Crustal reflections and structure in the Alborán basin: preliminary results of the ESCI-Alborán survey

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Abstract: The ESCI-Alb survey explores the crust beneath the Alborán Sea and the South-Balearic basin. Both extensional basins developed in the westernmost Mediterranean during the Neogene collision of the Eurasian and African plates. The ESCI-Alb profiles (Alb1 and Alb2) reveal shallow tectonic structures, and basins (filled mainly by Middle-to-Late Miocene to Recent sediments) located between fault-bounded highs of metamorphic basement and/or volcanic edifices. Profile ESCI-Alb1 sampled the Spanish margin and shows an extensional mid-Miocene basin deformed by later compressional structures, including folds and tectonic reversal of normal faults. The age of this compressional deformation spans up to the Late Pliocene. In the East Alborán and South Balearic basins, Late Miocene (?) rifting processes resulted in tilting and faulting of basement blocks (profile ESCI-Alb2). Structurally-induced bathymetric changes in the seafloor, either by extension or by compression, denote recent or present-day tectonic activity in the surveyed area. In profile ESCI-Alb1, a conspicuous package of dipping reflections (6-8 s TWT) could represent a detachment surface within the crust in the northern Alborán margin. Further South, a 60 km long zone from 6 to 9 s shows a distinctive layered lower crust where the lower boundary is interpreted as the reflective Moho. Scarce deep reflections are imaged at the ESCI-Alb2 profile; however, some single reflections might be ascribed to the reflection Moho of a possible transitional or oceanic crust in the South-Balearic basin.

Keywords: Mediterranean Sea, Alborán basin, deep seismic reflection, Neogene tectonics.

Resumen: Los perfiles sísmicos profundos ESCI-Alb (1 y 2) proporcionan imágenes corticales de la cuenca de Alborán y su transición a la Sud-Balear. Estas cuencas extensionales, situadas en el Mediterráneo más occidental, se originaron durante la colisión neógena de las placas Euroasiática y Africana. Según los datos geológicos y geofísicos publicados, los procesos extensionales y de adelgazamiento cortical han acaecido en esta región desde al menos el Mioceno inferior. Ambos perfiles ESCI-Alb muestran estructuras en el techo del basamento, así como la existencia de una cobertera sedimentaria formada por materiales básicamente de edad Mioceno superior a Pleistoceno. Varias sub-cuencas se ubican entre altos de basamento, formados por rocas metamórficas del Dominio de Alborán o por edificios volcánicos. El perfil ESCI-Alb1, en el margen norte del Mar de Alborán exhibe una cuenca extensional rellena por sedimentos del Mioceno medio al Pleistoceno, deformada por una compresión tardía, que da lugar a pliegues en los sedimentos e inversiones tectónicas de fallas normales. Esta etapa contractiva se prolongó al menos hasta el Plioceno superior. Estructuras extensionales probablemente de edad Mioceno superior, condicionan bloques fallados y basculamientos en el basamento de las cuencas Este de Alborán y Sud-Balear (perfil ESCI-Alb2). Una actividad tectónica reciente o actual en el conjunto del área reconocida (compresional en el margen septentrional de Alborán y extensional en las cuencas Este de Alborán y Sud-Balear) se refleja en cambios bruscos de la batimetría del fondo marino. En el margen septentrional del Mar de Alborán y a niveles corticales profundos, el perfil ESCI-Alb1 muestra un conspicuo paquete de reflexiones buzantes hacia al SW, a profundidades entre 6 y 8 s, que podría corresponder a una superficie significativa de despegue intracortical. Mas al sur, en este mismo perfil, una zona de aproximadamente 60 km de extensión, de 3 s de espesor y situada a 6-9 s de profundidad, presenta reflexiones sub-horizontales y paralelas características de la corteza inferior, en cuya base podría localizarse el Moho. En el estado actual del procesado sísmico, el perfil ESCI-Alb2 muestra escasas reflexiones profundas; sin embargo, algunas reflexiones singulares entre 6 y 7 s de profundidad, podrían asociarse al nivel del Moho en la cuenca Sur-Balear bajo una corteza probablemente oceánica o transicional.

Palabras clave: Mediterráneo, Alborán, sísmica de reflexión, tectónica, Neógeno.

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In the westernmost Mediterranean, the collision between the Eurasian and African plates during the Palaeogene and Neogene resulted in a broad area of distributed deformation rather than a discrete plate boundary (Olivet *et al.*, 1984; Dewey *et al.*, 1989; Srivastava *et al.*, 1990). This area embraces the Betic, Rif, and Tell Cordilleras, linked across the Gibraltar Arc, and includes extensional sedimentary basins beneath the Alborán and the South-Balearic seas (Fig. 1). The Alborán Sea basin, flanked to the E by the Gibraltar Arc, is considered a classical example of a "Mediterranean back-arc" extensional basin (Horvath & Berckhemer, 1982); and is generally

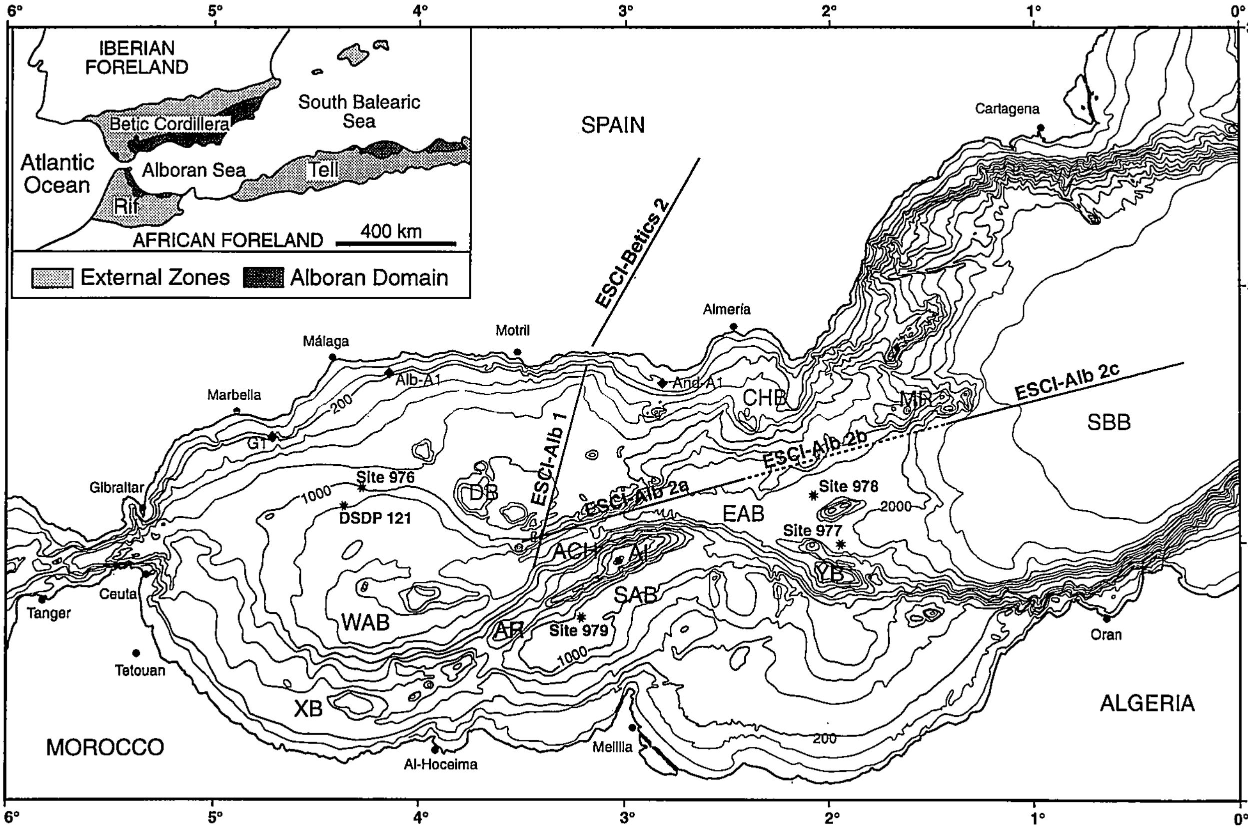


Figure 1.- Bathymetry of the Alborán Sea showing position of ESCI-Alb profiles and commercial boreholes G1, Alb-A1 and And-A1. Location of ODP Leg 161 drill sites (976 to 979), DSDP site 121, and ESCI-Béticas2 profile onland, are also shown. Bathymetry contour lines are in m. ACH: Alborán Channel. AI: Alborán Island. AR: Alborán Ridge. CHB: Chella Bank. DB: Djibouti Bank. EAB: East Alborán basin. MR: Maimonides Ridge. SAB: South Alborán basin. SBB: South Balearic basin. WAB: West Alborán basin. XB: Xauen Bank. YB: Yusuf basin. Inset map: Chains surrounding the Alborán Sea and subdivision of crustal domains onland.

identified as an area where crustal thinning processes have occurred at least since the Early Miocene. Furthermore, the Alborán Sea basin offers an advantageous area to integrate marine surveys with onshore geological and geophysical data, because its basement and Miocene-to-Pliocene sedimentary fill are cropping out at the surrounding Betic and Rif Chains.

