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Reply to the comment by A. G. Jones et al. on "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,[1,2] 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 Asensio[5]

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1. Introduction

[1] Scientific discussion and different points of view are a basis of the advancement of knowledge. We acknowledge the comments of *Jones et al.* [2012] as an opportunity to publicly discuss the structure and origin of the Atlas Mountains. Moreover, we welcome the opportunity to compare our results with those recently published by the group responsible for the comment [*Ledo et al.*, 2011], although it is not pertinent to comment in detail on a paper published in another journal. We also wish to remark that the paper of *Ledo et al.* [2011] was reviewed and published during the revision period of our contribution [*Anahnah et al.*, 2011]; therefore, they are two different approaches and data sets, measured in different sites and by different instruments for the same region, lending readers the chance to compare different interpretations. The main differences on the data sets are: the profile of *Anahnah et al.* [2011] compared with the profile of *Ledo et al.* [2011] is 170 km longer, vertical magnetic data were obtained and lower frequencies were recorded.

[2] We regret the style and way used by *Jones et al.* [2012]. We shall answer only those comments of *Jones et al.* [2012] related to objective issues.

[3] One of the final conclusions of *Jones et al.* [2012] might serve as the starting point of our reply:

> Crustal features of *Anahnah et al.*'s [2011] model are likely to be generally correct, however, and their model is virtually identical to the prior crustal model published by *Ledo et al.* [2011], with the difference being that the data of *Anahnah et al.* [2011] are modeled at an angle of N80°E, whereas crustal strike is N50°E. This means that the structures are more "fuzzy" and their geometries are less well resolved in *Anahnah et al.*'s [2011] model compared to that of *Ledo et al.* [2011].

[4] In general, we agree with this comment, although our strike analysis does not support a N50°E strike direction and we are confident that the selected one of N80°E represents the best choice of strike for our data set (see detailed explanation below). However, despite the difference in strike, *Anahnah et al.* [2011] obtained results similar to those of *Ledo et al.* [2011]. Major geological structures are identified in both cases, which constitute the basis for geological modeling and deriving tectonic implications.

[5] The 2D modeling of a 3D Earth is a staunch obstacle in geophysics. Even though 3D MT methods have undergone substantial development [e.g., *Siripunvaraporn et al.*, 2005], to date they still do not offer easy or suitable solutions. Galvanic distortion cannot be modeled as it has a random behavior in each site. Therefore, in a 3D earth the regional impedance tensor (free of distortion) cannot be recovered. As a result, it cannot be used in the inversion. This is a consequence of the fact that all the impedance components are affected (also phases) by the galvanic distortion [e.g., *Ledo et al.*, 1998]. For the time being, only identifying statistically similar data behavior among neighbor sites can determine (hypothetically) the regional behavior free of galvanic distortion [e.g., *Muñoz et al.*, 2008]. This approach assumes of course that galvanic distortion along the sites is random. With this understanding, should researchers conclude that 2D

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

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

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

[4] Instituto Geológico y Minero de España, Granada, Spain.

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

[6] GNS Science, Lower Hutt, New Zealand.

[7] Géosciences, Université Montpellier 2, CNRS, Montpellier, France.

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

[9] Centro de Geociencias, UNAM, Queretaro, Mexico.

Corresponding author: F. Anahnah, Departamento de Geodinámica, Universidad de Granada, E-18071 Granada, Spain. (fanahnah@ugr.es)

