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Deep resistivity cross section of the intraplate Atlas Mountains (NW Africa): New evidence of anomalous mantle and related Quaternary volcanism

Farida Anahnah,¹ Jesus Galindo-Zaldívar,^{1,2} Ahmed Chalouan,³ Antonio Pedrera,⁴ Patricia Ruano,¹ Jaume Pous,⁵ Wiebke Heise,⁶ Ana Ruiz-Constan,⁷ Mohamed Benmakhlouf,⁸ Angel Carlos López-Garrido,² M'Fedal Ahmamou,³ Carlos Sanz de Galdeano,² Jorge Arzate,⁹ Pedro Ibarra,⁴ Lourdes González-Castillo,¹ Naoual Bouregba,³ Fernando Corbo,⁹ and Eva Asensio⁵

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[1] The Atlas Mountains are characterized by high elevations and Quaternary volcanism. Long period magnetotelluric data acquired along a NNW-SSE transect reveal the presence of a conductive anomalous mantle below the High Atlas. Data dimensionality analyses show a preferent N80°E strike of the deep resistivity structure in agreement with the induction vector alignment at long periods. Accordingly, a 2D inversion of the data set was carried out. Large resistive bodies at the crustal basement most likely correspond to batholiths emplaced in more conductive metapelites. They are covered by outcropping conductive sedimentary detritic and carbonate rocks. Lithospheric thinning producing anomalous mantle and basin development in the Atlas probably started during Triassic-Jurassic rifting. Inversion tectonics since the Oligocene produced low shortening on previous lithospheric weak zones, with thrusting of the Atlas above the stable African plate. Melting at the top of the anomalous mantle is connected with Quaternary basaltic volcanism in the Middle Atlas.

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1. Introduction

[2] The mechanisms involved in the development of mountain belts determine the main features of the mountain roots. Crustal thickness and the nature of the lithospheric and sublithospheric mantles strongly influence their relief [Jackson *et al.*, 2004]. Therefore, seismic and gravity techniques are the classic methods used to determine such features. Yet deep resistivity studies based on long period magnetotelluric (MT) sounding have also proven useful in mantle studies, since they are sensitive to

thermal anomalies detected as conductors [e.g., Matsuno *et al.*, 2010; Miensoopust *et al.*, 2011]. Measured natural electrical and magnetic fields are converted to apparent resistivity based on Maxwell's theory with quasi-stationary approximation [Tikhonov, 1950; Cagniard, 1953].

[3] Most cordilleras are formed by convergence along plate boundaries and have related crustal and lithospheric thickening. The Atlas (Figure 1) is a prominent African intraplate mountain range [Mattauer *et al.*, 1977] near the boundary of the Eurasian plate. It is bounded to the northwest by the stable Meseta and the Gharb-Saïss foreland basin that constitute the southern boundary of the Rif Cordillera. To the SE, the Atlas is bounded by the Anti-Atlas Mountains, whose Precambrian rocks represent the stable African plate.

[4] As seen in Figure 1, the Atlas is formed by linear branches, the High and Middle Atlas, with respective ENE-WSW and NE-SW orientations. It corresponds to a Mesozoic inverted basin filled with Triassic to Jurassic rifting and Cretaceous postrif sediments [Mattauer *et al.*, 1977; Beauchamp *et al.*, 1999; Frizon de Lamotte *et al.*, 2000; Gomez *et al.*, 2000; Teixell *et al.*, 2003; Arboleya *et al.*, 2004]. The basin was uplifted after late Cenozoic [Babault *et al.*, 2008] and inversion tectonics that would have started in the Middle-Late Eocene [Frizon de Lamotte *et al.*, 2000] or Oligocene [Teixell *et al.*, 2007] through changes in the relative plate motion

¹Departamento de Geodinámica, Universidad de Granada, Granada, Spain.

²IACT, CSIC, Universidad de Granada, Granada, Spain.

³Département de Géologie, Université Mohammed V-Agdal, Rabat, Morocco.

⁴Instituto Geológico y Minero de España, Madrid, Spain.

⁵Departament de Geodinàmica i Geofísica, Universitat de Barcelona, Barcelona, Spain.

⁶GNS Science, Lower Hutt, New Zealand.

⁷Université Montpellier 2, Montpellier, France.

⁸Département de Géologie, Université Abdelmalek Esaadi, Tetuán, Morocco.

⁹Centro de Geociencias, UNAM, Queretaro, Mexico.

