Large scale structures in the Nevado-Filabride Complex and crustal seismic fabrics of the deep seismic reflection profile ESCI-Béticas2

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Abstract: The ESCI-Béticas 2 deep seismic reflection profile cuts across the Alborán Domain, an allocthonous composite terrane that has undergone complex orogenic evolution. After the development of several crustal thickening episodes, it was severely thinned during the Early and Middle Miocene and later folded. Two large-scale anticlines coinciding with the Sierra Nevada and Sierra de los Filabres mountain ranges have been identified. The anticlines are open and North-vergent and developed in the Late Tortonian. An analysis of the geometry of these folds and comparison with the seismic image of the upper crust in the ESCI-Béticas2 profile has led us to conclude that these structures are related to flat and ramp contractional faults. The reflection Moho found between 10.5 and 11 s TWT is continuous and nearly flat. A prominent Mid-Crustal Reflector (MCR), located variously from 5.5 to 6.5 s TWT, separates two crustal levels with different reflectivity patterns. The crust above the MCR is nearly transparent, although locally there are bands of high reflectivity. The most notable of these bands is the UCR (Upper Crustal Reflector), interpreted as a mylonitic band. The deep crust, in contrast, is highly reflective and shows broad domains of laminated crust, possibly due to pervasive ductile shearing. The deep crustal reflectors are cut by less reflective, SSW-dipping bands, with a geometry that can be interpreted as extensional shear zones.

Keywords: Fault-related folds, extensional shear zones, low-angle normal faults, crustal seismic fabrics, Nevado-Filabride complex, Betics.

Resumen: El perfil sísmico de reflexión profunda ESCI-Béticas2 discurre, con una dirección N30E, a través del Dominio de Alborán. Este dominio cortical es alóctono sobre los paleomárgenes Sud-Ibérico y Magrebí y muestra una complicada evolución orogénica que comporta, tras varios episodios de engrosamiento cortical, un drástico adelgazamiento extensional durante el Mioceno inferior y medio y subsecuente plegamiento en el Mioceno superior. Coincidiendo con las alineaciones montañosas de Sierra Nevada y Sierra de los Filabres se han reconocido dos anticlinales de gran escala, abiertos y de vergencia Norte, desarrollados en el Tortoniente superior. Del estudio de la geometría de estos pliegues y su comparación con la imagen sísmica de la corteza superior en el perfil ESCI-Béticas2, concluimos que se trata de estructuras relacionadas con fallas contractivas de geometría en escalera. El perfil sísmico muestra una Moho de reflexión suavemente ondulada, casi plana, situada entre 10'5 y 11 s TWT. En la corteza se observan dos dominios corticales con diferente patrón de reflectividad, separados por una banda de reflexiones prominente (MCR, Mid-Crustal Reflector) situada entre 5'5 y 6'5 s TWT. La corteza superior es casi transparente, aunque localmente se reconocen bandas con una alta reflectividad, entre las que destaca el UCR (Upper Crustal Reflector) que ha sido interpretado como una banda milonítica. La corteza profunda, por el contrario, es altamente reflectiva y muestra amplios dominios de corteza laminada con una alta reflectividad que puede ser debida en parte a cizallamiento dúctil. Los reflectores de la corteza profunda están interrumpidos por bandas menos reflectivas, buzantes al SSW, lo que dibuja un patrón asimétrico interpretable en términos de zonas de cizalla extensionales.

Palabras clave: Pliegues relacionados con fallas, zonas de cizalla extensionales, fallas normales de bajo ángulo, fábricas sísmicas corticales, complejo Nevado-Filábride, Béticas.

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The Betics, together with the Rif and Tell, are a segment of the peri-Mediterranean Alpine orogen whose inner parts extended during the Miocene (Dewey, 1988), forming extensional basins such as the Tyrrhenian (Malinverno & Ryan, 1986) and the Alborán basins (Comas *et al.*, 1992) (Fig. 1). The substrate of the Alborán basin consists of a thin continental crust (Hatzfeld, 1976) that developed from the thinning of a prior orogen. As a whole the region, lying between the Iberian and African plates, is highly deformed. Kinematic reconstructions reveal a continuous N-S convergence between Africa and Europe from 80 Ma. to the Miocene (Dewey *et al.*, 1973, 1989; Savostin *et al.*, 1986). Nevertheless, in the same time period, the geology of the Betics shows alternating

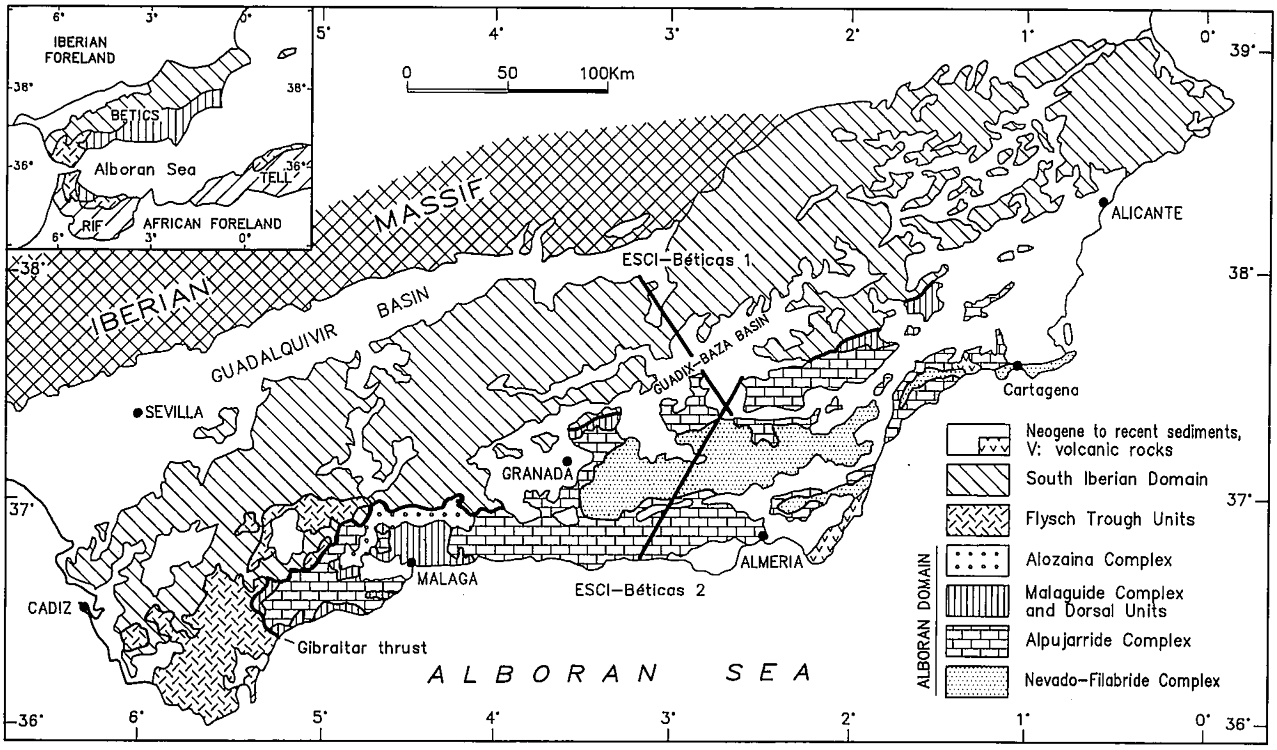

Figure 1.- Major tectonic elements of the Betics and location of the ESCI-Béticas deep seismic reflection profiles (modified from García-Dueñas *et al.*, 1994).

contractive and extensional events (De Jong, 1991; Balanyá *et al.*, 1993) with kinematic indicators having no direct relationship with the direction of convergence (García-Dueñas *et al.*, 1993). Various tectonic evolution models mainly supported by surface geology data have been proposed for the region (Platt & Vissers, 1989; García-Dueñas *et al.*, 1992; Royden, 1993). These models have significant differences and therefore the newly acquired ESCI-Béticas deep seismic reflection profiles provide a potential means of testing them.