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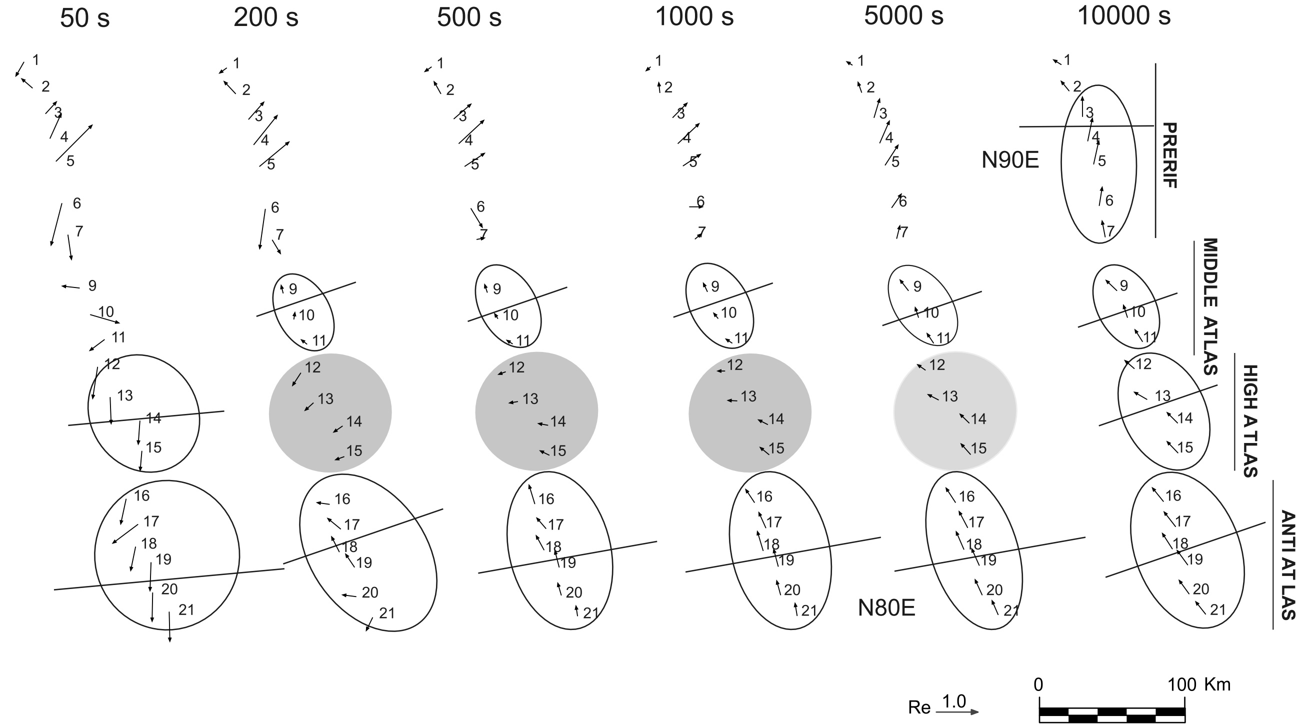

Figure 1. Real induction arrows (Parkinson convention) at periods of 50, 200, 500, 1000, 5000 and 10,000 s. The ellipses represent the induction arrows with homogeneous trends in each sector. In gray, anomalous areas in the High Atlas.

modeling is impossible or worthless? The answer is no. Although the data is partly noisy and incomplete, and moreover affected by 3D structures, it contains enough valuable information to construct a 2D model. The data used should nonetheless be processed and interpreted very carefully.

2. Data Analysis

[6] A major criticism by *Jones et al.* [2012] regards the consistency between the resistivity and phase data at site 15, commonly tested in MT studies using the approach proposed by *Parker and Booker* [1996]. The theory of dispersion relations for magnetotelluric impedance [*Weidelt*, 1972; *Weidelt and Kaikkonen*, 1994] proved the internal consistency of resistivities and phases in 1D and B-polarized 2D media. However, the electric and magnetic fields' causal correlation in 3-D environments [*Yee and Paulson*, 1988] is highly questioned [*Egbert*, 1990; *Svetov*, 1991]. Numerical experiments demonstrate that dispersion relations for off-diagonal impedances fail in 3D models [*Berdichevsky and Pokhotelov*, 1997]. In such complex media as the Atlas Mountains, where violation of the dispersion relations may occur, 3D conductivity is especially evident in some sectors, as the dimensionality analysis of *Anahnah et al.* [2011] reveals at site 15.

[7] One possibility is to test the consistency between phases and apparent resistivities using the *Parker and Booker* [1996] approach, verifying a priori if the data are compatible with two-dimensional B polarization, and discarding the inconsistent data. We opted not to reject those data including local inconsistencies, however. These distortions could be a consequence of 3D structures [*Berdichevsky and Zhdanov*, 1984]. As seen in Figure 1, the real induction arrows of site 15 deviate from the regional NW trend and point toward the west, revealing the presence of a nearby westward conductor. Data from site 15 did not fit with the 2D amplitude-phase based inversion, and therefore do not introduce artifacts in the inversion model, which is calculated using the nearby sites; yet the global RMS is higher than it would be if this site had been completely (or partially) discarded.

