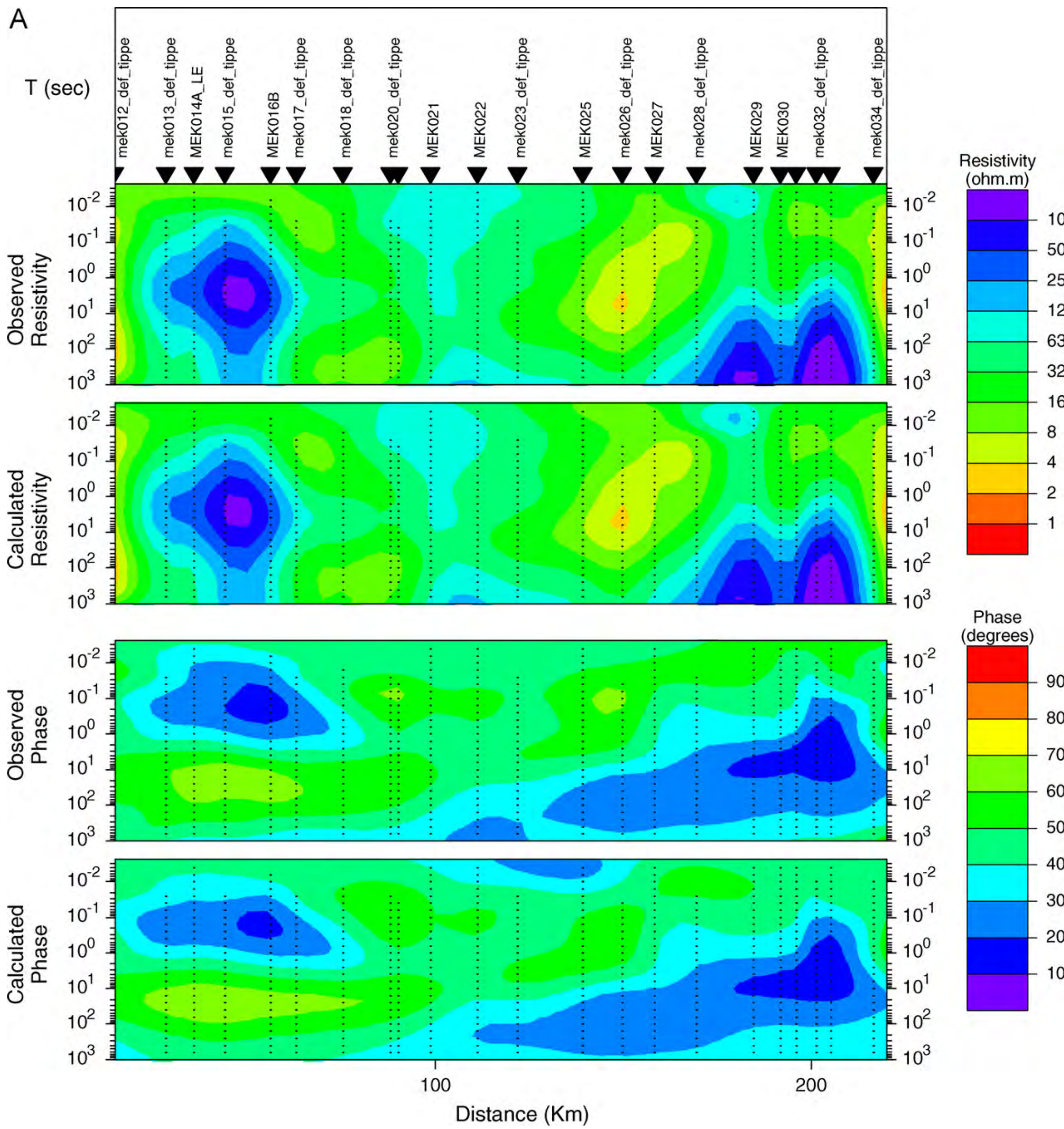

Fig. 3. Comparison of apparent resistivity and phases of (A) TM mode and (B) TE mode for the observed and model responses.

and no strong feature in the data is unexplained. Fig. 4 shows a tectonic interpretation of the resistivity model and is discussed in the following sections.

