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Crustal types and Tertiary tectonic evolution of the Alborán sea, western Mediterranean

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[1] Multichannel seismic reflection images across the transition between the east Alborán and the Algero-Balearic basins show how crustal thickness decreases from about 5 s two-way traveltime (TWTT, ~15 km thick) in the west (east Alborán basin) to ~2 s TWTT typical of oceanic crust (~6 km thick) in the east (Algero-Balearic basin). We have differentiated three different crustal domains in this transition, mainly on the basis of crustal thickness and seismic signature. Boundaries between the three crustal domains are transitional and lack evidence for major faults. Tilted blocks related to extension are very scarce and all sampled basement outcrops are volcanic, suggesting a strong relationship between magmatism and crustal structure. Stratigraphic correlation of lithoseismic units with sedimentary units of southeastern Betic basins indicates that sediments onlap igneous basement approximately at 12 Ma in the eastern area and at 8 Ma in the western area. Linking seismic crustal structure with magmatic geochemical evidence suggests that the three differentiated crustal domains may represent, from west to east, thin continental crust modified by arc magmatism, magmatic-arc crust, and oceanic crust. Middle to late Miocene arc and oceanic crust formation in the east Alborán and Algero-Balearic basins, respectively, occurred during westward migration of the Gibraltar accretionary wedge and shortening in the Betic-Rif foreland basins. Arc magmatism and associated backarc oceanic crust formation were related to early to middle Miocene subduction and rollback of the Flysch Trough oceanic basement. Subduction of this narrow slab beneath the Alborán basin was coeval with collision of the Alborán domain with the Iberian and African passive margins and subsequent subcontinental-lithosphere edge delamination along the Betic-Rif margins.

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1. Introduction

[2] Extension in the Mediterranean has been intimately related to orogenesis, initiating early as syn-orogenic extension affecting the shallower levels of the orogenic wedge [*Platt*, 1986; *Jolivet et al.*, 2003]. Further extension is commonly related to the interaction between the orogenic wedge and underlying subducted or delaminated lithosphere, producing backarc basins in the interior of tight orogenic arcs such as the Calabrian and Gibraltar arcs in the western Mediterranean [e.g., *Royden*, 1993; *Lonergan and White*, 1997; *Carminati et al.*, 1998; *Faccenna et al.*, 2001, 2004; *Rosenbaum and Lister*, 2004]. This post-orogenic extension is typically accompanied by magmatism and coeval shortening in more external regions of the orogenic arc [e.g., *García-Dueñas et al.*, 1992; *Martínez-Martínez and Azañón*, 1997; *Platt et al.*, 2003]. Post-orogenic extension is assumed to follow a retreating or delaminating slab, migrating behind the thrusting orogenic belt, such as in the Calabrian or Hellenic arcs [*Malinverno and Ryan*, 1986; *Royden*, 1993; *Faccenna et al.*, 2001; *Jolivet*, 2001].

[3] Application of this simple model of post-orogenic extension to the Gibraltar arc is controversial for several reasons, including the following:

[4] (1) The superposition of metamorphic units with contrasting P-T evolutions in the internal zones of the Betics where rocks with a clear post-orogenic extensional evolution have overthrusted rocks formed in a cooler orogenic setting [e.g., *Balanyá et al.*, 1997; *Azañón and Crespo-Blanc*, 2000; *Booth-Rea et al.*, 2005; *Platt et al.*, 2006].

[5] (2) The subcontinental Ronda peridotites register a lithospheric extensional event prior to their early Miocene intracrustal emplacement in the Betics and Rif [e.g., *Balanyá et al.*, 1997, 1998; *Lenoir et al.*, 2001; *Sánchez-Gómez et al.*, 2002].

[6] (3) The age and distribution of crustal extension in the Alborán and Algero-Balearic basins is partly contrary to the one that would be expected from a normal post-orogenic setting related to a westward-migrating orogenic wedge (Figure 1). A west to east migration in extension is observed at least for the Early to Late Miocene evolution of these basins. Basement highs drilled at ODP Site 976 in the west Alborán basin indicate extension started in the early Miocene or even late Oligocene (27 Ma) [*Platt et al.*, 1998; *Comas et al.*, 1999], while 200 km to the east in the Algero-Balearic basin, oceanic crust formed during the middle to late Miocene [*Comas et al.*, 1995; *Booth-Rea*, 2004; *Mauffret et al.*, 2004]. Middle Miocene to Pliocene extension and associated subsidence also occurred in the west Alborán basin, superimposed on the early Miocene extension, [*Rodríguez Fernández et al.*, 1999; *Hanne et al.*, 2003]. Late Neogene subsidence is also evident in the Betic margin [*Fernández and Guerra Merchán*, 1996; *Rouchy et al.*, 1998; *Soria et al.*, 2001], although its origin is controversial as we will see below.

[7] Currently two conflicting scenarios have been proposed for tectonics in the Alborán basin and the eastern Betics during the Serravallian-Tortonian (13.6–7.2 Ma): One scenario proposes contractive tectonics producing strike-slip faults and folds with sedimentation occurring in synclinal basins and in regions of subsidiary extension in transtensional fault segments [e.g., *Montenat and Ott d'Estevou*, 1990]. A second scenario proposes that arc magmatism [*Gierman et al.*, 1968; *Galdeano et al.*, 1974; *Gill et al.*, 2004; *Duggen et al.*, 2005], coeval crustal extension and associated subsidence [*Lonergan and Schreiber*, 1993; *Krautworst and Brachert*, 2003; *Booth-Rea et al.*, 2004a; *Meijninger and Vissers*, 2006] was more important than commonly proposed, but that this phase was masked by latest Tortonian (~8–7.2 Ma) to present contractive structures [*Booth-Rea et al.*, 2004b; *Martínez-Martínez et al.*, 2006; *Meijninger and Vissers*, 2006].

[8] Here we present reprocessed multichannel seismic reflection images of the transition between the east Alborán and the Algero-Balearic basins. The

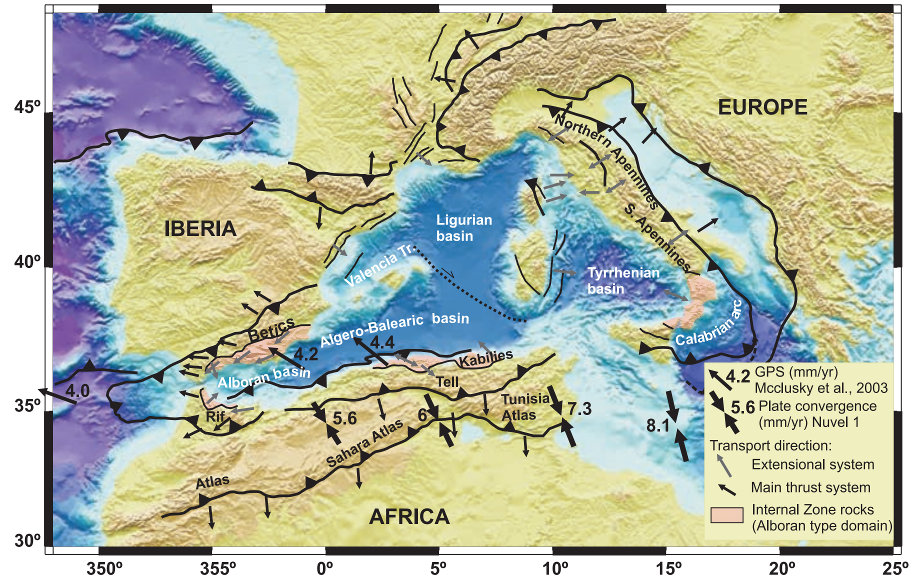

Figure 1. Tectonic map of the western Mediterranean region, modified from *Faccenna et al.* [2004].

reprocessed data image for the first time the entire crustal architecture, including abundant lower-crustal reflectivity and clear Moho reflections. To test the above hypothesis about the importance of late Miocene extension and magmatic arc growth we compared the tectonic structures and seismic stratigraphy interpreted in the lines with structural and stratigraphical data from the emerged Miocene Alborán basin that outcrops in the Betic margin. The seismic images may show the presence of continental crust formed or modified by magmatic processes in the east Alborán basin and oceanic crust in the Algero-Balearic basin. We later discuss the implications that this magmatism has in the Tertiary evolution of the Gibraltar arc and the Betic-Rif margins, in particular in relation to subduction and/or lithospheric mantle delamination processes.

2. Tectonic Setting

[9] The Betics in the westernmost Mediterranean region form the northern branch of the Gibraltar arc, an arched orogenic belt mainly formed during the Miocene collision between the Alborán domain and the south Iberian and Maghrebian passive margins in the context of N-S to NW-SE Africa-Iberia convergence (Figure 1). The Alborán domain (Figure 2) is formed by three poly metamorphic terrains, in ascending order: the Nevado-Filabride, Alpujarride and Malaguide complexes, together with the Dorsal and Predorsal units [*Balanyá and García-Dueñas*, 1987]. The Alpujárride and Malaguide complexes represent the remnants of an earlier orogenic wedge that underwent HP metamorphism [*Goffé et al.*, 1989; *Tubía and Gil Ibarguchi*, 1991; *Azañón et al.*, 1997; *Booth-Rea et al.*, 2002] and crustal stacking during the Eocene [*Lonergan*, 1993]; dated at approximately 50 Ma [*Platt et al.*, 2005], followed by late Oligocene to early Miocene extension in a backarc setting [*Balanyá et al.*, 1997; *Platt et al.*, 1998; *Azañón and Crespo-Blanc*, 2000; *Booth-Rea et al.*, 2004a, 2005] accompanied by tholeiitic dike intrusion dated between 33.6 and 17.7 Ma [*Torres-Roldán et al.*, 1986; *Turner et al.*, 1999; *Platzman et al.*, 2000; *Duggen et al.*, 2004]. Magmatic intrusion Ar-Ar ages determined from plagioclase separates are between 33.6 and 23 Ma and the younger 17.7 Ma whole-rock or matrix ages may represent thermal overprinting [*Platzman et al.*, 2000; *Duggen et al.*, 2004]. These orogenic events occurred in an easterly relative position, probably near the present position of the Algero-Balearic basin [e.g., *Balanyá et al.*, 1997; *Martínez-Martínez and Azañón*, 1997; *Platt et al.*, 2003]. Subsequent early to middle Miocene collision of the Alborán domain with the African and Iberian passive margins occurred after and during subduction of the "Flysch Trough" (Figure 2) basement formed by oceanic or very thin continental crust that was the locus of deep-water sedimentation during the Mesozoic and part of the Cenozoic [*Durand-Delga et al.*, 2000; *Luján et al.*, 2006]. The Trough was likely located between the above mentioned passive margins, along the length of the Iberia-Africa transform boundary, and spanned an area larger than the present Alborán sea [*Guerrera et al.*, 1993]. Tectonic inversion of both continental

