Deep electrical resistivity structure of the northern Gibraltar Arc (western Mediterranean): evidence of lithospheric slab break-off

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ABSTRACT

The uncertainties about the lithospheric structure of the Gibraltar Arc have generated the proposal of several contradictory models to explain its actual geodynamic setting. Here we present a novel 3D model of the lithospheric electrical resistivity distribution beneath the whole Betic Cordillera obtained by inverting both broad band and long period magnetotelluric data. The lithosphere-asthenosphere boundary under SW Iberia is shown as being deeper than under the Alboran Basin. In addition, the sensitivity tests confirm the presence of a N-S oriented low-resistivity anomaly at lithospheric mantle depths East of the 4ºW meridian. It coincides with an area without earthquake hypocenters and low velocities, and is interpreted as asthenospheric material intruded by the lateral lithospheric tearing and breaking-off of the E-directed subducting Ligurian slab under the Alboran Domain. This scenario suggests that the opening of the Alboran Basin is related to a westward rollback of this E-directed subducting slab.

Introduction

The convergence of the African and Iberian plates generated the Gibraltar Arc (Rif and Betic Cordilleras, Fig. 1) from the Late Cretaceous (García-Dueñas *et al.*, 1992; Azañón *et al.*, 2002). Different geodynamic models have been proposed to explain the lithospheric structure of this arc-shaped belt and the opening of the Alboran Basin based on Bouguer anomalies, heat flow, earthquake locations, seismic refraction, seismic tomography, geoid anomalies and elevation data (e.g. Morales *et al.*, 1997; Fernàndez *et al.*, 1998). Thus, the opening of the Alboran Basin has been explained involving a convective removal of the thickened lithospheric root that caused uplift and extension (Platt and Vissers, 1989; Platt *et al.*, 1998), a lithospheric delamination caused by gravitational collapse of this thickened lithosphere (Seber *et al.*, 1996; Mezcua and Rueda, 1997; Calvert *et al.*, 2000), a westwards to southwards rollback of an oceanic slab that generated back-arc extension (Royden, 1993; Lonergan and White, 1997; Gutscher *et al.*, 2002), a southeastwards rollback of an oceanic slab attached to the African plate (Doglioni *et al.*, 1997, 1999a), a southeastward delamination of the subcrustal lithospheric slab (Docherty and Banda, 1995) or a vertical broken off piece of a previously subducting lithospheric slab (Zeck, 1996, 1997).

The magnetotelluric method has been proved to be a useful technique to image the lithospheric resistivity structure beneath plate boundaries, providing constraints to geodynamic models. Continent-continent collision areas have been the focus of many studies whether or not they are active (Ledo *et al.*, 2000; Unsworth, 2010). Continent-ocean collision areas have also been imaged clearly depicting the subducting oceanic slab (Wannamaker *et al.*, 1989; Brasse and Eydam, 2008; Brasse *et al.*, 2009). Some magnetotelluric surveys have been carried out in the central Betics assuming 2D structures (Pous *et al.*, 1999; Pedrera *et al.*, 2009), but this can induce incorrect interpretations in complex geological areas with 3D structures (García *et al.*, 1999; Ledo, 2005). Martí *et al.* (2009a) presented a 3D resistivity model of the Central Betic Crust. To image the lithospheric structure of the Betics, we extended the study area to the whole Cordillera and included long period data up to 20000 s. Long period data allow for a deeper investigation depth, which is crucial to characterize the lithosphere-asthenosphere boundary (LAB) and the electrical resistivity of the lithospheric mantle and lower crust levels.

The Betic Cordillera (Fig. 2a, Fig. S1) is divided into the External Zones and the Internal zones (Azañón *et al.*, 2002). The External Zones include carbonate rocks from the South Iberian paleomargin as well as detritic rocks from the Flysch Trough Complex, with ages ranging from Mesozoic to Cenozoic. The Internal Zones, also known as Alboran Domain, include three Paleozoic to Triassic metamorphised nappe complexes. Post-orogenic Upper Miocene to Quaternary basins and the Alboran basin (the backarc basin of the Gibraltar Arc) lay discordant over these units. The northwesternmost mountain front of the Betic Cordillera is the only one that remains active (Ruiz-Constán *et al.*, 2009). Fullea *et al.* (2010) modeled the crustal thickness as 30 km beneath the External Zones and ranging beneath the Internal Zones from more than 36 km under the highest mountains to 20 km near the coastline, which matches existing deep seismic profiles (García-Dueñas *et al.*, 1994). The depth of the LAB under the Betic Cordillera increases from 100 km at the eastern boundary to 170 km at the western one (Frizon de Lamotte *et al.*, 2004; Soto *et al.*, 2008; Fullea *et al.*, 2010). None of these values were obtained from electrical resistivity models, so this is the first time the lithospheric structure of the northern Gibraltar Arc has been modeled from magnetotelluric data.

