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Marin-Lechado

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Stress distribution at the transition from subduction to continental collision (northwestern and central Betic Cordillera)

A. Ruiz-Constán

Géosciences Montpellier, Université Montpellier 2, CNRS, Place E. Bataillon, F-34095 Montpellier, France (ruiz@gm.univ-montp2.fr)

J. Galindo-Zaldívar

Departamento de Geodinámica, Universidad de Granada, Campus Fuentenueva s/n, E-18071 Granada, Spain (jgalindo@ugr.es)

Instituto Andaluz de Ciencias de la Tierra, CSIC-Universidad de Granada, E-18071 Granada, Spain

A. Pedrera

Instituto Geológico y Minero de España, Ríos Rosas 23, E-28003 Madrid, Spain (a.pedrera@igme.es)

B. Célérier

Géosciences Montpellier, Université Montpellier 2, CNRS, Place E. Bataillon, F-34095 Montpellier, France

C. Marín-Lechado

Instituto Geológico y Minero de España, Ríos Rosas 23, E-28003 Madrid, Spain (c.marin@igme.es)

[1] We analyze focal mechanisms of shallow-intermediate earthquakes in a NW-SE transect along the western Betic Cordillera and Alboran Sea, and deep earthquakes located in the central Betics to constrain the state of stress at the Gibraltar Arc slow convergence area. Shallow earthquakes (<40 km) are preferably clustered at the mountain front. A general NW-SE horizontal compression is compatible with the convergence, and NW plunging compression axes are in agreement with frontal thrust activity. Toward the Alboran Sea the earthquakes are progressively deeper, reaching intermediate depths (40–120 km) near the coast and supporting the present-day activity of subduction only in this area. The Iberian continental crust concentrates most of the intermediate seismicity and is forced to partially sink into the mantle, probably through the pull of the oceanic slab. This downdip pull together with the buoyancy of the Iberian continental crust produces the slab curvature, downdip extension in the external arc of the continental slab, and downdip compression in the inner arc. T axes highly dipping to the southeast at 90–120 km depth occur at the oceanic/ continental transition. Deep earthquakes (>620 km) show very similar focal mechanisms, fitting the general slab behavior of resistance to further descent at the 660 km discontinuity. Seismicity features evidence the present-day stress distribution in a context of transition from subduction to continental collision.

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1. Introduction

[2] In convergent plate boundaries, deformation is accommodated by collision or subduction depending on the buoyancy contrast between the competing lithospheres [Dewey, 1972; Cloos, 1993]. In oceanic-oceanic or oceanic-continental plate boundaries the denser oceanic crust is generally subducted. Over time, consumption of the subducting slab leads to closure of the oceanic basin followed by continental collision, thereby producing crustal thickening and the development of an orogen [O'Brien, 2001]. Although continental crust may be considered resistant to subduction because of its relatively low density [McKenzie, 1969], in certain convergence settings it may be at least partly subducted, as revealed by widespread occurrences of high-pressure metamorphic rocks [Goffe et al., 1989; Chemenda et al., 1996; Matte et al., 1997; Faure et al., 2003], some of them in the Betic-Rif Cordillera, and confirmed by thermomechanical models [Ranalli et al., 2000; Negredo et al., 2007].

[3] Stress distribution along subducting slabs, established through the inversion of earthquake focal mechanisms, has been well addressed in oceanic subduction zones [Isacks and Molnar, 1969; Okal and Kirby, 1998; Christova, 2001; Lemoine et al., 2002; Xu and Kono, 2002; Seno and Yoshida, 2004] and to a lesser extent in continental subduction zones [Singh, 2000; Khan, 2003]. Stress fields are largely controlled by the slab pull and the mantle's resistance to the sinking slab. These factors, in turn, are determined by the geometry and oceanic or continental nature of the slab among other features of the tectonic setting, including the age of the slab, rate of convergence [Fugita and Kanamori, 1981], bending of the slab [Christova and Tsapanos, 2000] or slab detachment [Sperner et al., 2001]. The establishment of the stress regime along the slab may help us understand and constrain the geodynamic evolution of the area and the mechanisms that determine its behavior.

[4] Seismic tomography sheds light on the deep geometry of most of the belts that surround the Mediterranean Sea [*Amato et al.*, 1998; *Wortel and Spakman*, 2000] (Figure 1a; Apennines, Dinarides,

Maghrebides), suggesting the presence of subducting slabs. In the western Mediterranean, considerable research has attempted to explain the development of the Gibraltar Arc. Subduction has also been invoked as a developmental mechanism of the Betic-Rif Cordillera although its nature (oceanic or continental), geometry, polarity, recent evolution and relationships with other mechanisms are not as well established as in other Alpine Mediterranean chains [Torres-Roldán, 1979; Blanco and Spakman, 1993; Lonergan and White, 1997; Morales et al., 1999; Thiebot and Gutscher, 2006; Bokelmann et al., 2010]. Alternative mechanisms based on the delamination of a lithospheric mantle [Platt and Vissers, 1989; Seber et al., 1996a; Calvert et al., 2000] have also been proposed. In any case, the deep structural data are key for any discussion of the geodynamic evolution of this controversial region.