[8] Furthermore, we disagree with the comment of *Jones et al.* [2012] that the low natural electromagnetic signal during our data acquisition in May-August 2009 highly affected the long periods. The data might be affected by the low signal in the dead band, at longer periods the 15 days of recording were enough to get good quality until 10,000 s at the majority of soundings.

3. Geoelectric Strike

[9] With respect to the comments on dimensionality analysis, we should stress first that *Ledo et al.* [2011] and *Anahnah et al.* [2011] do not use the same data set. The profile of *Anahnah et al.* [2011] is longer, extending 170 km to the north, and measurement sites are different and record lower frequencies than *Ledo et al.* [2011]. Thus, if dimensionality analyses suggest a reliable 2D resistivity structure for a 2D modeling approach, the *unique* strike for the profile in both cases would be close, but not the same.

[10] Many approaches have been proposed for analysis of the MT impedance tensor to derive the strike direction, impedances, and distortion parameters [e.g., *Bahr*, 1988, 1991; *Bailey and Groom*, 1987; *Groom and Bailey*, 1989, 1991; *Chakridi et al.*, 1992; *Zhang et al.*, 1987; *Smith*, 1995, 1997].

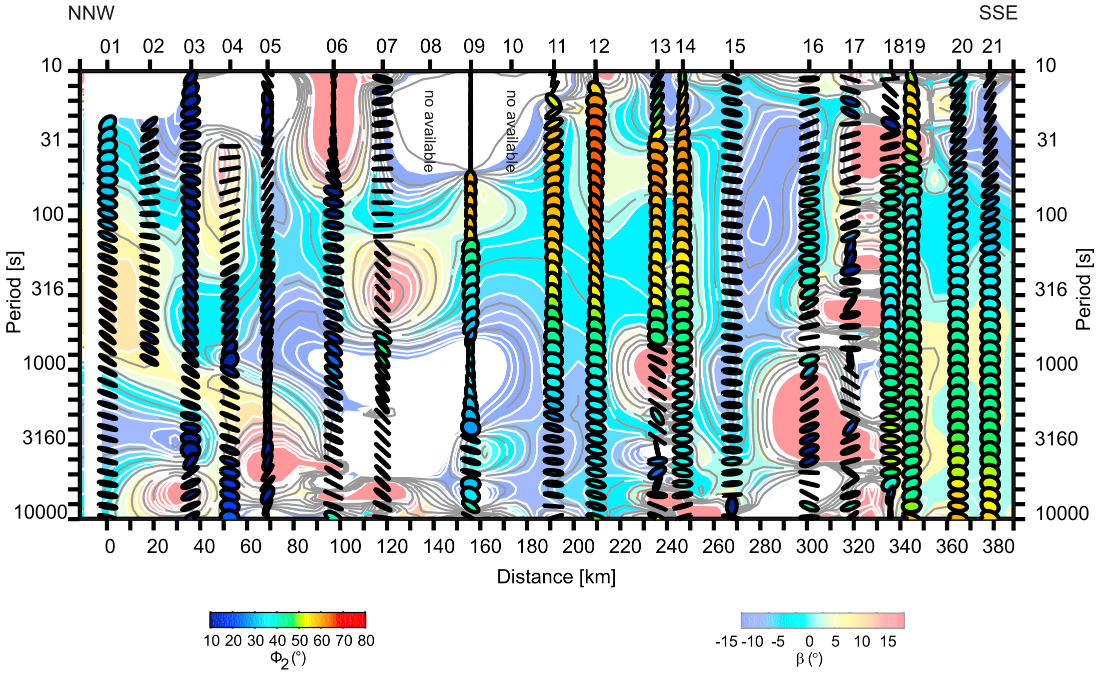

Figure 2. Phase tensor ellipse pseudosection for the Atlas profile. The color used to fill the ellipses shows the geometric mean of the maximum and minimum phase, while high values of Φ_2 indicate increasing conductivity with depth. The background color corresponds to the β parameter related to the dimensionality (0°, 1D; and high and low values correspond to 2D/3D).