Magnetotelluric data

The magnetotelluric method uses natural electromagnetic fields to characterize the structure of the subsurface. It is a valuable technique for imaging the lithosphere and the geometry of the LAB (Jones, 1999). Its investigation depth depends on both the recording period and the resistivity of the Earth.

The dataset we present consists of 100 magnetotelluric sites located over the Betic Cordillera (Fig. 1, Fig. S1), 41 of them including long period data. The time series were processed using robust algorithms (Egbert and Booker, 1986; Chave and Thomson, 2004) with remote reference when possible. Apparent resistivity and phase curves obtained cover periods from 0.001 s up to 20000 s in some of the sites, showing medium to high quality (Fig. S2).

We obtained a dimensionality map using the WALDIM code (Martí *et al.*, 2009b), based on the invariant rotation parameters of the impedance tensor presented by Weaver *et al.* (2000) to determine if the geoelectrical structures at different depths can be identified as 1D, 2D or 3D. The results (Fig. 3) show the predominance of 3D geoelectrical behaviour for periods longer than 10 s in the whole area. Thus, a 3D model is the most valid approach to properly characterize the deep crustal and lithospheric electrical structure beneath the Betic Cordillera.

Geoelectrical lithospheric structure

The geoelectrical structure of the Betic lithosphere was imaged by building a 3D resistivity model with 38 x 50 x 33 mesh elements. The initial model used for the inversion was a homogeneous 100 ohm·m block with the only exception of the sea, which was fixed with a constant value of 0.3 ohm·m according to the bathymetry of the Alboran Sea. The WSINV3DMT inversion code (Siripunvaraporn *et al.*, 2005) was used for inverting the off-diagonal components of the impedance tensor. The misfit between the data and the model responses has an RMS value of 5.2 when using only a 5% error for the impedance values. Fig. S2 shows the misfit between the data and model responses at each site.

The resulting model (Fig. 2b-i) is characterized at upper to middle crustal levels by a complex pattern of resistive and conductive zones. The shallow conductive zones are likely to be related to the detrital infill of the Neogene basins such as the Guadalquivir Basin (CGU), the Guadix-Baza basin (CGB) or the Granada Basin (CG). The External Zones are collectively depicted up to 10.5 km thick as a body of heterogeneous resistivity values due to their complex structure and variable composition of carbonate marls, mudstones and detritic rocks. To the North, South and beneath these conductive domains the resistive zones correspond to the igneous and metamorphic rocks of the Iberian Massif (RIM) and the metamorphic Paleozoic to Triassic rocks of the Internal Zones (RIZ), which continue up to mid-low crustal levels (Fig. 2c-d). The base of these two resistive bodies, located in the Moho, is not visible in the model as there is no variation in the electrical resistivity between the lower crust and the upper lithospheric mantle.

In the Internal Zones the model shows a low-resistivity anomaly located between upper-mid crustal depths of 4.5 km and 17.5 km. This conductive body (CB1) was interpreted by Martí *et al.* (2009a) as basic or ultrabasic rocks containing a conducting mineral phase. It is clear from our 3D model that it has no continuity towards the West and does not appear at these depths anywhere else in the study area.

At deeper levels, the resistivity model depicts a boundary at depths between 110 km and 160 km that marks the transition from values of 500 – 1000 ohm·m to values as low as 10 ohm·m (Fig. 2h-i). These low resistivity values can correspond to asthenospheric material (Eaton *et al.*, 2009) and, hence, this transition is interpreted as the boundary between the lithosphere and the asthenosphere (LAB). In accordance with the model presented by Fullea *et al.* (2010), the LAB is estimated to be located at 110 km under the Eastern Betics and it increases its depth toward the western Betics up to 160 km.