Several geophysical studies, particularly seismic refraction profiles, gravimetric data, and wide-angle reflection profiles have been carried out to determine the deep structure of the Betics (Hatzfeld, 1976; Ansorge *et al.*, 1978; Suriñach & Udías, 1978; Working Group for Deep Seismic Sounding in the Alborán Sea 1974, 1978; Banda & Ansorge, 1980; Medialdea *et al.*, 1986; Barranco *et al.*, 1990; Casas & Carbó, 1990; Torné *et al.*, 1992; Banda *et al.*, 1993). With the exception of some discrepancies in the earliest works, most papers confirm each others' results, reliably revealing the main aspects of the crust. Their more relevant findings are: differences between the crustal structures of the Iberian Massif and the Betics, notably the absence in the Betics of a layer with the seismic velocities to be expected from the lower crust; structural differences between the Internal and External Betics; great variations in crustal thickness, from 38-40 km to the North of Sierra Nevada to 16 km beneath the Alborán Sea; and finally, the presence of an anomalous upper mantle beneath the centre of the Alborán Sea. The current availability of several deep seismic reflection profiles opens new possibilities for understanding the crustal structure better. Results obtained from profile studies of this type are often a milestone event in the evolution of the geological history of a particular region, as was the case for the Pyrenees with the ECORS profiles (ECORS Pyrenees team, 1988).

The ESCI-Béticas project includes two reflection lines in the Alborán Sea, performed in 1993, and another two on land, carried out in 1991. The location of the onshore lines can be seen in Fig. 1. The ESCI-Béticas1 profile, about 90 km long, extends N150E from the Guadalquivir basin to the Guadix-Baza basin, crossing the cover of the South Iberian Domain, the Mesozoic to Cenozoic southern margin of the Variscan Iberian Massif. The ESCI-Béticas2 profile, around 106 km long, cuts N30E across the Alborán Domain, which comprises mainly Alpine metamorphic complexes. The technical characteristics of these profiles, together with a first description of them, can be found in García-Dueñas *et al.* (1994).

In this paper we analyse some of the newly acquired seismic reflection data and recently completed detailed field mapping around the ESCI-Béticas2 profile. This work is a preliminary study of this profile, with emphasis on the seismic fabric of the crust and a comparison and possible correlation with the large-scale structures recognisable from the surface geology.

Tectonic setting

Tectonic evolution of the Alborán Domain

The Alborán Domain is a terrane of continental crust consisting of primarily three metamorphic nappe com-

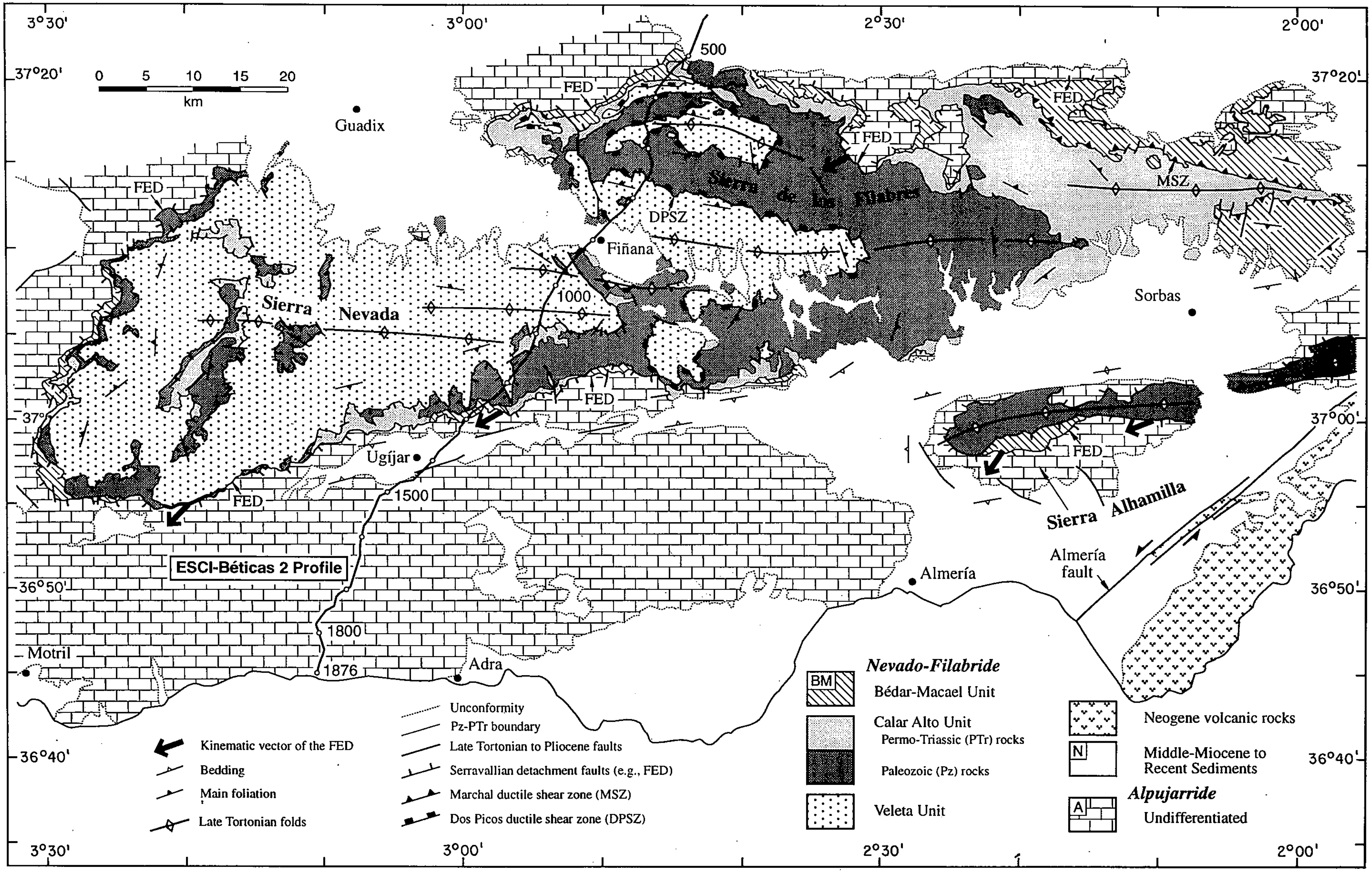

Figure 2.- Schematic tectonic map of the Central Betics with emphasis on the Nevado-Filabride complex, showing the main extensional detachments and shear zones. Late Tortonian large-scale anticlines are also shown.

plexes: the Nevado-Filabrides, the Alpujarrides, and the Malaguides, from bottom to top (Fig. 1). Most of these complexes stacked during the Palaeogene, East of zero meridian, in a polycollisional orogen (García-Dueñas *et al.*, 1992; 1993). During the Early Miocene, the Alborán Domain became the hanging-wall of the Gibraltar thrust, superimposing itself on both the South Iberian Domain and the External Rif after the disappearance of the Flysch Trough. During this event the footwall rocks were strongly shortened by thin-skinned thrusting and folding (Balanyá & García-Dueñas, 1988; Morley, 1987; Balanyá, 1991). At the same time as this thrusting, there was significant extensional thinning of the Alborán Domain, giving rise to the Alborán basin (Comas *et al.*, 1992). The extension continued and eventually invaded the contraction areas, producing the tectonic inversion of the Gibraltar thrust during the Middle Miocene, while the mountain front advanced in the footwall, moving towards the externalmost zones (Balanyá & García-Dueñas, 1988; García-Dueñas *et al.*, 1992). From this time to the present the rocks of the Alborán Domain were once again shortened during a Late Tortonian contractional episode (Weijermars *et al.*, 1985) and finally extended during the Plio-Quaternary.