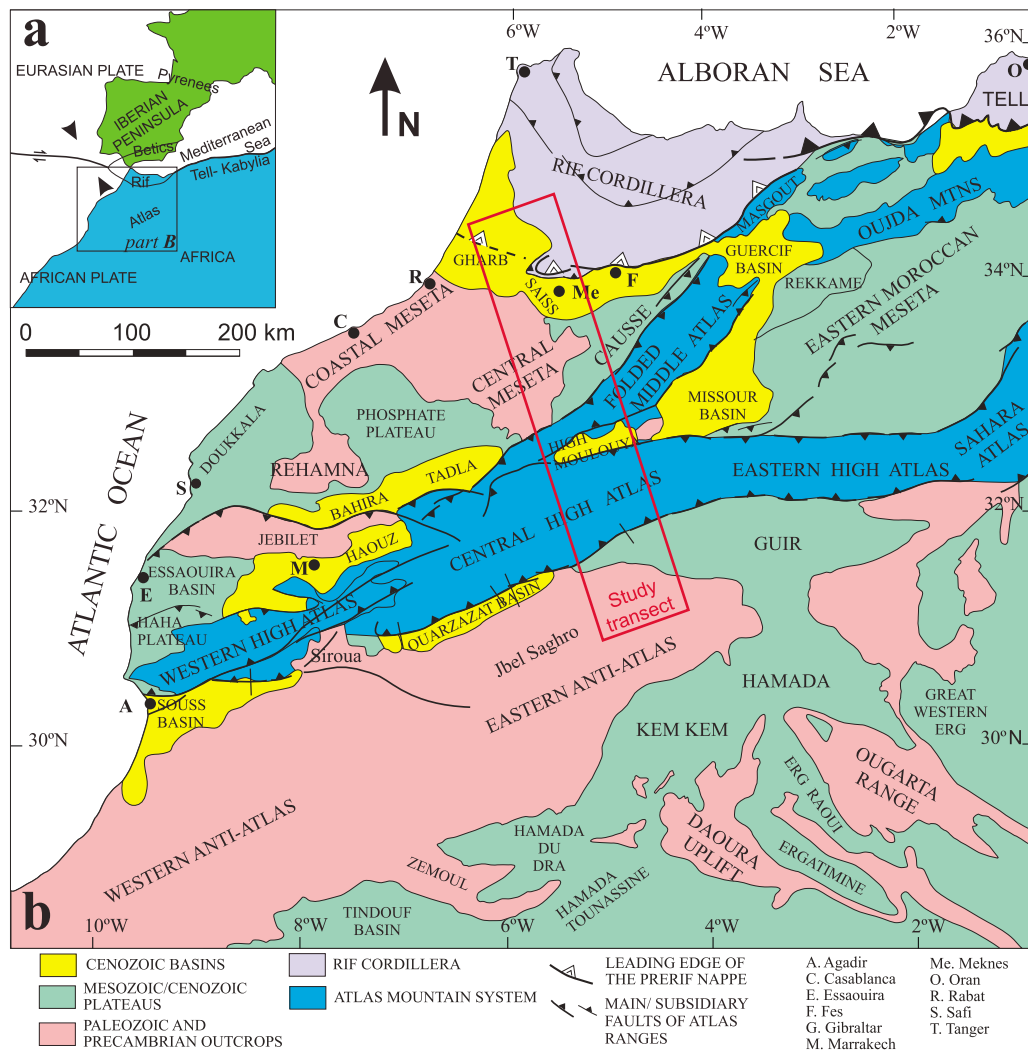


Figure 1. Geological setting of the Atlas System. (a) Eurasian-African plate boundary in the western Mediterranean. (b) Structural map of Northwestern Africa including the position of the study transect.

toward NW-SE convergence in the western Mediterranean [Rosenbaum et al., 2002]. This setting continues at Present, as revealed by shallow and intermediate (<150 km depth) earthquakes [Ramdani, 1998]. The Atlas may be considered as a narrow deformable zone bounded by rigid blocks inherited from the Mesozoic rifting [Gomez et al., 2000].

[5] The High Atlas is a double vergence orogen with elevations reaching over 4000 m, higher than the alpine Betic-Rif Belt. Yet the shortening determined by geological (<24%) [Teixell et al., 2003, 2007] and present-day GPS studies [Vernant et al., 2010] is very limited. In addition, crustal thickness as revealed by seismic refraction data [Makris et al., 1985; Wigger et al., 1992] is moderate (<40 km) for the observed reliefs [Teixell et al., 2003; Babault et al., 2008].

[6] MT research studies [Schwarz et al., 1992; Ledo et al., 2011] suggest the presence of shallow and intermediate crustal conductors beneath the Atlas related to basaltic volcanism. The presence of xenoliths in basalts indicates a rejuvenated mantle lithosphere below the Atlas [Raffone et al., 2009]. However, heat flow is relatively low [Rimi et al., 1998].

[7] This setting has attracted many seismological [Seber et al., 1996; El-Harfi et al., 2007], gravity [Van den

Bosch, 1971; Ayarza et al., 2005] or integrated modeling researchers [Zeyen et al. 2005; Teixell et al., 2005; Missenard et al., 2006], with new data acquired as recently as 2010 [e.g., Kiyani et al., 2010]. The High Atlas relief features are related to an anomalous mantle in addition to moderate shortening. The origin of this anomalous mantle is a matter of debate, with proposed models involving mantle delamination [Ramdani, 1998] or mantle plumes [Zeyen et al., 2005; Teixell et al., 2007, Duggen et al., 2009] contributing to discussion of the origin of this mountain chain [Berger et al., 2010].