Above this boundary the most remarkable, yet previously undescribed feature of the model appears. This is a N-trending conductive body (CB2) located East of the 4ºW meridian and extending in depth from 30 km down to 62 km (Fig. 2e-f). This CB2 body, located at lithospheric mantle levels, has resistivity values ranging from 5 ohm·m to 15 ohm·m and is sub-vertical, dipping almost 90º West. Despite the mainly N-trend, at its northern limit it turns West 90º and continues about 70 kilometers. The sensitivity tests performed to the CB2 body show that its bottom reaches depths of at least 62 km, but given the loss of resolution of the magnetotelluric method beneath a conductive body (Jones, 1999), its bottom can be located as far down as the asthenosphere without affecting the model responses (Fig. 4).

Geodynamic implications

According to lithospheric seismic tomography studies performed in the Betic Cordillera (Morales *et al.*, 1999), the location of the CB2 anomaly also compares well with a zone of low seismic velocity (up to a 6% decrease). In addition, the comparison between the presented resistivity model and hypocenter earthquake locations (Fig. 5) also shows a lack of hypocenters inside the CB2 body. In fact, it separates 3 main domains with different seismic activity and resistivity values. 1) A SW domain (D1) characterized by a resistive lithosphere which includes deep hypocenters with an increasing depth towards East and South. 2) A SE less resistive domain (D2) with high hypocenter density located, in this case, exclusively at upper crustal levels. 3) A N domain (D3) found to be more resistive with only a few shallow hypocenters located in the Iberian crust. Hence, geophysical observations point to the CB2 body to separate these main lithospheric domains and to be of a less rigid nature than the surrounding materials.

The previously presented geodynamic models have been analyzed with the constraint of the CB2 body. A convective removal or a gravitational collapse of a thickened lithosphere explain the presence of asthenospheric material at lithospheric mantle levels, but the strike of the CB2 body is at odds with both hypotheses, as it is clearly oriented N-S and those hypotheses would predict the asthenospheric material to be E-W directed. The southeastward delamination of a subcrustal lithospheric slab presented by Docherty and Banda (1995) suggests an asthenospheric upwelling matching the shape of the CB2 body but, again, the NE-SW strike this hypothesis needs is not compatible with the geometry of the CB2 body. Thus, the only remaining options are the ones involving subduction processes.

To explain the N-S strike of the CB2 body, the subduction needs to be East or West-directed. Although the main lithospheric subduction in the western Mediterranean is West-directed (Apennine subduction, Doglioni *et al.* 1999b), an East-directed subduction has already been proposed to explain the lithospheric structure of the Gibraltar Arc and the opening of the Alboran Sea (e.g. Gutscher *et al.*, 2002; Krijgsman and Garcés, 2004; Bokelmann *et al.*, 2010; Díaz *et al.*, 2010). This hypothesis combined with the lithosphere tearing model presented by Govers and Wortel (2005) allow us to interpret the CB2 body as asthenospheric material intruded into the lithosphere (Fig. 6). The shape and location of this asthenospheric intrusion can be correlated with a detachment of the East-directed subducting slab. A slab break-off is suitable in this setting (Govers and Wortel, 2005) and explains the recent uplifting of the whole area as suggested by Zeck (1996, 1997). This slab detachment is limited in the North by an E-trending lithospheric tearing in which asthenospheric material also intrudes at its W limit generating the 90º turn of the northern part of the CB2 body. The E-trending lithospheric tearing corresponds to the boundary between the Iberian plate and the eastwards subducting Ligurian oceanic lithosphere and progressively ends westwards near the 5ºW meridian (Fig. 6). The resulting LAB is outlined on the resistivity model in Fig. 5. Geophysical evidence of lithospheric slab detachments have been previously found in other subduction areas such as the Mediterranean-Carpathian region (Wortel and Spakman, 2000).

Conclusions

The deep electrical resistivity model presented in this work contributes to understanding the lithospheric structure of the northern Gibraltar Arc, beneath the Betic Cordillera. The existence of a low-resistivity anomaly at lithospheric mantle depths East of the 4ºW meridian compares favorably with the lack of earthquake hypocenter locations and a previously observed low velocity zone. The geodynamic setting our model suggests is based on the magnetotelluric constraints and shows that the lithospheric structure under the Betic Cordillera and the adjoining Alboran Basin are the result of the westwards roll-back of an E-directed lithospheric subduction that ends towards the North in a tearing sequence. This subduction resulted during its latest stages in a slab break-off phase and detachment with asthenospheric material then intruding and filling the resulting gap. This model partially agrees with the E-directed subduction proposed by previous works (Royden, 1993; Lonergan and White, 1997; Gutscher *et al.*, 2002), but introduces the lateral lithospheric tearing and the slab break-off. The outlining of the geometry of the lithosphere-asthenosphere boundary, located at a range of depths from 110 km (NE) to 160 km (SW), corresponds well with the ones presented by previous works, the only exception being the previously undescribed asthenospheric intrusion.

