Role of extension and compression in the evolution of the eastern margin of Iberia: the ESCI-València Trough seismic profile

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Abstract: The ESCI-València Trough deep seismic reflection profile crosses the eastern margin of Iberia and can be divided into three regions according to crustal structure. From NW to SE they are: a) the Ebro Basin, with a 33 km thick continental crust which remained almost undeformed during the Cenozoic and is very reflective in its lower part; b) the Continental Margin, made up of the Catalan-Valencian Domain and the Balearic Promontory with a thin (12 to 30 km thick) continental crust which was deformed during the Cenozoic, extensional structures predominating in the first domain and contractional structures in the second; and c) the Algerian Basin, with a 9 km thick oceanic crust. The oldest Cenozoic structures registered in the profile are contractional. During the Palaeogene, these structures affected the NW part of the Catalan-Valencian Domain and enabled this domain to be thrust over the Ebro Basin. During the Early and Middle Miocene, the extensional structures of the Catalan-Valencian Domain were formed in association with crustal thinning. At the same time, the contractional structures of the Balearic Promontory developed, propagating from SE to NW. Finally, during the Late Miocene, extensional structures were produced in the southern part of the Balearic Promontory in association with the formation of the oceanic crust. The displacement of the observed extensional faults is not sufficient to explain the crustal thinning. This implies that, during the Cenozoic, either crustal volume decreased or there were important faults that cannot be observed. It is suggested that a low angle fault of great displacement, that crosses the whole upper crust, may have existed prior to the Middle and Upper Miocene sediments. The thinning of the lower crust would have been achieved by an array of shear zones.

Keywords: Deep seismic reflection, crustal structure, València Tough, Balearic Promontory.

Resumen: De acuerdo con la estructura cortical, el perfil ESCI-Surco de València puede dividirse en tres regiones que de NW a SE son: a) La Cuenca del Ebro con una corteza continental de 33 km de espesor, poco deformada durante el Cenozoico y muy reflectiva en su parte inferior; b) El Margen Continental constituido por el Dominio Catalano-Valenciano y el Promontorio Balear, y caracterizado por tener una corteza continental delgada (entre 12 y 30 km de espesor) y por estar afectado por estructuras compresivas y extensionales cenozoicas; c) La Cuenca de Argelia con una corteza oceánica de 9 km. El límite entre la Cuenca del Ebro y el Margen Continental es el cabalgamiento frontal de las Cordilleras Costero Catalanas. El límite entre el Margen Continental y la Cuenca de Argelia es el escarpe Émile Baudot. El Dominio Catalano-Valenciano incluye las Cordilleras Costero Catalanas y se extiende hasta el eje del Surco de València. Aunque cabalga sobre la Cuenca del Ebro, su estructura es predominantemente extensional con fallas normales en la corteza superior y cizallas dúctiles en la inferior. El Promontorio Balear muestra una corteza relativamente delgada, con un máximo de 24 km, a pesar del sistema de cabalgamientos que lo afecta. Estas estructuras son dificilmente visibles en el perfil ESCI-Surco de València ya que no afectan a los sedimentos reflectivos; su importancia no obstante se manifiesta por: a) La corteza superior de la mitad NW del promontorio presenta tres protuberancias de probable origen compresivo; b) La mayoría de reflexiones de la corteza superior buzan hacia el SW sugiriendo una superposición de unidades; c) El engrosamiento relativo y local de la corteza inferior. En su mitad SE el Promontorio Balear está afectado por estructuras extensionales. Las estructuras cenozoicas más antiguas registradas a lo largo del perfil ESCI-Surco de València son de tipo compresivo. Durante el Paleógeno determinaron que la parte NW del Dominio Catalano-Valenciano cabalgase sobre la Cuenca del Ebro. Durante el Mioceno inferior y medio se formaron las estructuras extensionales del Dominio Catalano-Valenciano asociadas al adelgazamiento cortical. Al mismo tiempo se desarrollaron las estructuras compresivas del Promontorio Balear que se propagaron de SE hacia NW. Finalmente, durante el Mioceno superior se produjeron las estructuras extensionales en la parte meridional del Promontorio Balear asociadas a la formación de corteza oceánica de la Cuenca de Argelia. La extensión calculada a partir de las fallas extensionales observadas no es suficiente para explicar el adelgazamiento cortical. Ello implica que durante el Cenozoico la corteza ha disminuido de volumen o bien que existan fallas importantes no observadas. Se sugiere la posibilidad de que exista una falla de bajo ángulo y gran desplazamiento, anterior a los sedimentos del Mioceno medio, que atraviese toda la corteza superior. El adelgazamiento de la corteza inferior se realizaría mediante un conjunto de zonas de cizalla.

Palabras clave: Sísmica de reflexión profunda, Estructura cortical, Surco de València, Promontorio Balear.

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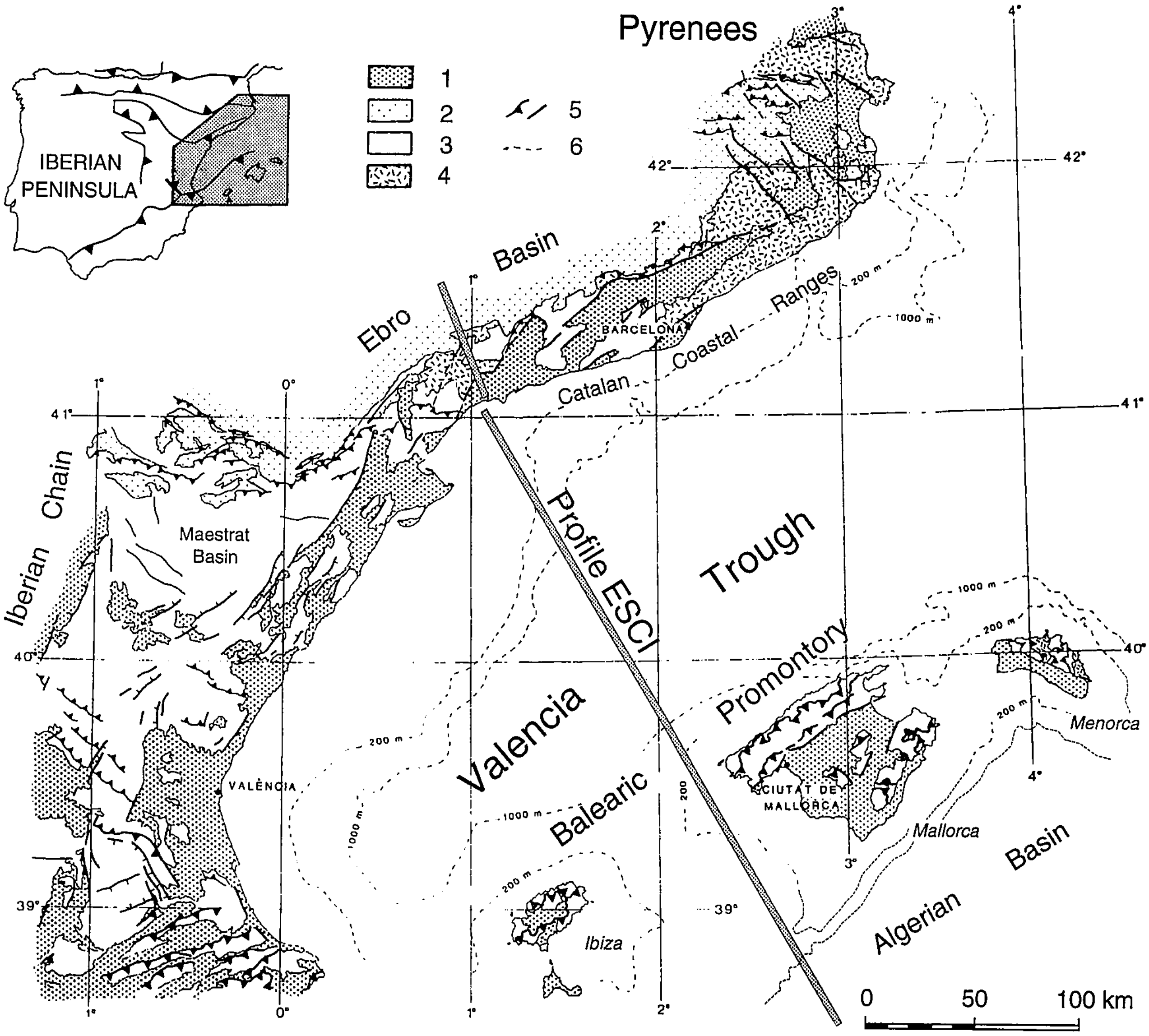


Figure 1.- Location of the ESCI-València Trough profile in the eastern margin of the Iberian Peninsula. The profile consists of an onshore section across part of the Ebro Basin and the Catalan Coastal Ranges, and an offshore section across the València Trough, the Balearic Promontory and the Algerian Basin. There is a 5 km gap between the onshore and offshore profiles that has not been sampled. 1, Neogene and Quaternary sediments. 2, Palaeogene sediments. 3, Mesozoic rocks. 4, Palaeozoic rocks. 5, faults. 6, Bathymetry.

Deep reflection seismic profiles allow crustal geometry to be studied as a whole. The ESCI-València Trough profile is situated on the NE margin of the Iberian Peninsula, in continuity with the ECORS-Pyrenees profile (Choukroune & ECORS Team, 1989). It has a NW-SE orientation and cuts across different geological regions, from the Ebro Basin in the NW to the Algerian Basin in the SE (Fig. 1). The profile is 450 km long, 50 km being onshore and the rest offshore (Gallart *et al.*, this vol.).

The profile was acquired in order to investigate the crustal structure of the different structural domains in the eastern margin of the Iberian Peninsula. This margin was formed during the Cenozoic, between the converging Africa and Europe continents. Comparison of domains that have experienced different evolutions in the same region provides an opportunity to analyse structures that have resulted from each of the successive tectonic events.

The aim of this paper is to provide an interpretation of the crustal structure based on the ESCI-València Trough profile integrating other geological and geophysical data, and discuss the evolution of this region. Some of the questions to be answered are: a) Is the lower crust thin in the same proportion as the upper crust or not? b) What mechanisms have produced the thinning? c) Is the thinning of the crust the result of one or several tectonic events? In this context it is important to set bounds on the chronology of successive deformations in each of the domains. The first question will be answered in a future article because depth converted sections are needed whereas in the present paper we use only time sections.

