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Mode of extensional tectonics in the southeastern Betics (SE Spain): Implications for the tectonic evolution of the peri-Alborán orogenic system

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Abstract. The Gibraltar arc, which closes the westernmost part of the Mediterranean basin, is a Miocene A-type subduction arc formed by the continental collision of various pre-Miocene terranes in the major zone of collision between the Iberian and African cratons. The hanging-wall block, known as the Alborán domain, has undergone more than 300 km migration from a more easterly position, where it was the continuation of the Alpine Cretaceous-Paleogene orogen. Contemporaneous with thin-skinned thrusting in the footwall, the Alborán domain underwent two episodes of nearly orthogonal extension in which extensional systems developed with directions of extension varying from a NNW-SSE system, orthogonal to the belt axis, in the late Burdigalian-Langhian to a WSW directed orogen-parallel one in the Serravallian. The superposition of these two systems resulted in a chocolate tablet megastructure. This extensional pattern is not satisfactorily explained in previously proposed models for the evolution of the arc. Orthogonal extension is plausible in a process of the gravitational collapse of an overthickened crust; nevertheless, orogen-parallel extension is more difficult to explain in this context. We advocate that the WSW directed low-angle normal faults formed during large-scale extension in connection with important westward arc migration.The driving force of extension in a general context of convergence is controversial and varies between a convective removal model and a delamination model. Constraints on both the timing and the kinematics of extension, as presented in this paper, seem to support the contribution of both mechanisms. Convective removal may have started the process, but continued N-S convergence could have resulted in westward tectonic escape and asymmetric lateral inflow of asthenospheric material accompanying lithospheric delamination.

Introduction

The confirmation of orogenic chains as preferential locations for lithospheric extension [*Dewey*, 1988] is a very interesting result in continental tectonics in recent years. Among other things it has explained one of the classic mountain chain problems, the exhumation of high-pressure metamorphic rocks without significant overprinting by Barrovian assemblages. Extensional denudation is the most likely mechanism for the rapid removal of the overburden that caused the high-pressure, inexplicable at normal erosion rates, and expected geothermal gradients [*Droop*, 1985; *Platt*, 1987]. The coexistence of large-scale contractional and extensional structures in these contexts is now accepted, yet it brings up a new question under discussion for many orogens, that is, how to distinguish between contractional low-angle structures related to nappe emplacement and low-angle normal faults related to syn-orogenic and late-orogenic extension.

In the peri-Mediterranean region the coexistence of contractional and extensional processes has given rise to the characteristic physiognomy of the western Alpine system, with a number of arcuate orogenic belts, such as the Carpathians, the Appenines-Maghrebides, and the Betic-Rif-Tell chains. On the concave side can be found areas of Neogene subsidence, such as the Pannonian, Tyrrhenian, and Alborán basins. The numerous explanations for the creation of these internal basins can be grouped into two general trends: (1) those that emphasize vertical movements and in which the main process is the postorogenic sinking of the lithospheric root [*Van Bemmelen*, 1969; *Platt and Vissers*, 1989] and (2) those that emphasize the importance of horizontal motions in the formation of arcuate mountain belts and extensional basins in the hinterland [*Malinverno and Ryan*, 1986; *Channel and Mareschal*, 1989; *Ratschbacher et al.*, 1991; *García-Dueñas et al.*, 1992; *Oldow et al.*, 1993; *Royden*, 1993]. The first group of hypotheses has been used to explain the circular shape of the orogenic belts, which almost wrap around the basins, as well as the supposed radial thrusting with tectonic transport directed away from the basins. The second group attempts to explain the new features observed in these orogenic systems that are not satisfactorily explained by the vertical tectonic models, such as the contemporaneity of the formation of the basins and the thrusting in peripheral orogenic belts; the substantial amount of crustal shortening in the external zones, of the order of hundreds of kilometers; the marked asymmetry of the extensional systems thinning the internal zones; and so on.

In the region of the Alborán Sea the hinterland corresponds to the basin itself and the crystalline and metamorphic units of the Betic and Rif internal zones constituting the so-called Alborán domain [*Balanyá and García-Dueñas*, 1987]. On the basis of paleogeographic considerations and geological similarities with the Kabyly, Calabrian, and western Alp nappes this domain has been interpreted as belonging to the

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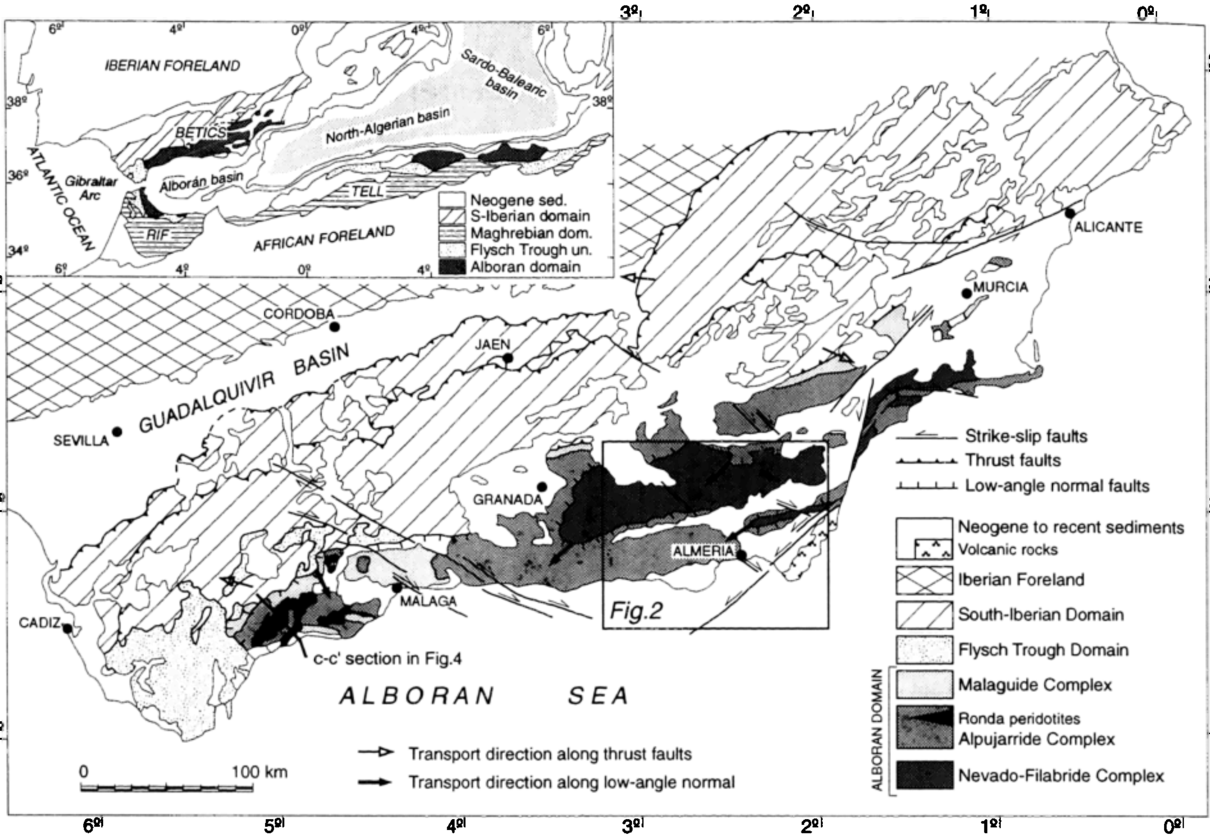

Figure 1. Tectonic map of the Betics and main tectonic domains around the westernmost Mediterranean.

formerly continuous Alpine Cretaceous-Paleogene orogen that was fragmented and dispersed during the Neogene [*Alvarez et al.*, 1974; *Bouillin et al.*, 1986]. This paper is concerned with a sector of the Alborán domain in the southeastern Betics (Figure 1) where large-scale extensional detachments and low-angle normal faults have been described in the last decade [*Aldaya et al.*, 1984; *García-Dueñas et al.*, 1986; *García-Dueñas and Martínez-Martínez*, 1988; *Galindo-Zaldívar et al.*, 1989; *Jabaloy et al.*, 1993; *Crespo-Blanc et al.*, 1994]. It focus on three essential aspects that are not dealt with extensively enough in the regional literature: the differentiation of pre-Neogene and Neogene structures, the timing of the Neogene extension, and the geometry and kinematics of the extensional systems, all of which are important geological constraints for the different models on the tectonic evolution of the orogen. Our metamorphic and structural data suggest that the structure of the Alborán domain in the southeastern Betics is a pre-Miocene nappe stack, thinned and fragmented by Miocene extensional tectonics. We therefore conclude that this region is a site of Miocene extension rather than of Miocene nappe emplacement, as other authors have suggested [*Platt et al.*, 1983; *Frizon de Lamotte et al.*, 1989; *De Jong*, 1991]. We have recognized two nearly orthogonal, successive extensional systems, a NNW directed system, orthogonal to the belt axis, and a WSW directed orogen-parallel system. The orthogonal extension is plausible in a process of the gravitational collapse of an overthickened crust; nevertheless, the orogen-parallel extension is more dificult to explain in this context. We argue that the WSW directed low-angle normal faults formed during large-scale extension in connection with important, westward arc migration.

Peri-Alboran Orogenic System

The Alborán Sea is surrounded on the north, west, and south by a Miocene contractional belt including the Betics in southern Spain and the Rif and Tell mountains in North Africa. The Betics and the Rif link across the Straits of Gibraltar to form the arcuate structure of the belt, commonly known as the Gibraltar arc (Figure 1). Several pre-Miocene terranes form part of the arc: (1) the Alborán domain, made up mainly of Paleozoic and Mesozoic rocks, most of which have been deformed under metamorphic conditions; (2) and (3) the South-Iberian and Maghrebian domains, which consist of nonmetamorphic sediments deposited on the continental margins of the southern Iberian peninsula and North Africa, respectively, during the Mesozoic and part of the Cenozoic; and (4) the intervening Flysch Trough domain, which, underlain by oceanic or very thin continental crust, was the locus of deep water sedimentation during the same period [*Biju-Duval et al.*, 1977]. The trough was likely between the above-mentioned paleomargins, along the length of the Iberia-Africa transform boundary, and likely spanned a larger area than the present Alborán Sea. Neogene deformation affected the different domains unequally: while the latter three were heavily shortened by thin-skinned thrusting and folding, the Alborán domain has greatly extended sections with the development of low-angle normal faults [*García-Dueñas and Martínez-Martínez*, 1988; *Galindo-Zaldívar et al.*, 1989; *Platt and Vissers*, 1989]. Thrusting is toward the WNW [*Guezou et al.*, 1991] or NW [*Lonergan et al.*, 1994] in southeast Spain, toward the west around the Straits of Gibraltar [*Balanyá and García-Dueñas*, 1988; *Balanyá*, 1991; *Flinch*, 1993; *Platt et al.*, 1995], toward the WSW to SW in the Rif [*Morley*, 1987; *Plaztman et al.*, 1993], and toward the south in the Tell mountains of Algeria [*Wildi*, 1983]. Paleomagnetic work has demonstrated that thrusting was accompanied by significant rotations, generally clockwise in southern Spain and counterclockwise in Morocco [*Osete et al.*, 1989; *Platzman*, 1992; *Villalaín et al.*, 1994].