3. Interpretation and discussion

3.1. Upper crust

The three units crossed by the magnetotelluric profile (Moulouya plain, High Atlas and Anti-Atlas) show different and distinct geoelectrical crustal signatures. At and close to the surface, all units have resistivity values below 100 Ω m that can be associated to late Precambrian to tertiary sedimentary deposits of varying thickness. The Moulouya plain upper crust shows high resistivity values that can be due to the lack of important thrusting systems. Low resistivity values are imaged in the upper crust below the High Atlas. The High Atlas is the zone that has accumulated the greatest tectonic shortening, and the structure is interpreted to be dominated by thick-skinned thrusting and folding. The low resistivity values in the upper crust are likely associated with Jurassic basin sequences and thrust fault systems of crustal-scale NHAF and SHAF (Figs. 1 and 4). In the Anti-Atlas, thick deposits of Paleozoic sedimentary rocks, that can reach up to 4 km depth (Robert-Charue, 2006), may be responsible for the resistivity values observed in the upper kilometres of the crust.

3.2. Lower crust

Two large scale conductive units are imaged in the lower crust beneath the profile (labeled A and B in Fig. 2). Geophysically, the crust below the Moulouya plain shows a minimum in the Bouguer anomaly (see Fig. 4), attributed to an offset crustal root of the