[8] The aim of the present study is to constrain the electrical resistivity of the lithosphere beneath the Atlas Mountains, so as to better define the main features of their root and shed light on their origin and Quaternary basaltic volcanism.

2. Acquisition and Processing of Magnetotelluric Data

[9] A NNW-SSE oriented MT profile (Figures 1 and 2) 380 km in length, including 21 stations of long period and broad band magnetotelluric soundings, was obtained in

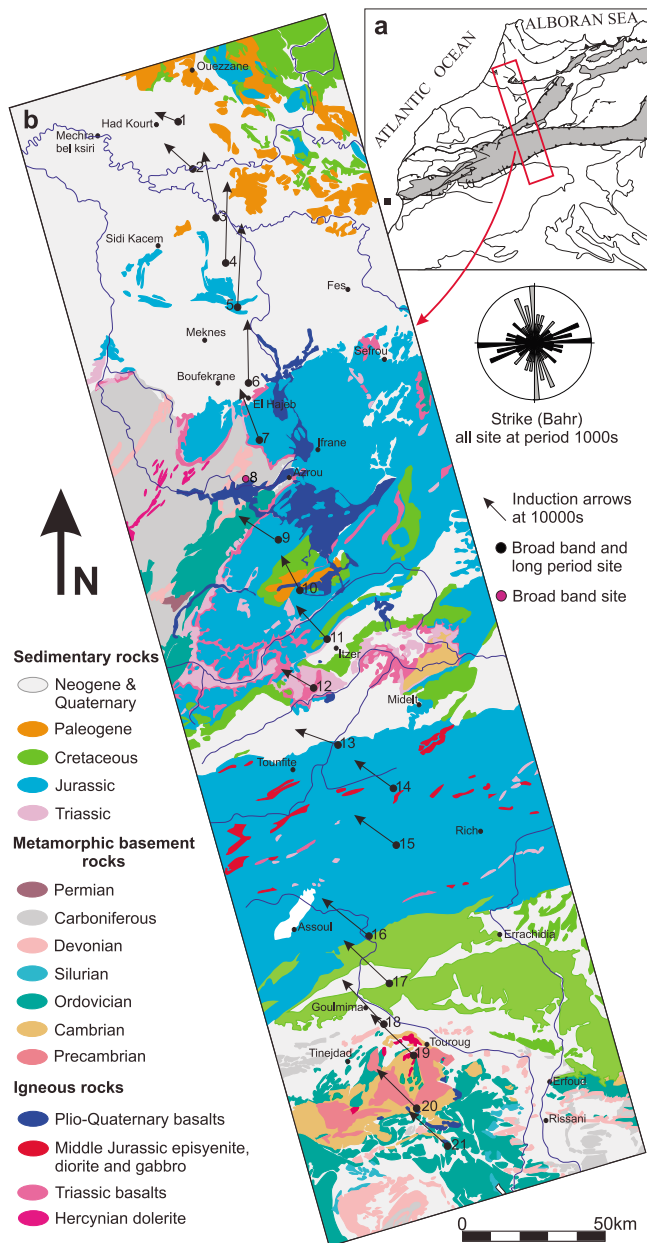


Figure 2. Geological map of the Atlas Mountains cross section. a, general setting. b, detailed map including MT sounding position, induction arrows obtained at period 10000 s and geoelectrical strike using Bahr method [Bahr, 1988, 1991] for all sites at period 1000 s, indicating a very consistent ENE-WSW direction with a conjugate orthogonal maximum.

central Morocco during May–July 2009. The profile runs from the front of the Rif Mountains, across the Saïss foreland basin, the Middle and High Atlas, to the Anti-Atlas. Spacing between sites was from 10 to 30 km. We selected this distance because the profile was aimed at the deep structure, at the expense of losing detail in the shallow crust. In acquiring data, we used long period (LEMI 417) instruments for 15 days, followed by broad band (ADU07) tools for 5 to 8 h for the lower period records, obtaining a total period range between 0.0001 s and 20.000 s.

[10] The time series data acquired were processed using the algorithm of *Egbert and Booker* [1986] for broad band data and a robust data code [Varentsov, 2007] for long period data in order to obtain transfer functions, apparent resistivities, phases and tipper. In general the data were of fairly good quality, but noisy site 8 had to be discarded for interpretation.

