

The Alpujárride Complex structure and its contribution to the ESCI-Béticas2 deep seismic reflection profile interpretation (Alborán Domain, Betic Chain)

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Abstract: Profile ESCI-Béticas2 crosses the South Iberian and Alborán Domains in a NE-SW direction, reaching the Mediterranean coast. Below the Alpujárride Complex, this profile shows an almost transparent upper crust, while the lower part of the crust shows moderate reflectivity. The tectonometamorphic evolution of the Alpujárride Complex, which includes a complex succession of contractional and extensional events, constrains the seismic interpretation below the unreflexive layer. The pre-Miocene evolution of the Alpujárride Complex preserves a high pressure event followed by an extensional episode, in turn followed by a second contractional event, yet still before the Miocene. During the Miocene, the rifting of the Alborán Domain occurs, giving way to the Alborán Basin. In its basement, the resulting geometry of the central Betics consists of extensional units bound by brittle faults belonging to two subperpendicular Miocene extensional systems. The lower part of the continental crust is believed to have been affected by the same extensional regime.

Keywords: Alpujárride Complex, Betics, tectonometamorphic evolution, geological constraints, seismic interpretation.

Resumen: El perfil ESCI-Béticas2 atraviesa los dominios Sudibérico y de Alborán siguiendo una dirección NE-SW hasta alcanzar la costa mediterránea. Por debajo del Complejo Alpujárride, este perfil muestra una corteza superior casi transparente, mientras que la parte inferior de la corteza presenta una reflectividad moderada. La evolución tectonometamórfica del Complejo Alpujárride, que incluye una compleja sucesión de eventos contractivos y extensionales, condiciona la interpretación sísmica por debajo del lecho no reflectivo. De la evolución premiocena del Complejo Alpujárride se ha preservado un evento de alta presión seguido de un episodio extensional, el cual es seguido por un segundo evento contractivo aún anterior al Mioceno. Durante el Mioceno tuvo lugar el rifting del Dominio de Alborán que dió lugar a la cuenca de Alborán. En el basamento, la geometría resultante en las Béticas centrales consiste en unidades extensivas limitadas por fallas frágiles pertenecientes a dos sistemas extensionales subperpendiculares de edad miocena. Se cree que la parte inferior de la corteza continental fue afectada por el mismo régimen extensional.

Palabras clave: Complejo Alpujárride, Béticas, evolución tectonometamórfica, condicionantes geológicos, interpretación sísmica.

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The overall objective of the ESCI-Béticas project is the seismic imaging of the crust of the Betic Chain and Alborán basin, situated in the westernmost end of the Alpine orogenic belt. The first part of the project resulted in the collection of two land reflection profiles: line ESCI-Béticas1 extends from the Guadalquivir foreland basin to the Baza basin, crossing the cover of the South Iberian Domain (Prebetic and Subbetic units), whereas line ESCI-Béticas2 (Profile 2 hereafter) cuts across the Alpine metamorphic complexes of the Betics (Fig. 1). The technical characteristics of these profiles (data ac-

quisition and processing) as well as the unmigrated stacked seismic reflection for most of the profile segments can be found in García-Dueñas *et al.* (1994).

Profile 2 crosses the South Iberian and Alborán Domains in a NE-SW direction, reaching the Mediterranean coast (Fig. 1). In its northern part, seismic information about the boundary between both domains is not available, because of the poor quality of the stacked section along the Neogene to Recent deposits of the Baza basin. Further to the South, the profile crosses the Alborán Domain, which consists mainly of three complexes of varia-

