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Interference pattern of extensional fault systems: a case study of the Miocene rifting of the Alboran basement (North of Sierra Nevada, Betic Chain)

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Abstract—In the Betic–Rif orogenic belt, in the westernmost part of the Mediterranean, early and middle Miocene crustal thinning of the upper part of the Alboran basement is well established by previous studies. In the Alboran domain of the central Betics, the present distribution of the Alpujarride units results from the extensional dismembering of a pre-Miocene nappe stack under brittle conditions. The interference of two subperpendicular and successive extensional fault systems can explain the current geometric pattern of the Alpujarride units: upper-Burdigalian–Langhian north–south extension was followed by west- to southwestward extension of Serravallian age. Northeast of Sierra Nevada, these two extensional systems have resulted in a spectacular chocolate tablet megastructure and the cropping out, at any one vertical sequence, of a varying number of extensional units belonging to the Alpujarride complex. This pattern can be considered representative of the middle Miocene tectonics of the entire Alboran domain in the Betics, and illustrates the development of rifting processes in the upper crust.

INTRODUCTION

The Betic and Rif chains, located north and south of the Alboran Sea, respectively, represent the westernmost segment of the Alpine–Mediterranean orogenic belt. The early and middle Miocene crustal stretching that took place in the inner part of the Gibraltar Arc, which linked the two chains, dismantled the sheets of a former nappe stack known as the Alboran domain, thereby forming the basement of the Alboran basin. Large-scale low-angle normal faults and extensional detachment faults (brittle to ductile) that developed during rifting, show various extensional episodes (García-Dueñas *et al.* 1992). Thus, the present day geometry of the contacts of the Alboran domain tectonic units is mainly extensional. The directions of extension during the Miocene show no direct relationship to the overall relative north–south directed motion of the African and Eurasian plates that bound the system (Dewey *et al.* 1989, Srivastava *et al.* 1990). A later compressive event gently folded these extensional structures during the upper Miocene. Part of the Miocene Alboran basin has now emerged, making possible the direct observation of rifting processes in its basement.

This paper describes the extensional features and the geometric pattern of two successive and superposed brittle extensional fault systems, both Miocene in age, located in the central part of the Betics, to the north-east of Sierra Nevada (Sierra de Baza area). They developed into the Alpujarride complex, one of the main complexes of the Alboran domain (Fig. 1). The resulting interference type can be described as a chocolate tablet mega-structure. It is representative of the overall geometry at shallow crustal levels in the Alboran domain, and illustrates the development of extensional processes in the upper crust. The paper contributes to our understanding of the kinematic evolution of the area.

GEOLOGICAL SETTING

Within the Betic–Rif orogenic belt, three pre-Miocene tectonic domains can be differentiated (Fig. 1):

(a) The South Iberian and Maghrebian paleomargins, outcropping in southern Spain and northern Africa, respectively, and consisting of autochthonous and parautochthonous nonmetamorphic Mesozoic and Tertiary cover, overlying a Hercynian basement;
(b) The Flysch Complex units, deposited in a deep trough of attenuated crust (Biju-Duval *et al.* 1978, Durand-Delga 1980, Dercourt *et al.* 1986)
(c) The Alboran crustal domain (Balanyá & García-Dueñas 1988), consisting mainly of three nappe complexes of variable metamorphic grade which are, from bottom to top, the Nevado–Filabride, the Alpujarride, and the Malaguide complexes (Fig. 1).

The stratigraphic sequences within the Nevado–Filabride and the Alpujarride units are roughly comparable: the simplified standard section consists of a metapelitic pre-Permian basement, a Permo-Triassic metaclastic sequence, and middle to upper Triassic carbonate rocks. The Alpine metamorphism evolves from a high pressure episode followed by an almost isothermal pressure decrease in both complexes (Goffé *et al.* 1989, Soto 1991, Tubía & Gil-Ibarguchi 1991, Azañón *et al.* 1992, Balanyá *et al.* 1993, Azañón *et al.* 1992, Soto & Azañón 1994). In contrast, the overlying rocks of the

