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Elastic block model for the Betic-Rif Arc from inversion of GPS data

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Introduction

This work provides an updated kinematic block model for the Betic-Rif region in western Mediterranean based on the compilation of the most recent GPS measurements. The study zone includes the tectonic plate boundary between the Nubia and Eurasia plates, where the exact boundary between the two plates is diffuse. The complexity of the plate boundary in the Betic-Rif arc is also evidenced by: i) broad spatial distribution of seismicity; ii) variety of focal mechanisms; iii) non-uniform crustal deformation field deduced from GPS observations.

Tectonic setting

The Betic Cordillera in southern Spain, together with the Rif Mountains in northern Africa, represent an arcuate shaped fold-and-thrust belt, which was formed as a result of complex tectonic processes that involved a convergence between Africa and Eurasia tectonic plates.

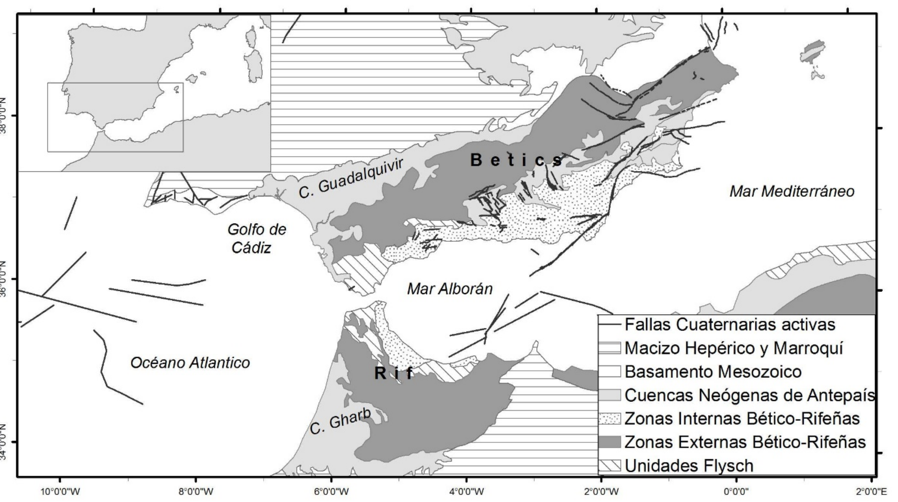


Figure 1: Geo-tectonic map of the Betic-Rif arc. Black thick lines indicate Quaternary active faults according to QAFI database (García-Mayordomo et al., 2012). Inset shows a location of the study area with respect to the Iberian Peninsula.

Seismicity

The Betic-Rif region is seismically most active region of the Iberian Peninsula and Africa. Only in Spain and Portugal, since the 15th century at least 15 earthquakes with intensities greater then IX have been registered. In northern Africa there have been at least 5 earthquakes of similar intensities, since the 17th century.

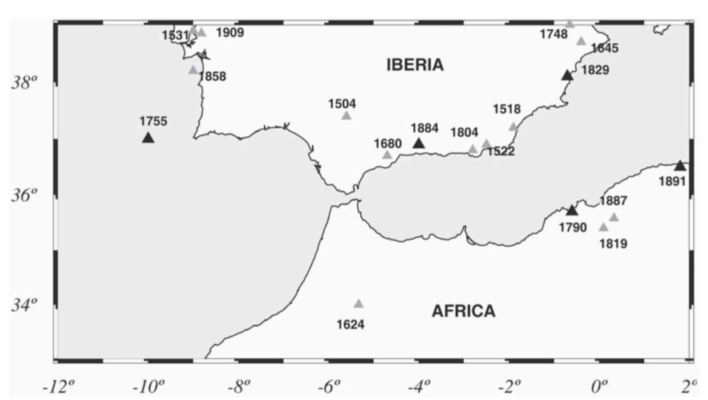


Figure 2: Historical seismicity of the Betic-Rif region. Earthquakes between 1500 and 1900 with MSK>IX according to *Martinez Solares y Mezcua* (2002) and *Buforn and Udias* (2007).