The origin of the arc has always been very controversial and has given rise to many interpretations. According to the oldest model the curvature of the orogenic belt is due to oroclinal bending [*Carey*, 1955; *Durand-Delgá and Fonboté*, 1980]. Another model relates the Gibraltar arc with the westward drift of the Alborán microplate, with the leading edge supposedly giving rise to a set of folds and radial thrusts [*Andrieux et al.*, 1971]. Related to this model, another hypothesis stresses the importance of the strike-slip faults in the WSW ejection of the Alborán block during the N-S convergence of Iberia and Africa [*Leblanc and Olivier*, 1984]. One of the most important failings of these models is the lack of an explanation for the severe thinning of the hinterland and for the formation of the Alborán basin. More recent hypotheses link the genesis of the Gibraltar arc with that of the Alborán basin but from very different viewpoints. While some authors accept the notion of significant westward motion of the Alborán domain [*Balanyá and García-Dueñas*, 1988; *García-Dueñas et al.*, 1992; *Royden*, 1993], others propose a vertical tectonic model based on the postorogenic extensional collapse of an overthickened collisional ridge in the Alborán region [*Doblas and Oyarzun*, 1989; *Platt and Vissers*, 1989; *Vissers et al.*, 1995]. Distances of some 250 km have been suggested for this movement to account for the significant E-W shortening in the footwall, taking into account only the restored Flysch unit stacks [*Didon et al.*, 1973; *Balanyá*, 1991]; however, this distance may be greater if we consider the shortening in the South-Iberian domain [*García-Hernández et al.*, 1980; *Guezou et al.*, 1991]. Contemporaneous to this thrusting, there was considerable extensional thinning of the Alborán domain thus giving rise to the Alborán basin [*Comas et al.*, 1992]. The extension continued and eventually invaded the contraction fields, producing the tectonic inversion of the Gibraltar thrust (the suture between the Alborán domain and the external domains) during the middle Miocene, while the mountain front advanced in the footwall, moving toward the externalmost zones [*Balanyá and García-Dueñas*, 1988; *García-Dueñas et al.*, 1992].

Metamorphic Complexes of the Alboran Domain

The rocks in the Alborán domain constitute a large number of tectonic units grouped into three nappe complexes: the Nevado-Filabrides, the Alpujarrides, and the Malaguides, from bottom to top, distinguished according to lithological and metamorphic-grade criteria [*Egeler and Simon*, 1969]. Even more useful, however, is the tectonometamorphic evolution, which varies from one complex to another [*Torres-Roldán*, 1979]. The Nevado-Filabride rocks, ranging in age from Paleozoic to Cretaceous, are for the most part metamorphosed to high-greenschist facies, although they reach amphibolite facies in the uppermost tectonic unit. Alpujarride rocks, Paleozoic to Triassic in age, show variable metamorphic grade, from upper amphibolite to granulite facies at the bottom of certain units to low metamorphic grade at the top. The Malaguide rocks, ranging in age from Silurian to Oligocene, have not undergone significant Alpine metamorphism, although the Silurian series have a very low metamorphic grade [*Chalouan and Michard*, 1990]. In the southeastern Betics, the two lower complexes are primarily represented, the Malaguides constituting only a few small outcrops not plottable in Figure 2. Both the Nevado-Filabrides and the Alpujarrides show significant differences in metamorphism and structural history, which are briefly described below.

Nevado-Filabride Complex

The most complete section of the Nevado-Filabrides can be found in the Sierra de los Filabres, where the three major thrust units crop out extensively (Figure 2).They are, from bottom to top: the Veleta, the Calar Alto, and the Bédar-Macael units, with respective structural thicknesses of 4000, 4500, and 600 m [*García-Dueñas et al.*, 1988 a, b]. The essential points of this threefold division have been accepted by other authors as well [*De Jong*, 1991; *Vissers et al.*, 1995]. The lithostratigraphic sequences of the units (Figure 3) consist primarily of black graphitic schists and quartzites of probable pre-Permian age [*Lafuste and Pavillon*, 1976]; a sequence of light-colored metapelites and metapsammites (probably Permo-Triassic); and a calcite and dolomite marble formation, which, although traditionally considered to be Triassic, locally contains microfossils of possible Cretaceous age [*Tendero et al.*, 1993]. Permian orthogneisses and late Jurassic metabasites are locally included at different levels of the sequence. The contacts between the units lie within broad ductile shear zones (500-600 m thick) with a flat geometry [*García-Dueñas et al.*, 1988 a, b]. In most of the Nevado-Filabride stack the main structure is a penetrative subhorizontal schistosity (S_2) subparallel to the lithologic banding and associated with isoclinal folds. The S_2 developed under greenschist facies conditions in the lower units and in amphibolite facies conditions in the highest one [*Martínez-Martínez*, 1986a; *Platt and Behrmann*, 1986; *García-Dueñas et al.*, 1988a, b]. An earlier foliation (S_1) is locally recognizable around the hinges of the F_2 folds and within some porphyroblasts. Relics of high-pressure (HP) assemblages such as glaucophane in blueschists and omphacite + garnet in eclogites have been associated with the first deformational episode [*Bakker et al.*, 1989], although the broad ocurrence of mimetic crystallization in the eclogites suggest that the HP minerals formed in a prekinematic stage without the involvement of penetrative structures [*Morten et al.*, 1987]. The main foliation (S_2) intensifies into the two shear zones where the structure is dominated by a platy-laminated mylonitic foliation (S_3) containing a variably oriented

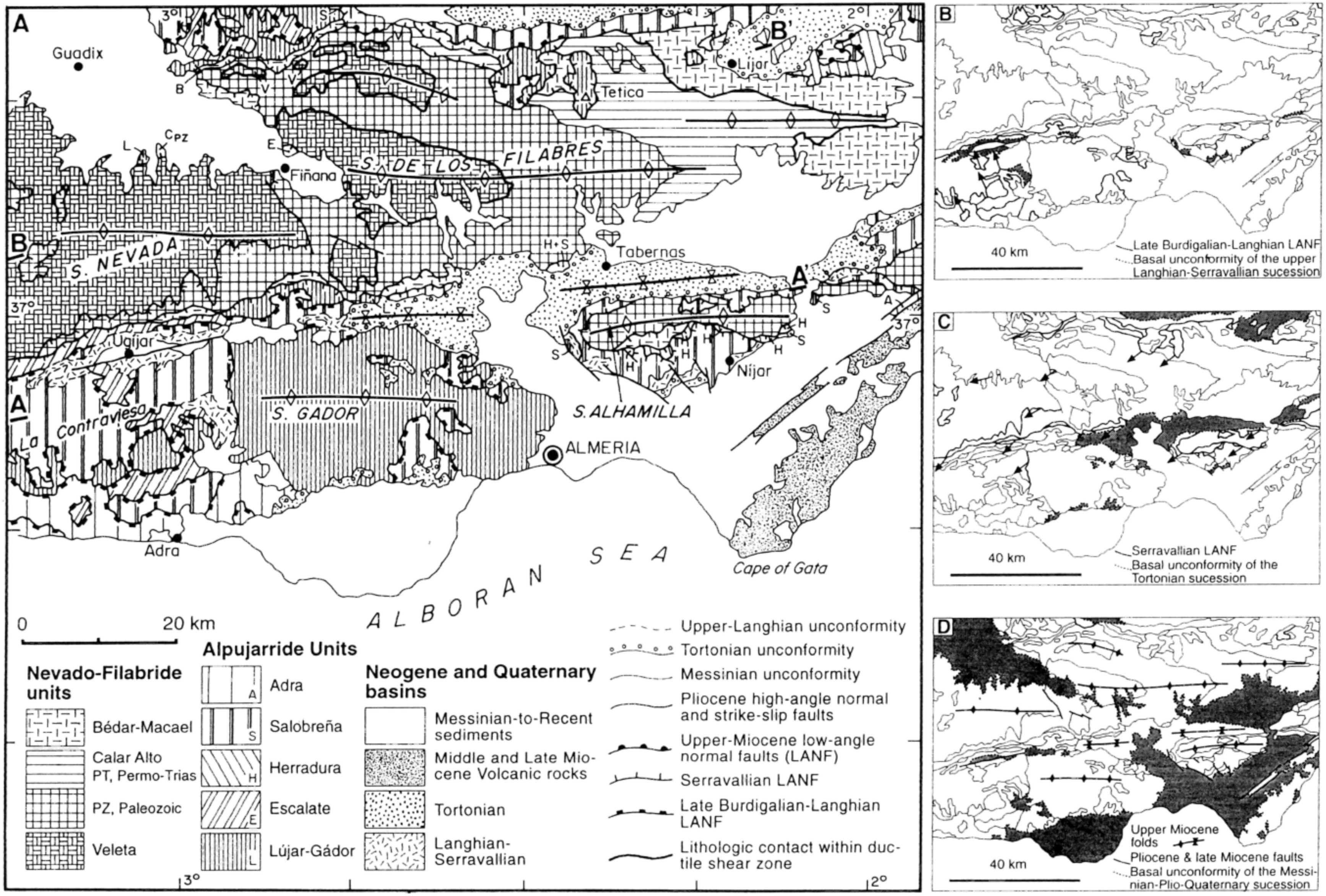

Figure 2. (a) Geological map of the southeastern Betics showing four large upper Miocene anticlinoria: the Sierra Nevada, Sierra de los Filabres, Sierra de Gádor, and Sierra Alhamilla. Nature and age of the different contacts are shown. (b), (c) and (d). Tectonic sketches showing for each tectonic event the active structures and unconformable sediments (shaded areas). Arrows show transport direction along low-angle normal faults.

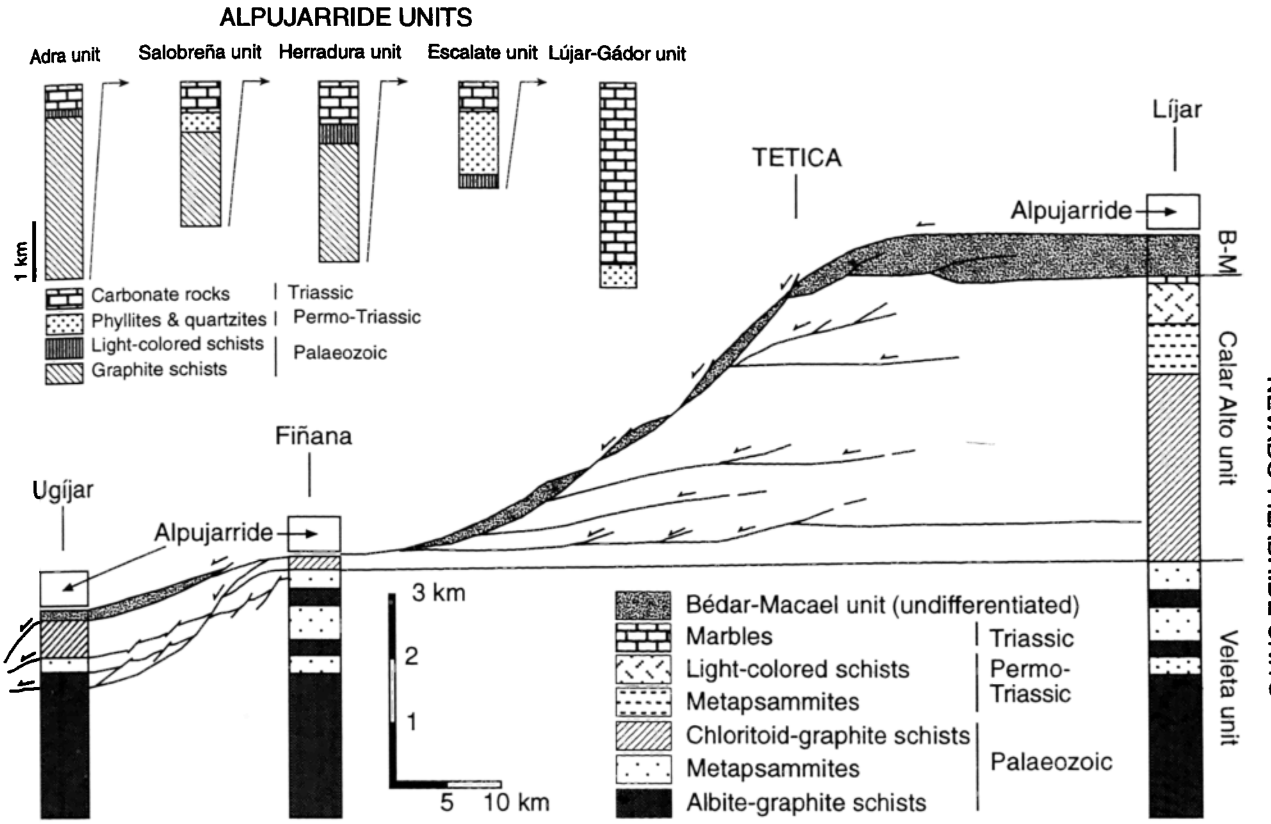

Figure 3. Nevado-Filabride tectono stratigraphic columns beneath the detachment surface at the base of the Alpujarrides. Standard lithostratigraphic columns in the different Alpujarride units are also shown.

stretching lineation [*Platt et al.*, 1984; *García-Dueñas et al.*, 1988a, b; *Jabaloy et al.*, 1993]. Published fabric data from the mylonitic rocks also indicate a great variability of transport direction: toward the NNE [*Behrmann and Platt,* 1982], the NW [*Martínez-Martínez,* 1986b], the north [*Alvarez,* 1987], and the west [*Jabaloy et al.*, 1993; *Gonzalez-Casado et al.*, 1995]. Both the S_2 and S_3 foliations are affected by south to SE vergent, metric-to-hectometric folds with an associated slight pervasive crenulation cleavage (S_4) that is, nevertheless, present throughout the entire Nevado-Filabride stack [*Vissers*, 1981; *Behrmann*, 1982; *Martínez-Martínez*, 1986a; *Soto*, 1993].