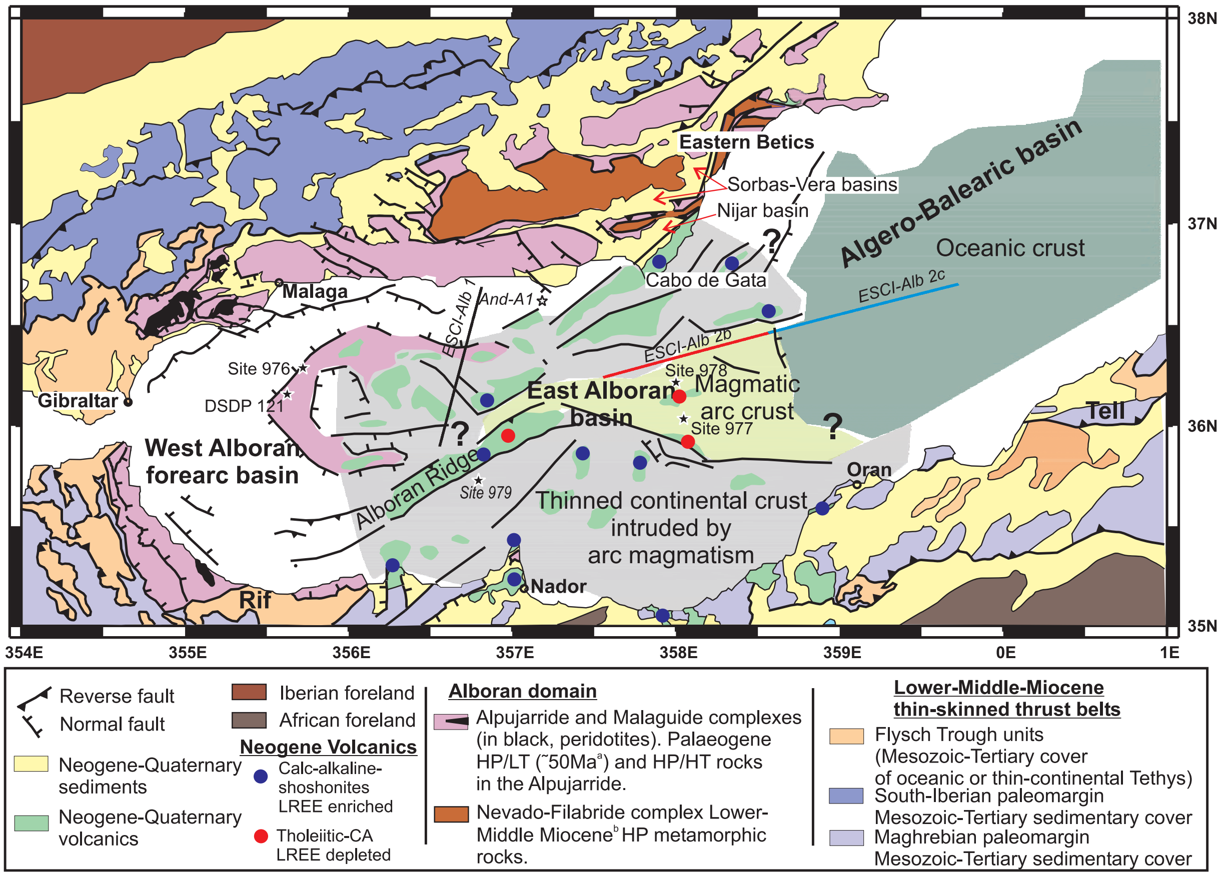

Figure 2. Simplified geological map with the main tectonic domains forming the Gibraltar arc, modified from *Comas et al.* [1999]. We have differentiated three domains formed by oceanic, magmatic arc, and thin continental crust intruded by arc magmatism taking into consideration the seismic facies of the ESCI Alb-2 lines, igneous geochemistry data [*El Bakkali et al.*, 1998; *Coulon et al.*, 2002; *Duggen et al.*, 2004, 2005], crustal thickness [*Torné et al.*, 2000], and previous work by *Comas et al.* [1999]. Age of metamorphism: (a) *Platt et al.* [2005] and (b) *Platt et al.* [2006].

margins developed a fold-and-thrust belt formed mostly by the detached Mesozoic sedimentary covers of both passive margins (Figure 2) [*Platt et al.*, 1995; *Crespo-Blanc and Campos*, 2001; *Platt et al.*, 2003; *Luján et al.*, 2003, 2006]. The Mesozoic sediments reached intermediate pressure-low temperature metamorphism (7–8 kbar and 350–400°C) during the early Miocene in the deeper units of the Rif external domain, the Temsamane units [*Negro*, 2005; *Negro et al.*, 2007]. Recent work suggests that the Paleozoic basement of the South Iberian margin reached HP-LT metamorphic conditions in the early to middle Miocene and was exhumed in the core of the Betics where it forms the Nevado-Filabride complex (Figure 2) [*Platt et al.*, 2004, 2006; *Booth-Rea et al.*, 2005]. Thrusting and westward migration of the fold-and-thrust belt was coeval with extension in the hinterland [e.g., *García-Dueñas and Martínez-Martínez*, 1988; *Platt and Vissers*, 1989; *Galindo-Zaldívar et al.*, 1989; *García-Dueñas et al.*, 1992; *Martínez-Martínez and Azañón*, 1997]. The main extension occurred along WSW-directed core-complex detachments that exhumed the Nevado-Filabride complex between the Serravallian (13.6 Ma) and present [*Johnson et al.*, 1997; *Martínez-Martínez et al.*, 2002, 2006].

[10] WSW-directed extension in the Betics and Rif was heterogeneous, resulting in different extensional styles, including: Upper crustal extension characterized by tilted block domains in the northeastern and western Betics and in the western Rif [e.g., *García-Dueñas et al.*, 1992; *Booth-Rea et al.*, 2003a, 2004a]. Core-complex structures in the central Betics and the Rif [e.g., *Martínez-Martínez et al.*, 2002, 2004; *Negro et al.*, 2007] and extension affecting the whole crust, producing extreme crustal thinning and magmatism in the Alborán basin [*Comas et al.*, 1999].

[11] NE-SW extensional exhumation of the Nevado-Filabride complex was coeval with

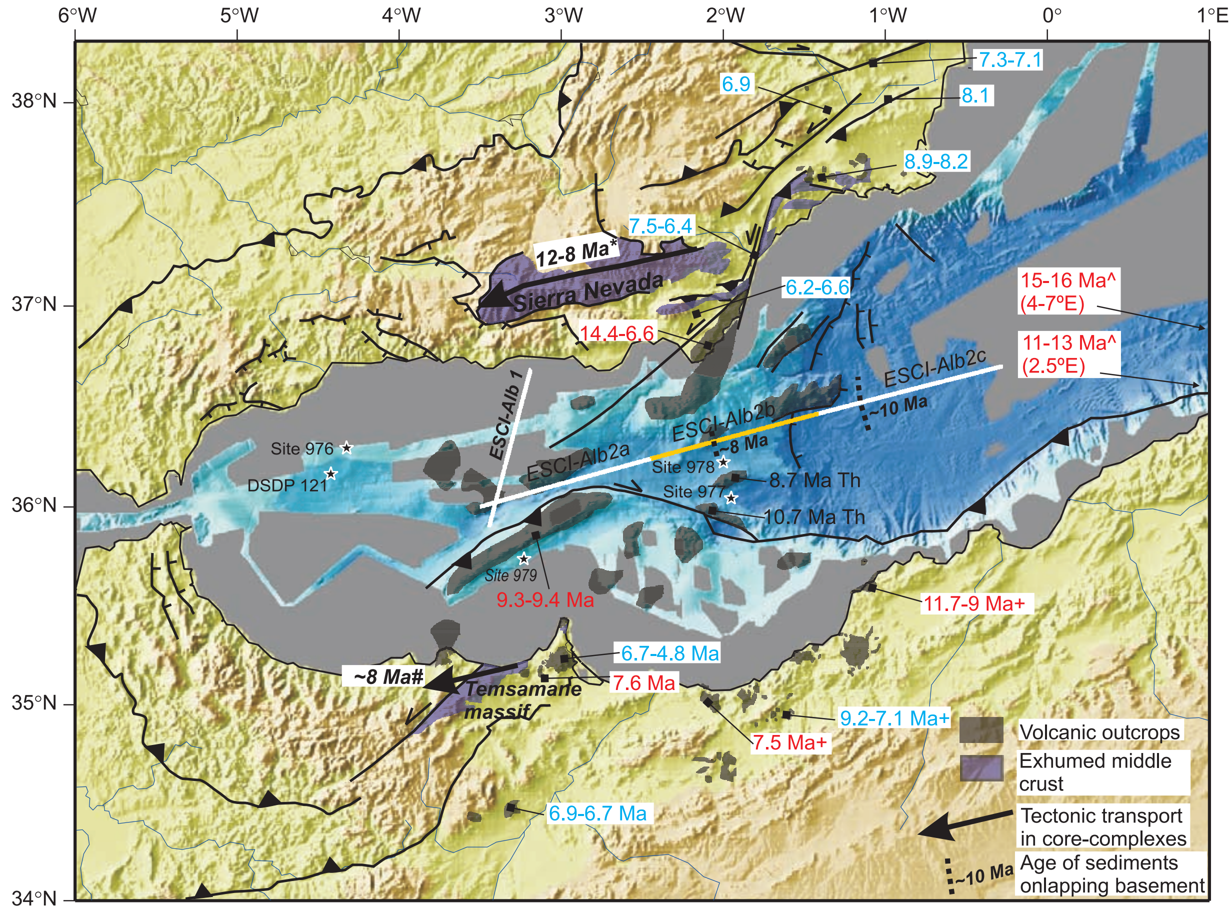

Figure 3. Bathymetry and topography of the Gibraltar Arc with the location of the ESCI-Alb seismic lines and volcanic outcrops. Age of volcanic outcrops from *Duggen et al.* [2004, 2005], *Coulon et al.* [2002] (plus symbols), and *Maury et al.* [2000] (caret symbols). Longitudes have been given for rocks that crop out of the map along the Algerian coast. The age of tholeiitic volcanism is in black type, calc-alkaline is in red type, and Si-K-rich shoshonitic is in blue type. Age of exhumation of middle crust in the Betic and Rif margins is from *Johnson et al.* [1997] (asterisks) and *Negro* [2005] (pound symbols). Bathymetry from *MediMap Group* [2005].

NW-SE contraction that folded the unloaded footwalls of the main extensional detachments producing elongated metamorphic domes [*Martínez-Martínez et al.*, 2002, 2004]. The modern NW-SE convergence of Africa and Europe in the Betic-Rif and Alborán sea regions is partly localized along a number of large strike-slip and reverse faults developed since the late Miocene [e.g., *Bousquet and Montenat*, 1974; *Bousquet*, 1979; *Weijermars et al.*, 1985; *de Larouzière et al.*, 1988; *Montenat and Ott d'Estevou*, 1990; *Comas et al.*, 1999; *Booth-Rea et al.*, 2004b; *Stich et al.*, 2006].

3. Acquisition and Processing of Seismic Data

[12] During the ESCI-Alborán experiment, about 400 km of multichannel seismic reflection data (Figure 3) were acquired by the seismic vessel Bin Hai 511 from Schlumberger Geco-Prakla in 1992 [*Comas et al.*, 1995]. The acquisition system consisted of a 4.5 km long streamer with 180 channels at 25 m spacing, and a 120 liter tuned air gun array, shot every 50 m, yielding 45 fold common mid point (CMP) gathers every 12.5 m. We selected for reprocessing lines ESCI-Alb 2b and 2c, 101.5 and 107.5 km long respectively, because they image the transition from the east Alborán to the Algero-Balearic basins where the nature of the crust is expected to change, thinning eastward. Crustal thinning from Moho depths of about 14 km to less than 10 km has been inferred between the two basins [*Polyak et al.*, 1996; *Torné et al.*, 2000]. Reprocessing of the lines was done using SEISMOS software (Schlumberger). The first steps consisted in frequency-wave number (F-K) filtering of CMP gathers and near trace muting to attenuate multiples. In line 2b numerous side-

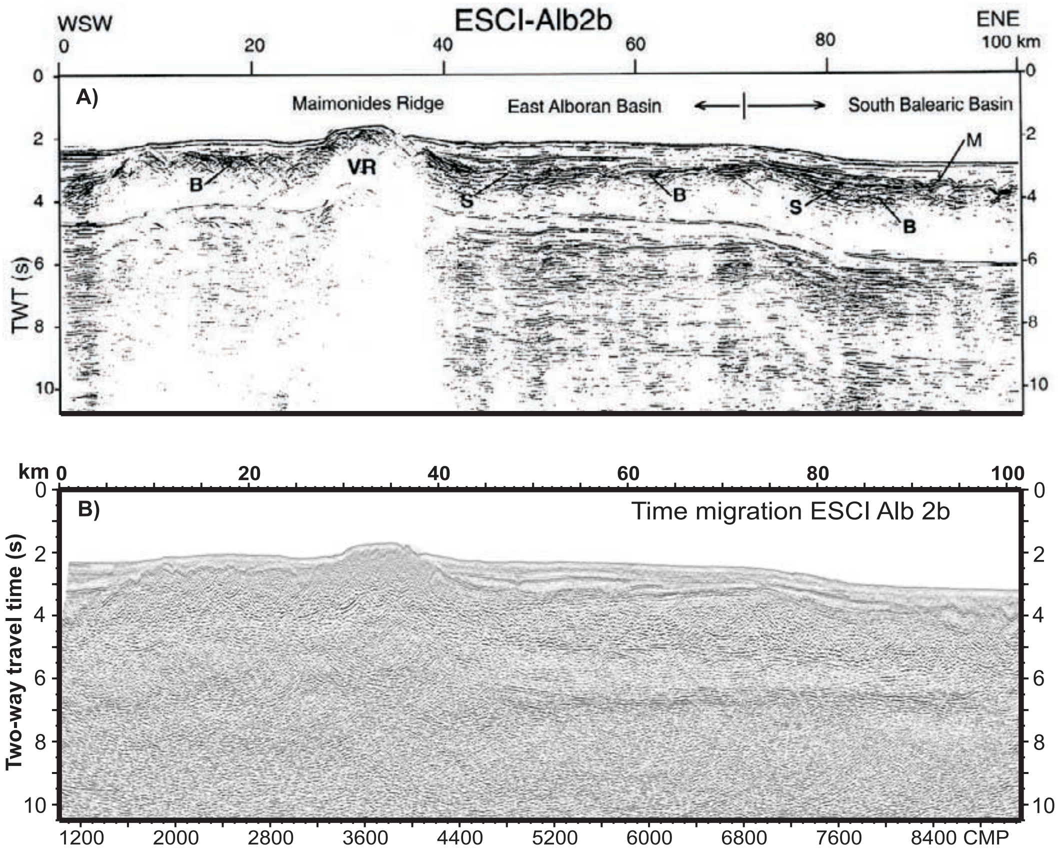

Figure 4. (a) Line ESCI-Alb 2b as published by *Comas et al.* [1995]. Labels are S, late Miocene? synrift sequence; B, top of the basement; VR, volcanic rocks; M, "Messinian" unconformity. (b) Line ESCI-Alb 2b with the seismic processing presented in this paper. Notice the rich lower crustal and Moho reflections uncovered under the multiples shown in Figure 4a.

