

Main features of the deep structure by local earthquake tomography and active tectonics: case of Rif Mountain (morocco) and Betic Cordillera (Spain)

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Abstract Within the Spain and Moroccan networks, a large volume of seismic data has been collected and used for investigating the lithosphere in the Betic–Rif Cordillera. The present study has two main goals: (1) Use the most actual seismological data from recent earthquakes in the Betic–Rif arc for investigating the lithosphere through the application of seismic local tomography techniques. (2) Define the possible structural blocks and explain the GPS velocities perturbation in this region. The resolution tests results indicate that the calculated images gave a close true structure for the studied regions from 5- to 60-km depth. The resulting tomographic image shows that the presence of two upper crust body (velocity 6.5 km/s) at 3- to 13-km depth between Iberian Betic and Moroccan Rif in the western and in the middle of Alboran Sea also shows the low velocity favoring the presence of melt in the base of these two bodies. The crustal bodies forms tectonic blocks in the Central Rif and in the Central Betic Cordillera.

Keywords Betic–Rif Cordillera · Earthquakes tomography · Crustal velocity · Tectonics blocks

1 Introduction

The Betic–Rif Cordillera is located in the area of interaction between the Eurasian and African plates in the western part of the alpine orogenic belt. A number of geological, seismic, gravimetric, and magnetometric studies have contributed to a better knowledge of the deep structure of this region. The seismic refraction profile made in the area (Working Group for deep seismic sounding in Spain 1974–1975, 1977; Ansorge et al. 1978; Working Group for deep seismic sounding in the Alboran Sea 1974–1975, 1978; Banda and Ansorge 1980; Banda et al. 1993) indicate that while the Betic Cordillera crust is somewhat thick (35 to 38 km). The crust thins progressively towards the Iberian Massif (near 30 km). The crustal thickness beneath the Alboran Sea range from 10- to 20-km and in the Rif Mountain is approximately 25- to 35-km. The crustal seismicity is scattered in West Alboran especially under the Rif and the Betic. The intermediate-depth earthquake are concentrated in N–S line at 4.5°W also in the central part of the Alboran Sea (Buforn et al. 1995; Seber et al. 1996; Calvert et al. 2000). Seismic studies have determined P and S wave velocities in the crust and mantle, as well as their principal structural features (Marillier and Mueller 1985; Krishna et al. 1992; Blanco and Spakman 1993; Paulssen and Visser 1993; Plomerova et al. 1993; Calvert et al. 2000). These studies show the presence of an anomalous mantle below the

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Betic–Rif cordillera and Alboran Sea. The gravimetry study confirmed this anomalous in the Betic–Rif cordillera (Hatzfeld 1976; Torné and Banda 1992). The Western Mediterranean evolution has been explained by a variety of geodynamic from break-off of subducting ocean plate (Royden 1993; Zeck 1996; Lonergan and white 1997) to convective removal or delamination model (Platt and Vissers 1989; Vissers et al. 1995; Seber et al. 1996; Mezcuca and Rueda 1997). Calvert et al. 2000, proposing extension was initiated by detachment of over-thickened continental lithosphere during late Oligocene–Early Miocene. The present-day movements of tectonic blocks in the Betic–Rif Arc from GPS velocities measurements shows that the convergence between the African (Nubian) and the Eurasian plates normally NW–SE is perturbed in the central part of the Rif Mountain in northern Morocco and the in the Central Betic cordillera in southern Spain. A south–westward motion is recorded in the central part of the Rif with respect to Africa and west–southwest motion is recorded in the south-western part of the Central Betic with respect to Iberia (Fadil et al. 2006; Tahayt et al. 2008; Vernant et al. 2010; Kouali et al. 2011).

The recent development of seismic networks in the north of Morocco and south of Spain allows the recording of new seismic data that can be used to investigate the lithospheric structure in the Betic and Rif Cordillera. In this paper, we first present the tectonic context, seismic data selection, and methods necessary for the 3-D structure velocity. We used the European PM2 model (Spakman et al. 1993) to perform relocation secondly. After the database preparation, we use local earthquake tomography to accurately obtain the velocity map and crustal structure in the Rif and Betic cordillera. The P arrival times are inverted to define and image the main features of the deep structure in the crust and hyper mantle. The interpretation of images is discussed and compared to the present-day blocks deformation in the Central Betic and Central Rif defined from GPS velocities measurements. Finally, we discuss the implication of new results carried out by this study in the comprehension of Betic–Rif tectonic structures

2 Geological setting

The western Alboran Sea corresponds to the western part of the plate boundary between Eurasia and Africa.

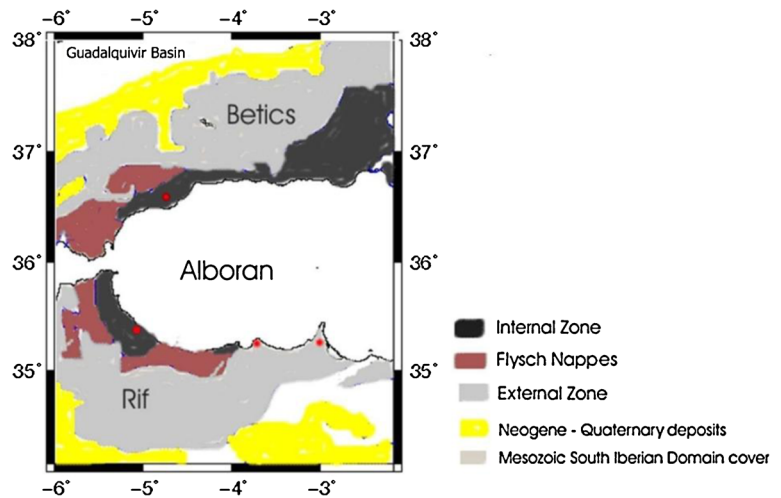
The Betic–Rif Cordillera has been interpreted as a collisional orogen bounded by The Betic–Rif arcuate mountain belt. The Betic and the Rif chain form the northern and the southern branch of the Betic–Rif arcuate orocline (Fig. 1). The convergence between Africa and Eurasia began in the Cretaceous (Dewey et al. 1989). The convergence directions were initially NNE–SSW to N–S before shifting to NW–SE oblique convergence during the Late Miocene time (Dewey et al. 1989). The convergence between the two plates involved northward subduction of the Tethyan oceanic crust that resulted in a NE–SW striking collisional orogenic system (Dewey et al. 1989; Zeck 1999). In the Late Oligocene to Early Miocene, a large extensional basin began forming on the overriding Eurasian plate (Jolivet and Faccenna 2000). The crustal thickness is approximately ~35 km beneath the Betic and the Rif. Beneath the center of the Alboran Sea, the thickness is ~15 km (Watts et al. 1993). Many of the rocks appear to have undergone significant exhumation (Platt et al. 1998; Zeck 1999). With this crustal thickness the heat flow reading in the Alboran Sea increases (Polyak et al. 1996). Both the Betic and Rif orogenic systems have three principal tectonic zones: (1) the internal zones; (2) the flysch nappes; and (3) the external zones (Gomez et al. 2000; Lonergan and White 1997). The internal zone mainly composed of metamorphic rocks containing high pressure, low-temperature units (Torres-Roldan 1979; Gómez-Pugnaire and Fernández-Soler 1987; Goffé et al. 1989; Bakker et al. 1989; Jolivet et al. 2003). The second section is the external zone, mainly formed by sedimentary rocks. Between the external and internal zones are the flysch units that were folded and thrustured during the westward migration of the internal zones.