The high-pressure/low-temperature assemblages have been related to a Cretaceous-Paleogene continental collision [*De Jong*, 1991]. It is constrained by an $^{40}Ar/^{39}Ar$ plateau age on barroisitic amphibole of 48 Ma [*Monié et al.*, 1991], which is a common transformation product after glaucophane [*Nijhuis*, 1964].

Alpujarride Complex

In the Alpujarrides, up to five types of superimposed units (from top to bottom: the Adra, Salobreña, Herradura, Escalate, and Lújar-Gádor units, Figures 2 and 3) have been recognized, showing significant differences in their metamorphic record, from low-grade conditions (pressure (P)<7 kbar/temperature (T)<400°C) in the lowest unit up to high-grade conditions (P>10 kbar/ T>550°C) in the highest unit. This fivefold division can be seen regionwide in the central and eastern parts of the internal Betics [*Azañón et al.*, 1994]. Most of the Alpujarride slabs are lens-shaped, nevertheless, maximum structural thickness has been established as follows: Lújar-Gádor, 3300 m, Escalate, 1700 m, Herradura, 4300 m, Salobreña, 3800 m; and Adra, 3700 m. Lithostratigraphic sequences have many similarities. The top of the standard section is constituted by a carbonate formation dated as Middle to Upper Triassic [*Kozur el al.*, 1974; *Balanyá*, 1991]. Below it a formation of fine-grained, light-colored schists and phyllites, generally attributed to the Permo-Triassic, crop out. The bottom of the sequence is often constituted by a graphite-schist succession (probably Paleozoic) overlying a gneissic formation that only appears in the higher unit.

The main structure in the Alpujarride units is a penetrative subhorizontal foliation (S_2) subparallel to the lithologic banding and generated by vertical shortening during a decompression process [*Balanyá et al.,* 1993, 1997]. An earlier foliation (S_1) is only preserved within porphyroblast and lens-quartz domains. During a D_3 contractional episode the S_2 foliation is affected by north-vergent folds with associated, locally penetrative crenulation cleavage [*Tubía et al.*, 1992; *Simancas and Campos*, 1993]. The metamorphic evolution includes a first high-pressure event followed by nearly isothermal decompression. The HP event produces the development of eclogite facies in the western Alpujarrides [*Tubía and Gil Ibarguchi*, 1991; *Balanyá et al.*, 1993] and the growth of carpholite-bearing assemblages in the Permo-Triassic levels of most of the units [*Goffé et al.*, 1989; *Azañón*, 1994]. The Alpujarride units show metamorphic zonation related to a medium-pressure growth stage produced during decompression. It is followed by a low-pressure episode, which induces the growth of sillimanite and andalusite [*Torres-Roldán*, 1981; *Balanyá et al.*, 1993, 1997].

The structures responsible for the superposition of the Alpujarrides over the Nevado-Filabrides are not well established, and there is no agreement on when it took place. The superposition must have occurred after the metamorphic episode that generated sillimanite and andalusite in the Alpujarrides, and the possibility cannot be excluded that it may be related to the north-directed contractional structures described in the Alpujarrides. The Malaguide overthrusting must have been earlier since it is thought to be responsible for the overburden necessary to generate the high pressure in the Alpujarrides [*Azañón*, 1994].

The above-described tectonometamorphic evolution is probably prior to the late Oligocene, as is supported by several points: first, the intrusion date of the undeformed granites (22 Ma) that cut across the F_3 north-vergent folds [*Muñoz*, 1991; *Balanyá et al.*, 1993; *Sánchez-Gómez et al.*, 1995] and second, the Oligocene-Miocene age of the unconformable formations overlying the Malaguides and Alpujarrides [*Durand Delgá et al.*, 1993; *Lonergan and Mange-Rajetzky*, 1994], which were exhumed during that period. This point is in contradiction with the radiometric ages (Rb/Sr, $^{39}Ar/^{40}Ar$, K/Ar in biotite, K-feldspar, phengite, and amphibole) for the Alpujarride metamorphism, which range between 18 and 25 Ma [*Zeck et al.*, 1989, 1992; *Monié et al.*, 1991, 1994]. We agree, however, with *Lonergan and Mange-Rajetzky* [1994] when they suggest that these ages may reflect cooling ages for older events or resetting by a Neogene thermal event. Evidence of a thermal event postdating the exhumation and decompression of the Alpujarride rocks in the western Alborán Sea have recently been presented [*Platt et al.*, 1996].

Miocene Extensional Tectonics

Both the Alpujarride and Nevado-Filabride units show significant lateral changes in thickness. These changes, of regional importance, have a tectonic origin and sometimes produce the partial or total omission of the units. This is the case with the lower Alpujarride unit (Lújar-Gádor unit), absent in the Sierra Alhamilla, as well as in the higher Nevado-Filabride unit (Bédar-Macael unit), which is strongly reduced to just a few meters (not represented in Figure 2) in the area 5 km west of Tabernas. These omissions, explainable by low-angle normal faulting, have generally been ignored in most previous structural studies which mainly focus on the internal structure and do not analyze the geometry of the unit boundaries [*Vissers*, 1981; *Behrmann*, 1982; *Konert and van den Eeckhout*, 1983]. The boundaries are commonly low-angle normal faults that do not modify the existing vertical order in the structural stack. Thus stratigraphical duplications produced by previous thrusting processes cause the extensional character of these tectonic contacts to be far from obvious. Several criteria have been used to demonstrate the extensional nature of these tectonic contacts: (1) excision of metamorphic zonation with lower-grade metamorphic rocks lying over higher-grade rocks [*Platt et al.*, 1983], (2) evolution of the deformation conditions (from ductile to brittle) along the contact [*Platt and Berhmann*, 1986; *Galindo-Zaldívar et al.*, 1989; *Jabaloy et al.*, 1993], (3) vertical omissions of the sequence together with the fault kinematics [*García-Dueñas et al.*, 1986], and (4) geometry and kinematics of linked fault systems [*García-Dueñas and Martínez-Martínez*, 1988; *Crespo-Blanc et al.*, 1994; *Crespo-Blanc*, 1995]. Additional evidence can be found in the relationship between the faults and syntectonic and posttectonic sediments.

Two generations of low-angle normal faults are recognized in the southeastern Betics. First-generation faults thinned the Alpujarride units and comprise listric faults coalescing in a sole detachment that coincides with the top of the Lújar-Gádor unit [*García-Dueñas et al.*, 1992]. Detailed geometrical and kinematic analysis of these normal faults has been done by *Crespo-Blanc et al.* [1994], who define the Contraviesa normal fault system as characteristically having a transport direction toward the NNW and being active during the late Burdigalian - Langhian, in agreement with the upper Langhian age of the lowest sediments sealing these faults [*Mayoral et al.*, 1994]. Unconformity can be observed around Ugíjar (Figure 2).

Younger low-angle normal faults and detachment faults affect deeper levels of the Alborán domain. They particularly attenuated the Nevado-Filabride stack and dismembered the previous thinned Alpujarride units in an ENE-WSW extensional direction, orthogonal to the prior one. The most significant of these faults is characterized by a broad zone with breccias, gouges, and cataclasites, within which lies the contact between the Alpujarrides and the Nevado-Filabrides. The notion that this contact was a major thrust has been held until quite recently, undoubtedly supported by the general superposition of the Alpujarrides over the Nevado-Filabrides. Some segments of the contact, nonetheless, have been described as normal faults [*Aldaya et al.*, 1984]. Subsequently, the contact has been proven to be brittle and to cut downsection with respect to the main regional foliation throughout its length, forming a large-scale extensional detachment, the Filabres detachment, which has linked listric-normal faults soling it [*García-Dueñas and Martínez-Martínez*, 1988]. Currently, almost no one disagrees with the extensional nature of this contact [*Galindo-Zaldívar et al.*, 1989; *Platt and Vissers*, 1989; *García Dueñas et al.*, 1992; *Jabaloy et al.*, 1993], although there are some differences with respect to its tectonic significance, as will be discussed below.

The Filabres detachment appears as a fault zone with discrete surfaces on which may be seen NE-SW to ENE-WSW striations. The main regional foliation, which we use as a key surface, reveals its general staircase geometry with low-angle footwall ramps and flats. Associated with the faulting are brittle and brittle-ductile deformations with foliated cataclasites, fault gouges, microbreccias, and coarse fault breccias. The relative movement among the fault blocks, that is, toward the SW and WSW for the hanging wall, is surmised from shear-sense indicators, including S-C-shaped structures in the fault rocks with striations on the C surfaces, striating ploughing elements on the slickensides, and sigmoidal tails of crushed pebbles and asymmetric clasts in the fault gouges.

A large-scale ramp is to be observed between Lfjar and Fiñana (Figures 2, 3, and 4). Around Lfjar the Alpujarrides overlie the Bédar-Macael unit; farther to the west, in the Tetica area, the Alpujarrides overlie the Paleozoic/Permo-Triassic boundary of the Calar Alto unit; and finally, they lie, north of Fiñana over the Veleta unit. The lithostratigraphic omissions associated with the Filabres detachment and linked faults, as well as its ramp cutting downsection toward the WSW, demonstrate its extensional character. The omissions due to the Lfjar-Fiñana ramp (more than 8000 m of structural section) and the average fault-bed angle (<8°), plotted in Figure 12 from *Wernicke and Burchfiel* [1982], point to westward displacements of the Alpujarrides over the Nevado-Filabrides in amounts exceeding 75 km, which agree with calculations by other authors [*García-Dueñas et al.*, 1992; *Jabaloy et al.*, 1992].