Structure of the Nevado-Filabride Complex

The Nevado-Filabride, the lowest complex in the Alborán Domain, is widely exposed along the ESCI-Béticas2 profile. Its structure therefore imposes significant geometrical and kinematic constraints on the interpretation of the seismic image.

The lithostratigraphic sequences of the Nevado-Filabrides consist essentially of low- to medium-grade metasedimentary rocks including a monotonous sequence of Palaeozoic graphite-schists and quartzites, a Permo-Triassic sequence of light-coloured albite schists, and Triassic calcite and dolomite marbles. Permian orthogneisses (Priem et al., 1966) and Late Jurassic metabasites (Hebeda *et al.*, 1980) are locally included at different levels of the sequence.

High-pressure relics in this complex (e.g. Nijhuis, 1964) have been related to a continental collision during the Palaeogene, although no structures have been associated with them. With the exception of the high-pressure metamorphism, the oldest tectonic event recognised is the unit-stacking that built up the Nevado-Filabrides into three major thrust units (Fig. 2): the Veleta unit (with a structural thickness –s.th.– of 4000 m), the Calar Alto unit (4500 m s.th.), and the Bédar-Macael unit (600 m s.th.), from bottom to top. The units are separated by two large-scale ductile shear zones with thicknesses of 500-600 m (García-Dueñas *et al.*, 1988). The shear zones have a flat geometry and have been interpreted as extensional ductile detachments superimposed over old thrusts (García Dueñas *et al.*, 1992; Soto, 1993; González-Casado *et al.*, 1995). They are characterised by a penetrative mylonitic foliation (Sm) containing a mean E-W stretching lineation (Lm). Away from the shear zones, the entire Nevado-Filabride stack shows the existence of a schistosity (Ss) that is the axial plane of tight-to-isoclinal folds. Inside the shear zones, the Ss is parallel to the Sm and the folds are rotated towards the Lm. Both the Ss and Sm foliations are affected by south-vergent, metric-to-hectometric folds, with an associated crenulation cleavage (Sc) (Vissers, 1981; Martínez-Martínez, 1986; Jabaloy-Sánchez, 1993; Soto, 1993).

The Nevado-Filabride units were later extended once again along ductile-brittle and brittle extensional detachments and associated low-angle normal faults. The most significant fault is the Filabres extensional detachment (FED, Fig. 2), which coincides with the current Alpujarride/Nevado-Filabride contact (García-Dueñas & Martínez-Martínez, 1988; Galindo-Zaldívar *et al.*, 1989). It has a flat and low-angle ramp geometry and is cut and tilted by out-of-sequence faults that penetrate downward into the footwall. Several kinematic criteria indicate a WSW- to SW-sense of movement of the hanging-wall, generating tilting of the reference surfaces towards the ENE to NE. In the footwall beneath the Filabres extensional detachment ramp, the key surfaces, including the foliations and the ductile shear zones, generally dip towards the East, which may be interpreted as tilting due to isostatic rebound of the ramp and/or to the action of deeper detachments that do not crop out (Martínez-Martínez, 1995).

The Filabres extensional detachment was active during the Serravallian, as may be deduced from its relation with Neogene sediments (García-Dueñas *et al.*, 1992). It was deformed in the Late Tortonian by north-vergent, open folds with large wavelengths (García-Dueñas *et al.*, 1986). The fold hinges are approximately E-W (Fig. 2), showing a variable plunge depending on the key surface that is folded: towards the West in the case of the Filabres extensional detachment and towards the East for the ductile shear zones. The folds are displaced due to the action of both N120-160E right-lateral and N10-60E left-lateral strike-slip faults during the Messinian to Pliocene (e.g. the Almería fault; Weijermars, 1987), and are finally cut by Plio-Quaternary high-angle normal faults, mainly trending NW-SE (Martínez-Martínez, 1995).

Geological cross-section along the seismic profile

With the aim of constructing a geological cross-section to coincide with a segment of the ESCI-Béticas2 profile, the surface geology was reviewed in a 10-20 km band on each side of the profile line between stations 300 and 1400, the sector in which the Nevado-Filabrides crop out (Fig. 3). Two north-vergent, open, large-scale anticlines (W = 20-25 km), Late Tortonian in age, are the most remarkable structures in this area. The anticlines have axial traces running near the topographical elevations of Sierra Nevada and Sierra de los Filabres and include associated smaller folds with similar characteristics (Fig. 4). The fold hinges trend N100-110E, and are therefore suborthogonal to the profile line. These folds are isopaque where they affect originally parallel surfa-

