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Active Tectonics of the western Mediterranean: Geodetic evidence for roll back of a delaminated subcontinental lithospheric slab beneath the Rif Mountains, Morocco

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ABSTRACT

Surface deformation in Morocco derived from five years of GPS survey observations of a 22-station network, four continuously recording GPS stations, and 4 IGS stations in Iberia indicate roughly southward motion (~3 mm/yr) of the Rif Mountains, Morocco relative to stable Africa. Motion of the Rif is approximately normal to the direction of Africa-Eurasia relative motion, which is predominantly strike slip, and results in shortening of the Rif and subsequent crustal extension of the adjacent Alboran Sea region. The sense, and the N-S asymmetry of the observed deformation (i.e., no evidence for north-directed shortening in the Betic Mountains north of the Alboran Sea) cannot be easily explained in terms of crustal plate interactions suggesting that dynamic processes below the crust are driving the recent geologic evolution of the western Mediterranean. The model that best fits the observations involves delamination and southward roll back of the African lithospheric mantle under the Alboran and Rif domains.

Keywords: GPS, active tectonics, Alboran Sea, continental dynamics

Tectonic Setting of the Western Mediterranean

In the western Mediterranean, the Alboran domain is caught between North Africa and Iberia at the westernmost limit of the Alpine mountain belt (Fig. 1). During the Cenozoic, the Alboran domain, along with the Atlas Mountains, grew thicker in this convergent setting (Chalouan and Michard, 2004; Platt and Vissers, 1989). Later during the Miocene, the Alboran domain stretched and subsided below sea level, accumulating more than 7 km of sediment (Watts et al., 1993).

Present-day tectonic processes occur within the context of ongoing, ~NW-SE convergence between Africa and Iberia in the Strait of Gibraltar (4.3 ± 0.5 mm/yr at of

116 ± 6° from GPS, McClusky et al., 2003). However, the location of a discrete Africa-Eurasia plate boundary is equivocal (Fig. 1). Geomorphologic studies demonstrate recent tectonic activity in the Rif (Morel and Meghraoui, 1996) and the Atlas Mountains (Gomez et al., 1996; Gomez et al., 2000), and suggest that most of the present-day convergence is accommodated in the Rif-Betic-Alboran region.

Ideas to explain the striking topographical symmetry of the region as well as the apparently synchronous extension of the Alboran Sea and shortening of the Betic and Rif mountain belts during the Neogene and Quaternary are still widely debated. Current tectonic models for the Alboran domain include four broad categories of hypotheses: (1) backarc extension driven by the westward rollback of an eastward subducting slab (Royden, 1993; Lonergan and White, 1997; Gutscher et al., 2002; Faccenna et al., 2004); (2) break-off of a subducting lithospheric slab (Blanco and Spakman, 1993); (3) crustal extrusion due to forces transmitted across the Eurasia-Africa plate boundary (Rebai et al., 1992); and (4) delamination and convective removal of the lithospheric mantle root beneath the collisional orogen (Platt and Vissers, 1989; Seber et al., 1996; Calvert et al., 2000). Testing these hypotheses by confronting their predictions with the present-day deformation field suggests that a subcontinental lithospheric slab is currently delaminating and rolling back under the Rif Mountains. Hence, this paper provides additional constraints on the tectonics of the Alboran domain, as well as the dynamics of subduction processes.

GPS Observations and Data Processing

The GPS network includes 22 GPS survey points (observed in October 1999, 2001, 2002, and 2004) and 4 continuous GPS stations (CGPS, Fig. 2). We analyze the GPS data using the GAMIT/GLOBK software in a two-step approach. The GPS solution is realized in the ITRF2000 global reference frame, and then rotated into an Africa reference frame using 13 stations (see online supplement for details).