Sierra Alhamilla Section

The Sierra Alhamilla range is a large-scale open E-W anticlinorium plunging to the west that formed during the late Tortonian [*Platt et al.*, 1983; *Weijermars et al.*, 1985]. Here both the Nevado-Filabride and the Alpujarride complexes crop out, because of the erosion of the Neogene sedimentary cover that completely surrounds the Sierra (Figures 2 and 5). In the Nevado-Filabrides, two tectonic units can be distinguished, the lowest one, comprising a sequence of low-grade graphite schists and quartzites, represents part of the Paleozoic sequence of the Calar Alto unit, which crops out largely farther north in the Sierra de los Filabres anticlinorium, to which it is connected by the Tabernas synclinorium (Figure 2). The upper unit is formed by a sequence of medium-grade metamorphic rocks including graphite and light schists, quartzites, tourmaline gneisses, and marbles [*Platt*, 1982], lithologically comparable to the Bédar-Macael unit. Overlying the Nevado-Filabrides, two main Alpujarride units have also been distinguished (Figure 5). The lower unit consists of a tectonostratigraphic sequence, including calcite-dolomite marbles, kyanite phyllites and quartzites, light-colored chloritoid-garnet schists, and staurolite-kyanite-garnet graphite schists, from bottom to top. The probable age of the rocks, Triassic for the marbles and Paleozoic for the graphite schists [*Platt et al.*, 1983], together with inverted metamorphic zonation indicate that this unit is overturned. The upper unit consists of a Permo-Triassic sequence of phyllites and quartzites underlying a Triassic carbonate formation. There are significant lithological and metamorphic differences between the two units that are particularly evident when their Permo-Triassic sequences are compared. In the phyllites of the upper unit, Fe-Mg carpholite-quartz assemblages and pseudomorphs after carpholite are very common [*Goffé et al.*, 1989]. Carpholite has been partially replaced by a low-temperature kaolinite-chlorite-

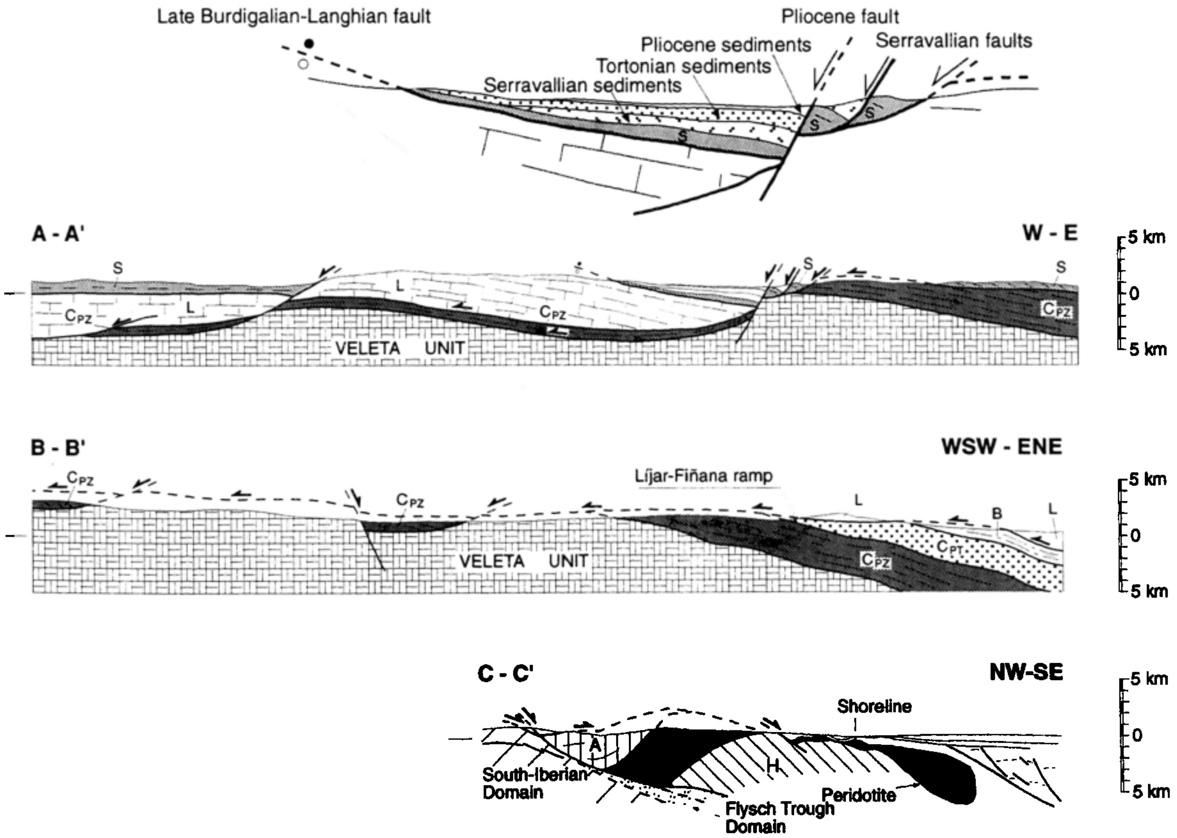

Figure 4. Structural sections (A-A' and B-B') through the Filabres extensional system in the southeastern Betics (location in Figure 2). C-C' section in western Betics showing the tectonic inversion of the Gibraltar thrust. Modified from *García-Dueñas et al.* [1992] (location in Figure 1). Same abbreviations as in Figure 2.

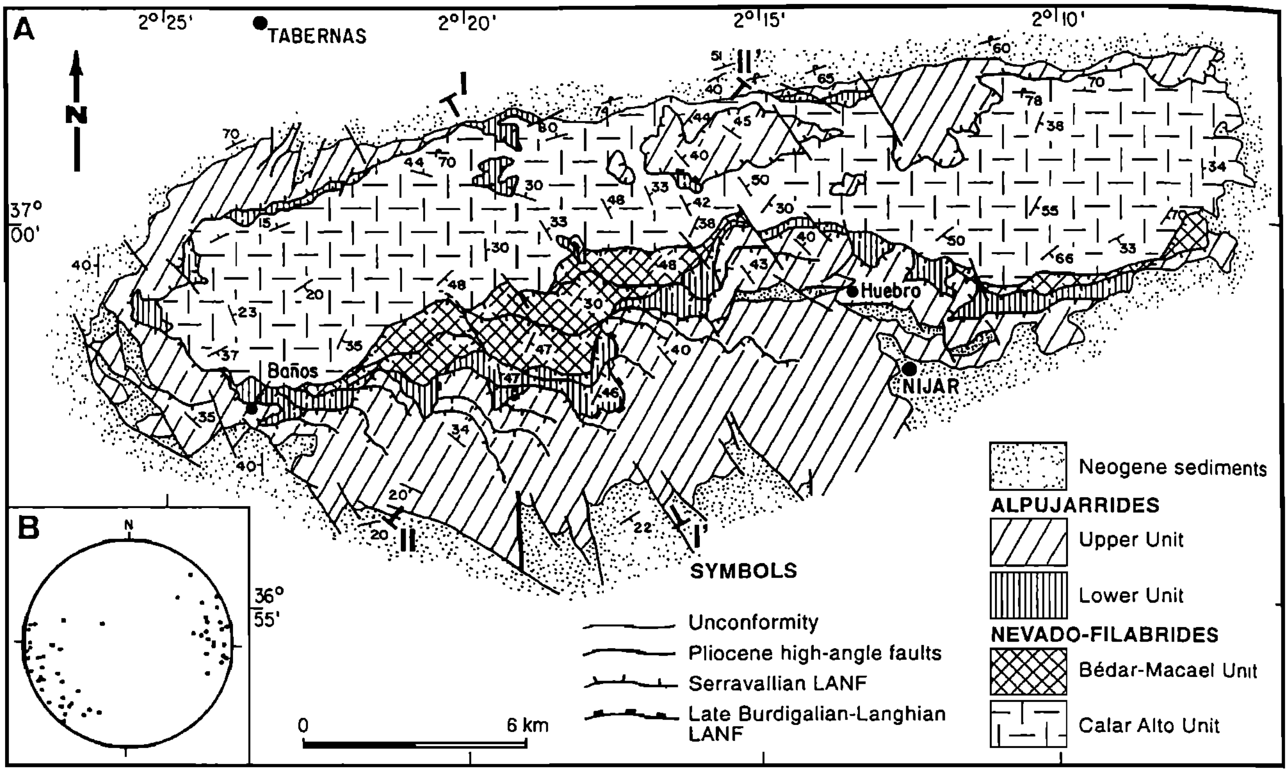

Figure 5. (a) Structural map of Sierra Alhamilla showing extensional detachments and main low-angle normal faults. Only main foliation and bedding are shown. Lines of sections in Figure 9 are given by I-I' and II-II'. (b) Equal-area orientation plot of striations on the fault planes belonging to the Filabres extensional system (Serravallian).

muscovite-paragonite-pyrophyllite assemblage. In the lower-unit phyllites, carpholite has been totally replaced (only scarce pseudomorphs bear witness to its former presence) by a mineral assemblage including kyanite but no pyrophyllite thereby indicating lower temperatures in the upper unit than in the lower unit. The differences in the metamorphic grade also result in noticeable lithological differences in the Triassic formations: the upper unit Triassic section is scarcely or not at all metamorphic, composed of limestones and dolostones, with locally abundant fauna allowing it to be dated as Middle Triassic [*Kozur et al.,* 1974]. In contrast, the lower unit section is formed by calcitic and dolomitic marbles that are sometimes banded.

An attempt has recently been made to correlate the central Betic Alpujarride units with the eastern ones [*Azañón et al.*, 1994]. The Sierra Alhamilla units are included in the correlation, for which lithostratigraphic development and metamorphic evolution criteria have been used. The possibility that they could correspond to low Alpujarride units such as Lújar or Escalate has been discarded; however, the lower unit has tentatively been categorized as an Herradura-type unit, and the upper one has been classed as a Salobreña-type unit (Figures 2 and 3).

The geological maps of Sierra Alhamilla [e.g., *Platt et al.*; 1983] reveal that the tectonic units and the various lithological formations vary in thickness laterally and wedge both toward the east and west as well as toward the north. The contacts between these units cut downsection and cause significant omissions in the tectonostratigraphic sequences, such that in a wide sector of the Sierra the carbonate formation (middle Triassic) of the highest Alpujarride unit lies directly over the graphitic schists (Paleozoic) of the lowest Nevado-Filabride unit. The juxtaposition of younger rocks over older ones with an associated omission is a common characteristic of tectonic blocks separated by normal faults [*Wernicke and Burchfiel*, 1982]. *García-Dueñas et al.* [1986], on the basis of stratigraphic omissions and kinematic analysis, demonstrated that some of the contacts between units cropping out in Sierra Alhamilla, previously thought to be thrusts, were actually brittle to brittle-ductile low-angle normal faults and detachment faults. Our own study extends this line of research in addition to using the geometry of linked fault families [*Gibbs*, 1990] as a supplemental criterium for the distinction of extensional versus contractional faults. A review of the maps that include a detailed analysis of the contacts between tectonic and lithological units was carried out in order to determine its geometry and kinematics, as well as to ascertain the general outlines of the internal structure of the units. Numerous low-angle faults both at contact boundaries and cutting across the boundaries have been identified (Figure 5). The faults are grouped together in large-scale extensional systems that postdate all the aforedescribed ductile structures, including the Nevado-Filabride south-to-SE vergent folds and the Alpujarride north-vergent folds.

Figure 6. A fault surface from the fault zone related to the Filabres extensional detachment. This surface is tilted by out-of-sequence faults. Striations plunge N60°E (see Figure 11)

The Filabres Extensional System

The Alpujarride/Nevado-Filabride contact is folded around the Sierra Alhamilla anticlinorium [*García-Dueñas et al.*, 1986], showing up as a fault zone with discrete surfaces on which may be seen NE-SW to ENE-WSW striations (Figures 5b and 6). The regional foliation, which we use as a key surface, reveals the general geometry of a low-angle footwall ramp, with occasional flats (Figure 5a) corresponding to the Lijar-Fiñana ramp belonging to the Filabres detachment (Figures 3 and 4). Associated with the detachment, are numerous faults both in the footwall and in the hanging wall, comprising an extensional system that has been coined the Filabres extensional system by *García-Dueñas et al.* [1992]. Most of these faults have striations oriented as in the detachment (Figure 5). A detailed structural map of the southern Sierra Alhamilla area has been drawn in order to illustrate the geometry, kinematics, and faulting sequence of this extensional system (Figure 7); only bedding and main foliation, which were used as key surfaces, are shown. Most of the contacts between the lithological and tectonic units have been identified as normal faults (Figure 8). The predominant direction of extension is ENE-WSW, as marked by the striations on the fault surfaces.