[5] Although many research efforts focused on determining the shallow (0–40 km) seismotectonics of the area [Galindo-Zaldívar et al., 1993, 1999; Fernández-Ibáñez and Soto, 2008; de Vicente et al., 2008], the Betic Cordillera-Alboran Sea is also affected by a substantial amount of intermediate seismicity (40-120 km) [Buforn et al., 1997] and scarce deep earthquakes (>620 km; Figure 1b). The intermediate seismicity is limited to the area around Malaga, as far as the Gibraltar Strait and northern coast of Morocco. Few deep focal mechanisms are located to the east, below the Granada region. The seismicity pattern in western Betics involves shallow earthquake hypocenters near the mountain front and a progressive deepening of seismicity toward the Alboran Sea, reaching depths over 120 km. Over the past decade, several studies have attempted to discern the state of stress related to the intermediate and deep seismicity [Morales et al., 1999; Henares et al., 2003; Buforn et al., 2004]. However, the growing seismic network and database on focal mechanisms, and newly available geophysical data allow a more detailed and precise analysis of this lithospheric structure, with limited lateral continuity.

[6] The aim of the present contribution is to constrain the present-day stress field along a transect of Geochemistry Geophysics Ceosystems Geosystems Ruiz-constán et al.: FROM SUBDUCTION TO CONTINENTAL COLLISION 10.1029/2011GC003824



Figure 1. (a) General location of the Betic Cordillera in the framework of the Mediterranean Alpine chains; (b) seismicity distribution along the Eurasia-Africa plate boundary (IGN database, http://www.ign.es) and geological map of the Betic Cordillera (modified from *Vera* [2004]). Grey lines are bathymetry in km (500 m contours). CA, Calabrian Arc; GA, Gibraltar Arc; GB: Guadalquivir Basin.

the western Betic Cordillera extending toward the Alboran Sea, parallel to the NW-SE present-day plate convergence, orthogonal to the NE-SW structural trend, and centered on the maximum density of intermediate earthquakes. In addition, we analyze the deep earthquakes beneath the central Betic Cordillera in order to discern their link with intermediate seismicity. Finally, we compare our results with those from other subduction zones and discuss the main active mechanisms.

2. Geological and Geophysical Setting

[7] The Betic-Rif Cordillera (Figure 1a), located at the western end of the Mediterranean Sea, forms an arc-shaped mountain belt connected at the Gibraltar Arc, which surrounds the Alboran Sea. The westward emplacement of the Alboran Domain (Internal Zones) during the Early Middle Miocene interacting with the N-S to NW-SE oblique Europe-Africa plate convergence determines the Gibraltar orogenic arc development. Since Late Miocene, the NW-SE convergence between the Eurasian and African major plates is the main mechanism contributing to the recent and present-day relief [*Dewey et al.*, 1989; *Braga et al.*, 2003; *Pedrera et al.*, 2011].

[8] The Betic Cordillera comprises three main domains with different lithological and structural features (Figure 1b): the External Zones, mostly composed of Triassic to Miocene sedimentary rocks deposited on the South-Iberian palaeomargin [*García-Hernández et al.*, 1980]; the Internal Zones, structured in three main stacked metamorphic complexes which are, in ascending order, the Nevado-Filábride, the Alpujárride and the Maláguide [*Egeler*, 1963; *Egeler and Simon*, 1969]; and the Flysch Units [*Didon et al.*, 1973] constituted



by Cretaceous to Miocene sediments that crop out between the Internal and the External Zones. Cropping out to the north is the Guadalquivir basin, an asymmetric Neogene foreland basin whose sedimentary infill increases southwards due to the load of the Betic Cordillera over the Iberian Massif foreland [Martínez del Olmo, 1984]. This basin is mainly filled by autochthonous sediments, although its southern edge is constituted by a large olistostrome emplaced through tectonic and gravitational mechanisms in relation with the Gibraltar Arc advance (Figure 1b). To the north, the Iberian Massif foreland is a part of the variscan belt formed by igneous bodies intruded in metapelitic host rocks [Julivert et al., 1974]. Seismic tomography and magnetic anomalies in the central Betic Cordillera [Serrano et al., 2002] and deep seismic reflection profiles in the eastern Betics [Galindo-Zaldívar et al., 1997] suggest the continuity of the variscan basement below the Betic Cordillera tectonic units, at least up to the External Zones.

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[9] Recent volcanism in the Betic-Rif Cordillera shows a widespread pattern and geochemical affinities both from active subduction zones [*Gill et al.*, 2004] and intraplate-related magmatism [*Duggen et al.*, 2005]. The first type entails Late Miocene to Early Pliocene (8.2–4.8 Ma) calc-alkaline and shoshonitic rocks, whereas the second involves Late Miocene to Pleistocene (6.3–0.65 Ma), Si-poor, Na-rich magmatic rocks. Volcanism, nevertheless, was apparently not as widespread in the Alboran Sea as in other subduction zones, and finished altogether in the Late Miocene when most of the oceanic lithosphere subduction stopped [*Duggen et al.*, 2008].

[10] A large variety of geophysical data have been used to constrain the deep structure of the cordillera. Early tomographic studies revealed a high-velocity P wave anomaly with a NW-SE trend 200–700 km beneath the Betic Cordillera-Alboran Sea [Blanco and Spakman, 1993]. However, recent tomographic models suggest the existence of a low seismic velocity anomaly 50-100 km beneath the western Alboran Sea, underlain by a steep and narrow highvelocity body dipping to the east that extends to a depth of 350 [Seber et al., 1996b] or 600 km [Calvert et al., 2000]. These studies are based on teleseismic P wave travel times and efficiency of Lg, Sn and Pn wave propagation, respectively. A low velocity body dipping to the south at 40-120 km depth has also been observed on local tomography images of the Malaga region [Morales et al., 1999]. SKS splitting [Buontempo et al., 2008; Diaz et al., 2010] and Pn data [Serrano et al., 2005] reveal that seismic anisotropy directions are tangential to the geological trend of the arc, as a consequence of a subductioninduced toroidal flow during slab roll-back. Electrical anisotropy directions between the Betic Cordillera and the foreland Iberian Massif show orthogonal trends and decreasing magnitude, reflecting higher deformation toward the axis of the Eurasian-African plate boundary due to the westward emplacement of the Internal Zones of the cordillera [*Ruiz-Constán et al.*, 2010].

