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Palaeomagnetic constraints on the geodynamic evolution of the Gibraltar Arc

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ABSTRACT

Subduction zone roll-back was recently put forward as a convincing model to explain the geometry and evolution of the Gibraltar Arc. For other subduction-related arc systems of the Mediterranean, such as the Calabrian Arc and the Hellenic Arc, palaeomagnetic rotation data from Neogene extensional basins provided important constraints on geodynamic evolution models. Here, we present the results of a palaeomagnetic study of 13 continuous sections that are located in E–W transects across the Neogene sedimentary basins of Morocco and Spain. They provide evidence that no significant rotation about vertical axes has occurred in the Gibraltar Arc since the late Tortonian. Comparison with other Mediterranean arc systems shows strong similarities as regards geodynamic evolution. The timing of rotation in the Gibraltar Arc is markedly older than in the Calabrian and Hellenic arcs, and suggests that it is related to the first Neogene extensional phase of the western Mediterranean in which the Algerian–Provençal Basin opened.

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Introduction

The Mediterranean is one of the most fascinating areas of the world to study geodynamic processes in a complex plate tectonic setting. The convergence of Europe and Africa caused the oceanic lithosphere of the African plate to subduct slowly under the European margin, resulting in the orogenic Alpine build-up and in the almost complete consumption of the westernmost part of the Tethys Ocean. In spite of convergence acting as the primary plate tectonic process, the Mediterranean is also known for its large-scale extensional basins (e.g. Aegean Sea, Tyrrhenian Sea, Pannonian Basin) and its diverse tectonic arcs (e.g. Gibraltar Arc, Hellenic Arc, Calabrian Arc, Carpathian Arc), which are all in different evolutionary stages of subduction zones (Fig. 1). They are mainly the result of the typical land-locked configuration of the Mediterranean region, in which slab roll-back of the trench system induced arc migration and extension in the lithosphere above the subduction zone (Wortel and Spakman, 2000). Consequently, arc formation in the Europe–Africa collision zone is generally characterized by significant translations and vertical axis rotations of individual blocks and microplates.

Palaeomagnetic studies can detect the sense of such rotations, the amount of rotation, and the timing of the different translation and rotation events. Most of the Mediterranean tectonic arcs can roughly be divided into two segments, which have experienced rotations in opposite directions (Fig. 1). In this way, the characteristic arc-shaped configuration was created in orogens above subduction zones bounding large extensional basins. Detailed palaeomagnetic studies show also that the Neogene sediments of the extensional basins in the Calabrian and Hellenic arcs experienced relatively young (Plio-Pleistocene) rotational movements (Kissel and Laj, 1988; Scheepers *et al.*, 1993; Speranza *et al.*, 1995; Duermeijer *et al.*, 2000). Such studies have proved to be crucial in understanding and quantifying plate tectonic processes and to test and validate the different kinematic models for orogenic belts (Laj *et al.*, 1982; Van der Voo, 1993).

Many geodynamic models for the western Mediterranean avoid including the enigmatic area of the Gibraltar Arc and the Alboran Basin (Carminati *et al.*, 1998; Faccenna *et al.*, 2001), because the tectonic and geodynamic processes in this region are still subject to controversy. For instance, serious debate is directed to the apparent paradox of coeval shortening and extension and to the formation of the Alboran Sea together with the surrounding arc-shaped Betic–Rif mountain belts in Morocco and Spain (Lonergan and White, 1997; Comas *et al.*, 1999; Calvert *et al.*, 2000; Platt *et al.*, 2003). Recently, however, seismic survey data and new traveltime tomographic results have offered clear evidence for active east-dipping subduction beneath the Gibraltar area (Bijwaard and Spakman, 2000; Gutscher *et al.*, 2002). In addition, westward roll-back of this subduction zone was postulated to produce significant changes in magma chemistry of the associated volcanism, causing uplift of the continental margins of southern Iberia and north-west Africa during the late Miocene (Duggen *et al.*, 2003). On the basis of these results, and because of structural similarities, it was suggested that the geodynamics of the Gibraltar region can be regarded as a western anologue of the Calabrian subduction system (Lonergan and White, 1997; Gutscher *et al.*, 2002). In contrast to the Calabrian region, however, the palaeomagnetic data from the Neogene of the Gibraltar Arc are relatively scarce and, when available, imply significant differences in the sense and timing of rotations (e.g. Allerton *et al.*, 1993; Calvo *et al.*, 1994, 1997).