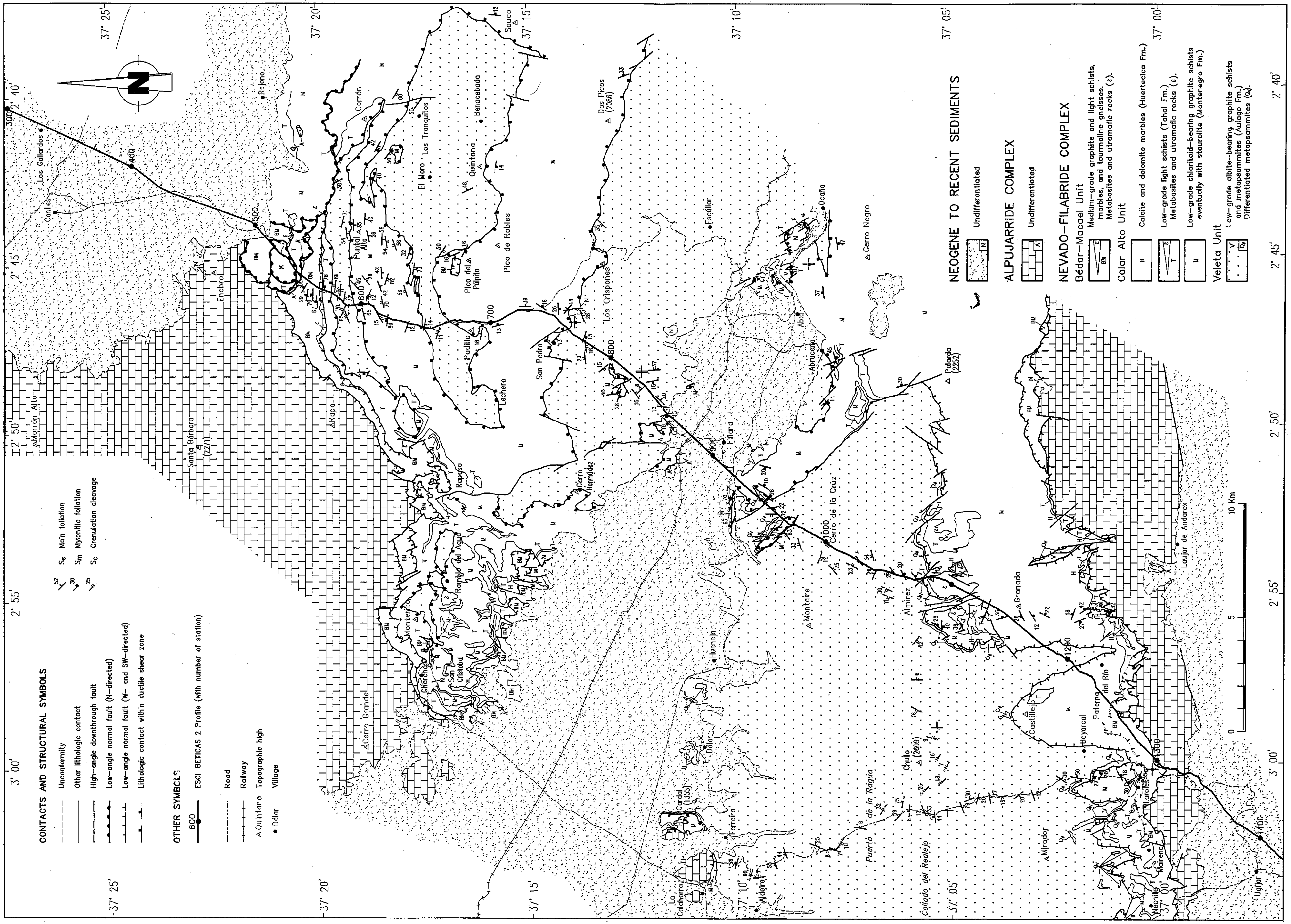

Figure 3.- Structural map of the Nevado-Filabride complex around the ESCI-Béticas 2 profile. Map compiled with revised cartographic data from Velando & Navarro (1979 a and b), Delgado *et al.* (1980), Almarza *et al.* (1981), Martínez-Martínez (1985), Jabaloy-Sánchez (1993), and with observations by the authors. Each symbol is a mean of several outcrop measurements. UTM projection.

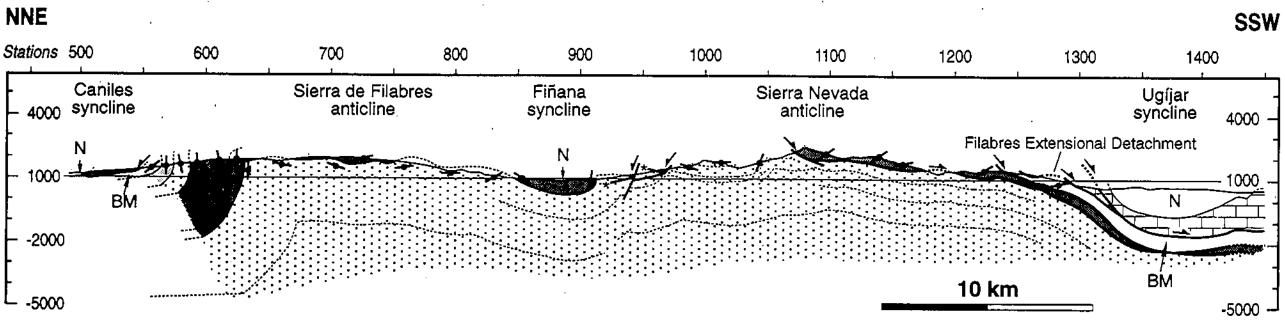

Figure 4.- Simplified geological cross-section along the ESCI-Béticas2 profile between Caniles and Ugíjar synclines. Dotted pattern, Veleta Unit; dark and light-grey, Palaeozoic and Permo-Triassic rocks of the Calar Alto unit, respectively; BM, Bédar-Macael Unit; bricks, Alpujarride complex; and N, Neogene sediments. Apparent dip of the key foliations along the section has been represented.

ces such as metapelite-metapsammite layering. No penetrative fabrics associated with this folding episode have been found. The folds deform all the above-mentioned penetrative structures, as well as the Serravallian extensional fault system associated with the Filabres extensional detachment, and they are previous to different sets of normal faults exposed in the area near the profile line, such as northwards-moving low-angle normal faults that are very common on the northern slope of both the Sierra de los Filabres (Jabaloy-Sánchez, 1993) and the Sierra Nevada, and high-angle normal faults trending NNW-SSE that cut across the latter faults (Figs. 3 and 4). The three known Nevado-Filabride units crop out along the length of the profile (Fig. 3). The Alpujarride/Nevado-Filabride contact (Filabres extensional detachment) lies in the NE of the map, several kilometres above the top of the Veleta unit while in the SW it is only 200 m above it. The Filabres extensional detachment is therefore a very low-angle footwall ramp (< 10°) in the study area. The contact between the Veleta and the Calar Alto units lies within the Dos Picos shear zone (García-Dueñas *et al.*, 1988), which is located in the Sierra de los Filabres anticline (Fig. 2). In the Sierra Nevada anticline, on the other hand, the two units are separated by a brittle extensional detachment with a WSW-to-SW sense of movement, above which the key surfaces inside the Calar Alto unit are commonly tilted towards the East (Figs. 3 and 4). This fault is thought to form part of the Filabres extensional system, and may represent the migration of the Filabres extensional detachment into the footwall (cf. García-Dueñas & Martínez-Martínez, 1988). In the southern half of the cross-section the Filabres extensional detachment is a hanging-wall ramp with tilted blocks above it (Fig. 4).

The highest unit in the Nevado-Filabride complex, the Bédar-Macael unit, crops out only in the northern and southern extremes of the cross-section. In the southern exposure, the rocks of this unit systematically show a planar-linear fabric with Lm trending N70-80E. The entire unit is thus affected by a ductile shear zone that is probably the continuation of the Marchal shear zone (see Figs. 2 and 3), which commonly separates the Calar Alto and Bédar-Macael units (García-Dueñas *et al.* 1988; Soto 1993). Nevertheless, the upper boundary of the Bédar-Macael unit (with the Alpujarride complex) and its lower one (with the Calar Alto unit) are currently extensional detachments with a SW movement of the hanging-wall, as may be inferred from slickenlines, shear bands, and other brittle structures in the associated fault rocks. Within the unit itself we have recognised other brittle faults with similar characteristics, and a pervasive tilting towards the NE (Figs. 3 and 4).

The northern limb of the Sierra de los Filabres anticline is subvertical and the three Nevado-Filabride units can be identified. Here, hectometric-to-kilometric lithostratigraphic repetitions, observed in the two lower units, can be interpreted as close-to-isoclinal folds prior to the development of the Sc (Jabaloy-Sánchez, 1993).