Ledo et al. [2011, p. 84] retrieve the strike of the regional structures and the regional impedance tensor applying the distortion decomposition method of *Groom and Bailey* [1989] (GB). They claim that, 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 multisite, multi-frequency GB regional strike is N50°E, which is consistent with the strike of the main surface geological structures." This last statement is not completely true, however, since the main geological features are in general ENE-WSW (N80°E) trending, particularly in the High Atlas, the region of greatest interest.

[11] We analyzed the dimensionality of the MT impedance tensor using two independent methods: Bahr and phase tensor [*Caldwell et al.*, 2004]. If the regional structure is 2D, the direction of *Bahr* [1988, 1991] strike and *Groom and Bailey* [1989] strike should coincide with the principal axes of the phase tensor [*Caldwell et al.*, 2004]. In addition, in a 2D Earth, induction arrows are associated only with E polarization and oriented perpendicular to the strike [e.g., *Jones and Price*, 1970; *Simpson and Bahr*, 2005]. In general, the impedance tensor of our data satisfies 2D according to Bahr analysis, and shows quite a consistent N80°E preferred electrical strike direction (with the ambiguity of 90°; Figure 2 [*Anahnah et al.*, 2011]). Phase tensor analysis gives a preferred direction of N90°E–N100°E (with the ambiguity of 90°; Figure 3 [*Anahnah et al.*, 2011]). The 90° uncertainty is usually resolved by the induction vectors. In the profile, however, the direction of the induction vectors varies with period and spatially, again showing that the data are affected

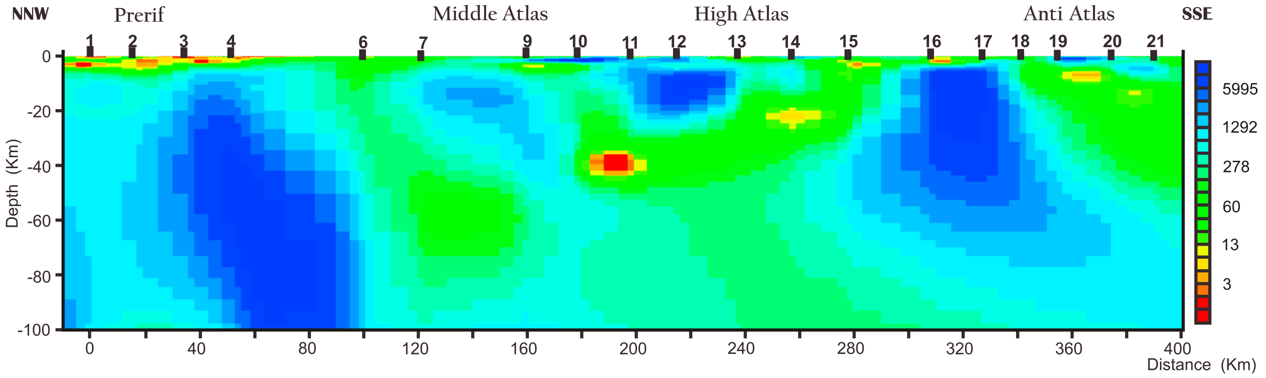

Figure 3. Two-dimensional resistivity model obtained by joint inversion of TM, TE and tipper. Data with strong 3D distortions were excluded.

by 3D structures (Figure 1) hampering the identification of the optimal strike.

[12] For 10,000 s periods (mantle depths), induction arrows point northwestward in the Atlas and northward in the Rif, suggesting that strike is closer to N70°–90°E. For 500–1000 s and 5000 s periods, they also generally point to the NNW (strike N80°E); but in the High Atlas, sites 12, 13, 14 and 15 were probably affected by the presence of a conductor located to the west, which results in the counterclockwise rotation of the induction arrows mainly at 200 s. The 3D influence in this region is also reflected by the inconsistency of site 15. In the Prerif, the induction arrows are more disperse. For the 50 s period the induction arrows are dispersed in orientation.