Active deformation of NW Africa

Figure 2 shows GPS velocities in an Africa-fixed reference frame. Uncertainties for survey sites are mostly < 1 mm/yr (1 sigma), and < 0.5 mm/yr for the 4 CGPS. The velocity uncertainties are large for two stations (BBFH, MDAR) near the epicenter of the Al Hociema earthquake because the cosesimic offsets break the time series. For the 13 sites located south of the Rif Mountains, GPS velocities are consistent with the motion of Africa at the 95% confidence interval (Fig. 2). However, there is a systematic trend for baselines crossing the Atlas mountain system that indicate shortening normal to the strike of the range (0.4 ± 0.6 mm/yr and 1.0 ± 0.6 mm/yr in eastern and western High Atlas). While these estimates are barely significant, they are consistent with the lower range of geological rates (~1–2 mm/yr, Gomez et al., 2000).

The anomalous motions of the western and central Rif Mountains are apparent in the Africa-fixed velocity map (Fig. 2). Northwestern Morocco is moving ESE as indicated by two CGPS (CEUT and TETN), and the survey site TNIN. In contrast, the central Rif Mountains are moving almost due south as defined by four survey sites (LAOU, BBFH, ZAGO, MSLA), and the CGPS IFRN. Southward motion of the central Rif is largest in the north (3.4 ± 1.2 mm/yr) and decreases to the south. These observations suggest two distinct kinematic patterns of deformation within the Rif.

To illustrate better the motion of the Rif and the relation to hypothesized plate boundaries, in Figure 3 we plot the components of the GPS velocities normal and parallel to two profiles striking N20°E, roughly perpendicular to the direction of Eurasia-Africa relative motion (~N110°E) (see location on Fig. 2). For the western profile, the velocity component in the direction of Eurasia-Africa motion (i.e., normal to the strike of the profile) clearly shows the relative plate motion (Fig. 3a), and no significant motion normal to the direction of relative plate motion (Fig. 3b). We use an elastic block model, (Meade and Hager, 2005), to investigate the consistency of the observed pattern of motion with the three hypothesized plate boundaries illustrated in Figure 1. The width of the deformation zone across block boundaries depends on the assumed fault-locking depth. We use a locking depth of 15 km for all faults, in agreement with the maximum depth of the seismicity (Calvert et al., 1997; Stich et al., 2005). Model results for the three plate boundary geometries illustrated in Figure 1 are shown in Figures 3a and 3b. In the westernmost Rif the GPS results are inconsistent with the plate boundary located south of the Rif (Bird, 2003), and support models where the boundary passes either through the Gibraltar Strait (Klitgord and Schouten, 1986) or the Betic Cordillera (Gutscher, 2004). The sparse GPS results available for the Betics do not allow us to distinguish between these two proposed boundaries. The models predict no significant motion normal to the direction of relative plate motion (N20°E), consistent with the GPS observations.

The second, more eastern profile crosses the central Rif (Fig. 2). As for the western profile, Eurasia/Africa relative motion is apparent (Fig. 3d), but the component of velocity normal to the direction of relative plate motion shows anomalous deformation in the Alboran/Rif area (Fig. 3e). None of the proposed plate boundary geometries can account for this anomalous motion. To account for this southward motion, we have developed a kinematic model including a central Rif block (Fig. 4). As for the other block models shown in Figure 1, we assign a 15 km locking depth to all block boundaries, except for the western boundary of the Rif block in N Morocco where we use a shallow (5 km) locking depth to match better the abrupt change in velocity between the western and central Rif. The western and southern boundaries of the Rif block are well constrained by the GPS velocities. However, no regional right lateral strike slip faults are reported where we locate the western Rif block boundary, suggesting that this boundary could be interpreted as a broad shear zone. The southern Rif block boundary corresponds to mapped Quaternary thrust faults along the southern edge of the Rif (Moratti et al., 2003). The northern and eastern boundaries of the Rif block are poorly constrained by the GPS results. We have chosen to locate the eastern boundary along the NS trend of the 1994 and 2004 Al Hoceima earthquakes, and the seismically active Alboran Ridge, consistent with most other interpretations (Fig. 1). The Rif-Alboran block we propose is a combination of previously proposed northern and southern boundaries, capturing aspects of each of these prior interpretations. The predicted interseismic motion along the two profiles for this model is in good agreement with the GPS velocities (Fig. 3).