The ESCI-València Trough profile has provided a continuous image along a section through the eastern margin of the Iberian Peninsula. The quality of the data and of the processing has allowed a good image to be obtained throughout the whole profile (Gallart *et al.*, this

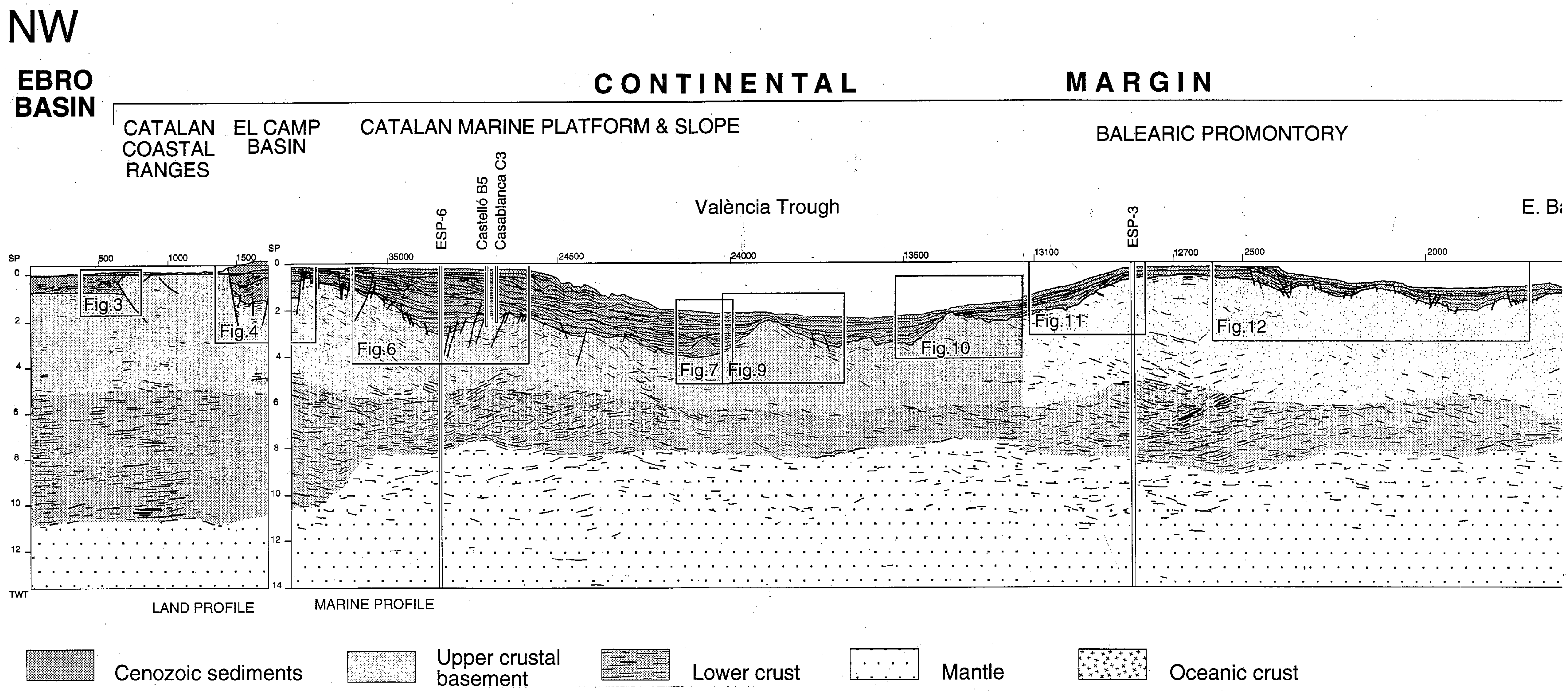
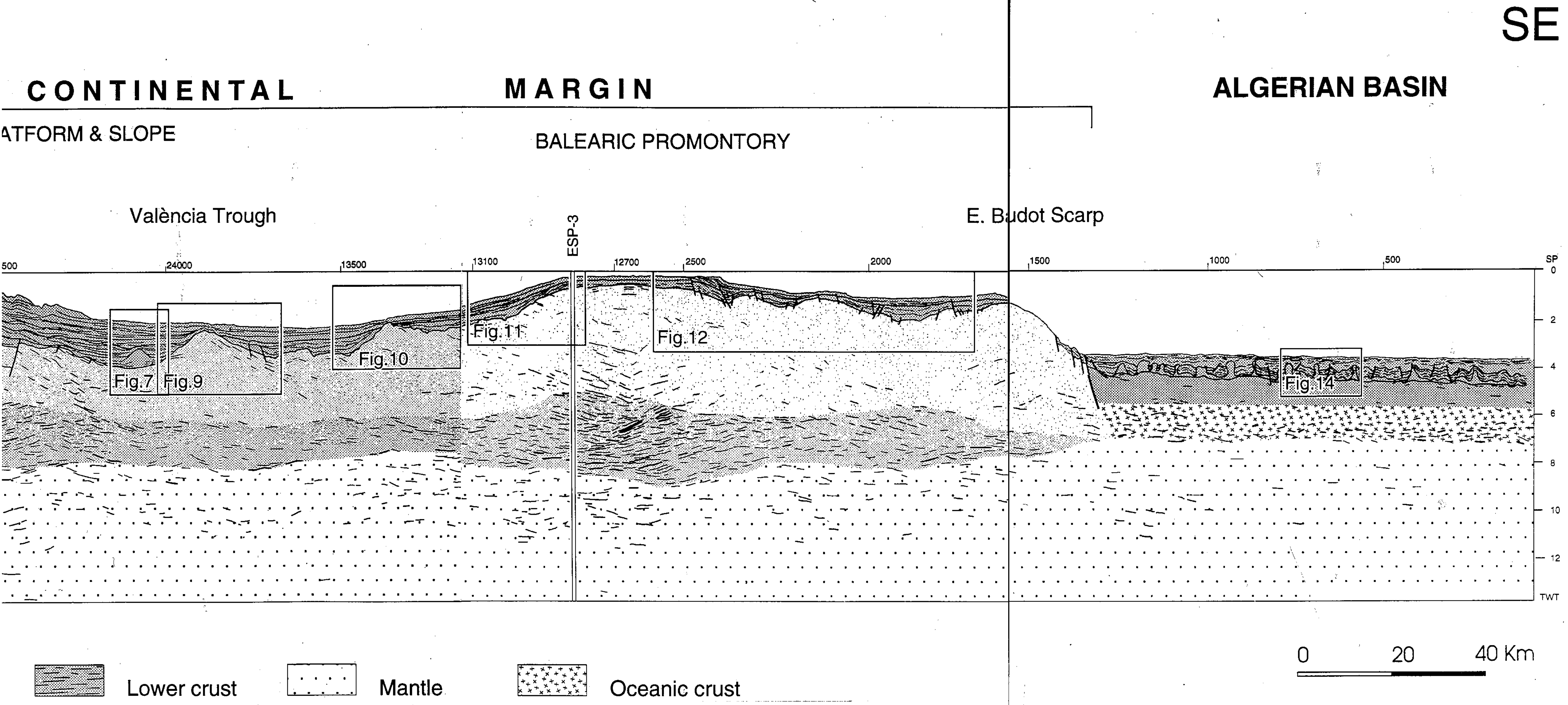


Figure 2.- Overall interpretation of the ESCI-València Trough profile, based on line drawings from stacked and migrated, land and marine, ESCI sections (see part of the data in Gallart *et al.*, this vol.). The oceanic crust, lower continental crust, upper crustal basement and the sedimentary package are differentiated. The Catalan Coastal Ranges, El Camp Basin, the Catalan Marine Platform and Slope, and the Balearic Promontory are considered to be parts of the continental margin of eastern Iberia. The positions of boreholes Castelló B5, Casablanca C3 (Lanaja, 1987) and the ESP 3 and 6 (Torné *et al.*, 1992) are indicated. The positions of the boreholes Senant-1 and Reus-1 are not shown because they are not located on the trace of the profile. The boxes in the surface part of the profile indicate figure positions.



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vol.), a stack and a migrated profile being available, though the processing has not managed to totally eliminate multiple reflections of the sea bed. Reflectivity of the crust is not uniform but varies both horizontally and vertically. In the uppermost part, there is generally a very reflective section that corresponds to Cenozoic sediments. Beneath this, the upper crust is not very reflective. Finally, reflectivity of the lower crust is variable but strong. In this paper, it is considered that the Moho is located at the lower limit of the reflective zone corresponding to the lower crust (Fig. 2). Sometimes this limit is not evident due to the weak reflectivity of the lower crust or the existence of a certain mantle reflectivity, but, in general, it is relatively clear and often coincides with high amplitude reflections. The upper limit of the reflective lower crust is considered to correspond to the limit between the lower and upper crust (Fig. 2).

Geological setting

The eastern margin of Iberia evolved by a succession of tectonic events during the NNW-SSE convergence of Africa and Europe in the Cenozoic (Srivastava *et al.*, 1990). From Late Cretaceous to Oligocene (80-28 Ma), this area was deformed by a compressive regime which initiated the inversion of several Mesozoic basins and gave rise to the Pyrenees (Muñoz, 1992), the Iberian Range (Guimerà & Álvaro, 1990) and the Catalan Coastal Ranges (Anadón *et al.*, 1982). Subsequently, during the Late Oligocene and Early Miocene (28-16 Ma), most of the region underwent a WNW-ESE extension (Fontboté, 1954; Roca & Guimerà, 1992; Bartrina *et al.*, 1992) associated to the rotation of Corsica and Sardinia (Westphal *et al.*, 1976), which initiated the formation of the València Through. During this period, the southeastern part of the region was subjected to a NW-SE compression responsible for the formation of the Betic-Balearic thrust belt (Fallot, 1922; Gelabert *et al.*, 1992). Finally, from the Early Miocene onwards, the internal areas of the Betic-Balearic Range were subjected to an extension forming the Algerian and Alborán basins (Galindo-Zaldívar *et al.*, 1989; García-Dueñas *et al.*, 1992; Comas *et al.*, 1992). This extension could be the result of detachment of the lithospheric root of the range (Platt & Vissers, 1989; Vissers *et al.* 1995).

The ESCI-València Trough profile has been shoot across a set of different domains that show different crustal geometry at the present time. From NW to SE they are as follows.

a) The Ebro Basin. This basin is situated in the interior of the Iberian Peninsula and is characterised by a continental crust with uniform structure and normal thickness (Banda *et al.*, 1983). During the Cenozoic, this domain was not deformed.

b) The Continental Margin. It includes the Catalan Coastal Ranges, the València Trough and the Balearic

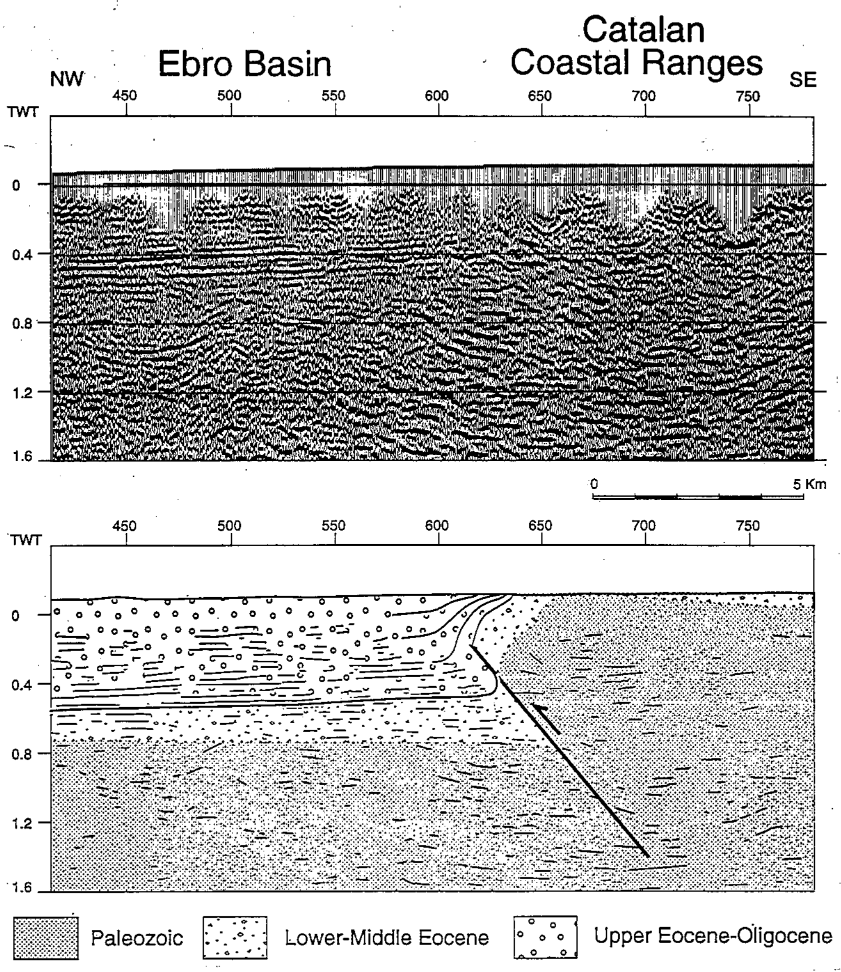

Figure 3.- Migrated seismic profile and interpretation of the thrust contact zone between the Ebro Basin and the Catalan Coastal Ranges. See location in Fig. 2 and explanation in the text.