[11] Dimensionality analysis of the resistivity structure was done using the Bahr’s phase sensitive strike [Bahr, 1988] of Figure 2 and the phase tensor analysis [Caldwell *et al.*, 2004] shown in Figure 3. The phase tensor can be represented as an ellipse with the principal axes (Φ_{\max} and Φ_{\min} , respectively) showing the major and minor axes of the tensor. In a 2D case, the orientation of the phase tensor gives the strike direction, while in 3D it indicates the direction of the largest resistivity gradient. The phase tensor is independent of galvanic distortion that is caused by near surface non-homogeneities. It therefore allows for identification of the strike direction and provides a method to visualize the major features of the conductivity structure. Figure 3 shows a phase tensor section for the long period data (10–10000 s). Although there are 3D effects visible in the data set, a preferred strike approximately E-W could be determined from the phase tensor directions at all sites and periods from 10 to 10000 s. The Bahr’s phase sensitive strike is shown for all sites at 1000 s in Figure 2, confirming a strike of N80°E. Both methods showed largely the same general 2D resistivity structure, which is in agreement with the orientation of the induction arrows at long periods (Figure 2, vectors drawn in Parkinson convention). The 90° ambiguity inherent to strike determination was resolved with the induction arrows, which point toward the high-conductivity zones and are orthogonal to the geoelectric strike, with a magnitude directly proportional to the lateral resistivity gradients. Induction arrows at mantle depths (Figure 2) point consistently toward the NNW and are roughly constant, suggesting that the regional conductivity structure strikes approximately ENE-WSW, orthogonal to the profile. Thus a preferred direction for the strike was determined to be N80°E. Accordingly, the impedance tensor was rotated -10° and a 2D joint inversion of apparent resistivities and phases and the longest periods (100 s to 20000 s) of the tipper (Figure 4) was carried out using the inversion code of *Rodi and Mackie* [2001]. The model obtained has an RMS of 5.3 applying an error floor of 10% for apparent resistivities, 5% for the phases and 0.08 for the tipper. In some sites the static shift was corrected as part of the inversion process. Figure 4 shows examples of data and model responses of some representative sites that correspond to different geological domains. The resolution is acceptable above 100 km depth. This was tested by changing the resistivity of different parts of the model, which consistently resulted in a greater misfit between data and model responses.

3. Deep Structure and Resistivity of the Atlas Profile

[12] The resistivity profile (Figure 4) shows a shallow highly heterogeneous crust above a deep and more homogeneous zone corresponding to the upper mantle. Magnetotelluric research does not have the resolution of other geophysical methods [e.g., *Makris et al.*, 1985; *Wigger et al.*,

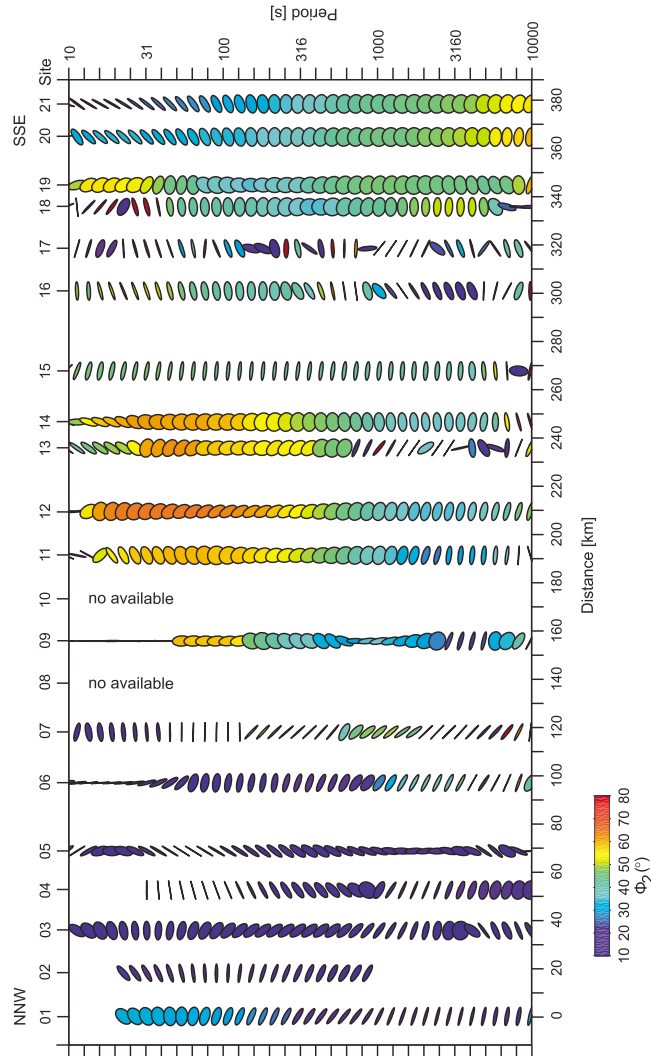


Figure 3. Phase-tensor ellipse pseudo-section for the Atlas profile. The color used to fill the ellipses shows the geometric mean of the maximum and minimum phase, while high values of Φ_2 indicate increasing conductivity with depth. The main orientation of the major ellipse axes is roughly NW-SE. In this setting, a two-dimensional inversion (2D) of the profile data provides reasonable results.