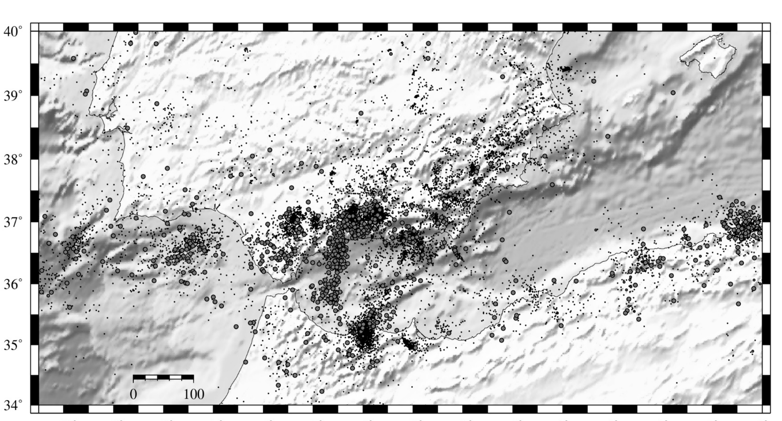


Figure 3: Instrumental seismicity from the NEIC/USGS catalog spanning 1976-2013 time period. Earthquakes With M>5 are shown with grey shaded larger circles.

Focal mechanisms

In terms of the instrumental seismicity, as can be seen from the figures 3 and 4, earthquake epicenters are concentrated in a Z-shaped region just east of the Strait of Gibraltar. This includes Cadiz region, south-central Betics and Al-Hoceima region in northern Morocco. There is also a concentration of earthquakes towards the east, in northern Algeria.

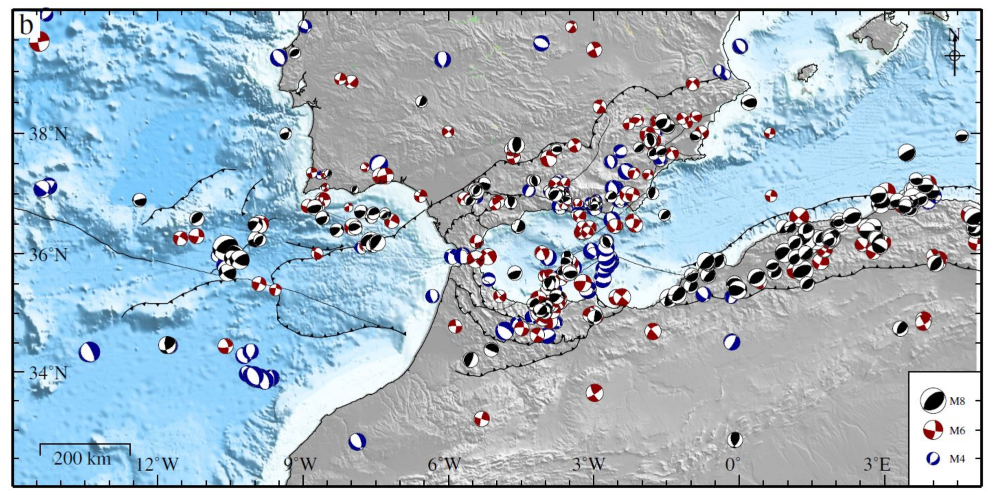


Figure 4: Focal mechanisms compiled by Palano et al. (2013) for more than 440 earthquakes recorded between 1951-2010, with 2<M<8. Focal mechanisms of strike slip faults are marked in red, black mechanisms indicate thrust faults, and normal faults are marked with blue focal mechanisms. Figure from Palano et al. (2013).

GPS data

Compilation of GPS velocities (see Figure 6)

- Echeverria et al. (2013): 18 stations in eastern Betics.
- Koulali et al. (2011): 82 stations in Morocco and Iberia.
- Palano et al. (2013): 2 stations in Betics.
- Topo-Iberia (UB): 29 CGPS stations.

Adjustment

We used 7-parameter Helmert transformation to rotate al the data sets into a common reference frame. Set of 4 velocity fields to the same reference system. We used the velocity field of Echeverria et al. (2013) for a reference frame.

Elastic block model: basic concepts

We use elastic block-modeling approach, that includes rigid block rotation and elastic strain accumulation on the faults that form block boundaries.