Promontory. It shows a thin continental crust (Banda *et al.*, 1980; Dañobeitia *et al.*, 1992) due to the deformation experienced during the Cenozoic (Fontboté *et al.*, 1990; Roca, 1992; Roca & Desegaulx, 1992; Torres *et al.*, 1993).

c) The Algerian Basin. It has a very thin and uniform crust of probably oceanic character (Hinz, 1972).

Ebro Basin

The crustal thickness in the NW extremity of the ESCI-València Trough profile is about 32 km thick (Banda *et al.*, 1983). The profile presents well differentiated reflective patterns. In the most superficial part, continuous reflections can be observed, which are subhorizontal and of relatively high frequency and high energy and which reach a depth of about 0.7-0.8 s of TWT (Fig. 3). Beneath these reflections, the crust shows little reflectivity until a layer between 5 and 11 s where the reflectivity becomes high again and is made up of short, subhorizontal reflections (Fig. 2). This reflective layer is attributed to the lower crust (Gallart *et al.*, this vol.) and its base, the Moho, is horizontal and parallel to the reflections.

The Ebro Basin is the southern foreland basin of the Pyrenees and is due to flexure of the lithosphere under the weight of that chain (Brunet, 1986; Millan *et al.*, 1995), though the weight of the chains that limit the basin to the south could also have had some influence (Zoetemeijer *et al.*, 1990). Cenozoic deformation in the Ebro Basin is sparse, this deformation being concentrated in the chains that surround the basin. The infilling sediments of the Ebro Basin range from Palaeocene to Middle Miocene in age and were formed in continental and marine environments (Riba *et al.*, 1983; Puigdefàbregas *et al.*, 1992). The Senant-1 borehole, situated near the trace of the ESCI-València Trough profile, passes through 1000 m of Upper Eocene-Oligocene, 400 m of Lower-Middle Eocene and 200 m of Triassic, before entering the Palaeozoic basement (Lanaja, 1987; cross-section J7 in Vergés, 1993). The superficial reflectivity is attributable to these sediments, especially Upper Eocene-Oligocene that are made up of alternating mudstones, sandstones and limestones.

Continental margin

We consider that the continental margin extends from the Ebro Basin and Catalan Coastal Ranges contact to the steep continental slope that separates the Balearic Promontory and the Algerian Basin (Émile Baudot Scarp). Thus, the Continental Margin comprises the Catalan-Valencian Domain - in the sense of Fontboté *et al.*, (1990) including the Catalan Coastal Ranges, El Camp Basin, the Catalan Marine Platform and Slope - and the Balearic Promontory (Fig. 2).

The continental margin crust is thin and of non-uniform thickness. The crust thins progressively from the Ebro Basin to the continental margin showing a step in the Moho beneath the coast line. Towards the axis of the València Through the crust thins to 13 km in some places (Dañobeitia *et al.*, 1992). In the central part of the Balearic Promontory, the crust is some 25 km thick beneath the island of Mallorca (Banda *et al.*, 1980; Dañobeitia *et al.*, 1992). In the SE part of the Balearic Promontory, the crust is again thinner, and the contact with the Algerian Basin is abrupt.

Four zones with different seismic character can be distinguished vertically in the profile. The uppermost part is very reflective and corresponds to Cenozoic sediments (Soler *et al.*, 1983). The intermediate part is very weakly reflective and is probably constituted by highly deformed Cenozoic sediments, Mesozoic material, Palaeozoic basement and other crystalline rocks of the upper crust. Beneath the intermediate part, there is a reflective zone where reflectivity varies laterally which is attributed to the lower crust. Finally, the lowest part of the profile is very weakly reflective and is attributed to the mantle. The thickness of the three crustal elements varies across the continental margin.

We describe below the crustal structure of the margin divided by areas from NW to SE. The areas are the Catalan Coastal Ranges, El Camp Basin, Catalan Marine Platform and Slope and the Balearic Promontory.

Catalan Coastal Ranges

The Catalan Coastal Ranges are made up of an elevated block devoid of reflective Cenozoic sediments (SE part of Fig. 3). Basement is uplifted 2 km in relation to the Ebro Basin. The upper crust of this zone has a greater thickness than that of the Ebro Basin, extending from the surface to 5 s of TWT. It is made up of Palaeozoic and (?) older rocks deformed during the Variscan orogeny, and a thin Mesozoic cover. The lower crust, similar to that of the Ebro Basin, is highly reflective made up of short horizontal reflections, and the Moho is situated at about 11 s (Fig. 2).

The ESCI-València Trough profile allows the contact between the Ebro Basin and the Catalan Coastal Ranges to be interpreted as a NW directed thrust (Fig. 3). This thrust does not appear on the surface because it is covered by Upper Eocene-Oligocene syntectonic sediments (Anadón *et al.*, 1986; Colombo & Vergés, 1992). As an unit, the Catalan Coastal Ranges have originated in transpression, generating at the same time folds, reverse faults (Ashauer & Teichmüller, 1935; Llopis-Lladó, 1947) and sinistral wrench faults (Anadón *et al.*, 1985) all of which are consistent with a N-S compression (Guimerà, 1984). The age of these structures increases northwards (Anadón *et al.*, 1982) and it is Late Eocene to Oligocene on the ESCI profile, as shown by the age of the syntectonic sediments.

El Camp Basin

The El Camp Basin is a nearly symmetric graben, bounded by normal faults. The fault with greatest displacement is the boundary between the Catalan Coastal Ranges and the El Camp Basin (Figs. 2 and 3). Reflecti-

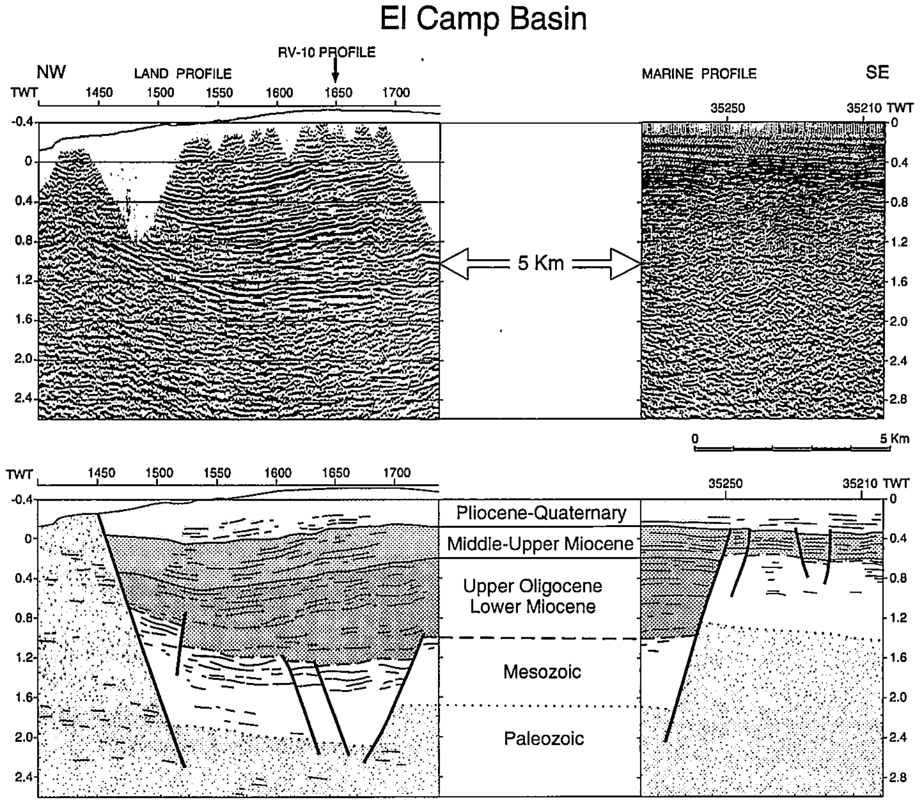

Figure 4.- Migrated seismic profiles and interpretation of the El Camp Basin. The study of this basin requires the use of both the onshore and offshore profiles, which are some 5 km apart. The datums of the two profiles are different and the zero time reference does not coincide. The stratigraphy of the sediments which fill the El Camp Basin is known from borehole Reus-1 (Lanaja, 1987). The projection of this borehole cannot be made directly onto the ESCI profile due to it being located in a structural high. Thus, the projection is done through the correlation with profiles RV-10 and RV-24 (Fig. 5). See location in Fig. 2 and additional explanation in the text.

ve superficial sediments are well developed. The weakly reflective upper crust is thinner than in the Ebro Basin and extends from 1.5 to 5 s TWT. The boundary between the weakly reflective upper crust and the reflective lower crust shows a positive protrusion. The Moho is located at about 10.5 s.

The El Camp Basin sedimentary infill exceeds 1.5 s of TWT (Fig. 4). The Reus-1 borehole is situated in the commercial RV-24 profile (Fig. 5) which cuts the ESCI profile orthogonally. The great lateral continuity of some of the reflective packages within the sedimentary record allows to correlate the two profiles. According to Lanaja (1987), the Reus-1 is 2228 m deep (Fig. 5) and passes through the Pliocene-Quaternary (300 m), Middle and Upper Miocene (ca. 350 m), Upper Oligocene and Lower Miocene (ca. 750 m), and Mesozoic (796 m). After tying-in the borehole and the seismic profiles, it can be observed that the Upper Oligocene and Lower Miocene sedimentary package increases in thickness towards the SE, reaching their maximum thickness in the region adjacent to the fault which bounds the basin to the SE, and are non-existent in the footwall of this fault. The Upper Oligocene and Lower Miocene package, thus, shows an apparent downlap to the NW (Fig. 4). The geometry described above shows that most of the movement of the SE fault took place during Late Oligocene and Early Miocene. Nevertheless, the faults bounding the basin were active during the whole Miocene. Moreover, the NW fault has been active until recent times (Masana, 1991; Masana & Guimerà, 1992). In addition, fault in the RV-10 profile (Fig. 5) shows a partial reversal before the Pliocene.

Catalan Marine Platform and Slope

The Catalan Marine Platform and Slope consist of a group of structural highs and basins. Consequently, the superficial reflective sediments show great lateral variations in thickness (Fig. 2). The sedimentary thickness is small near the coast, it increases SE in the marine platform zone and decreases again at the foot of the slope. The thickness of the upper and lower crustal levels decreases towards the centre of the València Trough where the upper crust is 4 - 6 s thick and the reflective Moho is reached at 8 s (Fig. 2) . Beneath the platform, closest to the coast, there is an abrupt variation in crustal thickness, and the depth of the reflective Moho changes from 10.5 s to slightly more than 8 s in only 15 km horizontal distance.

