

# Seismic and tectonic interpretation of the ESCI-Béticas and ESCI-Alborán deep seismic reflection profiles: structure of the crust and geodynamic implications

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**Abstract:** The seismic and tectonic interpretation of the ESCI-Béticas and ESCI-Alborán deep seismic reflection profiles provides an overall image of the crust on the northern flank of the Betic-Rif orogenic system. In these interpretations, previous wide-angle refraction-reflection and MCS industrial profiles were used in order to identify the sequence of collisional-extensional events that built up the crust in this escape-type orogenic area. A model of convergence between the Iberian crust and the Alborán domain, including coeval extension due to lateral escape, is consistent with the data presented in this paper.

**Keywords:** Deep seismic reflection profiles, Betic Cordillera, Alborán Sea, min reflectors, continental crust, oceanic crust.

**Resumen:** La interpretación sísmica y tectónica de los perfiles ESCI-Béticas y ESCI-Alborán proporcionan una imagen global de la corteza en el flanco norte del orógeno bético-rifeño. En esa interpretación se han utilizado otros datos procedentes de perfiles de sísmica de refracción-reflexión de gran ángulo y de perfiles de sísmica multicanal comerciales. Se propone una secuencia de procesos extensionales y colisionales que origina la estructuración de esta zona orogénica. Además se considera un modelo tectónico de escape lateral que es congruente con los datos presentados.

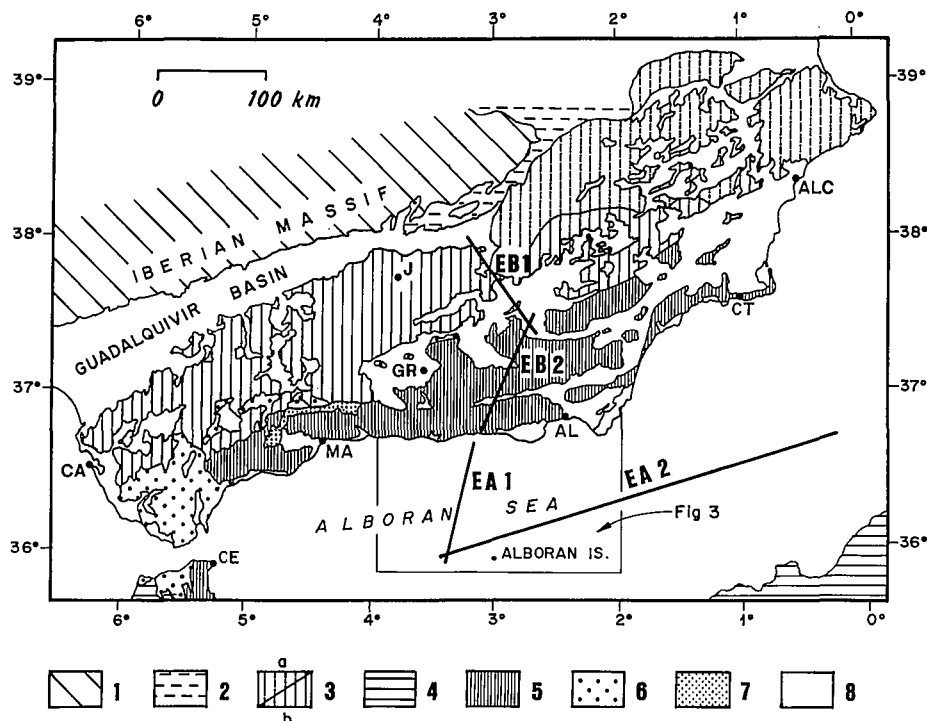
**Palabras clave:** Perfiles profundos de sísmica de reflexión, Cordillera Bética, mar de Alborán, principales reflectores, corteza continental, corteza oceánica.

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Long-range seismic profiles have as their main objective to find out about the architecture of the crust and the upper mantle. The derived crustal arrangement is fundamental for the construction of geodynamic models. Nevertheless, from a tectonic point of view, deep seismic data are often inconclusive, due to their inadequate situation and restricted resolution with regard to the main tectonic features constraining the geological evolution of the sampled areas. This is the case with the ESCI-Béticas and ESCI-Alborán profiles (Fig. 1) that were part of the ESCI-project and had the geodynamic evolution of the Betic Cordillera as one of their objectives. This evolution should be viewed in the context of the main boundary between the Iberian plate (welded to Eurasia) and the African plate. In current literature, since the model proposed by Andrieux *et al.* (1971), an intermediate crustal unit –the so-called Alborán plate– is widely ac-

cepted. This buffer-like plate constitutes the “internal zones” of both the Iberian and African deformed borders, the Betics and Rif, respectively. Two main hypotheses have been advanced: one considering a westward motion of the “Alborán plate”, that overrides both the Iberian and African margins and so caused their deformation; the other one envisages the Alborán plate as squeezed by the African and Iberian plates acting like a vice, without substantial E-W displacement. Nevertheless, the main problem resides in the crustal extension that was simultaneous with thrusting and folding in both the Betic and Rif areas. This extensional collapse in the inner part of the orogenic area gave rise to the Alborán basin, the seaway that now separates the orogenic area of Africa and the Iberian Peninsula.

In the “static hypothesis” the compression-extension process is explained as an orogenic collapse due to co-



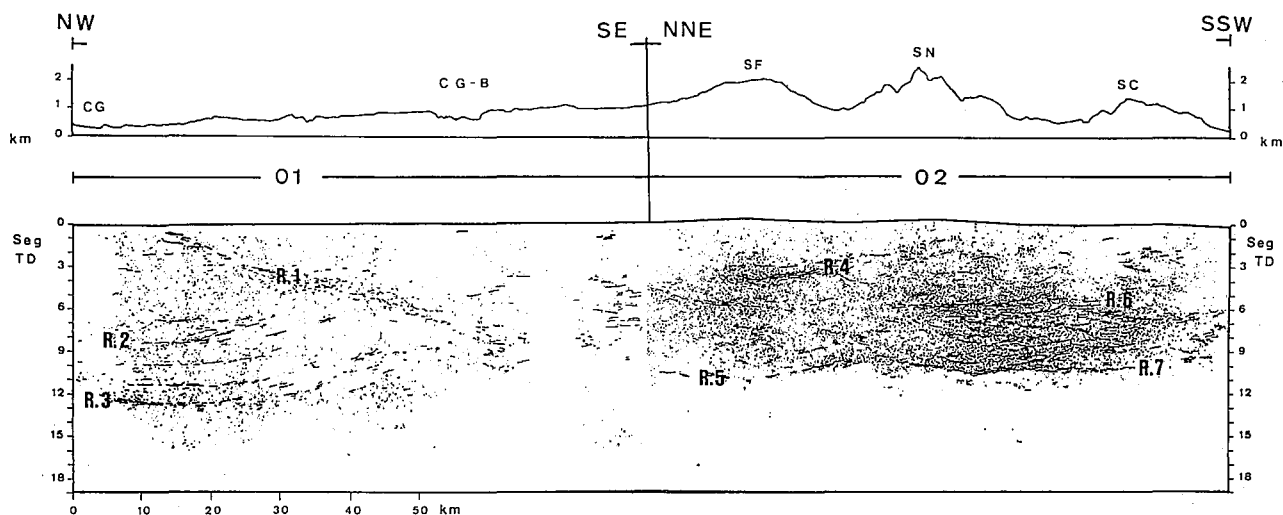
**Figure 1.-** Location and tectonic framework of the ESCI-Béticas and ESCI-Alborán profiles. 1: Hesperic Massif; 2: Sedimentary cover of the Hesperic Massif; 3: External Betics, a: Prebetics, b: Subbetics; 4: External Rif; 5: Internal Betics and Rif; 6: Flysch trough unit; 7: Alozaina complex; 8: Neogene-Quaternary materials (including volcanic outcrops); EB 1 and EB 2: ESCI-Béticas1 and ESCI-Béticas2 profiles; EA 1 and EA 2: ESCI-Alborán1 and ESCI-Alborán2 profiles; ALC: Alicante; AL: Almería; CA: Cádiz; CE: Ceuta; CT: Cartagena; GR: Granada; J: Jaén; and MA: Málaga.

lithospheric thickening. Lithosphere thickening caused an unstable root, whose removal was responsible for the foundering of the internal part of the orogenic area and for the outward thrusting in the peripheral zones (Platt & Vissers, 1989). The second hypothesis considers the coeval extension-compression as a result of asymmetrical mantle delamination causing simultaneously extension-shortening in the same orogenic area (García-Dueñas *et al.*, 1992). Both hypotheses seem inconclusive since they explain neither the shape of the buffer-like Alborán plate nor the intermediate and deep seismicity of the region.