Several hypotheses for the origin of the Alborán basin have been published. These consider the role of anomalous mantle diapirism (Weijermars, 1985; Wezel, 1985), the existence of subduction processes similar to that of the western Pacific back-arc basins (Biju-Duval *et al.*, 1978; Rehault *et al.*, 1984; Dercourt *et al.*, 1986; Malinverno & Ryan, 1986; Kastens *et al.*, 1988) or emphasise subduction causing detachment of a sinking lithospheric slab (De Jong, 1991; Zeck *et al.*, 1992; Royden, 1993). Removal or detachment of the lithospheric mantle either by delamination (García-Dueñas *et al.*, 1992; Comas *et al.*, 1992, 1993; Docherty & Banda, 1995) or by convection (Platt & Vissers, 1989; Platt and England, 1994) is now currently claimed to explain the lithospheric thinning which led ultimately to the formation of the Alborán basin.

The Alborán Sea has been the site of a vigorous program of oil and gas exploration since the early 70's and, as a result, a dense network of seismic reflection profiles is now available. These surveys are mainly confined to the Spanish and Moroccan margins, where they tie-in with commercial boreholes (Fig. 1, boreholes G1, Alb-A1 and And-A1). Since 1988, there have been several research cruises, mostly by Spanish, British and American groups in the Alborán Sea: single channel cruises (SISMAL I and II- R/V GARCIA DEL CID, 1990-91, and R/V CHARLES DARWIN-64, 1992); deep seismic reflection profiling (LDGO- R/V CONRAD, 1992; Watts *et al.* 1993); multichannel seismic profiling (R/V HESPERIDES, 1991), multibeam bathimetry and high-resolution seismic survey (ALBA campaign - R/V HESPERIDES, 1992); and side-scan sonar reconnaissances (GLORIA II system, R/V CHARLES DARWIN, 1992). In addition, a heat flow survey (FLUCALB campaign, Polyak *et al.*, in press) was conducted in September 1993, and a diving cruise with the submarine "CYANA" (CYANALBORÁN Campaign, R/V LE SUROIT, 1994) sampled volcanic rocks from outcropping basement highs (Comas *et al.*, in press). The origin and tectonic evolution of the Alborán Basin have also been the main tectonic objectives of the recent Ocean Drilling Program Leg 161 in the western Mediterranean (Comas, Zhan, Klaus *et al.*, 1996).

The ESCI-Alb survey is part of the Spanish National Program named "*ESCI project: Seismic Studies of the Iberian Crust*". The ESCI project in southern Spain targeted the deep seismic image of the Betic Cordilleras

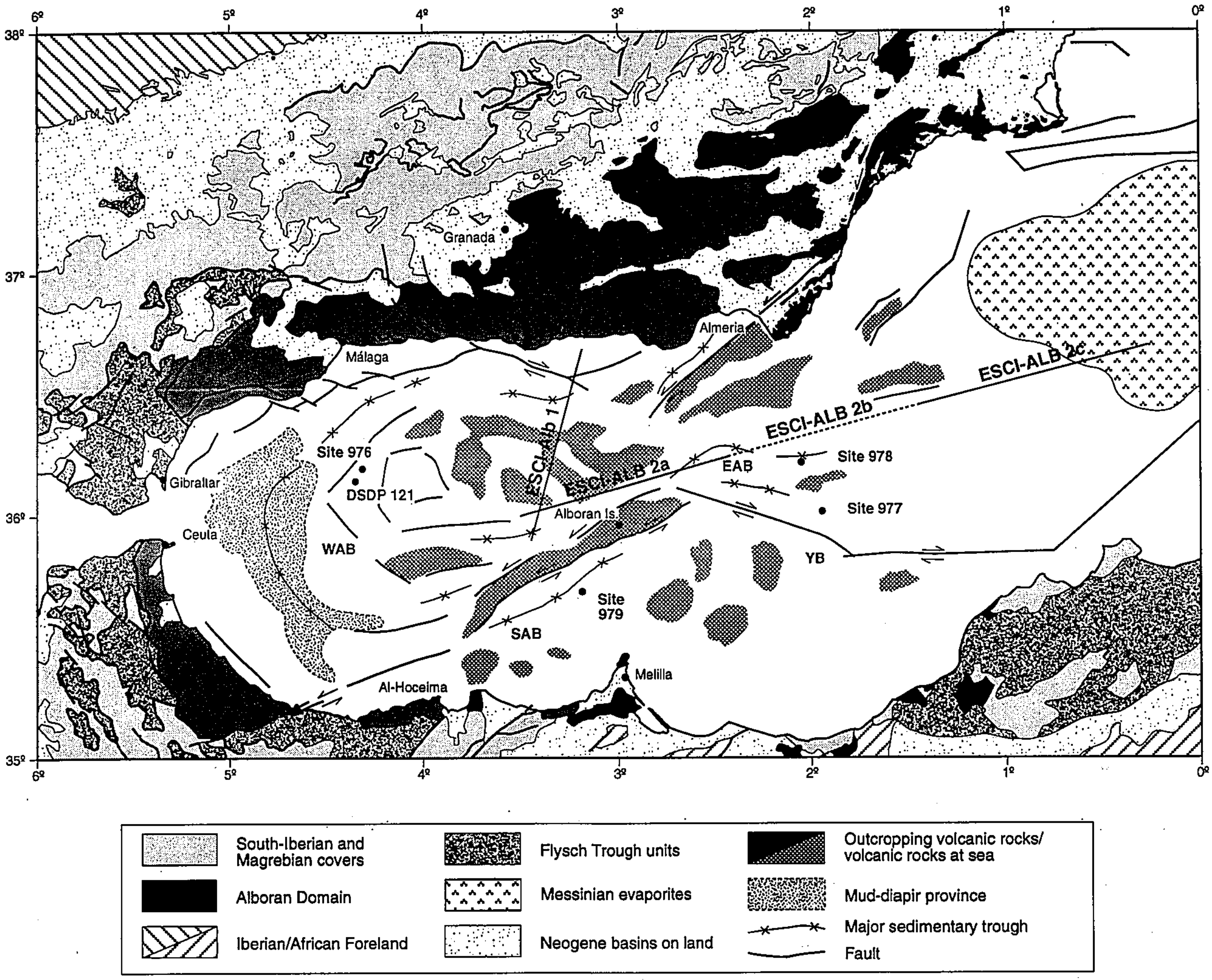


Figure 2.- Structural map of the Alborán Sea and the surrounding Betic and Rif Chains (from Comas *et al.*, 1993). Abbreviations as in Fig. 1.

(ESCI-Béticas, Garcia Dueñas *et al.*, 1994), the westernmost Mediterranean region, and the Alborán Sea (ESCI-Alb). The Alborán survey consisted in the acquisition during 1992 by the MV Bin-Hai 511 (owner GECO-Prakla) of about 400 km of multichannel deep seismic data in two profiles. Profiles ESCI-Alb1 and ESCI-Alb2 were shot across the northern Alborán Sea margin and from the central Alborán Sea to the South-Balearic basin, respectively (Fig. 1).

The purpose of the ESCI-Alb survey was to determine from deep seismic images the structure of the crust beneath the Alborán Sea and its transition to the South-Balearic basin; and then to compare the results from the ESCI-Alb profiles with crustal images in the Betic Cordillera from the ESCI-Béticas deep-seismic sections. This paper shows the stacked ESCI-Alb data and post-stack processed profiles selected to strengthen the main tectonic features imaged from the survey. A preliminary interpretation of significant deep-reflection events and shallow structures is also presented. This analysis was aided by data from contiguous commercial multichannel seismic lines, that tie-in with commercial and DSDP/ODP holes, in order to identify the sedimentary cover imaged in the ESCI-Alb profiles.

Geological setting

The Alborán Sea (Fig. 1) exhibits a complex seafloor morphology, with several sub-basins, ridges, and seamounts. The Alborán Ridge, locally emergent at the Alborán Island, and the Alborán Trough are the most prominent linear seafloor-reliefs. They extend 180 km and trend NE-SW across the Alborán Sea. The Alborán Ridge separates the three main sub-basins of the Alborán Sea (West, East and South Alborán basins in Fig. 1).

The internal complexes of both the Betic and Rif chains (the Alborán Domain of Balanyá & Garcia-Dueñas, 1987) have N-S continuity throughout the Gibraltar Arc. Units of these complexes likely form the continental basement of the Alborán Sea basin (see inset map in Fig. 1).