Seismic fabrics of the ESCI-Béticas2 profile

As may be seen in the ESCI-Béticas2 stacked section shown in Fig. 5, the quality of the seismic signal is irregular, with the result that there is a very good record under the Alpujarride and Nevado-Filabride complexes, yet an almost total absence of crustal reflections under the Guadix-Baza basin below 1.5 s TWT. This latter fact may be attributed to the screening effect of the basin sediments, which, in contrast, are revealed by a zone of quite continuous low-amplitude reflections that are either subhorizontal or gently dipping towards the SSW. Along the entire profile, two subparallel reflection bands are particularly noteworthy due to the great amplitude and lateral continuity of their reflections. The lower one, with a gently undulating geometry, is characterised by both discontinuous high-amplitude reflection bands and single reflections located between stations 650 and 1700 at 11 s TWT. It has been interpreted as the reflection Moho by García-Dueñas *et al.* (1994), which is supported by two seismic refraction profiles (Banda *et al.*, 1993) intersecting the ESCI-Béticas2 profile (Fig. 6). If this reflection band is indeed related to the crust-mantle boundary, it lies over a generally transparent mantle, although there are several instances of both SSW-dipping and flat-lying upper-mantle reflections (Fig. 5). There is also a reflection band between stations 650 and 1650 at 5.5 and 6.5 s TWT, respectively, with seismic characteristics very similar to those described for the reflection Moho. This reflection band, labelled MCR (Mid-Crustal

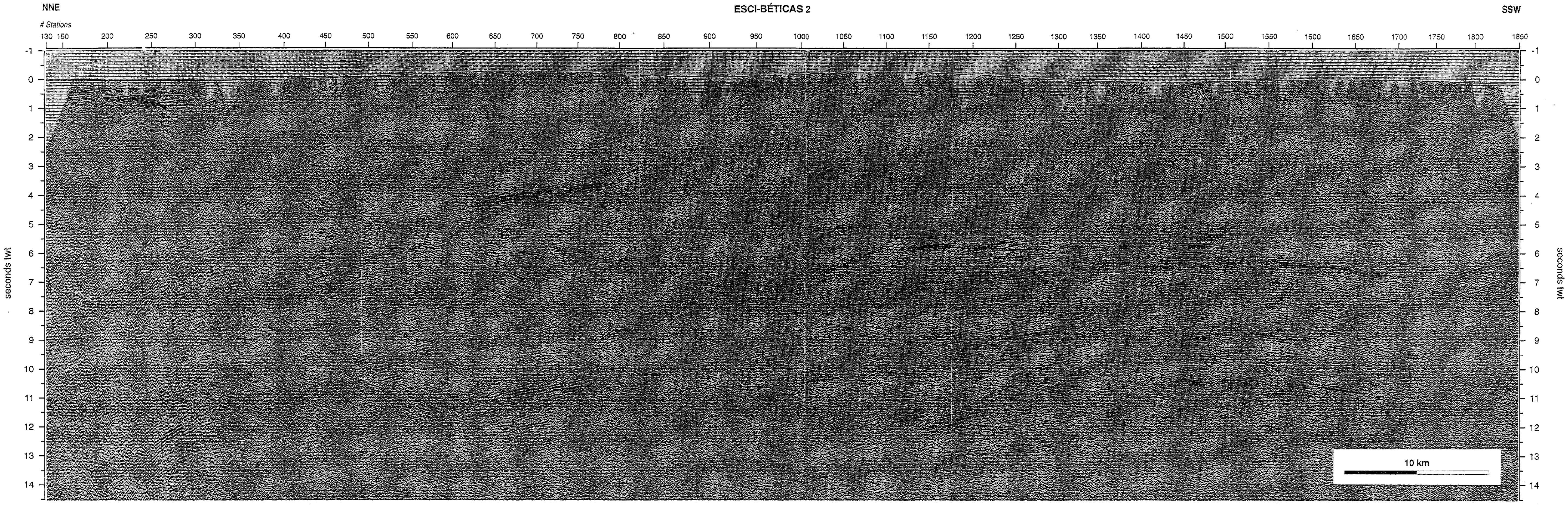

Figure 5.- Final stacked section of the ESCI-Béticas2 profile. See location in Figs. 2 and 3.

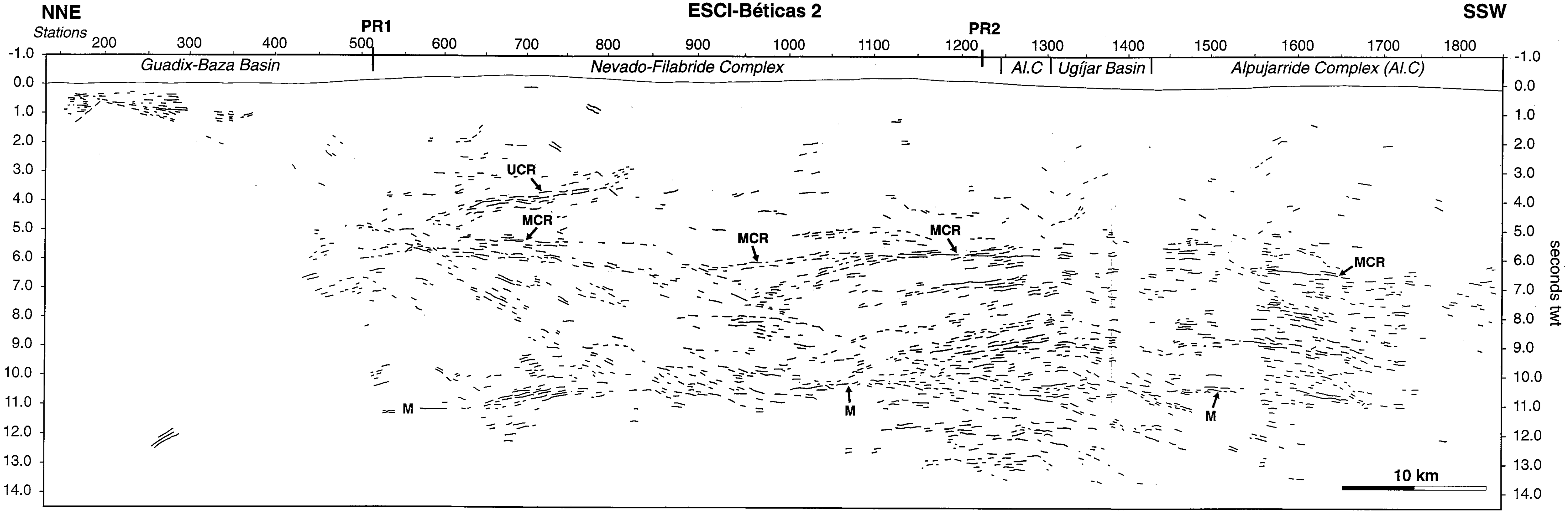

Figure 6.- Interpreted line drawing of the ESCI-Béticas2 deep seismic reflection profile. Boundaries between main geological units and intersection with PR1 and PR2 seismic refraction profiles (see Banda *et al.*, 1993) are shown. Line drawing constructed from final stacked section. UCR: Upper Crustal Reflector, MCR: Mid-Crustal Reflector, M: reflection Moho.