Rotations in the Gibraltar Arc

The Gibraltar Arc is a tightly curved orogenic belt that lies at the western end of the Alpine orogenic system

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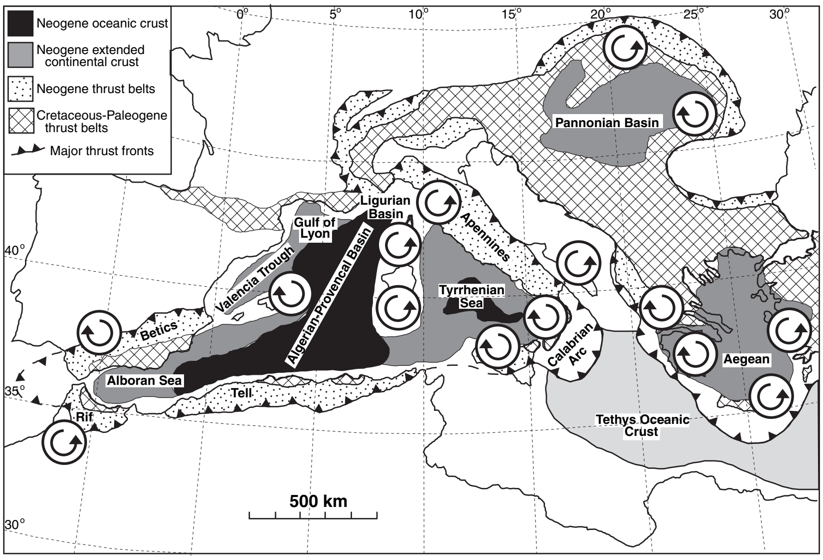

Fig. 1 Map of the Mediterranean Sea (after Lonergan and White, 1997) showing the principal thrust belts and Neogene extensional basins. Thrust belts have been simplified by division into two parts: (1) 'Internal Zones', deformed mainly during the Palaeogene, including metamorphic rocks; and (2) 'External Zones', which are thin-skinned and formed during the Neogene. Regions that have undergone Neogene extension (western Mediterranean, Aegean Sea, Pannonian Basin) are all surrounded by arcuate thrust belts. Arrows within circles indicate clockwise and anticlockwise rotations (see text for references).

(Fig. 2a). The belt can be broadly divided into Internal and External units that appear to curve symmetrically around the arc. Palaeomagnetic data from pre-Neogene outcrops indicate that large rotations about vertical axes have taken place in opposite sense in the Rif Mountains and Betic Cordillera. The Mesozoic limestone sequences of the Internal and External Zones in the Rif Mountains are rotated anticlockwise (Platzman *et al.*, 1993), whereas most sites in the Betic Cordillera experienced a clockwise rotation (Osete *et al.*, 1989; Platzman and Lowrie, 1992; Platzman, 1992; Allerton *et al.*, 1993; Platt *et al.*, 1995). Studies from the metamorphic massifs document the same rotational results in opposite sense and suggest that the major rotational phase took place in the early Miocene (Feinberg *et al.*, 1996). Allerton *et al.* (1993) suggested that the main rotation phase has occurred before the Tortonian, but their conclusion was only based on a single non-rotated normal polarity site. In their study, the youngest rocks that still experienced a clockwise rotation are of Aquitanian age. By contrast, however, Calvo *et al.* (1994, 1997) suggested that rotations in opposite senses continued until very recently, based on palaeomagnetic data from late Miocene to Pliocene sedimentary rocks. Caused by the lack of sufficient reliable data, the exact timing and sense of the tectonic rotations in the Gibraltar Arc are thus still subject to discussion. Evidently, good control on the rotational phases is crucial for tectonic reconstructions, as