coming events produced by a rough seafloor obscured deep crustal reflections. To attenuate side echoes, shotpoint gathers were gently F-K filtered. Further processing included predictive deconvolution before stack, 45 fold stacking and finite difference time migration at 4 ms sampling rate and 12.5 m trace spacing using a velocity model obtained after smoothing stacking velocities [*Booth-Rea*, 2004]. The attenuation of coherent noise in both seismic lines, especially in line 2c where strong multiples were produced by the Messinian evaporites, uncovered a great wealth of reflectivity in the basement. This reflectivity includes lower-crustal and clear Moho reflections (Figure 4), except under two short segments, one with particularly rough topography (km 20–45 of line 2b, Figures 5 and 7), and the other with shallow evaporite diapirs (km 90–105 of line 2c, Figures 6 and 7). Time migration has moved dipping reflections to a more correct location showing the relationships between lower-crustal events and Moho reflections. Furthermore, the collapse of diffractive energy also clarified the geometry of the top of the igneous basement and upper-crustal reflectivity (Figures 5 and 6). Below we describe the main features imaged by the seismic profiles, from the deep crust to the shallow sedimentary cover. Preliminary interpretation of stack sections of the entire ESCI-Alborán data set was presented by *Comas et al.* [1995], here we concentrate on the features unraveled by reprocessing and time migration.

4. Igneous Crust Structure

[13] As a first approximation, crustal thickness can be inferred from the TWTT between the top of the basement and the Moho reflection. This seems a reasonable assumption because average crustal velocity probably does not change markedly along the lines, and the greatest observed changes in crustal thickness are too large to be explained by moderate changes in seismic velocity. Seismic images show that crustal thickness generally decreases from west to east, in parallel to changes in the seismic character of the internal structure of the crust (Figure 7). From west to east the seismic

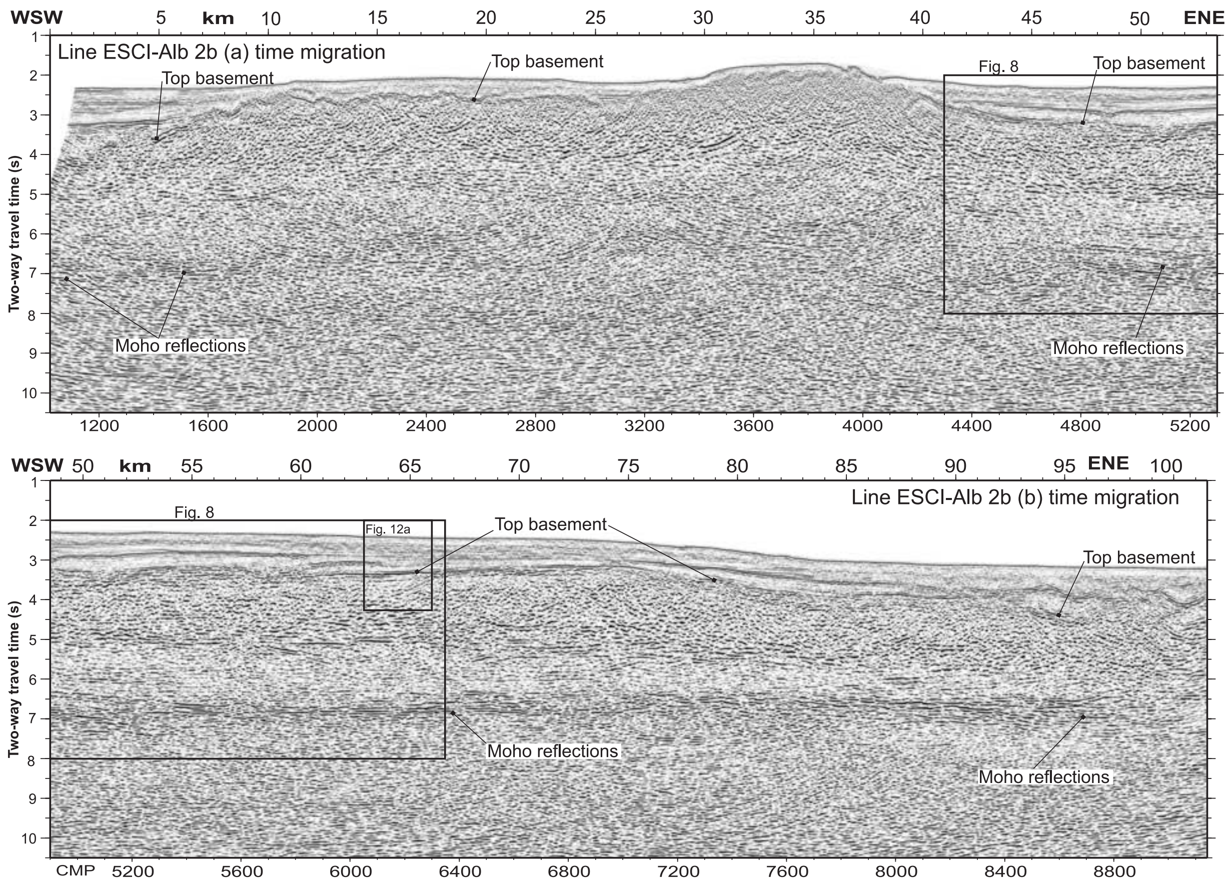

Figure 5. Time migration of seismic line ESCI-Alb 2b. Boxes have been enlarged in Figures 8 and 12a.

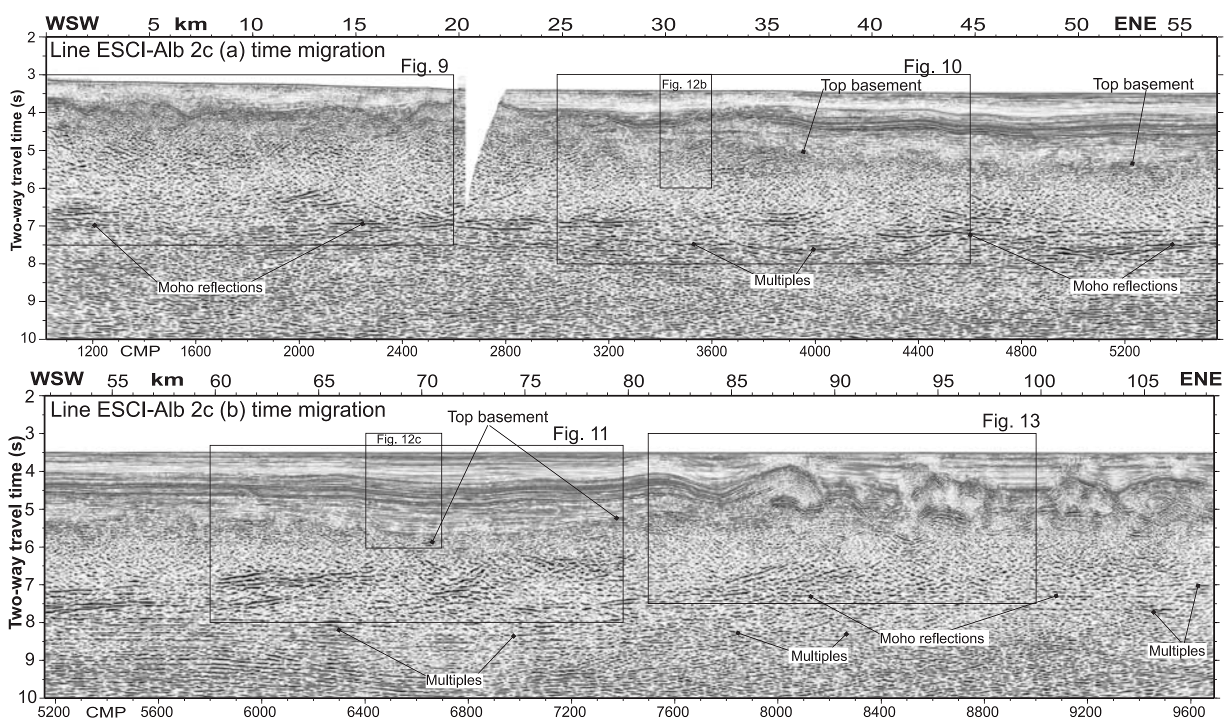

Figure 6. Time migration of seismic line ESCI-Alb 2c.

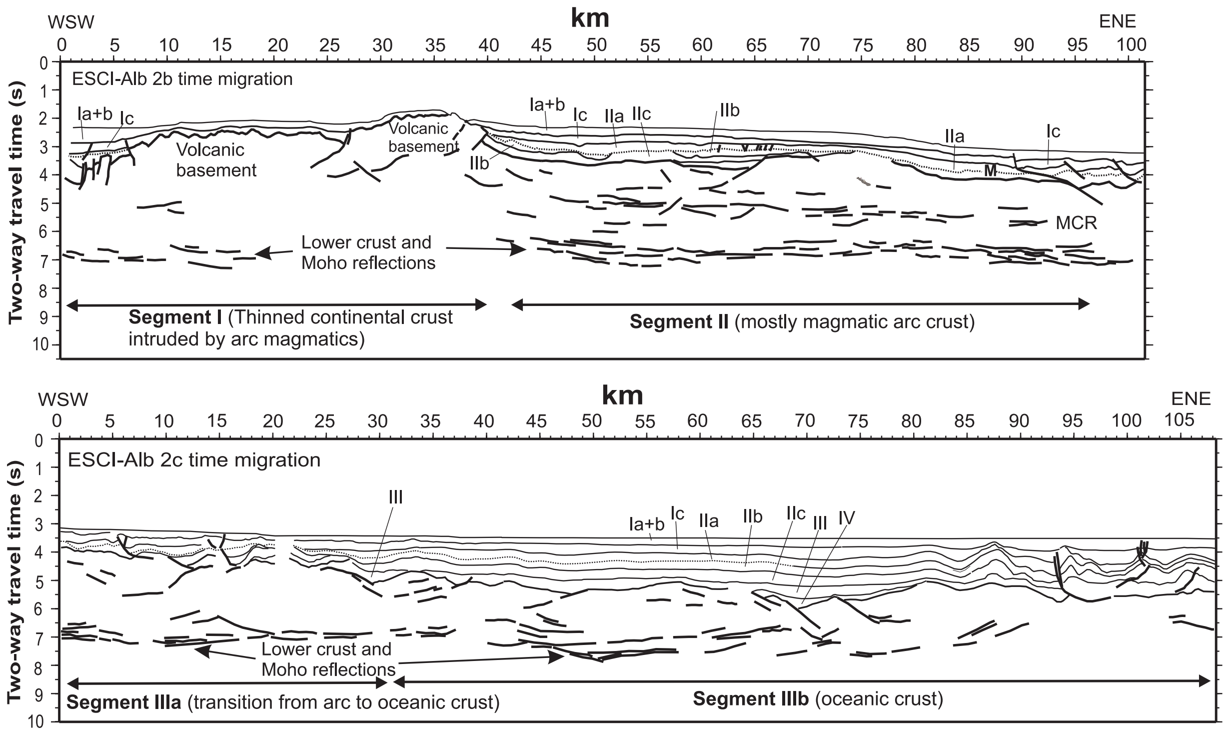

Figure 7. Line drawings with the main reflections and lithoseismic units from seismic lines ESCI-Alb 2b and 2c. Labels: MCR, mid-crustal reflectors; M, Messinian unconformity; Ia + b, Quaternary-late Pliocene unit; Ic, early Pliocene unit; IIa, late Messinian upper evaporite unit; IIb Messinian lower evaporite unit; IIc, Messinian pre-evaporitic unit; III, Tortonian unit; IV, Serravallian?-Tortonian unit.

data image three segments, each with distinct crustal thickness and distinctive seismic character.