Geophysical data provide interesting constraints on the regional crustal configuration of the entire area. There is evidence from seismic refraction and wide angle reflection studies of an anomalous low velocity zone (7.6-7.9 km/s) at relatively shallow upper-mantle levels (16 km, Hatzfeld, 1976). Furthermore, seismic and gravity data clearly indicate a conspicuous crustal thinning in the northern part of the Alborán basin, from 38 km beneath the Internal Betics to about 15-20 km beneath the central

Alborán Sea (Hatzfeld, 1978; Banda & Ansorge, 1980; Torné& Banda, 1992; Banda *et al.*, 1993; Watts *et al*, 1993). The analysis of recent heat flow data suggests a pronounced West to East decrease in lithospheric thickness from 60-90 km in the West Alborán basin to about 35-40 km in the East Alborán basin, as well as a corresponding crustal thinning from 14-16 km to 10-12 km, respectively (Polyak *et al.*, in press). Unfortunately, there is no crustal-velocity information within the basin and the Moho boundary has not been clearly imaged, and therefore, no unambiguous information on crustal thickness is available. There is no geological or geophysical evidence of any oceanic crust in the Alborán basin.

Recent drilling results from ODP Site 976 confirm the continental nature of the crust beneath the Alborán Sea. This Site drilled on a basement horst in the West Alborán basin (Fig. 2), sampled high-grade schist, gneissic and granitic rocks, which can be correlated with metamorphic units of the Alpujárride Complex belonging to the Alborán Domain (Comas, Zhan, Klaus *et al.*, 1996). East of 4° W, most of the basement highs appear to be made up by volcanic rocks, as revealed by dredging (Gierman *et al.* 1968) and diving data (Comas *et al.*, in press).

The main seismic aspects of the sedimentary cover in the Alborán Sea basin have been reported in several papers (Auzende *et al.*, 1975; Pastouret *et al.*, 1975; Mulder & Parry, 1977; Dillon *et al.*, 1980; Kazakov *et al.*, 1983; Gensous *et al.*, 1986; Comas *et al.*, 1992, 1993; Maldonado *et al.*, 1992; Watts *et al.*, 1993). Information on lithologies and ages of the complete sedimentary fill is provided by commercial exploration wells (Jurado & Comas, 1992). These data indicate the presence of Early Miocene (Aquitanian/Burdigalian) to Pleistocene marine sediments, which in places reach up to 6 km in thickness. Nevertheless, sample and stratigraphic data of the deep-sea deposits in the basin have only been gathered from drilling at DSDP Site 121 (Ryan, Hsü *et al.*, 1973) and Leg 161-ODP Sites 976 to 979 (Comas, Zhan, Klaus *et al.*, 1996).

Six lithoseismic units bounded by major regional unconformities of tectonic significance have been identified within the sedimentary cover of the Alborán Sea (Seismic Units I to VI of Comas *et al.*, 1992, and Jurado & Comas, 1992). Major unconformities occur at top of the Burdigalian deposits (Unit VI), within Upper Tortonian sediments (base of seismic Unit III) and at the base of the Plio-Pleistocene seismic Unit I. The reflection that marks the base of this Plio-Pleistocene unit corresponds to a strong erosional and locally angular unconformity, which correlates with the "M-reflector" –the top of the Messinian evaporites– recognised elsewhere in the Mediterranean (Ryan, Hsü, *et al.*, 1973).

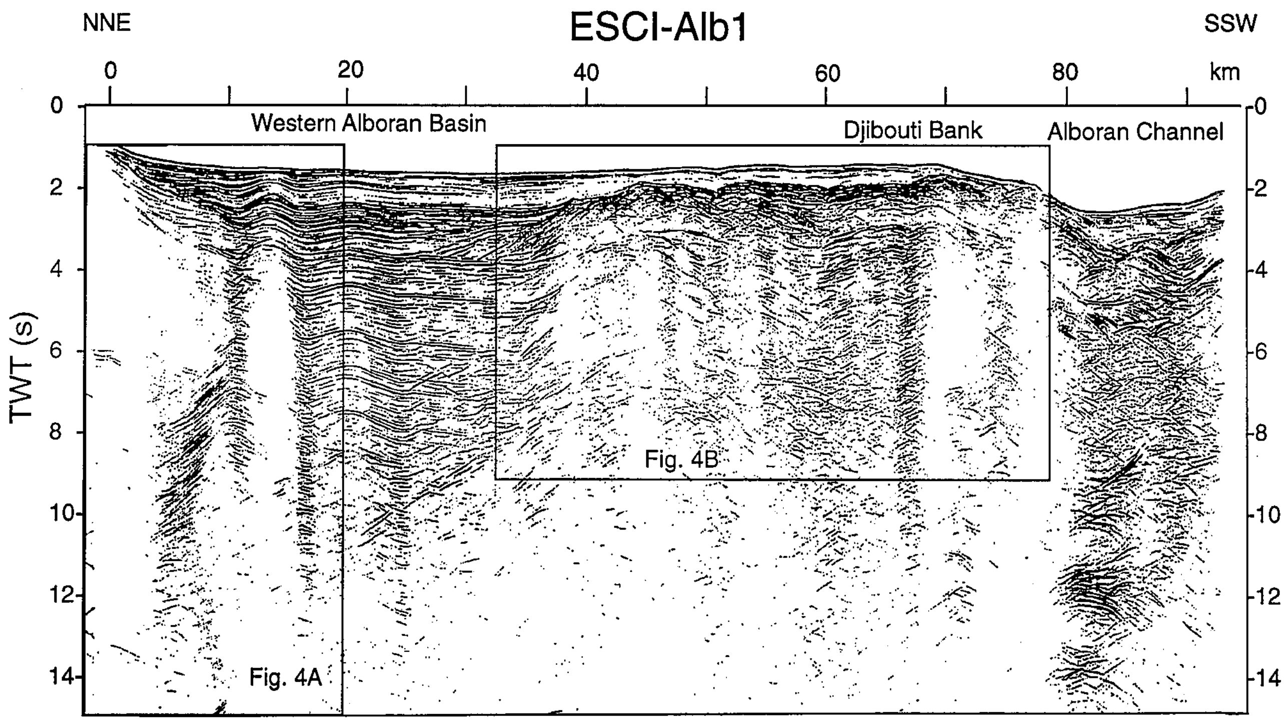
Early Miocene to Pliocene marine sediments cropping-out onland in the so-called "Neogene basins" of the Betic and Rif Cordilleras are similar to those that fill the Alborán Sea basin (Fig. 2). The existence of these outcrops indicates that during the Miocene the Alborán Basin occupied a broader area extended North and South beyond the present limits of the Alborán Sea.

Tectonic evolution of the basin

The structure of the Alborán Sea basin (Fig. 2) is the result of superimposed tectonic events (Comas *et al.*, 1992, García-Dueñas *et al.*, 1992). Initial stages of crustal stretching which led to the Early Miocene (Aquitanian, about 22 Ma) transgression, are not well identified in the available seismic data. However, two Middle Miocene rifting episodes (Burdigalian -Langhian, about 17-15 Ma; and Serravallian-Early Tortonian, about 14-10 Ma) can be clearly recognised in the West Alborán basin from seismic profiling. Results from the study of metamorphic rocks sampled at ODP Site 976 suggest that crustal extension was accompanied by heating at relatively low-pressure (Comas, Zhan, Klaus *et al.*, 1996), probably during the Early Miocene (by comparison with similar rocks dated on land, Zeck *et al.*, 1989; Monié *et al*, 1991; 1994). A predominant ENE-WSW extensional direction has been proposed for the middle-Miocene rifting in the West Alborán basin (Comas *et al.*, 1993). As a whole, the Early-to-Middle Miocene crustal thinning in the Alborán Sea basin is connected to large-scale extensional detachment systems known in the Betic and Rif chains. Both, the direction of extension and superimposed rifting episodes recognised offshore are consistent with those reported onland (among others Galindo-Zaldívar *et al.*, 1989; García-Dueñas *et al*, 1992; Jabaloy *et al.*, 1992).

Early Miocene and Late Serravallian-to-Tortonian alkaline and calc-alkaline volcanic rocks (Bellon *et al.*, 1983; Hernández *et al.*, 1987) are exposed onland and may have offshore counterparts. Some of these magmatic events (first occurrences: leucogranites at 22 Ma; rhyolitic tuffites at 22-19 Ma; Bellon *et al.*, 1983), as well as the notable mud diapirism recognised in the West Alborán basin (Fig. 2), likely resulted from these extensional processes. Seismic data indicate (Comas *et al.*, 1992) that the main extensional episode of the West Alborán basin ceased during the Late Miocene (Late Tortonian).