We use the program TDEFNODE (McCaffrey, 2009), where faults are represented in 3D space by nodes and surface deformation due to locked faults during the inter-seismic period is modeled using dislocations in an elastic half-space (Okada, 1985).

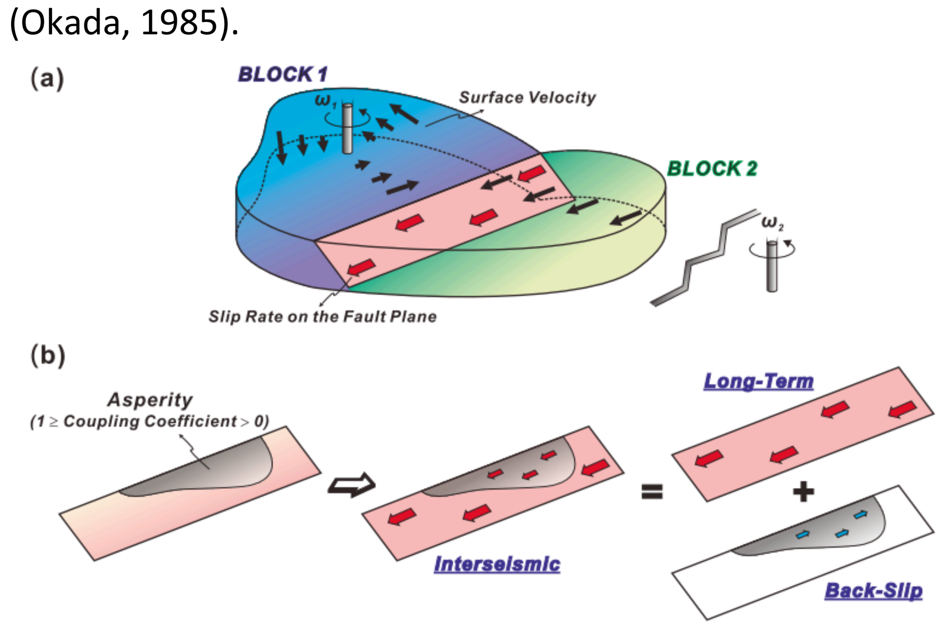


Figure 5: Simplified diagram of elastic block modeling from Ching Ching et al. (2011).

Elastic block model: blocks

After experimenting with numerous block configurations, we have arrived to the following preferred models that best fit the used geodetic and seismic data, as well, as represents realistically the location of the geologic faults and deformation zones. In the southern part of the model we have followed closely the previous models of *Vernant* et al. (2010) and *Koulali et al.* (2011).