[14] Segment I, corresponding to the east Alborán basin, (km 0–40 of line 2b, Figures 5 and 7) is about 4.5–5.0 s thick in TWTT (13.5–15.0 km assuming a 6 km/s velocity). Here the top of basement is comparatively rough, it is mostly free of intracrustal reflections and Moho reflections have only been detected in a few locations (Figure 7). However, along this segment multiple attenuation was the least efficient, probably because of the rough top basement and thin sedimentary cover causing scattering and poor energy penetration. The lack of intracrustal reflecting features may be partially caused by comparatively lower signal/noise ratio.

[15] Segment II images a markedly different structure in the transition from the east Alborán to the Algero-Balearic basin, extending from about km 40 to 95 of line 2b (Figures 5 and 7). A thinner crust ranging between 3.5 s TWTT in the west to 3.0 in the east (about 10.5 to 9 km) displays a notably smoother top of the basement. The crustal reflectivity clearly defines a thin lower crust with subhorizontal reflections, a fairly reflection-free middle crust, bounded at the top by a series of subhorizontal reflections of 1–3-km continuity (MCR in Figure 8), and an upper crust characterized by shorter, discontinuous reflections of higher amplitude (Figure 8). Crustal thinning from west to east is accompanied by the disappearance of the middle low-reflectivity crust, while the brittle upper crust appears to remain with a constant thickness (Figures 5 and 7).

[16] Segment III images a pronounced eastward thinning from 3.2 to about 2 s TWTT (about 9.6 to 6 km) in the first ~25 km of line 2c (segment IIIa, Figures 6 and 7). Eastward of ~25 km (segment IIIb) the crust remains about 2 s TWTT thick (Figure 7). Bright Moho reflections are locally overlaid by generally dipping, lower-crustal reflections that become dominant toward the east where the crust is ~2 s TWTT thick, and that have not been imaged in the other segments (e.g., Figures 9, 10, and 11). The top of the basement is notably rougher than in segment 2, with escarpments 0.2–0.6 s TWTT high. Most of the crustal thinning occurs abruptly across a large offset of the top of the basement at km ~25 probably representing a fault (Figure 10). Packages ~0.5–1.0 s TWTT thick of upper-crustal reflections commonly occur in the first ~35 km (e.g., Figures 9 and 10), and are

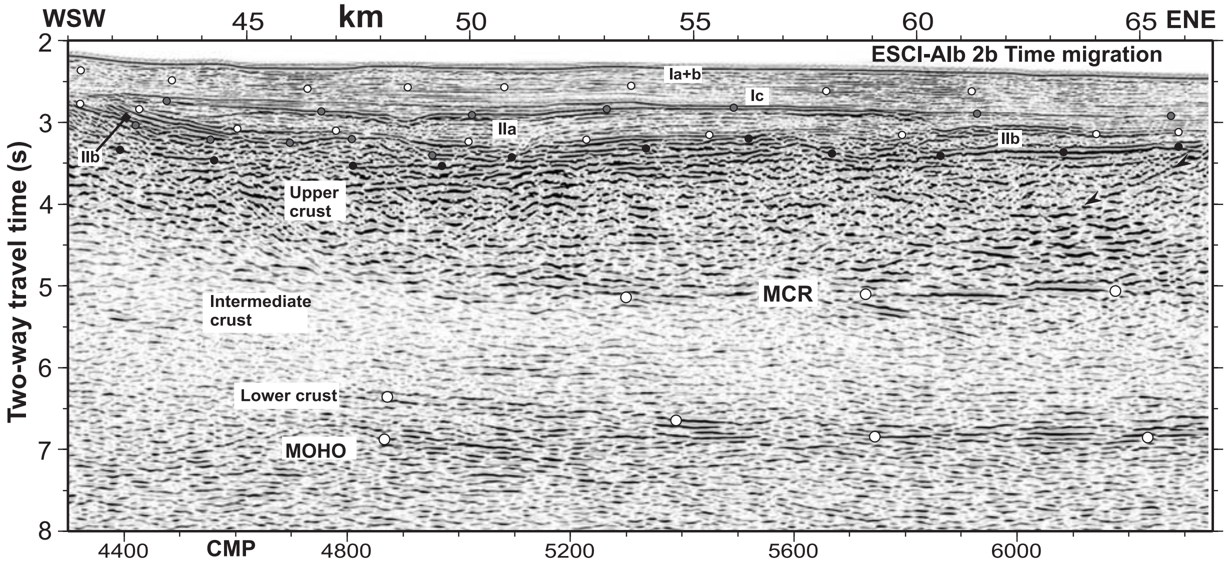

Figure 8. Details of line ESCI-Alb 2b representative of magmatic-arc crust showing clear lower and upper crustal differentiation and the reflection Moho. Notice also the main sedimentary lithoseismic units. Labels: MCR, mid-crustal reflectors; Ia + b, Quaternary-late Pliocene unit; Ic, early Pliocene unit; IIa, late Messinian upper evaporite unit; IIb Messinian lower evaporite unit.

largely absent eastward. Upper crustal reflections are characterized by short (1–2 km long) bright reflections, subhorizontal to slightly tilted westward (Figures 9 and 10).

5. Shallow Crustal Structure: Sedimentary Seismic Units

[17] The sedimentary cover thickens to the east from slightly less than 1.5 s TWTT (≈1.5 km) in most part of line 2b, except in regions with rough basement bathymetric highs (Figure 5a), to up to 2.5 s TWTT (>2.5 km) in the eastern section of line 2c (Figure 11). We have differentiated four main lithoseismic units formed by middle Miocene to Quaternary sediments (Figures 7 and 11), mostly following previous work done in the Alborán sea [*Jurado and Comas*, 1992; *Comas et al.*, 1992, 1995]. The main difference between the Algero-Balearic and the Alborán basins late Miocene stra-

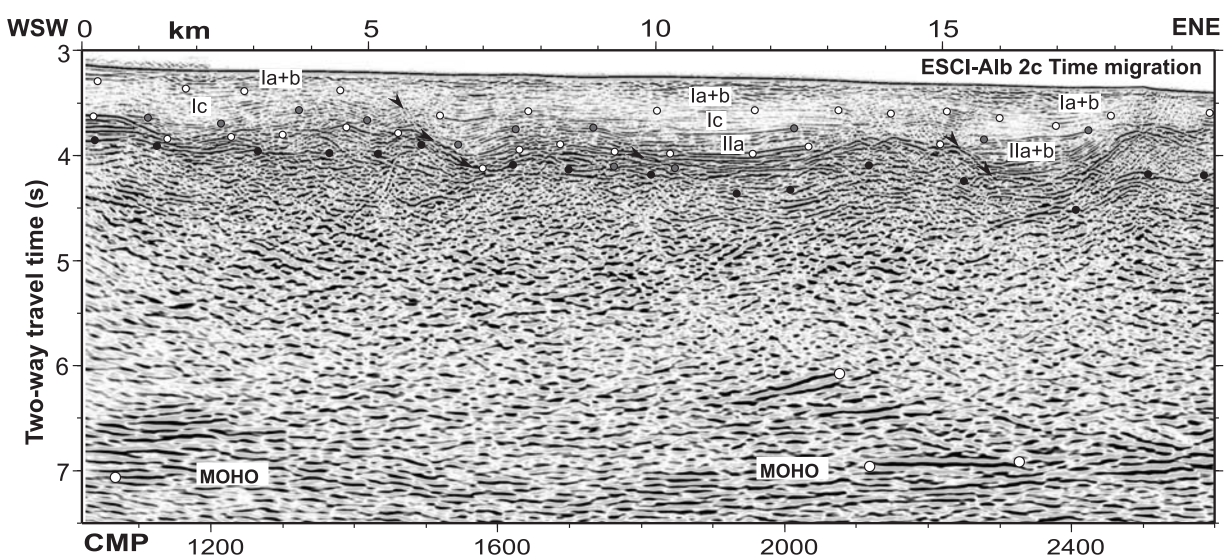

Figure 9. Details of the western termination of line ESCI-Alb 2c. Notice listric faults cutting the Messinian and Pliocene sedimentary sequence. The acoustic basement is marked with black dots. Labels: Ia + b, Quaternary-late Pliocene unit; Ic, early Pliocene unit; IIa, late Messinian upper evaporite unit; IIb Messinian lower evaporite unit.

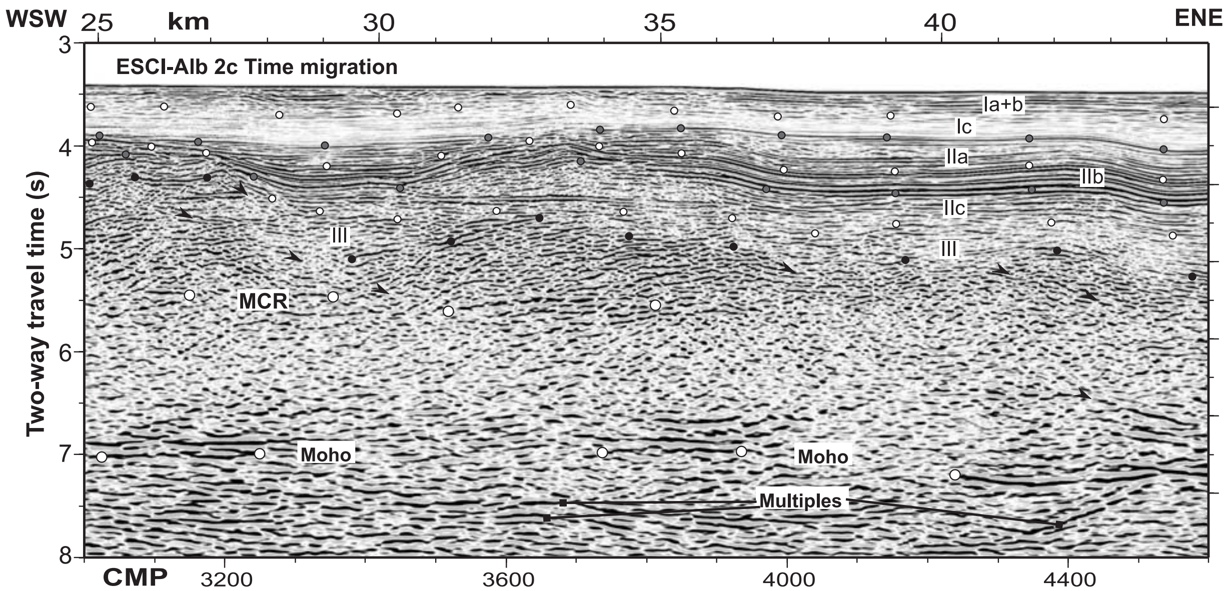

Figure 10. Segment of line ESCI-Alb 2c showing local tilting of the upper crust by extensional faults (marked with arrows). Notice how the M erosional unconformity in the western end of the profile is onlapped by unit IIa of latest Messinian age. The acoustic basement is marked with black dots. Labels: MCR, mid-crustal reflectors; Ia + b, Quaternary-late Pliocene unit; Ic, early Pliocene unit; IIa, late Messinian upper evaporite unit; IIb Messinian lower evaporite unit; IIc, Messinian pre-evaporitic unit; III, Tortonian unit.

tigraphy is that the Messinian erosional unconformity described in the Alborán sea is locally a paraconformity in the Algero-Balearic basin. This way, two different lithoseismic units formed mostly by evaporites deposited during the Messinian salinity crisis [*Hsü et al.*, 1973] have been differentiated in the Algero-Balearic basin [*Rehault et al.*, 1984].