[13] This behavior of the induction arrows does not allow one to clearly discriminate between the ambiguity of 0 or 90° with respect to the results of dimensionality from the impedance tensor. Since a N-S or N10°W strike direction would be incompatible with the geological strike, a common strike of N80°E for all data was considered as the most adequate and is also in agreement with the ENE-WSW geological strike of the High Atlas (Figure 1) [*Anahnah et al.*, 2011]), even taking into account that there are heterogeneities. Yet at mantle depth strikes may be different, probably close to E-W.

[14] The dimensionality analysis has likewise been improved by the presentation of the β parameter on the phase tensor plot (Figure 2) that indicated the distribution of dimensionality. The sites located below the High Atlas (12 to 15) show, in depth, a 3D character that is compatible with the zone of inconsistency in the induction arrows (Figure 1). The 3D behavior is also consistent with the presence of a heterogeneous anomalous mantle in the region, thereby supporting the tectonic model.

[15] Our decision for a N80°E strike is based on strike analysis (using different approaches) and induction vector data as well as the known geological strike directions. We realize that *Ledo et al.* [2011] came to a different conclusion regarding the strike for crust and mantle; however, this does not mean our strike is incorrect. The strike analysis, as described above, was carried out over a range of periods and showed consistent results. The methods used (phase tensor, Bahr) are well established and valid. Using the phase tensor analysis has the great advantage that the phase tensor is distortion independent and no assumptions of a dimensionality model underlie the approach as it is the case of *Groom and Bailey* [1989] and the related least squares algorithm of *McNeice and Jones* [2001]. Finally, we have to point out that *Ledo et al.* [2011] did not use the vertical magnetic field information, which is important to resolve the 90° ambiguity of the strike direction. Therefore, their decision was merely based on their understanding of the geology. It is well known that what happens at depth (mainly at mantle depths) does not always appear in the same manner as it is at surface.

4. Modeling

[16] Regarding 2D inversion, *Ledo et al.* [2011] performed a 2D joint inversion of TM and TE apparent resistivities and phases. We performed an inversion of the tipper at the longest periods together with the TM and TE modes. In addition to the above reasoning about not rejecting the inconsistent 1D-TM 2D data, we would underline that our RMS is higher because we fit the data up to longer periods, using a site spacing of about 10–30 km, as our target area is the lower crust and upper mantle. Since we know that the data are affected by 3D distortions, "overfitting" the data, especially the TE mode, should be avoided, as it could introduce artifacts into the model. *Anahnah et al.* [2011] also fit the tipper, giving more consistency to the inversion. Moreover, we are confident about our results because the conductive features revealed by our 2D inversion are in accordance with the results derived from the phase tensor, likewise sensitive to conductors.

[17] As it was suggested by the reviewers of this reply and in order to check that the features of the model presented by *Anahnah et al.* [2011] are not produced by 3D effects, we redid the inversion discarding any data inconsistent with the Sutarno phase consistent smoothing [*Sutarno and Vozoff*, 1991]. The new inversion (Figure 3) yielded an RMS of 4.06 using an error floor of 7% for apparent resistivities, 2 for the phases and 0.02 for the tipper. This means an average error of 28% for apparent resistivities and 2.3° for absolute phases. In this case the inversion was carried out until 10,000 s using the uniform grid Laplacian regularization, a τ smoothing factor of 5 and as the horizontal to vertical smoothing the values $\alpha = 1$ and $\beta = 0$. Figure 4 shows the pseudosections of data and model responses. Note that the new model (Figure 3) maintains precisely the most striking features of our first model, presented by *Anahnah et al.* [2011], including an anomalous conductive mantle below the High Atlas with high conductive bodies at its top, interpreted as magmatic chambers. In addition, it is closer to the model of *Ledo et al.* [2011], where the main difference was in the conductive zone at 30 km depth beneath the Anti-Atlas. Now, in the new model this conductive feature is also present, though discrepancies about its depth remain, probably due to the difference in the strike considered and the influence of the longest periods, which are required to better resolve such structures beneath the shallow conductive layers appearing in the Anti-Atlas.