For this complex and still unexplained plate boundary, a comparison with the Caribbean and Scotia-South Sandwich intermediate plates can be established. These

intermediate plates show some relevant similarities: an arcuate leading front similar to the Gibraltar Arc, two compressive borders with coeval extension and compression as well as lateral escape (e.g. Vegas *et al.*, 1995; Mann *et al.*, 1995). Case studies of the main plate boundaries in these regions may provide new insights into the plate-interaction scenarios, and will serve as possible examples for other arcuate regions formed by lateral escape between great plates, like the Betic-Rif and Alborán connection and the Carpathian Arc.

Within this tectonic background, this study attempts to interpret regionally the ESCI-Béticas-Alborán profiles in order to describe the main seismic features in terms of the processes of extension/compression that built up the crust in the area of the central Betics and the NE Alborán basin.



**Figure 2.-** Line drawing of the ESCI-Béticas1 and 2 profiles. The topographic section of the profile track is presented at the top. Both profiles are shown from their cross-point. CG: Guadalquivir basin; CG-B: Guadalquivir-Baza basin; SF: Los Filabres Range; SN: Sierra Nevada; SC: La Contraviesa Range. See text for the R legend and Fig. 1 for location.

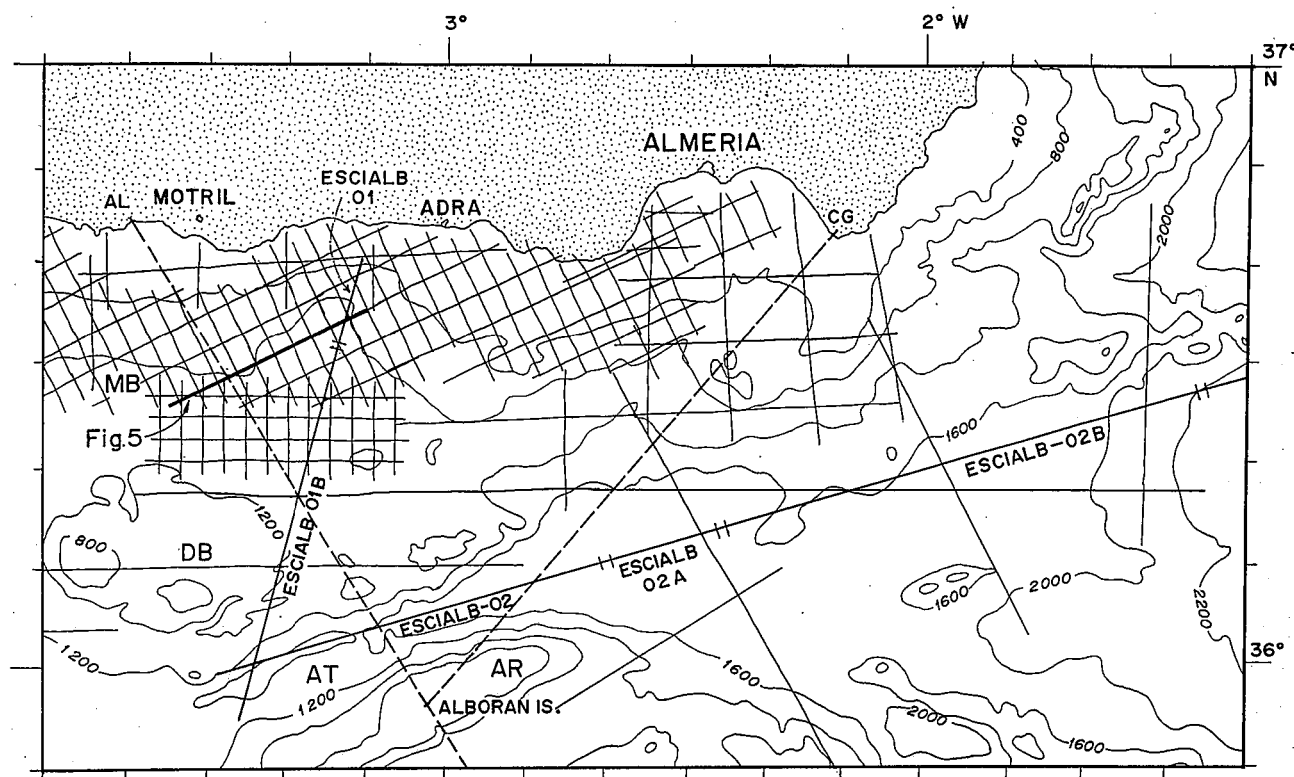


Figure 3.- Location of the seismic data used in this study. Heavy solid lines: ESCI-Alborán profiles; light solid lines: industrial seismic reflection profiles. Discontinuous lines: deep seismic refraction and wide-angle reflection profiles. AL: Almuñécar; AR: Alborán ridge; AT: Alborán trough; CG: Cabo de Gata; DB: Djibouti bank; MB: Motril basin. Bathymetric isolines are displayed every 400 m.

### Seismic data

Several seismic surveys have been integrated in the development of this study:

#### *ESCI-Béticas and ESCI-Alborán profiles*

The ESCI-Béticas profiles, whose technical characteristics are outlined by García-Dueñas *et al.*, 1994), are located between the Guadalquivir basin and the Alborán Sea (Fig. 1). The ESCI-Béticas1 profile crosses the South Iberian domain: the Guadalquivir basin, the Prebetic and Subbetic zones and the Neogene-Quaternary basin of Guadix-Baza, at the limit of the external-internal zones. The NW-SE direction of the line is parallel to the compressive tectonic transport (Banks & Warburton, 1991). The ESCI-Béticas2 runs across the emerged part of the Alborán domain (Nevado-Filábride and Alpujarride complexes and several intramontane basins) in a NNE-SSW direction. This direction is almost parallel to the extensional tectonic transport in this part of the chain (e.g. Galindo Zaldívar *et al.*, 1989; García-Dueñas *et al.*, 1992; Crespo-Blanc *et al.*, 1994). Final migration sections were used for the interpretation of these two profiles and a combined line drawing of both sections is shown in Fig. 2. The resulting image is only slightly distorted and provides a cross-section of the whole chain (Vegas *et al.*, 1994).

The ESCI-Alborán profiles are situated in the eastern part of the Alborán Sea (Figs. 1 and 3). The ESCI-Alborán1 and 1B profiles cross the northern continental mar-

gin between Adra and the Alborán ridge (Motril basin, Djibouti bank and Alborán trough) in a NNW-SSE direction. They are a continuation of the ESCI-Béticas2 line mentioned above. The ESCI-Alborán2, 2A, 2B and 2C profiles (WSW-ENE direction) begin in the Alborán trough and end in the South Balearic basin (at the Cartagena meridian). They provide an image of the crust transition between the Alborán basin (very thinned continental crust, Hatzfeld, 1976) and the South Balearic basin (floored by oceanic-type crust, Galdeano & Rossignol, 1977). The use of brute stacked sections and the bad quality of the data impose some limitations to the interpretation.

#### *Deep seismic refraction and wide-angle reflection profiles*

These profiles were considered complementary (especially at their cross points with the ESCI sections) to elaborating a velocity model and calculating the depth of the main reflectors. The results of the depth conversion of the ESCI-Béticas1 and 2 profiles were presented by Vegas *et al.* (1994) and are shown in Fig. 4a. Depth was calculated using the mean velocities shown in the sections for the first seconds and the velocity defined in the deep refraction-reflection sections of the same region (Banda *et al.*, 1993; Barranco *et al.*, 1990). For the ESCI-Alborán1 line (Fig. 4b), the root-mean square velocities indicated in the industrial seismic sections were considered for the sedimentary cover and the velocity defined in the deep refraction-reflection sections for deeper structures (Hatzfeld, 1976; Suriñach & Vegas, 1993).