3 Tomography study

3.1 Data selection and methodology

The arrival time data used in this study were obtained by the Moroccan and Spanish seismic networks from 1988–2008. In order to determine hypocentral parameters and find the local velocity structure of epicentral area, the P and S arrivals at 52 stations located at north of Morocco (National Institute of Geophysics, CNRST, Rabat), and Spain (Instituto Geografico National, Madrid) are used (Fig. 2). We used the travel times of 58,774 P arrivals

Fig. 1 Simplified geologic map of the Betic–Rif Cordilleras



collected from over 5,972 earthquakes from hypocentral depths of 0, 5, 15, 30, 45, 60, and 100 km. The preliminary estimate of origin times and hypocentral coordinates is determined by the HYPOCENTER 3.2 program (Lienert 1994) and the epicentral distribution (Fig. 3) includes all events from 1988 to 2008.

We used in this study the linearized inversion procedure that includes the following two steps: (1) finding the minimal 1-D model using VELEST (Kissling et al. 1994), and (2) simultaneous relocation of hypocenters

and determination of local velocity structure using linearized inversion (Thurber 1983; Eberhart 1990). The minimum 1-D model estimation by VELEST: Kissling et al. (1994) defines the minimum 1-D model. The 1-D velocity represents the least squares solution of the related equation to the coupled hypocenter-velocity model. In this model, the layer velocities are approximately equal to the average velocity in the 3-D tomographic solution within the same range. In the linearized approach, we use the SIMULPS program originally

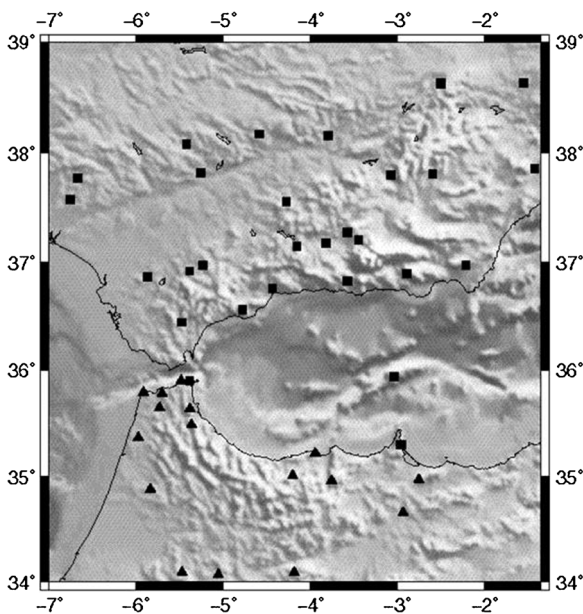


Fig. 2 Locations of stations in north of Morocco (*triangle*) and South of Spain (*square*)

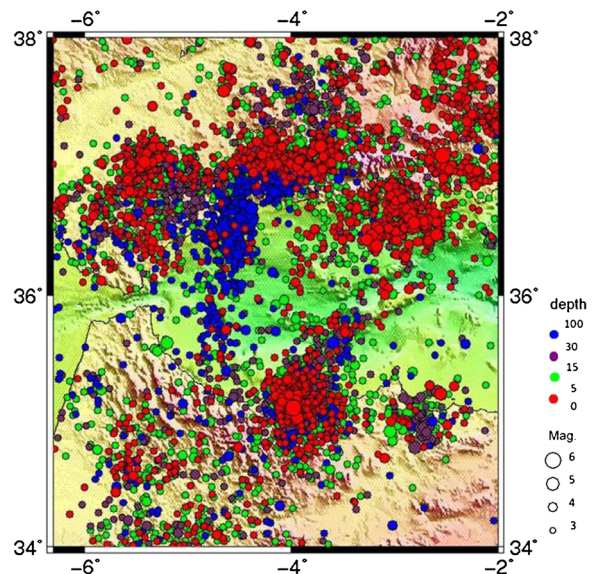


Fig. 3 The epicentral distribution is determined by Hypocenter 3.2 and includes all events from 1988 to 2008 (catalog of CNRST, Rabat and IGN Spain). The background topography is SRTM 3-arc-second digital elevation model

developed by Thurber (1983) using approximate ray tracing (ART) and pseudo-bending algorithms. This method was further improved by Eberhart (1990) for forward modeling of P and S wave arrival times in iterative, damped, least squares inversion for hypo-centers, and 3-D velocity structure. In this approach, the model parameterization assumes a continuous velocity field by linearly interpolating between velocities values defined at the nodes of a 3-D grid (Foulger and Toomey 1989). Nodal locations are fixed prior to an inversion. The earth structure is represented in three dimensions by velocity at discrete points, and the velocity at any intervening point is determined by linear interpolation among the surrounding 8-grid points. Values at the velocity nodes are systematically perturbed during the inversion. Except for the outermost nodes, which are always fixed, every node can either be kept fixed or included in the inversion. The ART algorithm selects the path with the least travel time from a suite of circular arcs connecting the source and the receiver. The iterative pseudo-bending method fine-tunes the ray path obtained by ART to better approximate the true path dictated by the local velocity gradients (Um and Thurber 1987). The P velocities (VP) are assigned in a grid point interval (25, 25 km) at each layer of the crust and in the upper mantle in depth (0, 5, 15, 30, 45, 60, 100 km), the number of points are 20 and 18 in longitude and latitude, respectively