[18] The uppermost unit (I) comprises three subunits deposited after the Messinian salinity crisis [*Hsü et al.*, 1977] between the Pliocene and the

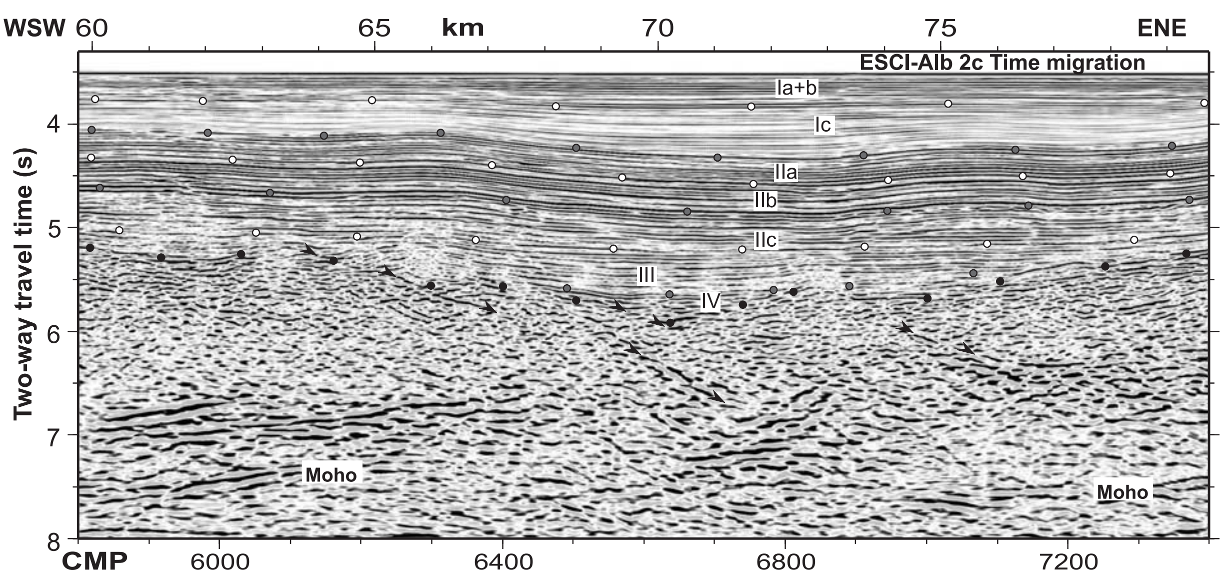

Figure 11. Segment of line ESCI-Alb 2c representative of oceanic crust in the western Algero-Balearic basin cut by faults. Notice how high-amplitude reflectivity of the lower crust is cut by faults. Labels: Ia + b, Quaternary-late Pliocene unit; Ic, early Pliocene unit; IIa, late Messinian upper evaporite unit; IIb Messinian lower evaporite unit; IIc, Messinian pre-evaporitic unit; III, Tortonian unit; IV, Serravallian?-Tortonian unit.

Quaternary [*Alvarez-Marrón*, 1999]. Unit Ia+b at the top of the sequence shows a lateral variation in its seismic facies, characterized by discontinuous irregular reflections interpreted as channels in the shallower regions and by more continuous high-frequency reflectivity in the deeper portions of line 2c. Clinoforms are observed in the transition between the two previous seismic facies, probably representing deep-sea fan lobes (Figure 10). Maximum thickness of this unit is approximately 0.35 s TWTT (~250–300 m). The base of unit Ia+b is mostly erosive, filling submarine channels along line 2b and in the western segment of line 2c (up to km 45, Figure 7). To the east it is a paraconformity defined by one reflection or a package of three continuous reflections, except above anticlinal or diapiric structures in line 2c, east of km 80, where it is an angular unconformity sealing Pliocene amplification of the anticlines (Figure 13). Unit Ia+b is probably equivalent to units Ia and Ib defined with high-resolution single-channel seismics in the east Alborán basin by *Alvarez-Marrón* [1999].

[19] Unit Ic is characterized mostly by low-reflectivity facies, clearly bounded by two more reflective seismic units. It reaches a maximum thickness of 0.6 s TWTT (~500 m, km 99) in line 2c (Figures 7 and 13). It is bounded at its base by a paraconformity in most of the region, although it locally shows onlapping relationships. Unit 1c onlaps the Messinian erosional unconformity, locally, in both seismic lines (kms 80 to 85, line 2b, Figure 5 and kms 22 to 26, line 2c, Figure 6). East of km 82 in line 2c it shows strong lateral thickness variations and progressive internal unconformities on the limbs of anticlines that developed during deposition (Figure 13). It is equivalent to unit Ic defined by *Alvarez-Marrón* [1999] in the east Alborán basin from single-channel high-resolution reflection lines.

[20] Unit IIa has been distinguished in the two seismic lines, filling synformal depressions, or half grabens. It generally shows high-amplitude reflections that onlap the Messinian erosive unconformity in regions where it occurs below unit Ic. In the deepest sedimentary depocenters the base of this unit is a paraconformity. In line 2c, where it reaches the greatest thickness, it shows 3 sequences that start with low-amplitude disorganized reflections capped by a high-amplitude continuous reflection (e.g., km 37, Figure 10). These sequences show upward increasing thickness. Toward the east of line 2c the reflections of unit IIa show a lateral change of facies, increasing in amplitude, (e.g., at km 79, line 2c, Figure 11) until they are very similar to the seismic facies of the underlying unit, formed by evaporites.

[21] Unit IIb occurs only locally and is characterized mostly by high-amplitude continuous reflections (Figures 7, 10, and 11). However, the basal part of this unit is less reflective, overlying a very clear, high-amplitude reflection with negative polarity (Figures 11 and 12c) that indicates a decrease in seismic velocity in the underlying sedimentary unit (velocities required to migrate the synclines to the east of line 2c abruptly change from 4 km/s in unit IIb to ~3 km/s in the underlying unit). Unit IIb is formed by evaporites deposited during the Messinian salinity crisis, bounded at the top by the M reflector, which is a local paraconformity above the evaporites and an erosive unconformity westward onlapped by units IIa or Ic in most of the Alborán basin [e.g., *Comas et al.*, 1992, 1999]. Unit IIb has a maximum thickness of approximately 0.25 s TWTT (~400–500 m). Toward the east in line 2b it interfingers with very reflective disorganized reflections filling channels and with downlapping clinoforms that could represent alluvial continental sediments fringing volcanic relieves, deposited during the Messinian emersion (Figures 7 and 8).

[22] Unit IIc shows discontinuous low-amplitude reflections and a strong decrease in seismic velocity compared to unit IIb. Reflections in unit IIc are mostly parallel to the ones in the overlying unit, suggesting the existence of a paraconformity between both units in great part of the seismic lines, except at the western part of line 2b (km 40 to 60, line 2b), where the continental facies of unit IIb cut into or downlap on unit IIc (Figures 7 and 8). Toward the west, in line 2b, Unit IIb shows different seismic facies characterized by higher reflectivity, probably related to a westward proximity to the source and increase in siliciclastics. Unit IIc onlaps the acoustic basement in most of line 2b (km 40–58 and 80–95) and in a segment of line 2c, between km 0 and 25. Unit IIc forms the core of the antiforms or diapirs in the eastern end of line 2c (Figure 13).

[23] Unit III onlaps the basement east of km 25 in line 2c and it reaches its maximum thickness in half grabens where it shows syn-rift characteristics (Figure 7). A clear rollover structure affects this unit between km 65 and 67 in line 2c (Figure 11). Its seismic facies are very similar to the overlying unit IIc. It seems to occur continuously east of km

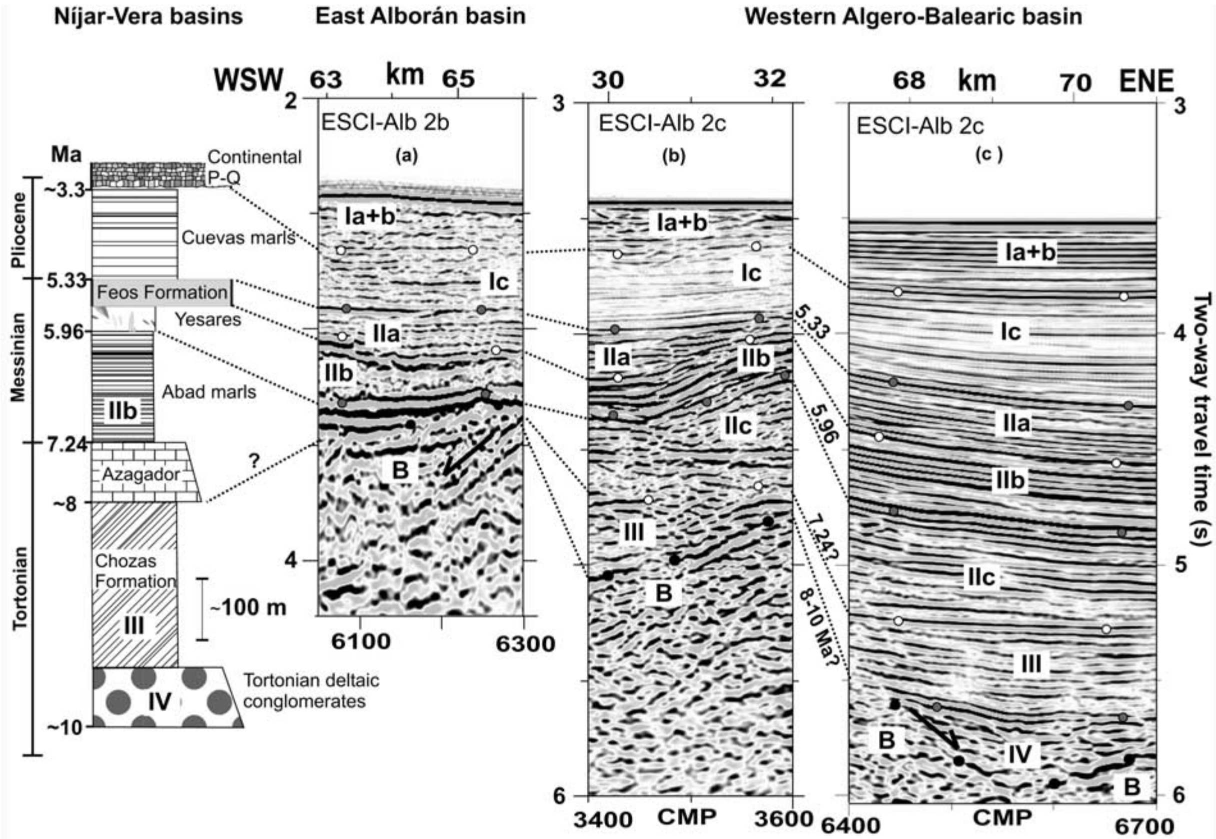

Figure 12. Synthetic stratigraphic column of the late Neogene sediments of the Níjar-Vera basins, correlated with the lithoseismic units differentiated in seismic lines ESCI-Alb 2b and 2c. See discussion and references in the text. Labels: Ia + b, Quaternary-late Pliocene unit; Ic, early Pliocene unit; IIa, late Messinian upper evaporite unit; IIb Messinian lower evaporite unit; IIc, Messinian pre-evaporitic unit; III, Tortonian unit; IV, Serravallian?-Tortonian unit; B, acoustic basement.

25 on line 2c, although it is difficult to identify below the antiforms at the end of this line (Figure 13).

[24] Unit IV has only been clearly identified in the eastern segment of line 2c (Figure 11). It is a syn-rift unit tilted by the main faults occurring between km 65 and 80. This unit is characterized by discontinuous high-amplitude reflections (Figures 11 and 12).

[25] A few normal faults have been observed, especially in line 2c. Normal faults in the eastern end of line 2c apparently cut the entire crust, displacing the lower-crustal reflectivity (km 70, line 2c, Figure 11). These faults were active during the deposition of units III and IV and are sealed by unit IIc. Further west where the crust is thicker the faults are only observed in the upper crust where they cut most of the sedimentary sequence, clearly affecting Pliocene sediments of unit Ic. Although, we do not have a three-dimensional control of the geometry of these normal faults, they clearly have a component of eastward-directed extension along the direction of the ESCI-Alb 2c seismic line. Eastward-directed late Miocene extension in the western Algero-Balearic basin contrasts with the westward-directed extension observed in core-complexes and tilted-block domains in the Betic [e.g., *García-Dueñas et al.*, 1992; *Martínez-Martínez and Azañón*, 1997; *Martínez-Martínez et al.*, 2002, 2006; *Booth-Rea et al.*, 2003a, 2004a] and Rif margins [*Negro*, 2005; *Negro et al.*, 2007], and in part of the Alborán basin [*Comas et al.*, 1992, 1995; *Chalouan et al.*, 1997] at the time.