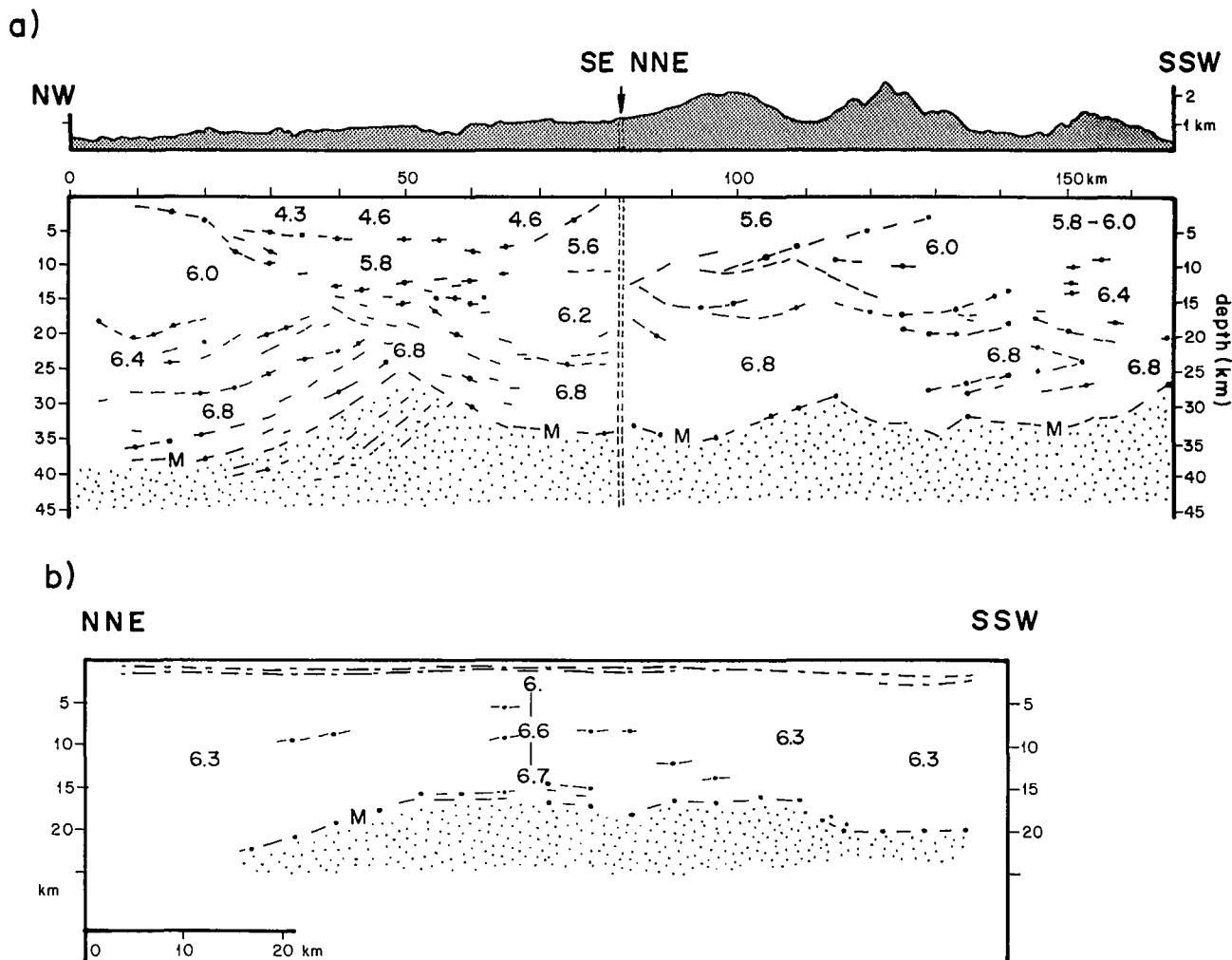


Figure 4.- Depth-converted profiles for the ESCI-Béticas (a) and ESCI-Alborán1 (b) profiles. Numbers represent P-velocities in kms-1.

#### Industrial seismic lines in the Alborán Sea

A dense grid of seismic reflection profiles was recorded for oil exploration in the northern Alborán Sea between 1974 and 1983 (Fig. 3). Its characteristics (sources, processing, etc.) vary, as does the quality, which is generally good. On the continental shelf of the eastern area the quality of the seismic sections is not very high; nevertheless, the available data allow correlation with the ESCI-Alborán profiles, especially the ESCI-Alborán1 (Fig. 5). The interpretation of these profiles allows us an analysis of the major structures and seismic units of the Neogene-Quaternary sedimentary basin. Some basement reflectors have also been traced and can be tied-in to intracrustal or deeper discontinuities. The structures have been correlated with those observed in the ESCI-Alborán profiles.

#### Methods

The ESCI-Béticas and ESCI-Alborán seismic profiles have been interpreted in terms of seismic fabric (Allmendinger *et al.*, 1987a), which permits a fuller structural interpretation (Berastegui, 1992) and the identification of great domains or structural units in the crust with a simi-

lar reflection pattern. The concept of seismic fabric is based on the geometric association of the reflectors at the profile scale and the description of the seismic facies. Main seismic reflectors and units were differentiated by the conventional criteria used in seismic analysis: 1) tracing of the main reflectors associated to the major discontinuities, 2) geometric configuration of the secondary reflectors and its relation with the major discontinuities and 3) the identification of seismic facies following Mitchum *et al.* (1977) with description and geological interpretation of the seismic unit parameters.

#### Seismic interpretation: main seismic units

##### ESCI-Béticas1

*Unit 1:* Low reflective fabric. It shows transparent to weak facies (Figs. 2 and 6). The unit has a wedge shape and is bounded at the top by the topographic surface and the R1 reflector and at the bottom by the R2 reflector (7s TWT depth). R1 is a discontinuity dipping to the South (1-8 s TWT depth). The continuous reflections observed at the top of the unit can be related to the cover-basement boundary of the Guadalquivir basin. This unit may be correlated to the upper Hesperic crust.