3.2 Relocation of local events

For the relocation of local events, an initial 1-D velocity model was constructed from a reference model (PM2) determined for Europe (Spakman et al. 1993). Each event was relocated using the same starting epicentral location and origin time, but using multiple starting hypocentral depths of 0, 5, 15, 30, 45, 60, and 100 km. Some criteria are used to remove poorly constrained events: the location with the high-weighted RMS residual (>1.0 s) and any event that has a horizontal or vertical shift more than 10 km is discarded. The final 1-D model velocity is shown in Fig. 4 and the final relocation when the two processes are performed (3-D model) is shown in Fig. 5. The crustal seismicity is scattered in the west Alboran beneath the Rif and the Betic and the seismic activity is abundant and present at both shallow and intermediate depths. In the Rif, the seismic activity is relatively limited to shallow depths. The intermediate seismic

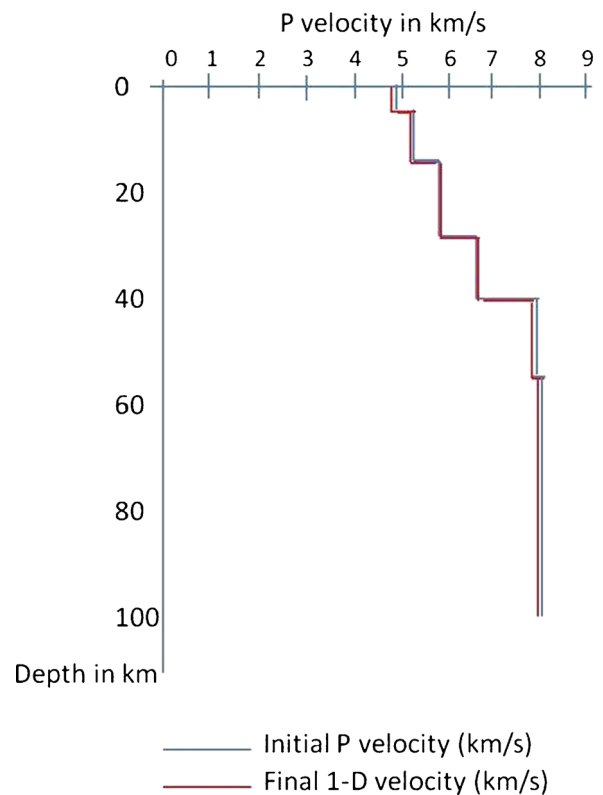


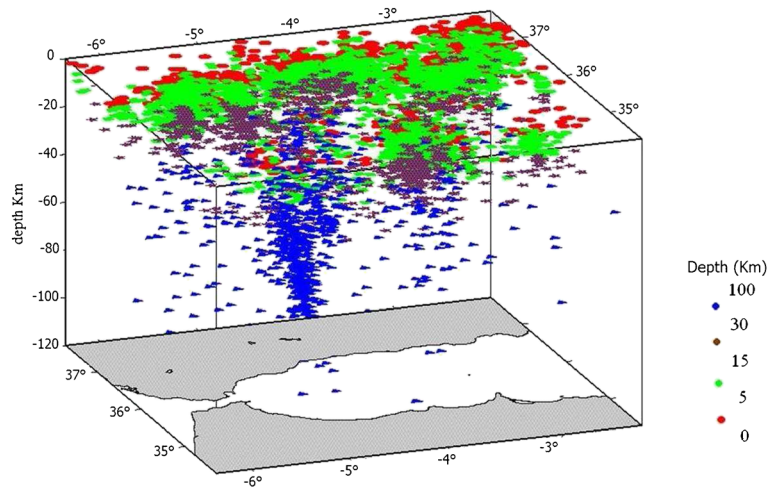
Fig. 4 Initial and Final 1D model velocity P

activity is present in the area from depths of 60 to 150 km and concentrated in a N–S line at 4.5° W also beneath the center of Alboran Sea (Buforn et al. 1995; Seber et al. 1996; Calvert et al. 2000). The depth seismicity is associated to lithospheric bodies detached that may have descended into the upper mantle.

3.3 Resolution analysis and synthetic tests

It is commonly recognized that the tomography inversion result must be assessed with a resolution. By the concept of resolution, we try to know how the true structure is reconstructed in the calculated image. The simplest means to evaluate the resolution of tomography is to invert a synthetic set of travel time and compare the results with the known velocity structure (Zhao and Negishi 1998; Zhao et al. 2001). In this study, the resolution and checkboard tests are used as additional techniques to improve resolution. For the resolution tests, we use the spread function of the averaging vector for the assessment parameter

Fig. 5 Final relocation for the period 1 December 1988 to 31 December 2008 using 3-D model. The crustal seismicity is scattered in West Alboran especially under the Rif and the Betic, and the seismic activity present at both shallow and intermediate. The error range for the estimated depth is ± 1 km



resolution (Foulger and Toomey 1989). A small value of spread function indicates localized averaging of velocity (Fig. 6). In the checkboard test, we first proceed with a variation of the order of $\pm 10\%$ for the P wave in the original 1-D model velocity; then, the estimated synthetics of arrival time for the P waves are calculated by forward problem. The synthetic data

are used for the inversion for the 1-D model with propose to produce a final model which is close to the synthetic one (Fig 7a, b). The quality of this test is verified by knowing at what level the nearly true velocity structure is present in the calculated image (Timoulali and Meghraoui 2011). The VP is assigned in a grid point at each layer of the crust and in the upper