Later on, a contractive reorganisation started and caused folding, strike-slip faulting and tectonic inversions in the basin (Comas *et al.*, 1992; Bourgois *et al.*, 1992; Woodside & Maldonado, 1992). Messinian lamproites, shoshonitic lavas (9-4.5 Ma.) and alkali basalts (6 -1.5 Ma.) erupted extensively during this compressional stage (Bellon *et al.*,1983; Hernández *et al.*, 1987, Montenat *et al.*, 1992; de Larouzière *et al.*, 1988). Many onland observations in areas surrounding the Alborán Sea indicate a NNE compression during the Late Tortonian and Messinian, changing to NNW/N compression during the Pliocene and Pleistocene (Ott d'Estevou & Montenat, 1985; Ait Brahim & Chotin, 1989; Morel, 1989; Galindo-Zaldívar *et al.*, 1993; Martínez-Martínez *et al.*, this vol.). These compression directions agree with the E-W trend of the Late Tortonian-Pliocene folds and the approximately NW and NE conjugate strike-slip fault systems noticed from seismic lines (Fig. 2). During this compressional stage, the Alborán basin was broken into sub-basins by emergent or submarine transverse ridges, causing small pull-apart ba-



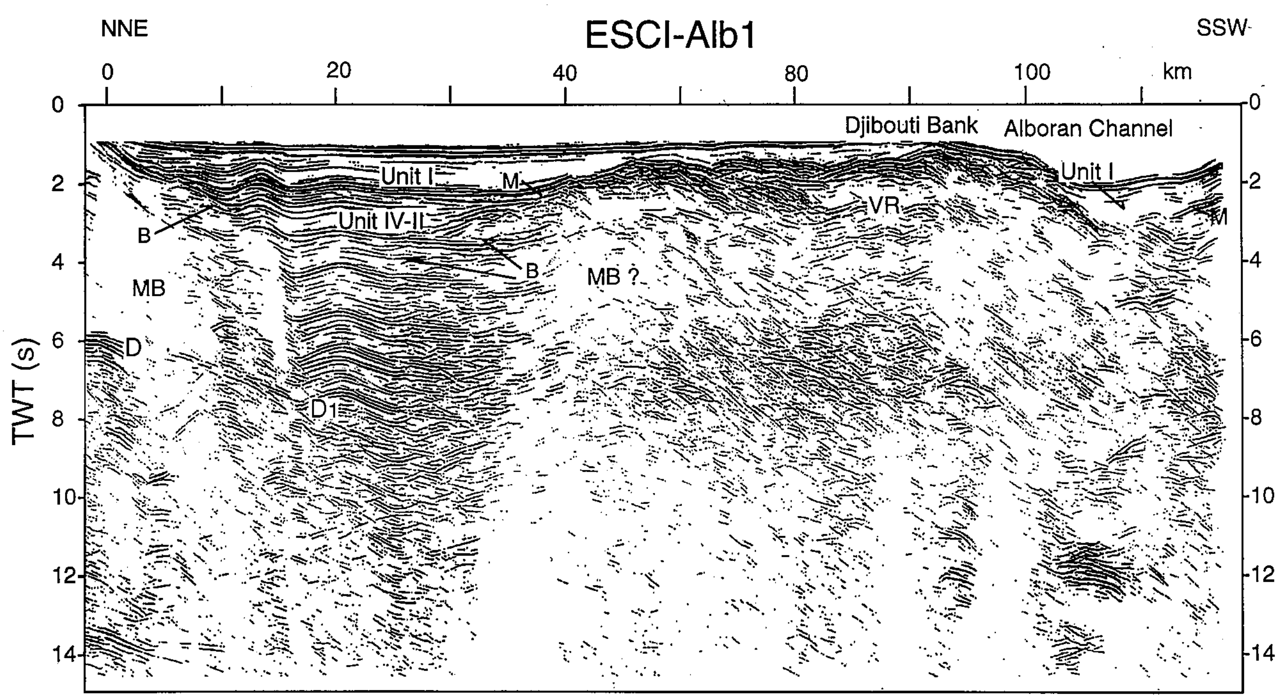


Figure 3.- **A)** Stack section of ESCI-Alb1 line. Boxes correspond to windows shown in Figs. 4A and 4B. A bandpass coherency filter with a slowness of 0.3 s km^{-1} and a window length of 1.0 km was applied to the original stack section. **B)** Stack section of ESCI-Alb1. A deconvolution after stack of 300 ms with an operator length of 1.2 s, a f-k filtering to suppress low and high velocities and a bandpass filter (5-35 Hz) was applied to the original stack section. B: top of the basement. D-D^1: intracrustal reflections. M: "M" reflector, which corresponds to the "Messinian unconformity". MB: metamorphic basement. VR: volcanic rocks. Units I to IV: lithoseismic units, see text for explanation.

sins to develop along major strike-slip faults (e.g.: the Yusuf basin, Fig. 2, Mauffret *et al.*, 1987). N-S shortening and considerable E-W elongation of the Alborán Sea basin occurred since the Late Miocene. Finally, a Pliocene/Pleistocene normal-to-oblique faulting event was probably related to basin subsidence and coeval uplift of the Iberian and African coasts. This last tectonic event is believed to be responsible for the present-day seafloor physiography and the geometry and location of the actual coastline (Comas *et al.*, 1992).

Data acquisition and processing

The MV Bin-Hai 511 acquired the ESCI-Alb profiles (Fig. 1) by towing an analogue streamer of 4500 m with

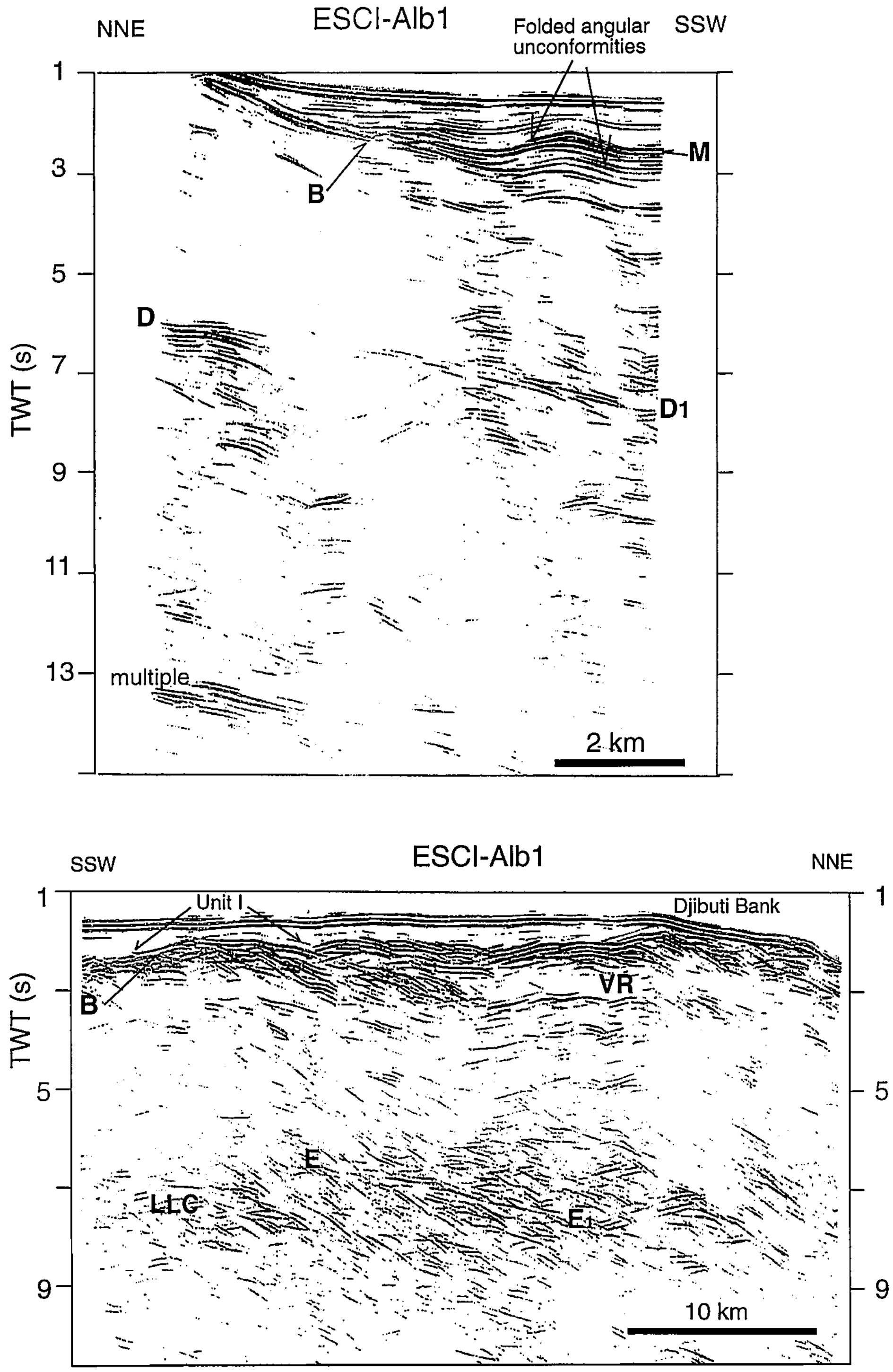


Figure 4.- **A**) Window of ESCI-Alb1 stack section, showing the southwest-dipping package of reflections (D-D_1) (see Fig. 3A for window location). These reflections are interpreted as a major crustal boundary. M: the Messinian 'M' reflector. B: top of the basement. **B**) Window of ESCI-Alb1 stack section, displaying a reflective lower layered crust (LLC) between 6-9 s (see Fig. 3A for window location). B: top of the basement. E-E_1 marks a gently dipping bright reflection within the LLC. VR: volcanic rocks.