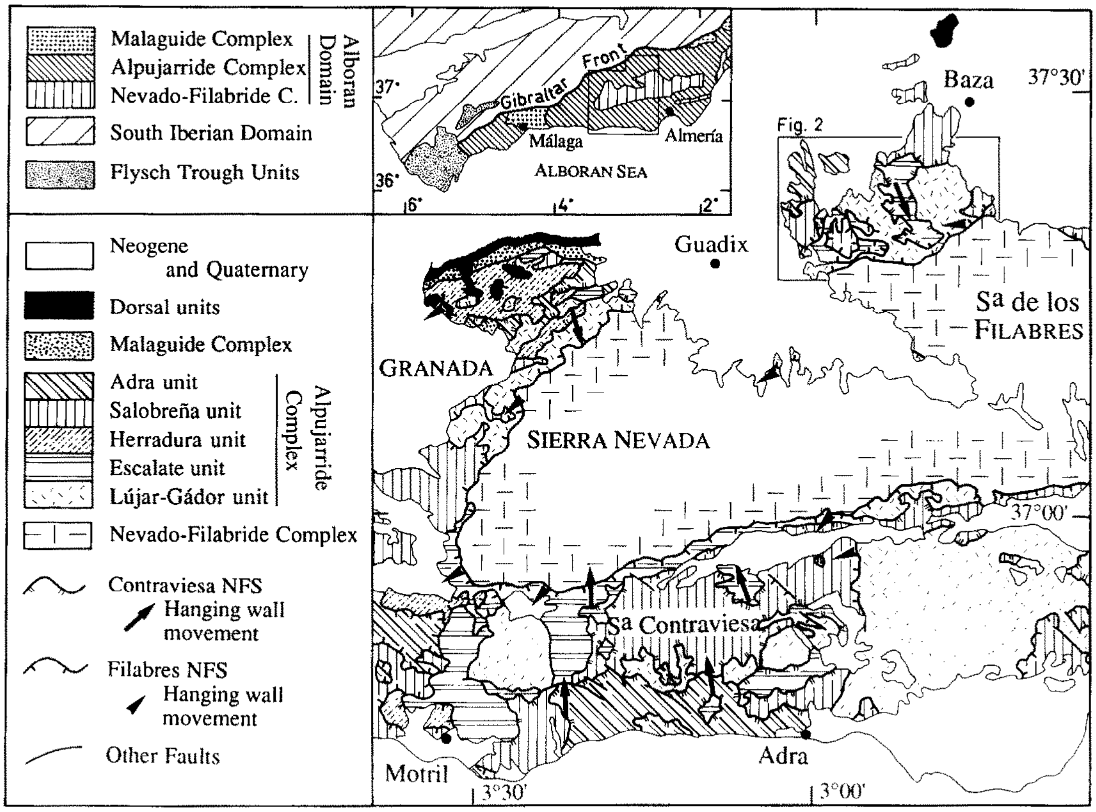

Fig. 1. Tectonic map showing the low angle normal faults and extensional detachment faults in the Central Betics (according to García-Dueñas *et al.* 1992, Crespo-Blanc *et al.* 1994 and own data). NFS: Normal fault system.

Malaguide units, ranging in age from Silurian to Oligocene, have undergone very low grade metamorphism in the case of the Silurian series, whereas the younger series are anchi- or unmetamorphosed. The high pressure mineral assemblages of the Alpujarride units are believed to have formed during a former crustal stacking event. In the western Betics, Balanyá *et al.* (1993) show that a ductile regional flattening follows this HP–LT metamorphic episode, because the zones of previous prograde metamorphism are thinned, and the path of *P–T* conditions is characteristic of an extensional regime. This first pre-Miocene extensional event is followed by N-vergent folding of the thinned metamorphic sequences (recumbent fold event; Balanyá *et al.* 1987, Simancas & Campos 1988).

The resulting stack is affected by lower and middle Miocene rifting. Therefore, the present units of the Alpujarride complex are extensional horses and riders, that is, parts of a previous nappe sheet limited by brittle-ductile and brittle extensional structures (García-Dueñas *et al.* 1992, Azañón *et al.* 1993, Crespo-Blanc *et al.* 1994). This crustal segment formed the basement of the Alboran basin, where the Moho is currently situated 20 km below sea level, with a sediment thickness of several kilometres (Banda *et al.* 1993). The extensional denudation processes were divided by Comas *et al.* (1992) and García-Dueñas *et al.* (1992) into three successive episodes with different extension directions. Only the last two of these were recognized in the studied area, the Sierra de Baza area, north of Sierra Nevada (Figs. 1 and 2). Older extensional systems have been described in the western Betics and northeast of Granada (Fig. 1), where early Miocene LANFs were reactivated or cut by late Burdigalian or Serravallian normal faults (e.g. García-Dueñas & Balanyá 1991, García-Dueñas *et al.* 1992, Alonso-Chaves *et al.* 1993).

The crustal thinning that affected the whole Alboran domain was almost contemporaneous with the westward migration of the Gibraltar thrust front, which represents the outer limit of the Alboran domain (Fig. 1). In the lower Miocene, this compressive front began to migrate through its footwall into the flysch trough, leading to the formation of a thrust stack that collided with the Maghrebian and Iberian paleomargins (Balanyá & García-Dueñas 1988, Balanyá 1991). Meanwhile, the Alboran basin formed in the inner part of the Gibraltar Arc (García-Dueñas *et al.* 1992).

Finally, from the late Tortonian to the Pliocene, the Alboran sea region underwent continuous N–S to NW–SE compression (e.g. Weijermars *et al.* 1985, Comas *et al.* 1992, Rodríguez-Fernández & Martín-Penela 1993). The extensional systems were folded (mainly large-scale E–W directed folds) and faulted, facilitating exposures at the present.

ALPUJARRIDE EXTENSIONAL UNITS AND MIOCENE SEDIMENTS

A number of tectonic units, differing from one traverse to another, crop out within the Alpujarride complex, giving it a characteristic lack of continuity. The