The high reflectivity of the Cenozoic sediments and the lateral continuity of the reflections allow the superficial structure of this region to be interpreted. A basement high in the NW is related to a group of extensional faults which displace the Middle and Upper Miocene sediments, and locally penetrate in the Pliocene-Quaternary sediments (Fig. 2).

In the Tarragona Basin (Fig. 6), the boreholes Castelló B5 and Casablanca C3 (Lanaja, 1987) penetrated the Pliocene-Quaternary (ca. 2000 m), Middle and Upper Miocene (ca. 600 m), Lower Miocene (ca. 200 m) and the Mesozoic (ca. 300 m). The Pliocene-Quaternary sediments, beneath a very thin water layer, show well developed SE progradating clinoforms. The base of the Pliocene-Quaternary is marked by a clear and extraordinarily irregular reflection which corresponds to the Mes-

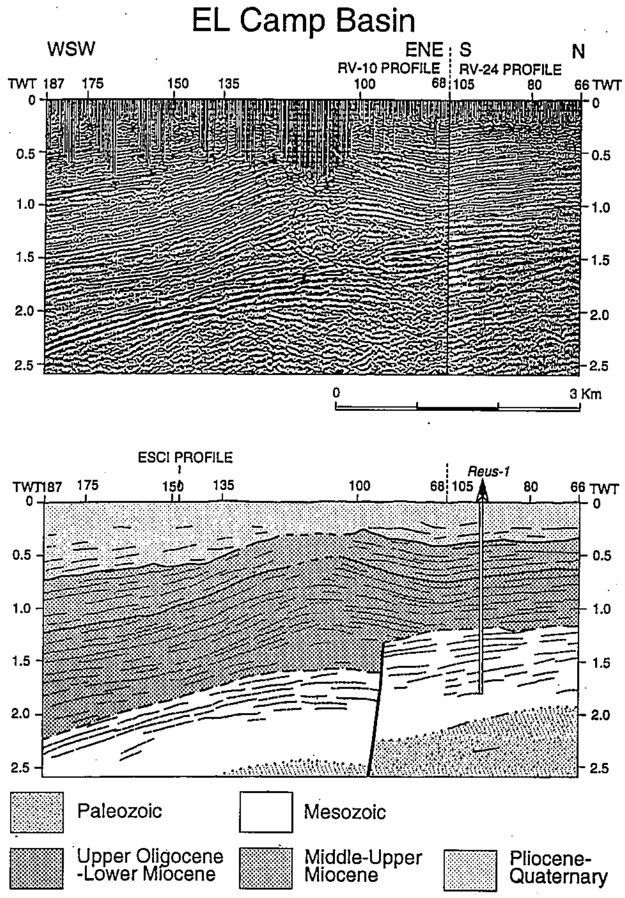

Figure 5.- Linking of the seismic profiles RV-24 and RV-10 and interpretation. The Reus-1 borehole is located in RV-24 and RV-10 cuts the ESCI profile perpendicularly. The correlation between the profiles RV and ESCI profiles is facilitated by some groups of reflections with characteristic character. Especially notable is the packet of intense and continuous reflections corresponding to the upper part of the Mesozoic rocks at 2.3 and 2.5 s at the WSW end of profile RV-10. Due to the Reus-1 borehole being situated on a structural high, the top of the Mesozoic is found at 1.2 s in the borehole, whereas at the crossover point of the ESCI and RV profiles it is at 2 s.

sinian erosion surface. The Middle and Upper Miocene package shows moderately inclined reflections which also indicate progradation towards the SE. The Lower Miocene sedimentary package shows great lateral variations in thickness but its internal reflections are parallel and sub-horizontal. A group of undulating, discontinuous reflections, parallel to the basement top probably belong to the basal part of the Lower Miocene or to the Upper Oligocene sediments (Clavell & Beràstegui, 1991). The top of the basement is interpreted to correspond with a strong reflection beneath the sedimentary pile. The interpreted normal faults in the Tarragona Basin are mostly in the SE part of the basin and dipping NW. The basin probably formed during or at the end of the Late Oligocene because it is filled with horizontal Lower Miocene sediments. However, most faults were also active during Early Miocene and some of them even during Middle and Late Miocene, especially those in the NW end (Fig. 6).

SE of the Tarragona Basin is the València Trough central part which is also affected by some normal faults (Fig. 2). In the deepest area of the València Trough (CMP 24100) there is a volcanic cone (Fig. 7). In this region there is a water layer of 2 s depth (1500 m) and the Messinian unconformity is easily recognisable. The volcanic edifice is 1 s thick, and shows a very reflective top and internal reflections. The upper part of the cone is made up of dipping layers facing the exterior and the weakly reflective base laterally interfingers with horizontal and very reflective Upper Oligocene-Lower Miocene sediments. The cone is covered in onlap by the upper part of Upper Oligocene-Lower Miocene sediments, and by those of the Middle and Upper Miocene. All these relationships imply that the volcano was formed during the first half of the Late Oligocene-Early Miocene. This volcanic edifice is part of a group of calcoalkaline volcanoes developed in the València Trough before Middle Miocene (Martí *et al.*, 1992).

The basement of the Catalan Marine Platform and Slope is partially made up of Mesozoic and Palaeozoic rocks (Clavell & Beràstegui, 1991; Roca, 1992). The Mesozoic, even though it shows weak reflectivity, has some characteristic pattern. The Castelló B5 and Casablanca C3 boreholes (Lanaja 1987) and the ESP-6 (Torné *et al.*, 1992; Pascal *et al.*, 1992) corroborate the existence of Mesozoic rocks in this region, but its thickness is very variable and it can even be locally non-existent (Clavell & Beràstegui, 1991; Roca, 1992). In this work, based on the ESP-6 results and the above mentioned reflective character, the Mesozoic rocks are interpreted to be approximately 1 s thick.

The lower crust shows important lateral variations in reflectivity (Fig. 2). In the region closest to the coastline, it has similar thickness to that of the Ebro Basin and is reflective with horizontal reflections. Immediately to the SE, the Moho shows an abrupt step, and the lower crust horizontal reflections abut against the inclined surface of the Moho (Figs. 2 and 8). In the zones where the lower crust is thin and reflective there are horizontal and inclined reflections (Fig. 8). We interpret the horizontal reflections to be the remains of those existing in the crustal undeformed zone. The inclined reflections are grouped into bands, most of them dipping NW, with the exception of the westernmost one which dips SE and extends up to a point beneath the El Camp Basin. These bands branch between them isolating losenge bodies with inner horizontal reflections. As the inclined reflective bands do not exist in the undeformed crustal zone, we interpret them to be shear zones associated with Cenozoic deformation. Using as a reference the boundary between the lower and upper crust, it can be seen how the northwesternmost shear zone which dips NW shows the geometry of an extensional shear. Assuming this type of displacement for the whole group of shear zones dipping NW, the described pattern could explain the lower crustal thinning. Following the same arguments, the shear zone dipping SE can be interpreted to be a reverse shear zone which could join with the Catalan Coastal Ranges frontal thrust.

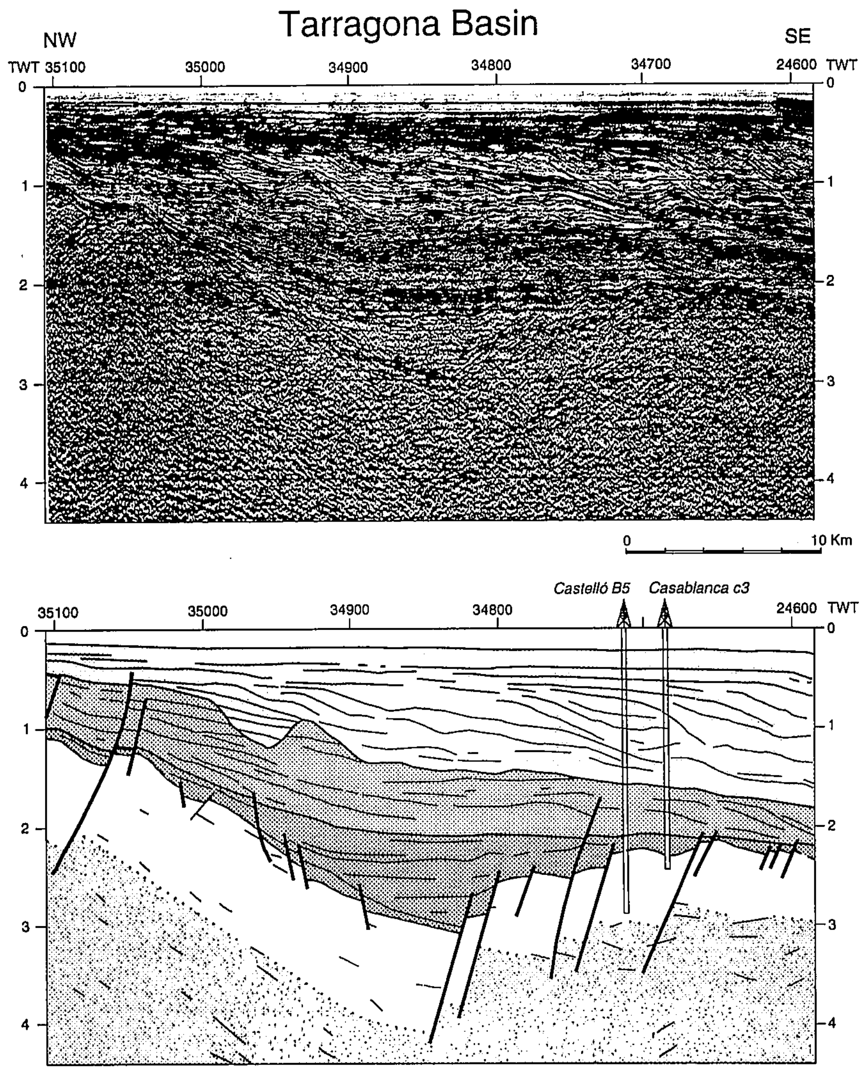

Figure 6.- Migrated seismic profile and interpretation of the Tarragona Basin. Its stratigraphy is known from the various commercial boreholes such as Castelló B5 and Casablanca C3 (Lanaja, 1987). Note the deep Messinian erosion in the NW half. See Fig. 7 for legend, location in Fig. 2 and additional explanation in the text.

Balearic Promontory

The Balearic Promontory extends from the volcanic cone in the central València Trough to the Émile Baudot Scarp, and comprises the València Trough SE flank and the platform where the Balearic islands rest (Fig. 2). The thickness of reflective, Cenozoic sediments is moderate, reaching a maximum in the central València Trough, and a minimum in the platform where the islands occur. The upper crustal basement thickness of the southern Balearic Promontory is similar to the one in the Ebro Basin, whereas the thickness in the northern part of the promontory is thinner. The lower crust is thin and shows a local thickening in the central part of the promontory. The reflective Moho is located between 7.5 and 9 s.

In the northern Balearic Promontory three basement highs stand out (the southernmost one makes up the Balearic islands platform). These three highs have some common characteristics (Figs. 2, 9, 10 and 11): (a) The highs are covered by Pliocene-Quaternary sediments, which cause the highs to have little or none topographic expression. (b) The highs are asymmetrical; their NW slope is abrupt whereas their SE slope is gentle. (c) In the upper part of the basement there are some short reflections that dip SE. (d) The Middle-Upper Miocene and Pliocene-Quaternary sedimentary wedges in their NW slopes show similar geometry. The lower layers are parallel to the slope of the basement high, or they show a gentle onlap, and at the foot of the high these layers are folded in a wide syncline (Fig. 10). This package of layers is itself covered by younger sediments in onlap. Finally, the deformed lower layers are erosionally truncated and unconformably covered by an upper group (Pliocene-Quaternary sediments in Fig. 10).