180 channels at a mean depth of 15 m, and a source of a wide (50 m) tuned gun-array of 6 strings (17.5 m long each) totalling 7118 cu. in (120 litres). The pop-rate used was 75 m and 50 m for the ESCI-Alb1 and the ESCI-ALb2 profiles, respectively. Acquisition parameters were adjusted to a record length of 18-22 s, 4 ms sample rate, and filtering of 5.3 Hz/18 dB for the low cut and 64 Hz/18dB for the high cut. Conventional processing was performed by GECO-Prakla Ltd with the following sequence: geometry specifications, re-sampling to 8 ms with 60 Hz anti-alias filter, spherical divergence compensation and exponential gain correction. A deconvolution operator (before stack) of 200 ms, with a predictive gap of 40 ms in windows of 4-10 s (near) and 5.5-12 s (far), was also applied. Normal Move Out (NMO) correction was performed using the brute velocity function, prior to a gun and cable static correction of 15 ms, to obtain the stacked section. To eliminate lateral echoes and spurious noise from the brute stack, a simple post-stack processing was applied. It mainly consisted of the application of deconvolution after stack (a mean operator length of 300 ms) to decrease the coherency of the multiples, and the use of different frequency-wavenumber filters (f-k). This processing reduced the noise of the ener-

getic water arrivals, with low apparent velocity, and other high velocities from artificial events that masked the correlation of the deep coherent reflections. Additional processing such as adjacent traces summation, trace equalisation and a bandpass filtering of 5-35 Hz was employed to enhance the signal-to-noise ratio. Finally, to display the sections, a coherency filter with a slowness of 0.3 s km^{-1} through a window-length of 1.0 km was performed. This procedure was particularly worthwhile in profile ESCI-Alb1, where the occurrence of high reflectivity of spurious events hampered the continuity of critical reflections within the crustal structure.

The ESCI-Alb1 profile

This profile runs for 95 km in a NNE-SSW direction from the Spanish shelf to a bathymetric low of 2600 m in the Alborán Channel, SE of the volcanic Djibouti Bank. The primary objective of the ESCI-Alb1 line was to record the crustal configuration near the Betic Cordillera - Alborán Sea basin transition. In addition, this profile provided information on the crustal structure beneath the central part of the Alborán Sea (Figs. 1 and 2).

At shallow levels, the northern part of the profile images a fault-bounded sedimentary basin about 30 km wide (from km-0 to km-40 in Figs. 3A, 3B), with a sedimentary fill up to 2.5 s (TWT) in thickness. The strong reflectivity of the seafloor and subsequent multiples partially mask the basement/sediment contact. However, the top of the basement can be identified at about 2.8 s and 4 s beneath the sea-level at km-15 and km-25 respectively ('B' in Fig. 3B). The sedimentary fill is represented by parallel to divergent, relatively continuous and subhorizontal reflectors, of high and medium reflectivity (Fig. 3B). These deposits are believed to form a stratigraphic sequence that includes from the seismic Unit V (Middle Miocene) at the bottom up to Unit I (Plio-Pleistocene) at the top. The unconformity at the base of the Pliocene ('M' reflector) is undoubtedly identified at about 2.2 s below the seafloor, imaged as the higher reflectivity marker within the sediments ('M' in Fig. 3B). The entire sedimentary sequence is folded in the NE (about km-15 to km-25, Figs. 3A, 3B). A close-up of this fold shows a prominent angular unconformity just below the 'M' reflector. Further unconformities are still recognised down into the sedimentary sequence (Fig. 4A). Southeast of this basin (from km-45 to km-80, Figs. 3A, 3B) the sedimentary cover is thinner (less than 1 s) and probably contains Unit I deposits only (Pliocene to Pleistocene in age). Southward, from Km-80 to the end of the profile, another small basin is delineated upon the basement. This small basin corresponds to the Alborán Channel, and contains a 2 s thick, ponded, sedimentary sequence, which also corresponds to Unit I. The "M" reflector here is identified as a NNE-dipping strong reflection (Fig. 3B).

At deep crustal levels, after the post-stack processing, a striking SSW-dipping package (marked 'D-D_I' in Fig. 4A), formed of three to four reflections, is observed from 6 s at the northern edge of the profile to about 8 s at km-25 (Fig. 3B). Further South, however, the identification of this reflectivity remains doubtful due to the interference of high-energy multiples. 'D-D_I' reflectivity can be correlated with similar reflections encountered in the onland ESCI-Betics 2 profile (Betic Cordillera), in which this reflectivity marks the top of a lower crustal reflective band placed at an uniform depth of 6-7 s (García-Dueñas *et al.*, 1994; Carbonell *et al.*, this vol.). The reflections present at 13 s (km-0 in Fig. 3B, and Fig. 4A) are interpreted as peg-leg multiple.

In the southern half of the profile, the post-stack suppression of strong multiple reflections enables the identification of a band of highly coherent reflectivity between 6-9 s in depth, mainly distributed from km-40 to km-95 as a diffuse pattern of gently dipping events (LLC in Fig. 4B). 'E-E_I' is a gently NNE-dipping reflection within the layered lower crust (Fig. 4B) beneath the Alborán basin. The bottom of this beam of reflections (LLC) might be attributed to the Moho boundary discontinuity, which is in agreement with that reported from stacked wide-angle data (Gallart *et al.*, this vol.). Other deeper events beneath 9 s, such as the band of bright reflections observed at 12 s (about km-150 in Fig. 3B), may belong to mantle levels.

The ESCI-Alb2 profile

The Profile ESCI-Alb2 runs WSW-ENE for 300 km from the volcanic Djibouti Bank to the western extreme of the South-Balearic basin. During acquisition it was divided in three segments, slightly overlapping each other, amounting to a length of 100 km each. The main aims of this profile were to investigate the crustal structure in the central and East Alborán Sea basin along the direction on which the Miocene extension was thought to have occurred; and to study the crustal structure in the transition zone toward the South-Balearic basin (Fig. 1 and 2).

The western segment ESCI-Alb2a runs along the Alborán Channel for the first 50 km, and further East along the East Alborán basin (Fig. 5A and B). Beneath the Alborán Channel, it shows a series of (fault-tilted ?) basement highs (VR in Fig. 5A), which accommodate a quite transparent sedimentary sequence up to 1.2 s thick, filling two small "perched" asymmetric basins (half-grabens). Beneath the East Alborán Basin the 'M' unconformity can be traced as a strong coherent reflection, which at places directly overlies the basement. Above the 'M' reflector, the sediments onlap a basement high towards the West and display the classical seismic image of Unit I, consisting of a transparent basal subunit (lower Pliocene deposits) overlaid by the parallel seismic facies of Upper Pliocene/Pleistocene deposits (Jurado & Comas 1992; Maldonado *et al.*, 1992; Comas, Zhan, Klaus *et al.*, 1996). Older sediments (Late Miocene?), with reflective parallel or sigmoidal seismic facies (marked 'S' in Fig. 5A), remain below the "M" reflector. It is noteworthy that these lowermost deposits are preserved in small fault-bounded basement lows (e.g., at