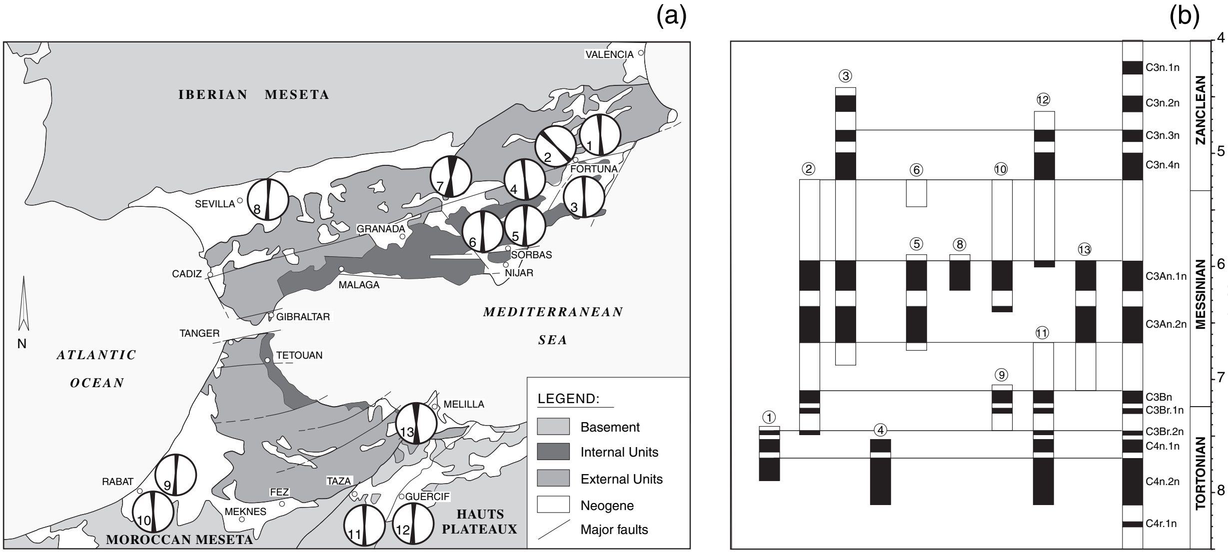

Fig. 2 (a) Simplified geological sketch map of the Gibraltar Arc, showing the rotational results of the 13 studied sections (see also Table 1) of the late Miocene Mediterranean–Atlantic gateway basins of southern Spain and northern Morocco. (b) Magnetostratigraphic correlations of the polarity patterns of these sections to the GPTS of Cande and Kent (1995). (1) Dinarès-Turell *et al.* (1999); (2) and (3) Garcés *et al.* (2001); (4) Krijgsman *et al.* (2000); (5) Sierro *et al.* (2001); (6) Krijgsman *et al.* (2001); (7) Garcés *et al.* (1997); (8) unpublished result; (9) Hilgen *et al.* (2000); (10) Krijgsman *et al.* (2004); (11) and (12) Krijgsman *et al.* (1999b); (13) Van Assen *et al.* (2004).

these palaeomagnetic data play a significant role in the different kinematic models for the Betic–Rif orogenic belt (e.g. Lonergan and White, 1997; Platt *et al.*, 2003).