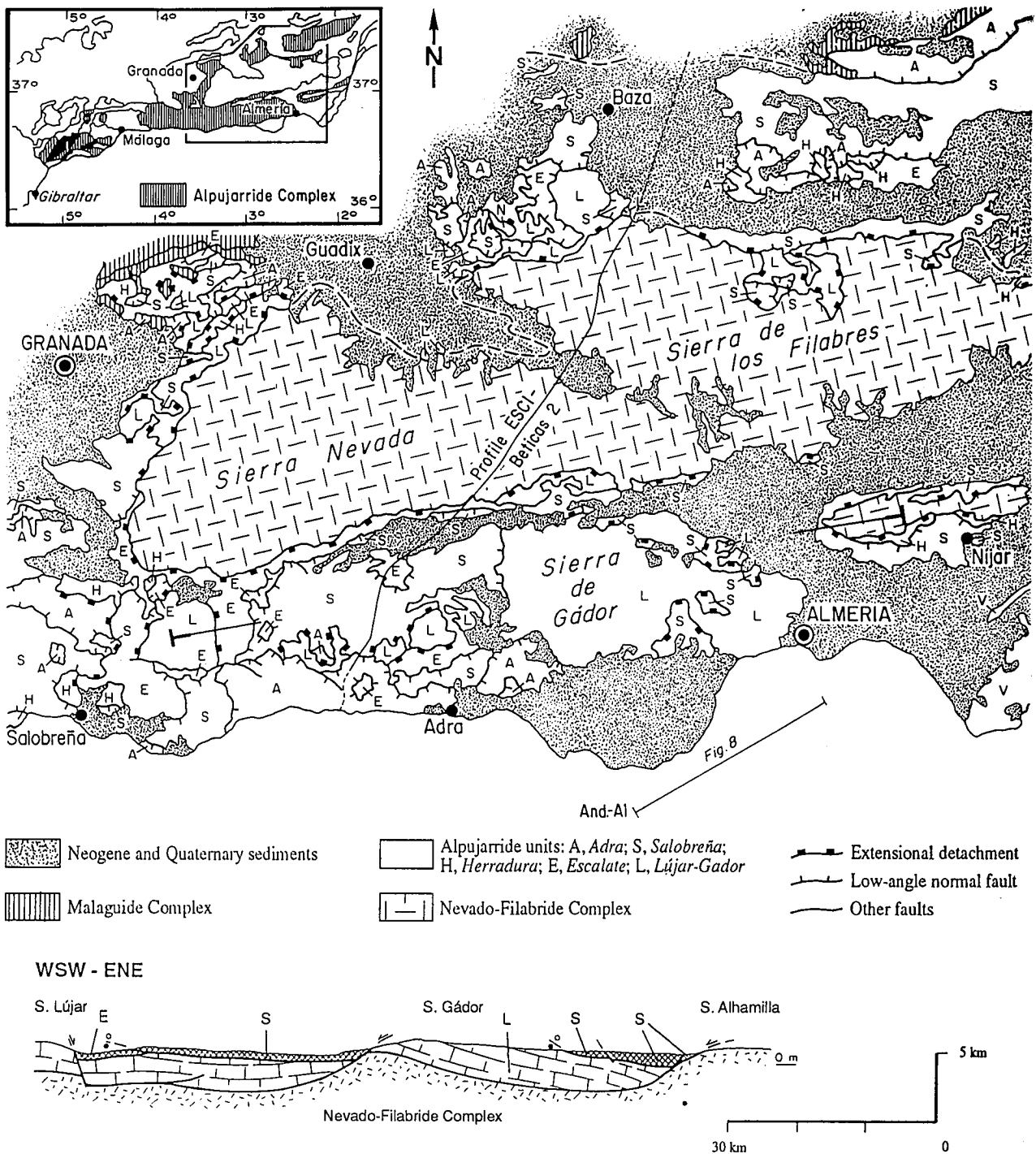


Figure 1.- Tectonic map of the central Betics. Name of units according to Azañón *et al.* (1994). Continuous line shows portion of Profile ESCI-Béticas2 presented as line drawing in Fig. 2. WSW-ENE cross-section illustrating the Filabres normal fault system developed in the Contraviesa area (based on García-Dueñas *et al.* 1992).

ble metamorphic grade – from bottom to top, the Nevado-Filábride, the Alpujarride, and the Maláguide complexes. In this segment, the profile runs along the Alpujarride and Nevado-Filábride complexes and reveals an almost transparent upper crust, whereas the lower part of the crust shows moderate reflectivity (Fig. 2). As any reflection can be traced to the surface, superficial geology must be used to constrain the seismic interpretation below the un-reflective layer. The aim of this paper is therefore to des-

cribe the structure and the tectonic evolution of the Alpujarride complex, on the basis of selected references together with our own data. The complementary segment of the profile in which the Nevado-Filábride complex crops out is discussed by Martínez-Martínez *et al.* (this vol.). Our article focuses specifically on the Alpujarride structure of the southern part of Profile 2, as the Alpujarride Complex near the Baza Basin (Fig. 1) was the subject of a recent structural study (Crespo-Blanc, 1995).

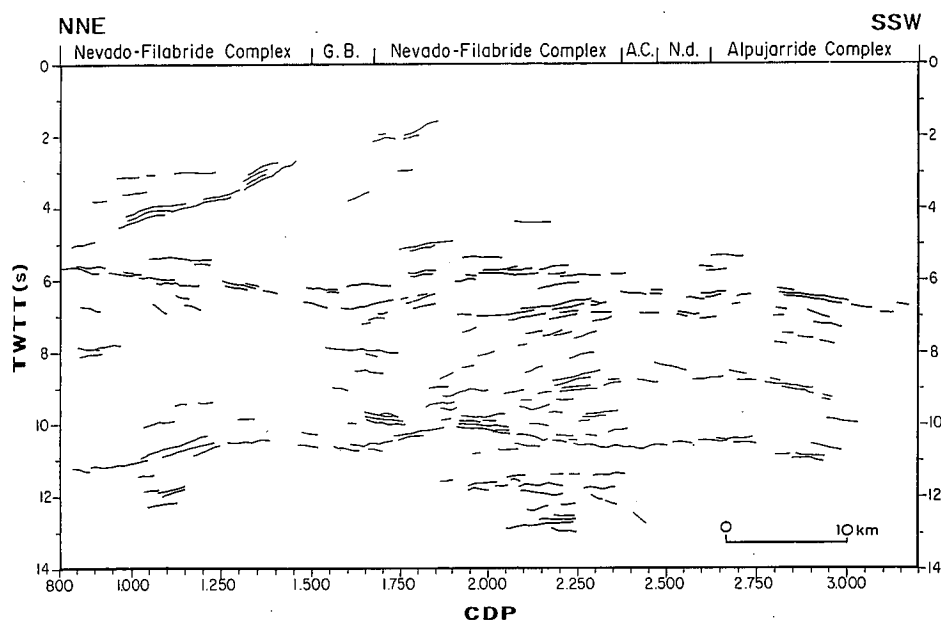


Figure 2.- Line drawing of part of Profile ESCI-Béticas2, according to García-Dueñas *et al.* (1994). Localisation on figure 1 (thick line).

Geological setting

The Betic and Rif mountain chains, respectively North and South of the Alborán basin, are linked by the so-called Gibraltar Arc. In this arc various pre-Miocene tectonic domains can be differentiated. The Alborán crustal Domain (Balanyá & García-Dueñas, 1988) corresponds to the internal zones of the Gibraltar Arc; the external part of the arc comprises the South Iberian and Maghrebian palaeomargins, which crop out in southern Spain and northern Africa, respectively, and consist of autochthonous and parautochthonous almost unmetamorphosed Mesozoic and Tertiary cover overlying a Variscan basement. A Flysch Complex located SE of the South Iberian margin and WNW of the Alborán Domain in Spain, and North of the Maghrebian margin in Africa, was deposited in a deep trough of attenuated crust (Biju-Duval *et al.*, 1978; Durand-Delga, 1980; Dercourt *et al.*, 1986). In the Lower Miocene, the compressive front of the Gibraltar thrust, which represents the outer limit of the Alborán Domain, began to migrate outwards through its footwall into the Flysch trough, leading to the formation of a thrust stack that collided with the Maghrebian and South Iberian palaeomargins (Balanyá & García-Dueñas, 1988; Balanyá 1991). Meanwhile, the Alborán basin formed in the inner part of the Gibraltar Arc and crustal thinning took place in the whole Alborán Domain (García-Dueñas *et al.*, 1992).