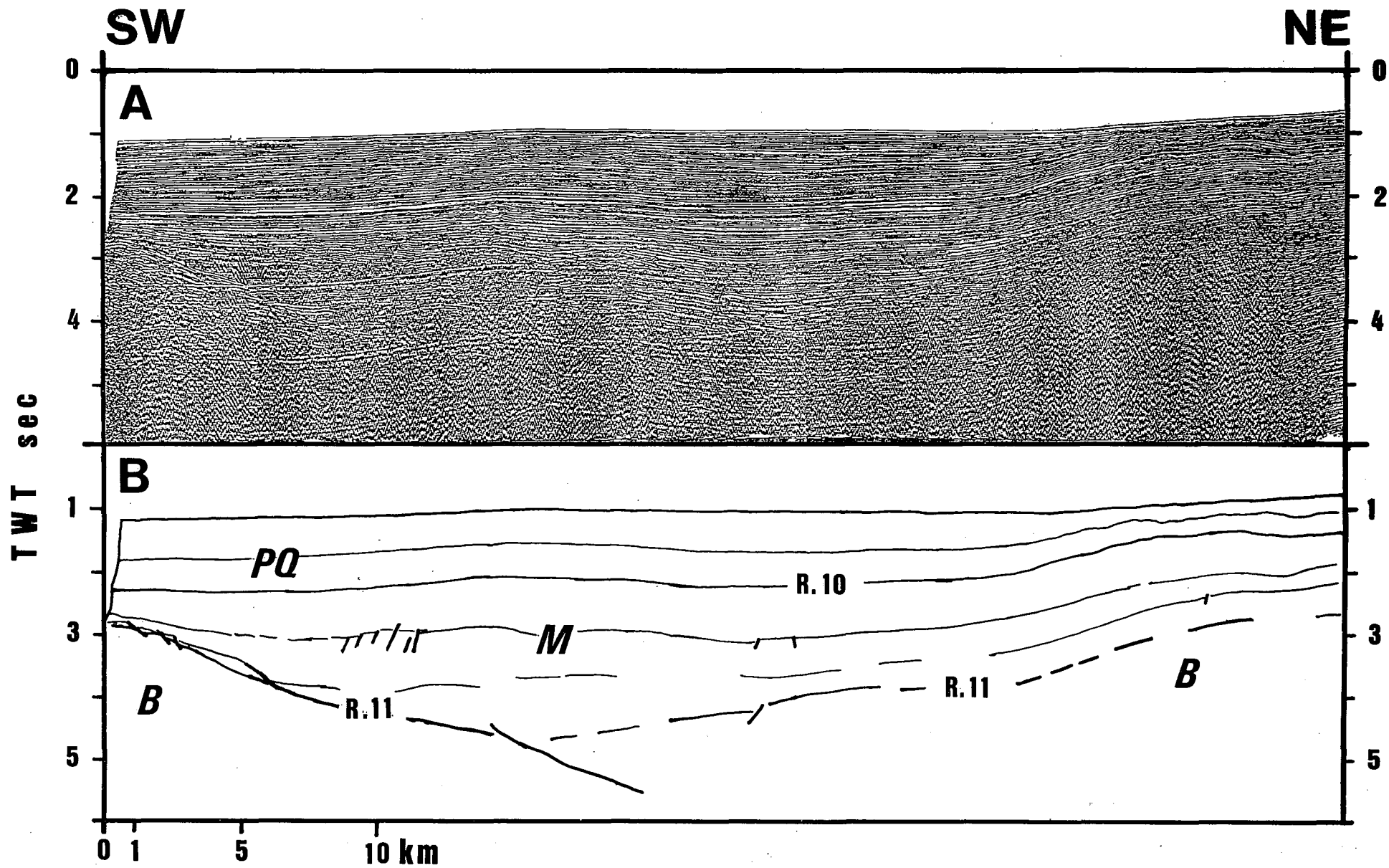
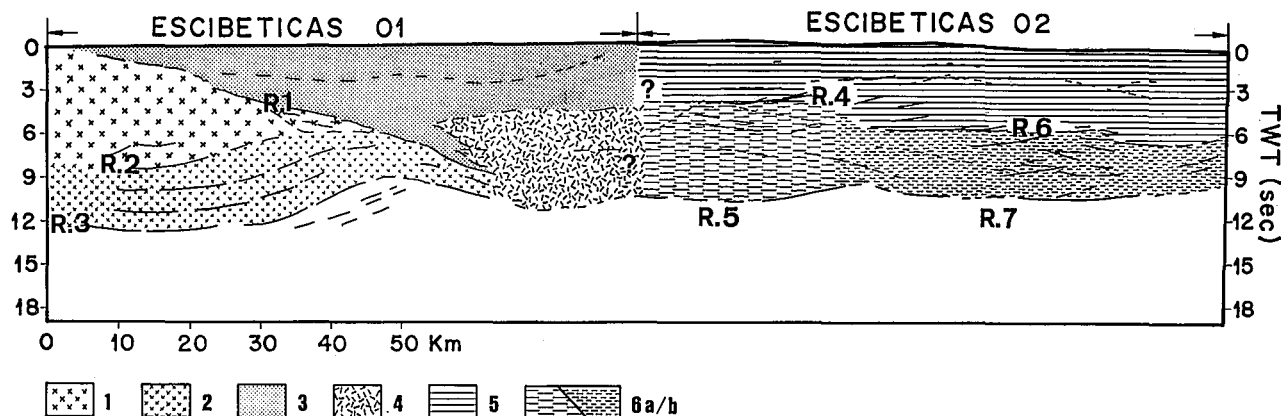


Figure 5.- Example of industrial MCS profiles used for complementary interpretation of ESCI-Alborán deep seismic reflection profiles. This seismic section crosses the Motril basin in an oblique direction. Note the R10 and R11 reflectors and the gross architecture of the Pliocene-Quaternary and Miocene sedimentary sequences over the basement (B). See Fig. 3 for location.



**Figure 6.-** Seismic and tectonic interpretation of the ESCI-Béticas 1 and 2 profiles. 1: Unit 1 (upper Variscan crust); 2: Unit 2 (lower Variscan crust); 3: Unit 3 (external Béticas); 4: Unit 4 (Alborán domain front); 5: Unit 5 (upper Alborán domain); 6: Unit 6 (middle and lower Alborán domain), 6a: northern sector, 6b: southern sector. See text for the R legend.

**Unit 2:** Layered fabric. The facies are very reflective with a subparallel configuration. Five reflectors can be distinguished. These reflectors are horizontal to the North, but to the South seem to curve under R1 (Figs. 2 and 6). The unit is bounded at the bottom by R3 (12.8 s TWT depth) and at the top by R2 (7 s TWT depth). This unit corresponds to the lower Hesperic crust and R3 to the crust-mantle discontinuity. The layered fabric points to the presence of intracrustal ductile shear zones or lithological boundaries (Passchier, 1986; Rey, 1993). These lower crust laminations have been described in other segments of the European Variscan belt (Meissner, 1988) and in the Basin and Range Province (Allmendinger *et al.*, 1987b). In both papers these features were correlated with modern extensional events, which means that this segment of the Hesperic crust could be considered the South Iberian continental margin during the Mesozoic time. The curved geometry could be attributed to a suture between two different crustal blocks.

**Unit 3:** Discontinuous dipping reflections fabric. The unit is characterised by weak facies with discontinuous reflections that dip gently to the South, although in the southern part of the unit the reflections dip to the North (Figs. 2 and 6). This unit corresponds to the upper crust of the external Betic zone. Two levels can be defined: the upper level related to the Guadix-Baza basin and the lower one to the Prebetic and Subbetic zones. The dipping reflections could be associated to thrust sheets.

**Unit 4:** Irregular fabric. It shows chaotic facies with discontinuous reflections (Figs. 2 and 6). This unit is probably associated to the Alborán crustal domain, or possibly to a wedge of the lower Hesperic crust.

#### ESCI-Béticas2

**Unit 5:** Low reflective fabric. The unit is characterised by transparent to weak facies. The reflections are smoothly dipping to the South and to the North (Figs. 2 and 6). North to the cross-point with ESCI-Béticas1, sha-

llower and continuous reflections are probably related to the sedimentary cover-basement limit of the Guadix-Baza basin. This unit corresponds to the upper crust of the Alborán domain (Fig. 6). The image provided by the seismic profile is too poor to discern the tectonic features (Fig. 2). The remarkably coalescent character of the reflections that limits this unit at the base (R4 and R6) may be related to a detachment behaviour in the building of the chain and to the extensional events that caused the present thinning.

**Unit 6:** Dipping and cross fabric. It is a high reflective unit, with progressive complexity in its structures southwestwards. Two sectors (North and South) can be defined, with some differences in their internal configuration. The unit is bounded at the top by R4 and R6 and at the bottom by R5 and R7 (Figs. 2 and 6). In the northern sector, the R4 upper limit dips gently to the North (4 s TWT depth). The R5 lower limit (11 s TWT depth) displays a complex signal with increasing amplitudes and continuity towards the South. The seismic facies are characterised by subparallel and discontinuous reflections that dip to the North. Downwards the facies become less reflective with discontinuous reflections that are horizontal or dip to the North. In the southern sector the upper boundary (R6) is horizontal (5.8 s TWT depth) and the lower (R7) rises towards the South (10.5 to 9 s TWT). The seismic facies show a clear cross-configuration, with continuous reflections dipping North and South. This unit can be associated to the lower-middle crust of the Alborán domain. The cross-fabric has been related to collisional processes with tectonic indentation (Meissner, 1988), but it could be simply attributed to a crustal segment where the tectonic processes (extensional and compressive) developed with more intensity, probably due to ductile behaviour. The thickness of the lower and middle crust in the Betic Cordillera is bigger in the northern part of the internal zones (Filabres Range), whereas the general thickness of the chain remains uniform. This fact could explain the gravimetric anomalies to the North of the Sierra Nevada range (Suriñach & Udías, 1978).