Geodynamic Implications

Present-day motions indicated by GPS in northern Morocco, and southern Iberia appear consistent, to first order, with geological indicators of active neotectonic deformation, indicating crustal shortening in the central Rif juxtaposed with extension of the Alboran Sea. Left lateral strike slip rates on NNE striking faults along the east side of the central Rif block derived from our model (~4–6 mm/yr) are roughly consistent with rates reported from studies of active faults in the Rif (Morel and Meghraoui, 1996), as well as with the sense of motion indicated by the 1994 and 2004 earthquakes (Calvert et al., 1997; Stich et al., 2005). Furthermore, the N-S width of the deep Alboran Basin is ~140 km. Assuming the NNE-SSW GPS extension rate of ~4.5 mm/yr is constant in time, the basin would be formed in ~31 Ma, in good agreement with geological estimates for the beginning of extension at 27 Ma (Platt and Whitehouse, 1999).

The general agreement between GPS and geologic indicators of neotectonic deformation suggests that the GPS results depict those geodynamic processes responsible for the geologic evolution of the Alboran Sea-Rif Mountain system, providing quantitative constraints on models for the evolution of this segment of the Africa-Eurasia plate boundary. The location of the Rif-Alboran block within the Eurasia/Africa collision zone raises the possibility that this block is being extruded southward. However, the occurrence of extension on the northern and northwestern boundaries of the Rif-Alboran block within the Alboran domain (Fig. 4) appears inconsistent with extrusion models that involve compressive forces transmitted across plate boundaries. West-directed roll back of an east dipping slab is also unable to account for the observed deformation since this model predicts westward motion of Gibraltar relative to Africa (Gutscher, 2004), inconsistent with the well defined eastward motion of GPS sites in northwestern Morocco.

An alternate geodynamic model proposes that the subcontinental part of the lithosphere under the Alboran domain has been removed by active delamination. As pointed out by Platt et al. (2003b), simple delamination would produce a radially symmetric pattern of surface deformation. Although GPS data are lacking in the Betics, the GPS velocity field indicates neither E-W nor N-S symmetry north of the Alboran Sea (Fig. 3e).

The observed, southward directed motion of the central Rif, roughly normal to the direction of Africa-Eurasia relative plate motion, supports the hypothesis that subcrustal process are controlling the opening of the Alboran Sea and adjacent shortening in the Rif. Based principally on the GPS results, the asymmetric deformation appears to be more indicative of a component of southward-directed slab roll back and associated N-S back arc opening (Fig. 3f) than with simple symmetric delamination confined to the Alboran Sea region. The direction of roll back corresponds to the direction of motion of the inferred Rif block (SSW relative to Africa). Because the Rif-Alboran-Betic region is continental in character (Platt and Vissers, 1989), the present-day slab is probably the mantle part of the continental lithosphere, which has become detached from the crust and is rolling back to the south, possibly due to the pull of an old slab (Faccenna et al., 2004). These results indicate that neotectonic deformation in the western Mediterranean, including juxtaposed extension of the Alboran Sea and shortening of the surrounding mountain ranges results from dynamic processes in the upper mantle associated with continued convergence of the African and Eurasian plates.