The pre-Miocene evolution of the Alborán crustal Domain includes a complex succession of contractional and extensional events (Balanyá *et al.*, submitted). The Alpine metamorphism evolves from a high pressure episode (Bakker *et al.*, 1989; Goffé *et al.*, 1989) followed by an almost isothermal pressure decrease, both in the Nevado-Filábride and Alpujarride complexes (e.g. Gómez-Pugnaire & Fernández-Soler, 1987; Tubía & Gil Ibarguchi, 1991; Azañón *et al.*, 1992; Balanyá *et al.*, 1993; García-Casco *et al.*, 1993; Soto & Azañón, 1994;

Azañón & Alonso-Chaves, 1996; Azañón *et al.*, 1996, 1997). In contrast, the overlying rocks of the Maláguide Complex conserve Variscan orogenic features (Chalouan & Michard, 1990) and its Mesozoic-Palaeogene cover has not suffered pervasive deformation or metamorphism. The high pressure mineral assemblages of the Alpujarride units are believed to have formed during a former crustal stacking, followed by a ductile regional thinning (Balanyá *et al.*, 1993; Azañón & Alonso-Chaves, 1996; Azañón *et al.*, 1996, 1997). Yet still before the Miocene, a second contractional event led to the north-vergent folding of the thinned metamorphic sequences (Balanyá *et al.*, 1987; Simancas & Campos, 1993; Azañón & Alonso-Chaves, 1996; Azañón *et al.*, 1996, 1997) and the overthrusting of medium and high grade metamorphic rocks onto lower grade rocks (Aldaya *et al.*, 1979; Tubía *et al.*, 1992; Azañón *et al.*, 1994; Balanyá *et al.*, submitted).

During the Miocene, the resulting Alborán Domain stack was again attenuated through extensional detachment and low-angle normal faulting (García-Dueñas *et al.*, 1986, 1992; Galindo-Zaldívar *et al.*, 1989; Platt & Vissers, 1989). The extensional denudation processes, which resulted in the opening of the Alborán Sea (Comas *et al.*, 1992), consisted of successive episodes with different extensional directions. Thus, the Alborán Domain units are extensional units, bounded by brittle shear zones in the central Betics (Fig. 1) (García-Dueñas & Martínez-Martínez, 1988; Crespo-Blanc *et al.*, 1994; Alonso-Chaves *et al.*, 1993; Crespo-Blanc, 1995), and with ductile and fragile boundaries in the western Betics (García-Dueñas & Balanyá, 1991; Balanyá *et al.*, 1993). Finally, from the Late Tortonian to the Pliocene, the Alborán region underwent continuous N-S to NW-SE compression, and the extensional systems were folded (mainly open plurikilometric E-W trending folds) and faulted (Weijermars *et al.*, 1985; Comas *et al.*, 1992; Rodríguez-Fernández & Martín-Penela, 1993).

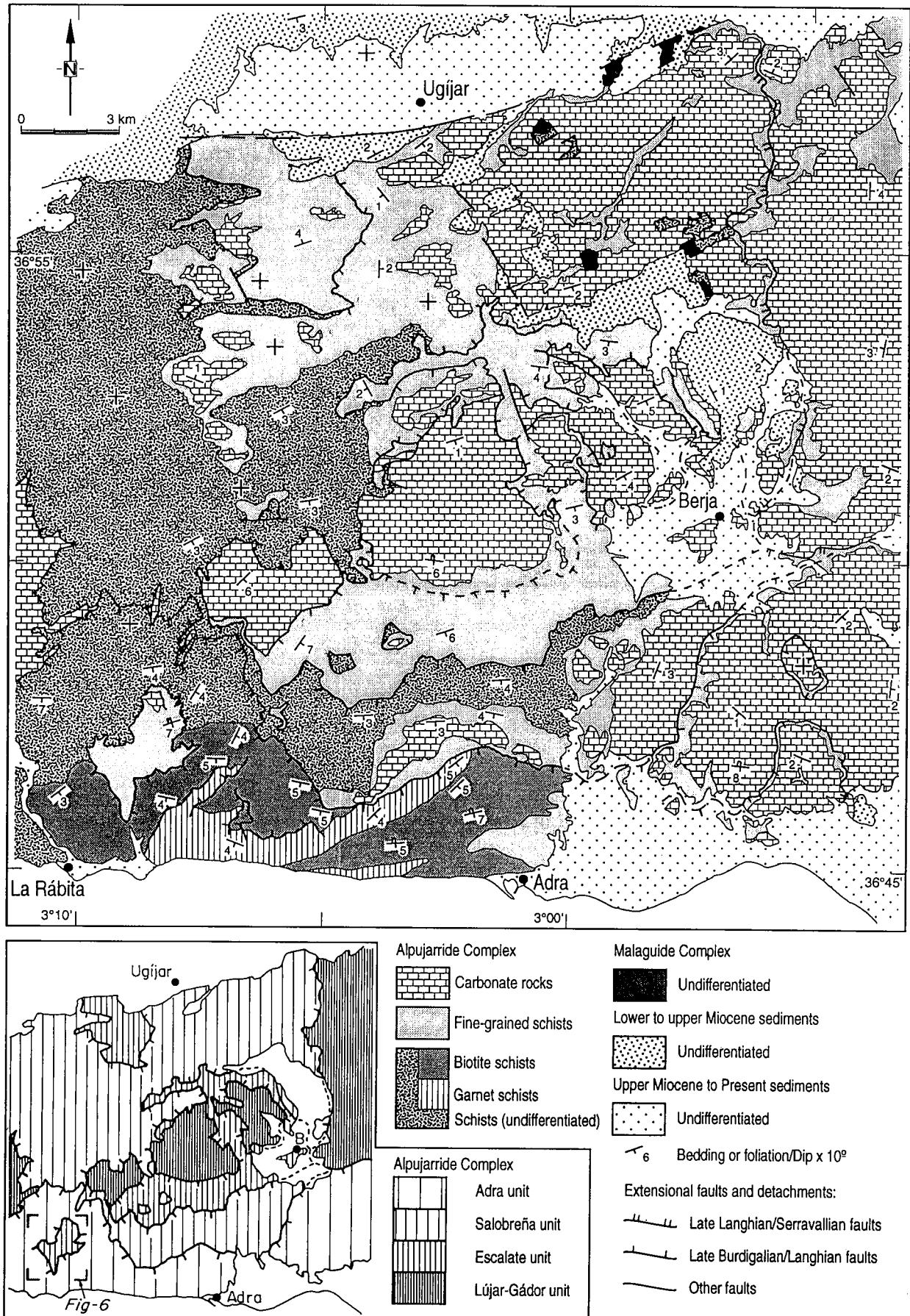


Figure 3.- Geological map of the Contraviesa area according to Aldaya *et al.* (1983a and b), modified. Name of units according to Azañón *et al.* (1994).