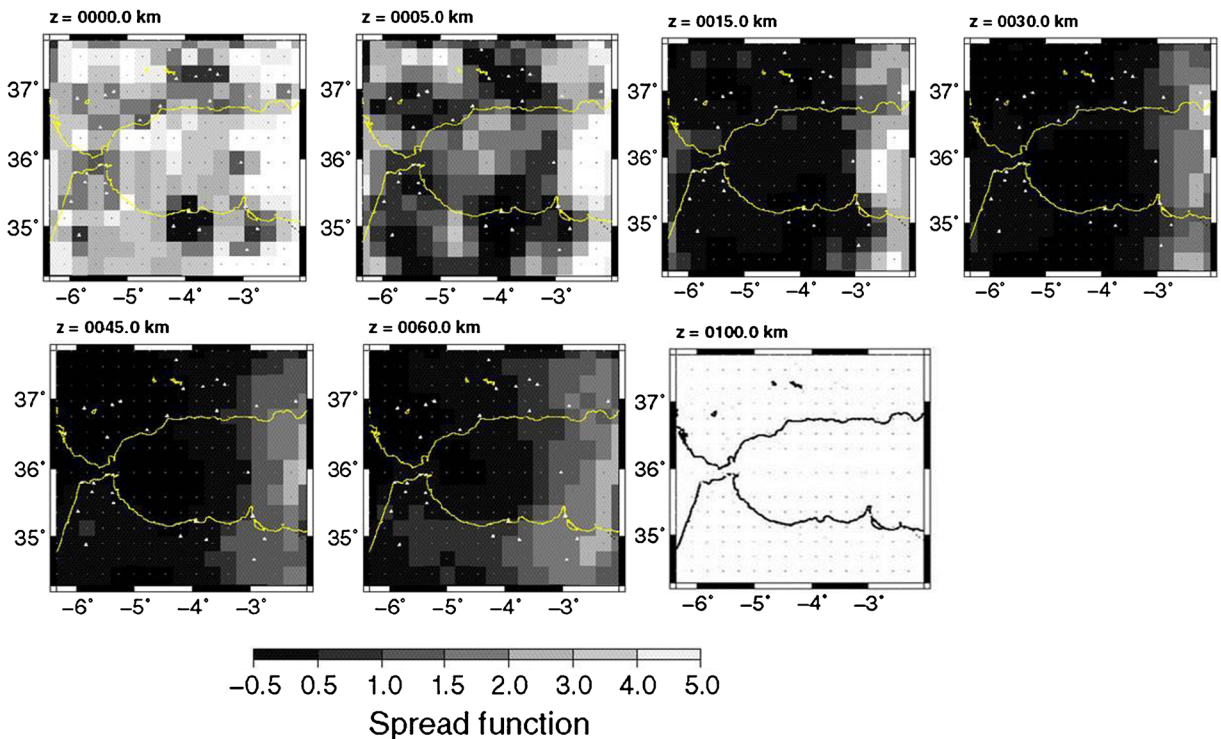


Fig. 6 Test of resolution Spread function at depths 0, 5, 15, 30, 45, 60, and 100 km. The depth of the layer is shown in the *top left corner* of each map. *Triangles* indicate seismic station

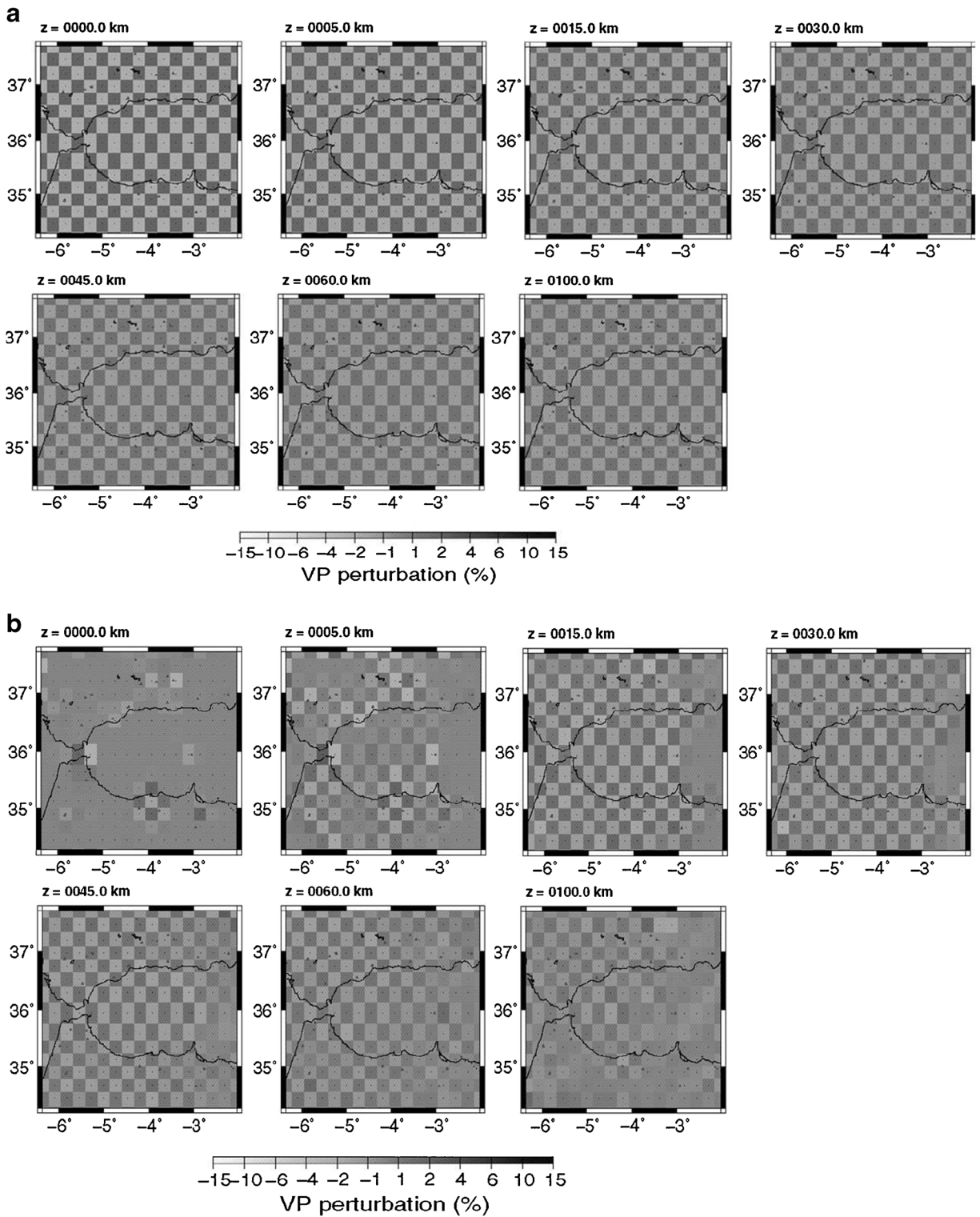


Fig. 7 a The synthetic model test for VP at depths 0, 5, 15, 30, 45, 60, and 100 km; the depth of the layer is shown in the *top left corner* of each map. **b** The synthetic model test results for VP at

depths 0, 5, 15, 30, 45, 60, and 100 km, the depth of the layer is shown in the *top left corner* of each map

mantle. The initial velocity calculated for grid is assigned to be +15 % faster or –15 % slower at the same depth. The resolution test result shows that the calculated images give a nearly true velocity structure from 0- to 60-km depth in the Alboran region.