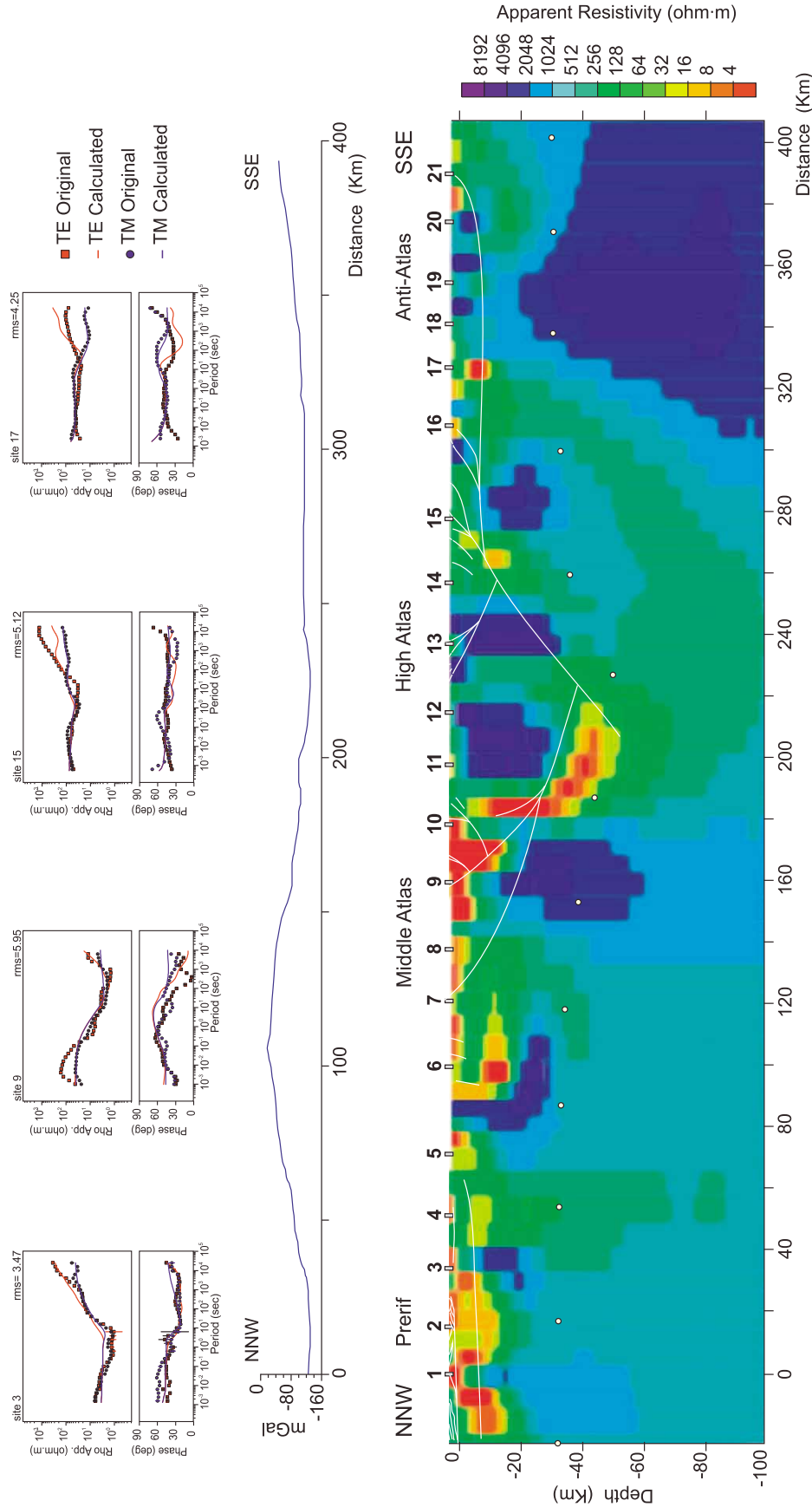


Figure 4. Magnetotelluric 2D inversion and Bouguer gravity profile across the Atlas Mountains. (bottom) Magnetotelluric resistivity model. White dots represent the approximate location of the Moho discontinuity in view of previous research [Arboleya et al., 2004; Ayarza et al., 2005] and roughly separate the crust characterized by variable resistivities and the more homogeneous upper mantle. White lines represent the main geological contacts. (top) Selected MT sites in different geological domains including observed and calculated phase and resistivities. (middle) Bouguer anomaly profile (data from map of Van den Bosch [1971]).