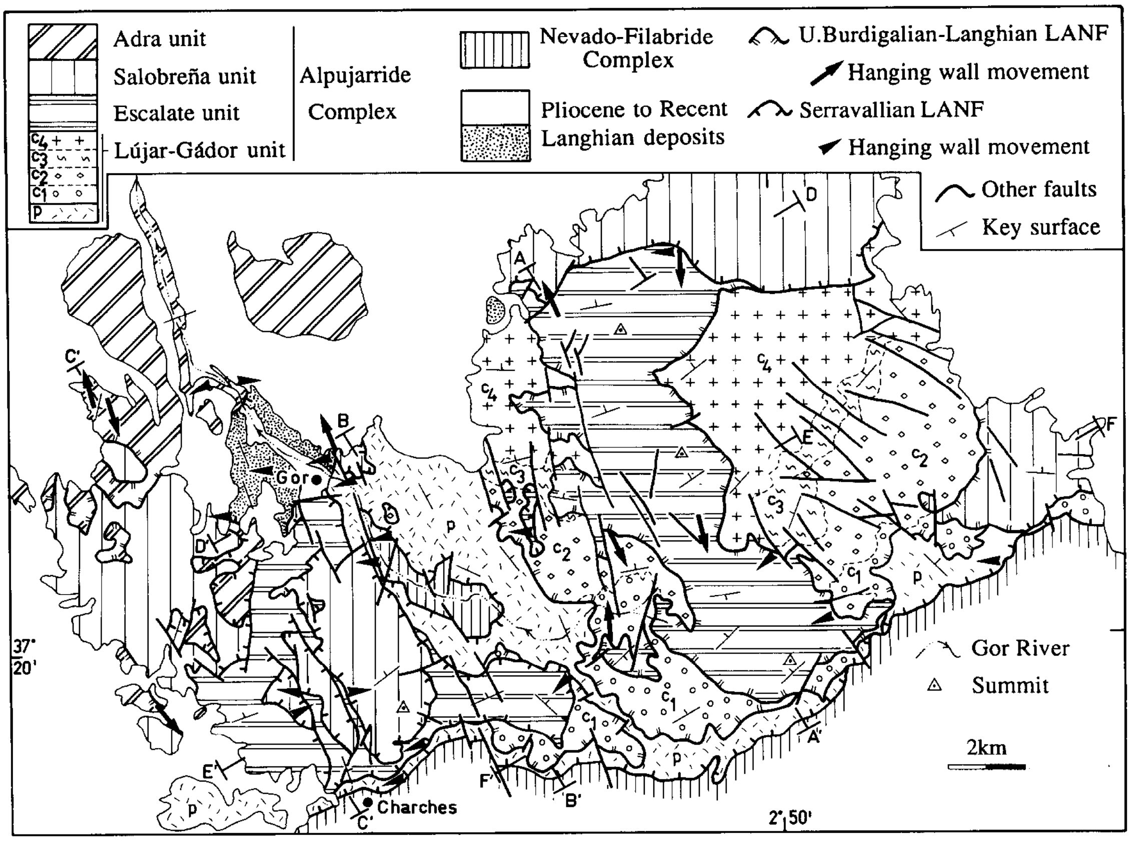

Fig. 2. Simplified geological map of the Sierra de Baza area according to Navarro & Velendo (1979), Comas *et al.* (1979), Aldaya *et al.* (1980), Delgado *et al.* (1980) and own data. Location in Fig. 1. LANF: Low-angle normal fault. Each arrow represents a minimum of five measurements. Lújar-Gádor unit: p, phyllites (Permo-Triassic); c1 to 4, carbonate rocks (Triassic, from lower to upper series, respectively). AA'–EE': location of cross-sections of Figs. 4 and 5. The upper-Burdigalian–Langhian LANFs are considered to be antithetic to the Contraviesa normal fault system. The Serravallian LANFs belong to the Filabres system (Fig. 1). Key surfaces may be bedding plane, foliation or schistosity.

geometry of the present units indicates the Miocene extensional dismembering of a pre-Miocene nappe stack in brittle to ductile conditions (García-Dueñas & Balanyá 1991, García-Dueñas *et al.* 1992, Azañón *et al.* 1993, Crespo-Blanc *et al.* 1994) and the attenuating effect of the low angle faults (i.e. severe thinning and faulting out of entire units). In the central and western Betics, their geometric pattern has been explained by the interference of two brittle subperpendicular extensional fault systems: the Contraviesa normal fault system, upper Burdigalian and Langhian in age (Crespo-Blanc *et al.* 1994), and the Filabres normal fault system, which developed during the Serravallian (García-Dueñas *et al.* 1992) (Fig. 1).

The Contraviesa normal fault system has been defined and described to the south of Sierra Nevada. A fan of listric faults sometimes showing high-extension geometries (Gibbs 1984) with a north-northwestward transport direction separates the Alpujarride units. In this paper, we will show that to the northeast of Sierra Nevada (Sierra de Baza area), one of the brittle extensional systems affecting the Alpujarride complex with south-southeastward transport extension is antithetic to the Contraviesa system. According to the present-day coordinates, together they produced approximately N–S extension.

The Contraviesa extensional system was followed by the development of Filabres normal fault system (García-Dueñas *et al.* 1992), whose sole extensional fault zone, with west to southwestward hanging-wall movement, is a spectacular detachment that includes the current contact between the Nevado–Filabride and the Alpujarride complexes (figs. 1 and 2; the 'Filabres extensional detachment' of García-Dueñas & Martínez-Martínez 1988). In the Sierra de Baza area, this system is represented by low-angle listric normal faults soling into the Filabres detachment, as well as antithetic faults with an eastward transport direction that affect the Alpujarride complex.