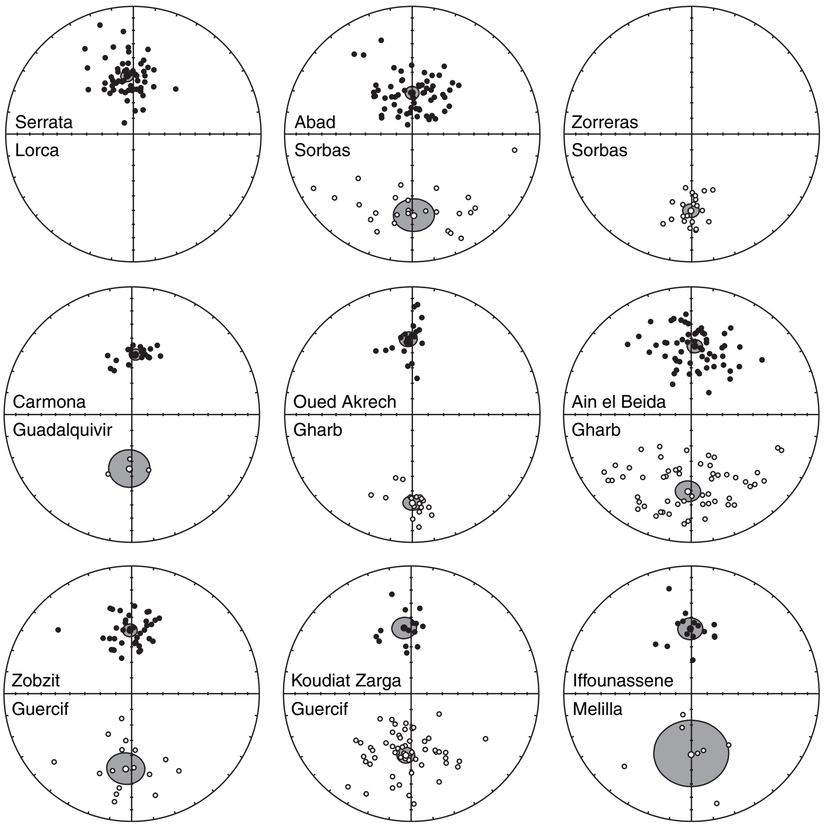

Fig. 3 Equal-area projections of the characteristic remanent magnetization (ChRM) results. Closed (open) circles represent downward (upward) projections. The grey circles give the α_{95} for the different section means (see also Table 1). Demagnetization criteria can be found in Krijgsman *et al.* (1999b, 2000, 2001, 2004), Hilgen *et al.* (2000), Sierro *et al.* (2001) and Van Assen *et al.* (2004). The results from the Chicamo, Chorrico and Librilla sections (Fig. 2) have previously been published in Dinarès-Turell *et al.* (1999) and Garcés *et al.* (2001).

New palaeomagnetic data from the Neogene basins

During the last decade, extensive magnetostratigraphic studies have been performed on the Neogene basins of southern Spain and northern Morocco, with the aim of obtaining a high-resolution chronology for the environmental changes that led to the Messinian Salinity Crisis of the Mediterranean (e.g. Krijgsman, 2002). This resulted in the construction of an accurate and reliable astrochronological time frame for the late Miocene (Hilgen *et al.*, 1995; Krijgsman *et al.*, 1999a). Straightforward magnetostratigraphic correlations with the Geomagnetic Polarity Time Scale (GPTS) have shown that the studied sediments of the Gibraltar region contain a primary magnetic signal (see Fig. 2b), which also makes them suitable for palaeomagnetic rotation studies. In addition, the use of long sections significantly increases the reliability of the rotation results, because small, scattered outcrops may suffer from disturbances by local tectonic features (faults, slumps, creep, etc.) and secular variation, even when deformation cannot be detected on the basis of visual observations (Schwehr and Tauxe, 2003).

Thirteen sections have been sampled, which are all located in E–W transects across the ancient marine gateways through Morocco and Spain that connected the Mediterranean to the Atlantic in Tortonian times (Fig. 2a). Palaeomagnetic studies have been performed using standard laboratory procedures, which are described in detail in earlier papers (e.g. Garcés *et al.*, 1998; Krijgsman *et al.*, 1999b). All samples have been thermally demagnetized and average directions were calculated using Fisher statistics (Fig. 3; Table 1). The average inclinations of all sections are significantly shallower than expected from the palaeolatitudinal position of Spain and Morocco in the Late Miocene. This is a common feature in Mediterranean Neogene sediments and is probably caused by sedimentary inclination error (Krijgsman and Tauxe, 2004). The declination results from 12 sections clearly indicate that no major deflection from the north has occurred since the deposition of the sediments. The Chorrico section of the Fortuna Basin is the only outlier, revealing a significant anticlockwise rotation of approximately 45°. This section, however, is located in the vicinity of a major NE–SW-trending sinistral strike-slip fault and its rotation can be interpreted by local deformation (Garcés *et al.*, 2001). Several sites in the Eastern Betics (Calvo *et al.*, 1994, 1997) also provide contrasting clockwise and anticlockwise rotations. These are most likely related to rotations of small blocks that are close to strike-slip faults as well, but that are only of minor relevance with respect to the emplacement of the Internal Betics. Hence, we can now firmly conclude that the Neogene basins of the Gibraltar Arc have not experienced any rotations about vertical axes since the late Tortonian.

Rotations and geodynamics of the western Mediterranean

The Neogene tectonic evolution of the western Mediterranean is characterized by two major episodes of extension under continuous N–S convergence between Africa and Europe. Palaeotectonic reconstructions illustrate that extension in the major basins is the result of trench migration and back-arc opening, which created the large oceanic basins we see today. The initial phase of lithospheric rifting in the Mediterranean started in the latest Oligocene – earliest Miocene as a result of back-arc extension caused by roll-back of a subducting slab and that

Table 1 Results from palaeomagnetic analysis of the different Neogene sections and basins of the Gibraltar Arc.