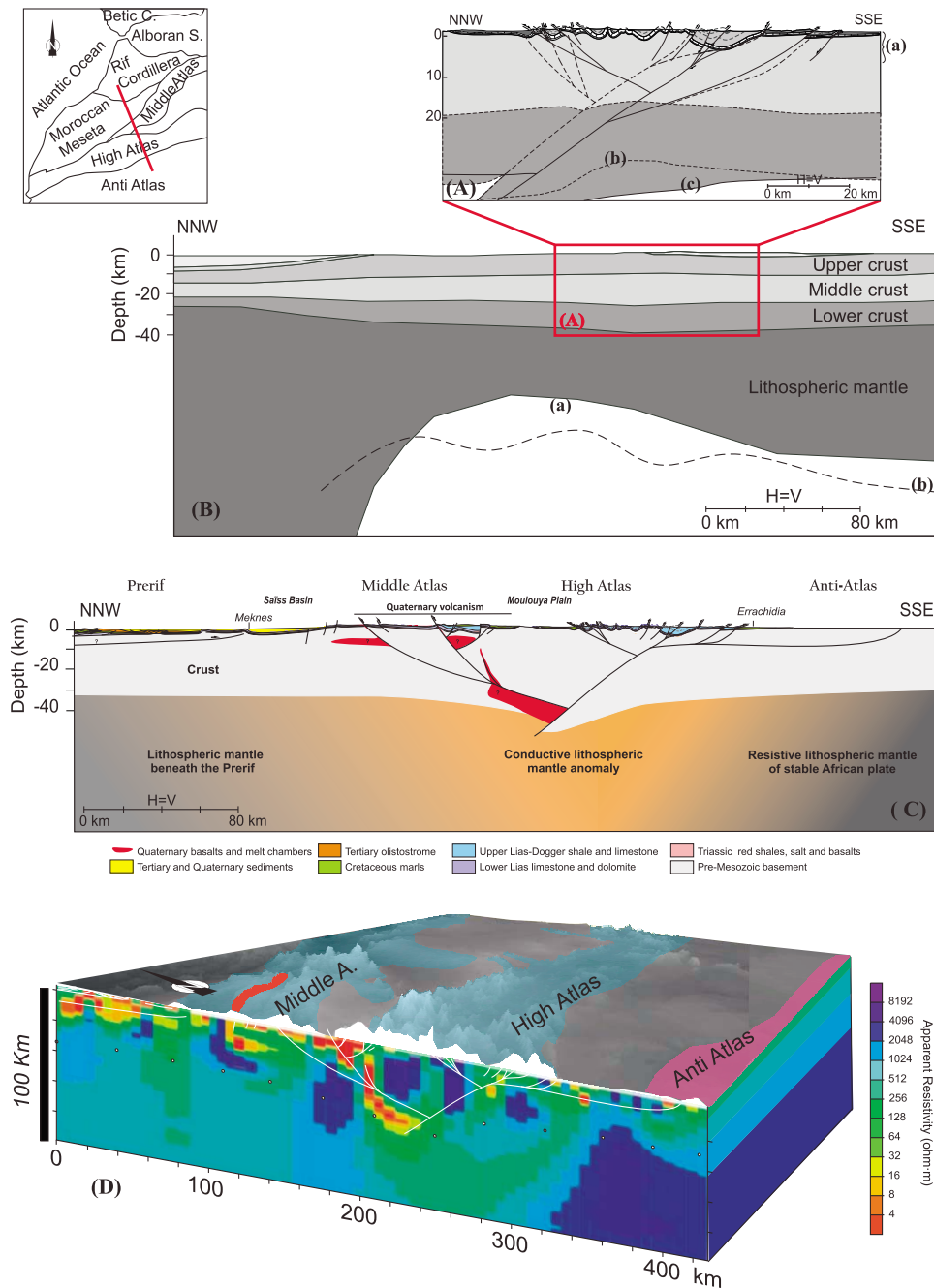


Figure 5. Comparison of previous crustal and upper mantle models across the Atlas Mountains and model proposed on the basis of new magnetotelluric data. (A) Detailed crustal structure of the High Atlas from: (a) Geological data [Teixell et al., 2003], (b) gravity data [Ayarza et al., 2005] and (c) integrating gravity and seismic data [Makris et al., 1985; Wigger et al., 1992; Arboleya et al., 2004]. (B) Lithospheric structure of the transect after (a) Zeyen et al. [2005] and (b) lithospheric-asthenospheric boundary proposed by Fullea et al. [2007]. (C) Geological transect across the Atlas Mountains integrating the new magnetotelluric and the previous geological [Teixell et al., 2003, Arboleya et al., 2004] and geophysical data [Arboleya et al., 2004 and Ayarza et al., 2005]. (D) Present-day crustal and mantle structure from MT data.

1992; Ayarza et al., 2005] necessary to accurately determine the Moho depth. However, the boundary between the uppermost heterogeneous and the deep and more homogeneous resistivity areas could be located at roughly 30–40 km depth, which is the Moho depth calculated by other studies

(Figure 5) [Arboleya et al., 2004; Ayarza et al., 2005; Zeyen et al., 2005; Fullea et al., 2007].

[13] Upper mantle resistivity is very high in the stable craton of the Anti-Atlas Mountains and extends northward deep below the southern border of the High Atlas. In con-

trast, the mantle below the High Atlas shows the highest conductivity values, reaching 32 ohm.m in some areas, and extending northward up as far as the southern Middle Atlas. Between sites 8 and 10, a not fully constrained resistive body constitutes the boundary with the northern part of the profile, characterized mainly by intermediate resistivities (≈ 500 to 1000 ohm.m). Figure 3 shows a section of phase tensors along the profile. Elevated Φ_2 values below the High Atlas indicate the presence of a conductive body, in contrast to what is observed in the Middle Atlas.