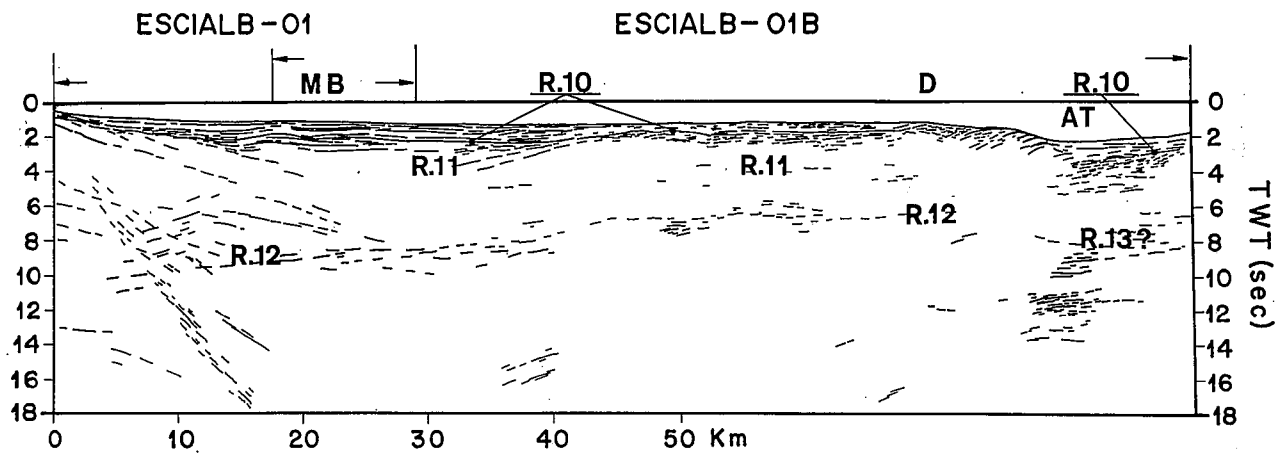


Figure 7.- Line drawing of the ESCI-Alborán(1, 1B) profile. MB: Motril basin; D: Djibouti bank; AT: Alborán trough. See text for the R legend.

#### ESCI-Alborán profiles

Seismic data from these profiles do not allow a detailed study of the seismic facies and, therefore, the tectonic fabric. The study is restricted to the upper part of the profiles where reflections are clean (sedimentary cover and cover-basement boundary) and completed with industrial seismic reflection profiles. The crust-mantle discontinuity and other deeper features will be only sketched.

**Unit 7:** Sedimentary fabric. The unit presents reflective and stratified facies with continuous and parallel reflections (Figs. 7 and 8). It is bounded at the top by the sea floor and at the bottom by a major discontinuity (R10), characterised by onlap landward and downlap seaward. This unit corresponds to the Pliocene-Quaternary formations of the Alborán basin. The upper reflective facies are probably associated to the Quaternary and Upper Pliocene sedimentary unit, whilst the lower transparent ones are probably related to the Lower Pliocene formations. In this sense, R10 represents the Miocene-Pliocene boundary (Upper Messinian unconformity).

**Unit 8:** Sedimentary fabric. This is a high reflective unit characterised by stratified facies with continuous and parallel reflections. It is bounded at the top by R10 and at the bottom by R11, defined by onlap terminations towards both sides of the basin. This unit only found in the Motril basin (Figs. 7 and 8), and is deformed in some asymmetrical anticlines, especially near the northern edge of the basin, where they also affect unit 7. Unit 8 is correlated with Miocene formations of the Motril basin and R11 is associated to the cover basement boundary in this basin. Deformation affecting units 7 and 8 is probably due to the sedimentary thrusts towards the basin edges.

**Unit 9:** Sedimentary fabric. This unit consists of stratified facies with subparallel and continuous reflections. Its geometry is conditioned by the basement morphology (Figs. 9 and 10). The upper boundary (R10) is continuous, whereas the lower is more irregular and is characterised by the Miocene formation of the central Alborán trough and the South Balearic basin.

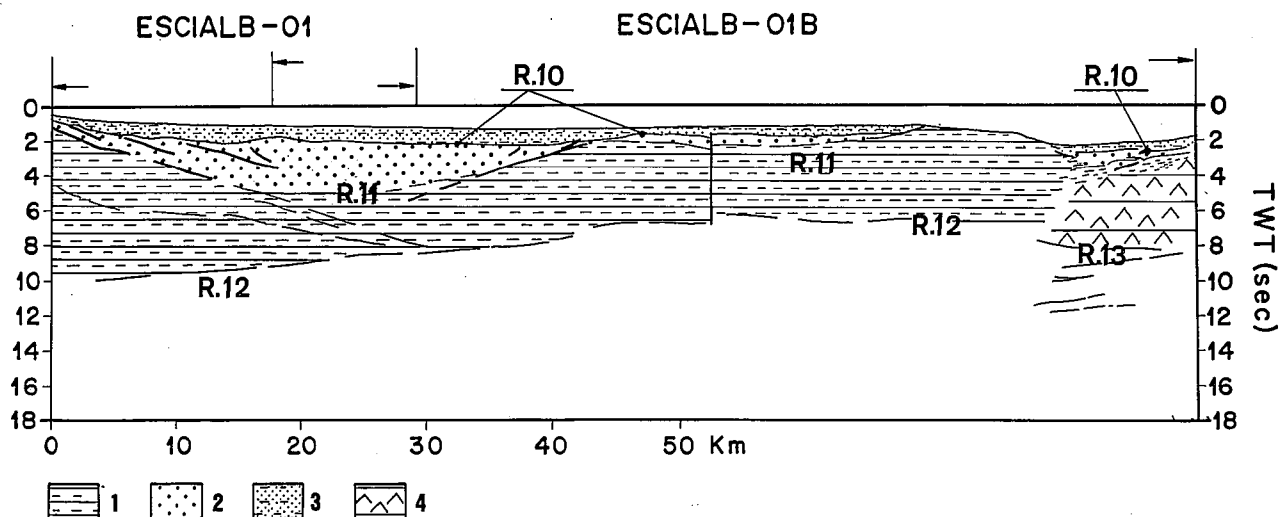


Figure 8.- Seismic and tectonic interpretation of the ESCI-Alborán(1, 1B) profile. 1: Unit 10: (thinned Alborán domain); 2: Units 8 and 9 (Miocene sedimentary sequences); 3: Unit 7 (Pliocene-Quaternary sedimentary sequences); 4: Unit 11 (very thinned Alborán domain and transitional crust to the South Balearic basin). See text for the R legend.

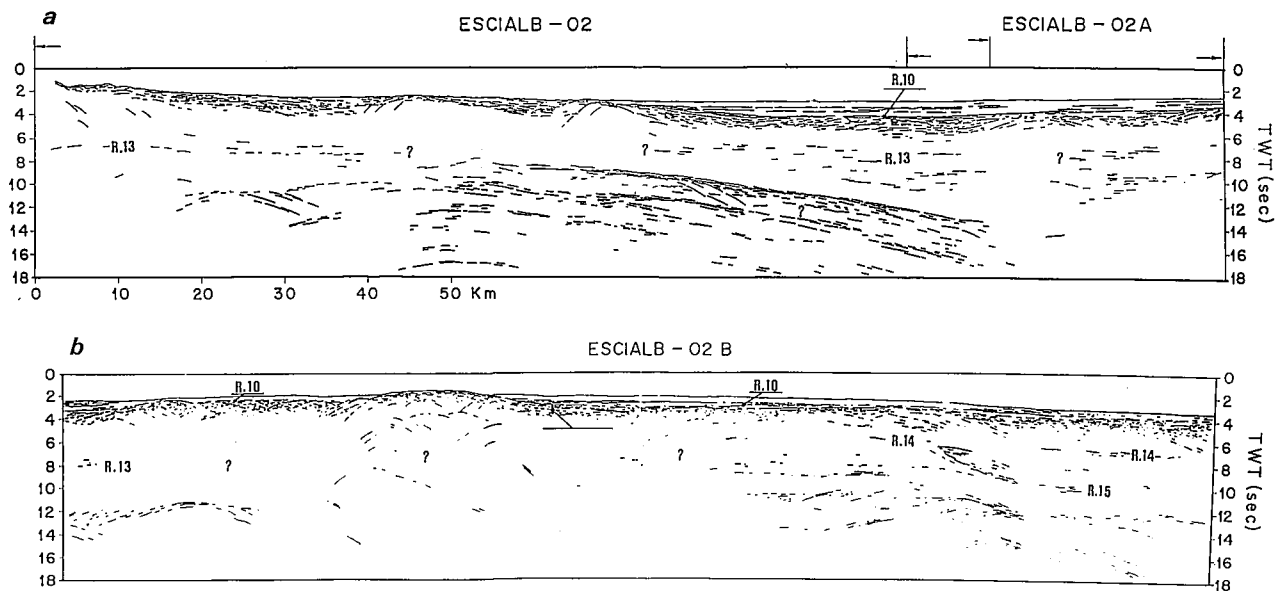


Figure 9.- Line drawing of the ESCI-Alborán2 profile. 9a: ESCI-Alborán2 and 2A profile; 9b: ESCI-Alborán2B profile. See text for the R legend.