Cross sections II-II', III-III', and IV-IV' (Figure 9) depict the geometry of this ENE-WSW extensional system, which overall (with multiple sets of faults cutting across each other) suggests a complex extensional history with more than one episode of normal faulting. Different extensional geometries may be observed in the sections: There are emergent listric fans coalescing to a floor fault, the Filabres detachment, at shallow levels, and there are extensional duplexes at deeper ones. The hanging-wall structure consists of a series of emergent imbricate wedges or riders [*Gibbs*, 1984]. In the riders the Alpujarride units show systematic tilting, and the main foliation and bedding dip to the NE and ENE (see Figures 9 and 10). Tilted hanging-wall blocks are affected by out-of-sequence faults cutting and tilting the Filabres detachment. The second set of faults sole into the contact between the Bédar-Macael and Calar Alto units, which represents another detachment below the Filabres one. The migration of the detachment toward the footwall as a result of unloading led to the formation of extensional duplexes. Horses are bounded by out-of-sequence faults and by inactive tilted faults belonging to the overlying listric fan (one of these duplexes is the Bédar-Macael unit which crops out immediately to the south of Colativí, see Figure 7). High-extension geometries appear in the hanging wall and are associated to the Filabres system, as indicated by the Alpujarride unit detached riders (Figure 11). Figure 11 shows the photograph and line drawing of an outcrop 1 km NE of Mina where an intermediate Alpujarride unit lies between the upper and lower units. The intermediate unit is a detached rider that is totally omitted just westward. Hanging-wall anticlines, produced by the progressive northeastward tilting of bedding and main foliation, occur as a consequence of the ramp-and-flat geometry of the detachment. Although fragmented by the activity of out-of-sequence normal faults, rollovers are still evident in the southwestern parts of the sections (Figure 9). New out-of-sequence faults cut the second detachment as well and penetrate down the footwall, which far from appearing to be undeformed has frequent extensional structures (Figures 12 and 13). The overall footwall-ramp geometry of the second detachment, as well as the existence of faults compatible with the system deforming the footwall, suggest there might be deeper detachments that do not crop out. In fact, a reflector

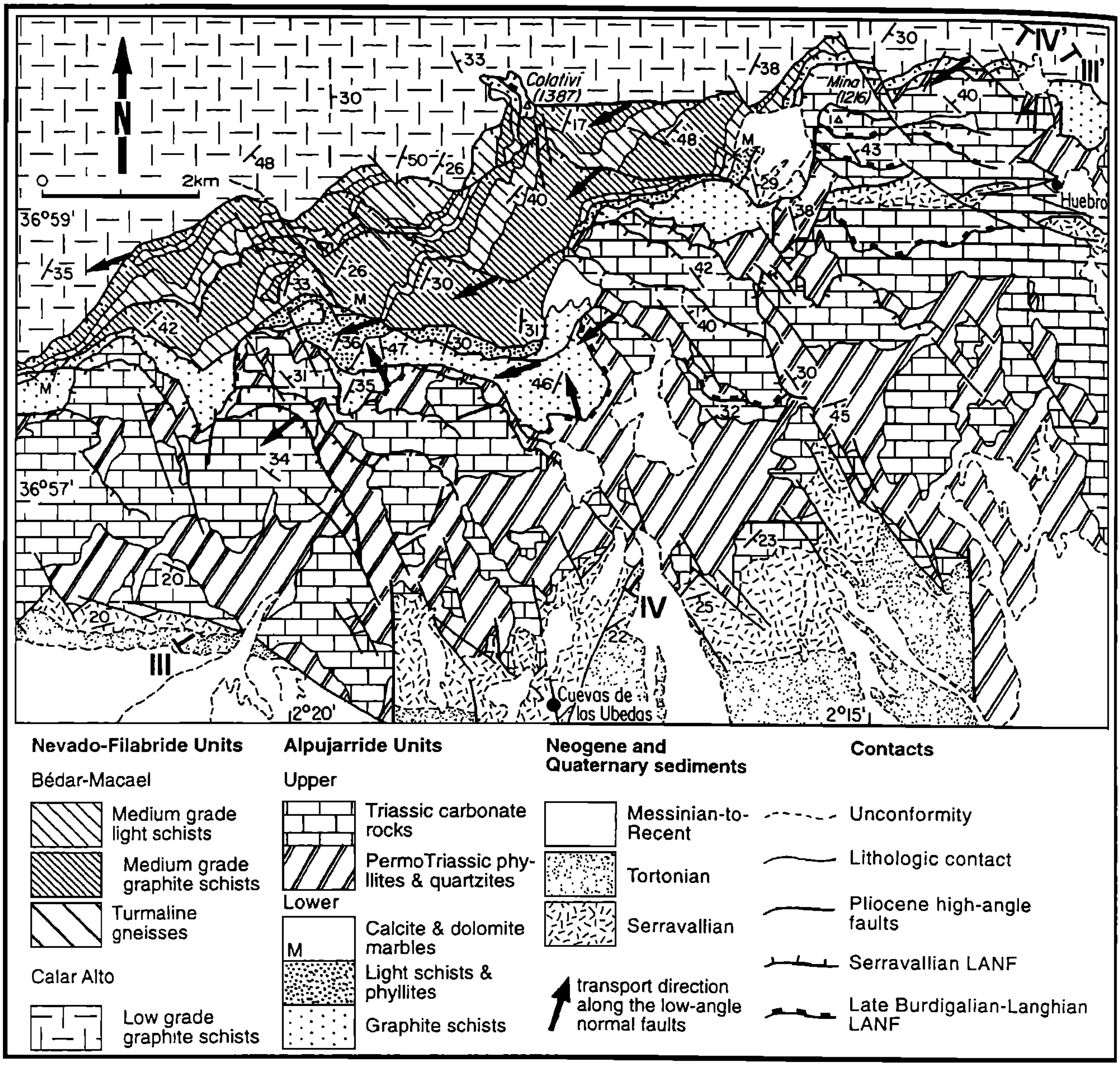

Figure 7. Geological map of southern Sierra Alhamilla. Lines of sections in Figure 9 are given by III-III' and IV-IV'.

situated 10 km deep, identified from wide-angle reflection profiles throughout Sierra Alhamilla, is interpreted as such a detachment [*Banda et al.*, 1993]. The existence of reflectors interpreted as extensional detachments throughout the Betic crust has recently been confirmed by the Esci-Béticas deep reflection seismic profiles [*García-Dueñas et al.*, 1994; *Martínez-Martínez et al.*, 1997].

North-Northwestward Normal Fault System

Cut by faults belonging to the Filabres system, there are other local faults whose striations trend NNW-SSE, orthogonal to the direction of extension in the system. This is the case of certain segments of the contact between the graphite schists from the lower Alpujarride unit and the upper unit phyllites, which we have interpreted as low-angle normal faults (Figure 7). These fault surfaces have been reworked by deformations associated with the Filabres system, locally with two sets of striations showing at times. Slickenlines and extensional shear bands on the faults point to a top-to-the-NNW sense of transport. The faults cut downsection toward the NNW, as may be seen in cross section I-I' of Figure 9 (roughly in the direction of extension). In the southern part of the section, both faults and foliations dip toward the south, as is to be expected from the southern limb of the Sierra Alhamilla late Tortonian anticlinorium [*Platt et al.*, 1983], but the fault dip is less than that of the regional foliation. These faults are relics of an extensional system that has been dismembered and tilted by the Filabres one. The effect of this system on the Alpujarride stack has been the northward

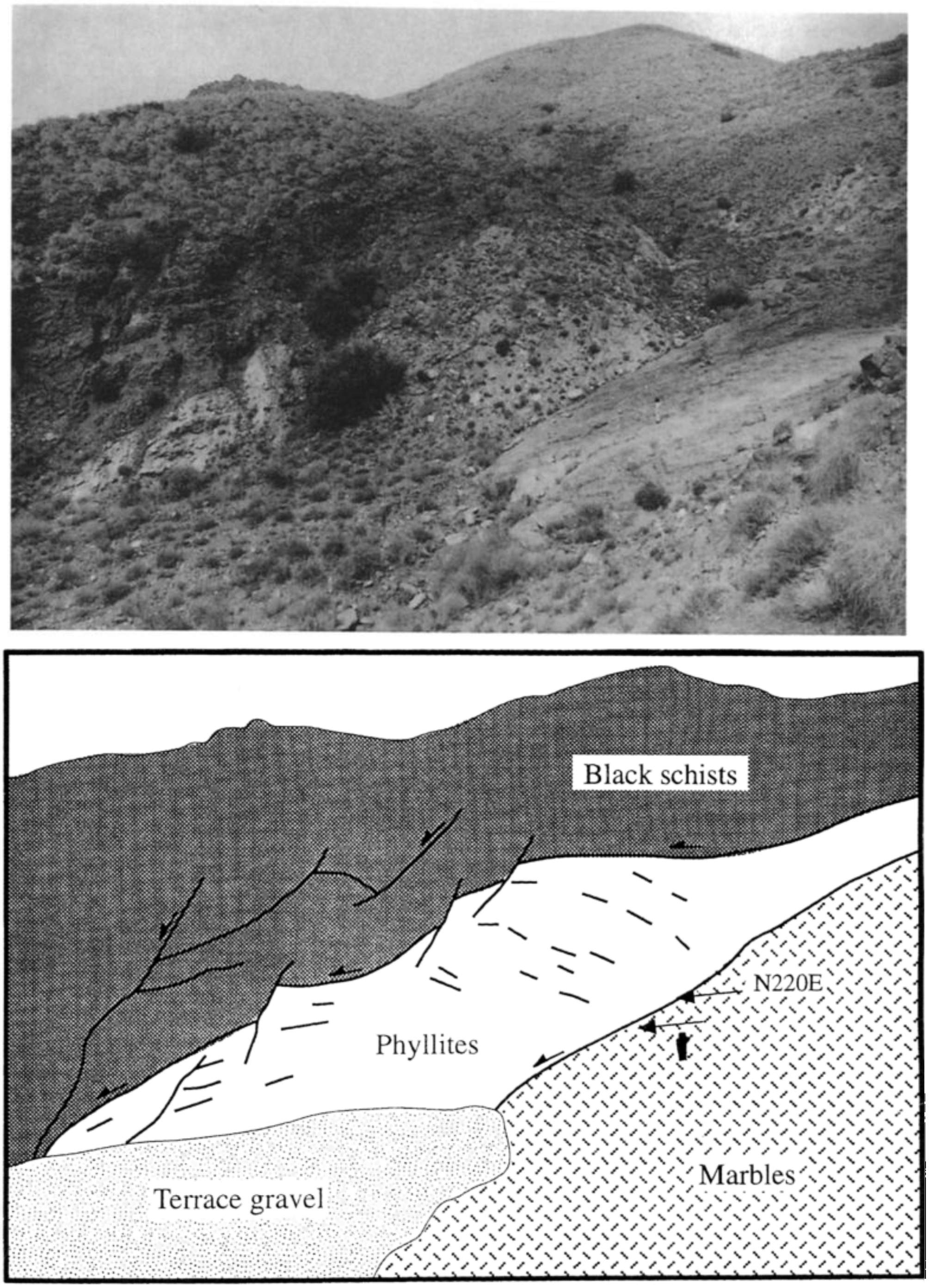

Figure 8. Example of low-angle normal faults affecting the lower Alpujarride unit. Outcrop 1 km NE of Baños village (Figure 5). The contacts among the lithostratigraphic units are faults cutting downsection to the SW. María is standing on the slickenside surface which shows striations plunging N220°E. The foliation in the hanging-wall phyllites has been tilted and dips NE.

wedging of the tectonic and lithological units, resulting in a direct contact between the upper unit carbonate Triassic rocks with the Nevado-Filabride rocks (e.g., in Colativí, Figure 7). Similar faults thinning the Alpujarride stack farther west (Figure 2) have been associated with the Contraviesa extensional system [*Crespo-Blanc et al.*, 1994].