Structure of the Alpujárride units outcropping around Profile 2

The Alpujárride complex has classically been considered a nappe-stack, although recently it was shown that the present units are the result of Miocene extensional deformation of this nappe-stack, giving way to the dismembering of the nappes in brittle and ductile conditions (García-Dueñas *et al.*, 1992). In the central Betics, across which Profile 2 runs, the characteristic lack of continuity of the Alpujárride tectonic units (shown in Fig. 1) evidences the omissions originated in extensional conditions. Aldaya *et al.* (1979) grouped these units—at that time, nappes—according to their relative position within the Alpujárride complex, the stratigraphic sequences, and the distribution of the metamorphic mineral assemblages. On the basis of these data, Azañón *et al.* (1994) use the metamorphic record with particular emphasis on the distribution of HP-LT mineral assemblages to discriminate between the Alpujárride units, formed under very different P-T conditions, although their tectonometamorphic evolution is similar. The five major tectonic units related with the nappe-stacking of the Alpujárride Complex, as established by Azañón *et al.* (1994), appear in Figs. 1 and 3. Nevertheless, work in progress reveals that the similarity of the HP-LT record in the uppermost units in the central Betics, that is, the Adra and Salobreña units, does not justify their distinction. These units probably represent the systematic repetition of a crustal element in the same structural level of the initial stack and need to be more clearly defined.

Table 1: Relationship between mineral growth and deformation phases in the fine-grained and garnet-bearing schists of Adra Unit.

Fine-grained schists (lower levels)			
	D1	D2	D3
Carpholite	—	—	—
Chloritoid	—	—	—
Kyanite	—	—	—
Chlorite	—	—	—
Phengite	—	—	—
Epidote	—	—	—
Rutile	—	—	—

Garnet-bearing schists (upper levels)			
	D1	D2	D3
Staurolite	—	—	—
Kyanite	—	—	—
Andalusite	—	—	—
Garnet	—	—	—
Plagioclase	—	—	—
Phengite	—	—	—
Chloritoid	—	—	—
Rutile	—	—	—
Ilmenite	—	—	—
Biotite	—	—	—

The structure of the Alpujárride complex will be discussed in two parts, by chronological order: a) the pre-Miocene ductile structures within each Alpujárride unit, and b) the Miocene extensional dismembering of the Alpujárride complex.

Pre-Miocene structures

Despite the omissions due to the Miocene extensional systems, a simplified standard section for most of the Alpujárride units can be established. It consists of a metapelitic pre-Permian basement, a Permo-Triassic metapelitic-psammitic-evaporitic sequence, and Middle to Upper Triassic carbonate rocks. Within the Palaeozoic schists of the uppermost unit (Adra unit), a garnet-bearing dark schist formation and a biotitic light-coloured schist and quartzite formation can be distinguished. The distribution of these formations South of Sierra Nevada, that is in the Contraviesa area, is represented in Fig. 3.

The main foliation S_2 , which draws kilometric-scale isoclinal rootless folds, is visible in all terms of the Alpujárride lithological sequence and can be recognised in each of the Alpujárride units on a regional scale. S_1 is a relic foliation, observed only in lenticular domains limited by the main foliation S_2 or preserved in porphyroblasts like garnet or kyanite.

It is beyond the scope of this paper to present the metamorphic evolution of each formation of the Alpujárride units that crop out along Profile 2. We do present however, in Table 1 and Fig. 4, the metamorphic evolution of the fine-grained schist formation and the uppermost levels of the garnet-bearing dark schist formation of the Adra unit, in order to illustrate the relationship between the mineral growth and deformation phases, and the P-T path of a typical Alpujárride unit outcropping along Profile 2. A more complete discussion of these data, based on metamorphic assemblages and P-T calculations, can be found in Azañón (1994) and in Azañón *et al.*, (1996). The Permo-Triassic fine-grained schists (usually called "phyllites" elsewhere in the Alpujárride Complex) include kyanite and carpholite-bearing assemblages ($P > 8\text{Kb}$, $T \sim 425^\circ\text{C}$), whereas the Palaeozoic schists present garnet-kyanite-andalusite-staurolite-phengite-biotite-rutile-ilmenite-quartz±chloritoid mineral associations. GARM (garnet-muscovite) and GRAIL (garnet-rutile-aluminosilicate-ilmenite) geothermobarometers applied in samples of the garnet schists gave temperature and pressure ranges of $540\text{--}600^\circ\text{C}$ and $9.5\text{--}11\text{Kb}$ (Azañón, 1994; Azañón *et al.*, 1996). Thus, the Adra unit underwent high pressure metamorphism during a first Alpine contractional event (D1 of Fig. 4). This high pressure event was followed by decompression at nearly isothermal conditions, associated with an important blastesis stage during which S_2 developed (Table 1 and Fig. 4). The almost isothermal decompressional P-T path during S_2 development obtained for the Adra unit is similar for most other the Alpujárride units. Taken together with the close proximity throughout the sequence of the prograde metamorphic mineral associations and the S_2 parallelism with both the lithological contacts and the metamorphic