[18] *Jones et al.* [2012] claim incompatibility with the directions of the vector at one and other side of the mantle conductor beneath the High Atlas. But this would only be true in a simple model with a precise high-conductivity zone between these two sites. This is not the case of the model in the High Atlas, as the influence of all the conductors, especially the crustal conductors, changes such expected easy behavior mentioned in their comment. In addition, note that the anomalous mantle has a slightly low resistivity (although not very low).

5. Conclusion

[19] Our N80°E strike is based on two different well established methods (phase tensor and Bahr) and the induction vector data. *Ledo et al.* [2011] came to a different conclusion regarding the geoelectric strike by using another method and without taking into account the vertical magnetic field information which is important to resolve the 90° ambiguity of the strike direction.

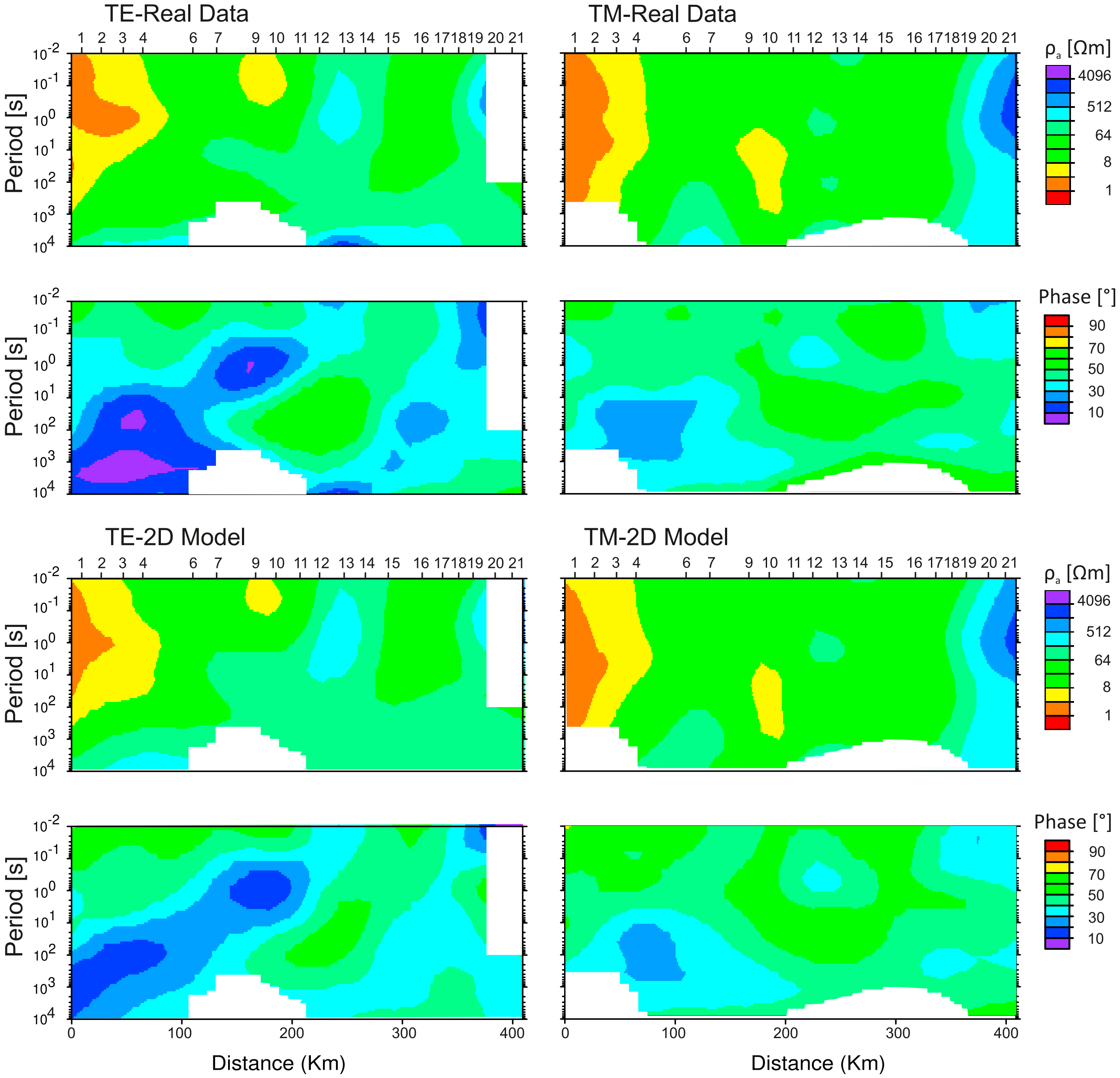

Figure 4. Data and model responses pseudosections.