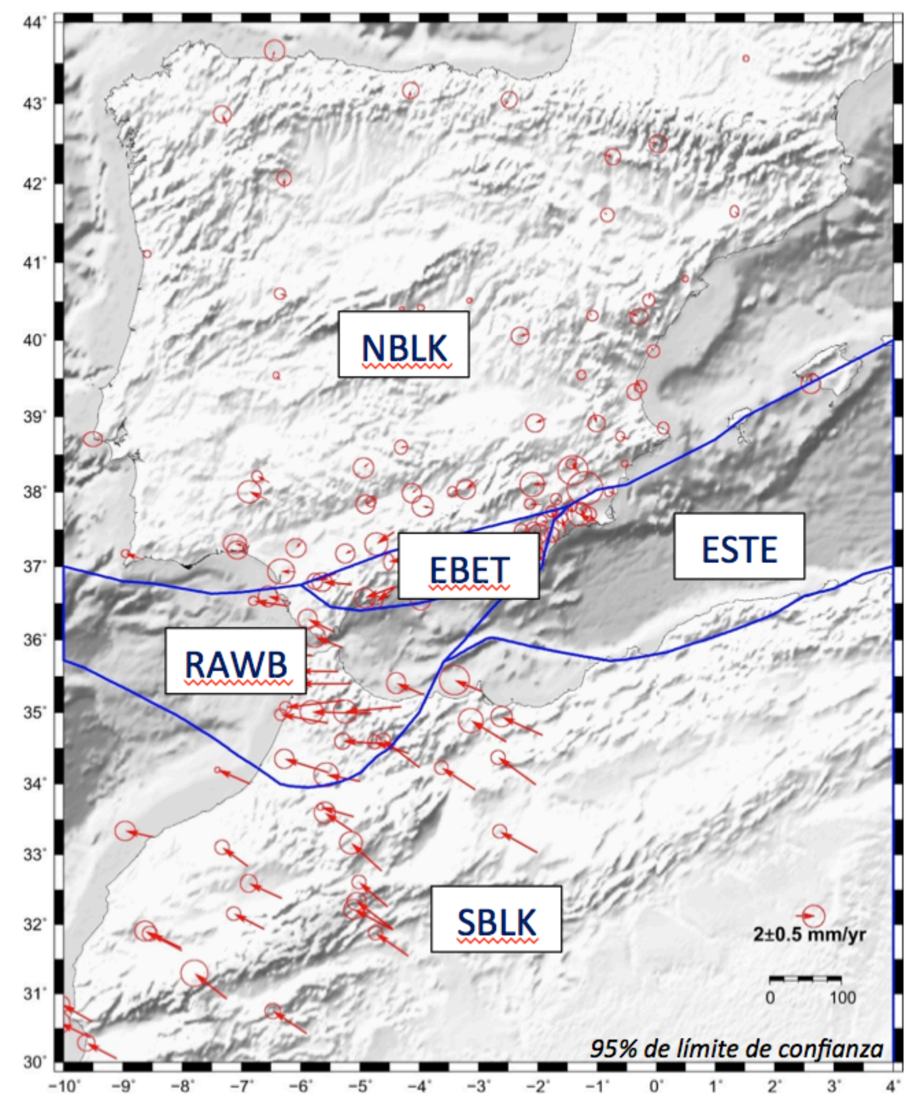
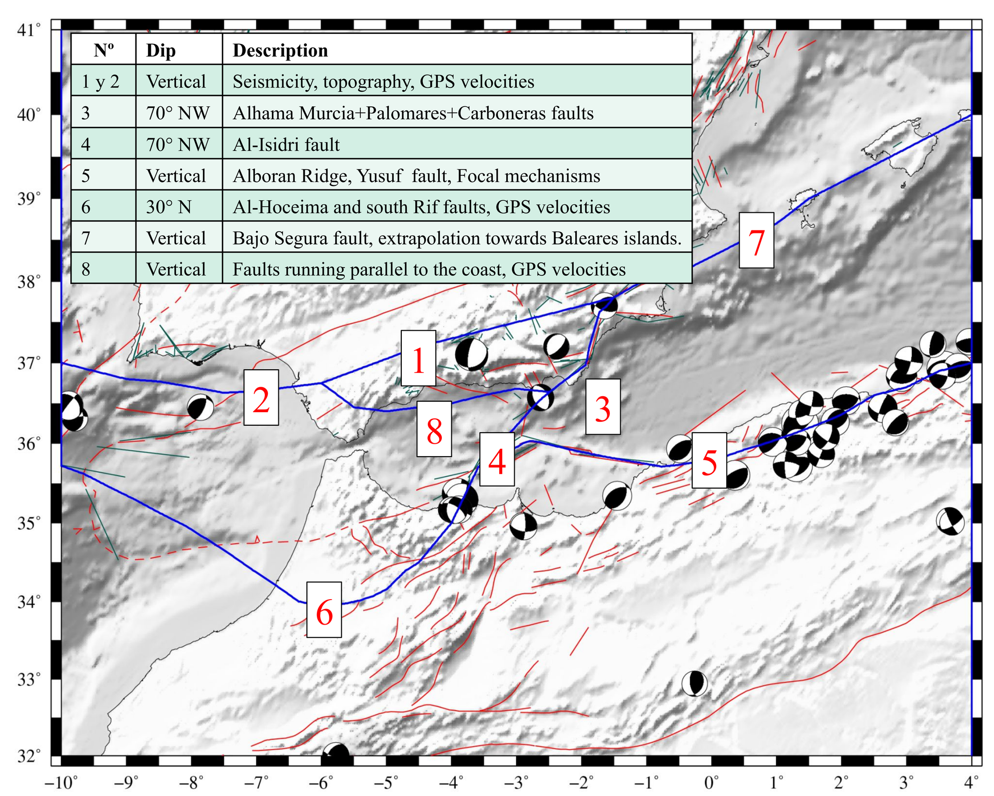