The interference pattern of these two successive extensional systems superimposed on a stack of tectonic sheets produced a chocolate tablet mega-structure in which the previous compressional stacking order is not modified. On the basis of the present position of the extensional units and the HP–LT metamorphic signatures, Azañón *et al.* (1994) defined five main types of allochthonous units of the Alpujarride complex in the central Betics that represent the pre-Miocene tectonic sheets of the complex. In the Sierra de Baza area, only four types of allochthonous units are present (Fig. 2). Although these units were identified by Navarro & Velendo (1979), Comas *et al.* (1979), Aldaya *et al.*

(1980) and Delgado *et al.* (1980) (MAGNA 1:50 000 geological maps), these authors consider them 'thrust nappes'. The present paper, however, presents them as extensional units bounded by low angle normal faults (LANFs) and detachments belonging to both the Filabres extensional system and the antithetic system of the Contraviesa. The units defined in the MAGNA maps—in ascending order: Santa Bárbara, Quintana, Blanquizares, and Hernán Valle—were respectively attributed by Azañón *et al.* (1994) to the Lújar-Gádor, Escalate, Salobreña and Adra allochthonous units.

In the studied area, marly green and yellow sediments lie upon the Alpujarride units around Gor (Fig. 2). Recently, Martín-Pérez & Viseras (1994) described foraminifera and nannoplankton associations which place these rocks within the lower Langhian to upper Langhian-lower Serravallian age. This helps to constrain the activity of the extensional fault systems, as do other deposits of the lower and middle Miocene Alboran basin overlying the Alboran Domain.

EXTENSIONAL FAULT SYSTEMS IN THE SIERRA DE BAZA AREA

A careful revision of the boundaries between units was carried out in order to determine the geometry and kinematics of the tectonic contacts between the Alpujarride units in the Sierra de Baza area. The fault rock bands that limit the units (LANFs of Fig. 2) formed in a brittle regime, when gouges and breccia developed. The main low-angle faults are localized along the boundary between the Triassic carbonate sequence of the lower unit and the Permo-Triassic phyllite sequence of the upper one, as would be expected because of the competence difference. Moreover, the carbonate sequence is generally detached from the phyllites of the same extensional unit.

S–C shaped structures with striae on the C surfaces ('almond' structures), trails of crushed pebbles, drag folds in phyllites, rough foliation in the fault rocks, and associated microfaults were used to measure the kinematics of the contacts. For example, the 'almond' structure cut by a microfault in a gouge (Fig. 3a) clearly indicates the hangingwall movement. The striae directions and the LANF shear senses are shown in Fig. 2. Two main transport directions of the hangingwall can be observed: a south-southeastward one and a west- to southwestward one. The first system of LANFs, the south-southeastward one, is supposed to be antithetic to the Contraviesa normal fault system (preliminary results in Crespo-Blanc 1995), whereas the second, the west- to southwestward one, belongs to the Filabres normal fault system described to the south of Sierra Nevada (see Discussion and Conclusions). The serial cross-sections of Figs. 4 and 5 that run subparallel to each of the transport directions illustrate the geometry of the extensional tectonic contacts. Small undulations of the LANFs are due to late Miocene folding.

South-southeastward normal fault system

In cross-sections AA′–CC′ (Fig. 4), which are NNW–SSE oriented, bedding, foliation or schistosity were used as key surfaces. A roll-over anticline, produced by the progressive northward tilting of the stratification of the Lújar–Gádor carbonate rocks along a south-southeastward listric normal fault that bounds the phyllites and the carbonate rocks of the same unit is observed in cross-section AA'. This explains why the carbonate sequence is progressively younger towards the north-northwest (Fig. 2). Nevertheless, it is also possible that the fold represents a ramp anticline formed during an earlier thrusting event. This structure is cut by another south-southeastward LANF, which bounds the Escalate unit and provokes drastic thinning of the Lújar–Gádor carbonate rocks towards the south-southeast (Figs. 2 and 4, cross-section AA′). A systematic tilting of the key surfaces towards the north in the Escalate unit is consistent with the extensional geometry of the faults, as the movement observed in the fault rock bands bounding the tectonic units is towards the SSE (e.g. Gibbs 1984). When northward antithetic movement is observed, particularly in the Adra unit (Figs. 2 and 4, NNW of cross-sections BB′ and CC′), the key surfaces are tilted towards the south. Thus, with respect to the foliation of the phyllites or schists, the faults consistently produce excisions in the sense of the hangingwall movement. In the Escalate unit, various south-southeastward LANFs separate the phyllites from post-metamorphic recumbend folds drawn by the carbonate sequence. Their axial plane is cut by the faults and tilted towards the north (cross-sections AA′ and BB′).

A transfer fault associated with a lateral ramp (Gibbs 1984) belonging to the south-southeastward extensional system is inferred NE of cross-section AA′ (Figs. 2 and 4). Such a structure must be observed in cross-sections subperpendicular to the direction of movement, that is, in the cross-sections of Fig. 5 (eastern part, subvertical fault with question mark). Its precise position is unknown, as it disappears below the LANF that limits the bottom of the Escalate unit (Figs. 2, 4 and 5). This transfer fault would be associated with the LANF causing the roll-over structure of the Lújar-Gádor limestones and dolomites. This is deduced from the geometric distribution of the carbonate rock sequence: the carbonate series becomes progressively younger when crossing from the western to the eastern block of the supposed transfer fault (Figs. 2 and 5, eastern part of cross-sections), and the total slip of the eastern block towards the SSE is greater than that of the western one. In addition, a ramp parallel to the transfer fault is deduced from the directional change of the roll-over anticline axis as it approaches the supposed transfer fault (observe key surface distribution in Fig. 2 of the c3 carbonate series of the Lújar–Gádor unit). Similar geometries are frequent in linked fault systems in the basin formation of the United Kingdom (e.g. fig. 8 of Gibbs 1990).