3. Geological and Geomorphic Evidence of Recent Deformations

[11] The relief that surrounds the Alboran Sea started to form in the Tortonian (11-6.5 Ma) as a consequence of shortening and crustal thickening [Sanz de Galdeano and Alfaro, 2004] related to the Eurasia-Africa plate convergence [DeMets et al., 1994] and other interacting mantle processes that are discussed at length in the literature [Platt and Vissers, 1989; Blanco and Spakman, 1993; Lonergan and White, 1997; Calvert et al., 2000; Gutscher et al., 2002]. Geomorphic data indicate recent and possibly present-day uplift at the southern edge of the Betic Cordillera along the studied transect (Figure 2), although most of it took place before the early Pliocene [Braga et al., 2003]. Nonetheless, the elevated marine terraces of the Malaga coastline [Zazo et al., 1999] and the marine Tortonian calcarenites that crop out widely in the region are scarcely affected by faults, and only in some sectors, like the Ronda Depression, are deformed by large open folds [Ruiz-Constán et al., 2008]. While marine Tortonian calcarenites are uplifted up to few hundred meters above the present-day sea level in the Betic Cordillera, northward, in the Guadalquivir foreland basin, Tortonian calcarenites have undergone subsidence due to the lithospheric flexure of the Iberian Massif [García-Castellanos et al., 2002] and as a consequence of the cordillera load. At present, shallow tectonic activity in this transect is recognized near the northwestern edge of the cordillera [Ruiz-Constán et al., 2009], with shallow seismicity and evidence of uplift that includes a sharp mountain front and river incision.

4. Seismicity Distribution and Earthquake Focal Mechanism Solutions

[12] Seismicity in the Betic-Rif Cordillera (Figure 1b) is characterized by continuous activity



Figure 2. (a) Map of epicenters at the Gibraltar Arc with magnitude greater than 3 for the period 1990–2010 (IGN database, http://www.ign.es); Green, yellow, blue and red circles correspond to shallow (depth < 40 km), intermediate (40 < depth < 120 km), deeper intermediate (120 < depth < 600 km) and deep events (depth > 600 km), respectively; (b) hypocenters projected along a cross section of the northwestern Betic Cordillera and the Alboran Sea.

of moderate events [Buforn et al., 1991]. Earthquakes in this region extend over a wide deformation zone associated with the major Eurasia-Africa plate boundary that interacts with the Alboran deforming domain. Hypocenters from the Instituto Geográfico Nacional (IGN) seismicity database (Figures 2a and 2b) underline the location of the main seismogenic areas of the region. The plot includes earthquakes of magnitude greater than 3 for the period 1990-2010. In the Gibraltar Arc, one of the most striking features is the intermediate seismicity that draws a narrow arched geometry between the Málaga coast and the Gibraltar Strait [Buforn et al., 1995]. In this zone, hypocenter depth increases progressively to the south, reaching approximately 120 km (Figure 2b). At shallow levels of the studied transect (<15 km; Figure 2b), seismicity is concentrated in the mountain front and may be indicative of its present-day activity. In addition, a few deep earthquakes (620 to 660 km) have been recorded below the Granada area, with magnitudes between 4.8 and 7.8 [Chung and Kanamori, 1976; Grimison and Cheng, 1986; Buforn et al., 1991, 2004]. In what follows we classify earthquakes according to their depth as shallow (0-40 km), intermediate (40-120 km) and deep (>620 km). We set the lower bound of intermediate seismicity at 120 km instead of the usual 300 km because of a seismic gap between 120 and 620 km below the Betic Cordillera: very few isolated earthquakes are recorded within this interval and none within our study area in the IGN database.

[13] We compiled 50 focal mechanisms for the period 1968–2011 (Table 1) from diverse sources in the literature [Chung and Kanamori, 1976; Coca and Buforn, 1994; Buforn et al., 1991, 1997, 2004; Bezzeghoud and Buforn, 1999; Coca, 1999; Morales et al., 1999; Stich et al., 2006, 2010; IGN database, http://www.ign.es]. These focal mechanism solutions were calculated by waveform modeling or inversion [Buforn et al., 1997; Coca, 1999], first-motion polarities [Bezzeghoud and Buforn, 1999; Buforn et al., 1991 and 2004; Coca and Buforn, 1994; Morales et al., 1999] or moment tensor inversion [Stich et al., 2006, 2010; IGN database]. In terms of depth, among the 19 shallow mechanisms (<40 km) 16 result from moment tensor inversion and 3 from first-motion solutions; among the 26 intermediate mechanisms (40-120 km) 15 were obtained from first-motion polarity, 10 by waveform modeling and 1 by moment tensor inversion; finally, among the 5 deep mechanisms (>620 km) 4 were determined from first-motion polarity and 1 by moment tensor inversion (Table 1).