4 Synthesis of result and implication for lithospheric structure

The resulting tomography image (Fig. 8) has a prominent high-velocity anomaly that shows a maximum increase in P wave velocity of approximately 10 % (blue color) and prominent low-velocity anomaly that shows a maximum decrease in P wave velocity of approximately 10 % (red color). The most striking feature of the velocity model that we obtained in the hyper crust is the significant positive anomaly that appears at 5 km. This crustal structure is presented by a continuous high crustal velocity (6.5 km/s) located between the Betic and the

Rif in the western and in middle of the Alboran Sea (Fig. 8). This proves that the upper crust is probably not totally collapsed or broken down during the Late Oligocene–Early Miocene extensional event. As we know, the convergence between Africa and Eurasia began sometime in the Cretaceous (Dewey et al. 1989; Srivastava et al. 1990) and produced a zone of thick crust (internal zones) that was located in the area between present-day Morocco and southern Spain. During the Late Oligocene–Early Miocene, the belt collapsed along with the limited injection of basaltic dikes beneath the Betic (Torres-Roldan et al. 1986).

At the surface (0–5 km depth), the negative anomaly that appears in the upper crust with low velocities (4.5–5 km/s) are presented by marine deposition when the western portions of west Alboran Basin has subsided below sea level (Comas et al. 1992).

At 15 km, the most striking feature is the positive anomaly with a fast Pn (7.0–7.5 km/s). We interpret this positive lithospheric anomaly as cooling asthenospheric

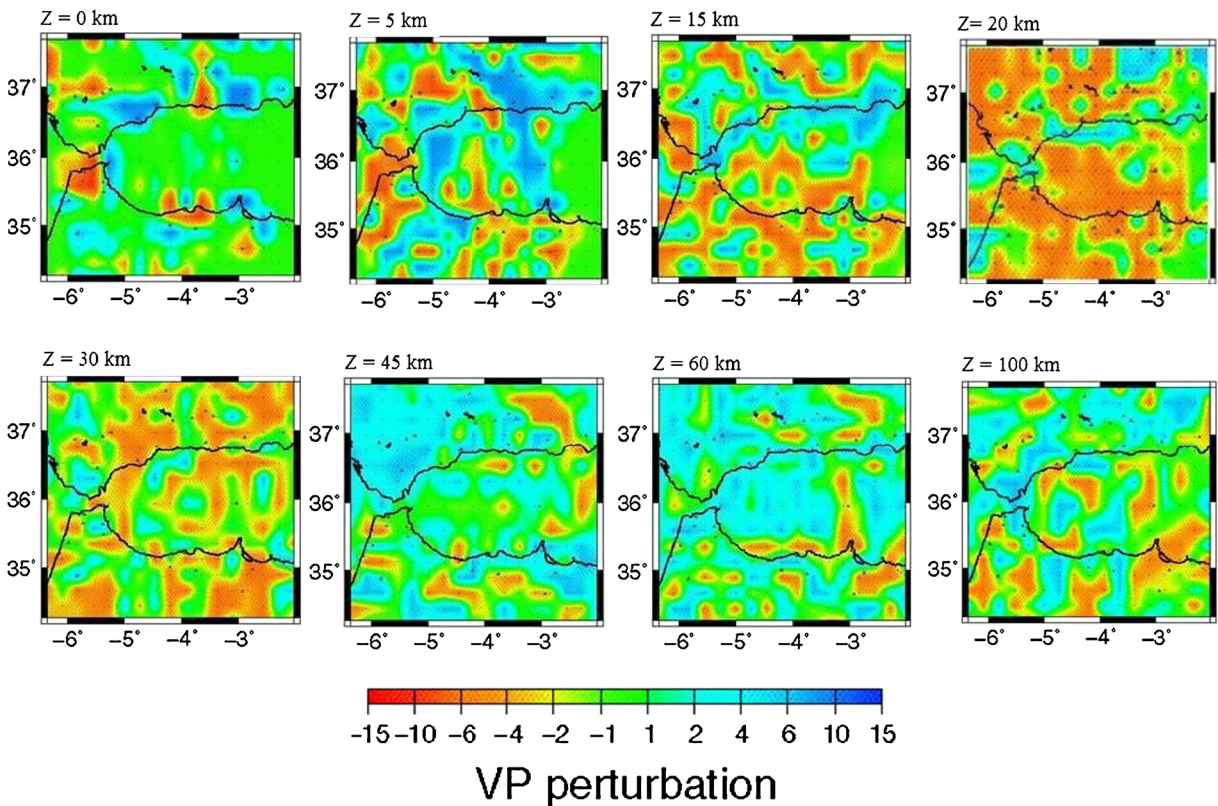


Fig. 8 P wave velocity perturbation (*VP*) relative to 1-D model in the Rif Mountain and in the Betic Cordillera. The depth of the layer is shown at the *top left corner* of each map. *Blue* and *red*

colors denote fast and slow velocities respectively. The velocity perturbation scale in percent is shown at the *bottom* of the figure

material. In the west Alboran Sea, a combination of isostatic surface/topographic uplift and erosion induce a rapid exhumation and cooling of deep crustal rocks (Platt et al. 1998).

In 20- and 30-km depth, the most striking feature is the negative anomaly with a slower Pn (7.0–7.5 km/s). We interpret this negative lithospheric anomaly as a hot asthenospheric material coming from depth to replace the part of crust detached. These anomalies are associated with region warm or absent mantle lithosphere or the presence of melt (Hearn T. 1996). The high-heat flow reading in the Alboran basin (Polyak et al. 1996) can be explained by the presence of hot ductile material. In the geodynamic model this extrusion of hot asthenosphere material is interpreted as an uplift and extension in the Alboran area (Thompson et al. 1997a, b).