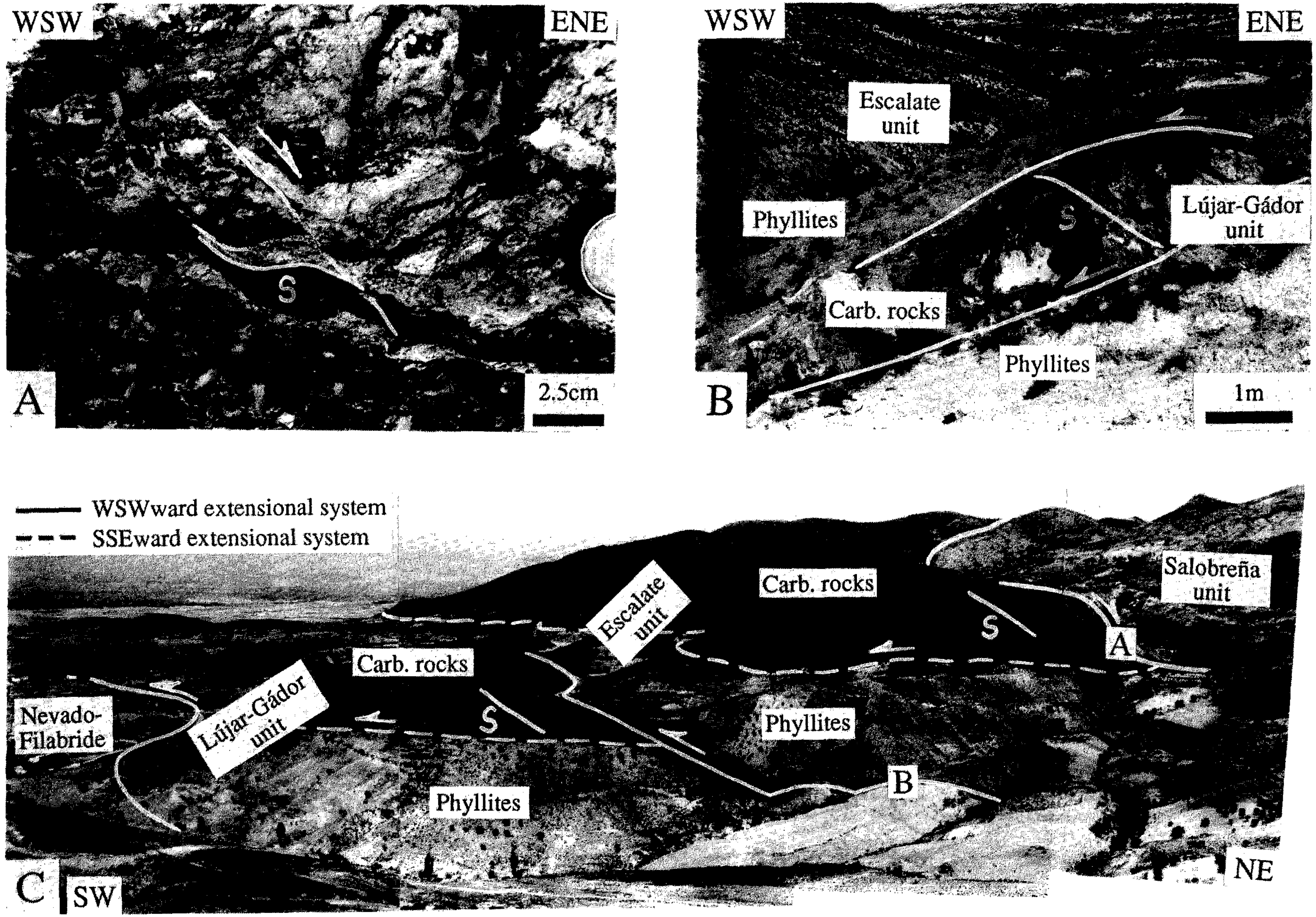

Fig. 3. (a) Fault gouge with an 'almond' structure cut by a microfault. Both structures indicate a dextral shear sense (antithetic eastward fault of the Filabres extensional system). This fault gouge is situated at the bottom of the Salobreña unit. Location in photograph C. (b) Rider of carbonate rocks of the Lújar–Gádor unit detached at high extension (Gibbs 1984). It marks the boundary between phyllites of the Escalate and Lújar-Gádor units. Observe the extreme thinning of the carbonate sequence (with an original thickness of approximately 4.7 km) and the key surface ("S") tilted by the low angle normal fault at the bottom of the dolomites (which belongs to the Filabres extensional system). Location in photograph C. (c) Panoramic view of Charches area (Fig. 2), showing the interference of two extensional fault systems. All the movements along the faults are oblique with respect to the photograph. S, key surface. Carb., Carbonate rocks. A and B: location of photographs A and B. Photograph taken from point 505,50/4128,10 U.T.M.