6. Age of the Sedimentary Seismic Units and Correlation With Onshore Stratigraphy

[26] Due to the limited penetration of ODP drill holes in the east Alborán basin we have correlated

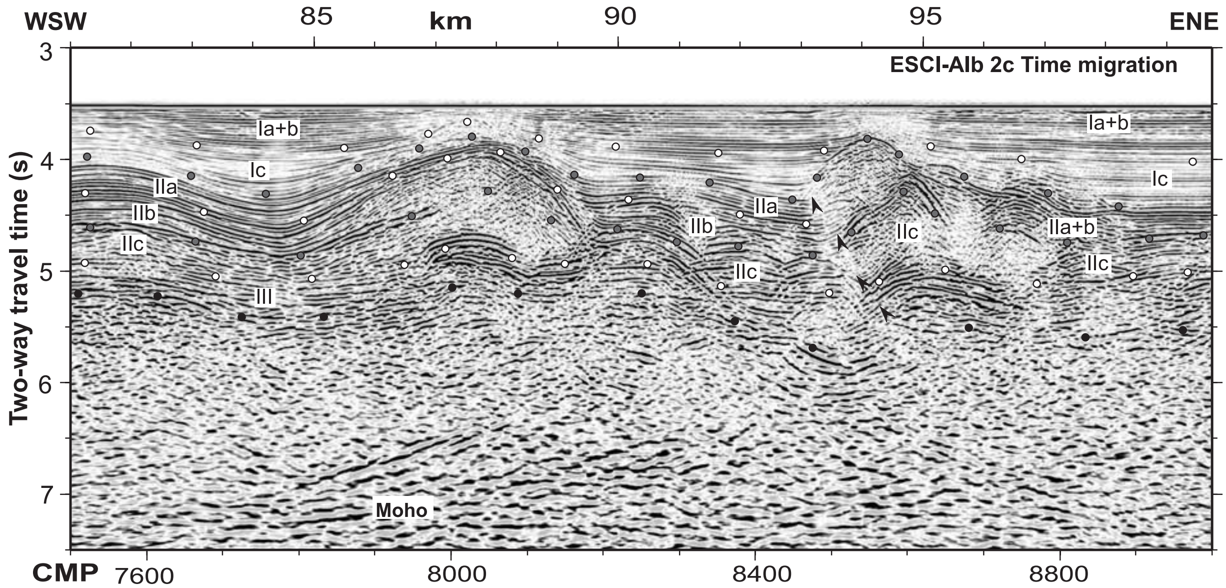

Figure 13. Segment of line ESCI-Alb 2c showing the effects of Messinian to present tectonic inversion and related folding in the western Algero-Balearic basin. Labels: Ia + b, Quaternary-late Pliocene unit; Ic, early Pliocene unit; IIa, late Messinian upper evaporite unit; IIb Messinian lower evaporite unit; IIc, Messinian pre-evaporitic unit; III, Tortonian unit.

the sedimentary seismic units with well-dated onshore exposures of marine sediments of the same age. Unit Ia + b was correlated with ODP site 978 and deposited between the late Pliocene and present, after the final phase of emersion of the southeastern Betic margin. The widespread transgressive nature of unit Ic and its low reflectivity appears to correlate with the characteristics of the early Pliocene Cuevas formation (Figure 12). This Pliocene sequence is formed by basin marls and silty marls that onlapped previous stratigraphic units and metamorphic basement in the southeastern Betic margin, in the Níjar and Vera basins [*Völk*, 1966; *Ott d'Estevou et al.*, 1990; *Booth-Rea et al.*, 2003b]. Unit Ic offshore includes also middle Pliocene sediments cored in ODP sites 977 and 978 [*Comas et al.*, 1999].

[27] Clear identification of the base of the Messinian evaporites [*Hsü et al.*, 1973; *Ryan et al.*, 1973] that is marked by a negative polarity high-amplitude reflection permits the correlation with stratigraphic units outcropping in basins of the southeastern Betic margin. Astronomical dating of the post-evaporitic Pliocene and the pre-evaporitic Messinian sediments provides an accurate time frame for the Messinian Salinity Crisis between 6.07–5.96 and 5.33 Ma [*Lourens et al.*, 1996; *Krijgsman et al.*, 1999, 2002; *Rouchy and Caruso*, 2006], including the period of evaporite deposition and subsequent Lago-Mare facies [e.g., *Hsü et al.*, 1977; *Cita*, 1982]. Two evaporitic units are differentiated in the western Mediterranean realm, lower evaporites of Sicily correlated with the Gessoso-Solfifera Formation of the Northern Apennines and the Yesares Formation of SE Spain; and the upper evaporites of Sicily, correlated with the Colombacci Formation of the Northern Apennines and the Zorreras and Feos formations of SE Spain [*Fortuin and Krijgsman*, 2003]. The Feos unit in the Níjar basin includes characteristic lago-mare facies deposited between 5.67–5.54 and 5.33 Ma [*Fortuin and Krijgsman*, 2003] and is probably equivalent to the upper-evaporitic unit (IIa) (Figure 12). Unit IIa that onlaps Unit IIb shows a lateral transition between low-velocity and low-amplitude to high-velocity and high-amplitude reflections probably showing the transition and interfingering between siliciclastic sediments with stenohaline biotas [*Braga et al.*, 2006], lago-mare marls and evaporites. Thus we interpret unit IIa to be equivalent to the Feos unit and to an evaporite-rich olistostrome [*Alvado*, 1986; *Ott d'Estevou et al.*, 1990] outcropping in the Vera basin, further east. Evaporites in unit IIa are probably in part resedimented from the underlying unit IIb as observed in the Vera basin, where olistostrome outcrops are formed by gypsum blocks within marine marls dated as latest Messinian [*Barragán*, 1997]. Unit IIb probably has the same age as the Yesares Formation of the Níjar and Sorbas basins in SE Spain that deposited between 5.96 and 5.67–5.54 Ma [*Krijgsman et al.*, 2001].

[28] The seismic facies of unit IIc underlying the evaporites indicate that it is formed by low-velocity and low-reflectivity sediments that may correspond to hemipelagic marls or shales. The Turre formation outcropping in the Níjar, Sorbas and Vera basins includes a basal sequence of temperate carbonates (Azagador member) that onlap the metamorphic basement or older tilted sediments [*Völk and Rondeel*, 1964] and an upper sequence formed by marls, turbiditic shales and sapropelitic laminites called the Abad member. A drill hole in the main depocenter of the Vera basin shows that in the deepest part of the basin, the Azagador member shows a transition toward deeper facies formed by silty glauconitic fine-grained sandstones [*Booth-Rea et al.*, 2003b]. We correlate the Turre formation with a thickness of at least 500 m onshore [*Barragán*, 1997] with unit IIc defined in the seismic lines. A high-resolution stratigraphy determined for the Abad marls in the Níjar and Sorbas basins [*Sierro et al.*, 2001] indicates an astrochronological age for the base of the Abad member of 7.24 Ma. The underlying Azagador member overlies volcanic rocks of approximately 8 Ma in the Cabo de Gata region [*Martin et al.*, 2003] having then a latest Tortonian age. The Azagador member includes tufite levels with rhyodacite clasts of the shoshonitic volcanic series in drill cores from the Vera basin [*Booth-Rea et al.*, 2003b]. The data above indicate that Unit IIc, which onlaps most of the acoustic basement of line 2b and part of 2c has a late Tortonian to Messinian age, approximately between 8 and 5.96 Ma. Early Messinian marls, equivalent to the upper part of unit IIc, deposited in deep marginal basins across the western and central Mediterranean (western Mediterranean, Central Sicilian basin, Balearic islands, southeastern Spain and north Algeria) [*Rouchy and Caruso*, 2006].

[29] Unit III has seismic facies similar to unit IIc, probably being also formed by hemipelagic fine-grained sediments. The late Tortonian Chozas formation [*Völk and Rondeel*, 1964; *Völk*, 1966] underlying the Turre formation is a transgressive unit formed mostly by marls and silty marls with intercalated sandy turbidites that may be equivalent to unit III. This unit deposited during one of the main tectonic subsidence pulses recorded in the Alborán basin and in most of the currently onshore Betic basins between approximately 10 and 8 Ma [*Cloetingh et al.*, 1992; *Rouchy et al.*, 1998; *Rodríguez Fernández et al.*, 1999; *Rodríguez-Fernández and Sanz de Galdeano*, 2006].

[30] Unit IV could represent both the more detrital base of the Tortonian sedimentary sequence, filling semigrabens, early Tortonian carbonates that occur interbedded between calc-alkaline volcanic rocks outcropping in the Cabo de Gata region in SE Spain [*Braga et al.*, 1996] or late Serravallian sediments that are related to the onset of westward-directed extension onshore [e.g., *García-Dueñas et al.*, 1992; *Mayoral et al.*, 1994; *Martínez-Martínez et al.*, 2002]. Serravallian sediments form the base of the thick sedimentary sequence (≈4 km) drilled in the Habibas well in the western Algerian margin [*Mauffret*, 2007].

7. Discussion

7.1. Magmatic Arc Crust in the East Alborán Basin and Its Transition to the Algero-Balearic Oceanic Crust

[31] Reprocessing the ESCI-Alb 2b and c seismic lines shows for the first time the characteristics of the deep crust in the transition between the east Alborán and the Algero-Balearic basins. The Moho reflection has been well imaged, showing how the crust thins toward the east between the two basins. Conspicuous high-amplitude reflectivity is observed at the base of the crust, probably reflecting shearing or magmatic layering. Although, the east Alborán crust has been assumed to be thinned continental crust [*Comas et al.*, 1995, 1999] we have observed that the upper crust is formed mostly by high-amplitude subhorizontal reflections, with practically no tilted blocks [*Watts et al.*, 1993] as commonly found in non-volcanic rifted basins, such as the Galicia Interior basin or the North Sea basin [*Pérez-Gussinyé et al.*, 2003; *Cowie et al.*, 2005]. Furthermore, the basement highs sampled in the Alborán basin are all formed by volcanic rocks ranging between 12.1–8.7 Ma for tholeiitic series and between 10.1 and 6.1 Ma for calc-alkaline series [*Turner et al.*, 1999; *Duggen et al.*, 2004, 2005]. Sampled volcanic highs close to the studied seismic lines in the east Alborán basin (Yusuf and Mansour) and the Alborán ridge are formed by LREE-depleted rocks of the tholeiitic series, characteristic of immature oceanic arcs [*Gill et al.*, 2004; *Duggen et al.*, 2004] (Figures 2 and 3). LREE-enriched calc-alkaline and shoshonitic rocks that bear a continental crust contamination geochemical signature have been sampled in thicker crustal domains near the studied ESCI-Alb lines [*Hoernle et al.*, 2003; *Duggen et al.*, 2004, 2005].

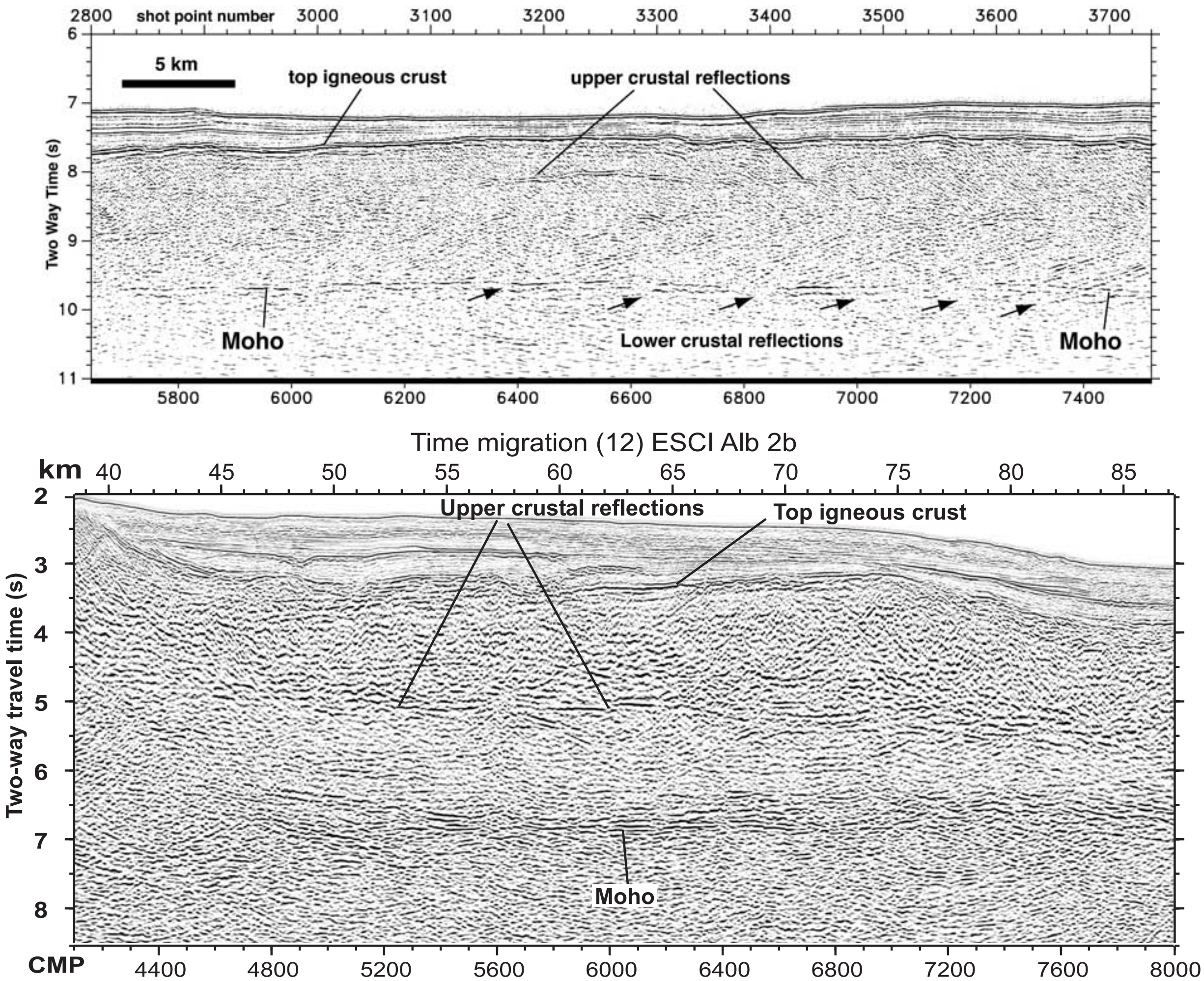

Figure 14. Comparison between seismic lines from a fast spreading ridge [*Ranero et al.*, 1997] and segment II of ESCI-Alb 2b representing the magmatic Alborán arc crust.