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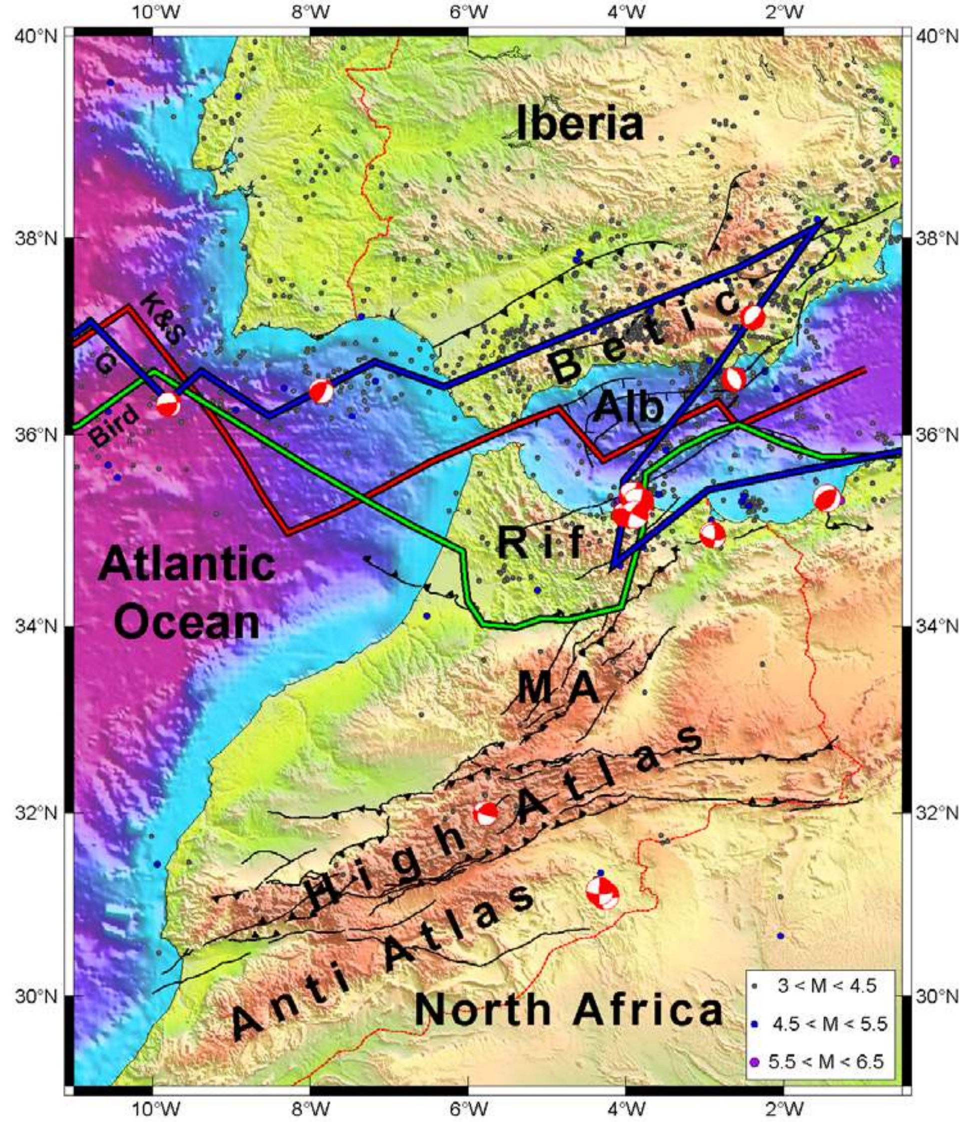

Figure 1. Seismotectonic and topographic/bathymetric (SRTM30 PLUS) map of the westernmost Mediterranean region. Black lines are mapped faults. Three hypotheses for the geometry of the plate boundary are show in red (Klitgord and Schouten, 1986), green (Bird, 2003), and blue (Gutscher, 2004). Crustal earthquake focal mechanisms are from Harvard catalog (magnitudes 5–6.5, 1976 – 2005). Crustal seismicity is from NEIC catalog crustal earthquakes with magnitudes from 3 – 6.5 (1976 – 2005). MA = Middle Atlas.

