Orthogonal extension in the hinterland of the Gibraltar Arc (Beltics, SE Spain)

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Abstract: The Gibraltar Arc, the westernmost segment of the Alpine peri-Mediterranean orogenic system, is a Miocene arcuate orogen formed by the continental collision of various pre-Miocene terranes in the major zone of collision between the Iberian and African cratons. The upper plate (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 lower plate, 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, perpendicular 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. Perpendicular 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.

Key words: Mediterranean, Betics, Gibraltar Arc, Alborán domain, orthogonal extension, extensional detachments, extensional collapse, lithospheric delamination.

Introduction

The Betics in southern Spain and the Rif Mountains in North Africa constitute the westernmost segment of the Alpine peri-Mediterranean orogenic system. The Betics and the Rif link across the Straits of Gibraltar to form a Neogene arcuate thrust and fold belt (Gibraltar Arc) containing Cenozoic and Mesozoic sedimentary rocks, the South-Iberian and Maghrebian domains, originally deposited on the South-Iberian and North-African continental margins, respectively. The hinterland of this Neogene orogen is formed by a pre-Miocene terrain: the Alborán domain, mainly consisting of Palaeozoic and Mesozoic rocks, most of which have been deformed under variable metamorphic conditions. A highly deformed four domain, the Flysch Trough domain separates the Alborán domain from the South-Iberian and Maghrebian domains in the western Betics and Rif. The trough, underlain by oceanic or very thin continental crust, was the locus of deep-water sedimentation during the same period (Biju-Duval et al., 1977). On the basis of paleogeographic considerations and geological similarities with the Kabyly, Calabrian and western Alp nappes, the Alborán domain has been interpreted as belonging to the formerly continuous Alpine Cretaceous-Paleogene orogen that was fragmented and dispersed during the Neogene (Alvarez et al., 1974; Bouillin et al., 1986). Palinspastic reconstruction's situate the Flysch trough at the South and West of this orogen, along the length of the Eurasian-Africa transform boundary. Neogene deformation affected the different domains unequally: while the South-Iberian, Maghrebian and Flysch Trough domains were heavily shortened by thin-skinned thrusting and folding, the Alborán domain has greatly extended sections with the development of low-angle normal faults (extensional detachments) (García-Dueñas and Martínez-Martínez, 1988; Galíndo-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 W 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). Paleomagnetic work has demonstrated that thrusting was accompanied by significant rotations, generally clockwise in southern Spain and counter-clockwise in Morocco (Osete et al., 1989; Platzman, 1992; Villalaín et al., 1994).

The origin of the Gibraltar 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 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

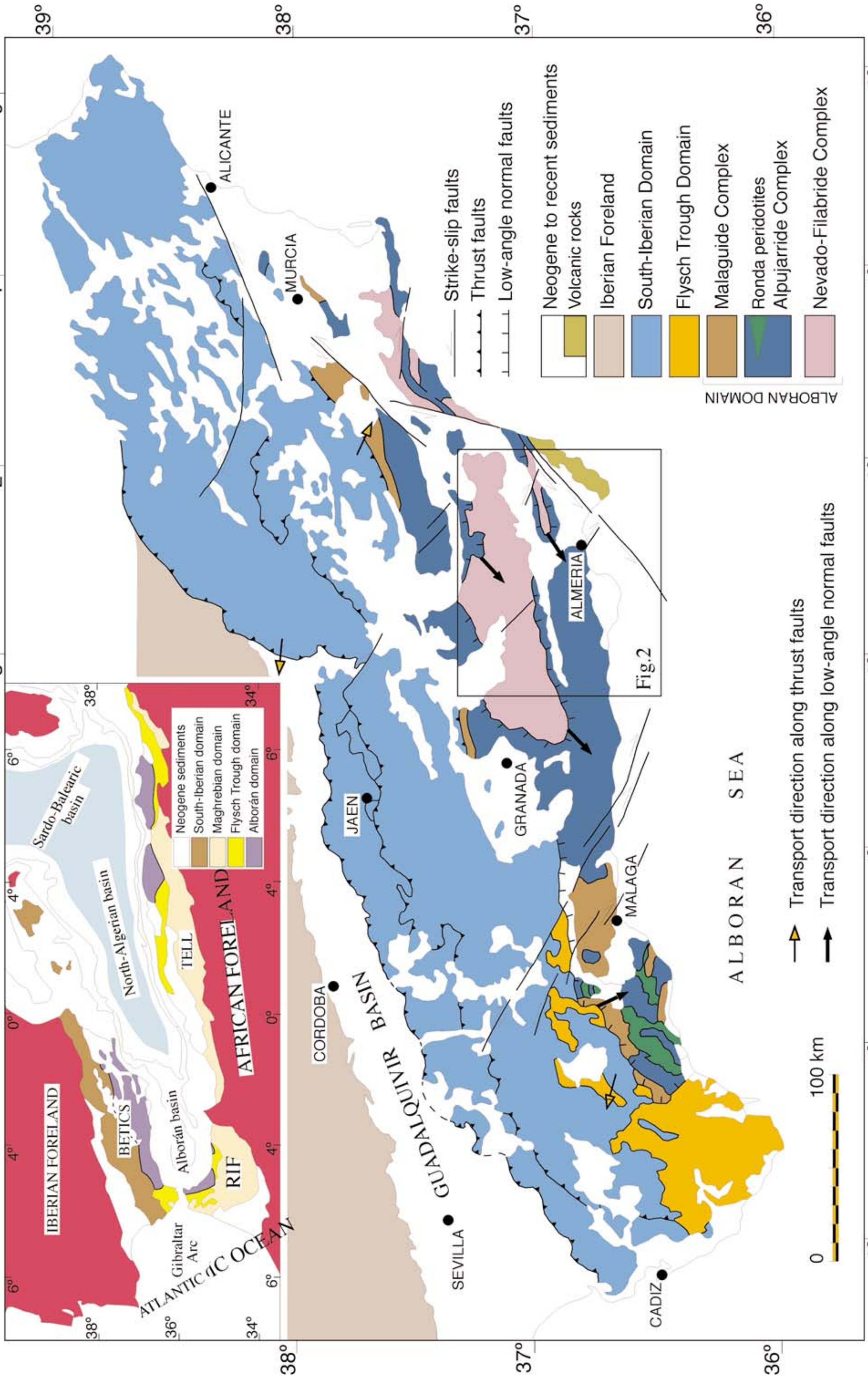

Figure 1. Tectonic map of the Betics and main tectonic domains around the westernmost Mediterranean.

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 post-orogenic extensional collapse of an overthickened collisional ridge in the Alborán region (Doblas and Oyarzun, 1989; Platt and Vissers, 1989; Vissers et al., 1995). The last 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 first 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, on the order of hundreds of kilometers; the marked asymmetry of the extensional systems thinning the internal zones, and soon. Distances of some 250 km have been suggested for the westward motion of the Alborán domain to account for the significant E-W shortening in the footwall only taking into account 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).