Figure 6: Preferred model geometry. The 5 blocks are: NBLK= Eurasia; SBLK= Africa; RAWB= Rif, Gulf of Cadiz and Alboran Sea; EBET= Betics; ESTE= eastern Betics. Adjusted velocity field in western Europe reference frame with 95% confidence limits. See Asensio (2014) and Echeverria et al. (2013) for details.

Elastic block model: block limits

Majority of the block limits coincide wi the location odf the known tectonic faults. Although, in some cases (fault 7) the limit has been extrapolated to achieve the closure of the block polygon.



Nº	Dip	Description
1 y 2	Vertical	Seismicity, topography, GPS velocities
3	70° NW	Alhama Murcia+Palomares+Carboneras faults
4	70° NW	Al-Isidri fault
5	Vertical	Alboran Ridge, Yusuf fault, Focal mechanisms
6	30° N	Al-Hoceima and south Rif faults, GPS velocities
7	Vertical	Bajo Segura fault, extrapolation towards Baleares islands.
8	Vertical	Faults running parallel to the coast, GPS velocities

Figure 7: A maps showing the outline of the blocks and a table describing the criteria used in choosing the block limits. The locking depth is fixed to 15 km depth.

Elastic block model: rotations

Tdefnode models long-term signal detected by the GPS measurements treating each constituent block as a rigid body.

Euler poles for each block			
Block	**Lon**	**Lat**	**Omega(°/Ma)**
NBLK	-3.0157	42.1316	-0.0838±0.0097
RAWB	-4.5646	42.7542	-0.3175±0.0892
EBET	2.3949	9.4475	0.0343±0.0521
ESTE	5.1344	40.1429	-0.1245±0.1375
SBLK	-18.2264	7.3915	0.0768±0.0181

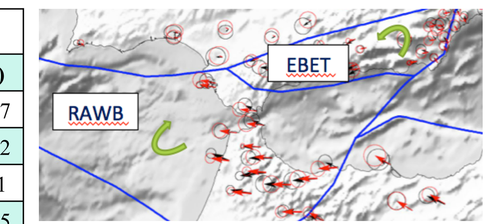


Figure 8: Model predicts a rotation in opposite direction of the RAWB and EBET. Red: Observed; black: Model.

Elastic block model: fault slip rates

We have inverted for the fault slip-rates to study a style of defromation across the block boundaries.