[14] The solutions are highly variable throughout the region (Figure 3). At shallow depths (0–40 km) the focal mechanism solutions mainly show NW-SE subhorizontal P axes, while T axis orientations range from subvertical to E-NE-N-ward plunging (Figure 4). There are also three focal mechanisms with subhorizontal N-S P axes (events 34, 38 and 39). The intermediate focal mechanisms (40–

 Table 1. Focal Mechanism Solutions^a

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ID	Date	Lat.	Long.	Ζ	Strike	Dip	Rake	mb	Mw	Reference	Method	Stress Tensor
1	540321	37.00	- 3.70	640	179	88	- 122	-	7.8	1	2	-
2	680213	36.48	- 4.56	91	334	10	5	4.3	-	2	2	3
3	730130	36.90	-3.70	660	191	74	- 56	-	4.8	3	2	-
4	740613	36.87	- 4.12	60	78	72	- 69	4.1	-	2	2	3
5	750807	36.41	- 4.59	105	186	42	138	5.2	-	2	2	3
6	790501	36.95	- 5.42	24	249	35	-24	4.0	-	4	2	-
7	791222	37.06	- 4.34	40	210	64	- 86	4.0	-	4	2	2
8	801203	36.92	- 5.67	27	114	68	155	4.3	-	4	2	1
9	810121	36.85	-4.71	5	153	56	46	4.0	-	4	2	1
10	860513	36.6	-4.48	90	87	74	- 123	4.3	-	5	1	3
11	870327	36.79	-4.10	79	69	72	76	3.5	-	5	1	2
12	880530	36.52	- 4.63	80	75	88	35	3.6	-	6	2	2
13	881128	36 30	- 4 57	100	93	88	- 85	35	-	5	1	-
14	881212	36.28	- 4 57	95	232	87	146	45	-	5	1	3
15	890719	36.64	-443	95	296	79	94	3.0	-	5	1	3
16	900206	36.57	-453	68	270	23	96	34	-	5	1	2
17	900308	37.00	-3.60	637	177	62	_ 91	-	48	3	2	-
18	900502	36.53	_ 4 55	95	36	49	57	42		5	1	3
10	001118	36.75	- 4.55	95 85	175	51	30		-	5	1	5
20	010825	36.82	- 4.59	58	286	30	- 30 173	2.9	-	5	1	- 2
20	020314	36.51	- 4.48	50 64	280	14	- 173	3.6	-	3 7	1	2
21	020003	26.49	- 4.43	0 4 86	208	14	- 125	2.5	-	6	1	-
22	920903	26.80	- 4.42	662	298	41 60	- 01	5.5	-	0	$\frac{2}{2}$	-
23	930731	26.40	- 3.43	70	222	60	- 91	25	4.4	0 6	2	- 2
24	931109	26.57	- 4.42	/0	223	00 71	00 102	5.5 25	-	0	2	3
23	940101	26.27	- 4.57	08	100	/1	- 105	5.5	-	0	2	3
20	950517	30.82	- 4.34	50	100	85 50	- 50	4.0	-	8	2	3
27	951118	37.02	-4.32	52	238	39	154	3.6	-	8	2	-
28	951128	30.70	- 4.38	08	33	84 59	/0	3.5	-	8	2	2
29	960622	36.71	- 4.45	68	120	28	1/2	3.9	-	8	2	3
30	961227	30.50	- 4.65	59	60	60	49	3.8	-	8	2	2
31	9/0318	36.96	- 4.23	56	43	34	8/	3.7	-	8	2	3
32	970820	36.40	- 4.65	68	6/	86	-63	4.2	-	8	2	3
33	020824	36.46	- 4.56	70	96	21	165	-	4.2	9	3	3
34	020915	37.16	- 5.27	4	273	68	58	-	4.1	9	3	-
35	030725	36.90	- 5.56	6	29	40	82	-	3.5	9	3	l
36	060311	36.87	- 4.98	22	243	88	- 170	-	3.9	10	3	l
37	060326	36.83	- 5.04	14	151	70	5	-	3.7	10	3	1
38	070102	37.11	- 5.39	10	135	79	- 174	-	3.6	10	3	1
39	070102	37.16	- 5.33	14	136	71	- 152	-	3.6	10	3	-
40	070630A	37.07	- 5.44	8	81	45	123	-	4.4	10	3	1
41	070630B	37.08	- 5.42	8	103	58	158	-	3.6	10	3	1
42	070914A	37.08	- 5.47	12	65	35	107	-	3.6	10	3	1
43	070914B	37.08	- 5.47	8	51	54	97	-	3.6	10	3	1
44	070918	37.01	- 5.43	8	52	34	103	-	3.9	10	3	1
45	081002A	37.04	- 5.42	4	54	44	103	-	4.5	10	3	1
46	081002B	37.02	- 5.43	12	54	39	92	-	3.9	10	3	1
47	081002C	37.06	- 5.43	6	44	45	109	-	3.4	10	3	1
48	081002D	37.06	- 5.40	16	87	66	166	-	3.2	10	3	1
49	081008	37.06	- 5.41	12	211	69	24	-	3.5	10	3	1
50	100411	36.95	-3.51	623	192	73	-110	-	6.2	11	3	-

^aFrom left to right, columns give: (1) identity number in Figure 3a; (2) year/month/day; (3) latitude and (4) longitude (degrees); (5) depth, (km); (6) strike, (7) dip, (8) rake of one of the two nodal plane with *Aki and Richards* [2002] convention; (9) m_b from reference; (10) M_w from reference; (11) article reference (1, *Chung and Kanamori* [1976]; 2, *Coca and Buforn* [1994]; 3, *Buforn et al.* [1991]; 4, *Bezzeghoud and Buforn* [1999]; 5, *Buforn et al.* [1997]; 6, *Morales et al.* [1999]; 7, *Coca* [1999]; 8, *Buforn et al.* [2004]; 9, *Stich et al.* [2006]; 10, *Stich et al.* [2010]; 11, IGN database (http://www.ign.es)); (12) method (1, waveform modeling; 2, first-motion polarities; 3, moment tensor inversion) and (13) stress tensors as referred to in Table 2. Dashes in column 13 indicate events that have not been used in the stress inversion.