This paper is concerned with a sector of the Alborán domain in the southeastern Betics (Fig. 1) where large-scale extensional detachments and low-angle normal faults have been described in the two last decades (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: (1) the differentiation of pre-Neogene and Neogene structures; (2) the timing of the Neogene extension; and (3) 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, perpendicular to the belt axis and a WSW-directed orogen-parallel system. The perpendicular extension is plausible in a process of the gravitational collapse of an overthickened crust; nevertheless, the orogen-parallel extension is more difficult 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.

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 tectono-metamorphic 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 Fig. 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 (Fig. 2).They are, from bottom to top: the Ragua, 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; Martínez-Martínez et al., submitted to Tectonics). The Ragua unit, consisting largely of Paleozoic albite-rich graphite mica-schist with metapsammite at top, crops out widely in the central Sierra de los Filabres and the eastern Sierra Nevada (Fig. 2). In contrast, westward its outcrops are limited to various tectonic windows whose location generally coincides with that of various antiformal nuclei (Fig. 2). The lithostratigraphic sequence of the Calar Alto unit (Fig. 3) consist primarily of clorithoid-rich graphite schist and quartzites (Montenegro formation) of probable pre-Permian age (Lafuste and Pavillon, 1976); a sequence of light-colored metapelites and metapsammites (Tahal formation, probably Permo-Triassic); and a calcite and dolomite marble formation (Atalaya formation), which,

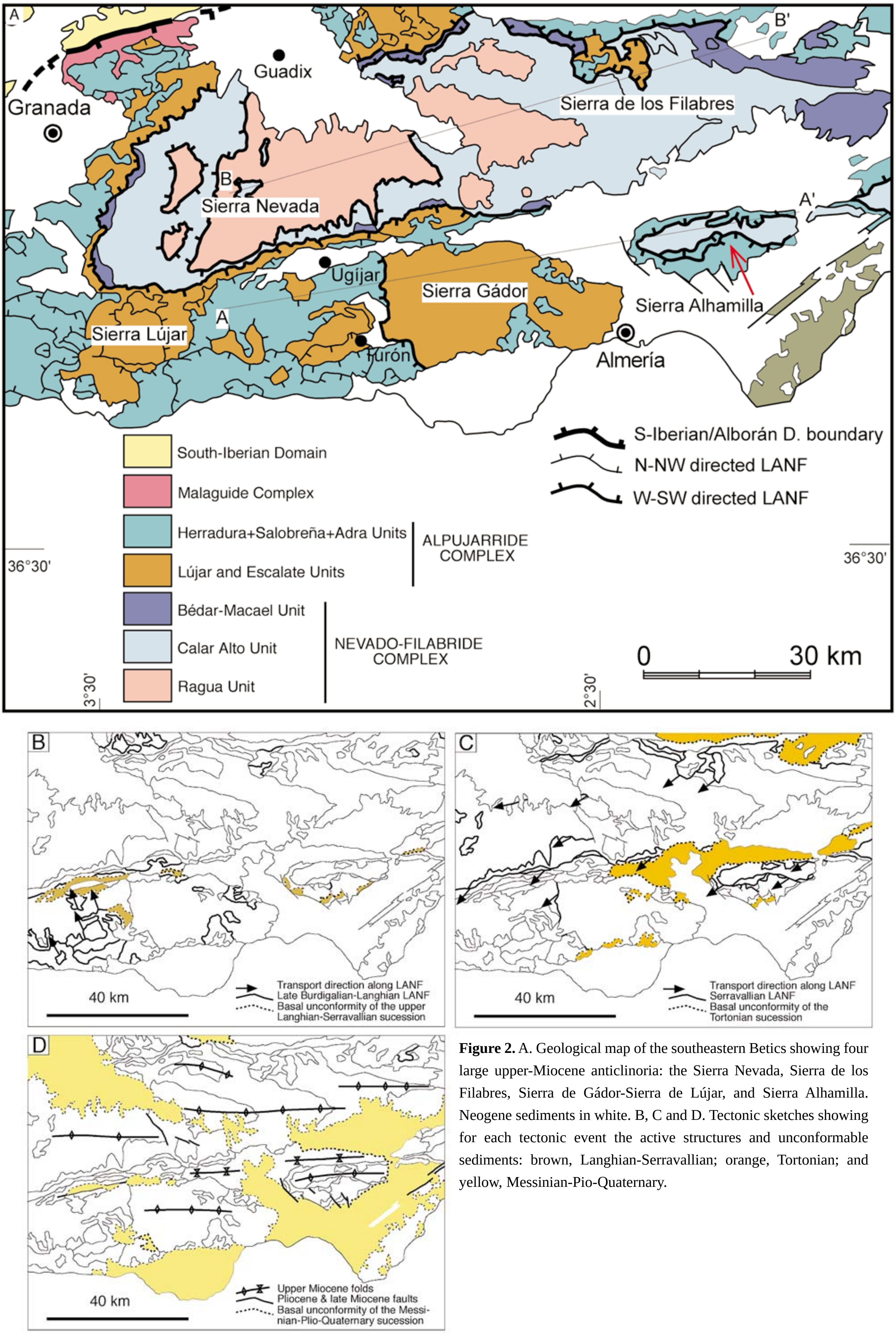

Figure 2. A. Geological map of the southeastern Betics showing four large upper-Miocene anticlinoria: the Sierra Nevada, Sierra de los Filabres, Sierra de Gádor-Sierra de Lújar, and Sierra Alhamilla. Neogene sediments in white. B, C and D. Tectonic sketches showing for each tectonic event the active structures and unconformable sediments: brown, Langhian-Serravallian; orange, Tortonian; and yellow, Messinian-Pio-Quaternary.