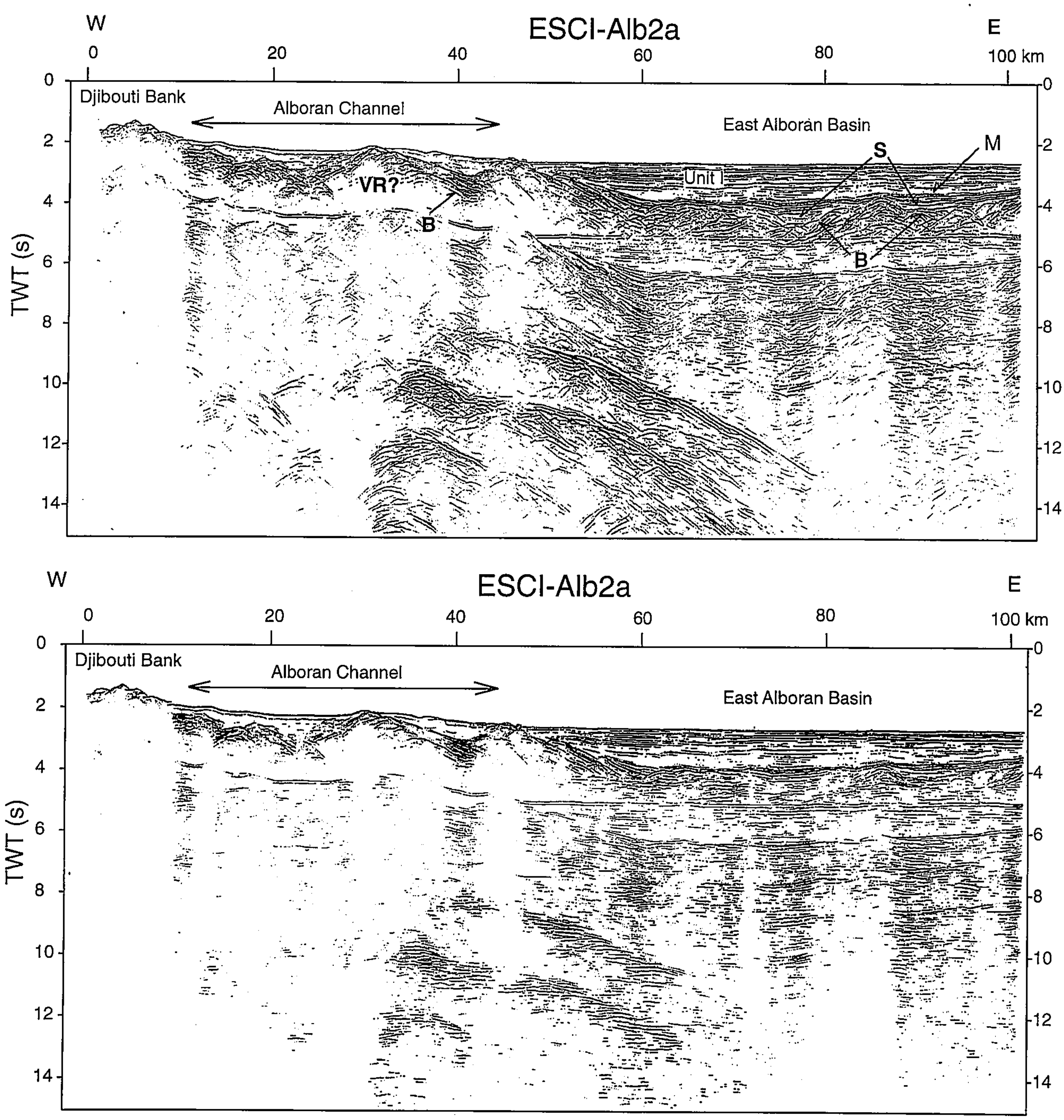


Figure 5.- **A**) Stack section of ESCI-Alb2a segment (coherency filter as in Fig. 3A). B: top of the basement. M: the Messinian 'M' reflector. S: Late Miocene? synrift sequence. VR: volcanic rocks. **B**) Stack section of ESCI-Alb2a segment. A similar post-stack processing as in Fig. 1b. Note the attenuation of the long dipping artefacts (between 9-14 s).

km-60 and km-80, Fig. 5A). The top of the basement along the East Alborán basin is delineated between 4 to 4.5 s below the sea level (marked 'B', between km 70 and 90 in Fig. 5A).

Deep crustal features in segment ESCI-Alb2a are hampered by the persistence of the seafloor, top-of-basement and 'M' reflector multiples. The northeast-dipping, coherent long reflections observed below 9 s in the ESCI-Alb2a stack section have partially disappeared (at least the tails of the two major sub-parallel reflections) after applying a strong f-k filtering (compare Fig. 5A and Fig. 5B). The remaining part of the signal in Fig. 5B is thought to be very strong peg-leg multiples.

The ESCI-Alb2b segment (Fig. 6) displays shallow features similar to those described in the ESCI-Alb2a segment. The main prominent basement high (around km-30) corresponds to the southwestern prolongation of the Maimonides Ridge,which is probably constituted by volcanic rocks, as the strong magnetic anomaly reported at this site indicates (Galdeano *et al.*, 1974). A change in the seismic character and geometry of the basement to the East of this high suggests a change in the nature of the basement toward the South-Balearic basin. Outstanding normal faulting is indicated by west-tilted basement blocks (e.g., top-of-basement dipping to the West from km-50 to km-75, B in Fig. 6), and wedge-shaped sedi-

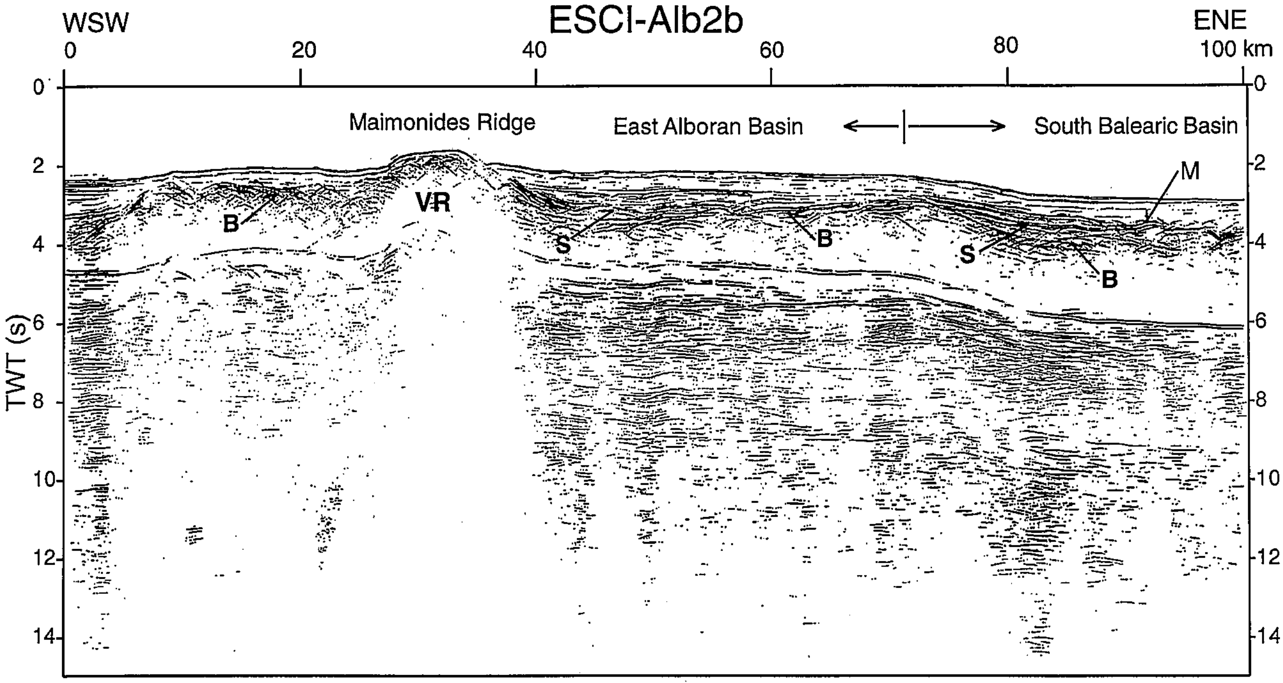


Figura 6.- Stack section of ESCI-Alb2b segment (coherency filter as in Fig. 3A). B: top of the basement. M: the Mesinian 'M' reflector . S: Late Miocene? sediments. VR: volcanic rocks.

ment bodies. A step down of about 350 m in the seafloor-bathymetry, coincident with a dipping-to-the-East basement escarpment, is interpreted as resulting from a major normal fault (at km-80, Fig. 6). The 'M' unconformity is at a depth of about 2.8 s and 3.5 s East of the Maimonides high and East of the above-mentioned major normal fault, respectively (Fig. 6). From this fault toward the East, the thickness of the sedimentary cover increases, which coincides with the start of diffractions within the sediments. These features suggest the existence of a thin Messinian-salt layer which led to incipient halokinetic structures that deformed the 'M' unconformity.

The easternmost segment (ESCI-ALb2c, Fig. 7) shows from km-0 to km-30 a formal prolongation of the diffractions seen at the end of segment ESCI-Alb2b, thought to represent discrete halokinetic structures. Towards the East, sediment thickness increases and widespread diffractions here are probably related to a major development of salt diapirs, as a result of a thicker salt layer within the Messinian sediments (Mauffret *et al.*, 1992). The 'M' unconformity appears as a strong reflector bounding the top of some lenticular transparent bodies interpreted as salt pillows (e.g., at km-20 and km-35, Fig. 7). To the East, the 'M' reflector corresponds to the top of a series of three strong parallel reflections that may correspond to the latest-Messinian evaporite cycles widely recognised in the South-Balearic basin (Fig. 2) (Comas, Zhan , Klaus *et al.*, 1996). The lowermost location of the "M" reflector along this segment is at 4.7 s below sea level (at km-65 in Fig. 7). East-dipping normal faults (from km-35 to km-70, Fig. 7) in the basement are sealed by a very strong reflection (marked 'TS' in Fig. 7) of unknown nature. A package of reflections (labelled 'S' in Fig. 7) with dipping and hummocky pattern can be seen filling basement half-grabens underneath the 'TS' unconformity. Maximum sediment thickness is about 2.4 s at km-65 in the depocentre of one of these half-grabens. At the eastern end of the section, the top of the basement is masked by the occurrence of widespread diffractions. The overlaying latest Miocene-Pliocene sedimentary sequence is folded, showing open 2-4 km-wide anticlines and tight narrower synclines (from km-70 to km-100 in Fig. 7). These structures may be induced, at least in part, by halokinesis of underlying Messinian evaporites; however, some additional local compression might contribute to that folding. These folds affect latest Pliocene or Pleistocene deposits, indicating a very recent tectonic activity in the area. Similar images are observed along a multichannel seismic profile acquired to the SE of Mallorca at the northwestern edge of the South-Balearic Basin (Vidal, 1995).