Geochemistry 10.1029/2011GC003824 RUIZ-CONSTÁN ET AL.: FROM SUBDUCTION TO CONTINENTAL COLLISION Geophysics Geosvstems coast line A b 20 40 Ê 60 Alboran Sea 80 Magnitude 4≤M<5 100 120 5°W 4°W 40 60 80 100

Figure 3. (a) Earthquake focal mechanism solutions in the western Betic Cordillera (see text and Table 1 for details); numbers refer to the ID of Table 1 and colors to stress tensor groups (shallow earthquakes in green; intermediate events in yellow and orange for the external and internal arc of the slab, respectively; deep earthquakes in red; nonexplained solutions are in black). (b) Cross section along line A-A' showing vertical distribution of focal mechanism solutions in equal area and vertical projection. Earthquake focal mechanism solutions are scaled by magnitude and compressional quadrants are shaded; the topographic profile is shown with a vertical exaggeration of a factor of 4 for legibility.

120 km) are more variable, with some predominant NW-SE to subvertical trends of P axes, and subvertical to southward plunging T axes. Deep earthquakes beneath the Granada region (>620 km) show very similar solutions, with a subvertical N-S plane and a subhorizontal nodal plane (Figure 4). Their tensional and compressional axes plunge toward 15–35°W and 40–75°E, respectively.

5. Methods

[15] We combine two different methods to constrain the state of stress from earthquake focal mechanisms: the right dihedra method and fault slip inversion. Both methods seek a single stress tensor that is compatible with all observed movements. In general and for both methods, the higher the number of available data the more representative and stable the stress tensor solution is [*Casas Sainz et al.*, 1990].

[16] The right dihedra method determines graphically, by means of a stereographic projection, common zones of compression and tension for a given set of focal mechanisms that define the possible locations of the maximum and minimum principal stress directions [*Angelier and Mechler*, 1977].

[17] The inverse methods determine a four parameters reduced stress tensor that contains information not only on the principal stress directions, but also on the principal stress aspect ratio, $R = (\sigma_1 - \sigma_2)/(\sigma_1 - \sigma_3)$, with $\sigma_1 \ge \sigma_2 \ge \sigma_3$ [*Carey and Brunier*, 1974; Angelier, 1975]. We mainly used the Monte Carlo search method proposed by Etchecopar et al. [1981], and implemented in the FSA software [Burg et al., 2005; Célérier, 2011], but we also used the method proposed by Gephart and Forsyth [1984] and implemented in the software FMSI [Gephart, 1990]. Because the nodal plane that corresponds to the fault plane is not determined in our data set, the inversion was set to automatically select the nodal plane with the smallest rake misfit in both software. To separate nonhomogeneous data into homogeneous subgroups we relied on the analysis of the misfit angle between the predicted and observed rake for each data: we considered misfit above 20° as indicating incompatible data requiring further sorting (Figure 5).

6. Results

[18] Earthquake focal mechanism solutions are grouped by depth for their inversion in order to provide a roughly homogeneous stress solution (Tables 1 and 2 and Figures 3 and 4). Shallow focal mechanisms in the western Betics (<40 km; in green in Figure 3), mostly located at the front of the mountain range, are predominantly reverse and strike-slip faults. The focal mechanism inversion mainly shows NW-SE horizontal compression (stress tensor 1, Table 2), parallel to the Africa-Eurasia convergence (Figure 6), with a high axial ratio (R = 0.68) that reveals the prevalence compression. The predicted rake is within 20° of the



Figure 4. (a, b) Horizontal and (c, d) NW-SE vertical projection of the pressure, P, and tensional, T, axes of the focal mechanism solutions (different lengths of axes are due to projection into profile line). Stereographic projection of (e-g) P and (h-j) T axes of the different groups of earthquakes (equal area, lower hemisphere projection).

observation for all events except three (events 6, 34 and 39; in black in Figure 3a) that were discarded for the inversion (Figure 5a). These 3 events could be related to local perturbations due to interaction between blocks or change of principal stress axes after relaxation that also produce shortening in a N-S direction. However, there are not numerous enough to invert for the secondary perturbed stress field.