Section/Basin		Pol.	*N*	Dec.	Inc.	*k*	α_{95}	Age
1.	Chicamo/Fortuna	N	91	360	52	11	5	Tortonian
		R	40	171	−38	8	9	(7.8–7.5 Ma)
		total	131	357	48	9	4	
2.	Chorrico/Fortuna	N	69	317	30	12	5	Tort./Mess.
		R	52	120	−22	11	6	(7.6–6.0 Ma)
		total	121	309	27	10	4	
3.	Librilla/Fortuna	N	86	354	43	20	4	Mess./Plio.
		R	75	185	−45	11	5	(6.8–4.6 Ma)
		total	161	359	44	12	3	
4.	Serrata/Lorca	N	57	354	52	25	4	Tort. (7.8–7.5 Ma)
5.	Abad/Sorbas	N	63	360	64	18	4	Messinian
		R	25	179	− 36	7	12	(6.8–6.0 Ma)
		total	88	359	57	10	5	
6.	Zorreras/Sorbas	R	21	181	−40	46	5	Mess. (5.6–5.3Ma)
7.	Galera/Guadix	N	19	357	49	8	13	Plio-Pleostoc.
		R	16	195	− 39	5	19	(3.5–1.7 Ma)
		total	35	5	45	6	11	
8.	Carmona/Guadalquivir	N	22	3	51	70	4	Messinian
		R	4	183	−55	55	12	(6.3–6.0 Ma)
		total	26	3	52	69	4	
9.	Oued Akrech/Gharb	N	23	357	41	36	5	Tort./Mest.
		R	18	180	−31	44	5	(7.6–7.0 Ma)
		total	41	358	37	35	4	
10.	Ain el Beida/Gharb	N	60	3	45	17	5	Messinian
		R	56	182	−40	8	7	(6.5–5.5 Ma)
		total	116	3	43	10	4	
11.	Zobzit/Guercif	N	38	359	49	30	4	Tort./Mess.
		R	16	184	41	12	11	(7.6–7.0 Ma)
		total	54	360	47	20	4	
12.	Koudiat Zarga/Guercif	N	14	354	47	31	7	Mess./Plio.
		R	55	185	− 50	14	5	(6.0–4.8 Ma)
		total	69	2	49	15	5	
13.	Iffounassene/Melilla	N	15	359	48	28	7	Messinian
		R	7	180	−51	8	22	(6.5–6.0 Ma)
		total	22	359	49	17	8	

Pol. = polarity (N = normal, R = reversed); *N* = number of specimens; Dec. = declination; Inc. = inclination; *k* = Fisher's precision parameter; α_{95} = 95% cone of confidence. Demagnetization criteria can be found in (1) Dinarès-Turell *et al.* (1999); (2) and (3) Garcés *et al.* (2001); (4) Krijgsman *et al.* (2000); (5) Sierro *et al.* (2001); (6) Krijgsman *et al.* (2001); (7) Garcés *et al.* (1997); (8) unpublished result; (9) Hilgen *et al.* (2000); (10) Krijgsman *et al.* (2004); (11) and (12) Krijgsman *et al.* (1999b); (13) Van Assen *et al.* (2004).

generated the Algerian–Provençal Basin (Fig. 1). This phase was accompanied by a 25–30° anticlockwise rotation of the Calabria–Sardinia–Corsica block (Vigliotti *et al.*, 1990; Van der Voo, 1993), possibly including the Epiligurian units of the northern Apennines of Italy as well (Muttoni *et al.*, 1998). At the same time, lithospheric rifting occurred in the Valencia trough, causing a 20° clockwise rotation of the Balearic Islands (Freeman *et al.*, 1989; Pares *et al.*, 1992). As attested by palaeomagnetic and geochronologic data, this initial rotation and extension phase ended approximately in the Langhian at approximately 16 Ma (Van der Voo, 1993; Vigliotti and Langenheim, 1995; Speranza *et al.*, 2002).

Between the Langhian and late Tortonian (~16–10 Ma), stretching and subsidence was probably restricted to the southern part of the Algerian–Provençal Basin. No significant block rotations have been reported from the sedimentary and volcanic deposits during this time interval, although the African plate continued its slow northward convergence. This period of relatively quiet tectonics was recently explained by slab detachment processes along the north African margin (Carminati *et al.*, 1998), possibly in combination with restriction of the subduction process to the upper 670 km of the mantle (Faccenna *et al.*, 2001). These models are in agreement with seismic tomography investigations of the mantle beneath Italy and the Tyrrhenian Basin (Lucente *et al.*, 1999; Wortel and Spakman, 2000).