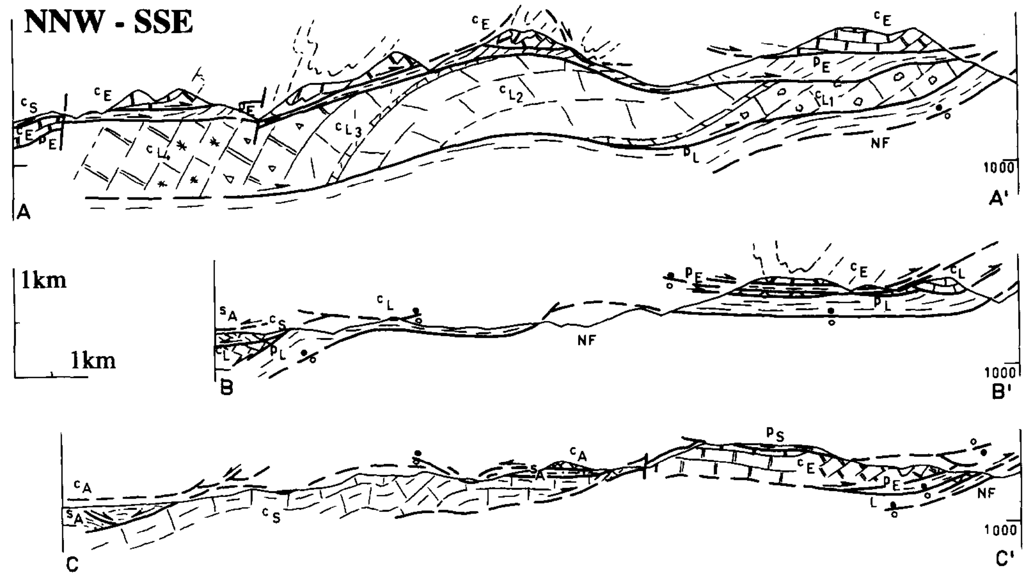

Fig. 4. Serial cross-sections in a NNW–SSE direction, illustrating the geometry and extensional nature of the south-southeastward fault system (antithetic with the Contraviesa normal fault system). Location on Fig. 2. The dips (foliation and low-angle normal faults) have been calculated to include vertical scale exaggeration. Open and solid circles: motion away from and towards the observer, respectively. NF: Nevado–Filabride complex, L: Lújar-Gádor unit (1 to 4, respectively from lower to upper series of the carbonate sequence), E: Escalate unit, S: Salobreña unit, A: Adra unit, s: Palaeozoic schists, p: Permo-Triassic phyllites and quartzites, c: Triassic carbonate sequence.

Filabres normal fault system and its relationship to the south-southeastward system

Cross-sections DD′–FF′ (Fig. 5) illustrate ENE–WSW directed extensional structures. A drastic thinning or even omission of the units takes place in the western part of the sections due to a fan of listric normal faults with west-southwestward movement (e.g. in cross-section EE′, the Lújar–Gádor unit almost disappears towards the west-southwest). These faults tend to coalesce with the sole detachment of this extensional system, the Filabres detachment (García-Dueñas & Martínez-Martínez 1988). The faults of the Filabres extensional system produce the tilting not only of the bedding or foliation towards the east-northeast, but also of the LANFs with south-southeastward hangingwall movement. For example, the south-southeastward LANF separating the Salobrea unit from the Lújar–Gádor unit (Figs. 2 and 5, east-northeast of cross-section FF′) is cut and tilted by a west-southwestward LANF of the Filabres system. Moreover, most of the LANFs associated with SSE–NNW extension were reactivated during the ENE–WSW extensional episode, as two sets of striae are observed along the same fault plane, the ENE–WSW ones cutting the SSE–NNW ones. This clearly shows that the south-southeastward system is older than the Filabres system.

High extension geometries associated with the Filabres system are evidenced by the detached riders (Gibbs 1984) of the Salobreña and Adra units that nearly superpose the Nevado–Filabride complex (western part of section DD′). On a scale of metres, a similar detached rider structure is illustrated by a wedge-shaped segment of carbonate rocks of the Lújar–Gádor unit underlining the boundary between the Lújar–Gádor and the Escalate phyllites (Fig. 3b). Although the tilting of the bedding or foliation of the carbonate rocks and the striae and shear sense observed along the rock segment boundaries reveal only movements to the west-southwest, it must be stressed that such thinning is due not only to the action of the Filabres extensional system, but also to that of the south-southeastward extensional system.

Antithetic eastward LANFs can be observed WSW of section EE′, at the bottom of the Salobreña unit (also see Fig. 3a). The resulting geometric distribution of the Escalate carbonate rocks in the Charches area (Fig. 2) can be seen in the panoramic view of Fig. 3(c): owing to the eastward extensional thinning, these rocks are thicker towards the west. The same photograph shows the interference of both extensional systems: the faults of the Filabres system cut the south-southeastward LANFs. Observe that the northward tilting of the carbonate rocks of the Lújar–Gádor unit produced by a southward LANF at the bottom of the limestones and dolomites is conserved between the two west-southwestward LANFs that bound the unit. The described structures are cut and rotated by two listric faults that are coalescent with the Filabres detachment (Fig. 5, west-southwest of section EE′).