[32] The only metamorphic basement sampled in the area is at drill hole And-A1, cored at shallow depth near the shore (Figure 2), where the crust is thicker than the one imaged by ESCI-Alb 2 lines [*Torné et al.*, 2000]. Thus it is probably not representative of the crustal type occurring in the transition between the east Alborán and the Algero-Balearic basins. The age of the volcanic rocks dated in the east Alborán basin highs, coincides, or is slightly older than the age of the base of the sediments onlapping the basement in seismic lines ESCI-Alb 2b and 2c (Figures 3 and 7), i.e., the age of the base of Unit IIc (7.5–8 Ma) in most of line 2b and the base of Unit III (9–10 Ma) in most of line 2c. The structure imaged in the seismic data shows three crustal domains that indicate different formation origin. Segment I showing the thickest crust displays a rough top of basement that probably represents volcanic constructions as indicated by hydrosweep data and sampling of rock nearby [*Hoernle et al.*, 2003]. The over 15 km thick, poorly reflective crust of segment I shows little evidence of extensional faulting and may represent extended continental crust heavily intruded by arc magmatism, as suggested by the LREE-enriched calc-alkaline to shoshonitic geochemical signature of volcanic rocks sampled nearby [*Duggen et al.*, 2004; *Duggen et al.*, 2005, Figure 2]. This geochemical signature indicates clear continental contamination of subduction-related magma.

[33] The seismic structure of segment II to the SE resembles greatly the structure of oceanic crust formed at intermediate to fast spreading mid-ocean ridges (Figure 14). The top of the crust is extremely smooth, showing little evidence of even minor faulting, indicating that magmatism has filled small-scale topography formed by faulting. This

type of basement has been described with seismic images of crust formed at fast spreading centers [*Ranero et al.*, 1997; *Reston et al.*, 1999]. The base of the crust is defined by clear and continuous Moho reflections, the upper crust by subhorizontal reflections and the lower crust by distinct reflectivity. However, several features differentiate the crust of segment II from typical oceanic crust:

[34] (1) The main difference is the thickness of the crust. Whereas crust formed at fast-intermediate spreading mid-ocean ridges elsewhere typically is about 2 seconds s TWTT thick, corresponding to ~6–7 km thickness, the crust of segment II is 3.0–3.5 s TWT thick corresponding to a 9–11 km thick crust. At mid-ocean ridges such a thick crust is only formed near hot spots, but in the east Alborán basin it may represent the crust formed at a magmatic arc or thin continental crust modified by arc magmatism.

[35] (2) The upper crust characterized by discontinuous reflections and longer subhorizontal reflections at its base is similar to images of oceanic crust, but the relative proportion of upper crust is larger indicating that shallow magmatism may be more important in the formation of segment II crust than at typical mid-ocean ridges. This would be an expected difference as the magmatic arc does not drift away from the zone of magmatic accretion, unless subduction rollback takes place at a pace similar to oceanic accretion.

[36] (3) Segment II has a thick and transparent mid crust and a comparatively thick reflective lower crust. The geochemical evidence from volcanic rocks sampled in nearby areas with a similar crustal thickness at the Yusuf and Al Mansour seamounts (LREE-depleted tholeiitic samples near ODP sites 977 and 978, Figure 2), indicate an immature volcanic-arc crust [*Duggen et al.*, 2004]. Thus segment II crust may have formed by magmatic processes rather than by thinning and intrusion of pre-existing crust and it may represent magmatic arc crust.

[37] Segment IIIa-b crust in line ESCI Alb 2c is thinner, ranging between 2.0–2.5 s TWTn (~6–8 km) and it lacks the mid-crust low-reflectivity layer. The reflective upper crust is comparatively much thinner, and additionally, it contains lower-crustal dipping reflections, thus showing a crustal structure remarkably similar to oceanic crust formed at fast spreading rates where magmatism dominates tectonic processes.

[38]]The age of the sediments onlapping the acoustic basement can be used to estimate a minimum age for the formation of the western Algero-Balearic basin oceanic crust and its transition toward the east Alborán basin magmatic-arc influenced region. This way the Algero-Balearic basin is formed by oceanic crust probably older than 10–12 Ma east of km 65 in line 2c (segment IIIb, approximately east of meridian 1°W, Figure 3) and by thick oceanic crust older than ≈10 Ma between km 25 and 65 of line 2c (segments IIIa and part of IIIb, Figure 7). The east Alborán basin may be formed by magmatic arc crust older than ≈8 Ma in segment II (Figure 7) (approximately up to 2°W, Figure 3) and by thin continental crust modified by arc magmatism in the thicker crust of segment I (Figure 7). The volcanic ridge west of km 40 in line 2b is covered only by Pliocene sediments, thus arc magmatism in segment I could be as recent as ≈6 Ma, youngest ages obtained in the region for calc-alkaline and shoshonitic arc volcanism [e.g., *Duggen et al.*, 2004, 2005].

7.2. Tectonic Implications of Arc Magmatism and Oceanic Crust Accretion

[39] Middle to late Miocene oceanic accretion and magmatic arc formation in the transition between the east Alborán and the Algero-Balearic basins has important implications for the tectonic evolution of the Gibraltar arc region. This magmatism was coeval with shortening and thrust emplacement in the Betic foreland basins. Thrusting was active until the latest Tortonian [*Berástegui et al.*, 1998] or the Messinian [*Roldán-García*, 1995] in the Guadalquivir basin and at least until the latest Tortonian [*Medialdea et al.*, 2004; *Iribarren et al.*, 2007] in the Gulf of Cádiz accretionary wedge. Thus arc magmatism can be directly related to active subduction occurring during the middle to late Miocene below the Alborán and Algero-Balearic basins.

[40] It is generally assumed that the main period of westernmost Mediterranean basin formation was during the early Miocene, the age inferred for initial extension, based on drilling the west Alborán basin [*Comas et al.*, 1999], and of coeval thrusting in the Flysch-Trough units [e.g., *Crespo-Blanc and Campos*, 2001]. However, restoring the early to middle Miocene thrusts in the Flysch Trough and South Iberian margin cover units displaces the west Alborán basin approximately 300 km eastward [e.g., *Balanyá*, 1991; *Martínez-Martínez and Azañón*, 1997; *Platt et al.*, 2003]. This displacement

situates the locus of early Miocene N-S extension in the present Algero-Balearic basin, thus implying that early Miocene extension represents the opening of the proto Algero-Balearic basin and not of the present Alborán basin. Recent models of N-S early Miocene opening of the Algero-Balearic basin [*Martin*, 2006; *Schettino and Turco*, 2006] do not take into account this westward displacement and coeval oceanic accretion, thus omitting the importance of middle to late Miocene east-west opening of the Algero-Balearic basin [*Acosta et al.*, 2001; *Mauffret et al.*, 2004] and concomitant westward migration of the west Alborán basin forearc region. The Algero-Balearic basin probably records both the early Miocene N-S and the middle to late Miocene E-W-directed extensions, such as observed in the Betic margin [e.g., *García-Dueñas et al.*, 1992; *Martínez-Martínez and Azañón*, 1997; *Booth-Rea et al.*, 2004a], and further work is necessary to recognize both extensional systems.

7.3. Subduction Versus Sublithospheric Delamination or Remotion Tectonic Models

[41] A drawback of subduction models for explaining the tectonic evolution of the Gibraltar arc system is that they fail to explain the P-T path of metamorphic rocks cored in ODP site 976, high-grade schists that show late heating by about 75°C during the decompression P-T segment [*Soto and Platt*, 1999]. Complete removal of the mantle lithosphere at depths below 60 km by mantle lithosphere delamination or remotion appears required to model the P-T path evolution of these rocks [*Platt et al.*, 1998]. However, these authors indicate that delamination or remotion must have occurred in the Oligocene at 27 Ma, at least 13 Ma before the subduction-related arc magmatism observed in the east Alborán and Algero-Balearic basins initiated. Thus we argue that the evolution of these high-grade metamorphic rocks is related to an earlier, probably early Eocene [*Platt et al.*, 2005, Figure 15], collision process and subsequent Oligocene to early Miocene crustal extension in a backarc setting that formed in a more easterly position [e.g., *Booth-Rea et al.*, 2005, Figure 15].

[42] Another argument invoked against subduction for the Gibraltar arc is that the orogenic wedge preserved in the Internal Betics is formed by thrust units that include continental Paleozoic basement intruded by Jurassic metabasites (Nevado-Filabride complex) that underwent eclogite facies followed by amphibolite or higher-greenschist facies alpine metamorphism in a collisional context. Moreover, these rocks reached their thermal peak during the early middle Miocene [e.g., *Augier et al.*, 2005; *Platt et al.*, 2006] coeval and just before the subduction-related arc magmatism described here. However, in contrast with this collision setting, there is evidence that the Flysch Trough units were floored by oceanic crust that presently crops out as thin slivers of E-MORB-type basic rocks between the Flysch Trough units [*Durand-Delga et al.*, 2000]. Thus, during the early Miocene the region between Iberia and Africa was formed by different domains, including thinned continental crust in the passive margins, locally with exhumed mantle in the Maghrebian margin [*Michard et al.*, 1992, 2006], and oceanic crust between the margins (Figure 15). During its westward migration, the early to middle Miocene Alborán orogenic wedge encountered these different domains, producing collision and associated HP/LT to IP/LT metamorphism affecting the basement of the Iberian and Maghrebian passive margins, respectively [*Booth-Rea et al.*, 2005; *Negro*, 2005; *Platt et al.*, 2006; *Negro et al.*, 2007], together with subduction of the Flysch-Trough oceanic lithosphere in the region between the margins (Figure 15).

[43] Subduction of the Flysch-Trough crust initiated during the early Miocene resulting in the formation of a thrust imbricate stack [e.g., *Luján et al.*, 2006]. The first evidence of clear subduction-related magmatism is of middle Miocene age (≈16 Ma), suggesting a certain time elapsed between the inception of subduction and the time the slab reached the adequate depth to produce arc magmatism. Subduction-related arc magmatism initiated first under the Algerian margin between 4–7° east (15–16 Ma [*Maury et al.*, 2000], Figure 16) and later migrated toward the west until the Tortonian-Messinian (≈ 9–6.6 Ma [*Duggen et al.*, 2004, 2005]) in the east Alborán basin and the Rif (Figure 16). Migration of the magmatic arc was probably related to rollback of the narrow Flysch-Trough slab. Westward slab retreat was probably aided by westward propagation of the Oranie-Melilla slab window [*Carminati et al.*, 1998; *Maury et al.*, 2000; *Faccenna et al.*, 2004; *Spakman and Wortel*, 2004]. This subduction-transform edge-propagator fault [*Govers and Wortel*, 2005] beneath the Maghrebian margin may have propagated from central-eastern Argelia toward the eastern Rif between 16 and 7.5 Ma (Figure 16).