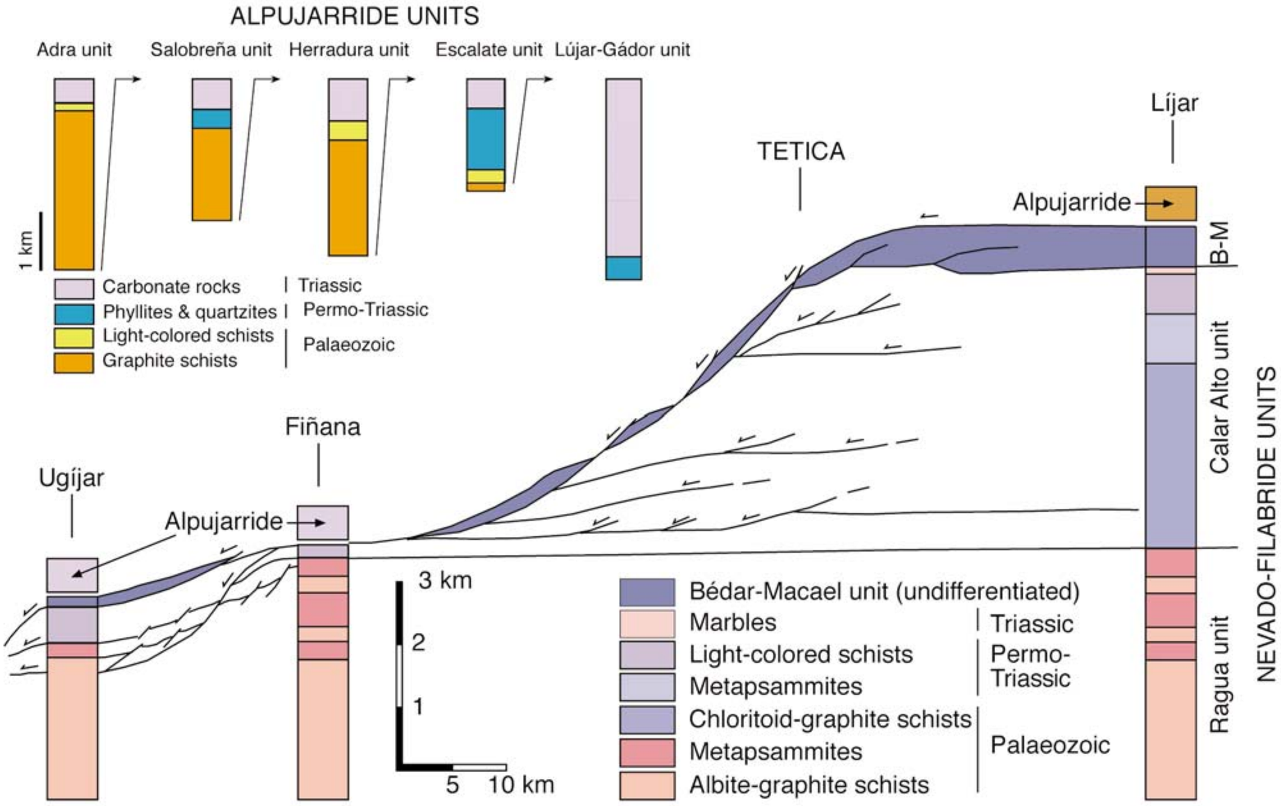

Figure 3. Several Nevado-Filabride tectono-stratigraphic columns at different localities beneath the detachment surface at the base of the Alpujarrides. Note the westward attenuation of the units. Standard lithostratigraphic columns in the different Alpujarride units are also shown.

although traditionally considered to be Triassic, locally contains microfossils of possible Cretaceous age (Tendero et al., 1993). The Bédar-Macael unit consists of a more variegated sequence of medium-grade metamorphic rocks including staurolite graphite mica-schist, tourmaline gneiss, light-colored schist, serpentinite, amphibolite, and marble, from bottom to top. It appears as lenses sandwiched between the overlying Alpujarride complex and the underlying Calar Alto unit. Permian orthogneisses (269 ± 6 Ma, Priem et al., 1966) and late Jurassic metabasites (146 ± 3 Ma, Hebeda et al., 1980) are locally included at different levels of the sequences. The contacts between the units lie within broad ductile shear zones (500-600 meters 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 schistosity (S_2) subparallel to the lithologic banding, and associated with isoclinal folds which produces the regional inversion of the lithologic sequences showing reverse limbs with the Tahal formation underlying the Montenegro formation. The S_2 developed under greenschist facies conditions in the lower units and in amphibolite facies conditions in the highest one (Martínez-Martínez, 1984; Platt and Behrmann, 1986; García-Dueñas et al., 1988 a, 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 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 H-P minerals formed in a pre-kinematic 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 mylonitic foliation (S_3) containing E-W-trending stretching lineation (García-Dueñas et al., 1988 a, b; Soto et al., 1990; Soto, 1993; González-Casado et al., 1995). Both the S_2 and S_3 foliations are affected by S to SE vergent, metric-to-hectometric folds with associated crenulation cleavage $_{(S4)}$ that is present throughout the entire Nevado-Filabride stack (Vissers, 1981; Behrmann, 1982; Martínez-Martínez, 1984; Soto, 1993).

The high-pressure/low-temperature mineral 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; Figs. 2 and 3) have been recognized, showing significant differences in their metamorphic record, from low-grade conditions (P<7 kb/T<400ºC) in the lowest unit up to high-grade conditions (P>10 kb/ T>550ºC) 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: 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 D3 contractional episode, the S_2 foliation is affected by N-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; 1997) 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 N-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 tectono-metamorphic 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 N-vergent folds (Muñoz, 1991; Balanyá et al., 1993; 1997; Sánchez-Gómez et al., 1995). 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 post-dating the exhumation and decompression of the Alpujarride rocks in the western Alborán Sea have recently been presented (Platt et al., 1996).

Miocene Extensional Tectonics

The knowledge of the internal structure in the Alboran domain has been broadly improved after the first news about the existence of extensional detachments in the Betics (Platt et al., 1983; Aldaya et al., 1984; Martínez-Martínez, 1984). Numerous additional documentation has been reached from that time, so the greater part of the tectonic unit boundaries are considered to be low angle normal faults (García-Dueñas et al., 1986; García-Dueñas and Martínez-Martínez, 1988; García-Dueñas et al., 1988, Galindo-Zaldívar et al., 1989; Platt and Vissers, 1989; García-Dueñas et al., 1992; Jabaloy et al.,1993; Crespo-Blanc et al., 1994; Crespo-Blanc, 1995; Martínez-Martínez and Azañón, 1997). 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. 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 analyse 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 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: a) excision of metamorphic zonation with lower-grade metamorphic rocks lying over higher-grade rocks (Platt et al., 1983); b) evolution of the deformation conditions (from ductile to brittle) along the contact (Platt et al., 1984; Platt and Berhmann, 1986; Galindo-Zaldívar et al., 1989; Jabaloy et al., 1993); c) vertical omissions of the sequence together with the fault kinematics (García-Dueñas et al., 1986); d) geometry and kinematics of linked fault systems (García-Dueñas and Martínez-Martínez, 1988; Crespo-Blanc et al., 1994; Crespo-Blanc, 1995; Martínez-Martínez and Azañón, 1997); e) the timing of rapid unroofing across the system (Johnson et al., 1997).

In the next sections we present detailed documentation about three representative areas in the Alborán domain where large segments of the upper crust have undergone severe extensional thinning.

Sierra de Gádor-Sierra de Lújar section

In this section, the characteristic lack of continuity of the Alpujarride tectonic units that appears in Figure 2, evidences the omissions originated in extensional conditions. Aldaya et al. (1979) grouped these units -- at that time, nappes -- according the relative position of the units within the Alpujarride complex, the variation of the stratigraphic formations and the distribution of the metamorphic mineral assemblages. Azañon et al. (1994) chose to integrate these data and to use the metamorphic record with particular emphasis on the distribution of HP-LT mineral assemblages to discriminate the Alpujarride units as the P-T-t path of the rocks forming them show very different P-T conditions, although their tectonometamorphic evolution is similar.