At the present stage of seismic processing, only a few deep reflectionshave been distinguished along the ESCI-Alb2 profile. Nevertheless, a reflective package of isolated reflections displayed between 6 and 7 s (labelled 'OB' in Fig. 7, between km-40 and km-70) may be associated to the reflection Moho.

Discussion and conclusion

At the present stage of understanding, the ESCI-Alb data reveal well- defined reflective features at upper crustal levels, whereas at deeper levels the images are mostly hampered by noise and only scarce primary reflections can be detected. Our structural interpretation based on the presence of deep crustal reflections and sedimentary reflectors are presented in line-drawing sections in Figs. 8 and 9.

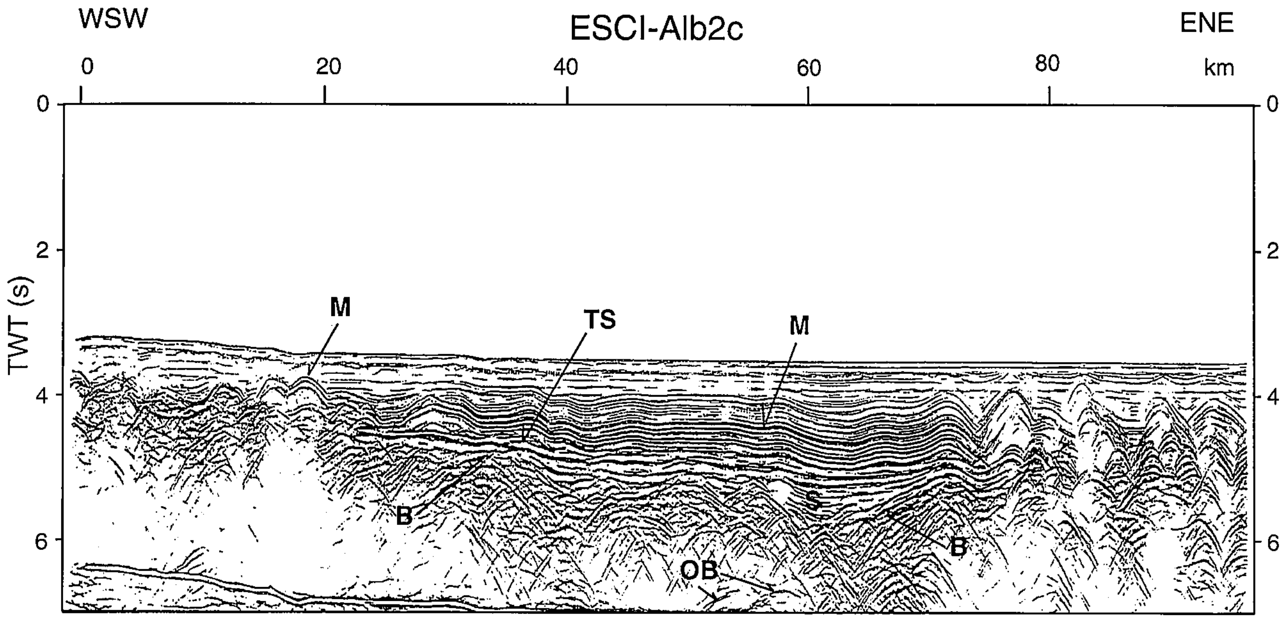


Figure 7.- Stack section of ESCI-Alb2c segment (coherency filter as in Fig. 3A). B: top of the basement. M: the Messinian 'M' reflector. OB: oceanic? basement reflections. S: Late Miocene? synrift sequence. TS: top of S synrift sequence.

Shallow Crustal Features

Profile ESCI-Alb1 (Fig. 8) reveals prominent compressional structures at shallow crustal levels in the northern Alborán Sea margin and provides information about the Middle Miocene extensional evolution of the Alborán basin.

The deep sedimentary basin displayed in profile ESCI-Alb1 is interpreted as resulting from the Middle Miocene rifting event, well documented in the West Alborán basin. Several unconformities imaged within the synrift sequence (Fig. 4A) demonstrate synsedimentary extension. Faults bounding this basin were later modified by post-Messinian tectonic inversions occurring mainly at the south-dipping faults. Folds in the uppermost sedimentary strata modifying the seafloor topography indicate a roughly N-S compressive event that spans till Late Pliocene, or even till now. Above the basement, the lowermost sediments can be correlated with the Langhian-Serravallian synrift sequence (Middle Miocene Unit IV, even including part of the Early Langhian Unit V, Fig. 8), sampled to the SE of Almería in commercial well And-A1 (Jurado & Comas, 1992) (Fig. 2). Assuming this, we conclude that the earliest syn-rift deposits in the northern part of the Alborán Sea margin are middle Miocene in age.

Shallow crustal structures imaged in profile ESCI-Alb2 (Fig. 9A, B and C) provide essential information on the post-Middle Miocene to Pleistocene sediments and tectonic behaviour of the East Alborán basin and its transition to the South-Balearic basin.

Seismic interpretation and correlation with comparable sedimentary sequences in the East Alborán basin, sampled at ODP Sites 977 and 978 (Comas, Zhan, Klaus *et al.*, 1996) (Fig. 2 and 9), allow us to infer that most of the sedimentary cover in this region is formed of post-

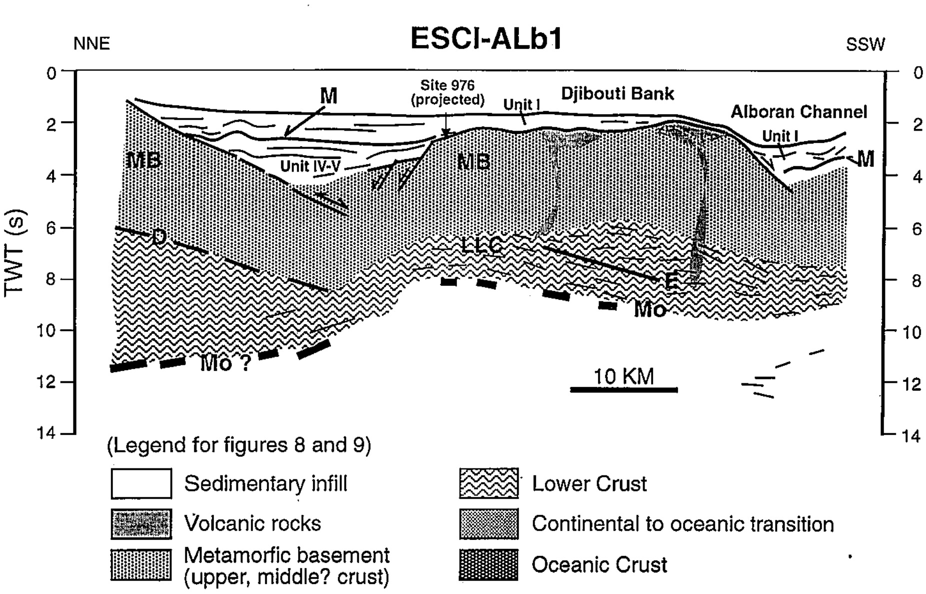


Figure 8.- Structural sketch time section of the ESCI-ALb1 profile showing the interpreted crustal features (see text for explanation). D: major crustal boundary. E: intracrustal SW dipping reflector. LLC: layered lower crust. M: "Messinian" unconformity ('M' reflector). MB: Metamorphic basement. Mo: reflection Moho. Units I to IV: Middle Miocene to Pleistocene lithoseismic units.