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FIGURE CAPTIONS

Figure 1. Regional tectonic scheme of the western Mediterranean showing the main tectonic units. The dashed line frames the study area. Black dots indicate the location of the magnetotelluric sites.

Figure 2. (a) Simplified geological map of the study area with distinguished main tectonic units in the Betic Cordillera. IM-Iberian Massif (dark grey); IZ-Internal Zones (orange); EZ-External Zones (light grey); NB-Neogene Basins (white). (b-i): Top view slices selected from the 3D resistivity model with the main resistive and conductive bodies identified. RIM-Resistive Iberian Massif, RIZ-Resistive Internal Zones, CGU-Conductive Guadalquivir Basin, CG-Conductive Granada Basin, CGB-Conductive Guadix-Baza Basin, CB1-Conductive Body 1, CB2-Conductive Body 2. Black dots show the locations of the magnetotelluric sites. A-A', B-B' and C-C' on each slice show the location of the vertical slices in Fig. 5.

Figure 3. Dimensionality analysis results from the magnetotelluric data at six period bands. Black dots indicate lack of information at the corresponding site and period band.

Figure 4. Results from the sensitivity tests performed to the CB2 body, comparing the RMS value obtained for the whole dataset when placing its base at different depths.

Figure 5. (a) Geological map of the Betics with the location of the magnetotelluric sites (black dots) and the slices. A-A', B-B' and C-C' are side-view slices of the 3D resistivity model crossing the CB2 body including the hypocenter locations (white dots) within 8 km from each profile recorded since 1900. Dashed black line shows the lithosphere-asthenosphere boundary inferred from the resistivity distribution. D1, D2 and D3 are the main tectonic domains described in the text.

Figure 6. (a-b) Geodynamic 3D scheme and cross-section of the inferred lithospheric structure under the Betics and northern Alboran Sea. IC-Iberian Crust; AC-Alboran Crust (Internal Betics and Alboran Sea); LC-Ligurian Crust; ILM-Iberian Lithospheric Mantle; ALM-Alboran Lithospheric Mantle; LLM-Ligurian Lithospheric Mantle. AS-Asthenosphere. Dashed black line

shows the coast-line. (c) Inferred lithospheric structure superposed to the corresponding resistivity model slice A-A’.