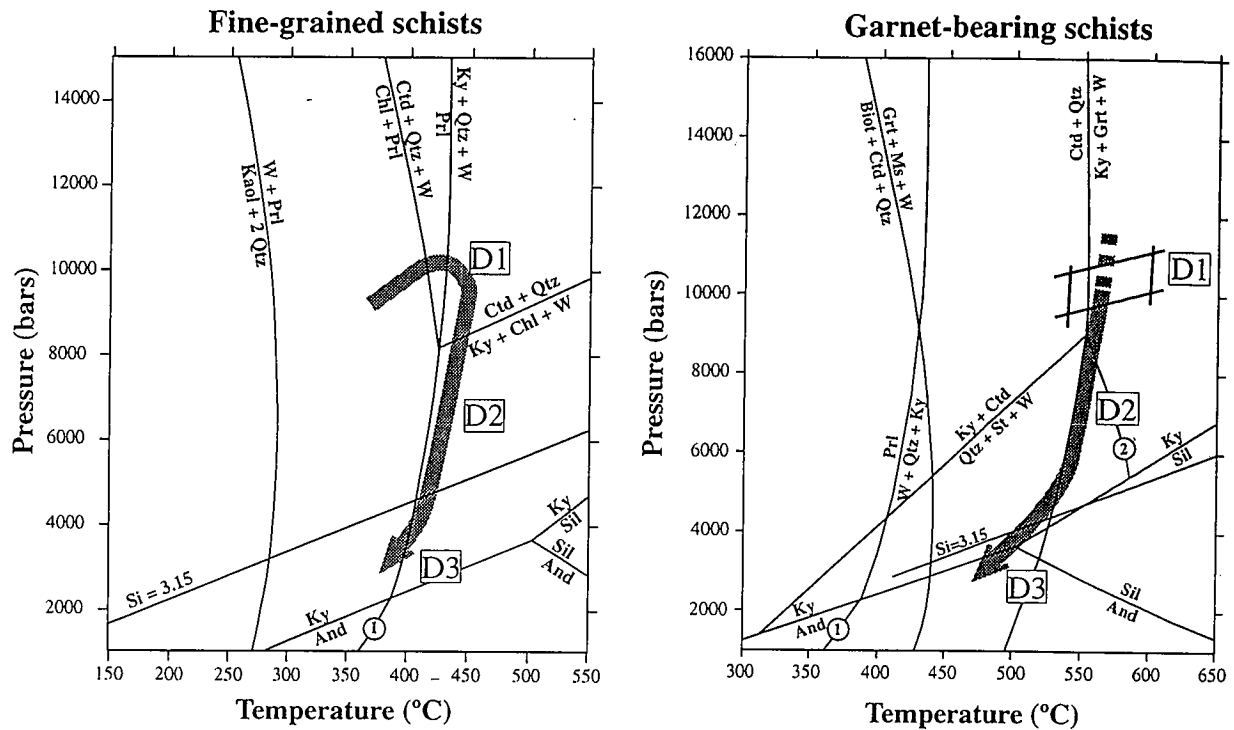


Figure 4.— P-T-t paths from fine-grained schists and garnet-bearing schists of Adra unit. Phase equilibria estimated by calculation using PTAX, a further development of GEO-CALC software (Brown *et al.*, 1988), with the internally consistent data set by Berman (1988). Activity models for Fe/Mg carpholite, chloritoid, and chlorite are based on simple ideal site solution. The garnet activity model used is from Ganguly and Saxena (1985). All calculations were made with the chemical system $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-MgO-FeO-K}_2\text{O-H}_2\text{O}$. P and T conditions in the garnet bearing schists (rhomb) were obtained with a GRAIL geobarometer (Bohlen *et al.*, 1983) and GARM geothermometer (Hynes and Forest 1988), according to Azañón *et al.* (submitted b). D1: high pressure event and formation of an S1 relic foliation. D2: main foliation development during decompression. D3: recumbent fold event. Abbreviations: And: andalusite; Biot: biotite; Chl: chlorite; Ctd: chloritoid; Grt: garnet; Kaol: kaolinite; Ky: kyanite; Ms: muscovite; Prl: pyrophyllite; Qtz: quartz; Sill: sillimanite; St: staurolite; W: water. Si=3.15 content of phengite. Reaction list (assemblages on right are stable at high temperature): 1) $\text{Prl} = \text{And} + \text{Qtz} + \text{W}$; 2) $\text{St} + \text{Qtz} = \text{Grt} + \text{Ky} + \text{W}$.

zones, the P-T path demonstrates the extensional character of the main S_2 foliation in the Alpujarride Complex (Balanyá *et al.* 1993; Azañón & Alonso-Chaves 1996; Azañón *et al.* 1996, 1997). The main foliation S_2 is therefore associated with a regional thinning related to overall metamorphism in nearly isothermal decompression conditions.

The S_2 foliation—and consequently the metamorphic isogrades and lithologic sequences—are deformed by large-scale overturned folds. Around Profile 2, the geometry of these folds is well illustrated in the higher Alpujarride units. The lithologic sequence of the Adra unit depicts a large-scale overturned syncline whose core is occupied by Permo-Triassic fine-grained schists North of Adra, and by Triassic carbonate rocks to the East (Fig. 3). Below this main fold, and separated by an extensional fault, another syncline appears in the Salobreña unit, with a core of carbonate rocks. Cross-section A-A' of Fig. 5 illustrates the described geometry. The lithologic sequence is locally inverted by this folding phase: for example, in the Escalate unit of the Rambla de Huarea window, the Permo-Triassic fine-grained schists are situated above the Triassic carbonate rocks (Fig. 6).

These folds have been described in all the Alpujarride units of the central and western Betics, and their fold axes range from NE-SW to E-W (e.g. Avidad & García-Dueñas, 1981; Balanyá *et al.*, 1993; Simancas & Cam-

pos, 1993; Azañón *et al.*, 1996, 1997). Nevertheless, as these folds are strongly asymmetric and show mainly normal limbs, the lithostratigraphic sequence in most Alpujarride units is rightside up, the grade of metamorphism increasing downwards (e.g. Balanyá, 1991; Azañón, 1994; Alonso-Chaves, 1995). The folds are associated with a penetrative crenulation cleavage (S_{en}). The recrystallisation coeval with the development of S_{en} depends on the structural level at which the folds occur. For example, in the Adra unit, the P-T fields during S_{en} formation for fine-grained schists and upper levels of the garnet-bearing schists are constrained by the respective appearance of syn- S_{en} kyanite and andalusite (Table 1 and Fig. 4). In the lowest levels of the same unit, Cuevas (1988) documented syn- S_{en} sillimanite-staurolite-bearing assemblages.

The presence of these large-scale E-W-directed folds affecting the main regional foliation make it clear that there was a second compressional event. This second event may be associated with a nappe-forming event responsible for the general reorganisation of the initial Alpujarride stack and the superposition of various sheets with different metamorphic records. For example, in the Alpujarride units that crop out around Profile 2, the medium-to-high grade Palaeozoic rocks of Adra unit lie over the less metamorphosed rocks of the Lújar-Gádor unit ($P < 7\text{Kb}$, $T < 400^\circ\text{C}$ in the fine grained schists, Aza-