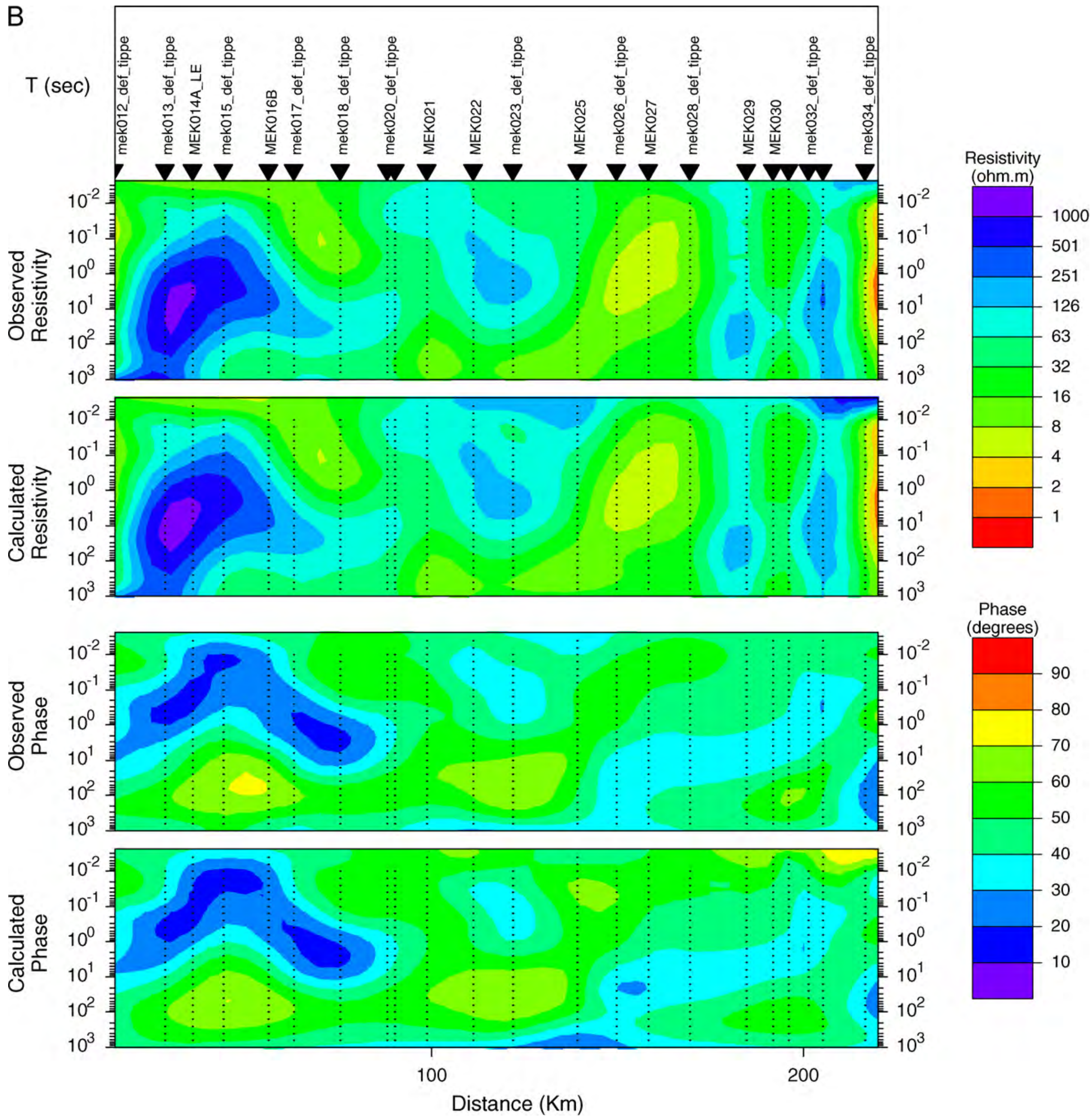

Fig. 3. (*Continued*)

High Atlas (Ayarza et al., 2005), fewer earthquakes than the adjacent Middle and High Atlas (Peláez et al., 2007) and a low velocity anomaly at lower crustal levels (Calvert et al., 2000). To the north, this feature is limited by the North Middle Atlas Fault (ANMA in Fig. 4). Moreover, the Moulouya Plain and especially the Middle Atlas to the north host large Neogene-Quaternary intraplate alkaline volcanic fields. These features coincide with a marked lithospheric thinning that has been modelled with potential fields (Teixell et al., 2005; Zeyen et al., 2005; Fullea et al., 2007), and has been associated either to Canary mantle plume flow beneath Africa (Duggen et al., 2009, 2010) or to the interplay between the Alpine contractional structures and the thermal erosion of the lithosphere (Berger et al., 2009). In either case, all authors agree that the velocity anomalies originate by low degree partial melting of sublithospheric mantle sources (Raffone et al., 2009; Duggen et al., 2009; Bouabdellah et al., 2010; El Azzouzi et al., 2010). The amount of partial melting necessary to explain the electrical resistivity observed in structure A (2–5 Ω m) is between 2% and 8% according to the Modified Brick Layer Model (MBLM) suggested by (Partzsch et al. (2000). Another area in which high elevations are being supported dynamically by hot asthenosphere (Keskin, 2003) is in Eastern Anatolia (Arabia–Eurasia collision zone). An MT study there (Türkoğlu et al., 2008) found a low resistivity structure at lower crustal depths below a Neogene intraplate volcanism zone of mantle origin (Notsu et al., 1995) that was interpreted as accumulations of magma.

The Precambrian accretion of the Anti-Atlas to the West African super Continent (WAC) was a four stage event, involving early extension, subduction, moderate collision and late extension. Two main events during Pan African orogeny may be the cause of the resistivity anomaly observed: (i) a relic of a subduction process or (ii) deep mineralization associated to magmatism. Ennih and Liegeois (2001) suggested that the Anti-Atlas consists of Precam-