After the successive activity of these two roughly orthogonal extensional systems the Alpujarride units thinned and fragmented, giving rise to a chocolate tablet megastructure. This structure is quite widespread, having been seen in many other areas where the Alpujarride complex crops out [*García-Dueñas et al.*, 1992; *Azañón et al.*, 1994; *Crespo-*

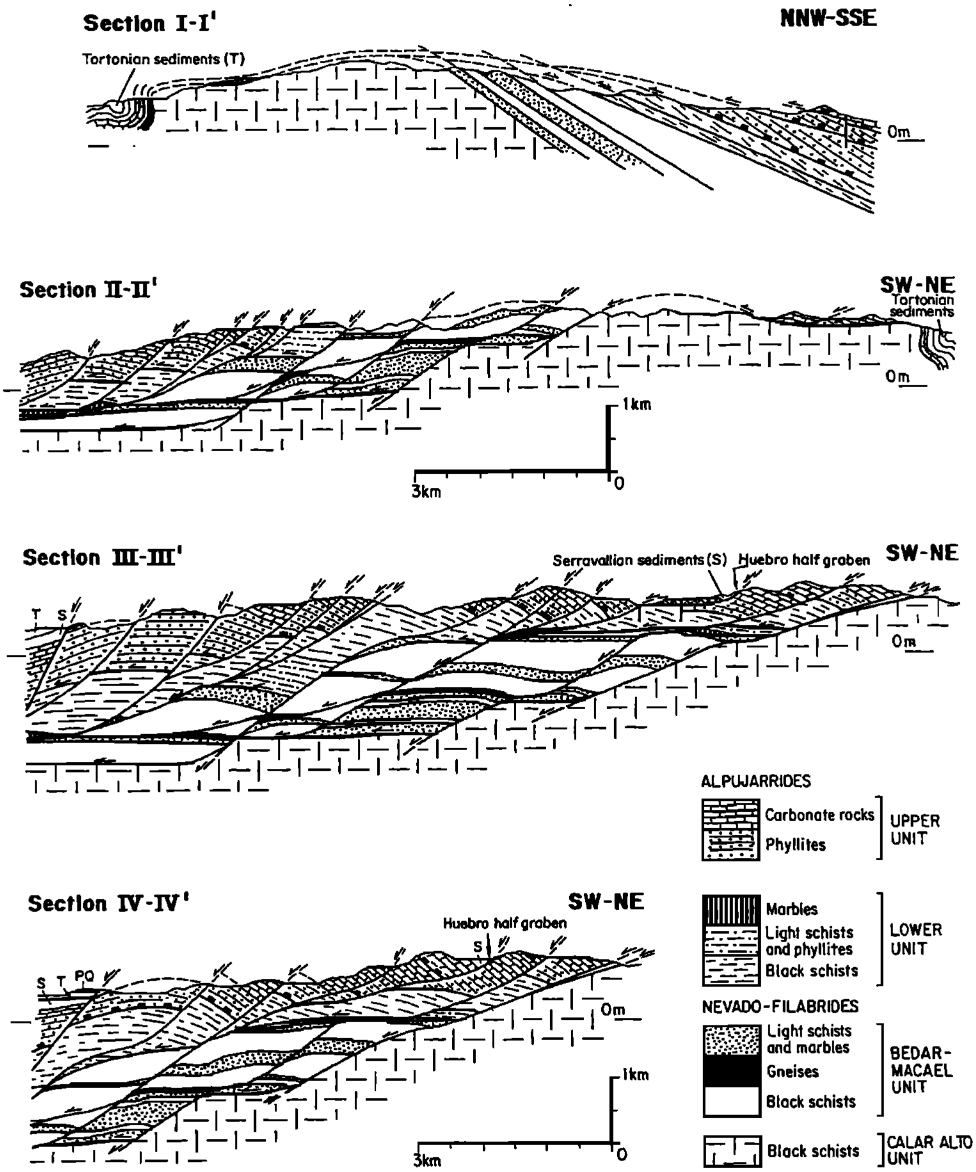

Figure 9. Structural sections through the Sierra Alhamilla anticlinorium, showing the geometry of the middle Miocene extensional systems and the relationships among the lithologic and tectonic units. Section lines are located on Figures 5 and 7. Section I-I' is roughly parallel to the striations of the NNW directed system. The other three sections are roughly parallel to the extension direction of the Filabres extensional system. Abbreviations are as follows: S, Serravallian; T, Tortonian; and PQ, Plio-Quaternary. See description in text.

Blanc et al., 1994; *Crespo-Blanc*, 1995]. These systems are the cause of considerable omissions in the tectonostratigraphic sequences, although they do not upset the preexisting order of superposition. The present-day tectonic units are thus nappe fragments with different degrees of thinning and are termed allocthonous extensional units (as per *Wernicke* [1985]). An example of such units is the so-called Castro slice, interpreted as a fault-bounded "horse" formed during nappe emplacement [*Platt*, 1982]. It is an allocthonous extensional unit, bounded by two brittle low-angle normal faults and represents a fragment of the Bédar-Macael unit. The floor fault of this extensional unit omits more than 1.5 km of structural section, deduced from the thickness of the Permo-Triassic sequences from the Calar Alto unit, completely lacking in Sierra Alhamilla (see Figure 2). The omission associated with the roof fault is around 5 km long, as inferred from the thickness of the two lowest Alpujarride units, the Lújar-Gádor and the Escalate [*Azañón et al.*, 1994], which are well represented in the westernmost regions, such as the Contraviesa and the Sierra de Gádor, but which are absent in the study area (Figure 2).

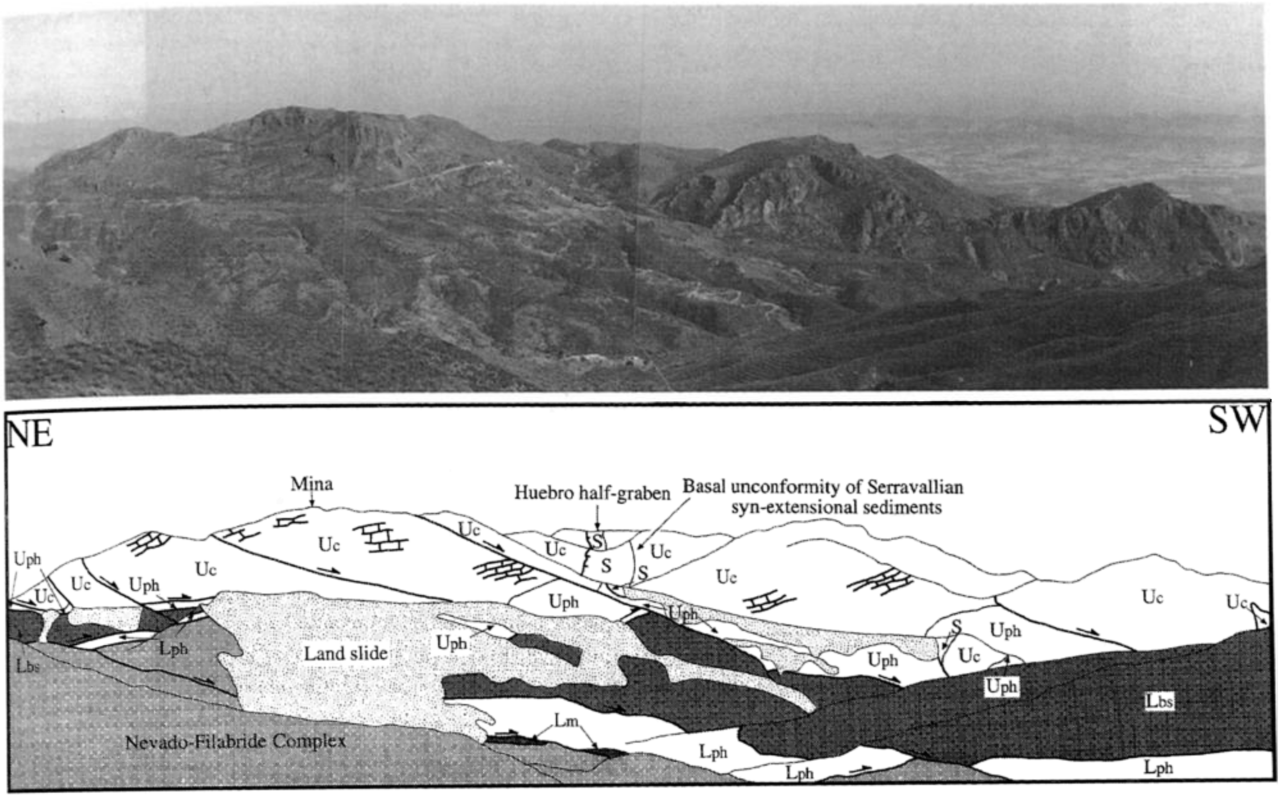

Figure 10. Panoramic view of Filabres extensional system southeast from Colativí showing the tilted hanging-wall blocks of the listric fan. The reference surfaces, including bedding, metamorphic foliation, and detachment faults that developed in the early stages of extension, dip NE. The Serravallian sediments (S) have also been tilted. Abbreviations are as follows: U, upper and L, lower Alpujarride units; c, carbonate rocks; ph, phyllites, bs, black schists; and m, marbles.

Neogene Sediments and the Age of Extensional Systems

The Sierra Alhamilla metamorphic rocks are unconformably overlain by marine and continental sediments ranging in age from upper Langhian to Tortonian [*Ott d'Estevou and Montenat*, 1990; *Serrano*, 1990]; they completely surround the Sierra in the west, outlining a periclinal (Figures 2 and 5). The Messinian-to-Recent sediments unconformably overlie folded Tortonian sediments [*Ott d'Estevou*, 1980]. Figure 2 shows the sediments grouped so that the major internal stratigraphic discontinuities are visible, notable among which are the Serravallian/Tortonian and the Tortonian/ Messinian boundaries. Stratigraphic sequences are well documented in the various basins around the Sierra: The upper Langhian-Serravallian sequence, described by *Serrano* [1990], around Níjar, consists of a basal layer (upper Langhian) of continental or shallow marine conglomerates and sandstones rich in Alpujarride detritus, followed by marls and turbidites (Serravallian) deposited in a marine basin open to pelagic influence. Outcrops of upper Langhian-Serravallian sediments are dispersed and generally lie over the Alpujarride rocks. Around Ugíjar (see Figure 2) they seal faults belonging to the NNW directed Contraviesa extensional system, which was active during the late Burdigalian-Langhian [*García-Dueñas et al*, 1992; *Crespo-Blanc et al.*, 1994; *Mayoral et al.*, 1994]. In the Sierra Alhamilla, middle Miocene sediments form part of the tilted blocks from the Filabres extensional system, being the most superficial formation in certain listric fan riders (e.g., the Huebro half graben; see Figure 9, structural sections III-III' and IV-IV', and Figure 10). The Tortonian sequence has a basal layer (lower Tortonian) comprised by red continental and marine conglomerates rich in Nevado-Filabride detritus, followed by transgressive and turbiditic sediments [*Weijermars et al.*, 1985; *Kleverlaan*, 1989; *Ott d'Estevou and Montenat*, 1990]. It lies unconformably over the middle Miocene sequences and overlaps the basement sealing the tilted blocks thereby postdating the Filabres system, which must therefore have been active during the Serravallian. The basal boundary of the Tortonian sequence can therefore be taken as a breakup unconformity separating synrift and postrift sediments.The lower Tortonian conglomerate layer was deposited on the different Nevado-Filabride units along the length of the Líjar-Fiñana ramp, the higher Nevado-Filabride unit rocks being the source of detritus in the east and the lower unit rocks being the source in the west (Figure 2), which suggests that during the deposition of this layer the main ramp in the Filabres detachment was already readjusted into flat orientations [*García-Dueñas et al.*, 1992]. The shallowness of the basin at the end of the Serravallian,