[14] The middle and lower crust along the profile (approximately 15 to 35 km in depth) can be generally characterized by an alternance of high resistivity bodies (reaching more than 8000 ohm.m) that are tens of kilometers long and have intermediate conductivities (60 to 500 ohm.m). Remarkable, however, is the presence of a highly conductive body reaching 4 to 8 ohm.m that is located at the top of the mantle along the boundary between the High and Middle Atlas (sites 10–12, Figure 4), and extends up to the surface in the Middle Atlas. Moreover, shallow crustal levels show a very heterogeneous resistive nature, determined in general by wide and thin conductive bodies in the northern part of the profile, and intermediate to resistive bodies in the southern part.

[15] The Bouguer Anomaly profile (Figure 4), calculated from the Gravity Map of Morocco [Van den Bosch, 1971], shows negative values corresponding to continental crustal areas. Minima of -130 mGal are located in the High Atlas and Prerif, with nearby relative maxima reaching -15 mGal in the Middle Atlas and -45 mGal in the Anti-Atlas.

4. Discussion

[16] The magnetotelluric data obtained along a NNW-SSE transect across the Atlas (Figures 2 and 4) contribute to discussion of the origin of this intraplate cordillera. Its uncommon features (low shortening, high relief, absence of basement outcrops and Quaternary volcanism) make this mountain chain very attractive to diverse petrological and geophysical researchers.

[17] The 2D MT inversion is a suitable approximation in view of the elongated tectonic features of the Atlas. The profile is roughly orthogonal to the geoelectrical strike, as confirmed by the NNW orientation of induction arrows at long periods (Figure 2) corresponding to deep levels. Although they may be related to a conductive body at the northern extremity of the profile, the induction arrow modulus remains constant, thus supporting an upper mantle anisotropy.

[18] Moho depth is known from seismic and gravity data [Makris et al., 1985; Wigger et al., 1992; Arboleya et al., 2004; Ayarza et al., 2005]. Integrated quantitative modeling of available seismic, gravity and topography data [Zeyen et al., 2005; Fullea et al., 2007] would further support a moderate crustal thickening in the region and an uprising of the asthenosphere, although the proposed geometry is different in detail for each type of research (Figure 5). Thus, the new MT data given in Figure 4 allow us to more precisely delimit the deep geometry of the region, quantifying a different physical property than the methodologies previously used in the region.

[19] The mantle is heterogeneous and shows remarkable anomalies, with low resistivities below the High Atlas and

the southern Middle Atlas, also confirmed by high Φ_2 values (Figures 3 and 4), in contrast with the highly resistive mantle below the stable Anti-Atlas. Low resistivities in the homogenous mantle rocks are probably a consequence of Fe-enrichment favored by melt migration and deformation at the lithospheric mantle, as suggested by petrological studies in xenoliths of Quaternary basalts [Raffone et al., 2009]. These results are in agreement with previous seismicity [Ramdani, 1998], gravity [Ayarza et al., 2005] and integrated modeling research findings [Teixell et al., 2005; Zeyen et al. 2005; Missenard et al., 2006], pointing to the presence of low densities and low seismic propagation velocities below the Atlas, and suggesting asthenospheric uplift (Figure 5). The Bouguer anomaly minimum in the High Atlas (Figure 4) is a consequence of the moderate crustal thickening and a probable low lithospheric density [Ayarza et al., 2005]. In contrast, the Anti-Atlas and Middle Atlas are characterized by relative maxima corresponding to more stable basements. The low Bouguer anomaly values in the Prerif would be a consequence of the thick sedimentary cover.

[20] All these data support the presence of an anomalous mantle below the Atlas which formed as a consequence of the tectonic evolution that took place in the region. Several origins have been proposed for this anomalous mantle, including delamination [Ramdani, 1998] and the presence of elongated mantle plumes [Zeyen et al., 2005; Duggen et al., 2009]. Another alternative hypothesis is the progressive development of the anomalous mantle initiated during the extensional Triassic to Jurassic rifting [Mattauer et al., 1977], when a narrow deformable zone occurred between rigid crustal blocks [Gomez et al., 2000]. Later transcurrent and final compressional deformations, resulting from the relative Eurasian-African plate motion [Rosenbaum et al., 2002] may have led to the present-day emplacement of the anomalous mantle.

[21] Several questions remain unsolved in the proposed models. The presence of delamination during the orogenic wedge development implies the sinking in the mantle of a dense body that has not been imaged by any geophysical method to date. Moreover, this model implies extensional tectonics that does not agree with the late uplift and moderate shortening of the Atlas. In the context of the mantle plume hypothesis, the mechanisms causing the coincidence at narrow bands of recent mantle plumes with previous elongated Mesozoic extensional basin are not explained. Moreover a variable age of the volcanism along the Atlas Mountains should be expected, but the propagation of the mantle plume is not clearly observed. Finally, if the anomalous mantle originated in the Mesozoic weakness zone between rigid blocks, the resulting thermal anomaly did not reach the upper crust for a very long period (less than 100 Ma). In any case, the origin of the anomalous mantle remains controversial, but the new deep resistivity profile show that the last stage of the evolution of the weak High Atlas Lithosphere entailed concentrated deformation, moderate crustal thickening, and southward thrusting upon the stable African Lithosphere [Teixell et al., 2005; Zeyen et al. 2005; Missenard et al., 2006; Babault et al., 2008].