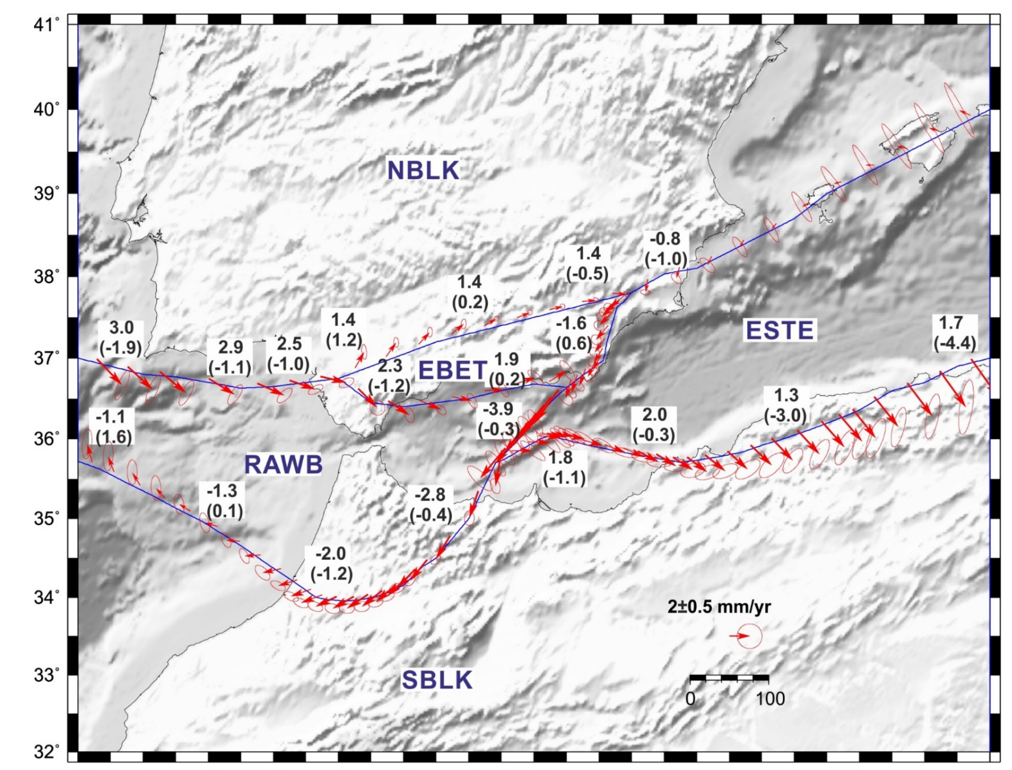


Figure 9: Inverted slip rates for each segment of the fault. Numbers show fault parallel and normal (in parenthesis) slip rates in mm/yr. Negative values indicate left-lateral and compressive type motion.

Elastic block model: velocity profiles

We have projected the velocities along the three profiles parallel to the convergence of the Nubia-Eurasia convergence direction.