At 45 and 60 km, the most striking feature is the positive anomalies with fast Pn (7.5–8.0 km/s) associated to the lithospheric body that has descended into the upper mantle. The profile in the Alboran basin indicates that the crust thickness is relatively thin (15–20 km) in agreement with previous proposals that the continental crust beneath the Alboran is thin (e.g.,

Working Group for Deep Seismic Sounding in the Alboran Sea 1978). The profile in the south-eastern Betic show the thickness of crust is relatively thin (~24 km) also in agreement with the work of (Banda and Ansorge 1980).

4.1 Crust and upper mantle velocity in the Rif Mountain

The most striking feature of velocity model we obtained in the Rif Mountain is located in the Central Rif (Fig. 8). This significant positive anomaly is defined as upper crust body with high velocity (6.5 km/s). This crustal structure is presented by two crustal bodies. The first one is oriented in direction NW–SE and dipping in SE. This body is extended in the southern part of Alboran Sea beneath the Rif Mountain (Figs. 9, 10, 11). We interpreted this body as remainder of Alboran lithosphere detached from crust and still attached and extended from the western part of the Rif. The second crust body is located in the south beneath the Rif, oriented NE–SW and dipping SW (Figs. 9, 10, 11). This body is interpreted as a remainder of Ligurian

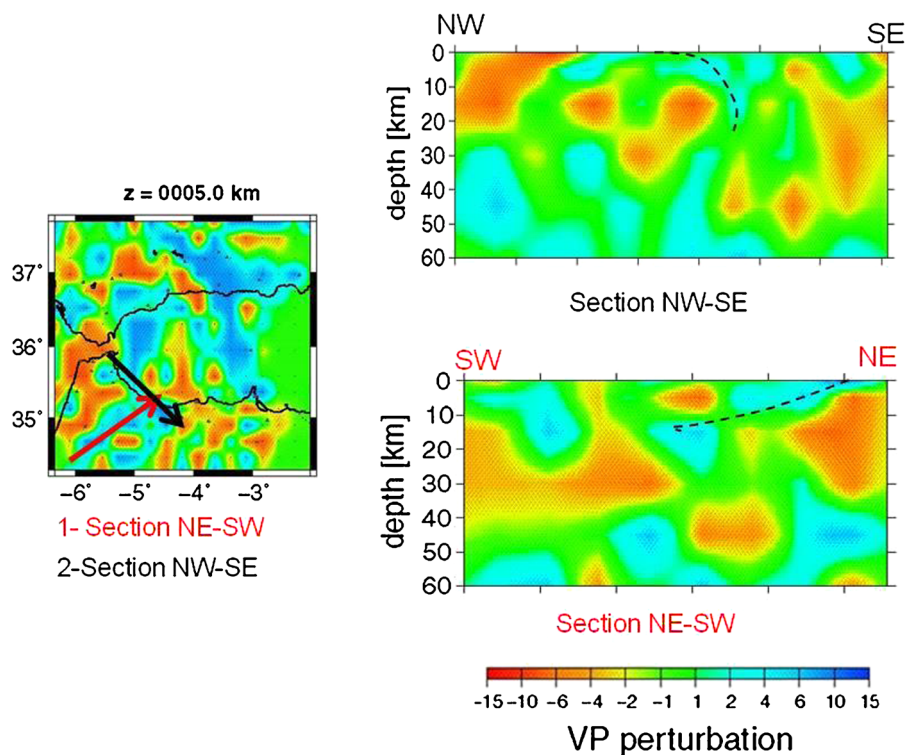
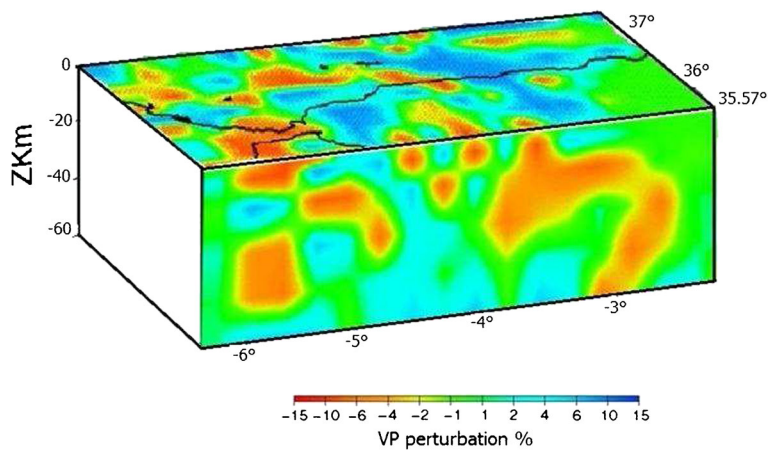


Fig. 9 Upper crust body (velocity 6.5 km/s) defined between Iberian Betic and Moroccan Rif in the western and in the middle of Alboran Sea. *Section 1* show the crustal bodies oriented NE–SW and *Section 2* show the crustal body oriented NW–SE located beneath in the Rif

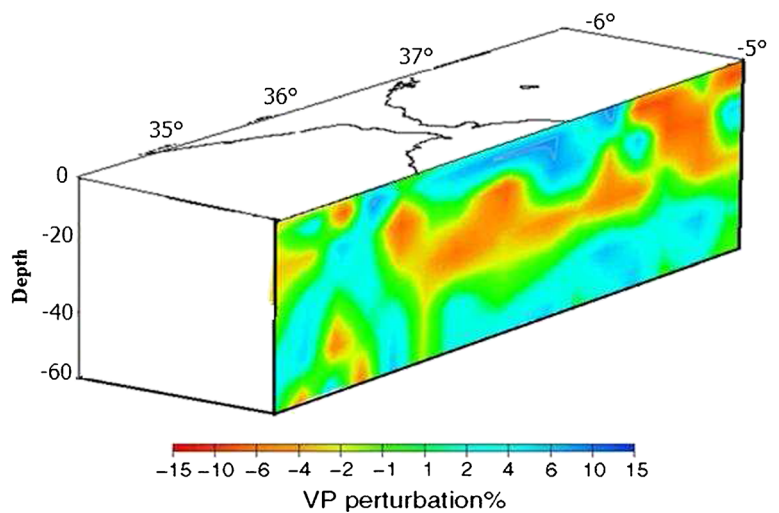
Fig. 10 Vertical cross section along profile 35.57 °N in Rif Mountain showing the crustal body oriented NW–SE dipping in SE. The P wave velocity perturbation (in percent), *Blue* and *red* colors denote fast and slow velocities, respectively



ocean lithosphere separated Iberia and Africa still at present continental lithosphere (Schettino and Scotese 2002).