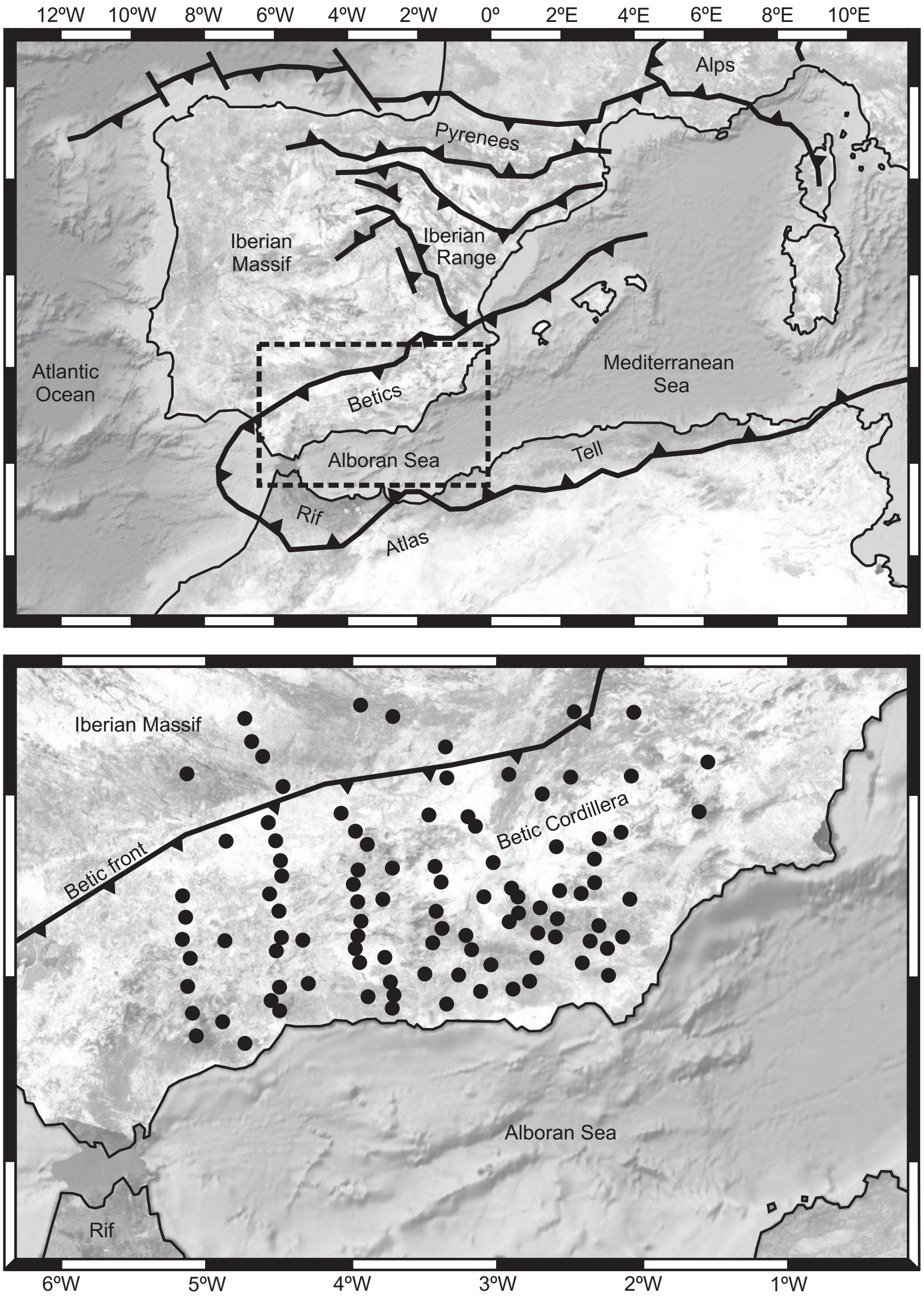

Figure 1 Rosell et al. (2010)