The regional structure of the Alpujarride complex in the area is characterized by a nappe-stacks thinned by low-angle normal faults. The internal structure of the units consists of pre-Miocene recumbent kilometric folds (F_3), marked by an schistosity (S_2) subparallel with the lithological boundaries. The folds developed pervasive crenulation cleavage (S_3). Relationships between the key surfaces (S_2 and S_3) and the low-angle faults clearly points to the subtractive character of these faults. The remarkably severe thinning or even omission of the units in this section is due to a fan of listric normal faults with northwest to north-northwestward movement. These faults, belonging to the so-called Contraviesa extensional system (Crespo-Blanc et al., 1994), tend to coalesce with a sole fault, the Turón extensional detachment (García-Dueñas et al., 1992) that bounds the upper part of the Lújar-Gádor unit (Figure 4). The detachment and associated faults can be observed in the Sierra de Lújar, Sierra de Gádor and Turón tectonic windows (Figure 2). Kinematic indicators, including slickenlines and tail of microcrushed material on the fault planes, S-C shaped microstructures and the orientation of the calcite vein associated with the low angle normal faults in the carbonate rocks point to a NNW sense of shear. The listric character of faults is inferred by the tilting of the key surfaces and the thinning of the units limited by the faults towards the NNW. It must be stressed that the faults associated with this extensional system cut clearly through the F_3 folds. The relationships with the sedimentary cover constrain the age of the basement brittle faults: Serravallian shales and sandstones clearly post-date the NW to NNW-ward extensional system (near of Ugíjar town, Figure 2). As can be appreciated in the figure 2, the western boundary of the Sierra de Gádor is a high-angle normal fault with W-SW transport sense that cut the Contraviesa system fault and produce the boudinage of the Lújar-Gador unit (Figure 5). The present dip of the low-angle normal faults which bound the Alpujarride extensional units of the area is due to a N-S to NW-SE compression that affected the Alboran region from Late Tortonian to Recent times. The low-angle faults form very open large-scale folds, approximately E-W-directed. These folds, together with the tilting of the structures along low-angle normal faults with northward movement, explain why the S_2 foliation generally dips moderately towards the south.

Sierra de los Filabres section

The Sierra de los Filabres is a range mainly controlled by a large scale, W-E trending, N-vergent, double plunging anticlinorium that generated in the upper Miocene. One of the more noticeable structural features in this area is the regionally systematic eastward dip component of both the schistosity and the mylonitic foliation in the Nevado-Filabride units. The Alpujarride/Nevado-Filabride contact, folded around this anticlinorium, is a ductile-brittle extensional detachment characterized by a broad zone with breccias, gouges and cataclasites. 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 in the Sierra Nevada area (Aldaya et al., 1984; Martínez-

Figure 4. The Turon extensional detachment, the sole fault of the Contraviesa extensional system, separating carbonate rocks of the Lújar-Gádor unit from phyllites belonging to the overlying Escalate unit. Slickenlines and tail of crushed material indicate a NNW-sense of shear (right side of photograph).

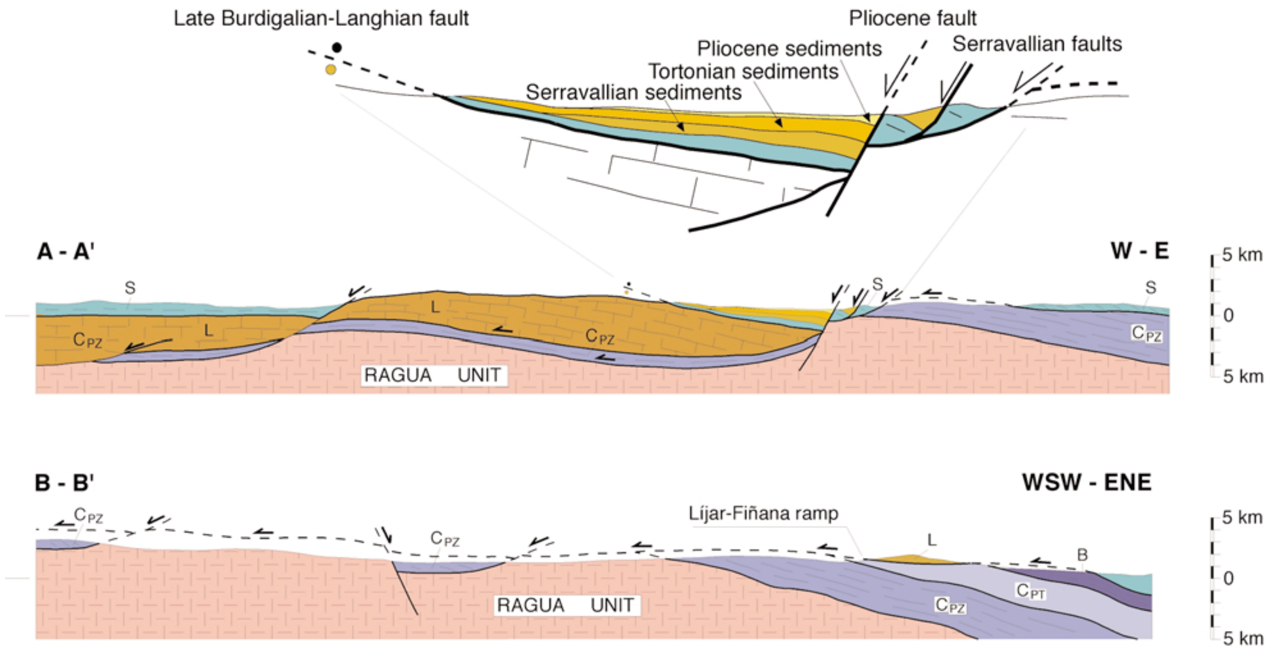

Figure 5. Structural sections (A-A' and B-B') trending sub-parallel to the direction of extension of the Filabres extensional system in the southeastern Betics (location in Fig. 2). Abbreviations: Nevado-Filabride complex: CPZ, Palaeozoic of the Calar Alto unit; CPT, Permo-Triassic of the Calar Alto unit; B, Bédar-Macael unit. Alpujárride complex: L, Lújar-Gádor unit; S, Salobreña unit.

Martínez, 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).

The Filabres detachment appears as a fault zone with discrete surfaces on which may be seen NE-SW to ENE-WSW slickenlines. The main regional foliation, which we use as a key surface, reveals its general staircase geometry with low-angle footwall ramps and flats. Nature of the associated fault rocks (foliated cataclasites, fault gouges, microbreccias, and coarse fault breccias) point out the brittle and brittle-ductile character of deformation. Kinematic indicators, including S-C shaped structures in the fault rocks with slickenlines on the C surfaces, striating ploughing elements on the slickensides, and sigmoidal tails of crushed pebbles and asymmetric clasts in the fault gouges, show top-to-the-SW and WSW sense of shear. A large-scale ramp is to be observed between Líjar and Fiñana (Figs. 2, 3 and 5). Around Líjar the Alpujarrides overlie the Bédar-Macael unit; further to the W, in the Tetica area, the Alpujarrides overlie the Palaeozoic/Permo-Triassic boundary of the Calar Alto unit; and finally they lie, north of Fiñana, close to the top of the Ragua 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. Both, the lithological omissions due to the Líjar-Fiñana ramp (more than 8000 meters of structural section) and the average fault-bed angle (<8) 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; Crespo-Blanc, 1995).