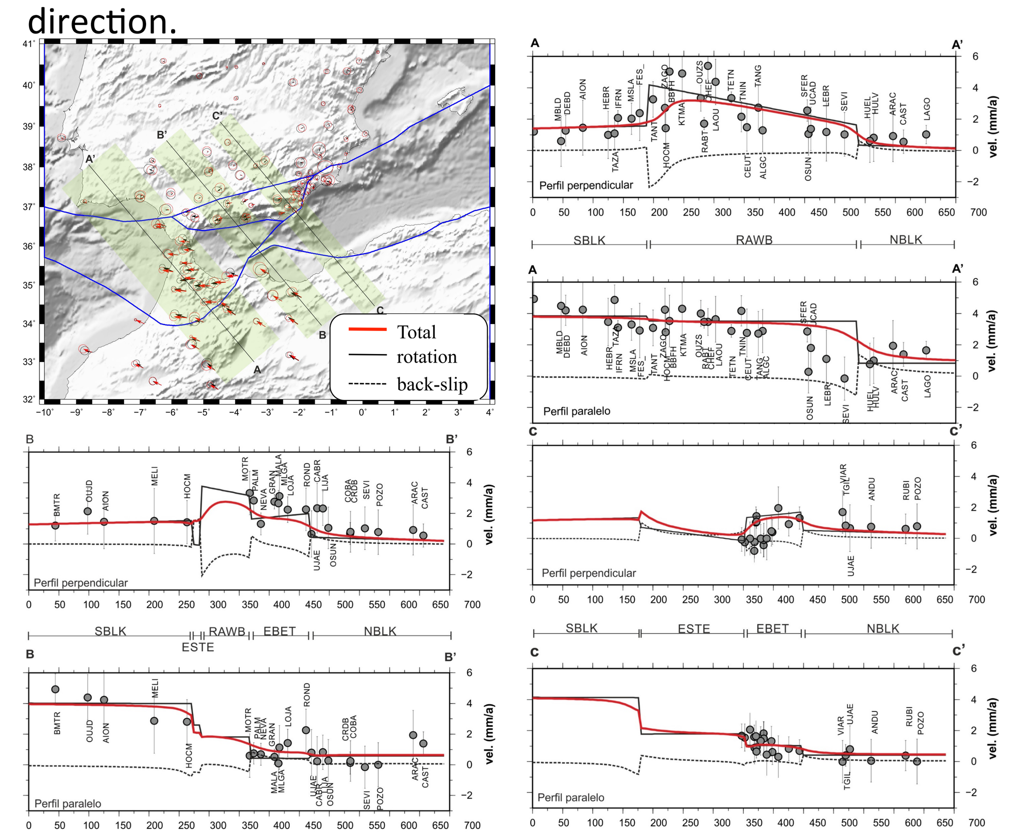


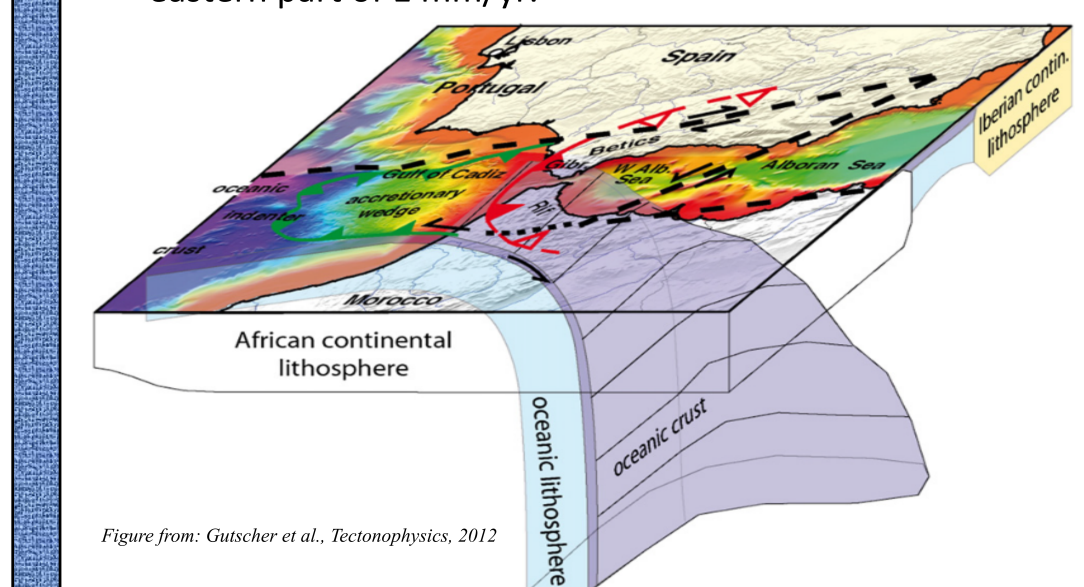
Figure 10: Measured GPS velocities (grey circles); Long-term rotation rates (black solid lines); back-slip due to the fault locking (black dashed line) and a sum of the two in red.

Discussion

We developed a new elastic block model from the velocity field, which explains the geodynamic behavior of this complex plate boundary. The model shows that the principal deformations are concentrated at the Betic-Rif-Alboran domain. The proposed model consists in 5 blocks: two blocks that represent the African and Eurasian plates, a block which includes the Rif and the Alboran sea, a block with the central and eastern Betics, and finally a block with the easternmost part of the Betics range.

The main behavior of faults, which separate blocks, obtained by the modeling are:

- A right-lateral motion of the fault with E-W orientation from Gulf of Cadiz to the eastern Betics.
- A left-lateral movement of the Trans-Alboran Shear Zone faults, with a minor extensional component, consistent with historical seismicity and mapped faults (Morel y Meghraoui, 1996; Stich et al., 2003; Tahayt et al., 2008).
- The transpressive behavior of the Rif and north Argelia faults. The earthquake magnitudes in this area are high, and the focal mechanisms show reverse and strike-slip faults.
- The right-lateral movement of the faults that run parallel to the Andalusian coast. This movement has an average rate of ~2 mm/yr and has a compressive component at the western part of 1 mm/yr and extensive component at eastern part of 1 mm/yr.



Final Remarks

Finally, we suggest that the geodynamic models of convective removal (Platt and England, 1994) and/or delamination (Calvert et al., 2000) can not explain well the obtained deformation in this region. Based on the model results of presented in this thesis, we suggest that GPS velocities support a geodynamic model that suggests a continued active slab subduction beneath the Strait of Gibraltar, with a consequent back-arc extension in the eastern Betics (Gutscher et al., 2012). This model explains well the westward motion of the central Rif GPS stations, as well as the extension of the eastern Betics.

Acknowledgements

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