These common geometries in the three highs suggest that they have had the same origin. The described geometry is very different from that of the volcanic edifice described above. Therefore, contrary to what Gallart *et al.* (this vol.) have suggested, we consider that these highs are not volcanic edifices and ought to be related to faults. The highs could be fault propagation folds associated to SE dipping thrusts. We consider that these basement highs have developed after the sedimentation of the deformed Cenozoic layers and before the sedimentation of the onlapping and unconformable layers. Correlation of the reflections (especially the one corresponding to the base of the Pliocene-Quaternary) indicates that the final emplacement of the three basement highs did not occur simultaneously. The deformation propagated to the

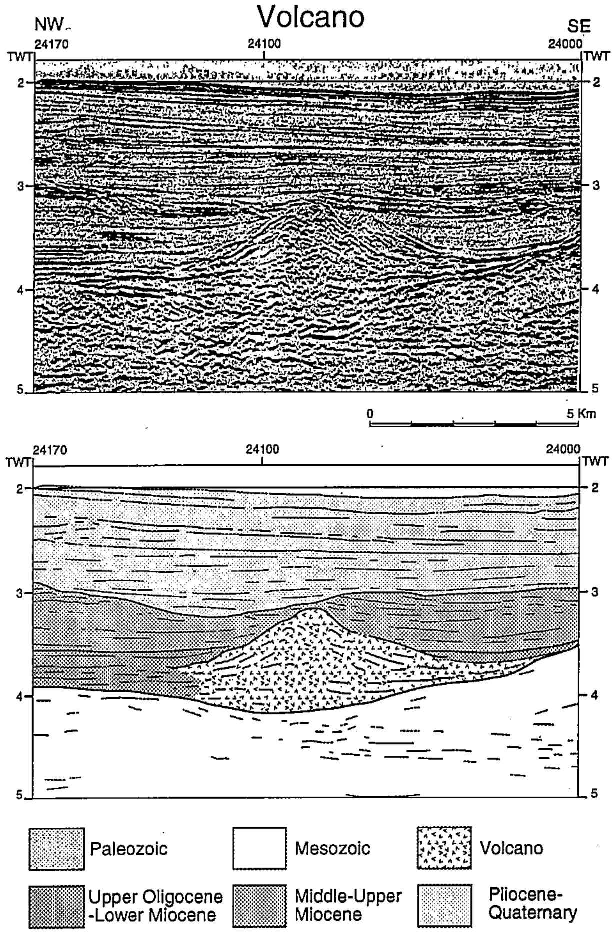

Figure 7.- Migrated seismic profile and interpretation of the volcanic edifice in the central València Trough in an area with a 1500 m water layer. The age of the sediments that interfinger with the base of the volcano and the age of the sediments that onlap it prove that the volcano was formed during the first half of the Late Oligocene-Early Miocene. See location in Fig. 2 and additional explanation in the text.

NW, deduced from the fact that the SE high and the central one rose mainly during the second half of the Middle and Late Miocene whereas the NW high rose during the first part of the Pliocene-Quaternary.

The Balearic Promontory southern part is characterised by (Fig. 12): (a) The existence of three minor subbasins with Middle Miocene to Quaternary sediments below a water layer of 0.5 or 1 s (375 or 750 m). (b) The Cenozoic sediments and also the seabed show gently antiforms located between basins. (c) At the platform margin, the Pliocene-Quaternary sediments show SE progradating clinoforms. (d) The base of Pliocene-Quaternary package produces a reflection of great intensity and lateral continuity. (e) Both the Pliocene-Quaternary and the Middle and Upper Miocene sediments thicken in the sub-basins centre. Thickness variations are bigger in Middle and Upper Miocene sediments. (f) Normal faults with small displacement deforming the Middle and Late Miocene sediments dip either NW or SE. Taking all of these features into account, it can be deduced that, from the Middle Miocene to present times, the region has been subjected to an extensional tectonic regime, with the greatest activity during the Middle and Late Miocene.

As can be seen on the islands, the Balearic Promontory basement is partially made up of Palaeozoic (Bourrouilh, 1983) and Mesozoic rocks (Fallot, 1922; Bourrouilh, 1983; Gelabert *et al.*, 1992) and sediments from the Palaeogene to Middle Miocene (Ramos-Guerrero *et al.*, 1989). These materials were deformed in a thrust and fold system during Late Oligocene-Early Miocene (Fallot, 1922; Darder, 1925; Rangheard, 1972; Bourrouilh, 1983; Sàbat *et al.*, 1988; Gelabert *et al.*, 1992). The basement reflectivity is generally weak but locally, especially in the central part of the Promontory where the crust is thickest, reflections of certain intensity can be noticed.

The base of the Mesozoic is interpreted from the ESP-3 results (Torné *et al.*, 1992; Pascal *et al.*, 1992)

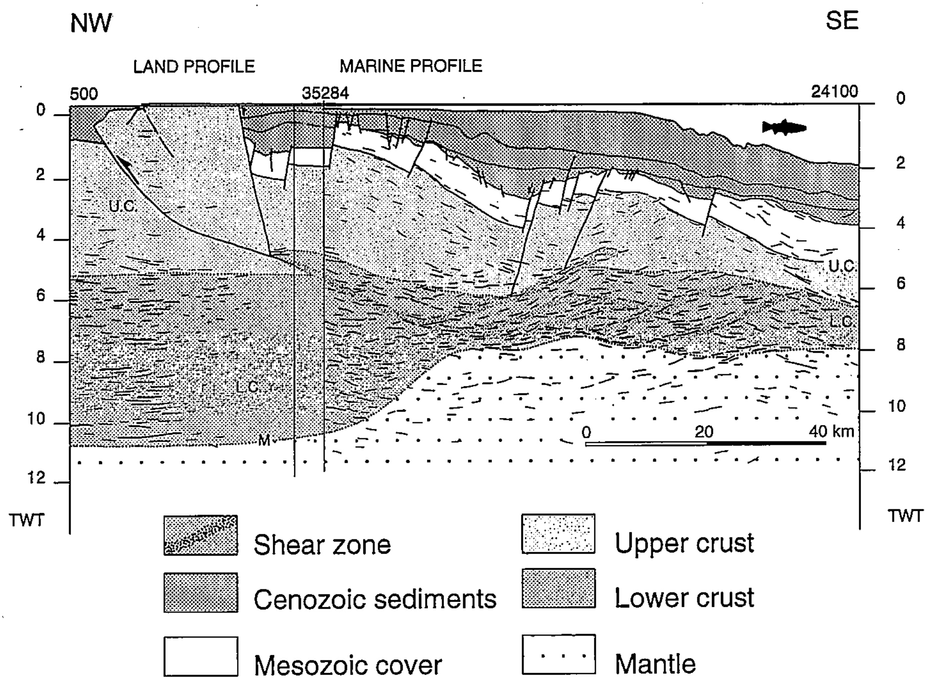

Figure 8.- Crustal interpretation of the Ebro Basin and the Catalan-Valencian Domain. The lower (Moho) and upper boundaries of the reflective lower crust are indicated, as are the deformation structures that affect the crust: faults in the upper crust and shear zones in the lower crust. The base of the Mesozoic is interpreted from the arrangement of reflections and from information supplied by boreholes Reus-1, Castelló B5 and Casablanca C3 (Lanaja, 1987) and the ESP-6 (Torné *et al.*, 1992). Additional explanation in the text.

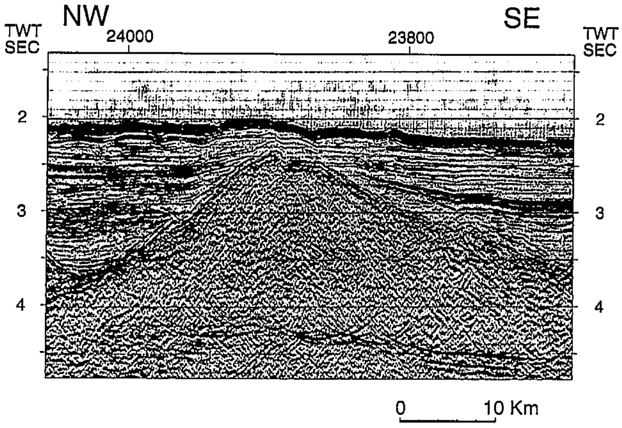

Figure 9.- Migrated seismic profile of the northern Balearic Promontory basement high. In the seismograph corresponding to CMP 23800, the seabed is found at 2.2 s TWT, the base of the Pliocene-Quaternary at 2.7 s and the base of the sediments at 3 s, whereas the reflection at 4.4 s corresponds to a multiple of the seabed. In the seismograph corresponding to CMP 24000, the seabed is found at 2 s, the base of the Pliocene-Quaternary at 3 s and the base of the sediments at 3.5 s. On the NW slope of the high, it is noticeable how the reflections at 2.7 s corresponding to the Pliocene are folded and erosionaly truncated. See location in Fig. 2.

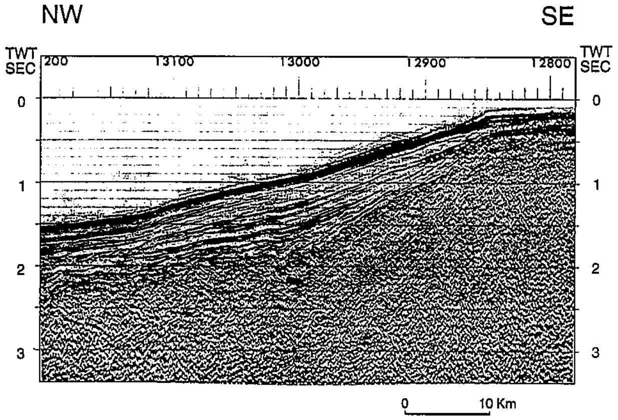

Figure 11.- Migrated seismic profile of the NW slope of the southern Balearic Promontory basement high. In the seismograph corresponding to CMP 13000 the seabed is found at 1 s TWT, the base of the Pliocene-Quaternary at 1.3 s and the base of the sediments at 1.8 s. Around the CMP 12900 the erosional truncation of the Middle and Upper Miocene sediments can be observed. See situation in Fig. 2.

and from the reflections (Figs. 2 and 13). It has been interpreted as a tectonic contact based on field data in Mallorca that indicate the existence of a basal thrust for the Oligocene and Miocene thrust system at the Palaeozoic-Mesozoic boundary (Fallot, 1992; Sàbat *et al.*, 1988; Gelabert *et al.*, 1992). Some of these thrusts have been subsequently reactivated as normal faults (Roca, 1992; Gelabert *et al.*, 1992) which suggests that the detachment was also reactivated as an extensional detachment during Middle Miocene to Quaternary times.