The second major phase of lithospheric rifting took place during the late Tortonian to Quaternary. Extensional tectonics separated Calabria from the Sardinia–Corsica block and initiated the opening of the Tyrrhenian Basin. The extension in the Tyrrhenian domain is matched by compressional tectonics in Italy, where east-vergent folding and thrusting gave rise to the Apennines. The arc-shaped configuration of the Calabrian subduction zone was created when Sicily (30–35°) and the Calabro-Peloritan block (± 15°) experienced clockwise rotations in the Pliocene and Pleistocene (Oldow *et al.*, 1990; Scheepers and Langereis, 1994; Duermeijer and

Langereis, 1998) at the same time as the Apenninic foreland underwent 20–40° anticlockwise rotations (Sagnotti and Speranza, 1993; Scheepers *et al.*, 1993). During the Quaternary, the geodynamics of this region probably changed, as indicated by the rapid elevation of Calabria by more than 1 km (Westaway, 1993). GPS data show that the outward migration of the Calabrian arc has now almost stopped (McClusky *et al.*, 2000), which supports the conclusion that slab detachment processes beneath Calabria have been completed very recently (Wortel and Spakman, 2000).

Discussion and conclusions

The first extensional episode in the Gibraltar Arc took place during the early Miocene, as the oldest synrift deposits in the Alboran Sea date back to the Aquitanian (Comas *et al.*, 1992). Similar to the Calabrian system, the lithospheric extension occurred contemporaneously with an overall outward migration of external thrust fronts (Lonergan and White, 1997). The palaeogeography of the Gibraltar Arc changed radically when the Neogene extensional basins developed, coupled with strike-slip tectonics and inversion of previous normal faults (Sanz de Galdeano, 1990).

Active eastward subduction beneath Gibraltar provides an elegant explanation for the geodynamic evolution of the Rif–Betic region (Gutscher *et al.*, 2002). Slab roll-back towards the west may cause extension and subsidence in the Alboran Sea, while the associated westward advance of the Gibraltar Arc may drive compressional deformation in the Betic and Rifian orogens. In this scenario, the Gibraltar subduction can be seen as an analogue of the Calabrian Arc system, with Gibraltar located at the western termination of the palaeo-Maghreb subduction system and Calabria at the eastern end (Gutscher *et al.*, 2002). Palaeomagnetic data indeed show that major rotations have taken place in opposite senses in both regions, but they also indicate a major difference in the timing of rotational movements between the two end-systems. Although rotations in the Calabrian Arc are known to be of Plio-Pleistocene age, the new data from our Spanish and Moroccan sections show that no significant rotational movements have taken place in the Gibraltar Arc since the late Miocene.

The youngest sequences of the Gibraltar region that definitely show major block rotation about vertical axes are dated as early middle Miocene (Allerton *et al.*, 1993; Platzman *et al.*, 2000). The arcuate shape of the Gibraltar area therefore most likely formed contemporaneous with the opening of the Algerian–Provençal Basin, during (or at the end of) the first major extensional phase of the western Mediterranean. The Calabrian arc formed during the second extensional phase of the western Mediterranean, while all rotational movements in the Gibraltar arc had ceased. Although the timing is different, the geodynamic evolution of the Gibraltar Arc appears to be markedly similar to that of the Calabrian Arc. A large extensional basin (Alboran Sea/Tyrrhenian Sea) was created by subduction zone roll-back, accompanied by significant block rotations in opposite senses. Both regions also reveal that no rotation about vertical axes is currently taking place, and that the main extension phase has stopped. Deformation mechanisms in the Gibraltar Arc changed from vertical axis rotation toward strike-slip deformation after the end of the first west Mediterranean extension phase. Rotational movements in the Calabrian Arc stopped very recently (Plio-Pleistocene age) when the slab detachment processes beneath the Tyrrhenian were completed. Using the same line of reasoning, it is not surprising that vertical axes rotations are still occurring in the Hellenic arc (Duermeijer *et al.*, 2000), as the roll-back process of the African lithosphere beneath the Aegean Sea have not (yet) finished.

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