[44] Subduction and/or delamination models have been supported recently by seismic tomography

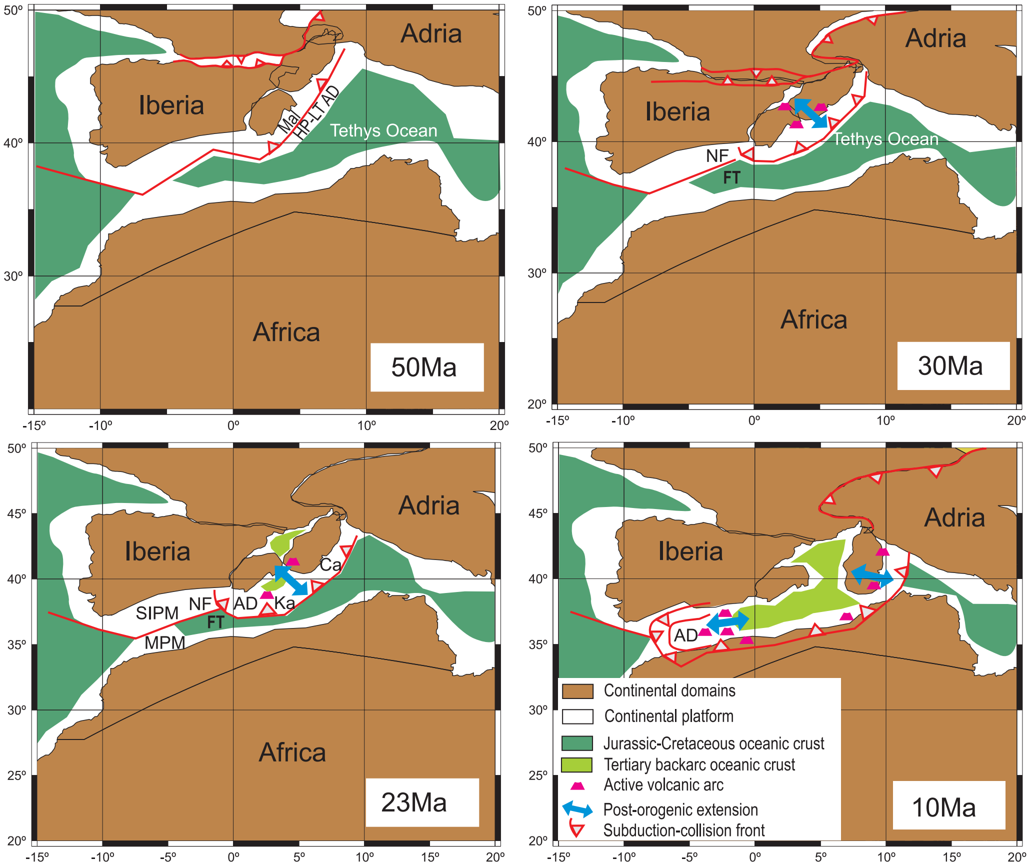

Figure 15. Reconstruction of the evolution of the western Mediterranean in relative (fixed Africa) reference frame in four stages, from 50 to 10 Ma. Motion of the main plates taken from the ODSN Plate Tectonic Reconstruction Service (http://www.odsn.de/odsn/services/paleomap). Tectonic evolution modified from *Rosenbaum et al.* [2002] and *Faccenna et al.* [2004]. Abbreviations: Mal, Malaguide-Ghomaride domain; HP-LT AD, high pressure-low temperature Alboran domain type rocks (Alpujarride-Sebtide complexes, Kabilye and Calabrian HP rocks); NF, Nevado-Filabride complex (mostly Paleozoic basement of the south Iberian passive margin?); FT, Flysch Trough; Ka, Kabilye; Ca, Calabria); SIPM, South Iberian passive margin; MPM, Maghrebian passive margin.

studies of the western Mediterranean. These suggest the existence of an east to southeast dipping high-velocity body in the upper mantle below the Gibraltar arc, interpreted as subducted oceanic or delaminated continental lithospheres [*Blanco and Spakman*, 1993; *Calvert et al.*, 2000; *Gutscher et al.*, 2002; *Faccenna et al.*, 2004; *Spakman and Wortel*, 2004]. Geochemical evidence derived from Neogene volcanics suggest that it could be a combination of both, oceanic lithosphere under the central areas of the Alborán basin, coupled to delaminated continental lithospheric mantle under the Betic-Rif margins [*Duggen et al.*, 2003, 2004, 2005].

[45] A growing body of evidence supports the hypothesis that both subduction rollback and edge delamination beneath the continental margins may have contributed to the formation and development of the Gibraltar arc, including the following:

[46] (1) Middle to late Miocene volcanic rocks of tholeiitic through calc-alkaline series typical of subduction arc magmatism outcrop across the central and eastern Alborán basin and the Betic-Rif margins (Figure 3). Their chemistry reflects fluids and melted sediments from subducted Tethys oceanic lithosphere [*Gill et al.*, 2004; *Duggen et al.*, 2004, 2005]. Late Miocene to Pliocene Si-K-rich magmatism together with coeval to Quaternary intraplate-type magmatism in the southeast Iberian and Maghrebian margins indicate the melting and interaction of two different mantle sources, metasomatized subcontinental lithosphere and sublithospheric plume-contaminated mantle [*Duggen et al.*, 2005]. This magmatic suite and coeval lithospheric uplift has been related to subcontinental-edge delamination and associated sub-lithospheric mantle upwelling [*Duggen et al.*, 2003, 2005; *Gill et al.*, 2004] and/or slab break-off in the Algerian-

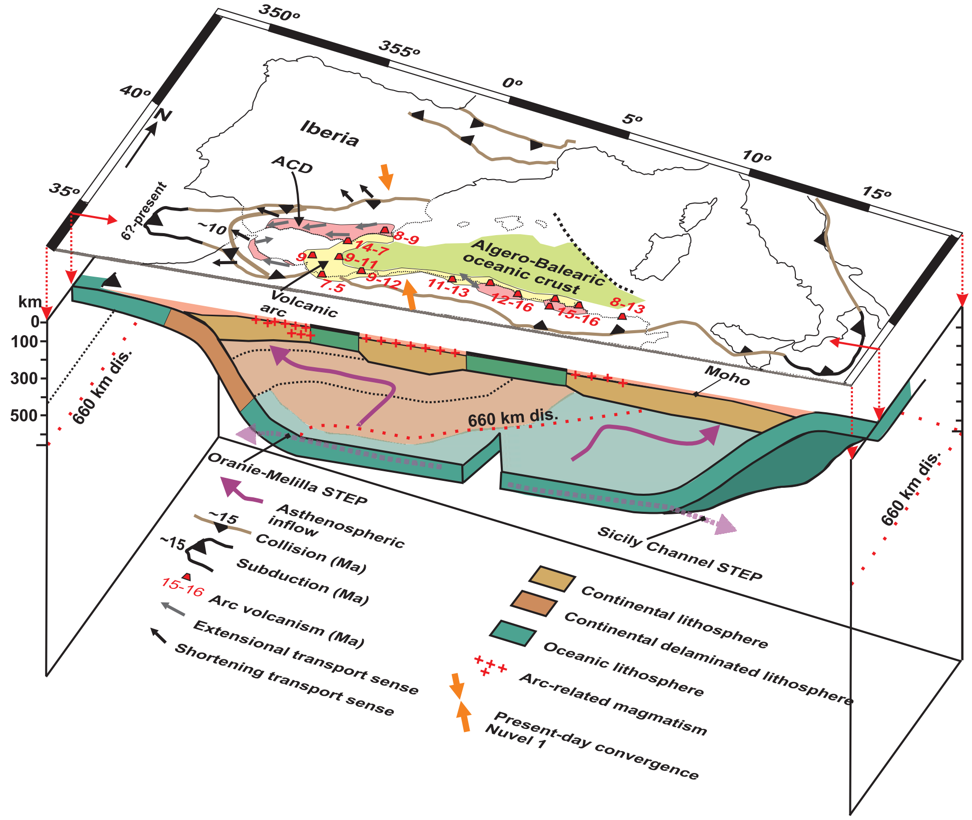

Figure 16. Cartoon of the present-day structure of the western Mediterranean. Volcanic ages from *Maury et al.* [2000] and *Duggen et al.* [2004, 2005]. Sublithospheric structure modified from *Faccenna et al.* [2004].

Rifean margin [*Carminati et al.*, 1998; *Maury et al.*, 2000; *Fourcade et al.*, 2001; *Coulon et al.*, 2002; *Spakman and Wortel*, 2004].

[47] (2) Westward-directed extension along detachments soling at a depth near the brittle/ductile transition [*García-Dueñas and Martínez-Martínez*, 1988; *Galindo-Zaldívar et al.*, 1989; *García-Dueñas et al.*, 1992; *Jabaloy et al.*, 1993; *Martínez-Martínez and Azañón*, 1997; *Martínez-Martínez et al.*, 2002, 2004] contributed to the exhumation of HP-LT South Iberian and IP/LT Maghrebian basements represented by the Nevado-Filabride complex [*Platt et al.*, 2004, 2006; *Booth-Rea et al.*, 2005] and the Ras Afrau unit [*Negro*, 2005; *Negro et al.*, 2007], respectively. These low-angle extensional faults and associated E/W-oriented dextral and sinistral transfer faults [*Martínez-Martínez*, 2006] are in principle incompatible with the general NW-SE plate convergence between Africa and Iberia and have been related to deep lithospheric processes occurring below the Betics-Rif, such as subcontinental lithospheric delamination [*García-Dueñas et al.*, 1992; *Martínez-Martínez and Azañón*, 1997; *Martínez-Martínez et al.*, 2006] or slab rollback [*Royden*, 1993; *Lonergan and White*, 1997].

[48] (3) Active seismicity in the Gibraltar arc region is produced mostly by structures formed in the context of NW-SE plate convergence [*Grimison and Chen*, 1986; *Buforn et al.*, 1995; *Morel and Meghraoui*, 1996; *Stich et al.*, 2003, 2006]. However, both the presence of intermediate and deep earthquakes below the Alborán basin and the Betic margin [e.g., *Buforn et al.*, 2004] and the occurrence of many focal mechanisms with E/W- to NE/SW-oriented, tectonic shortening axes [*Martínez-Martínez et al.*, 2006] may be related to the presence of a deep slab that disturbs the strain field expected from NW-SE plate convergence.

[49] In summary, the crustal structure observed in the transition between the Alborán and the Argelo-Balearic basin can be explained in the context of middle to late Miocene subduction-related arc magmatism and oceanic crust accretion. Early to late Miocene subduction beneath the Alborán and Algero-Balearic basins was probably coeval with continental collision derived processes in the Betic-Rif margins, producing HP-LT rocks and their later exhumation during the middle to late Miocene, coeval with the development of the Alborán mag-

matic arc (Figure 15) and to further shortening in the Betic-Rif foreland domains. This model explains the crustal structure observed in the east Alborán and Algero-Balearic basins, the geochemical signature of the volcanic rocks outcropping in the basins and the Betic-Rif margins, the tomographic and seismological evidence and the tectonic events described onshore. Furthermore, this model proposes a different meaning for the early Miocene extension observed in the west Alborán and the Betic-Rif margins [e.g., *Comas et al.*, 1999]. This extension may represent the opening of the proto-Algero-Balearic basin, which would have been floored by extended continental crust, later displaced westward and preserved in a forearc context by the development of the middle to late Miocene arc and backarc regions.

8. Conclusions

[50] The ESCI-Alb 2 seismic lines image the transition between the east Alborán and the western Algero-Balearic basins showing how crustal thickness decreases toward the east from slightly above 4 s TWTT to values typical of oceanic crust (≈2 s TWTT) between both basins. Crustal thinning occurs locally without apparent faulting, tilted blocks are very scarce and all outcropping basement is volcanic. This structure suggests that the crust was formed mostly by magmatic processes in the transition between backarc, magmatic arc and arc-influenced thinned continental crust, related to early to late Miocene subduction beneath the Alborán and Algero-Balearic basins. Sediments onlapping the acoustic basement indicate that oceanic and magmatic arc crust formation migrated westward between approximately 12 and 8 Ma, from 0.5°W to 2.3°W, respectively, coinciding with radiometric dating of volcanic rocks in the region [e.g., *Duggen et al.*, 2005]. Magmatic arc formation was coeval with shortening and thrust emplacement in the Gibraltar arc foreland basins active at least until the latest Tortonian [*Berástegui et al.*, 1998; *Medialdea et al.*, 2004; *Iribarren et al.*, 2007].

[51] Neogene subduction beneath the Alborán and Algero-Balearic basins was coeval with continental collision and subsequent delamination processes (Figure 15) producing exhumation of HP-LT rocks and Si-K-rich volcanism in the Betic-Rif margins. Subduction beneath the Alborán and Algero-Balearic basins thus occurred between the early to late Miocene, resulting in the formation of the Alborán volcanic arc between the middle and late Miocene. Subduction stopped or slowed down greatly after the late Miocene [*Gràcia et al.*, 2003; *Medialdea et al.*, 2004; *Iribarren et al.*, 2007], probably because the subducting oceanic lithosphere was consumed and replaced toward the west by continental lithosphere of the Maghrebian and South Iberian passive margins.

[52] Understanding the middle to late Miocene tectonic events in the western Mediterranean helps to establish a tectonic framework for the earlier events recorded in the region (Figure 15). This way, late Oligocene to early Miocene extension and associated volcanism preserved in the Alborán crustal domain may have occurred in an easterly position, related to the N-S opening of the proto Algero-Balearic basin (Figure 15). This extension contributed to the collapse of a previous, probably Eocene, orogen that developed in the region now occupied by the Algero-Balearic basin (Figure 15).

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