[20] The new inversion presented here shows the reliability of the previous model of *Anahnah et al.* [2012] and, as a consequence, it validates the geological interpretation. We hold that the geological model presented by *Anahnah et al.* [2011] is an essential and relevant matter. *Jones et al.* [2012] make only general comments questioning our geological model and do not formulate precise discrepancies with the new tectonic interpretation presented by the paper. We must disagree with *Jones et al.* [2012], as from our viewpoint the resistivity models are virtually identical, we would underline that the major discrepancies between *Ledo et al.* [2011] and *Anahnah et al.* [2011] reside in the geological interpretations. Our tectonic model also addresses petrological, tectonic and geophysical data available in the region that support the presence of anomalous mantle below the High Atlas, probably related to a major lithospheric thinning. Moreover, there are major differences with respect to the interpretation of the tectonic evolution of the Atlas proposed by *Anahnah et al.* [2011], who support the presence of high relief and basaltic volcanism instead of other less constrained interpretations.

[21] Our main scientific aim is to reveal the deep structure of the Atlas Mountains. Our long-period magnetotelluric data widely cover a complete section and recorded longer periods than the broadband data of *Ledo et al.* [2011], which are complementary and provide a more detailed view of the shallow part of the southern Atlas cross section. Given these considerations, we publicly offer to combine our data in order to construct the most accurate model of this fascinating region.

References

Anahnah, F., et al. (2011), Deep resistivity cross section of the intraplate Atlas Mountains (NW Africa): New evidence of anomalous mantle and related Quaternary volcanism, *Tectonics*, *30*, TC5014, doi:10.1029/2010TC002859.

Bahr, K. (1988), Interpretation of the magnetotelluric impedance tensor: Regional induction and local telluric distortion, *J. Geophys.*, *62*, 119–127.

Bahr, K. (1991), Geological noise in magnetotelluric data: A classification of distortion types, *Phys. Earth Planet. Inter.*, *66*, 24–38, doi:10.1016/0031-9201(91)90101-M.

Bailey, R. C., and R. W. Groom (1987), Decomposition of the magnetotelluric impedence tensor which is useful in the presence of channeling, paper presented at 57th Annual International Meeting, Soc. Explor. Geophys., New Orleans, La.

Berdichevsky, M. N., and D. O. Pokhotelov (1997), Violation of the dispersion relations in a three-dimensional magnetotelluric model, *Izv. Phys. Solid Earth, Engl. Transl.*, *33*(8), 603–612.

Berdichevsky, M. N., and M. S. Zhdanov (1984), *Advanced Theory of Deep Geomagnetic Sounding*, Elsevier, Amsterdam.

Caldwell, T. G., H. M. Bibby, and C. Brown (2004), The magnetotelluric phase tensor, *Geophys. J. Int.*, *158*, 457–469, doi:10.1111/j.1365-246X.2004.02281.x.

Chakridi, R., M. Chouteau, and M. Mareschal (1992), A simple technique for analysing and partly removing galvanic distortion from the magnetotelluric impedance tensor: Application to Abitibi and Kapuskasing data (Canada), *Geophys. J. Int.*, *108*, 917–929, doi:10.1111/j.1365-246X.1992.tb03480.x.

Egbert, G. (1990), Comments on "Concerning dispersion relations for the magnetotelluric impedance tensor", by E. Yee and K. Paulson, *Geophys. J. Int.*, *102*, 1–8, doi:10.1111/j.1365-246X.1990.tb00525.x.

Groom, R. W., and R. C. Bailey (1989), Decomposition of magnetotelluric impedance tensors in the presence of local three-dimensional galvanic distortion, *J. Geophys. Res.*, *94*, 1913–1925, doi:10.1029/JB094iB02p01913.