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, due to the erosion of the Neogene sedimentary cover that completely surrounds the Sierra (Figs. 2 and 6). In the Nevado-Filabrides two tectonic units can be distinguished, the lowest one, comprising a sequence of low-grade graphite schist and quartzite, represents part of the Paleozoic sequence of the Calar Alto unit, which crops out largely further N in the Sierra de los Filabres anticlinorium, to which it is connected by the Tabernas synclinorium (Fig. 2). The upper unit is formed by a sequence of medium-grade metamorphic rocks including graphite and light schist, quartzite, tourmaline gneiss, and marble (Platt, 1982), lithologically comparable to the Bédar-Macael unit. Overlying the Nevado-Filabrides, two main Alpujarride units have also been distinguished (Fig. 6). The lower unit consists of a tectonostratigraphic sequence, including calcite-dolomite marbles, kyanite phyllite and quartzite, light-colored chloritoid-garnet schist, and staurolite-kyanite-garnet graphite schist, from bottom to top. The probable age of the rocks, Triassic for the marble and Paleozoic for the graphite schist (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 pyrophyllite-carpholite phyllite and quartzite underlying a Triassic carbonate formation.

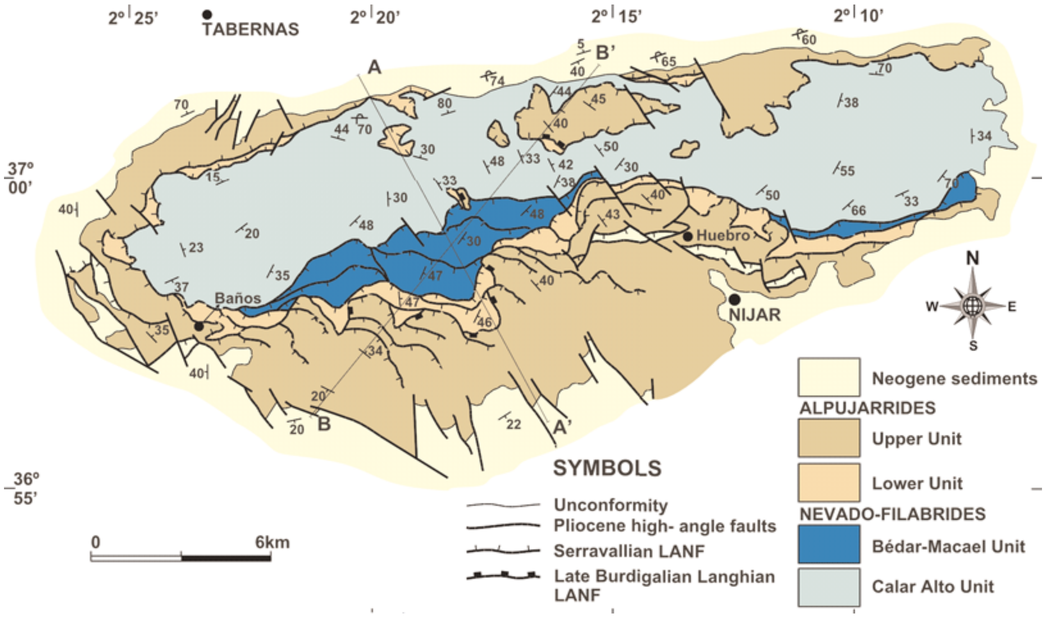

Figure 6. Structural map of Sierra Alhamilla showing extensional detachments and main low-angle normal faults. Only main foliation and bedding are shown. Lines of sections in Fig. 9 are given by A-A' and B-B'.

The geological maps of the 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 E and W as well as toward the N. 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 graphite schist (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 (Fig. 6). The faults are grouped together in large-scale extensional systems that postdate all the afore-described ductile structures, including the Nevado-Filabride S-to-SE-vergent folds and the Alpujarride N-vergent folds.

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 slickenlines (Figs. 6 and 7). The regional foliation, which we use as a key surface, reveals the general geometry of a low-angle footwall ramp, with occasional flats. Associated with the detachment are numerous faults both in the footwall and in the hanging wall, that have slickenlines oriented as in the detachment (Fig. 6). 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 (Fig. 8); 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. The predominant direction of extension is ENE-WSW, as marked by the slickenlines on the fault surfaces.

Cross-sections B-B', C-C', and D-D' of Fig. 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 patterns may be observed in the sections: There are emergent listric fans coalescing to a floor fault (first detachment) at shallow levels and 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 Figs. 9 and 10). Tilted hanging-wall blocks are affected by out-of-sequence faults cutting and tilting the detachment. The second set of faults sole into the contact between the Bédar-Macael and Calar Alto units, which represents an underlying, second detachment. 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

Figure 7. A fault surface belonging to the WSW-directed extensional system. This surface is tilted by out-of-sequence faults. Slickenlines plunge N60E (toward lower-right corner of photograph) (see also Fig.11).