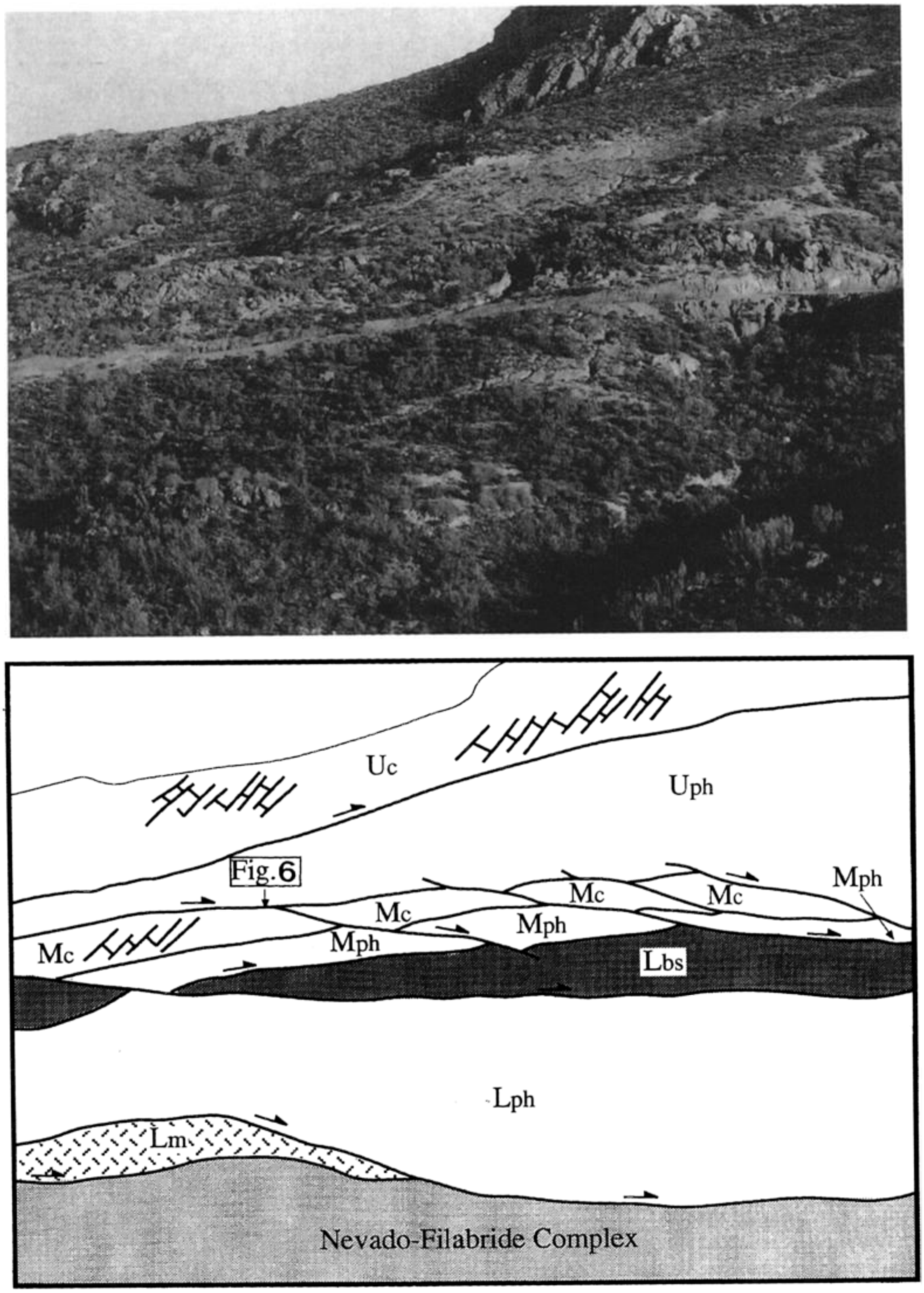

Figure 11. Riders of carbonate rocks (Mc) and phyllites (Mph) detached at high extension representing remains of an intermediate unit (M) between the lower (L) and upper (U) Alpujarride units. Observe tilting of bedding in hanging-wall carbonate rocks moving WSW (right side of photograph). Faults that developed early on in the extension have also been tilted. Outcrop is 1 km NE of Mina (Figure 7). Abbreviations are as follows: c, carbonate rocks; ph, phyllites; bs, black schists; and m, marbles.

determined by the sedimentation of lower Tortonian continental conglomerates on pelagic Serravallian sediments, may be related to the isostatic adjustment of the detachment and subsequent flooding throughout the Tortonian, controlled by the thermal subsidence that followed. The sedimentary sequences from the Messinian to the present, including conglomerates, reef limestones, and evaporites, reveal progressive shallowness interrupted only by the early Pliocene transgression [*Montenat et al.*, 1990; *Rodríguez-Fernández and Martín-Penela*, 1993]. The

Figure 12. S-C-shaped structures produced by shear faulting of a preexisting foliation. Both shear faults (C planes) and foliation (S planes) are tilted and dip east (right side of photograph).

Tortonian/Messinian boundary is a regional angular unconformity [*Ott d'Estevou*, 1980], that occurred after folding of the substrate during the late Tortonian [*Weijermars et al.*, 1985]. The folds affect the extensional systems and the synrift and postrift sediments. The emersion of the basin and the reduction of the Miocene Alborán basin area may be related to this contractional episode [*Comas et al.*, 1992; *Watts et al.*, 1993].

Role of Footwall Metamorphic Tectonites in Extensional Tectonics

The Filabres detachment footwall has a noteworthy presence of mylonites and other planar-linear tectonites, rocks showing strong ductile deformation characterized by platy-laminated foliation and by variably oriented stretching lineation [*Platt et al.*, 1984; *García-Dueñas et al*, 1988a, b;

Figure 13. Extensional listric fault dipping west in the footwall of the Filabres extensional system.

Jabaloy et al., 1993]. Its tectonic significance is controversial, as also occurs in North American Cordilleran metamorphic core complexes. Certain authors associate the mylonitic deformation with the Alpujarride/Nevado-Filabride contact. However, some of these authors, basing this hypothesis mainly on data from Sierra Alhamilla, describe it as a crustal-scale shear zone, the Betic Movement Zone, and believe it to represent the suture between two collisional continental blocks along which the northward emplacement of the Alpujarride nappes occurred [*Platt and Vissers*, 1980; *Platt and Behrmann*, 1986]. Yet other researches, in turn, interpret this deformation as a Miocene extensional shear zone progressing from ductile to brittle conditions during the Burdigalian-early Tortonian [*Galindo-Zaldívar et al.*, 1989; *Jabaloy et al.*, 1993; *Vissers et al.*, 1995]. Nevertheless, these tectonites are not distributed in a single deformation band; instead, they affect different levels of the Nevado-Filabride tectonostratigraphic sequence, with two noteworthy principal shear zones about 500 m thick subparallel to the main regional foliation and located on levels more than 5 km apart. These shear zones have a flat geometry and contain the boundaries between the three major units comprising the Nevado-Filabride complex (Figure 2), leading them to be interpreted as thrusts [*Martínez-Martínez*, 1986a, b; *García-Dueñas et al.*, 1988a, b].

The controversy is based on two main points: (1) the extensional or contractional nature of the ductile shear zones and (2) their relationship with the Alpujarride/Nevado-Filabride contact. The difficulty with point (1) lies in the flat geometry of the shear zones subparallel to the main foliation (S_2) in all the outcropping segments. Thermodynamic conditions deduced from fluid inclusions trapped in quartz grains from the tectonites point to an isothermal decompression path, evidence of the extensional nature of the shear zones, which have probably reworked previous thrusts [*González-Casado et al.*, 1995]. On the other hand, the Alpujarride/Nevado-Filabride contact, widely considered nowadays as a brittle detachment [*García-Dueñas and Martínez-Martínez*, 1988; *Galindo-Zaldívar et al.*, 1989; *Platt and Vissers*, 1989], only occasionally comes into contact with the mylonitic bands. In fact, given the geometry of this detachment, with very low-angle (<8°) ramps and flats [*García-Dueñas and Martínez-Martínez*, 1988], there are sections (flats) that coincide with the key surfaces in the footwall, locally a mylonitic foliation. Other sections (ramps), however, cut across the main foliation in the footwall, including the ductile shear zones; such is the case of the Líjar-Fiñana ramp cropping out in the Sierra de los Filabres, which cuts across the Nevado-Filabride stack downsection from the Bédar-Macael unit to the Veleta unit, east to west (Figures 2 and 3). An interesting characteristic of the footwall ramp structure is the systematic attitude of the main foliation and shear zones which, apart from the effect of the upper Miocene folds, all dip toward the east, while after restoration of the folds the ramp is in a horizontal position (Figure 4). This framework could have been caused because of isostatic rebound by the Filabres detachment in response to the tectonic denudation during the Serravallian, which moved the ramp section toward a horizontal position and regionally tilted the footwall toward the east [*García-Dueñas et al.*, 1992; *Martínez-Martínez et al.*, 1997]. It thus appears that the Filabres detachment is not the most superficial and brittle part of a deep ductile shear zone, as suggested by *Galindo-Zaldívar et al.* [1989], but instead represents a different detachment. In addition, several reasons lead us to believe that the working of the Filabres detachment and the shear zones has been neither simultaneous nor progressive: First, there is variability in the attitude of the streching lineation of the mylonites [*Platt et al.*, 1984; *Jabaloy et al.*, 1993] with respect to the constant trending of the detachment striations (WSW oriented). Second, the SE vergent folds affect the whole Nevado-Filabride stack, including the mylonites, but are cut by faults associated with the detachment. Third, the successive superposition of extensional systems extend nearly orthogonally, indicating that the thinning took place in extensional spurts rather than continuously. In addition, although an age of 16-17 Ma has been suggested for the activity of the Nevado-Filabride ductile shear zones [*Monié et al.*, 1991], the fact that micas collected outside the shear zones are of the same age could indicate that the age is not that of the deformational process; rather, the dating could represent a more recent thermal event or a cooling age for older events that were more generalized than the shear zones. The micas may even date unroofing related to the Filabres extensional system.

Discussion and Tectonic Implications

In the Alpine history of the Alborán domain, two major orogenic cycles can be distinguished: (1) During the Cretaceous-Paleogene this terrain was involved in a complicated orogenic evolution with alternating contractional and extensional events [*De Jong*, 1991; *Balanyá et al.*, 1993] that eventually led to the stacking of the metamorphic complexes. (2) In the Neogene the Alborán domain, already consisting of a thick-skinned nappe stack, became the hanging wall of a major thrust, the Gibraltar thrust [*Balanyá and García-Dueñas*, 1988], along which there occurred westward movement of more than 300 km. Neogene deformation produced folding and thin-skinned thrusting in the foreland (South-Iberian and Maghrebian domains), coeval with severe thinning in the hinterland thus resulting in the formation of the Alborán basin.