Groom, R. W., and R. C. Bailey (1991), Analytic investigations of the effects of near-surface three-dimensional galvanic scatterers on MT tensor decompositions, *Geophysics*, *56*, 496–518.

Jones, A. G., D. Kiyan, J. Fullea, J. Ledo, P. Queralt, A. Marcuello, A. Siniscalchi, and G. Romano (2012), Comment on "Deep resistivity cross section of the intraplate Atlas Mountains (NW Africa): New evidence of anomalous mantle and related Quaternary volcanism," *Tectonics*, *31*, TC5011, doi:10.1029/2011TC003051.

Jones, F. W., and A. T. Price (1970), The perturbations of alternating geomagnetic fields by conductivity anomalies, *Geophys. J. R. Astron. Soc.*, *20*, 317–334.

Ledo, J., P. Queralt, and J. Pous (1998), Effects of galvanic distortion on magnetotelluric data over a three-dimensional magnetotelluric data, *Geophys. J. Int.*, *132*, 295–301, doi:10.1046/j.1365-246x.1998.00417.x.

Ledo, J., A. G. Jones, A. Siniscalchi, J. Campanya, D. Kiyan, G. Romano, M. Rouai, and MT TopoMed (2011), Electrical signature of modern and ancient tectonic processes in the crust of the Atlas mountains of Morocco, *Phys. Earth Planet. Inter.*, *185*, 82–88, doi:10.1016/j.pepi.2011.01.008.

McNeice, G. W., and A. G. Jones (2001), Multisite, multifrequency tensor decomposition of magnetotelluric data, *Geophysics*, *66*, 158–173.

Muñoz, G., A. Matéus, J. Pous, W. Heise, F. Monteiro Santos, and E. Almeida (2008), Unraveling middle-crust conductive layers in Paleozoic Orogens through 3D modeling of magnetotelluric data; the Ossa Morena Zone case study (SW Iberian Variscides), *J. Geophys. Res.*, *113*, B06106, doi:10.1029/2007JB004987.

Parker, R. L., and J. R. Booker (1996), Optimal one-dimensional inversion and bounding of magnetotelluric apparent resistivity and phase measurements, *Phys. Earth Planet. Inter.*, *98*(3–4), 269–282, doi:10.1016/S0031-9201(96)03191-3.

Simpson, F., and K. Bahr (2005), *Practical Magnetotellurics*, Cambridge Univ. Press, Cambridge, U. K., doi:10.1017/CBO9780511614095.

Siripunvaraporn, W., G. Egbert, and Y. Lenbry (2005), Three-dimensional magnetotelluric inversion: Data-space method, *Phys. Earth Planet. Inter.*, *150*, 3–14, doi:10.1016/j.pepi.2004.08.023.

Smith, J. T. (1995), Understanding telluric distortion matrices, *Geophys. J. Int.*, *122*, 219–226, doi:10.1111/j.1365-246X.1995.tb03549.x.

Smith, J. T. (1997), Estimating galvanic-distortion magnetic fields in magnetotellurics, *Geophys. J. Int.*, *130*, 65–72, doi:10.1111/j.1365-246X.1997.tb00988.x.

Sutarno, D., and K. Vozoff (1991), Phase-smoothed robust m-estimation of magnetotelluric impedance functions, *Geophysics*, *56*, 1999–2007.

Svetov, B. S. (1991), Transfer functions of the electromagnetic field, *Izv. Phys. Solid Earth*, *27*, 119–128.

Weidelt, P. (1972), The inverse problem of geomagnetic induction, *Z. Geophys.*, *8*, 257–290.

Weidelt, P., and P. Kaikkonen (1994), Local 1D interpretation of magnetotelluric B-polarization impedances, *Geophys. J. Int.*, *117*, 733–748, doi:10.1111/j.1365-246X.1994.tb02466.x.

Yee, E., and K. V. Paulson (1988), Concerning dispersion-relations for the magnetotelluric impedance tensor, *Geophys. J.*, *95*(3), 549–559.

Zhang, P., R. G. Roberts, and L. B. Pedersen (1987), Magnetotelluric strike rules, *Geophysics*, *52*, 267–278.