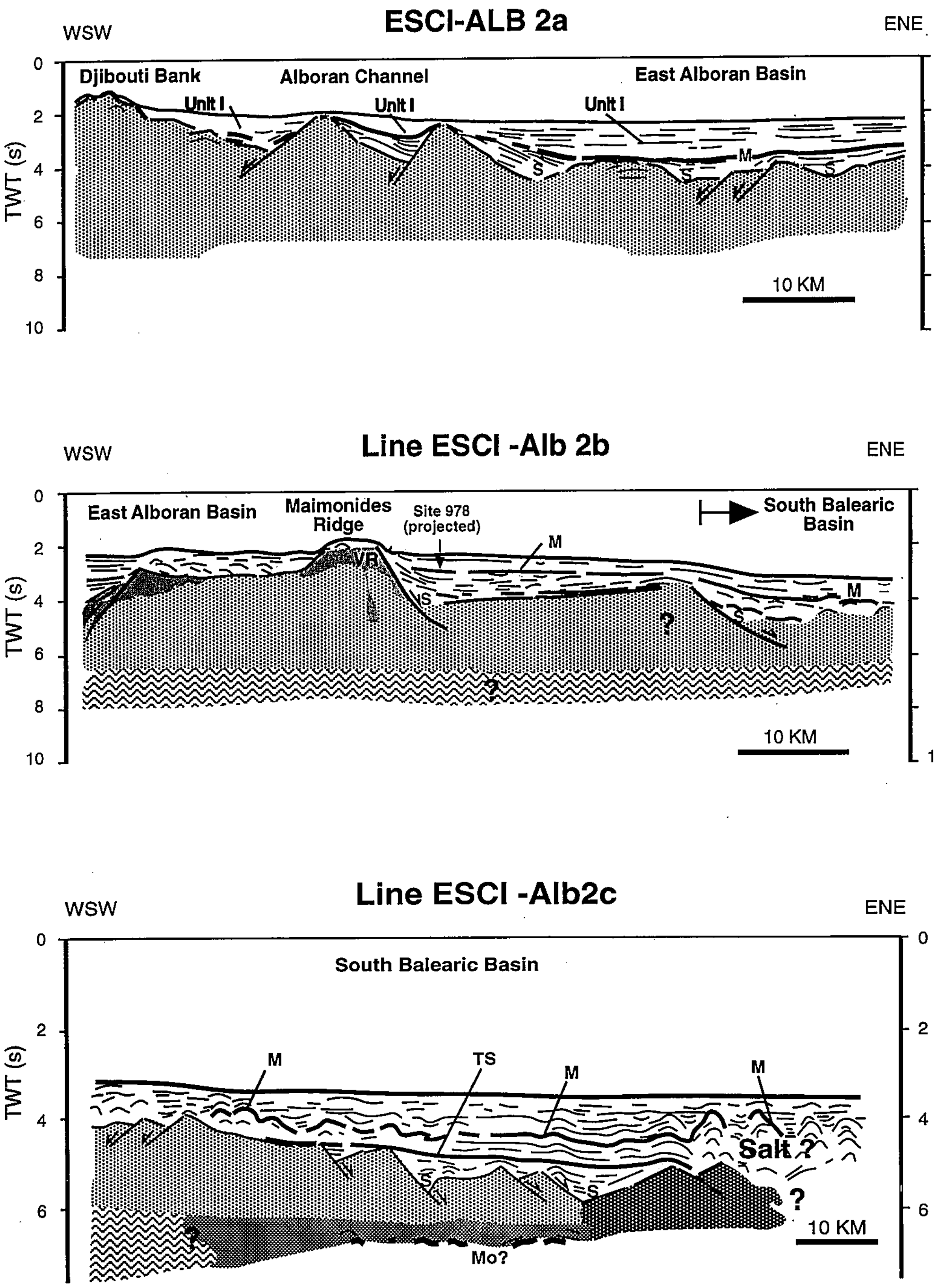


Figure 9.- Structural sketch time sections of the ESCI-Alb2 segments (a, b and c), showing the interpreted crustal features. M: "Messinian" unconformity. Mo?: possible Moho boundary. S: Late Miocene? synrift sequence. TS: top of S synrift sequence. Unit I: Pliocene to Pleistocene lithoseismic unit.

Messinian deposits. Older sediments appear only filling discrete grabens or half-grabens upon the basement (edge-shaped sedimentary bodies, 'S' in Fig. 5A and 9A), that we interpret as representing the synrift sequence in the easternmost Alborán and South-Balearic basins. Although no direct sample information exists about the age of these older sediments, correlation through MCS lines suggests that they could correspond to upper Miocene deposits. In addition, there is a significant contrast between the thin sedimentary cover observed in most of the ESCI-Alb2 profile (maximum about 2.4 s, less than 3 km in thickness) and the thick sequences (at places up to 6 km thick) of the West Alborán basin, or even in the northern Alborán Sea margin (e.g., in the basin shown in profile ESCI-Alb1). This contrast can be interpreted in terms of time- different tectonic evolution for each one of these regions.

Another interesting piece of data from the sedimentary cover revealed in profile ESCI-Alb2 is the change in lithology in the Messinian sequences at sites of transition from the East Alborán to the South-Balearic basins. It is known, that the Messinian deposits (seismic Unit II) in the Alborán Sea are formed of distal marine or shallow-water carbonate facies and minor gypsum and anhydrite intervals, but no substantial evaporite or salt layers exist (Comas *et al.*, 1992). On the contrary, ESCI-Alb data reveal that toward the South-Balearic basin the Messinian salt layer appears, associated with the "upper evaporite" Messinian sequence (Ryan, Hsu *et al.*, 1973; Comas, Zhan, Klaus *et al.*, 1996).

The main shallow structures observed beneath the Alborán Channel (Fig. 9A), and in the East Alborán and South-Balearic basins (Fig. 9 B and C), are interpreted as normal faults producing a horst-and-graben basement architecture. Some of these faults, which have a high dip angle, may have some strike-slip component, as deduced from the Alborán Sea basin structure (see map in Fig. 2). However, other faults imaged in the ESCI-Alb2b and-Alb2c profiles, near the transition toward the South-Balearic basin and in this basin itself, are low-angle normal faults producing basement-block tilting, that accommodate sequence 'S' (Fig. 9B and C). The timing of this extension is constrained by the probable age of reflectors overlying the faults; since basement blocks are sealed by the unconformity at the top of the synrift sequence ('TS', in Figs. 9B and C) and no major faulting is observed at the Messinian 'M' reflector ('M', Figs. 9B and C).

The unknown nature of the 'TS' reflector does not allow us to determine the exact age of this faulting. However, as explained above, seismic correlation suggests a Late Miocene age for the rifting at the transition between the Alborán and South-Balearic basins. A pre-Messinian age of this rifting is clearly demonstrated by the unfaulted display of the well identified 'M' reflector. We conclude that a roughly E-W crustal extension occurred at the transition between the Alborán and the South-Balearic basins probably at times as young as Late Miocene.

Post-Messinian deformation, during Pliocene and Recent times, is illustrated by the monoclinal bend of the youngest sediments (normal-fault related?), expressed as a bathymetric lowering (Fig. 9B) at the limit between the Alborán and the South-Balearic basins. Both bathymetric change and flexure may reflect near-present thermal subsidence in the South-Balearic Basin. In addition, post-Early Pliocene folding demonstrates the near-Recent tectonic activity at this basin boundary. Whether these folds (Fig. 9C) were produced either by Messinian salt diapirs exclusively or by additional local compression remains an open question.

From this survey there is no way to determine on the nature of the basement along profile ESCI-Alb2; however, regional data suggest that most of the outcropping or sub-outcropping basement highs are volcanics. In addition, the existence of discrete volcanoes producing high-and-low irregular features on top of the deeper basement at segments ESCI-Alb2b and Alb2c cannot be ruled out. From these images, we suggest that most of the volcanic activity should be older than the "M" reflector (i.e. pre-Pliocene). The presence of a Messinian salt layer in this sector, as reported for other Mediterranean areas (Ryan, Hsu *et al.*, 1973), may well be related to the existence of oceanic basement beneath the South-Balearic basin at the eastern end of profile ESCI-Alb2.

Deep Crustal Structures

The seismic image observed at deep crustal levels in profile ESCI-ALb1 shows a southwest-dipping coherent reflection ('D' in Fig. 8), which coincides with a reflection obtained by wide-angle stacked sections acquired with the same shot source (Gallart *et al.*, this vol.), and correlates with a strong reflectivity change at similar crustal levels (6-7 s) in profile ESCI-Béticas2. This reflection has been interpreted as the top of the lower crust and may represents a major contact between two different crustal domains ('TLC', Garcia-Dueñas *et al.*, 1994). Whether 'D' reflection marks the top of the lower crust or represents a detachment cutting across the middle and lower crustal levels is to be decided after further analysis and processing of the ESCI-Alb profiles.

Our preliminary conclusions point to the presence of a layered lower crust ('LLC' in Fig. 8) beneath the central Alborán basin. We suggest that the bottom of this reflection might be attributed to the Moho boundary discontinuity.

Scarce deep structures were revealed by the stacked and filtered profile ESCI-Alb2. In the ESCI-Alb2c segment, however, a few isolated deep reflections were distinguished between 6.5 and 7 s ('OB', Figs. 7 and 9C) underneath the area with salt diapirs and folds. These reflections may be interpreted as being associated with Moho reflectivity. They would represent the presence of a thin transitional or oceanic crust (basement of 2 s in thickness) in the western South-Balearic basin adjacent to a progressively thickened continental crust, with extensive volcanic components, toward the Alborán basin.

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