The Miocene Alborán basin covered a greater area than at the present [*Comas et al.*, 1992; *García-Dueñas et al.*, 1992; *Rodríguez-Fernández and Martín-Penela*, 1993; *Watts et al.*, 1993]; the partial emersion of the basin began in the late Tortonian because of the development of large-scale open folds. Subsequent erosion has uncovered its thinned basement in the southeastern Betics, while in the present-day Alborán Sea the basement is covered by sedimentary sequences up to several kilometers thick. Rather than a continuous extensional process as suggested by *Watts et al.* [1993], the thinning of the Alborán domain during the Miocene took place in various rifting episodes with changing directions of extension [*Comas et al.*, 1992] and the development of extensional systems that successively affected deeper levels of the domain. The data presented here reveal that during the middle Miocene the basement underwent thinning as the result of the superposition of two successive extensional systems with nearly orthogonal extension. The youngest system

(Serravallian in age) has a floor detachment, the Filabres detachment [*García-Dueñas and Martínez-Martínez*, 1988], which corresponds to the Alpujarride/Nevado-Filabride contact; it is an ENE-WSW system with a main WSW sense of transport. It is markedly asymmetrical with an almost complete predominance of WSW dipping faults, some of which cut the detachment and penetrate its footwall, suggesting the existence of other deeper detachments [*Banda et al.*, 1993; *Martínez-Martínez*, 1995; *Martínez-Martínez et al.*, 1997]. The late Burdigalian-Langhian system extends NNW-SSE with a NNW sense of transport and affects only the Alpujarride units. The superposition of the two systems caused the fragmentation and thinning of the aforementioned units with the resulting chocolate tablet megastructure. Similar structures have been recognized in other areas where the Alborán domain crops out [*García-Dueñas et al.*, 1992; *Crespo-Blanc* et al., 1994; *Crespo-Blanc*, 1995], indicating that this mode of extension is generalized. The thinning of the Malaguide and of the higher Alpujarride units, which crop out widely in the western Betics, is due to the activity of extensional systems active during the late Oligocene to Aquitanian [*Aldaya et al.*, 1991; *García-Dueñas et al.*, 1992; *Lonergan and Platt*, 1995]. This complex pattern of extension is not satisfactorily explained in the different models for the tectonic evolution of the peri-Alborán orogenic system.

Models supporting extensional collapse and convective removal of the lithospheric root [*Platt and Vissers*, 1989; *Doblas and Oyarzun*, 1989] suitably explain the early Miocene reheating [*Platt et al.*, 1996] but are fixist models that limit the tectonic evolution of the Alborán domain to the region around the Alborán Sea and do not take into account the palinspastic reconstructions placing this domain in a more easterly position during the Paleogene [e.g., *Bouillin et al.*, 1986; *Guerrera et al.*, 1993]. More than 300 km of westward motion is also necessary to explain the significant E-W shortening in the Gibraltar thrust footwall both in the Betics [*Didon et al.*, 1973; *García-Hernández et al.*, 1980; *Balanyá*, 1991; *Guezou et al.*, 1991] and in the Rif [*Morley*, 1987]. Paleomagnetic rotations, clockwise in the Betics and counterclockwise in the Rif, are consistent with this motion [*Platzman*, 1992; *Platzman et al.*, 1993; *Villalaín et al.*, 1994]. Moreover, the restoration of the hinterland extension, according to known kinematic vectors, situates the Ronda peridotites, a tectonic element in the higher Alpujarride units now close to the Gibraltar arc, to a pre-Miocene position around zero meridian [*García-Dueñas et al.*, 1993]. On the basis of our calculations for the displacement of the Filabres detachment (>75 km), we conclude that the palinspastic position of the hanging wall before the Serravallian was in or very close to the western North Algerian basin. It is therefore possible to relate the late Burdigalian-Langhian system with the opening of this basin, which on the basis of the general trend of the magnetic anomalies [*Rehault et al.*, 1985] spread in the same direction as the system extension.

Most models supporting significant Miocene westward motion of the Alborán "microplate" proceeding from the location where the North Algerian basin is currently found [e.g., *Andrieux et al.*, 1971; *Leblanc and Olivier*, 1984], nevertheless, fail to explain the severe extensional thinning of the Alborán domain coeval with thrusting in the external

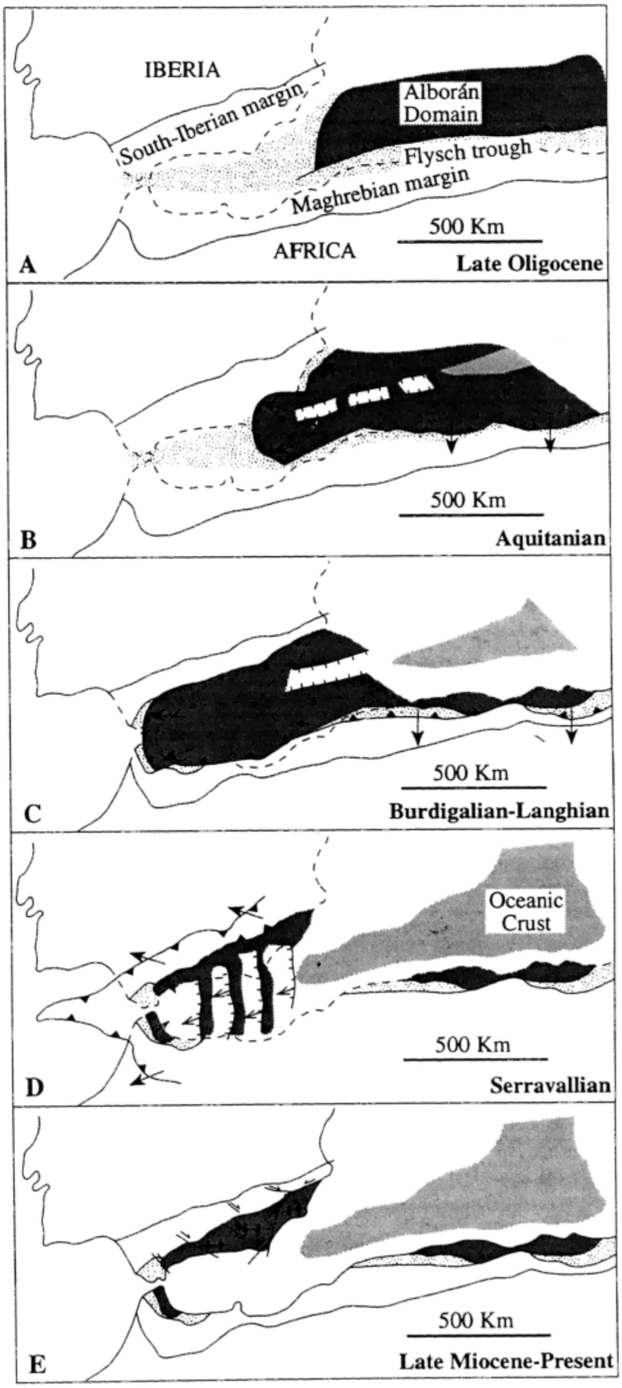

Figure 14. Hypothetical evolution of westernmost Mediterranean region from the late Oligocene to the Present: (a) late Oligocene, (b) Aquitanian, (c) Burdigalian, (d) Serravallian, and (e) late Miocene to Present. Kinematic vectors according to data from:*Wildi*, 1983; *Morley*, 1987; *Balanyá and García-Dueñas*, 1988; *Balanyá*, 1991; *Guezou et al.*, 1991; *García-Dueñas et al.*, 1992; *Plaztman et al.*, 1993; *Crespo-Blanc et al.*, 1994; *Lonergan et al.*, 1994; *Platt et al.*, 1995 and our own data. Oceanic crust in north Algerian basin after *Rehault et al.*, 1985. The position of the Iberian and African coastline is as in the Present. The convergence between Iberia and Africa from the Oligocene to the Present has not been taken into account. See explanation in text.

zones. We propose an alternative model that, taking into account the idea of westward motion, tries to explain the complicated pattern of extension described above, as well as other geological and geophysical data documented in the literature. Five structural and paleogeographic sketches (Figure 14) help to illustrate a history of westward tectonic escape from a N-S collision zone similar to the model proposed by *Royden* [1993]. Figure 14a shows our reconstruction of the westernmost Mediterranean after the Paleogene collision between Africa (with Apulia) and Europe (with Iberia) after the closure of the Ligurian Tethys. The Alborán domain was most likely a collisional ridge similar to the one proposed by *Platt and Vissers* [1989] but in a more easterly position. It is separated from the northern Africa margin by the so-called Flysch Trough [*Didon et al.*, 1973]. A derivation of this trough was probably located between the southeastern Iberian margin and the Alborán domain [*Guerrera et al.*, 1993].

The Aquitanian time slice (Figure 14b) depicts south directed contraction in the Flysch Trough of North Africa. Rifting within the Alborán domain is parallel to the regional axis of shortening and is compatible with extensional collapse and convective removal of the lithospheric root [*Platt and Vissers*, 1989]. The reheating detected in the western Betics [*Platt et al.*, 1996] could be related to asthenospheric uplift during this period. Continued convergence caused the westward tectonic escape of a portion of the Alborán domain [*Royden*, 1993].

During the Burdigalian (Figure 14c), an oblique collision of the Alborán domain with both the southeastern Iberian and northwestern African margins occurs after the obliteration of the Flysch Trough that gave rise to the Gibraltar arc [*Balanyá and García-Dueñas*, 1988]. Clockwise rotation occurs within the South-Iberian thrust belt, as does counterclockwise rotation in the external Rif. Late Burdigalian-Langhian NNW-SSE extension in the easternmost part of the Alborán domain may be related to the North Algerian basin opening. Seismic tomography suggests the presence of a detached slab of cool mantle at 200-600 km beneath the eastern Betics [*Blanco and Spakman*, 1993], and therefore lateral inflow of the asthenosphere occupying the space left by the detachment is a very likely mechanism for drive extension [*Platt and Vissers*, 1989].

Large-scale longitudinal extension is illustrated in the Serravallian structural sketch (Figure 14d). WSW directed low-angle normal faults thinned most of the Alborán domain. The extension invaded the contractional areas, resulting in the tectonic inversion of the Gibraltar thrust with SSE directed low-angle normal faults in the western Betics and NE directed ones in the Rif. The mountain front meanwhile migrated westward to the externalmost zones [*García-Dueñas et al.*, 1992], which seems to indicate that the engine of extension is the same as that producing arc migration. Two mechanisms have been suggested, delamination of the lithospheric mantle in conjunction with asymmetric thickening of the lithosphere [*García-Dueñas et al.*, 1992] or westward retreat of an east dipping subduction boundary [*Royden*, 1993]. Geophysical evidence for lithospheric delamination beneath the western Alborán Sea has recently been presented. The presence of a seismically active, high-velocity body in the upper mantle at 60-150 km deep beneath an anomalously low-velocity, aseismic zone between about 20 and 60 km deep is used to argue that asthenospheric material is underlain by a rigid upper mantle, interpreted as being detached at present [*Seber et al.*, 1996]. The fact that a slab of lithospheric mantle beneath the eastern Alborán Sea is found at much greater depths [*Blanco and Spakman*, 1993] indicates that here the lithospheric mantle was removed at an earlier stage [*Seber et al.*, 1996]. Both geophysical and geological data therefore suggest that delamination migrated westward, which is consistent with the mechanisms proposed by both *García-Dueñas et al.* [1992] and *Royden* [1993].

The late Miocene-to-Present structural framework (Figure 14e) is controlled by a general situation of approximately N-S contraction, resulting in the E-W trending, large-scale open folds affecting the extensional systems and conjugate left- and right-lateral strike-slip faults.

In short, our model explains several characteristics of the peri-Alborán orgenic system: (1) the high values of shortening in the Gibraltar thrust footwall, (2) the absence of a broad radial pattern in both extension and thrusting, and (3) the timing and modes of extension in the Alborán domain. The driving force of extension in a general context of convergence is controversial and varies between a convective removal model and a delamination model. Constraints on both the timing and the kinematics of extension, as presented in this paper, seem to support the contribution of both mechanisms. Convective removal may have started the process, but continued N-S convergence could have resulted in westward tectonic escape and asymmetric lateral inflow of asthenospheric material accompanying lithospheric delamination.

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