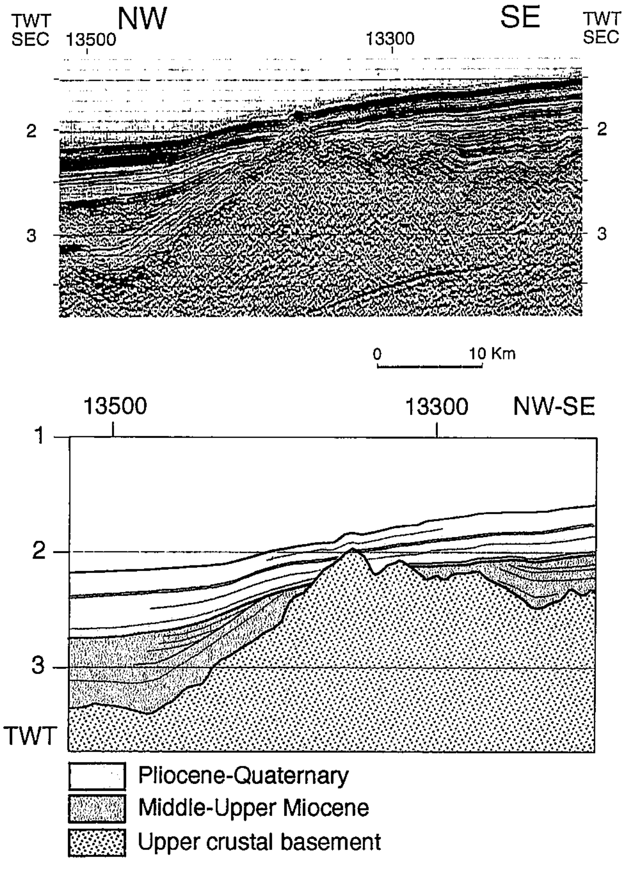

Figure 10.- Migrated seismic profile and interpretation of the Balearic Promontory basement second high. The geometry of the Middle and Upper Miocene sediments shows that the emplacement of this high is synchronous with its deposition. See location in Fig. 2 and additional explanation in the text.

The lower crust shows a laterally variable reflectivity and its thickness (2-3 s) is smaller than the one in the Ebro Basin; however, a local thickening is present in the central Balearic Promontory (Fig. 13). Inclined reflections can only be seen in the zone where the lower crust is thickest and most reflective. The bands dip NW and, in accordance with the displacement of the boundary between the lower and upper crust, they could be interpreted as reverse shear zones. The local crustal thickening could be due to the functioning of these reverse shears.

Algerian Basin

This oceanic basin is located between the Balearic Promontory and the North African shelf. The limit between the promontory and the Algerian Basin is very abrupt and coincides with the submarine Émile Baudot Scarp (Fig. 2). The profile shows various reflective patterns. Below a water layer of nearly 4 s (3000 m) there is an upper, very reflective sedimentary package, 1 s thick. Underneath these sediments, the rest of the crust is weakly reflective. There are a few short, but relatively intense, reflections situated at 7 s which have been interpreted to correspond to the Moho. Seismic refraction data (Hinz, 1972;1973) suggest that it is an oceanic crust 9 km thick.

The lack of drilling in the basin prevents us from knowing the age and characteristics of the sedimentary fill and, therefore, the age of the basin. The stratigraphy that we use is based on correlation with known areas nearby (Mauffret *et al.*, 1973; Sans & Sàbat, 1993). The visible sedimentary fill thickness increases slightly towards the SE (Fig. 2). The seabed is subhorizontal but shows small

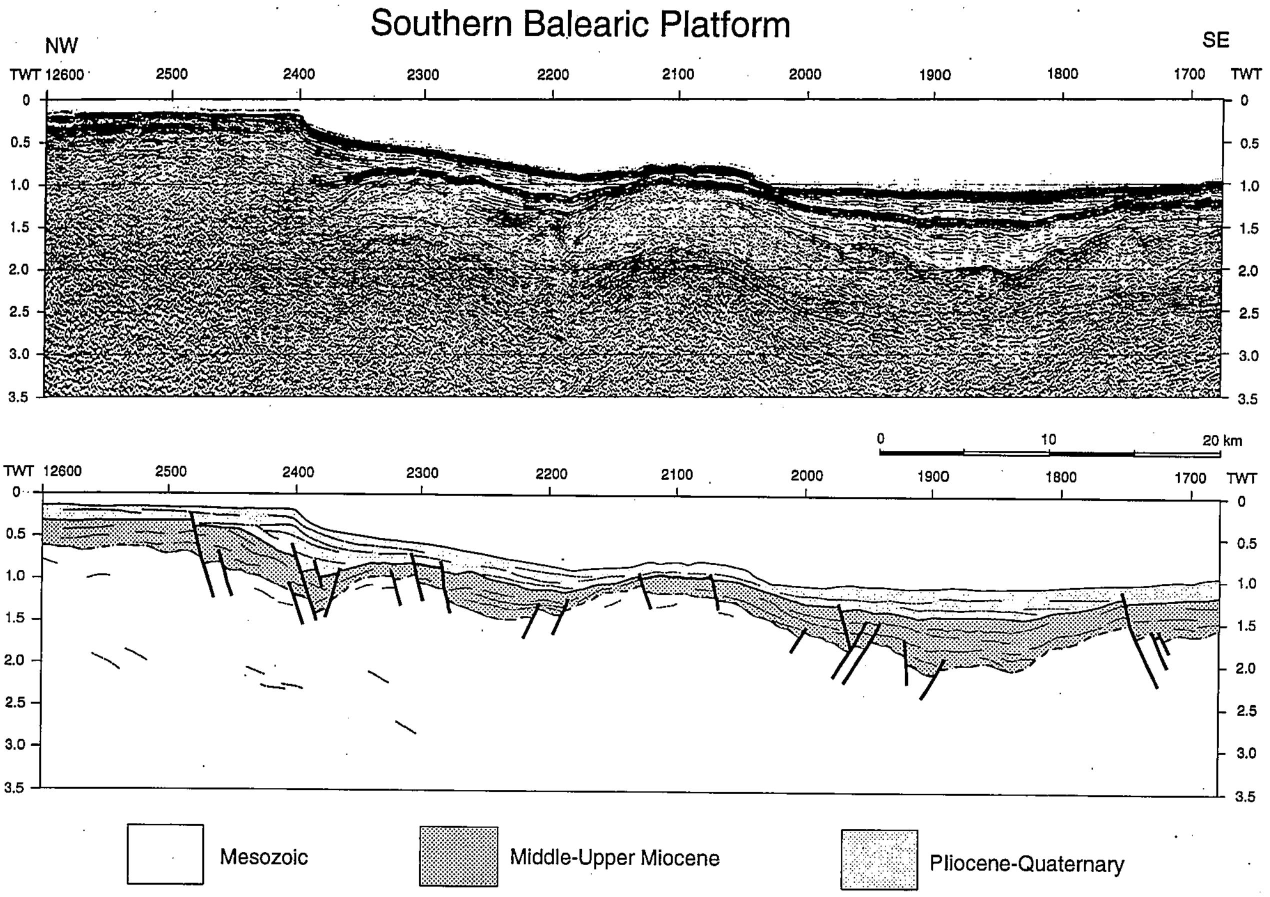

Figure 12.- Migrated seismic profile and interpretation of the southern Balearic Promontory. Beneath the CMP 2000 the seabed occurs at 1 s TWT, the base of the Pliocene-Quaternary at 1.25 s and the base of the sediments at 1.7 s, whereas the reflections at 2.3 and 2.55 s are multiples. See location in Fig. 2 and additional explanation in the text.

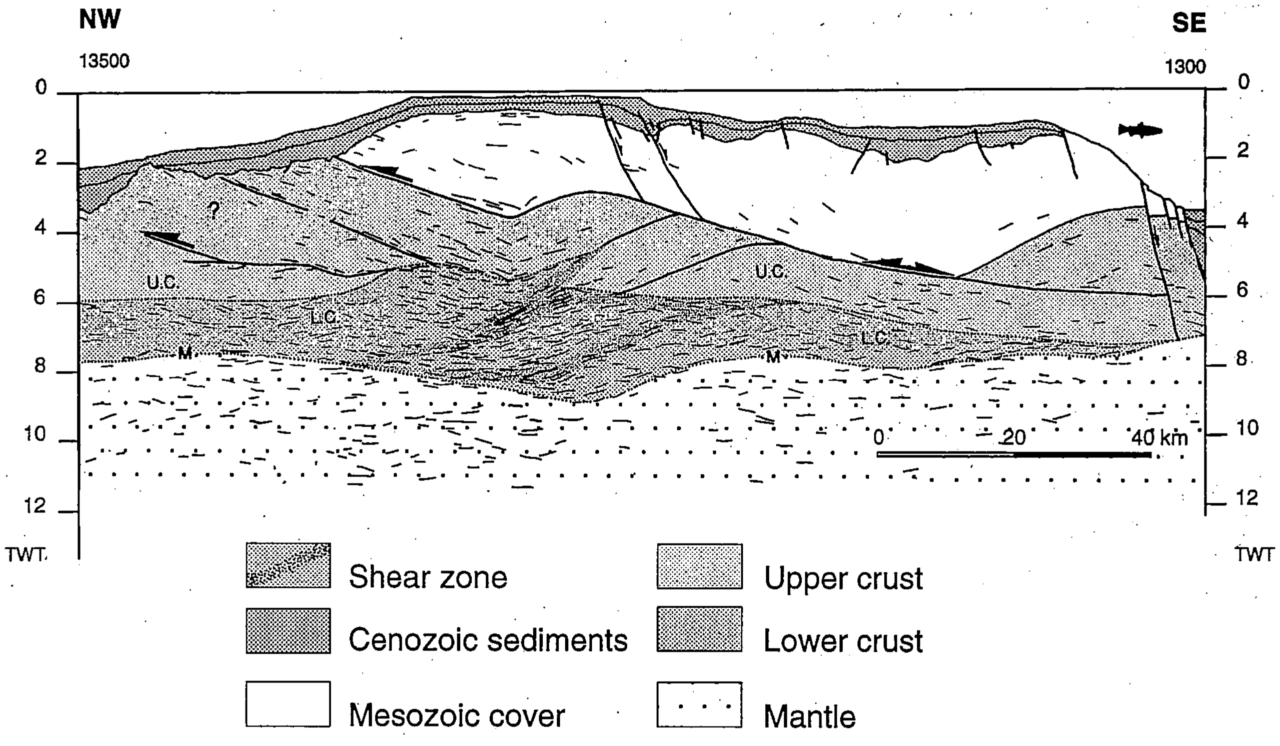

Figure 13.- Crustal interpretation of the central and southern Balearic Promontory. The base of the Mesozoic is interpreted from stratigraphical columns measured in the Balearic islands, the ESP-3 (Torné *et al.*, 1992) and the reflective pattern. Additional explanation in Fig. 8 caption and in the text.

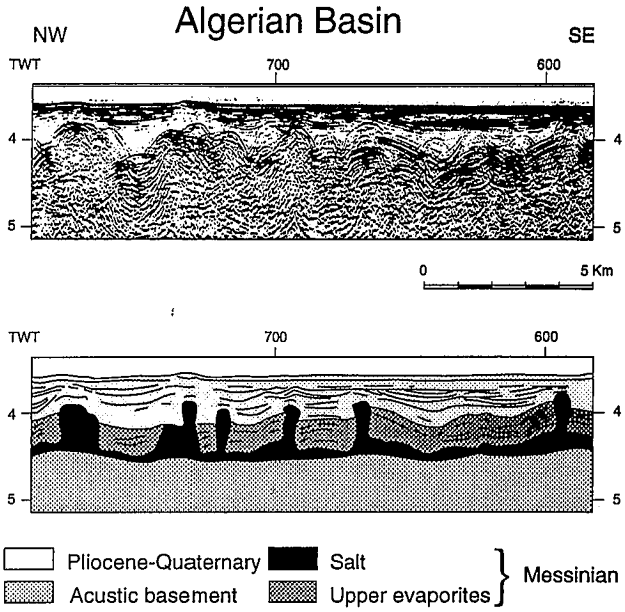

Figure 14.- Migrated seismic profile and interpretation of a segment of the Algerian Basin. The seabed is found at about 3,5 s, the base of the Pliocene-Quaternary at about 4 s and the base of the salt at 4.5 s. The seismic image shows a great number of lateral reflections, due to the presence of diapirs. That is to say, that the profile is not perpendicular to a cylindrical structure. See location in Fig. 2 and additional text explanation.

steps that could correspond to present-day normal faults of very little displacement which may contribute to larger subsidence in the SE extremity of the profile. The basin contains a group of salt diapirs and associated normal faults (Figs. 2 and 14). The diapirs have been formed by movement of probably Messinian salt (Hsu, 1978), they started to form in the Late Messinian and developed till very recent, even locally affecting the seabed (Fig. 14). The Pliocene-Quaternary sediments show internal unconformities related to the final emplacement of the diapirs, which is more recent towards the NW.