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[19] Focal mechanism solutions of intermediate seismicity, limited to the southeastern edge of the profile (in yellow and orange, Figure 3), are quite variable, fundamentally involving reverse and strike-slip faults, although normal faults and focal mechanisms showing subvertical and subhorizontal nodal planes are also frequent. The stress pattern is

complex and could not simply be related to depth. However, we can distinguish the lower from the upper part of the subducting slab and will call them internal and external arcs, respectively (Figure 3b). The orientations of the T-axis suggest a general downdip extension along the external arc of the seismic zone (Figures 3 and 4a). On the other hand, P-axis plunge evolves from almost horizontal at shallow and frontal positions of the Cordillera, to downdip compression in the internal arc defined by the seismic zone, and roughly orthogonal to the body defined by the seismicity in its outer part. Thus, intermediate seismicity cannot be explained by a unique stress tensor (Figure 5b) and we have differentiated two subsets based on the location inside the seismogenic body, the orientation of the tensional and compressional axes



Earthquake focal mechanism solution

Figure 5. Difference between observed and predicted rakes as a function of focal mechanism solution number for (a) shallow and (b) intermediate seismicity. Only data below the horizontal dashed line with $< 20^{\circ}$ misfit have been used for the determination of the stress tensor solution. Focal mechanisms and stress tensors numbering as in Tables 1 and 2.

and the rake slip misfit defined in the preceding section.

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[20] Stress inversion indicates a maximum compression plunging 37° SE and a maximum extension plunging 41° WSW in the internal arc of the slab (stress tensor 2, Table 2 and Figure 6) with an axial ratio of R = 0.58. In the external arc of the seismogenic body (stress tensor 3, Table 2) the inversion yields a minimum stress axis plunging 57° SE and a NW-SE maximum compression plunging 33°NW and an axial ratio of R = 0.61. Seven events are very well explained by the stress tensor 2 (Figure 5, dashed line) while they could not be explained by tensor 3 (Figure 5, solid line). Conversely, sixteen events are very well fit by stress tensor 3 and show very high misfits with respect to stress tensor 2. Only four data are

Table 2. Reduced Stress Tensors Determined by the FSA Software^a

Stress Tensor	N _{tot}	N _{inv}	σ_1	σ_2	σ_3	R
		Sha	llow Depth (<40 km)	1		
1	19	16	317/01	047/12	223/79	0.68
		Interme	diate Depth (40–120	km)		
2: Internal arc	26 ^b	7	147/37	035/27	278/41	0.58
3: External arc	26 ^b	14	316/33	047/02	139/57	0.61

^aN_{tot}, total number of earthquake focal mechanisms; N_{inv}, number of earthquake focal mechanisms used in the inversion; σ_1 , maximum principal stress trend and plunge; σ_2 , intermediate principal stress; σ_3 , minimum principal stress; $R = (\sigma_1 - \sigma_2)/(\sigma_1 - \sigma_3)$ principal stress magnitude aspect ratio (see text).

^bThis value is the combined number of earthquake focal mechanisms for both the internal and external arcs.





Figure 6. Perspective sketch of the slab based on the seismic tomography of *Wortel and Spakman* [2000]. Results of the analysis of the three groups of earthquake focal mechanisms in equal area stereographic projection (lower hemisphere). Color coding and symbols indicate results of the right dihedra [*Angelier and Mechler*, 1977] and inversion (FSA [*Célérier*, 2011]) methods, respectively. The resulting principal stress directions are shown as arrows in the perspective sketch.

incompatible with the stress tensor solutions and have been discarded for the analysis. The right dihedra diagram (Figure 6) shows orientations with a 100% pressure dihedra and orthogonal 100% tension dihedra in all the subsets, in approximate agreement with the main axes orientation determined by stress inversion.

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[21] Finally, the low amount of deep seismic data (5) and their similar orientation preclude a stress tensor inversion. However, the P axes show a well defined intermediate to high plunge $(40-75^\circ)$ toward the east and the T axes are gently plunging $(15-35^\circ\text{W})$.

7. Nature and Stress Field Along the Subducted Slab

[22] Seismicity in the western Betic Cordillera draws a narrow arched geometry between the Málaga coast and the Gibraltar Strait, progressively deepening toward the south, from the surface to 120 km (Figure 2b). In addition, a few deep earthquakes (~ 620-660 km) have been recorded beneath the Granada sector. There is a good correlation between the seismicity distribution and the seismic velocity anomalies detected by different tomographic studies. A low seismic velocity anomaly was imaged beneath the western Alboran Sea between 50 and 100 km [Seber et al., 1996a; Morales et al., 1999], featuring a steep and narrow high-velocity body dipping to the east that extends to different depths depending on the authors: as far as 350 km [Seber et al., 1996b], 600 km [Calvert et al., 2000] or up to 700 km deep [Blanco and Spakman, 1993].

[23] To reconcile the different seismic tomography results, the low velocity anomaly could be interpreted as the extent of the continental Iberian Massif below the Betic Cordillera and the high velocity anomaly its transition to oceanic lithosphere. Therefore, the recorded intermediate and deep seismicity could be interpreted as a consequence of the present-day stress distribution along a remnant oceanic subducted slab that has evolved to a context of continental collision. Interactions between the overriding and subducting plates, slab nature and buoyancy contrast could explain the seismicity distribution and the observed stress pattern.

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[24] The stress tensor analysis of 50 earthquake focal mechanisms located in the western Betic Cordillera and Alboran Sea shows differences between shallow, intermediate and deep seismicity, as well as between the external and internal arc of the slab (Figure 6). The consistency of the results obtained by the right dihedra method and the two inversion procedure, FSA and FMSI, confirm the stability of the solutions (Figure 6 and Table 2). At shallow levels (<40 km) the most remarkable feature, among other local stresses, is a NW-SE maximum horizontal compression, parallel to the major plate convergence, that has been reported in previous studies [*Morales et al.*, 1999; *Henares et al.*, 2003; *Buforn et al.*, 2004].