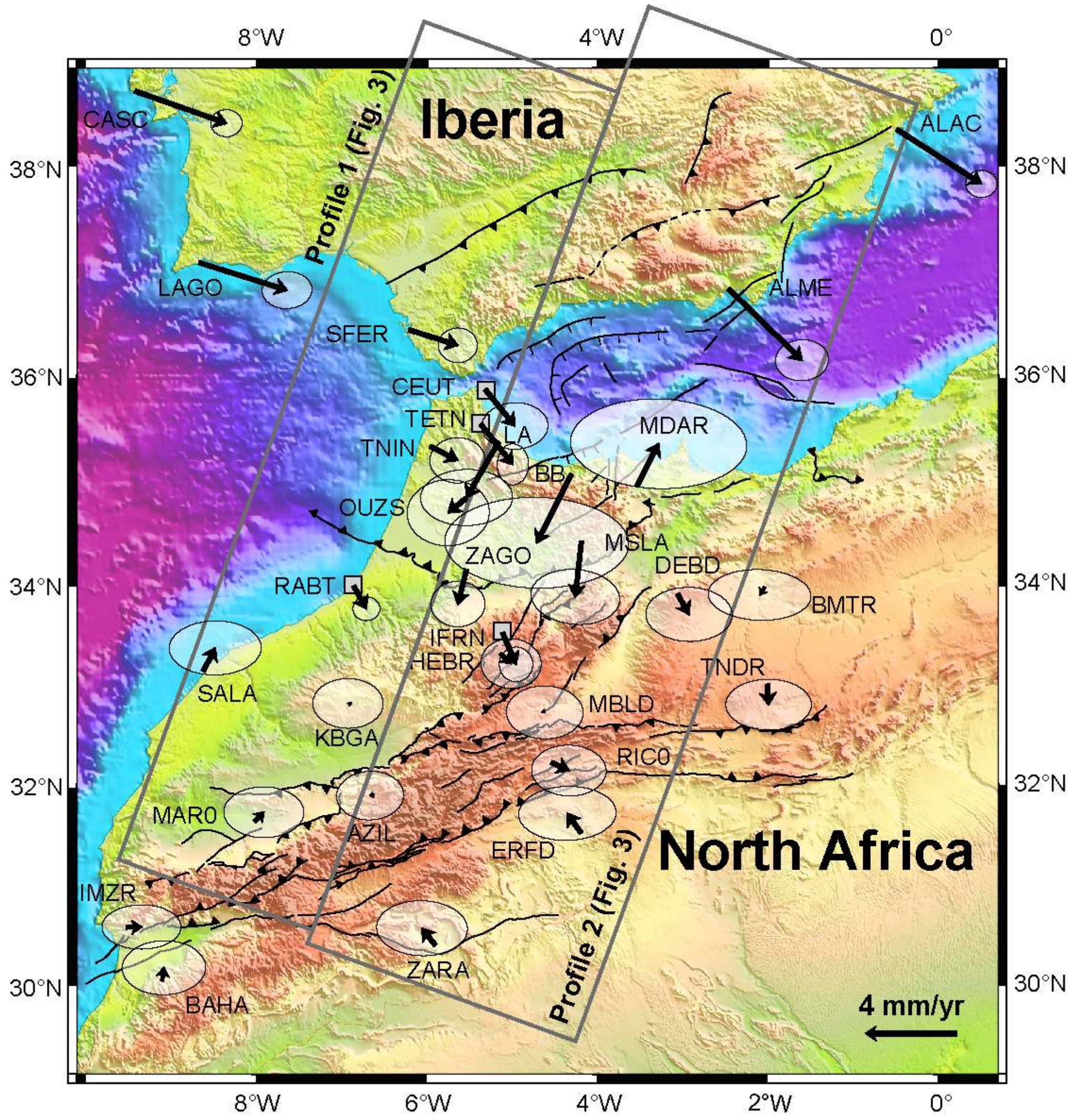

Figure 2. Map showing GPS-derived site velocities and 95% confidence ellipses relative to Africa for sites in Morocco and adjacent Iberia (GPS stations are identified by 4 letters, BB = BBFH, LA = LAOU). Continuously recording GPS stations in NW Africa are indicated by squares. The gray boxes show the orientation and width of profiles 1 and 2 in Figure 3, the profiles go farther north to southern France. Base map as in Figure 1.