There are very few deep reflections because the salt diapirs absorb nearly all of the energy. There are probably Cenozoic sediments older than Messinian salt, located beneath it, but there are no reflections either from these sediments or from their basement. The crust thickness (including the sediments) is only 3.5 s and the oceanic accretion in the profile section would be pre-Messinian.

The Émile Baudot Scarp represents the abrupt transit between continental crust of the Balearic Promontory and oceanic crust of the Algerian Basin. The contact between these two different crusts can be interpreted as a major fracture (or a group of fractures) which affected and subdivided the continental crust prior to lateral accretion of the oceanic crust.

Summary of the chronology of the superficial structures

The oldest structure is the Palaeogene thrust (43-28 Ma) which placed Palaeozoic basement and deformed Mesozoic cover of the Catalan Coastal Ranges over the Ebro Basin.

During the Late Oligocene-Early Miocene (28-15 Ma), the tectonic regimes in the Catalan-Valencian Domain and the Balearic Promontory were opposite. The Catalan Coastal Ranges, the El Camp Basin and the Catalan Marine Platform and Slope were being subjected to extension, generating normal faults that compartmentalised the domain into a group of horsts and grabens. This extension produced subsidence and, in turn, allowed sedimentation to occur. In contrast with the Catalan-Valencian Domain, Upper Oligocene- Lower Miocene sediments have not been recognised along the profile in the Balearic Promontory. These sediments are present in the Balearic islands but they are deformed by a thrust and fold system and incorporated in the upper crustal basement. During the first half of the Late Oligocene-Early Miocene, volcanic edifices were generated, like the one recognised in the central València Trough.

During the Middle and Late Miocene (15-5 Ma), most of the normal faults of the Catalan-Valencian Domain were no longer active, except those located near the Catalan Coastal Range. In the Balearic Promontory, compression continued only in its northern part where the three basement highs were formed coeval with the formation of extensional basins in the southern part of the promontory. At the same time the extensional Algerian Basin was being formed. Because Messinian salt is the oldest known deposit in the Algerian Basin, the oceanic crust was formed prior to the Messinian.

During the Pliocene-Quaternary (5 Ma to present), diapirs developed in the Algerian Basin with small normal faults deforming the overlying sediments.

Discussion

The interpretation of the ESCI-València Trough profile is summarised in Fig. 15. In this figure one can clearly recognise three sections with different structure. (1) The Ebro Basin, located in the NW extremity of the profile, with a continental crust of uniform thickness that remained undeformed during the Cenozoic. (2) The Continental Margin, which occupies most of the profile and is made up of continental crust thinner than in the Ebro Basin and deformed during the Cenozoic. (3) The Algerian Basin, located in the SE part of the profile, made up of a very thin crust of probably oceanic character that originated during the Cenozoic.

In the region with continental crust, the positions of the Moho, the boundary between lower and upper crust, the Mesozoic rocks, and the different stratigraphic units of Cenozoic sediments have been indicated. There are no data to prove the nature of two of the basement highs located in the northern part of the Balearic Promontory. In the region of probable oceanic crust, the position of the Moho have been interpreted and a possible location for the base of the Cenozoic sediments have been suggested.

The lower crust of the continental margin, the region deformed during the Cenozoic, is in general less reflective and much thinner than the lower crust of the Ebro Basin. Therefore, it seems obvious that reflectivity is not associated with extension and formation of the València Trough. On the contrary, the reflectivity is prior to the extension (Watts *et al.*, 1990) and its weaker intensity in the deformed crust has to be associated with extension and coeval thinning; otherwise, it could be due to a seismic artefact.

Although part of the Balearic Promontory upper crustal basement has a thickness similar to that of the Ebro Basin, in general, the upper crust contributes as much as the lower crust to total thinning in the region of deformed continental crust (Fig. 15). The determination of precisely how much each of the crustal levels thins is a key aspect for discriminating different stretching models. This entails working on a profile converted to depth, which is an aspect that will be tackled in a future work.

If there is volume conservation during plane strain deformation, thinning results from extension. As an alternative to the volume conservation hypothesis, some kind of interaction between the crust and the mantle could be considered; for example, the detachment of a crustal root or the digestion of part of the crust by ascending mantle. In the digestion process, crustal thinning should occur essentially in the lower crust, and the rising Moho would progressively cut the horizontal reflections of the lower crust. This cutting relationship would be most noticeable in the regions where crustal thickness varies abruptly and where the Moho shows a step.

The ESCI-València Trough Profile shows some evidence of a possible mantle front ascending through the lower crust; for instance, the abrupt interruption of lower crust horizontal reflections against the Moho step that is located near the coast on the Catalan Marine Platform (Figs. 2 and 8). On the other hand, there is no evidence that the upper crust has suffered an important extension, one that is consistent with the crustal thinning. Although there is the possibility of some kind of interaction between the crust and the mantle, and also signs that this type of processes could have contributed to the evolution of the València Trough, these possibilities will not be considered further in the present work. In the following discussion, we assume constant crustal volume during plane strain deformation in order to use normal balancing rules at crustal scale, and we examine the consequences that follow from this assumption.

Extensional as much as contractional deformation has contributed to the deformation of the eastern margin of the Iberian Peninsula. As has been seen when dealing with the chronology of superficial structures, extension and contraction occur simultaneously in adjacent areas. Most of the Catalan-Valencian Domain superficial structures are extensional, whereas contractional structures predominate in the Balearic Promontory. However, the resulting thin crust all along the continental margin points out that extension has been larger than compression.

Two different hypothesis are proposed, each from the premise of volume conservation and plane strain, which provide an idea of how the different structures may be interrelated and enable us to discuss the overall structure and its evolution.

Hypothesis A (Fig. 16)

We have suggested above that there are shear zones in the lower crust. In the Catalan-Valencian Domain, most of them are probably extensional and this could explain the thinning of the lower crust in this sector. In the València Trough centre, the lower crust is weakly reflective and thinner, and the shear zones are not visible, which, however, does not mean that they do not exist. In the Balearic Promontory, where the lower crust is reflective, there are similar zones with the same disposition as those of the Catalan-Valencian Domain. This suggests that both shear zone groups could have been generated by extension, even though those observed in the central Balearic Promontory could have been subsequently inverted as thrust shears. In summary, the internal structure of the lower crust is not always visible, and where it is visible a system of shear zones can be detected. These shears zones could explain the lower crust thinning as most of them could be extensional.

During the Palaeogene (43-28 Ma), the contact between undeformed continental crust of the Ebro Basin and the present thin, deformed continental crust would probably have a moderate SE dip. It would have been located in the Catalan Coastal Ranges frontal thrust and its continuation to depth, and it would have joined with the lower crust reverse shear zone (see also Fig. 8). During the Neogene (from 28 Ma), the NW limit of thinning would not have been so sharp and it would have been located approximately beneath the NW boundary of the El Camp Basin. Since the Late Miocene (10 Ma), the contact between the Continental Margin thin crust and the oceanic crust is abrupt and occurs at level of the Émile Baudot Scarp. In effect, the Algerian Basin oceanic crust is leaning against the Balearic Promontory continental crust, and it cuts the basal thrust of the Oligocene-Miocene Mallorcan thrust system which were active until the Langhian (Ramos-Guerrero *et al.*, 1989). Thus, the oceanic crust was formed during the Middle Miocene and/or Late Miocene, being later than Langhian (15 Ma) and earlier than Messinian, age of the salt (6 Ma).

Due to the fact that the Balearic Promontory is structured in a thrust system and that Mesozoic rocks are present in the foreland (Catalan-Valencian Domain) and in the highest parts of the Promontory itself, the basement highs in the north promontory region would have to be made up of Mesozoic rocks. The Cabriel B2-A and Ibiza Marino AN-1 drill-holes (Lanaja, 1987) suggest that this deduction could be correct, since the holes penetrate Mesozoic material and are located in a position that could be comparable to that of the basement highs, though respectively 80 and 140 km further to the West of the ESCI-València Trough profile.

It is important to emphasise that the main structure of the Balearic Promontory upper crustal basement being a thrust system, and if that of the lower crust is a system of extensional shear zones, the contact between the lower

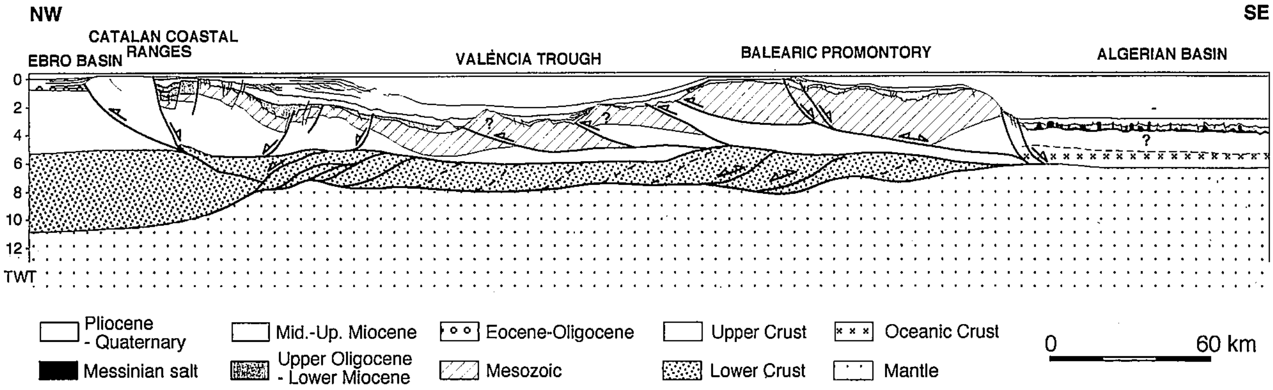

Figure 15.- Summary interpretation of the ESCI-València Trough profile. The oceanic crust, lower continental crust, and upper continental crust are differentiated, as well as Mesozoic rocks and different stratigraphical units of the Cenozoic sedimentary package. The observed upper crustal faults and the lower crustal shear zones are also shown. The nature of two Balearic Promontory basement highs and the position of the top of the oceanic crust are unknown.

and upper crusts should have acted as a detachment. In addition, the normal faults of the Catalan-Valencian Domain should then branch in this detachment and transfer their movement to the extensional shear zones in the lower crust.

The above considerations, together with the lateral thickness variations at both crustal levels, suggest us to consider the evolution of deformation in the eastern margin of the Iberian Peninsula as follows:

1) During the Palaeogene (43-28 Ma), the compressive deformation was simple shear, it affected both crustal levels and it was restricted to very definite points, such as the contact zone between the Ebro Basin and the Catalan-Valencian Domain.