[25] At intermediate depths (40–1200 km), the great complexity of the focal mechanisms has led previous studies to interpret either a scattered distribution [*Henares et al.*, 2003] or predominant nearly vertical tension [*Buforn et al.*, 1997] and horizontal to downdip compression [*Morales et al.*, 1999]. Our analysis instead reveals two different stress regimes in the external and the internal parts of the continental slab. Whereas the inner part of the slab is subjected to downdip compression and along-strike horizontal extension, the outer-upper part is clearly dominated by an oblate stress characterized by NE-SW extension. This stress field would be related to the bending of the slab due to the pull of the oceanic lithosphere.

[26] According to available seismic tomography images, the transition zone between continental and oceanic lithosphere should be located around 120 km depth [*Blanco and Spakman*, 1993; *Seber et al.*, 1996b; *Morales et al.*, 1999]. Therefore, most of the analyzed seismicity is concentrated in the subducted Iberian continental lithosphere. This result is in agreement with the fact that, under similar conditions, granitic and metapelitic crusts are more deformable than basic igneous rocks [*Ranalli and Murphy*, 1987; *Ranalli*, 1997]. The presence of T axes highly dipping to the southeast at around 120 km depth coincides with this oceanic/continental transitional zone. Such downdip extension could be explained by the pull of the dense oceanic slab.

[27] The 300–500 km interval is a low seismicity zone for all subduction zones, however, the seismic gap between 120 and 300 km suggests that the subducted slab is detached [Lonergan and White, 1997] or that the intermediate and deep earthquakes are related to different processes of subduction [Buforn et al., 1995, 2004; López Casado et al., 2001]. However, the seismogenic portion of the slabs is frequently shallower than the real slab extent, as revealed by seismic tomography elsewhere in the world; that is, the maximum depth of earthquakes is not indicative of the maximum depth reached by the slabs [Carminati et al., 2005]. Recent studies of P wave dispersion support the existence of a continuous slab over a certain depth range [Bokelmann et al., 2010] and seismic anisotropy data [Diaz et al., 2010] also suggest a significant coupling between the crust and deeper levels of the upper mantle. Although the existence or absence of slab detachment cannot be asserted categorically through the stress inversion, the mechanisms of the deep events of the Betic Cordillera, with mainly downdip compression, fit the pattern of seismicity at the bottom of slabs when they reach the 660 km discontinuity and experience resistance to further descent [Isacks and Molnar, 1969, 1971; Ringwood, 1994]. Coherent downdip compression can be observed in subduction zones such as Kamtchatka [Christova, 2001], Tonga-Kermadec [Okal and Kirby, 1998; Brudzinski and Chen, 2005], Java, Bolivia [Okal, 2001] and Argentina [Huang et al., 1998], in contrast to deep detached slabs with disperse focal mechanism solutions in Vityaz or Fiji [Okal and Kirby, 1998].

8. Recent Evolution and Formation of the Gibraltar Arc

[28] In subduction settings, once roll-back starts it should continue until the system completely runs out of dense oceanic lithosphere and the arc collides with continental lithosphere. Roll-back to the west in the Betic-Rif Cordillera occurred during the early Miocene until most of the subductable oceanic lithosphere was exhausted in the vicinity of Gibraltar [*Lonergan and White*, 1997]. Subductionrelated volcanism in the Alboran Sea ceased in the Late Miocene when hydrated oceanic lithosphere stopped subducting [*Duggen et al.*, 2008]. Although these authors evoke delamination of subcontinental lithosphere beneath the edges of southern Iberia and northwestern Africa to explain the end of the volcanism, the transition between oceanic-subduction to continental-subduction could also trigger the same pattern in the volcanic record of the Alboran basin. The end of volcanism may be a consequence of the refractory nature of the continental crust and the reduced present-day lateral continuity of the subduction zone as a remnant of the Miocene one.

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[29] High-pressure metamorphic units are widely exposed in the Alpine Mediterranean belt [Goffe et al., 1989; Monié et al., 1991; Jolivet et al., 2003]. In the Internal Zones of the Betic Cordillera, both the Nevado-Filábride Complex and the overlying Alpujárride Complex, with different ages and exhumation rates, underwent similar metamorphic evolutions. Subduction and crustal thickening during the Eocene to the Oligocene generated high-pressure low-temperature metamorphism in the Alboran domain [Monié et al., 1991; Puga et al., 2002; Augier et al., 2005]. The peak of pressure was followed by an extensional process during the Lower and Middle Miocene [Zeck et al., 1992; Monié et al., 1994; Balanyá et al., 1997; Augier et al., 2005; Platt et al., 2005]. This extensional process was characterized by the formation of pervasive extensional crenulation cleavage and localized ductile shear zones with a top-to-the-west shear sense [Jabalov et al., 1993, among others] probably associated with westward oceanic slab roll-back [Royden, 1993; Lonergan and White, 1997]. In this context, the space created by the roll-back favors the exhumation of the previously subducted buoyant continental crust [Brun and Faccenna, 2008].

[30] Recent uplift of the Betic Cordillera is highly related to the development and evolution of subduction. The subduction of oceanic crust and slab roll-back controlled the Alboran back-arc basin during the Early and probably part of the Middle Miocene. Since the Late Miocene, subduction evolved to a continent collision conditioning the higher rates of vertical uplift recorded in the area [Braga et al., 2003]. In this stage, the Alboran Basin boundaries were uplifted, marked by the presentday position of the Tortonian calcarenites up to 1800 m a.s.l. in the central Betics and 550 m in the western part of the cordillera [Sanz de Galdeano and Alfaro, 2004]. Although the continental collision continued, the uplift rates have decreased since the Pliocene.