The middle Miocene deposits in the Sierra de Baza area constrain the age of activity of both extensional systems. The boundary of the green and yellow marls, from lower to upper Langhian in age (Martín-Pérez & Viseras 1994), with the Alpujarride complex is marked by a LANF (Figs. 2 and 5, cross-section DD′). Although it was impossible to measure in situ kinematic criteria, this LANF probably belongs to the Filabres system, as the stratification planes of the marls are systematically tilted towards the E, and when LANFs are present in the marls, only east–west striae are observed. Therefore,

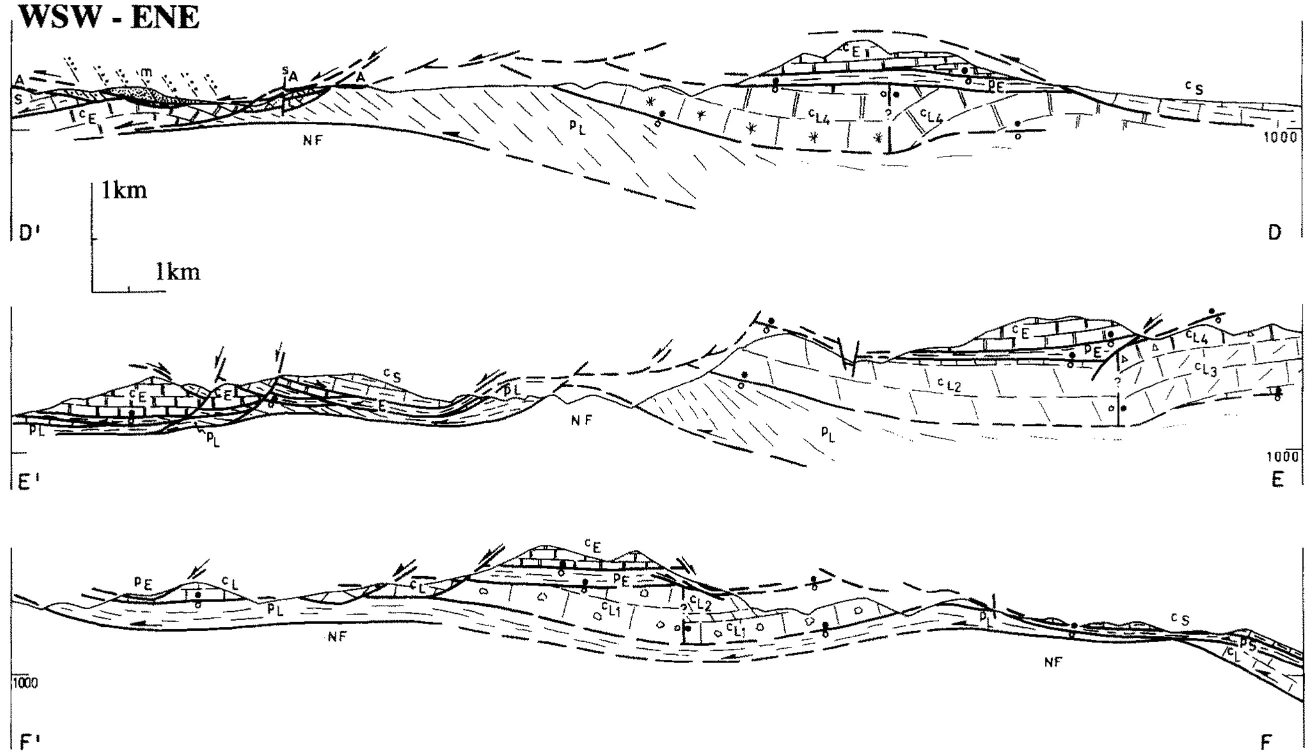

Fig. 5. Serial cross-sections in a WSW–ENE direction, illustrating the geometry and extensional nature of the west-southwestward Filabres fault system. Location on Fig. 2. The dips (foliation and low-angle normal faults) have been calculated to include vertical scale exaggeration. Open and solid circles: motion away from and towards the observer, respectively. Same legend as Fig. 4.

Table 1. Extension estimation. In parentheses, estimations calculated in the Contraviesa area (south of Sierra Nevada, Fig. 1) according to the cross-sections of Crespo-Blanc *et al.* (1994)

	Estimation of amount of extension: β stretching factor for each of the normal fault system		
		Contraviesa system and its antithetic	
Methods	Filabres system	Sa de Baza area	Contraviesa area
Restoring line	1.5	—	—
Tilting	1.3 (1.3)	1.3	1.4

the E–W to NE–SW extensional system of this area, the Filabres normal fault system, can be considered post-upper Langhian, whereas the NNW–SSE extensional system can be interpreted as prior to or/and simultaneous with the Langhian deposits.

ESTIMATION OF AMOUNT OF EXTENSION

Accurate evaluations of extension are difficult in cases where high extensional structures appear. Nevertheless, a rough estimation of the amount of extension resulting from the described extensional systems in the studied area is presented in Table 1. These estimates are then contrasted with those made for the Contraviesa area, south of Sierra Nevada, on the basis of cross-sections presented in Crespo-Blanc *et al.* (1994), and using two distinct methods:

(1) Sequentially restoring the faults along lines of cross-sections. Using this technique in the cross-sections of Fig. 5 without vertical exaggeration, a β stretching factor of 1.5 is estimated for the Filabres system. No restoration was made for the Contraviesa system south of Sierra Nevada and its antithetic system in the Sierra de Baza area because of the lack of a key line.