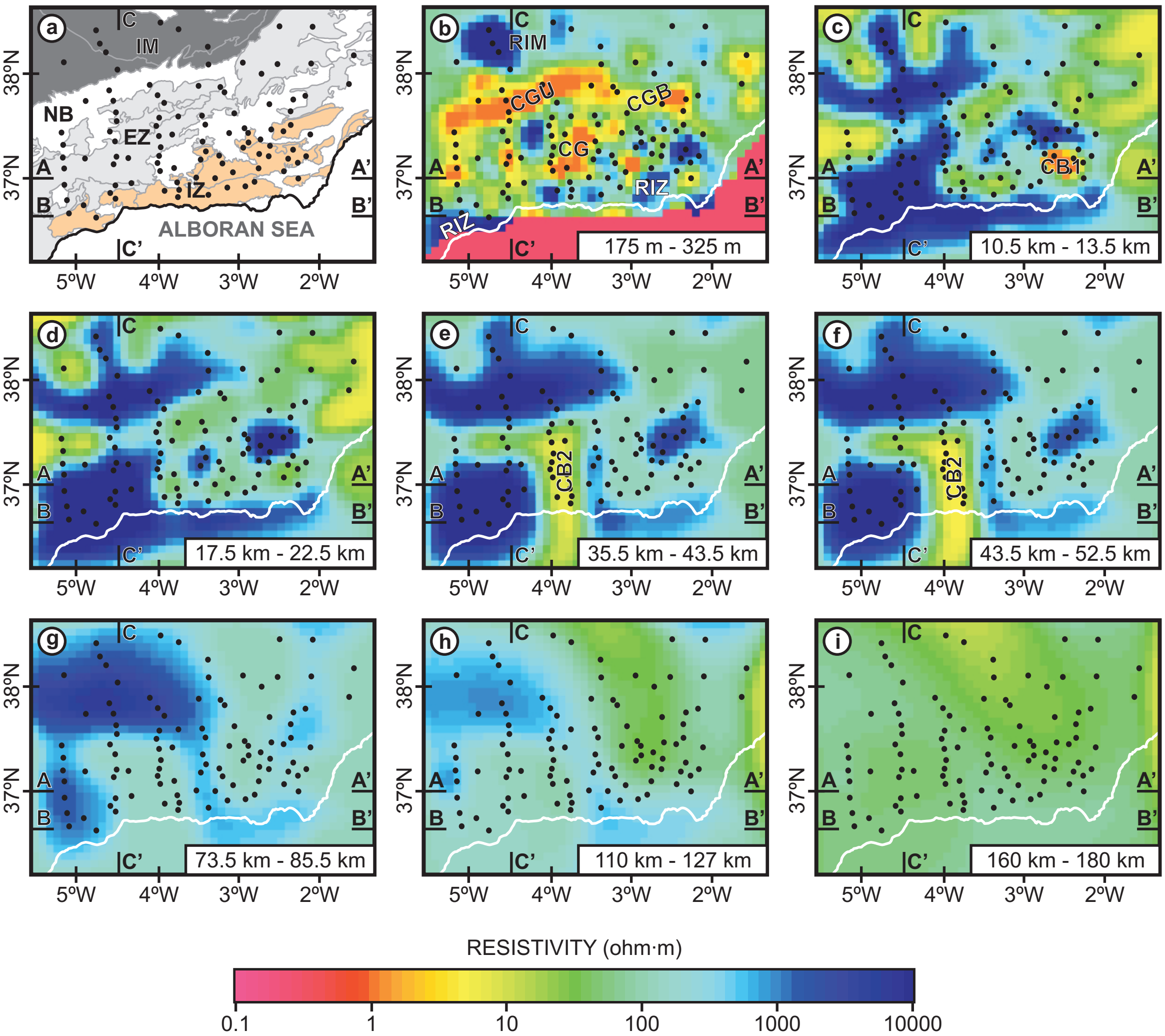

Figure 2 Rosell et al. (2010)