[31] Notwithstanding, the plate tectonic evolution, the presence of oceanic crust and the polarity and evolution of the subduction zones is still poorly constrained in the western Mediterranean. Previous geodynamic models of the area sustain that an Oligocene northward subduction zone of remants of the Tethyan Ocean welded to the African plate was split into two fragments after its collision with Africa, probably in the Early Miocene, and rolled back generating the Calabrian Arc to the east, and the Gibraltar Arc to the west [Rehault et al., 1984; Jolivet et al., 2008]. However, the strike of the subducted slab (Figure 6) based on available seismic tomography sections [Wortel and Spakman, 2000] shows a clear NE-SW orientation, more compatible with a Euroasiatic origin of the subducted lithosphere [Pedrera et al., 2011]. The presence of the Iberian Massif continental lithosphere in transition with the oceanic lithosphere also points to such an origin. In this setting, the subduction may have started in a zone of transcurrence between the Iberian and African plates [Rosenbaum et al., 2002] acting since the Cretaceous, until the consumption of oceanic lithosphere at the Gibraltar Arc during the Late Miocene. After a limited amount of continental subduction (presently restricted to the western part of the Gibraltar Arc), convergence finally led to continental collision.

[32] On the basis of marine research, an active eastdipping subduction zone constrained in a E-W section west of the one studied here [Gutscher et al., 2002; Thiebot and Gutscher, 2006] has been invoked to explain some observed features, such as the west-vergent thrusting in the Gulf of Cádiz, the high P wave velocity slab detected by seismic tomography, or the presence of active mud volcanoes and destructive historical earthquakes. However, the Plio-Quaternary stress distribution and GPS velocity vectors [Stich et al., 2005, 2006; Pedrera et al., 2011] do not seem to require active E-W subduction. In addition, seismic tomographies suggest that the slab dips with a very high angle. Numerical and analog models [Martinod et al., 2005; Royden and Husson, 2009] show that when continental lithosphere sinks in a subduction setting, the slab steepens up to around 80°, the radius of curvature decreases and the velocity of subduction diminishes due to the resistance of the buoyant part of the slab to sinking.

[33] Intermediate seismicity in this area has a SE-dipping pattern, and the active structures progressively become shallower to the N-NW, until reaching the cordillera mountain front, where seismicity is very shallow (3–4 km). At this depth the stress is compressive, due to the NW-SE Eurasia-Africa plate convergence, indicating that the mountain front in this transect is active and that the regional uplift is caused by propagation to the



NW of crustal detachments, producing the elevation of hanging wall without deforming the surface. This deformation pattern implies that deformation remains active; yet the Miocene subduction zone has evolved to a continent-continent collision with limited activity in sectors with a favorable orientation with respect to the present-day plate convergence as the one studied here.

9. Conclusions

[34] Seismic activity in the Gibraltar Arc is characterized by shallow (0–40 km) and intermediate (40– 120 km) earthquakes. However, the instrumental record also reveals 5 deep events at depths between 620 and 660 km. Intermediate and deep seismicity along the Betic Cordillera and Alboran Sea could be interpreted as a consequence of an arched remnant subducted slab that has evolved into a context of continental collision, in the framework of the NW-SE oriented Eurasia-Africa plate convergence.

[35] The present-day stress distribution along the slab is determined from the analysis of earthquake focal mechanisms. Most of the analyzed seismicity is concentrated in the Iberian continental lithosphere. Shallow seismicity (<40 km) is mostly located at the mountain front, its focal mechanism inversion mainly revealing NW-SE horizontal compression, parallel to the Africa-Eurasia convergence. At intermediate depths (50-80 km), the bending of the slab produces downdip compression and along-strike horizontal extension in its inner part, whereas NE-SW extension prevails in the external part. The presence of T axes highly dipping to the southeast at around 90-120 km depth coincides with the transition between oceanic and continental lithosphere. This downdip extension could be explained by the pull associated with the negative buoyancy of the oceanic lithosphere sinking into the mantle. Deep events clearly show downdip compression and suggest the continuity of the oceanic lithosphere down to the 660 km discontinuity, where slabs experience resistance to further descent.

[36] During the development of the Gibraltar Arc, the westward emplacement of the Alboran Domain occurred above an eastward-subducted Euroasiatic oceanic lithosphere during the Early Middle Miocene, interacting with N-S to NW-SE Europe-Africa plate convergence [*Dewey et al.*, 1989]. Since Late Miocene, the subduction stopped due to the consumption of most of the oceanic lithosphere, and the NW-SE convergence between the Eurasian and African major plates became the main geodynamic mechanism. Therefore, present-day subduction could be

considered practically deceased (greatly reduced intermediate and deep seismogenic areas) due to the unlikelihood of subducting continental lithosphere. The Iberian continental crust is forced to sink into the mantle by plate convergence at shallow levels, linked in depth to the pull of the oceanic lithosphere slab that is restricted to the western and central Betic Cordillera and Alboran Sea. The transition between the continental and oceanic lithospheric slab would be located around 90–120 km, in view of available seismic tomography images [*Blanco and Spakman*, 1993; *Seber et al.*, 1996b; *Morales et al.*, 1999]. The Gibraltar Arc is now in the transition from a subduction to a continental collisional setting.

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