**Unit 10:** Irregular fabric. This unit is characterised by weak facies with discontinuous reflections dipping to the North and South, with some diffractions. It is found on the northern margin of the Alborán Sea (Figs. 7 and 8) and outcrops in the northern scarp of the central Alborán trough. It corresponds to a segment of the Alborán crustal domain, probably very thinned continental crust. In the northern part of the ESCI-Alborán1 line (Fig. 7), a discontinuous reflector (R12) is observed dipping to the North, related to the crust-mantle discontinuity. The R12 depth is 10 s TWT under the continental shelf and 8 s

TWT South of the Motril basin. Under the eastern part of the Djibouti bank, R12 ranges from 7 to 6.5 s TWT depth by means of two small steps. The upper step, which can also be observed on R10 and R11, could be interpreted as a strike-slip fault.

**Unit 11:** Weak reflective fabric. It is characterised by weak and transparent facies with diffractions. The upper limit is reflective and shows discontinuous reflections and diffractions (Figs. 9 and 10). The lower limit is not well defined, but sometimes it is possible to observe discontinuous reflections at 7.5 s TWT (R13). This unit is

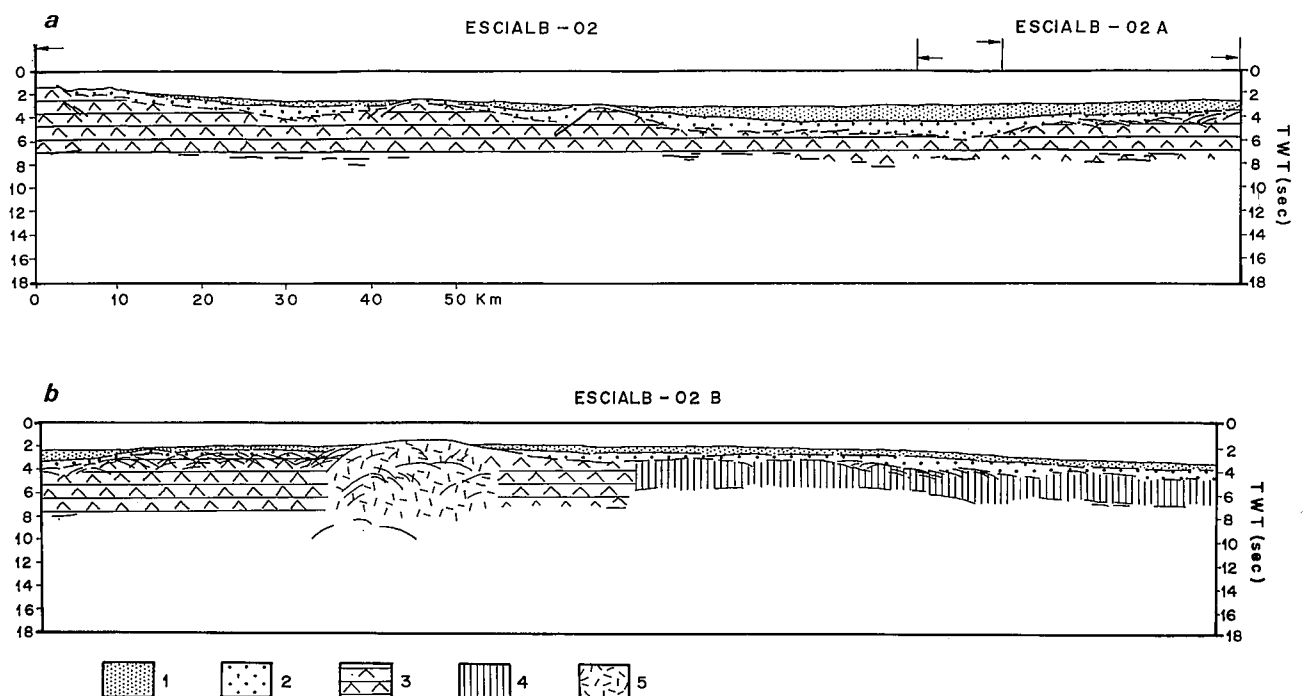


Figure 10.- Seismic and tectonic interpretation of the ESCI-Alborán2 profile. 10a: ESCI-Alborán2 and 2A profile; 10b: ESCI-Alborán2B profile. 1: Unit 7 (Pliocene-Quaternary sedimentary sequences); 2: Unit 9 (Miocene sedimentary sequences); 3: Unit 11 (very thinned Alborán domain and transitional crust to the South Balearic basin); 4: Unit 12 (oceanic-type crust); 5: igneous intrusions. See text for the R legend.



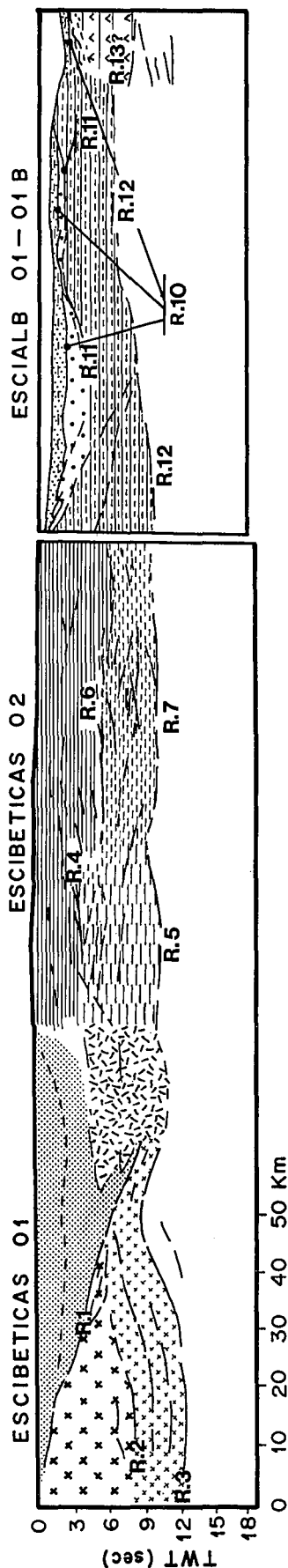


Figure 11.- Synthetic cross section through the Central Betic Cordillera and the northern continental margin of the Alborán Sea interpreted from the ESCI-Béticas1 and 2 and the ESCI-Alborán1 profiles. See legends of Figs. 6 and 8.

associated to the Alborán Domain (central Alborán trough) and the transition to the South Balearic basin. It probably consists of a very thinned continental crust with important igneous intrusions (vertical areas with diffractions). The lower limit (R13) must correspond to the crust-mantle discontinuity.

**Unit 12:** Low reflective fabric. It is characterised by transparent facies and is bounded at the top and the bottom by two well-defined discontinuities. The upper limit shows numerous diffractions near unit 9, and the bottom is characterised by some strong discontinuous reflections (R14) of high amplitude (Figs. 9 and 10). Curved geometry could be observed affecting this unit and the R15 reflector. This unit shows typical oceanic crust facies. Diffractions are frequently found in the sedimentary cover-basement boundary, due to the irregularities of the volcanic basement. A lack of reflections and diffractions is observed as the depth increases, which is caused by the progressive change from volcanic to plutonic character in normal oceanic crust. The flexure observed in this unit could be related to two different segments of oceanic crust. R14 is associated to the Moho discontinuity.