The profile along 5°W in Fig. 11 show that the Alboran crust is oriented N–S and extended from the extremely south west of Iberic Cordillera to the Rif in the south. The contact between Iberic Cordillera and the Alboran crust is clearly defined in the SW Iberic region. In this profile, two crust bodies with crustal velocity 6.5 km/s are detected in the southern part. The crust body oriented NE–SW dipping in SW has been recently detected by GPS with a west–southwest motion with respect to Africa.

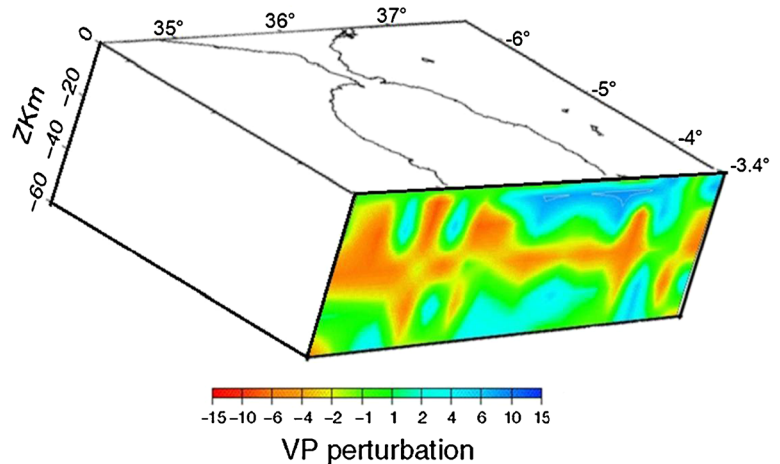
Fig. 11 Vertical cross section along profile 5°W in Betic–Rif Cordillera showing the crustal body oriented NE–WS and dipping SW and that oriented NW–SE dipping in SE beneath the Rif mountain. The P wave velocity perturbation (in percent) *blue* and *red* colors denote fast and slow velocities, respectively



4.2 Crust and upper mantle velocity in the Betic Cordillera

The most striking positive anomaly imaged in the Betic Cordillera is in Central Betic Cordillera. This structure is oriented N–S direction and dipping to the North (Figs. 8, 12). This crustal structure is interpreted as an upper crust body presented with crustal velocity (6.5 km/s). This body was detected by magneto-telluric survey carried in the central part of Betic (Pous et al. 1995). The negative anomaly structure is located from 25- to 30-km depth with a Pn velocity that varies from 7.0 to 7.5 km/s and showing a low-velocity zone in the Betic and NW Betic

Fig. 12 Vertical cross section along profile 3.4°W showing the main features of the deep structure in the Central Betic. The P wave velocity perturbation (in percent) *blue* and *red* colors denote fast and slow velocities, respectively



cordillera. These negative anomalies are associated with region warm or absent mantle lithosphere or the presence of melt (Hearn 1996; Seber et al. 1996; Calvert et al. 2000). The high-heat flow reading in Alboran basin (Polyak et al. 1996) confirm the presence of hot material. The profile along 37°N in the Betic Cordillera (Fig. 13) show that the thickness of crust beneath the Central Betic Cordillera varied from 30- to 40-km and contains low-velocity anomalies. This confirms the modest crustal tectonic shortening and thickening in the Betic cordillera. The VP perturbation profile along 37°N (Fig. 13) show that the upper crust have a sub horizontal contact at 10 km in depth in major part of Central Betic Cordillera. The lower crust below the conductor body in the Central Betic is replaced and heated by asthenospheric material. Banda et al. (1993) suggest that there is no lower crust below the internal zones of the Cordillera.

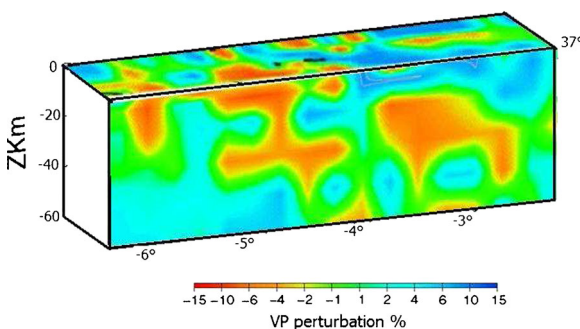


Fig. 13 Vertical cross section along profile 37°N in the south of Betic Cordillera showing the main features of the deep structure in the Central Betic. The P wave velocity perturbation (in percent) *blue* and *red* colors denote fast and slow velocities, respectively

4.3 Geodynamic model and present-day deformation in the Betic–Rif Arc from GPS velocities

The convergence between Africa and Eurasia began in the Cretaceous (Dewey et al. 1989). During the Late Cretaceous, the lithospheric thickening through Paleogene resulted in a large, gravitationally unstable lithospheric in NE striking zone of thickened crust. During the Late Oligocene and Early Miocene, a delamination process began (Torres-Roldan et al. 1986). The lithosphere was detached beneath the area of the Alboran Sea and slowly peeled back to the west or northwest (Calvert et al. 2000). The major part of this lithosphere was removed beneath the area except in the western and in the middle part of the Alboran Sea. In these two regions, this study shows the presence of a continuous crustal block with high velocity (6.5 km/s) at 5 km (Fig. 8), which proves that the upper crust in the West Alboran Sea is not totally collapsed or broken down during the Late Oligocene–Early Miocene. The removal of lithosphere from the base of the crust was replaced and heated by extrusion of asthenospheric material. The extension and uplifting in the Alboran sea area followed this delamination process.

In the most western part of the Alboran Sea, this study shows also the presence of two lower crustal structures that is still attached to the western block beneath the Rif. The first is oriented NW–SE and dipping in SE beneath the Rif and the second is oriented NE–SW and dipping SW from the Central Rif (Figs. 9, 10, 11).