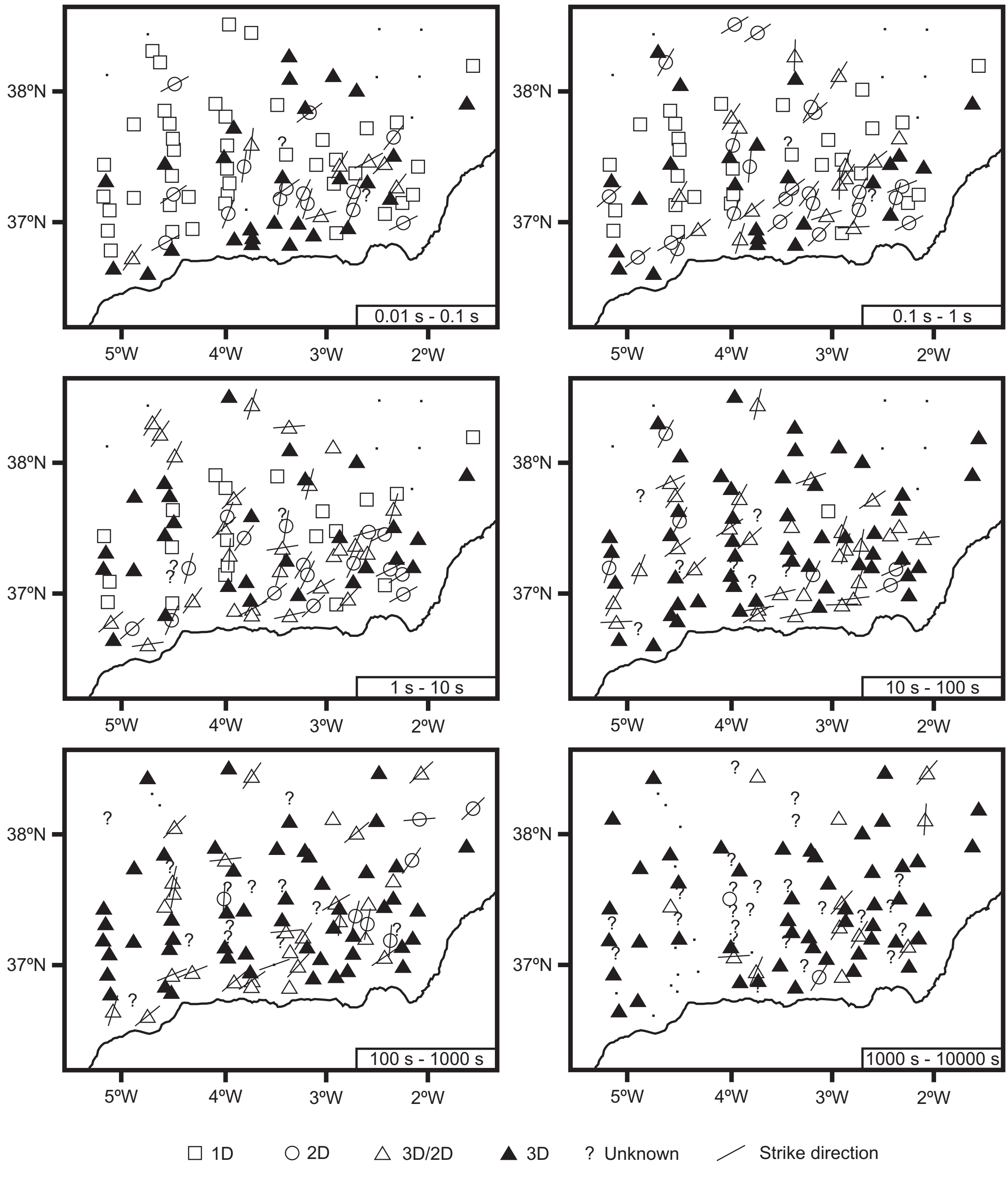

Figure 3 Rosell et al. (2010)

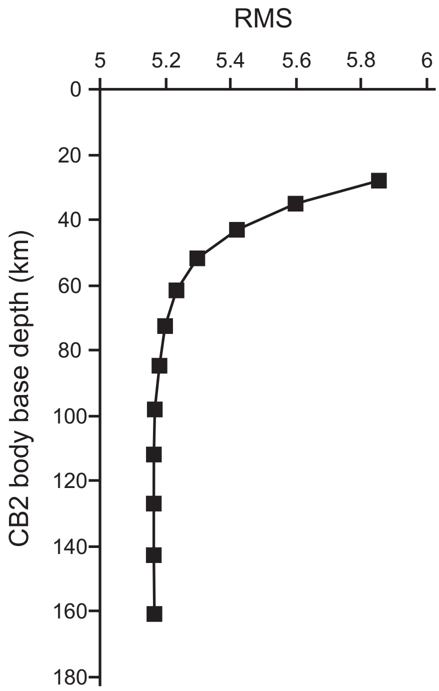

Figure 4 Rosell et al. (2010)