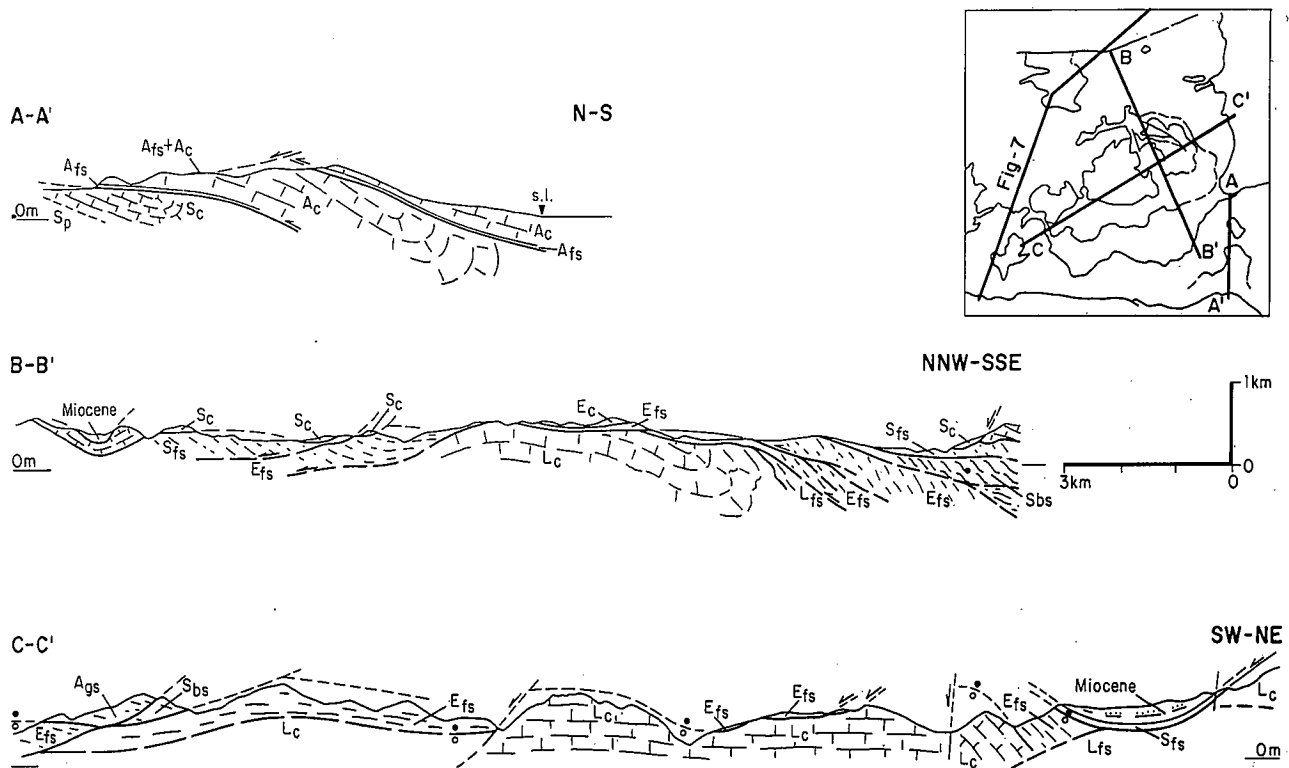


Figure 5. - A-A'. Cross-section illustrating the kilometric folding of the lithological sequence in Adra and Murtas units. B-B'. Geometry of the Contraviesa normal fault system, from cross-section parallel to the fault movement direction (according to Crespo-Blanc *et al.*, 1994). C-C'. Geometry of the Filabres normal fault system in the Contraviesa area, from cross-section parallel to the fault movement direction. Fault surfaces belonging to the Contraviesa normal fault system are cut by the faults with a SWward transport direction. The dips (foliation and low-angle normal fault) were calculated with vertical scale exaggeration. Solid and open circles indicate motion away from and towards the observer, respectively. A, Adra unit; S, Salobreña unit; E, Escalate unit; L, Lújar-Gádor unit; c, Carbonate rocks; fs, fine-grained schists; bs, biotite schists; gs, garnet schists.

ñón *et al.* 1994) (Figs. 1 and 3). On a larger scale, in the Betics, the structurally highest Alpujárride units show the highest P-T conditions (Aldaya *et al.*, 1979; Azañón *et al.*, 1994 and references therein).

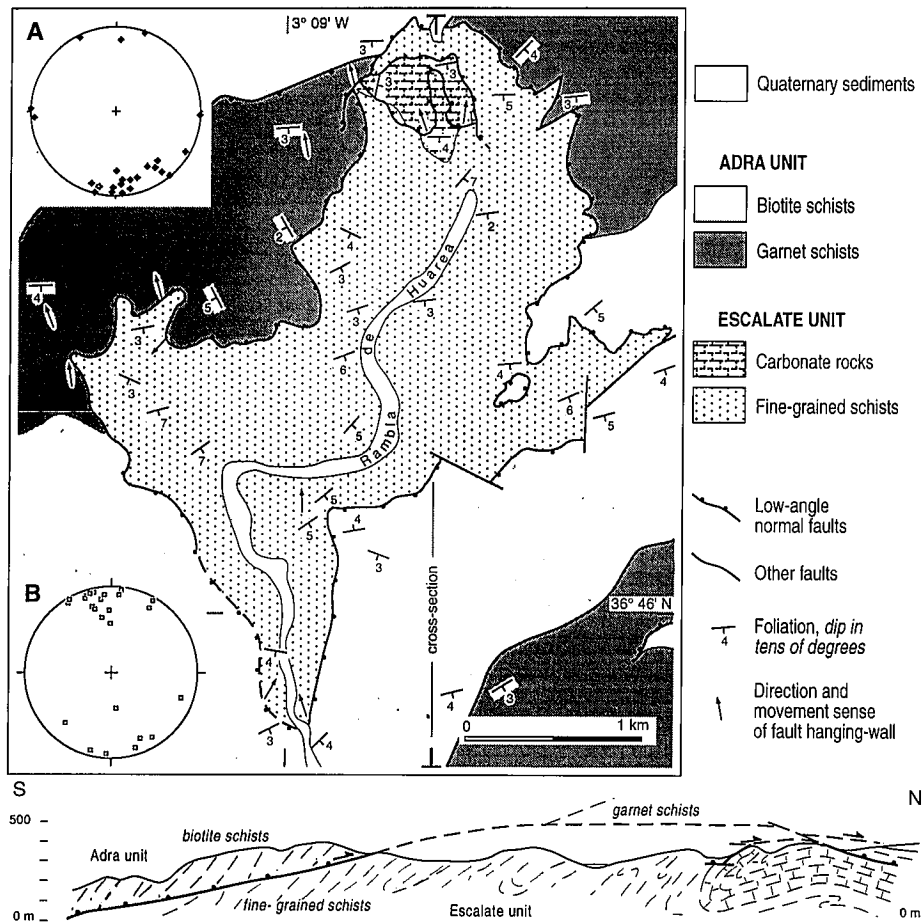
Timing criteria indicate that this compressional event took place prior to the Aquitanian: a) Late Oligocene-Early Miocene marine deposits contain clasts of Alpujárride metamorphic rocks (Durand-Delga *et al.*, 1993; Lonergan & Mange-Rajetzky, 1994); b) in the western Betics, anatectic leucogranites including metamorphic xenoliths showing S_{en} crenulation cleavage (Sánchez-Gómez *et al.*, 1995) intruded in the higher Alpujárride units are dated as 22 ± 4 Ma (Rb-Sr whole rock isochron, Priem *et al.*, 1979); and c) in the eastern Betics, undeformed leucogranitic dikes of 18.4 ± 0.6 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$ data, Zeck *et al.*, 1992) are intruded in the Alpujárride rocks.