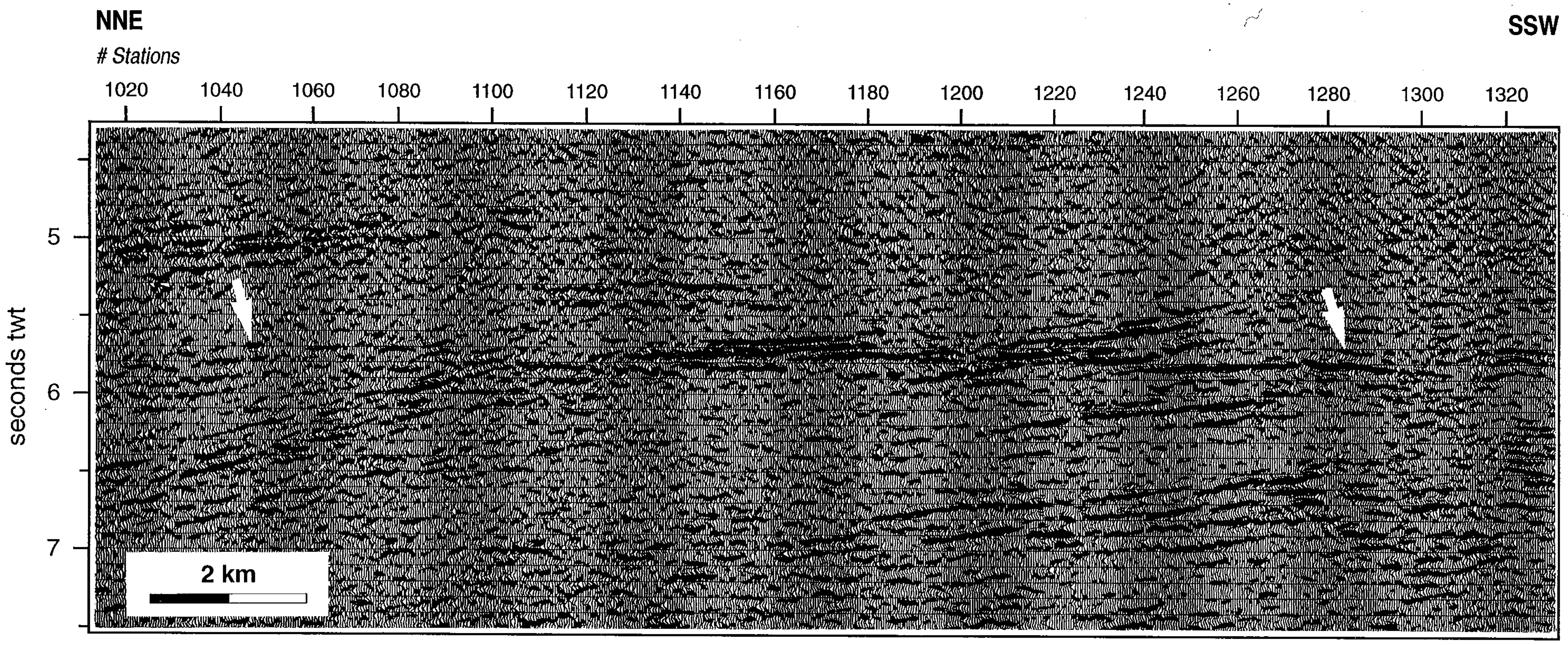

Figure 7.- Enlarged window of the ESCI-Béticas2 stacked section. Arrows point to the Mid-Crustal Reflector (MCR). Note the obliquity of the reflections above and below it.

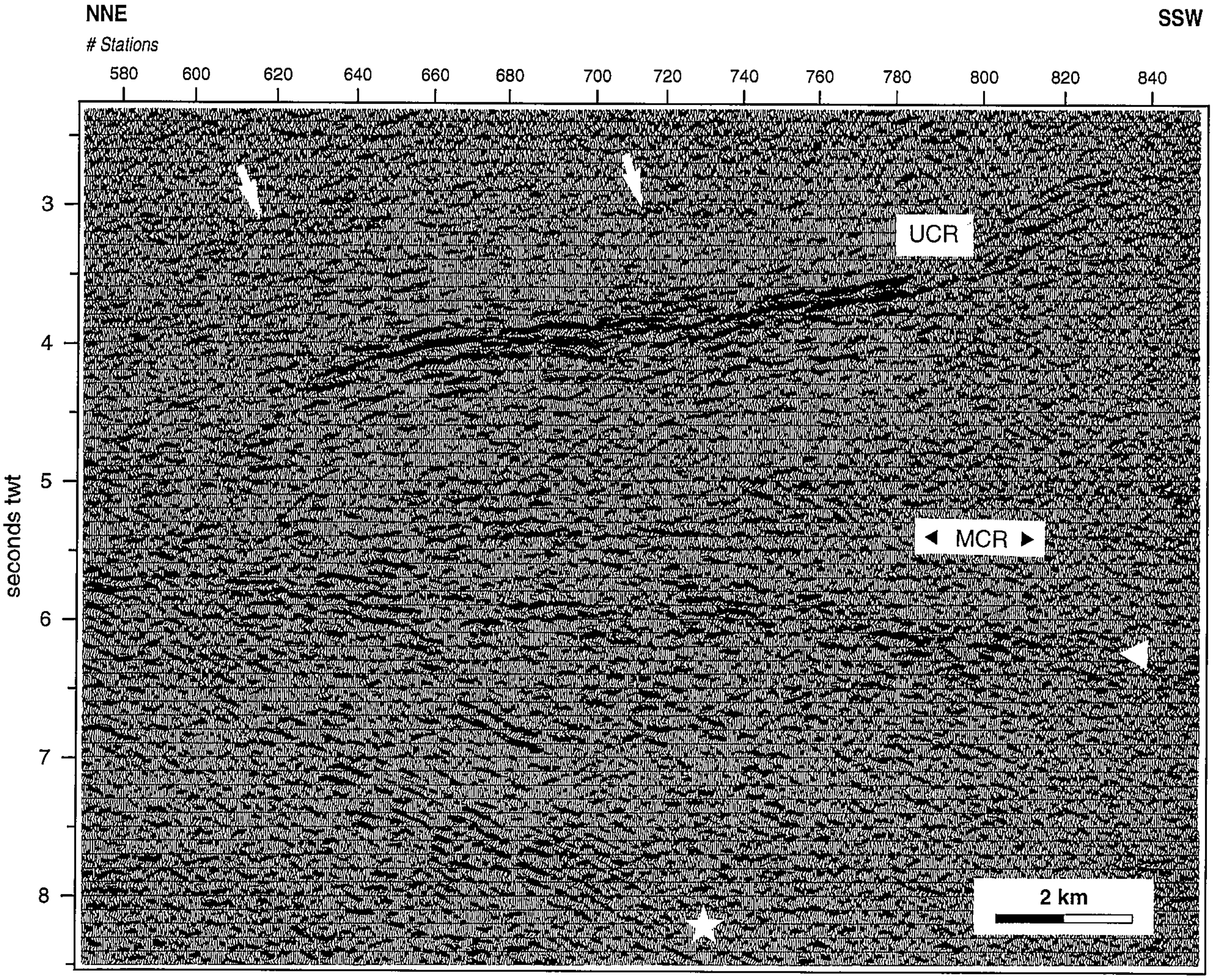

Figure 8.- Enlarged window of the ESCI-Béticas2 stacked section, showing the Upper Crustal Reflector (UCR) and the Mid-Crustal Reflector (MCR). Arrows indicate subhorizontal reflections in the uppermost crust. Low and intermediate dipping segments of different SSW-dipping reflection bands are shown by a triangle and star, respectively.

Reflector) in the line drawing in Fig. 6, separates two crustal levels with different reflectivity patterns and is oblique to the reflection bands in both the upper and lower crustal levels (Fig. 7).

The upper crustal level is fairly transparent with the exception of a few NNE-dipping reflection bands, some of which coalesce with the Mid-Crustal Reflector (Fig.7). None of these bands can be traced up to the surface, not even the most conspicuous one, the so-called UCR (Upper Crustal Reflector, García-Dueñas *et al.*, 1994), which evanesces above 3 s TWT (Fig. 5). Other scarce reflections, both variably dipping and subhorizontal, discontinuous and of lesser amplitude, complete the seismic fabric of the upper crustal level. In general they are distributed above the domain with NNE-dipping reflections, as is the case of the subhorizontal reflections lying above the Upper Crustal Reflector between stations 600 and 800 at 3 s TWT (Fig. 8).