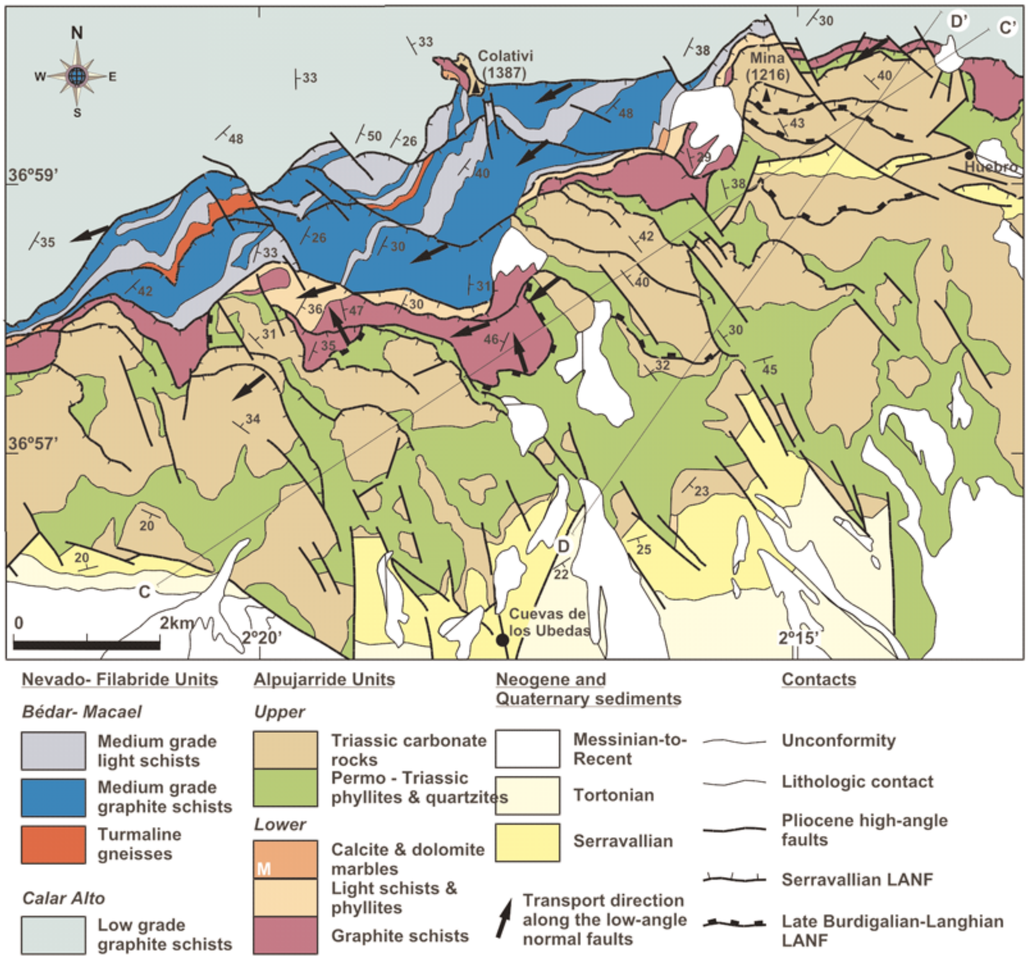

Figure 8. Geological map of southern Sierra Alhamilla. Lines of sections in Fig. 9 are given by C-C' and D-D'.

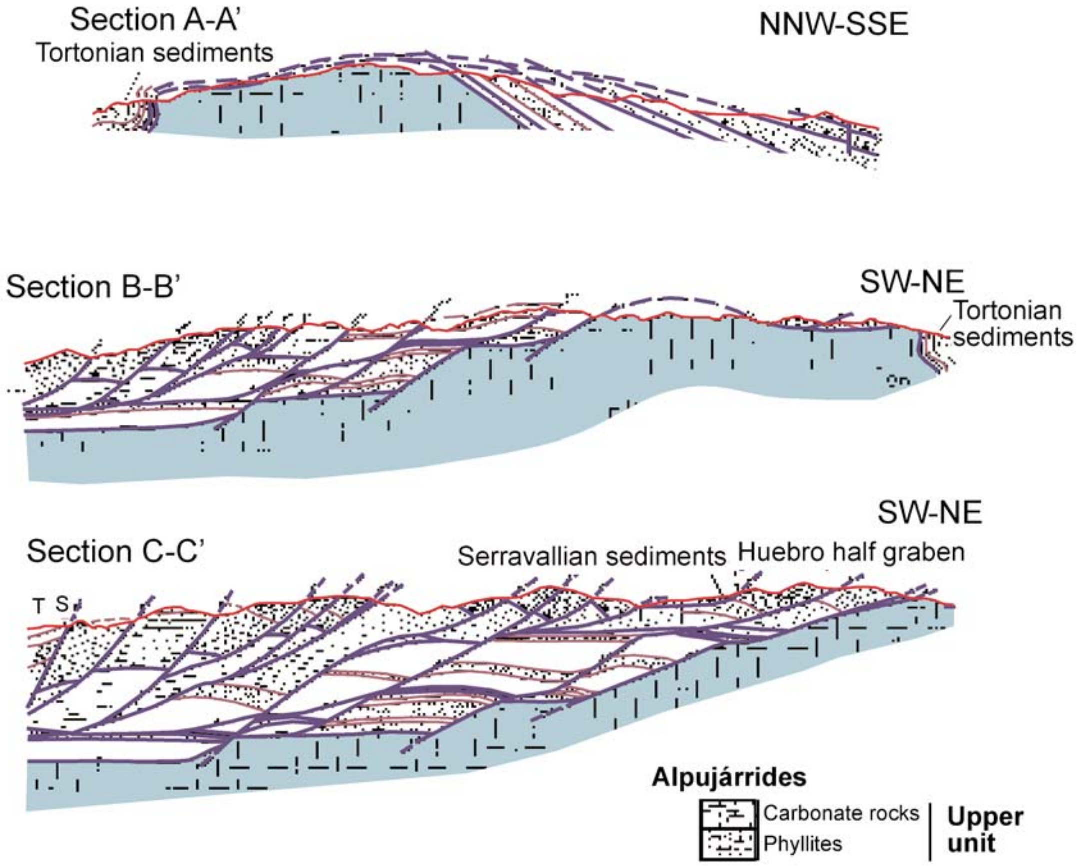

Figure 9: Structural sections through the Sierra Alhamilla anticlinorium, showing the geometry of the middle-Miocene extensional systems and the relationships among the lithologic and tectonic units. Section lines are located on Figs. 6 and 8. Section A-A' is roughly parallel to the slickenlines of the NNW-directed extensional system. The other three sections are roughly parallel to the direction of extension of the WSW-directed extensional system. S, Serravallian; T, Tortonian; PQ, Plio-Quaternary. Description in text.

which crops out immediately to the S of Colativí; see Fig. 8). High-extended riders appear in the upper plate of the extensional system (Fig. 11). The figure 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 (Fig. 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 (Fig. 12). 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 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 a, b).

Cut by faults belonging to the WSW-directed extensional system, there are other local faults whose slickenlines 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 schist from the lower Alpujarride unit and the upper-unit phyllite, which we have interpreted as low-angle normal faults (Fig. 8). Slickenlines on fault surfaces and shear bands point to a top-to-the-NNW sense of shear. The faults cut downsection toward the NNW, as may be seen in cross-section A-A' of Fig. 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 el 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 WSW-directed one. The effect of this system on the Alpujarride stack has been the northward 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, Fig. 8).