Tectonic boundaries of the Alpujárride units

After this succession of pre-Miocene major extension and contraction events, a marine basin was originated over the Alborán domain, its older syn-rift deposits being of the Late Oligocene-Early Miocene (Bourgeois, 1978; Jurado & Comas, 1992; Durand-Delga *et al.*, 1993). Detachments and low-angle normal faults developed and produced the thinning of the pre-Miocene Alpujárride stack. The extension of the Alborán basin, as registered in its basement, is divided into successive epis-

odes with different extensional directions and took place along several progressively deeper extensional detachments (García-Dueñas *et al.*, 1992). Around Profile 2, the tectonic boundaries between different Alpujárride units are brittle faults. The geometric relationships between the S_2 regional foliation, the axial planes of the D3 folds, and the faults provide evidence that these boundaries are low-angle normal faults and not thrusts, as these low-angle normal faults systematically thin the units or even omit them (García-Dueñas *et al.*, 1992; Crespo-Blanc *et al.*, 1994). Thus, the principal units are extensional units, their geometric distribution in the Contraviesa area explained by the interference of two brittle subperpendicular extensional fault systems: the Contraviesa normal fault system, upper Burdigalian and Langhian in age and with an approximately N-S extensional direction (Crespo-Blanc *et al.*, 1994; Crespo-Blanc, 1995), and the Filabres normal fault system, which developed during the Serravallian and shows a west-to-southwestward transport direction (García-Dueñas *et al.*, 1992). Some of the faults of these extensional systems have been mapped in Fig. 3.

A local example of faults associated with the Contraviesa system are those observed in the Rambla de Huerea area. The direction of striae over fault planes (stereogram A and arrows in map of Fig. 6) and the orientation of the calcite vein associated with the low-angle normal faults in the carbonate rocks (stereogram B) show a NNW-SSE



extensional direction. Moreover, kinematic criteria such as S-c shaped structures, trails of crushed pebbles, drag folds in fine-grained schists, and rough foliation in the fault rocks and associated small-faults, indicate a NNW-ward hangingwall movement. The cross-section of Fig. 6 illustrates the subtractive character of the faults and the thinning of the units towards the NNW, which is coherent with the tilting of the key surfaces with respect to the low-angle normal faults. On a larger scale, listric fans and high extension geometries such as horses and detached riders (Gibbs 1984) related with the Contraviesa system are well illustrated in the NNW-SSE cross-section of Fig. 5BB'. The listric character of the low-angle normal faults is inferred by the tilting of the key surfaces and the thinning of the units limited by the faults towards the NNW. Cross-section 5B-B' also illustrates the slight folding of the low-angle normal faults, owing to Late Tortonian to Pliocene N-S to NW-SE compression (Weijermars *et al.*, 1985; Comas *et al.*, 1992; Rodríguez-Fernández & Martín Penela, 1993). This folding produced the southward dipping of some low-angle normal faults, as illustrated in the cross section of Fig. 6.

Fault surfaces belonging to the Contraviesa normal fault system are cut by other normal faults with a west-to-southwestward transport direction, associated with the Filabres normal fault system (García-Dueñas *et al.*, 1992; Crespo-Blanc *et al.*, 1994). An important low-angle normal fault of this latter system in the Contraviesa

area bounds the Lújar-Gádor unit west of the Sierra de Gádor (Figs. 1 and 3). It provokes a strong thinning, the uppermost Alpujarride unit (Adra unit) lying directly over the lowermost unit (Lújar-Gádor unit). The northeastern part of the cross-section of Fig. 5C-C', NE-SW directed (that is, parallel to the extension direction of the Filabres system), illustrates how a roll-over anticline and associated syncline are due to the flat ramp geometry of this main low-angle normal fault. In the same cross-section, all the previous structures, including the upper Burdigalian and Langhian faults, are tilted by the Serravallian faults. The ENE-WSW cross-section of Fig. 1 amplifies the geometric pattern resulting from the development of the faults that belong to the Filabres extensional system, from Lújar Sierra to Alhamilla Sierra. They cut the lowermost Alpujarride unit, which can be described as a megaboudin.

Constraints for Profile 2 seismic interpretations

To summarise, the Alpujarride Complex structure in the central Betics consists of pre-Miocene isoclinal or closed kilometric folds marked by an extensional foliation (main foliation S_2) subparallel to the lithologic succession. These folds are cut by brittle faults belonging to two roughly orthogonal extensional systems, Early to Middle Miocene in age, whose interference results in a large-scale chocolate tablet geometry. As the fold axes