In the lower crustal level, seismic refraction data reveal the absence of a level with velocities appropriate to the lower crust (Banda *et al.*, 1993), leading us to use the term "deep crust", in the broad sense of Holbrook *et al.* (1992), for the crust below the Mid-Crustal Reflector. This crustal level, unlike the upper crust, is highly reflective, although its reflectivity varies laterally from a SSW-domain of laminated crust to a NNE-domain of less reflective crust. The boundary between the two domains coincides with a SSW-dipping band of discontinuous, low-amplitude, short reflections that penetrates the entire deep crust and appears to merge with the Moho (below station 1100, at 10.5 s TWT) and continue towards the SSW, where there are reflections with similar characteristics in the mantle (Fig. 5). The NNE domain is less reflective and is characterised by bands of discontinuous reflections dipping towards the SSW, which locally appear as high-amplitude reflections (Fig. 8). The SSW-domain, on the contrary, has broad areas of laminated crust with densely-packed reflections that disappear as they approach the boundary of the NNE domain. The attitude of the seismic fabric in this domain varies laterally: between stations 1000 and 1300 the reflections systematically dip NNE, while between stations 1300 and 1500 they are subhorizontal and between 1500 and the SSW end of the section, they gently dip SSW. In summary, the organisation of this SSW domain reproduces the geometry of a large-scale gentle antiform (Fig. 5). In this last sector the presence of local hyperbola-shaped events characteristic of a diffractive crust are noteworthy.

Discussion

Remarks on the origin of Late Tortonian folds

Several processes have been invoked to explain the origin of the Late Tortonian folds. As a first step, two possibilities will be examined: a) folds produced by isostatic rebound subsequent to the extensional denudation generated by the Filabres extensional system (Galindo-Zaldívar *et al.*, 1989; Galindo-Zaldívar, 1993); b) folds produced in a N-S contractional event (Weijermars et al., 1985). Another interpretation suggests that these folds were generated as accommodation folds associated to the Filabres extensional system, later being modified during a Quaternary contractional episode (Jabaloy-Sánchez, 1993). Since the main Filabres extensional detachment footwall ramp (see Fig. 2) was horizontal on a shallow sea floor just before the Tortonian (García-Dueñas *et al.*, 1992), an isostatic rebound as the main origin for the formation of the Late Tortonian folds may be discarded. In addition, the folds are oblique or longitudinal to the Filabres detachment extension direction and are generally north-vergent. Moreover, the emersion of the Nevado-Filábride units from the Tortonian (Rodríguez-Fernández & Sanz de Galdeano, 1992) to the present, without these reliefs being in general limited by normal faults, supports the hypothesis of a contractional origin. The existence of conjugate sets of strike-slip faults (Montenat & Ott d'Estevou, 1990), together with palaeostress estimates (Estévez & Sanz de Galdeano, 1983; Galindo-Zaldívar *et al.*, 1993), also points to the presence of approximate NNW-SSE contraction in nearby areas within the period under consideration.

The seismic image of the upper crust beneath the Nevado-Filabrides suggests that the Sierra de los Filabres and Sierra Nevada anticlines do not continue beyond the first few seconds of depth (cf. Galindo-Zaldívar *et al.*, 1995). These data, along with the morphology of the folds, allow us to interpret these structures as contractional fault-related folds.

The deduced shortening comprises some 8 km, taking as a reference the length of the highest-preserved level of the Veleta unit from among the axial traces of the Caniles and Ugíjar synclines (Fig. 4). Nevertheless, the increase in area above the horizontal datum at the height of the Caniles syncline hinge is quite considerable (≈160 km^2). One possibility, assuming plane strain, is that the disappearance of the folds could have occurred some 20 km beneath the datum, thus presupposing detachment folds (Mitra & Namson, 1989). This suggestion is not likely, however, because there are no known lithological changes towards the anticline cores that might indicate a marked decrease in rock strength, the presence of which is a specific characteristic of detachment folds (Homza & Wallace, 1995). In addition, the supposition of a detachment inside the reflective deep crust (top located at 6 s TWT≈18 km; Fig. 5) is not congruent with the seismic image, since the first subhorizontal reflections, which coincide with the disappearance of the shallow domain marked by reflections dipping in opposite directions, are located between stations 600 to 1500 at around 3 and 4 s TWT (≈9 and 12km), respectively (Figs. 5 and 8). The Upper Crust Reflector underlies such flat reflections and is not folded by the Sierra de los Filabres anticline. Moreover, the gentle antiform-shaped feature described above within the reflective deep crust, between stations 1000 and 1700, is clearly decoupled from the shallow Late Tortonian folds, because this antiform-shaped feature has a wavelength four times larger and its hinge zone is unconformably below the Ugíjar syncline.

The first appearance of subhorizontal reflections below the Sierra de los Filabres and Sierra Nevada anticli-

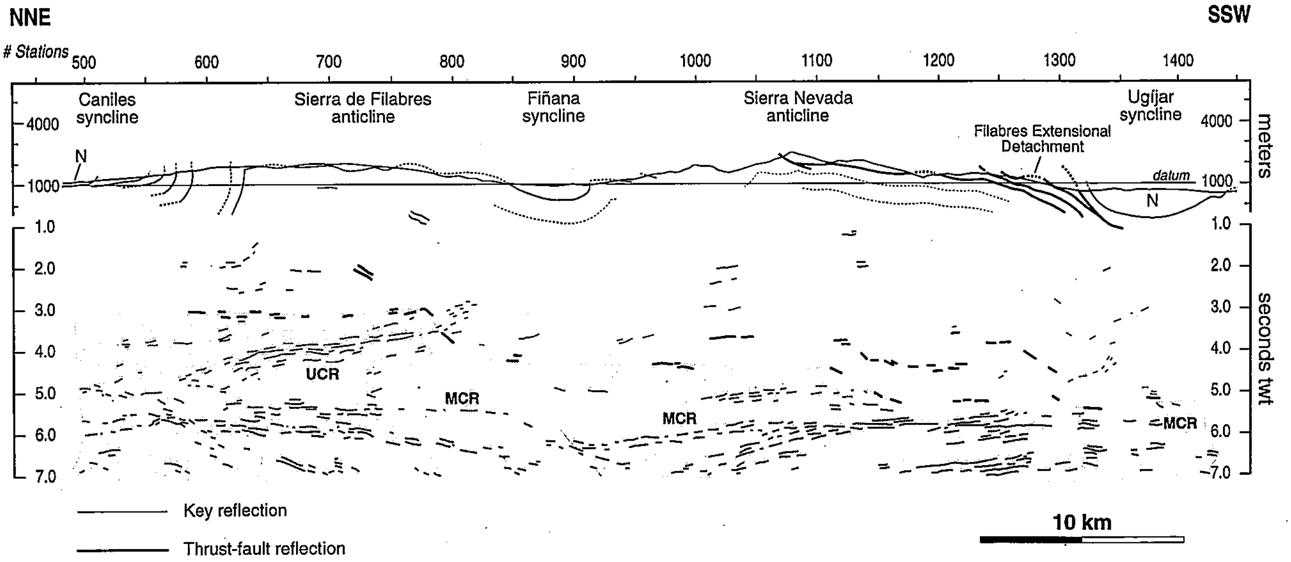

Figure 9.- Schematic upper crustal cross-section along the central segment of the ESCI-Béticas2 profile. The section shows interpreted upper crustal reflections of the profile displayed in Fig. 6. In the uppermost part of the section structures from surface geology are also included for reference. The crust below the sole thrust has been shaded.

nes could be interpreted as flat segments of a staircase fault. Ramps can be ascribed to SSW-dipping, low-amplitude reflections connecting flat reflections located at different depths (Fig. 9). We should point out that the two large anticlines could correspond to hanging-wall anticlines related to footwall ramps, although their marked asymmetry appears to have also been influenced by forelimb thrusts and propagation folds. The outermost part of the sole thrust probably coincides with the subhorizontal reflections lying immediately over the Upper Crustal Reflector, while in the southern sector of the cross-section it lies close to the Mid-Crustal Reflector. It is important to note that many of the key surfaces affected by these structures were not horizontal at the beginning of the folding, but rather generally dipped towards the ENE (see above sections). On the other hand, it is possible that the ramp-and-flat thrust geometry determining the folding could be partially ascribed to previous low-angle normal faults from the Filabres extensional system (cf. Jabaloy-Sánchez, 1993). This possibility, toge ther with the oblique directions of transport between the two episodes, means that the resulting geometry cannot be balanced in two dimensions.