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

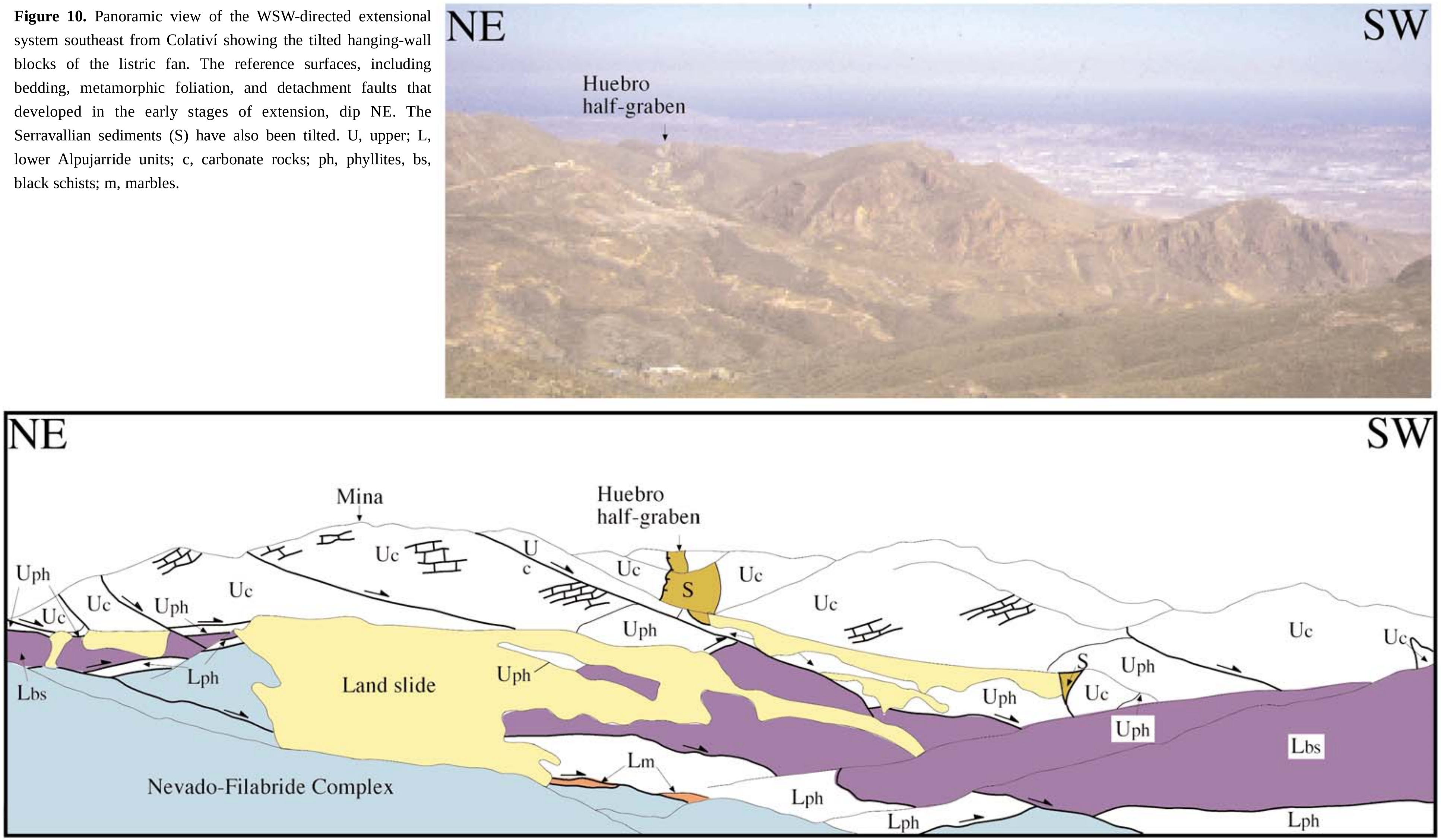

Figure 10. Panoramic view of the WSW-directed extensional system southeast from Colativí showing the tilted hanging-wall blocks of the listric fan. The reference surfaces, including bedding, metamorphic foliation, and detachment faults that developed in the early stages of extension, dip NE. The Serravallian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

complex crops out (García-Dueñas et al., 1992; Azañón et al., 1994; Crespo-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 pre-existing 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 Fig. 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 are absent in the Sierra Alhamilla area (Fig. 2).

Neogene sediments and the age of extensional systems

Marine and continental sediments ranging in age from upper Langhian to Tortonian unconformably overlain the metamorphic units of Sierra de los Filabres and Sierra Alhamilla (Ott d’Estevou and Montenat, 1990; Serrano, 1990); they completely surround the Sierra Alhamilla in the W, outlining a periclinal (Figs. 6 and 13). The Messinian-to-Recent sediments unconformably overlie folded Tortonian sediments (Ott d’Estevou, 1980). Fig. 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 Alhamilla: The upper Langhian-Serravallian sequence, described by Serrano (1990) around Níjar, consists of a basal layer (upper Langhian) of continental or shallow marine conglomerate and sandstone rich in Alpujarride detritus, followed by marl and turbidite (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 Fig. 2) they seal faults belonging to the NNW-directed Contraviesa extensional system 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 WSW-directed extensional system, being the most superficial formation in certain listric fan riders (e.g. the Huebro half-graben; see Fig. 9, structural sections C-C' and D-D', and Fig. 10). The Tortonian sequence has a basal layer (lower Tortonian) comprised by red continental and marine conglomerate 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 onlaps the basement sealing the tilted blocks, thereby postdating the WSW-directed extensional 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 syn- and post-rift 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 E and the lower unit rocks the source in the W (Fig 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, 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 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 syn- and post-rift 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; Watt et al., 1993).

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, 1997) that eventually led to the stacking of the metamorphic complexes, formation of HP mineral assemblages and ulterior isothermal decompression. 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 due to the development of large-scale

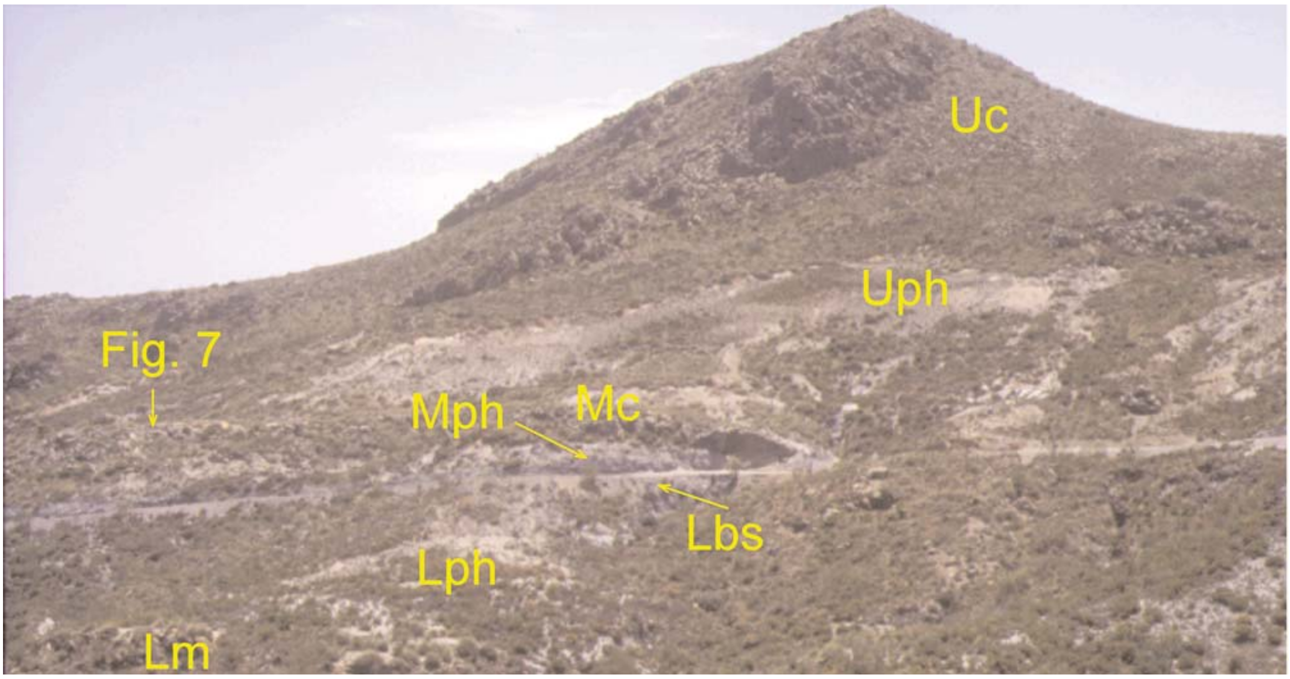

Figure 11. Riders of carbonate rocks (Mc) and phyllites (Mph) detached at high extension representing remains of an intermediate unit (M) between the lower (L) and upper (U) Alpujarride units. Observe tilting of bedding in hanging-wall carbonate rocks moving WSW (right side of photograph). Faults that developed early on in the extension have also been tilted. Outcrop 1 Km NE of Mina (Fig. 8). c, carbonate rocks; ph, phyllites; bs, black schists; m, marbles.