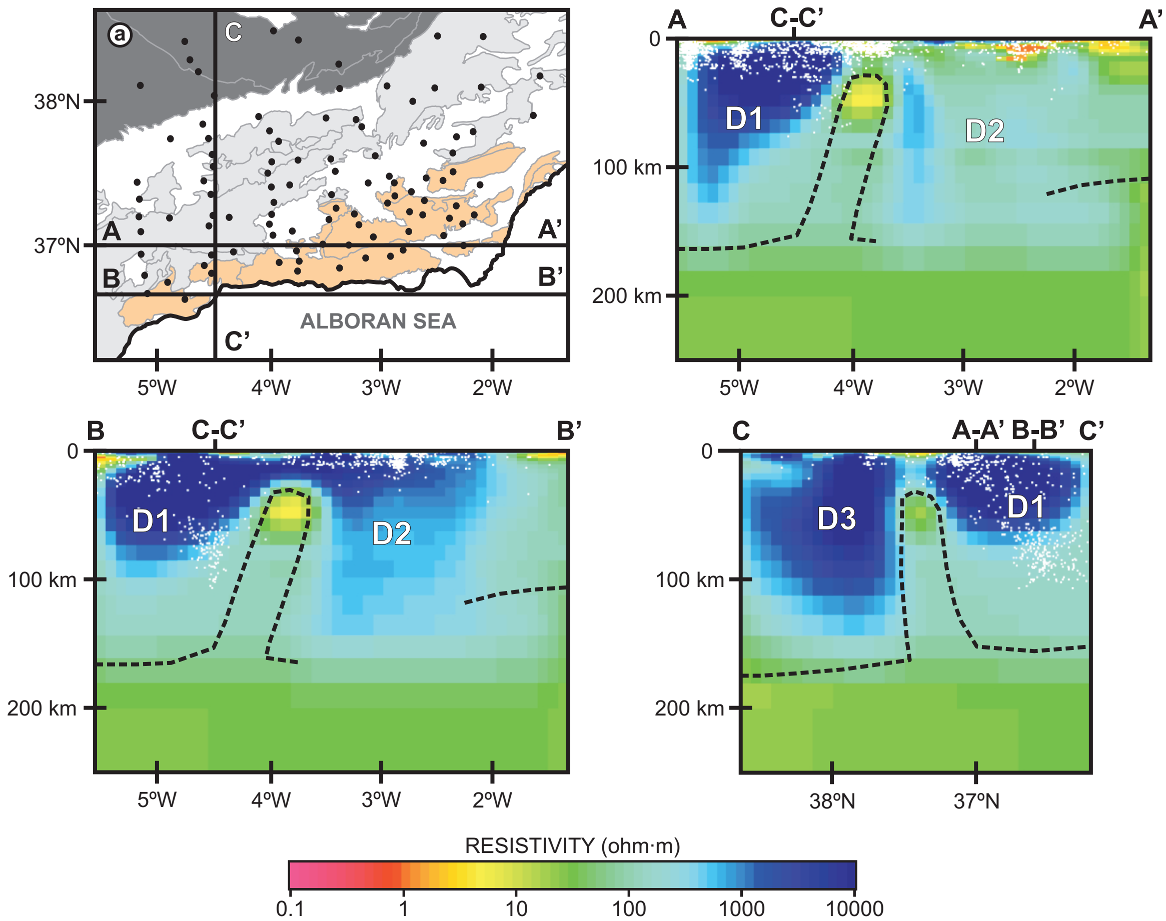

Figure 5 Rosell et al. (2010)

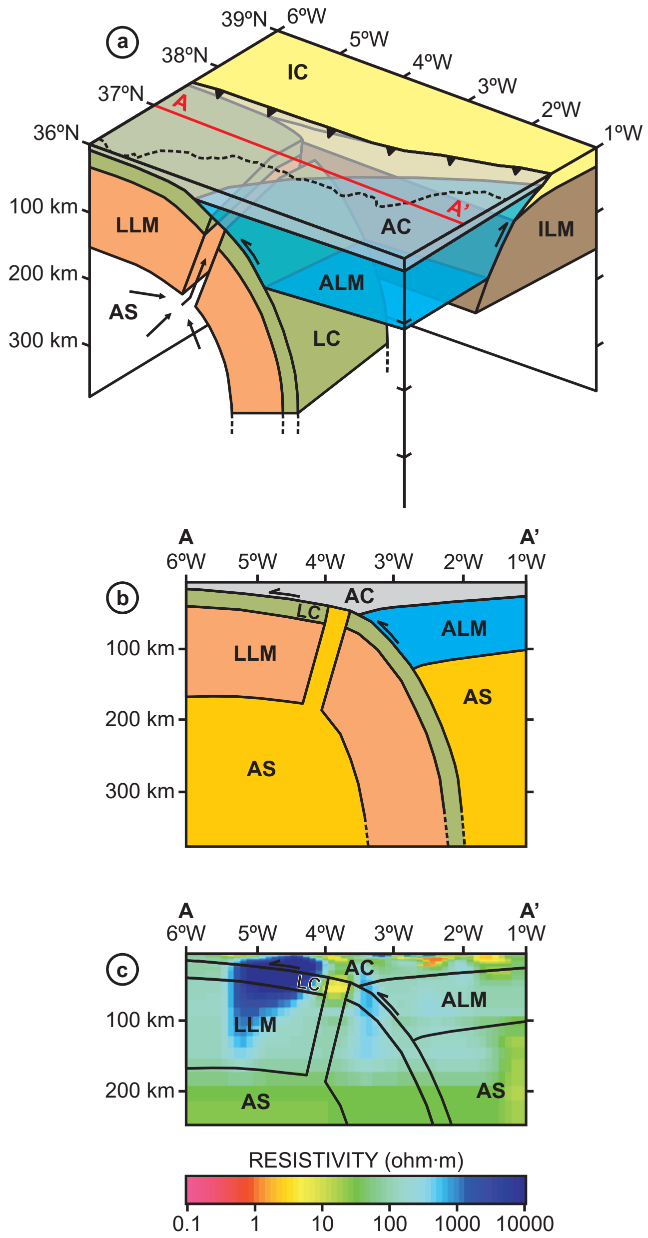

Figure 6 Rosell et al. (2010)