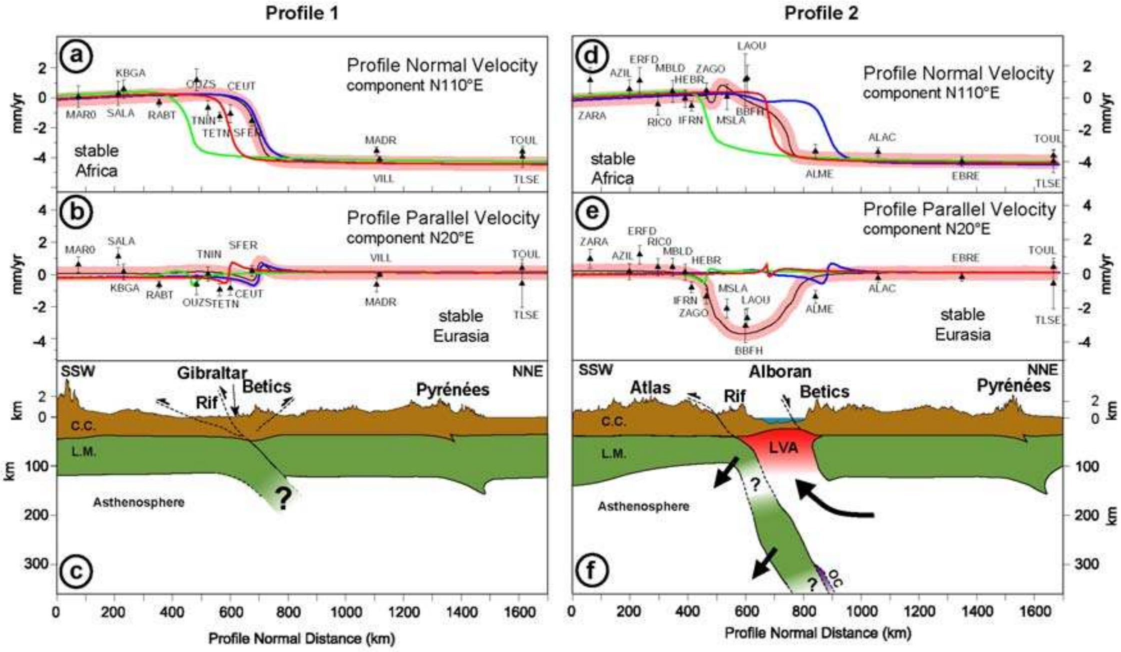

Figure 3. Profile 1 and profile 2 (western profile in Fig. 2). a) and d) Component of velocities and 1-sigma uncertainties along the direction of plate motion (normal to profile), b) and e) Component of velocities and 1-sigma uncertainties normal to the direction of plate motion (i.e., parallel to profiles). The interseismic deformation predicted by elastic block models is shown for the three main hypothesized plate boundaries (Red = (Klitgord and Schouten, 1986); Green = (Bird, 2003); Blue = (Gutscher, 2004), see Figure 1 for geometry). The thick pink line with a thin black line in the center is for a model with a central Rif block (see Figure 4 for geometry). c) and f) Topography and interpretative cross section along profiles 1 and 2. LVA = low velocity and high attenuation anomaly (Calvert et al., 2000; Seber et al., 1996). CC = continental crust, LM = lithospheric mantle, OC = oceanic crust