2) During the Late Oligocene and Early Miocene (28-15 Ma), the upper crust of the Catalan-Valencian Domain was extended by an array of normal faults while the upper crust of the Balearic Promontory was shorte-

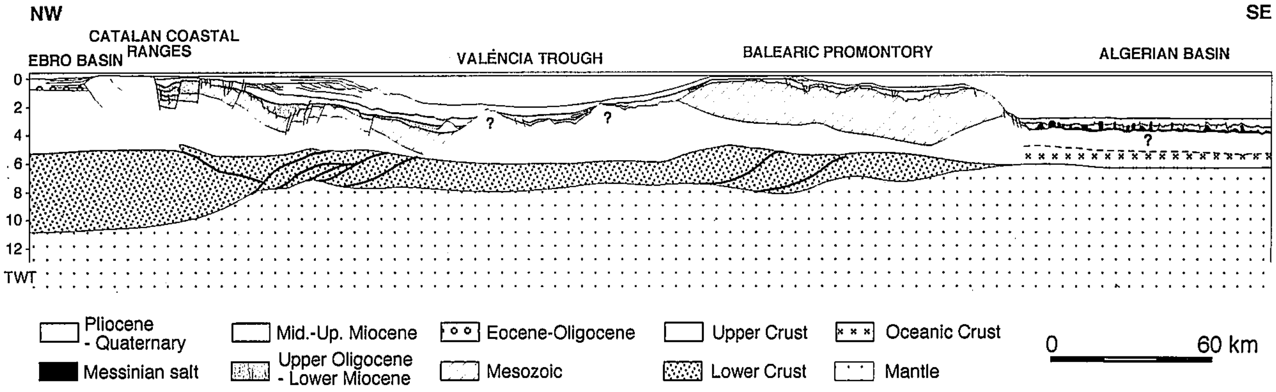

Figure 16.- Hypothesis A. From this hypothesis it follows that the Balearic Promontory basement highs are made up of Mesozoic material. Additional explanation in the text.

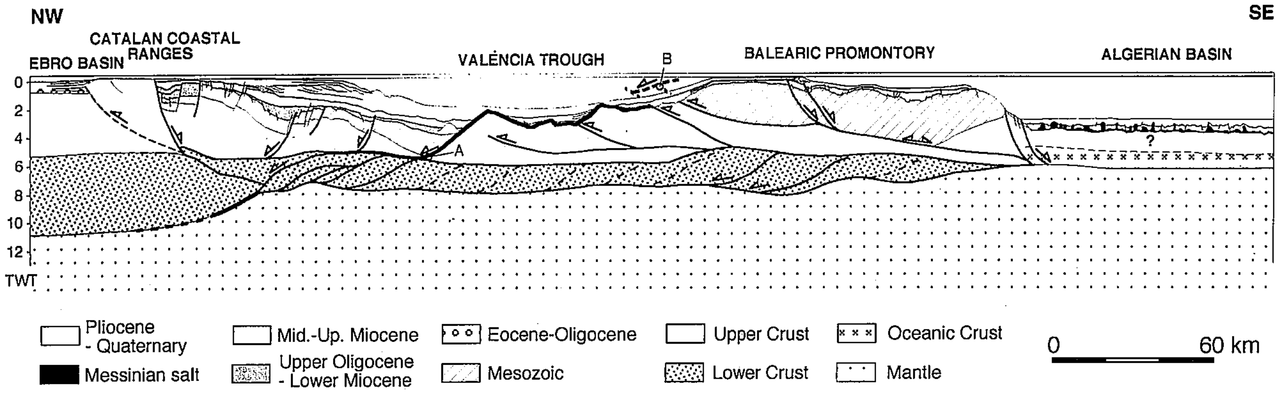

Figure 17.- Hypothesis B. The contact between the upper crust and the sediments in the Balearic Promontory basement highs is interpreted as low-angle extensional fault that passes through the upper crust and cut-off the base of Mesozoic rocks at points A and B. Additional explanation in the text.

ned by a system of thrusts and folds. At the same time, the lower crusts of both these domains were extended by an array of rotating shear zones giving rise to an overall pure shear like deformation. At the end of this period, the upper crust of the Catalan-Valencian Domain would be thin whereas that of the Balearic Promontory (at least the central part) would be relatively thick, and the lower crust of both domains would be uniformly thin.

3) During the Middle and Late Miocene, (15-5 Ma) the Algerian Basin and its oceanic crust were formed and, in relation to this, the southern part of the Balearic Promontory upper crust was extended. The northern part of the Balearic Promontory upper crust, however, was shortened, generating the basement highs. In the Catalan-Valencian Domain the extensional faults that are closest to the coast were active. Some of the lower crust extensional shear zones were inverted, initiating thickening of the central part of the Balearic Promontory lower crust. These local and late thickenings are probably those that isostatically raised the islands (lifting of the Upper Miocene reef platform of Llucmajor in the southeastern part of Mallorca). At the end of this period, the upper crust of the Catalan-Valencian Domain would be thin, the upper crust of the Balearic Promontory (especially the central and southern parts) would be similar to that of the Ebro Basin, and the lower crust of both domains would be thin but not uniformly so.

4) At least at the beginning of the Pliocene-Quaternary, regimes similar to those of the previous period existed.

This hypothesis takes into account most of the geological observations carried out on the surface as well as those based on the ESCI-València Trough profile. Particular observations which stand out are the present-day crustal structure, as well as the different associations and ages of structures. This enables us to suggest how the crustal structure developed during deformation. This scheme emphasises the changing tectonic regimes in both space and time. Thus, at a given moment, there can be compression and extension in adjacent zones, and also in superimposed zones, as in the proposed contemporaneous elongation of upper crust and shortening of lower crust in the Balearic Promontory.

Regardless of how well it fits the geological data, this hypothesis has a serious difficulty because the resulting geological cross-section is not balanced. The extension produced by the visible upper crust faults is not sufficient to explain the upper crustal thinning. It is also much less than the extension due to shear zones, if this is what produced the lower crustal thinning.

Hypothesis B (Fig. 17)

A solution to the previous problem could be to consider that unobserved extensional structures have produced large extensions in the upper crust. A probable reason for the fact that these structures have not been observed is that they may only affect the upper crust and may be older than the Cenozoic reflective sedimentary cover. In the València Trough and Balearic Promontory there could be hidden extensional faults with large displacements in various locations. For instance, a system of extensional faults may have affected the Balearic Promontory prior to compression, similar to faults in the Catalan-Valencian Domain, and could have been obliterated by later compressive structures. Another possibility is that the contact between the basement highs in the northern part of the Balearic Promontory and the overlying Middle and Upper Miocene sediments could have been a major fault. This second possibility will be discussed further, not because the first suggestion is considered to be inadequate, but because the second possibility is more distinct from hypothesis A

It is intended to interpret the contact between the upper crust and the sediments along the two northern highs as an onlap on a low-angle extensional fault, of about 80 km displacement prior to the Middle Miocene. This fault would have passed through and displaced the whole upper crust and would have linked up with the system of lower crustal shear zones and with the Catalan-Valencian Domain normal-fault system. According to this hypothesis, the upper crust highs are located in the footwall of the low-angle fault and are made up of basement material. The fault would have displaced the Mesozoic (points A and B in Fig. 17 would be equivalent), folding the hangingwall into a rollover anticline of great extent that occupies the whole Catalan-Valencian Domain. As the fault would have affected deeper levels of the crust toward the NW, the metamorphic grade of the rocks which make up the basement highs should also increase in that direction.

The low-angle extensional fault would have emerged at the syndepositional surface as it would have existed prior to the Middle Miocene and would have been covered by sediments of that period. In any case, the fault would be later than the Mesozoic as it would have folded the materials of that period in the rollover anticline. The low-angle extensional fault would probably have been formed during the Late Oligocene (and Early Miocene), which was the period of greatest activity for the Catalan-Valencian Domain normal faults.

It is worth noticing that the volcanoes in the central part of the València Trough, such as the one that can be observed in the ESCI-València Trough profile, would have been located in the hangingwall precisely next to the extensional fault. Also worth noticing is that, according to this hypothesis, the Mesozoic cover was at least 80 km narrower than at the present time.

The upper and lower crustal extension mechanisms would have been very different. Whereas in the upper crust the greatest part of the displacement would have been produced by only one structure and the extension mechanism would have been simple shear, in the lower crust the displacement would have shared a multitude of shear zones making the extension mechanism more like pure shear. This difference in the extension mechanism would imply that the contact between the lower and upper crusts was a detachment, as in the previous hypothesis. In this case, extension would also have occurred in the lower crust of the Balearic Promontory, at the same time as shortening in the upper crust. But the disharmony would have been much more spectacular than in hypothesis A because the total extension is greater.

The low-angle extensional fault would originally have had a regular dip and would have been deformed after its formation. It would probably have been cut by the detachment of the Mesozoic cover associated with the Oligocene-Miocene Mallorcan thrust system. During the second half of the Middle and Late Miocene and the first half of the Pliocene-Quaternary, the low-angle extensional fault would have been folded due to the NW propagation of contractional structures, and the basement highs would have formed. In some respects, these structures would be similar to the Sierra Nevada and Sierra Filabres of the Betic Ranges, though, in these cases it refers to the internal zones of the Betic orogen and, in the València Trough, to the external zones. In effect, the present-day contact between the Nevado-Filabres and Alpujarrides units is a Middle Miocene low-angle extensional fault of great displacement which was later folded into broad anticlines in the Late Miocene (Galindo-Zaldívar *et al.*, 1989; García-Dueñas *et al.*, 1992; Crespo-Blanc *et al.*, 1994).

Conclusions

Along the ESCI-València Trough profile, three regions with different crustal structure are distinguished and characterised.

a) The Ebro Basin, located at the NW end, consisting of continental crust with regular thickness made up of seismically transparent upper crust and reflective lower crust.

b) The Continental Margin, in the centre and occupying nearly all of the profile, which possesses a thin crust that is also made up of transparent upper crust and reflective lower crust. This crust was deformed during the Cenozoic in compression and extension, both types of deformation coexisting with each other in adjacent areas, and even superimposed on each other in the same area, during certain periods.

c) The Algerian Basin, located in the SE part of the profile, with a recent, very thin and weakly reflective crust of probable oceanic character.

Although compressional and extensional structures exist in certain sectors, like the Balearic Promontory for example, if a plane strain and constant volume deformation is accepted, it follows that extension should predominate in the continental margin crust as a whole because the end result is crustal thinning. Alternatively, part of the thinning could be considered to be due to a decrease in crustal volume.

The crustal thinning affects both the upper and lower crust. Normal faults are the only visible extensional structures in the upper crust of the Catalan-Valencian Domain. Their displacement is insufficient to explain the thinning of this region. In the thinned lower crust, as well as horizontal reflections characteristic of undeformed lower crust, inclined reflections are observed which are interpreted as extensional shear zones which could explain the thinning of the lower crust.

In addition to extensional and contractional structures, which are visible in the ESCI profile and are mapped on the ground, the possible existence of non-observable extensional faults, which are necessary for balancing the geological cross-section, is noted. Among these possible structures, attention is drawn to a hypothetical Late Oligocene-Early Miocene low-angle extensional fault of great displacement whose footwall would be the Balearic Promontory (Fig. 17). This fault would later have been folded due to the NW propagation of contractional structures which affect the Balearic Promontory. If this hypothesis is correct, the upper crust would have been extended through simple shear while the lower crust as a whole would have been extended in a more like pure shear manner, implying that the contact between the two crusts acted as a detachment. At a given moment, this detachment would have enabled the lower crust of the Balearic Promontory to be stretched while the upper crust was shortened.

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