[22] The basaltic Quaternary volcanism may be a consequence of anomalous mantle uplift that also conditions its rejuvenation [Raffone et al., 2009]. The volcanic lava

flows are represented at surface by conductive bodies [Schwarz *et al.*, 1992] emplaced along crustal faults that continue in depth toward the base of the crust below the boundary between the High and Middle Atlas (Figure 4). At the top of the mantle, a flat and wide melt chamber with a conductive character can be recognized, similar to those found in other active volcanic settings (e.g., Mount St. Helens [Hill *et al.*, 2009]).

[23] Although the resolution for shallow crustal structures is poor, main features are in agreement with the regional surface geological data [Hollard, 1985]. The Anti-Atlas (sites 18 to 21) is characterized by high resistivities corresponding to low-grade metamorphic Precambrian rocks, with slightly lower resistivities at depth and southwards, probably having a more pelitic nature. Cretaceous detritic and marly cover of the Saharan craton by Errachidia is characterized by low resistivity values. In the High Atlas, resistivities are variable due to the presence of resistive Jurassic carbonates along with Jurassic and Cretaceous detritic and marly rocks. The Middle Atlas is generally conductive due to its sedimentary cover and basalts. The foreland Saïss basin and the front of the Rif Cordillera feature wide and thin conductive bodies corresponding to detritic rocks that alternate with marly and carbonate series. The alternance of highly resistive bodies in the middle crust surrounded by intermediate resistivity zones (Figure 4) may represent large granite batholiths emplaced in metapelitic basements.

5. Conclusions

[24] The Atlas constitutes an intraplate alpine chain characterized by high reliefs developed through inversion tectonics in a low shortening setting. The NNW-SSE magnetotelluric profile from the stable African plate at the Anti-Atlas Mountains, up to the front of the Rif Cordillera, evidences a low resistivity anomalous mantle beneath the High Atlas, in agreement with previous low seismic velocities, low lithospheric densities and asthenospheric uplift determined from integrated modeling.

[25] The lower and intermediate crust (≈ 15 to 35 km) is characterized by kilometer-sized resistive bodies (located below MT sites 1, 3, 6, 9, 13, 15) that may be interpreted as granite batholiths in a metapelitic host rock. The shallow crustal levels reveal the presence of wide and thin conductive bodies associated to the sedimentary rock cover (MT sites 1 to 10 and 14 to 18), in addition to resistive carbonate bodies within the Atlas (MT sites 11 to 13) and metapelitic rocks in the Anti-Atlas (MT sites 18 to 20).

[26] Quaternary basaltic volcanism in the Middle Atlas is associated with conductive bodies. They are connected at depth with melting chambers located at the top of the anomalous mantle, below the boundary between the Middle and High Atlas.

[27] The origin of the anomalous mantle is related with the tectonic evolution of the area, although models proposed thus far (delamination, mantle plumes or Mesozoic extensional tectonics) are controversial. Resistivity data suggest, however, that at present the anomalous mantle is located at shallow levels, above the stable African lithosphere. The melting of the top of the anomalous mantle, which is connected through fractures up to the surface basaltic flows, would have taken place at least during the Quaternary in the Middle Atlas.

[28] The deep structure of the Atlas, which was underlined by seismicity and gravity data, is now better constrained by new magnetotelluric data based on different rock properties. These results help to improve the knowledge on the mechanisms involved in the development of intraplate orogenic belts.

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- M. Ahmamu, N. Bouregba, and A. Chalouan, Département de Géologie, Université Mohammed V-Agdal, Ave. Ibn Battota, BP 703, 10106 Rabat, Morocco.
- F. Anahnah, J. Galindo-Zaldívar, L. González-Castillo, and P. Ruano, Departamento de Geodinámica, Universidad de Granada, E-18071 Granada, Spain. (fanahnah@ugr.es)
- J. Arzate and F. Corbo, Centro de Geociencias, UNAM, Campus Juriquilla, 76220 Queretaro, Mexico.
- E. Asensio and J. Pous, Departament de Geodinàmica i Geofísica, Universitat de Barcelona, E-08028 Barcelona, Spain.
- M. Benmakhlof, Département de Géologie, Université Abdelmalek Esaadi, Tetuán, Morocco.
- W. Heise, GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand.
- P. Ibarra and A. Pedrera, Instituto Geológico y Minero de España, La Calera 1, Tres Cantos, E-28760 Madrid, Spain.
- A. C. López-Garrido and C. Sanz de Galdeano, IACT, CSIC, Universidad de Granada, E-18071 Granada, Spain.
- A. Ruiz-Constan, Géosciences, Université Montpellier 2, CNRS, Place E. Bataillon, F-34095 Montpellier CEDEX 5, France.