### Contribution of ESCI-Béticas and ESCI-Alborán profiles to the crust structure

#### *South Iberian Domain*

The R1 discontinuity separates the Variscan crust from the Betic orogenic domain (Fig. 11). This boundary is related to a major thrust, or its lateral ramp, that links the external Betic zones and the Alborán crustal domain over the Hesperic Massif. It could be associated with a suture zone between two different crusts.

**The Foreland Region:** The Hesperic crust shows a thickness of 36-38 km in the undeformed region; its overall structure is similar to that found in other Variscan regions of the Iberian Peninsula (Suriñach & Vegas, 1988). Greater thickness could be explained by the overload of the external zones, that were detached and piled up on the Iberian border. Under R1, the Variscan crust is characterised by the presence of two levels: the upper level shows transparent facies (unit 1), whereas the lower one (unit 2) is more reflective and layered. The layered fabric and the thinning towards the South of the Variscan crust suggest the presence of a continental margin during the Mesozoic time span in the South Iberian region (García-Hernández *et al.*, 1980).

The geometry of the Variscan-Alborán boundary and the underlying antiformal bending of the Variscan crust could be interpreted in terms of the mechanical impossibility of extending the shortening along the Hesperic Massif. The geometry also excludes the existence of a major thrust rooted in an intracrustal or subcrustal detachment of the Hesperic Massif as a result of a process of continuous collision. Therefore, the idea of a major thrust related to the formation of the Spanish Central System (Banks & Warburton, 1991; Ribeiro *et al.*, 1990) must be rejected.

**External Zones:** The basement of the external zones is constituted by Variscan crust. The thinning of this crust can be related to the development of the South Iberian continental margin in the Mesozoic time. The extensional structures originated during the rifting episode were reactivated as compressive thrusting. Over the crustal thrust (R1), a unit associated to the Mesozoic cover of the South Iberian continental margin (unit 3) can be differentiated. This unit is structured and detached in thrusts mainly towards the foreland and is secondary to the Alborán domain (e.g. Banks & Warburton, 1991). This piling-up balances the general thickness of the crust.

#### *Alborán Crustal Domain*

The boundary between the two crustal domains is unclear in the lowest part of the crust. A wedge, probably of the Alborán crustal domain, is observed under the Subbetic units and over the crustal thrust. In the Alborán Domain, the crust thins progressively to the South.

**The Internal Zones:** Two levels are neatly differentiated in the crust: the upper (unit 5) and the lower-middle crust (unit 6). The thickness of the crust is at its maximum (36 km) under the Los Filabres Range. It is important to point out the absence of roots under the main reliefs of the Betic Cordillera, although they were suggested by Suriñach & Udías (1978) on the basis of gravimetric and deep seismic refraction data. The lower-middle crust shows a complex cross-fabric, probably caused by the development of important tectonic processes (compressive and extensional) through the Betic Cordillera history. It is defined at the top by a conspicuous reflector at 15 - 20 km depth. The coalescent character of the reflections suggests detachment behaviour.

The upper crust shows several reflectors that should represent detachment zones related to the extensional events (e.g. García-Dueñas *et al.*, 1992; Jabaloy *et al.*, 1992). The upper crust is thinned with respect to the lower crust of the central chain. However in the southern part, where the extensional processes gave rise to the Alborán Sea, the thinning seems to have developed with higher intensity in the lower crust and there is a quite abrupt thinning of the lower crust southwards. The Moho discontinuity varies from 10.5 to 9 s TWT depth in the South. The complex structure of the lower crust and the absence of orogenic roots could indicate the response of the crust to stretching processes.

**Alborán Basin:** Most of the Alborán basin basement corresponds to a very thinned continental crust. The main thinning seems to have taken place in the lower crust (Fig. 8). In the northern part of the ESCI-Alborán1 profile (Fig. 11) extensional events have been stronger. The crust-mantle discontinuity rises from 9.5, near the coast, to a depth of 7.5 s TWT South of the Motril basin. Southwards, the thinning takes place more progressively and the lower crust disappears totally, leaving only the upper crust, which also shows some thinning. This thinning of the lower crust could be explained in terms of a ductile stretch with progressive layering –as shown by

the wedging of the lower crustal reflectors under the continental shelf– while the upper crust seems to follow an asymmetrical shear model.

Under the South Balearic basin, the crust is oceanic. The boundary between the thinned continental crust and the oceanic crust cannot be traced accurately. The transition occurs gradually with thinning of the continental crust, igneous intrusions and the presence of oceanic crust materials, which are indicated by an increase in seismic facies (units 11 and 12), generally associated to oceanic crust towards the East. A flexural feature is observed in unit 12 in relation to two oceanic crust segments, located at different depths. This is related to their cooling stage and therefore to their age: the deeper segment must be the older one. According to this interpretation, two episodes of oceanic crust formation could be defined in the Alborán Sea. The older can be related to the opening of the South Balearic basin, and the younger, East of the Alborán ridge, corresponded to an ephemeral oceanic opening forced by the extensional processes in the Alborán basin.

Deep reflections should be treated with caution because the seismic data can be artefacts. Deep reflectors of the mantle ought to be related to the extensional processes that gave rise to the Alborán basin, as extensional detachments, or to the compressive Pliocene-Quaternary event, as an incipient subduction.

#### **Tectonic significance and geodynamic implications**

One of the most relevant features identified in the profile ESCI-Béticas1 corresponds to a ramp that limits the boundary between the Variscan crust of the Iberian foreland and the orogenic front of the Betic Cordillera (Figs. 2 and 6). Above this ramp, the Mesozoic cover appears as a typical double-vergent structure with foreland-directed folds and thrust (pro-shear thrusts) and back-thrusts (retro-shear thrusts). Both groups of thrusts are probably coeval. The ramp deepens and separates the lower crust of the Iberian Massif from the extra-Iberian crust of the Alborán Domain. It is difficult to clarify whether the "Iberian" crust extends under the Alborán upper crust, forming the lowermost seismic unit of the profile ESCI-Béticas2. Anyway, the interpretation of the profiles ESCI-Béticas precludes the existence of a vertical shear zone strike-slip zone between the external and internal zones of the Betic Cordillera.

Another important feature, from a tectonic point of view, is the absence of crustal roots under the main reliefs of the chain, as other "Alpine" ranges seem to have. This may indicate either a lithosphere flexure or a detachment of the upper crust above the main reflector that separates it from the lower crust.

Three aspects of the ESCI-Alborán profiles are worth of mention: the crustal thinning and basin formation, the basin inversion and the nature of the oceanic crust in the abyssal plain of the eastern Alborán Sea.

Crustal thinning in the Alborán domain may correspond to the main phase of basin formation that reached

the stage of thermal subsidence in many places. Basin inversion, in form of reactivated listric faults, seems to occur at least in Plio-Quaternary sediments. On the other hand, there could be oceanic crust in the eastern depths of the Alborán basin, extending into the South Balearic Sea. This oceanic crust seems to correspond to "forced" and dispersed spreading centres, as revealed by the interpreted igneous centres along the profiles ESCI-Alborán2. The sharp flexure occurring between the oceanic areas may represent two different stages of oceanic crust formation, the older being the floor of the South Balearic Sea.

Although the profiles studied offer only a partial view of the northern border of the complex plate-boundary, the tectonic features they record can be, at least, included in a geodynamic model. We favour a model in which westward directed translation of the extra-Iberian Alborán domain causes at its frontal and lateral faces overthrusting and deformation in the external zones on both margins. This translation is only possible if a "free face" is located at the front. The starting phase of this translation must be placed somewhere in the present-day South Balearic basin. This continental collision caused the expulsion of the Alborán domain as a consequence of oceanic crust consumption (related to the slab now described in tomographic studies, Blanco & Spakman, 1993) and HP-LT metamorphism, as well as of pervasive deformation including extensional and compressional phases. The oblique Africa/Europe convergence during these Upper Cretaceous to Eocene Alpine collisions caused expulsion and lateral transport of the Alborán domain. The ramp observed can be ascribed to this displacement, whose characteristics fit easily with the model of "orogenic float" described by Oldow *et al.* (1994).