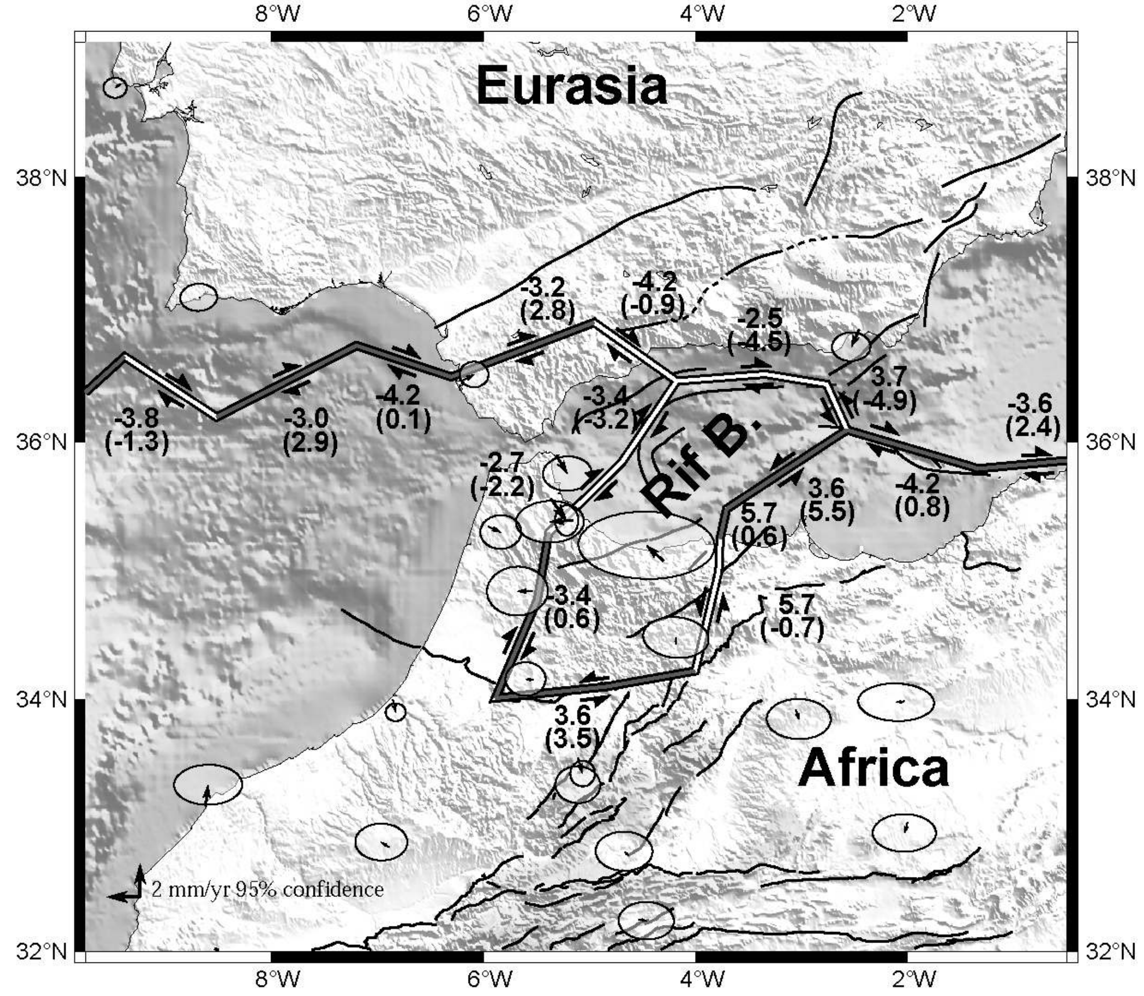

Figure 4. Map showing elastic block model for the Africa-Eurasia plate boundary in the western Mediterranean and GPS residual velocities and 95% confidence ellipses for our preferred model. Numbers show strike slip and fault normal average slip rates along each segment in mm/yr (fault normal component in brackets; negative for left-lateral and extension). Grey modeled faults indicate segments with fault-normal shortening. Formal uncertainties on model slip rates are ~1 mm/yr.

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