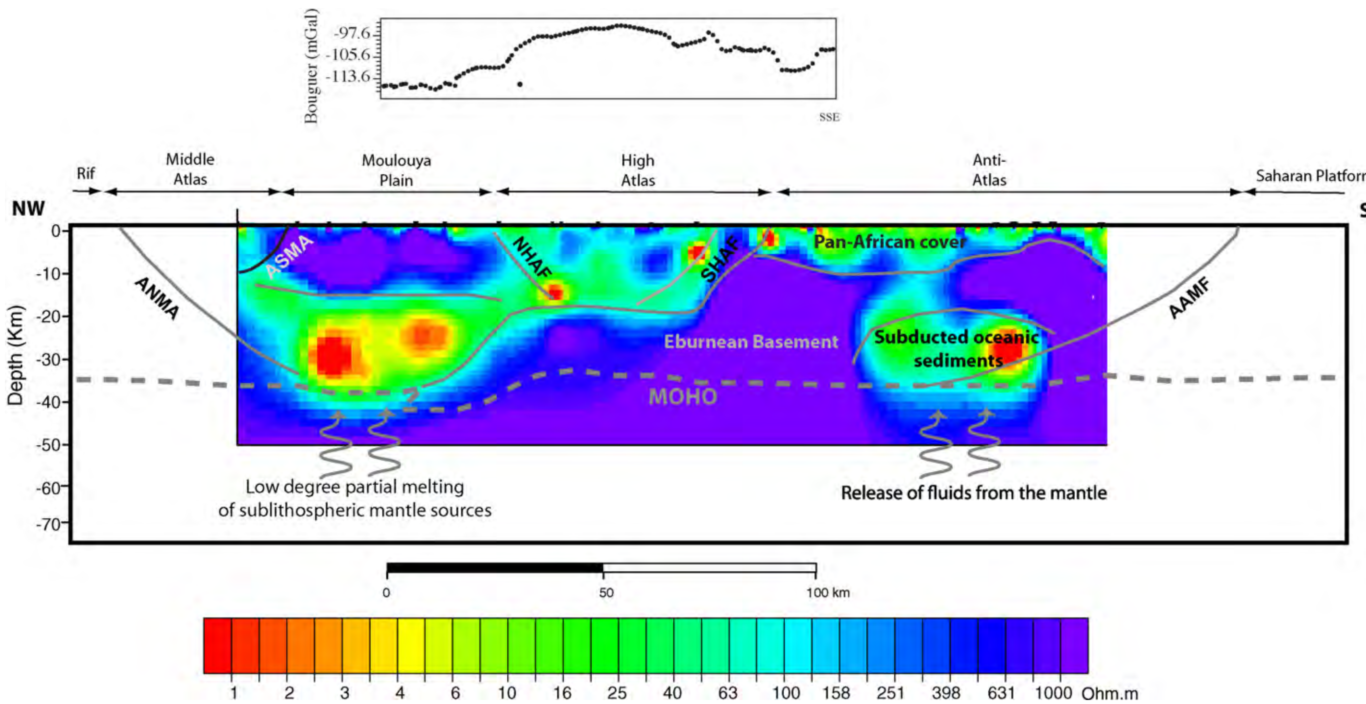

Fig. 4. Tectonic interpretation of resistivity model. ANMA: North Middle Atlas Fault; ASMA: South Middle Atlas Fault; NHAF: North High Atlas Front; SHAF: South High Atlas Front; AAMF: Anti-Atlas Major Fault.
The Moho depth and the Bouguer anomaly are based on Ayarza et al. (2005).

brian crystalline basement that collided at approximately 685 Ma with an oceanic crust, preserved in the Bou Azzer ophiolite assemblage (Le Blanc, 1976). The low resistivity structure could be associated to relic subducted oceanic sediments, as is the case for one of the longest conductivity anomalies known on the globe, namely the Trans-Hudson orogen (Jones et al., 2005). On the other hand, the Anti-Atlas was affected at the end of the Pan-African orogeny (ca 585–560 Ma) by high-K calc-alkaline and alkaline magmatism, and also the Proterozoic inliers in the Anti-Atlas are highly mineralized, among them the Imiter deposit which is one of the largest silver deposits in the world (Levresse et al., 2004). The subduction-related calc-alkaline magmatism was associated with large-scale base metal and gold mineralization. Metallogenic activity was greatest during the final extensional stage, at the Precambrian–Cambrian boundary and is characterized by world-class precious metal deposits, base-metal porphyry and SEDEX type occurrence (Gasquet et al., 2005). The geochemical characteristics of the Imiter Ag deposit and other metal accumulations in the Anti-Atlas were formed by fluids of essentially mantle origin, accompanied by SO_2 degassing producing sulphides (Levresse et al., 2004; Gasquet et al., 2005). All of these metallic bodies will be highly conducting. Low resistivity anomalies localized in the lower crust have been associated elsewhere to precipitated minerals during the release of fluids from the mantle (Heinson et al., 2006; Jones and Garcia, 2006).

4. Conclusions

The thick-skinned tectonic model for the High Atlas, dominated by inversion of Mesozoic extensional faults and buckling of both pre-Mesozoic basement and its sedimentary cover, is consistent with the low resistivity values observed in the upper crust. Sedimentary sequences in the Moulouya Plain and in the Anti-Atlas correlate with low resistivity structures. At deeper levels, the electrical resistivity model across the central Atlas in Morocco reveals two major resistivity anomalies at lower crustal depths. The first one, below the Moulouya plain, we interpret as due to the presence of small amounts of partial melt in the Atlas crustal root, the consequence of either the Canary mantle plume flow (Duggen et al., 2009) or thermal erosion of a metasomatized lithosphere (Berger et al., 2009). The anomaly found below the Anti-Atlas could be due to either ancient subduction of oceanic sediments or to minerals precipitated from fluids released from the mantle during the Precambrian accretion of the Anti-Atlas to the West African super continent.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.pepi.2011.01.008.

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