Several studies analyze the current displacement of the Earth's surface in the Gibraltar region (Stich et al. 2006; Fernandes et al. 2007; Fadil et al. 2006; Tahayt et al. 2008; Vernant et al. 2010). The complete GPS-

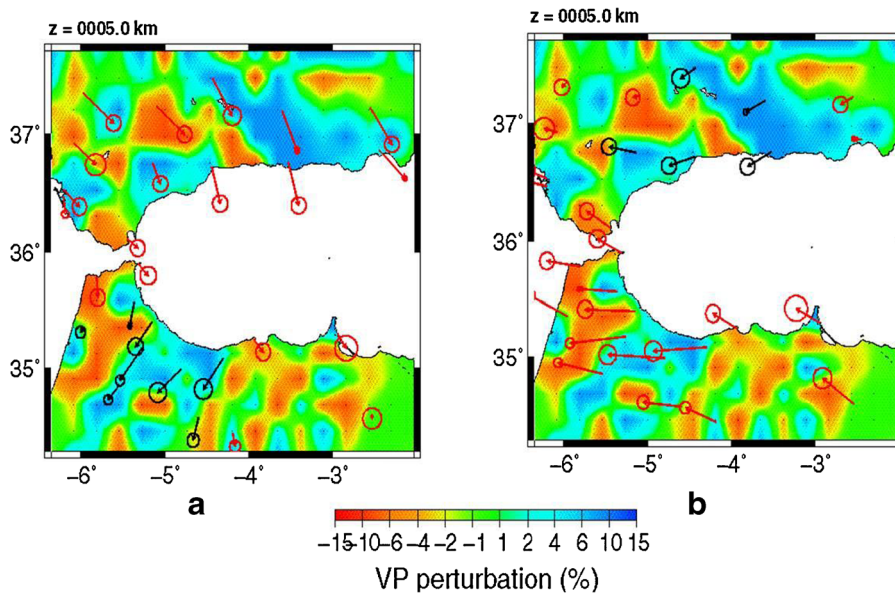


Fig. 14 Crustal blocks defined with a high-velocity anomaly in the Central Rif and Central Betic are consistent with the GPS' positions that recorded south–westward motion in the central

part of the Rif with respect to Africa (a) and west–southwest motion in the Central Betic Cordillera with respect to Eurasia (b)

derived velocity field has been recently provided by Kouali et al. (2011) based on a GPS network including 31 GPS survey points observed for different time intervals (1999–2009) and 65 continuously recording GPS stations extending Morocco to southern Spain. These papers shows the presence of independent blocks situated between the obliquely converging Iberian and African plates, showing a south–westward motion (3.5 to 4.0 mm/year) in the central part of the Rif with respect to Africa and west–southwest motion (3 mm/year) in south–western part of the Central Betic with respect to Eurasia.

The crustal blocks clearly defined with a high-velocity anomaly in the Central Rif and Central Betic are consistent with the GPS' positions that record the south–southwest motion in the Rif Mountain and west–southwest motion in the Central Betic Cordillera. In the Central Rif, the location of the south–southwest motion recorded by GPS coincided with the location of the crustal body oriented in direction NE–SW and dipping SW (Fig 14a). This body is interpreted as a remainder of Ligurian ocean lithosphere separated Iberia and Africa still at present continental lithosphere. The kinematics of this body is associated with slowly peeled back direction. In the Central Betic Cordillera, the crustal body oriented N–S and dipping to the North present west–southwest motion (Fig 14b). The presence of these

crustal blocks whose boundaries are well defined by tomography in the Betic–Rif Cordillera, characterized by their own movements recorded by GPS allows as to define a tectonic blocks in the surface (Fig 15) also to helps us to explain the seismicity generated inside and in the border of these crustal blocks.

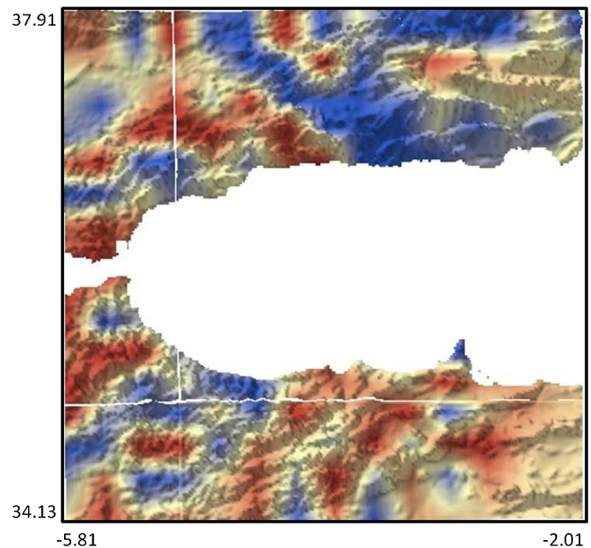


Fig. 15 High-velocity anomaly (Blue colors) on the surface projected delimiting major tectonic blocks in the Betic–Rif Cordilleras. The background topography is SRTM 3-arc-second digital elevation model

5 Conclusion

Based on the analysis of local P waves travel times and profiles, we can find that the crustal structure in the Betic–Rif cordillera is complex. The tomography result shows the following:

- A continuous high velocity demarcates two crustal blocks located between the Betic and the Rif in the western and middle part of the Alboran Sea which proves that the upper crust in the West Alboran Sea is not totally collapsed or broken down during the Late Oligocene–Early Miocene. The major part of the lithosphere was removed beneath the area by delamination process except in the western and middle part of the Alboran Sea.
- The removal of lithosphere from the base of the crust was replaced and heated by extrusion of asthenospheric material.
- A part of the lithosphere was detached beneath the area of the Alboran Sea and slowly peeled back to the west, still attached to the western block beneath the Rif. The most obvious are the lower crustal structures beneath the Rif oriented NW–SE and dipping in SE beneath the Rif.
- The crustal blocks clearly defined with a high-velocity anomaly in the Central Rif and in Central Betic are consistent with the GPS' positions that record the south–southwest motion in the Rif Mountains and west–southwest motion in the Central Betic Cordillera.
- In the Central Rif, the location of the south–southwest motion recorded by GPS coincided with the location of the crustal body oriented in direction NE–SW and dipping SW. This south–southwest motion put this crustal body in evidence in present day. This body is interpreted as remainder of Ligurian ocean lithosphere separated Iberia and Africa still at present continental lithosphere.
- In the Central Betic Cordillera, the crustal body oriented N–S direction and dipping to the north present west–southwest motion.
- The presence of these crustal blocks with boundaries are well defined in the Alboran Sea and in the Betic–Rif Cordillera, allowing us to explain better the seismicity generated inside and in the border of these crustal blocks, since the area with high-velocity values could represent brittle and competent parts of the

crust and lithosphere which sustain seismogenic stress where asperities along the faults could exist and probably more with the Iberia–Africa plate convergence.

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