The extensional phase can, in turn be understood by an expansion of this "orogenic float" over a very thin oceanic-type crust (the basement of the "synorogenic" flysch). This extension persists until no free face is available in the westward displacement of the Alborán domain. It seems to occur in the Uppermost Miocene time, when basin inversion gave rise to compressed structures in the Alborán basin. Some resemblance to the plate-boundary mentioned in the first paragraphs of this study can be considered. Indeed the three phases described in this model may correspond to different slip-vectors of the Europe-Africa convergence.

## References

- Allmendinger, R.W., Hauge, T.A., Hauser, E.C., Potter, C.J., Klempere, S.L., Nelson, K.D., Knuepfer, T. and Oliver, J. (1987a): Overview of the COCORP 40o N Transect, Western United States: the fabric of an orogenic belt. *Geol. Soc. Amer. Bull.*, 98: 308-319.
- Allmendinger, R.W., Hauge, T.A., Hauser, E.C., Potter, C.J. and Oliver, J. (1987b): Tectonic heredity and the layered lower crust in the Basin and Range Province, Western United States. In: *Continental Extensional Tectonics* (M.P. Coward, J.F. Dewey and P.L. Hancock, Eds.). *Geol. Soc. London, Spec. Pub.*, 28: 223-246.
- Andrieux, J., Fontboté, J.M. and Mattauer, M. (1971): Sur un modèle explicatif de l'Arc de Gibraltar. *Earth Planet. Sci. Letters*, 12: 191-198.
- Banda, E., Gallart, J., García-Dueñas, V., Dañoibeitia, J. J. and Makris, J. (1993): Lateral variation of the crust in the Iberian peninsula: new evidence from the Betic Cordillera. *Tectonophysics*, 221: 53-66.
- Banks, C. J. and Warburton, J. (1991): Mid-crustal detachment in the Betic system of southeast Spain. *Tectonophysics*, 191: 275-289.
- Barranco, L., Ansorge, J. and Banda, E. (1990): Seismic refraction constraints on the geometry of the Ronda peridotitic massif (Betic Cordillera, Spain). *Tectonophysics*, 184: 379-392.
- Berastegui, X. (1992): Interpretación de los perfiles 85PYR 01 y 86PIR 01 ECORS en términos de facies sísmicas. *Proyecto Hispano-Francés ECORS-Pirineos*, 4: 51-61.
- Blanco, M. J. and Spakman, W. (1993): The P-wave velocity structure of the mantle below the Iberian Peninsula: evidence for subducted lithosphere below southern Spain. *Tectonophysics*, 221: 13-34.
- Crespo-Blanc, A., Orozco, M. and García-Dueñas, V. (1994): Extension versus compression during the Miocene tectonic evolution of the Betic chain. Late folding of normal fault systems. *Tectonics*, 13(1): 78-88.
- Galdeano, A. and Rossignol, J.C. (1977): Assemblage à altitude constante des cartes d'anomalies magnétiques couvrant l'ensemble du bassin occidental de la Méditerranée. *Bull. Soc. géol. France*, 19(3): 461-468.
- Galindo-Zaldívar, J., González-Lodeiro, F. and Jabaloy, A. (1989): Progressive extensional shear structures in a detachment contact in the western Sierra Nevada (Betic Cordilleras, Spain). *Geodinamica Acta*, 3: 73-85.
- García-Dueñas, V., Balanya, J.C. and Martínez-Martínez, J.M. (1992): Miocene extensional detachments in the outcropping basement of the northern Alborán basin (Betics) and their tectonic implications. *Geo-Mar. Lett.*, 12: 88-95.
- García-Dueñas, V., Banda, E., Torné, M., Córdoba, D. and ESCI-Béticas Working Group (1994): A deep seismic reflection survey across the Betic Chain (southern Spain): first results. *Tectonophysics*, 232: 77-89.
- García-Hernández, M., López-Garrido, A. C., Rivas, P., Sanz de Galdeano, C. and Vera, J. A. (1980): Mesozoic paleogeographic evolution in the External Zones of the Betic Cordillera (Spain). *Geol. Mijnb.*, 59: 155-168.
- Hatzfeld, D. (1976): Étude sismologique et gravimétrique de la structure profonde de la mer d'Alborán: mise en évidence d'un manteau anormal. *C. R. Acad. Sci. Paris*, 283: 1021-1024.
- Jabaloy, A., Galindo-Zaldívar, J. and González-Lodeiro, F. (1992): The Mecina Extensional System: their relation with the post-Aquitainian piggy-back Basins and the paleostress evolution (Betic Cordilleras, Spain). *Geo-Mar. Lett.*, 12: 96-103.
- Mann, P., Taylor, F.W., Edwards, R.L. and Ku, T.L. (1995): Actively evolving microplate formation by oblique collision and sideways motion along strike-slip faults: An example from the northeastern Caribbean plate margin. *Tectonophysics*, 246: 1-69.
- Meissner, R. (1988): Rupture, creep, lamellae and crocodiles: happenings in the continental crust. *Terra Nova*, 1(1): 17-28.
- Mitchum, R.M., Vail, P.R. and Sangree, J.B. (1977): seismic stratigraphy and global changes of sea level. Part 6: Stratigraphic interpretation of seismic reflection patterns in depositional sequence. In: *Seismic Stratigraphy. Applications to hydrocarbon exploration* (Ch.E. Payton, Ed.). *Amer. Assoc. Petrol. Geol., Mem.*, 26: 117-133.
- Oldow, J.S., Bally, A.W. and Lallemand, H.G.A. (1990): Transpression, orogenic float and lithosphere balance. *Geology*, 18: 991-994.
- Passchier, C.W. (1986): Mylonites in the continental crust and their role as seismic reflectors. *Geol. Mijnb.*, 65: 167-176.
- Platt, J.P. and Vissers, R.L.M. (1989): Extensional collapse of thickened continental lithosphere: A working hypothesis for the Alborán Sea and Gibraltar Arc. *Geology*, 17: 540-543.
- Rey, P. (1993): Seismic and tectono-metamorphic characters of the lower continental crust in Phanerozoic areas: a consequence of post-thickening extension. *Tectonics*, 12(2): 580-590.
- Ribeiro, A., Kullberg, M.C., Kullberg, J.C., Manupella, G. and Phipps, S. (1990): A review of Alpine tectonics in Portugal: Foreland detachment in basement and cover rocks. *Tectonophysics*, 184: 357-366.

- Suriñach, E. and Udías, A. (1978): Determinación de la raíz de Sierra Nevada- Filabres a partir de medidas de refracción sísmica y gravimetría. In: *Reunión sobre la Geodinámica de la Cordillera Bética y Mar de Alborán* (Comisión Nacional para el Proyecto Geodinámico, Ed.): 25-34, Granada.
- Suriñach, E. and Vegas, R. (1988): Lateral inhomogeneities of the Hercynian crust in central Spain. *Phys. Earth Planet. Interiors*, 51: 226-234.
- Suriñach, E. and Vegas, R. (1993): Estructura general de la corteza en una transversal del Mar de Alborán a partir de datos de sísmica de refracción-reflexión de gran ángulo. Interpretación geodinámica. *Geogaceta*, 14: 126-128.
- Vegas, R., Medialdea, T., Suriñach, E. and Vázquez, J.T. (1994): La deformación intraplaca del centro de España y la interpretación de los perfiles profundos de sísmica de reflexión en las Cordilleras Béticas. *Geogaceta*, 15: 124-126.
- Vegas, R., Acosta, J. and Uchupi, E. (1995): Continental-oceanic crustal transition in the Bransfield trough and the south Scotia ridge (Antarctica): Preliminary results. In: *Rifted Ocean-Continental Boundaries* (E. Banda, M. Torné and M. Talwani, Eds.): 265-289, Kluwer Academic Publishers.

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