The upper crust

The upper crust in the ESCI-Béticas2 profile is generally transparent or quasitransparent. This feature is probably due both to the crustal structure and to an effect derived from the seismic method itself. Thus, in relation to this latter effect, the progressive density increase towards deeper layers may result in the appearance of more continuous reflections (the Fresnel-zone effect; Mooney, 1989). However, since the increase in reflector continuity does not occur gradually, this possibility is not an important factor. The widespread existence of brittle deformations, including high- and low-angle normal faults, as well as the large-wavelength folds that affect most of this domain, are structures that typically produce interference and loss of the acoustic signal (Brown et al., 1983, among others). In addition, layered crystalline rocks generally have reflection coefficients three times lower than stratified sedimentary rocks (Smithson & Johnson, 1989). The lithological homogeneity of the stratigraphic sequence in the lowest Nevado-Filabride unit, the Veleta unit, could also contribute to the low reflectivity of the upper crust.

The Upper Crustal Reflector is the most noticeable reflection band in the upper crust. We agree with García-Dueñas *et al.* (1994) in that it may be interpreted as a mylonitic band capable of generating marked seismic anisotropy (cf. Smithson & Johnson, 1989). Taking into account the structure of the Nevado-Filabrides shear zones seen on the surface (Fig. 2), the NNE dip of the Upper Crustal Reflector may be due to tilting and/or isostatic rebound related to the Filabres extensional system.

The deep crust

The presence of a reflection band in intermediate layers of the crust (Mid-Crust Reflector) is one of the most characteristic aspects of the ESCI-Béticas2 profile. The discrepancy between the Mid-Crust Reflector (5.5-6.5 s TWT≈18 km) and the position of the prominent upper-crustal reflector at 10-12 km examined by Banda et al. (1993) in two refraction profiles, seems to indicate that the former is not the boundary between zones with significant contrasts in velocity. As has been made clear in many continental areas, the boundary between a laminated deep crust and a transparent upper crust cannot be equated to any specific velocity limit (Mooney & Brocher, 1987). In consequence, the Mid-Crustal Reflector cannot correspond to compositional discontinuity, but rather to a rheological discontinuity.

Beneath the Mid-Crustal Reflector, the crust extends to 11 s TWT, where the reflection Moho is located (Fig. 6). The high reflectivity of the crustal segment in the southwestern domain of the profile can be interpreted in terms of a stratified crust with alternating layers with significant velocity contrasts. Among the various proposals that have been made in different regions to explain this situation, we would like to emphasise the quite probable enhancement of the deep crustal reflectivity by ductile shearing. In fact, the expected low viscosity of the deep crustal materials as a function of the existing heat flow (Polyak *et al.*, in press), leads one to expect, on the scale of the entire lower crust, the generation of subhorizontal anisotropic fabrics (Mooney & Meissner, 1992). In addition, the existence of a subhorizontal Moho beneath regions with different rates of supracrustal extension implies regional-scale flow within the crust (Block & Royden, 1990).

During the Miocene extension, the upper crustal layers of the Alborán Domain underwent an exhumation of several kilometres. This suggests that the subhorizontal position of the Moho must be Miocene to Recent in origin and that the generation of this structure must have been accompanied by large-scale intracustal flow.

Taking into account that the laminated fabric of the deep crust seems interrupted by less marked, SSW-dipping reflection bands, these could be ascribed to younger shear zones. The recognisable offset shown by the Mid-Crustal Reflector (Figs. 5 and 7) and the reflection Moho (Figs. 5 and 6) suggests an extensional character for these bands. The NNE dip of the laminated fabric between stations 1000 and 1300 could represent a rollover anticline structure (Fig. 5). We favour a Plio-Quaternary age for these SSW-dipping bands in agreement with the NW-SE trending, high-angle normal faults that are widely exposed in the study area and that produce NE-tilting of the Pliocene sediments.

Conclusions

In the ESCI-Béticas2 profile two subparallel reflection bands are especially noteworthy due to the great amplitude and lateral continuity of their reflections. The uppermost band (the Mid-Crustal Reflector), separating two crustal levels with different reflectivity patterns, lies between 5.5 y 6.5 s TWT. The deeper band lies around

11s TWT and must be the reflection Moho, in accordance with results from previous seismic refraction soundings. The highly reflective deep crust appears sandwiched between two fairly transparent major levels: the upper crust and the lithospheric mantle, respectively. Together with this vertical zoning, the existence of lateral changes within the deep crust should also be noted, from a SSW domain characterised by a laminated fabric to a less reflective NNE domain. The boundary between these two domains coincides with a SSW-dipping band of low-amplitude reflections.

Late Tortonian folds greatly control the outcrop distribution of the Nevado-Filabride units and are therefore a key structure in understanding the tectonic fabric of the upper crust. They are north-vergent, large-scale (W=20-25 km) open folds that deform the Serravallian Filabres extensional system and older ductile shear zones separating the three main Nevado-Filabride units. We discard that the two main culminations (Sierra de los Filabres and Sierra Nevada anticlines) were generated by isostatic rebound in response to Serravallian extensional denudation. On the contrary, we favour the interpretation that these structures correspond essentially to hanging-wall anticlines related to footwall ramps, their remarkable asymmetry being probably in places influenced by propagation folds. Ramp and flat geometry can be attributed, respectively, to subhorizontal and SSW-dipping discontinuous reflectors located at 3-5 s TWT below the outcropping Nevado-Filabride complex.

The Upper Crustal Reflector, the most conspicuous reflection band within the upper crust, is not folded by the Sierra de los Filabres anticline, which is located below the folded uppermost crustal level. Due to its highly reflective character and in line with a previous interpretation (García-Dueñas *et al.*,1994), we suspect the Upper Crustal Reflector is a mylonitic band. The NNE dip of the Upper Crustal Reflector compares well to other Nevado-Filabride shear zones widely exposed at the surface where they regionally dip towards the NE as a result of large-scale tilting and/or isostatic rebound during the development of the Filabres extensional system.

The Mid-Crustal Reflector cannot correspond to any specific velocity boundary (compositional discontinuity), but instead to a rheological discontinuity. The Mid-Crustal Reflector and the laminated fabric of the deep crust are cut by poorly marked reflection bands dipping towards the SSW. Such bands also cut the reflection Moho in places, which shows apparent normal offsets. Given that the reflection Moho probably acquired its subhorizontal geometry in the Miocene, we interpret the SSW-dipping bands as extensional shear zones of probable Plio-Quaternary age similar to the high-angle fault system known at the surface.

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