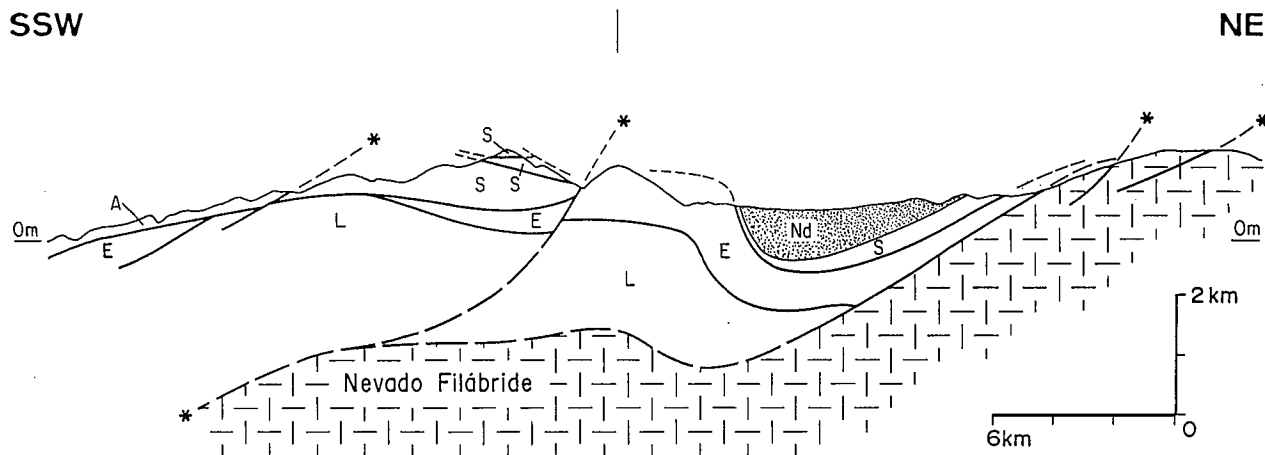


Figure 7.- Cross-section along Profile 2. Heavy lines: faults which bound the units. Asterisk: Faults which belong to the Filabres extensional system. Alpujárride Complex: A, Adra unit; S, Salobreña unit; E, Escalate unit; L, Lújar-Gádor unit. The dips of low-angle normal faults were calculated with vertical scale exaggeration. Localisation on Fig. 5.

are approximately ENE-WSW directed, one consequence of the W-to-SWward movement along the listric faults of the Filabres extensional system is the tilting of these kilometric folds, their plunge indicating an eastward component. This tilting provokes, for example, the closing of the syncline in the uppermost Alpujárride unit around the locality of Adra (Fig. 3).

The cross-section in Fig. 7 illustrates the interference of both extensional systems along Profile 2. All the extensional horses and riders of the Contraviesa normal fault system made up part of the hangingwall of the Filabres detachment. This detachment separates the Alpujárride and Nevado-Filábride complexes and is the sole detachment of the Filabres extensional system (García-Dueñas & Martínez-Martínez, 1988; Galindo-Zaldívar *et al.*, 1989). Although the amount of extension is difficult to estimate, this is clearly the most important of the Miocene extensional systems that contribute to Alborán Ba-

sin rifting. Total movement of more than 100 km due to the Filabres system has been estimated by García-Dueñas *et al.* (1992). The geometric distribution of the units that belong to the Alborán Domain, the Flysch Trough and to the South Iberian palaeomargin can largely be explained by an asymmetrical shear towards the WSW (García-Dueñas, 1995). It is then surprising that in Profile 2, the fault zone associated to the Filabres detachment, which is sometimes up to several hundreds of meters thick and should be a zone of strongly anisotropic material, cannot be traced below the surface as a reflector. Nevertheless, it seems to be possible to observe this detachment in an other seismic profile. Indeed, a SW-dipping reflector appears on a multichannel seismic reflection profile between the Andalucía-A1 well and offshore Algeria (ICR of Fig. 8, according to Fig. 4b of Watts *et al.*, 1993). Onshore, the Filabres detachment crops out North of Almería, where Middle Miocene sediments lie

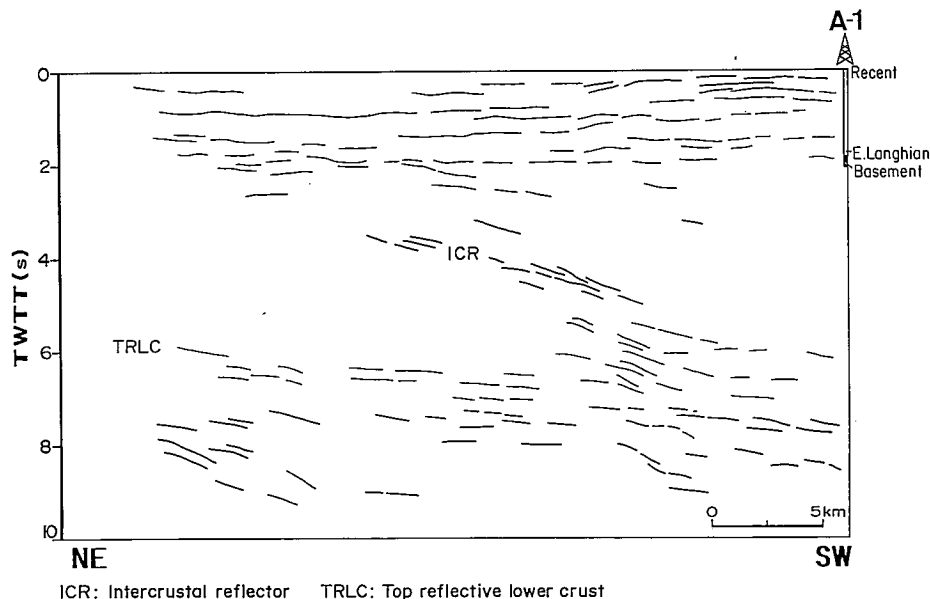


Figure 8.- Line drawing of multichannel seismic Line 824 of the Spanish continental shelf between the Andalucía-A1 well and offshore Almería (localisation on Fig. 1), according to Fig. 4b of Watts *et al.* (1993).

over Alpujárride units, less than 1 km thick (Figure 1). It is suggested that this intracrustal reflector (ICR) dipping 15° towards the SW (dip estimated according to the seismic velocities proposed by Banda *et al.*, 1993) represents the Filabres detachment. The wedge limited by Middle Miocene sediments, according to Andalucía-A1 well data (Fig. 8), and this reflector would then represent the Alpujárride units, thicker towards the SW as a consequence of the geometry of the faults belonging to the Contraviesa and Filabres normal fault systems. A similar SW-ward thickening of the Alpujárride units is observed in cross-section of Fig. 7. Moreover, the top of the lower crust recognised in Profile 2 between 6s and 7s (Fig. 2) corresponds to the top reflective lower crust which appears in the multichannel seismic line (TRLIC of Fig. 8).

In conclusion, it is believed that the lower part of the continental crust has been affected by the large-scale extension recognised in the Alpujárride complex. In this extensional regime associated with the Miocene rifting of the Alborán Basin, delamination and the convective removal of the lithosphere together with the ascent of the upper limit of the asthenosphere (Channel & Mareschal, 1989) could explain the heterogeneities observed in the lower part of the continental crust, situated below the units that crop out in the Contraviesa area (Carbonell *et al.*, this vol.). It is noteworthy that these heterogeneities have a wedge-shaped geometry similar to that of the Alpujárride units.

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