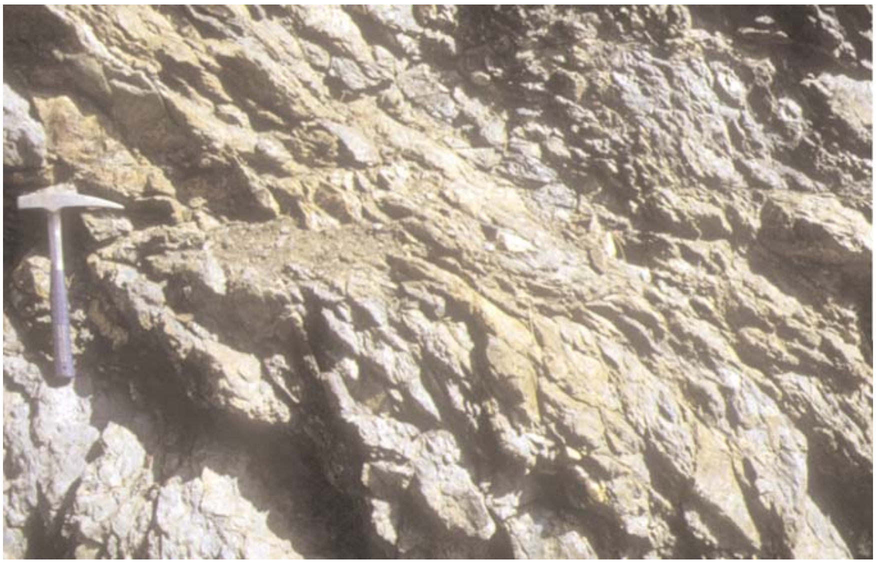

Figure 12. S-C shaped structures produced by shear faulting of a pre-existing foliation. Both shear faults (C-planes) and foliation (S-planes) are tilted and dip E (right side of photograph).

Figure 13. Upper Tortonian turbidites dipping westward (left side of photograph) at the western periclinal of the Sierra Alhamilla anticlinorium. This sedimentary rocks seal the northeastward dipping tilted blocks in the hanging wall of the WSW-directed extensional system.

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., 1977 a, b). 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 afore-mentioned 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 Betic-Rif 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 fixit 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 reconstruction's placing this domain in a more easterly position during the Palaeogene (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 counter-clockwise 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). Based on 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, based on 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 zones. We propose an alternative model that, taking into account the idea of westward motion, tries to explain the complicated pattern of extension described

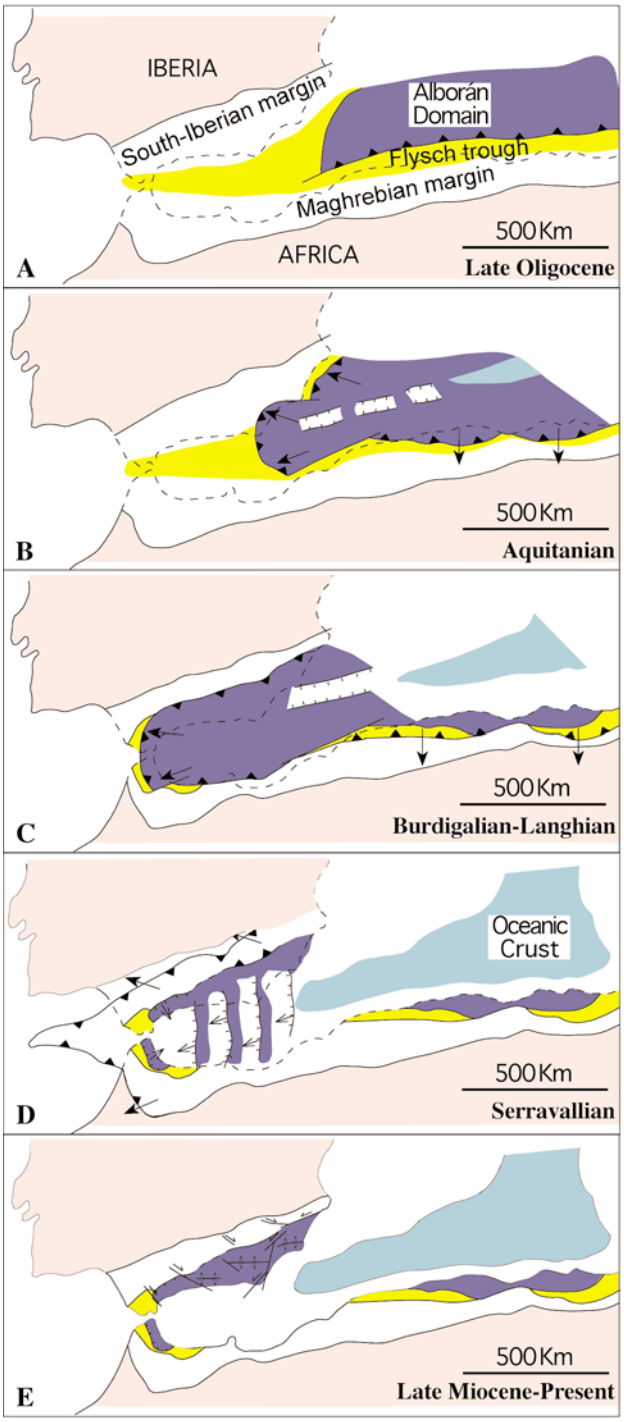

Figure 14. Hypothetical evolution of westernmost Mediterranean region from the late Oligocene to the present. Kinematic vectors according to data from:Wildi, 1983; Morley, 1987; Balanyá and García-Dueñas, 1988; Balanyá, 1991; Guezou et al., 1991; García-Dueñas et al., 1992; Plaztman et al., 1993; Crespo-Blanc 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 coast line is as in the Present. The convergence between Iberia and Africa from the Oligocene to the Present has not been taken into account. Explanation in text.

above, as well as other geological and geophysical data documented in the literature. Five structural and paleogeographic sketches (Fig. 14) help to illustrate a history of westward tectonic escape from a N-S collision zone similar to the model proposed by Royden (1993). Fig. 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 (Fig. 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 (Fig. 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 counter-clockwise 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 (Fig. 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. Various 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 (Fig. 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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