(2) Estimating the percentage of extension by using key surface-to-fault angles and the amount of tilting. The listric fault case of Wernicke & Burchfiel (1982, fig. 10) was used for this estimation. A β factor of 1.3 was estimated for the Filabres system, whereas a similar value was calculated for the system antithetic to the Contraviesa system. A slightly higher value of β = 1.4 was estimated for the Contraviesa system south of Sierra Nevada.

DISCUSSION AND CONCLUSIONS

Most of the tectonic contacts in the Sierra de Baza area have been shown to be brittle low-angle normal faults, and not thrust faults as proposed by authors of the MAGNA geological map (Navarro & Velendo 1979, Comas *et al.* 1979, Aldaya *et al.* 1980, Delgado *et al.* 1980). These LANFs, which divide the Alpujarride complex into extensional units, belong to two different but successive extensional systems (Figs. 1 and 2): a

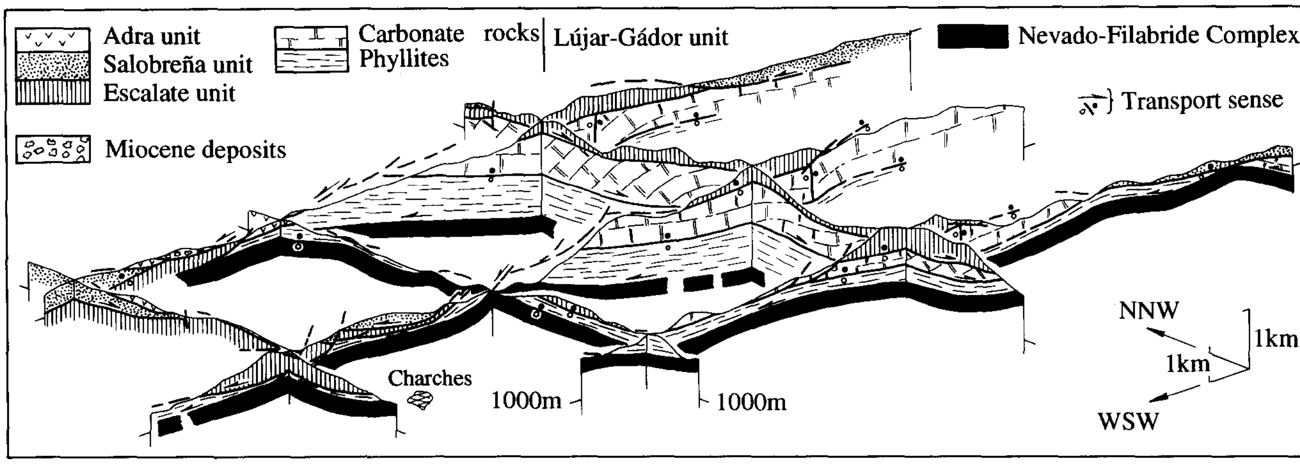

Fig. 6. Fence diagram representative of the interference of the extensional systems observed in the Sierra de Baza area, resulting in a chocolate tablet mega-structure. Transport sense: open and solid circles represent motion away from and towards the observer, respectively.

NNW–SSE system, with a main south-southeastward transport direction, that is prior to or/and simultaneous with the deposition of the Langhian Gor marls (Fig. 2); and a south- to southwestward extensional system, whose sole detachment, the Filabres detachment (Martínez-Martínez & García-Dueñas 1988), corresponds with the boundary between the Alpujarride and the Nevado–Filabride complexes. Both systems belong to the Filabres detachment hangingwall. The resulting extensional units of the south-southeastward system were partly dismembered by the west-southwestward LANFs of the Filabres extensional system. In the studied region, the age of activity of the Filabres extensional system is constrained to be post-upper Langhian on the basis of its relationship with the Miocene sediments. This would be compatible with the Serravallian age of activity attributed to this system by Garcia-Dueñas *et al.* (1992).

South of Sierra Nevada, in the Contraviesa area, the structural relationships and age constraints between the Filabres and Contraviesa normal fault systems are similar to those of the Sierra de Baza area (Crespo-Blanc *et al.* 1994). The Contraviesa normal fault system was active during the upper Burdigalian and Langhian and shows north-northwestward transport. The same direction is observed north of Sierra Nevada, yet the shear sense is opposite. It is therefore concluded that the south-southeastward LANF system described in this paper is antithetic to the Contraviesa system.

South-southeastward movements along extensional systems are not limited to the studied area. García-Dueñas *et al.* (1992) describe the activity of similar LANFs during Langhian times in the Alpujarride units between Granada and Guadix (Fig. 1) and in the western Betics. Offshore, in the eastern Alboran Sea, multichannel seismic data also reveal southeastward extensional movements during the latest Burdigalian and middle Miocene (Comas *et al.* 1992). These data clearly indicate that the Alboran domain undergoes NNE–SSE extension during upper Burdigalian and Langhian times.

The three-dimensional interference pattern of these two successive and almost perpendicular extensional systems is illustrated for the Sierra de Baza area in the fence diagram of Fig. 6, using data in the cross-sections in Figs. 4 and 5. Each Alpujarride unit corresponds to a rider limited by listric faults belonging to a fan of normal faults from the Contraviesa or Filabres extensional system. This gives rise to the chocolate tablet megastructure and the outcropping, at any one vertical point, of a varying number of extensional units within the Alpujarride complex. For example, the boudin-shaped Lújar–Gádor unit shows an E–W directed neck in the southern part of the diagram due to the Contraviesa system, and a N–S directed one in the western part due to the Filabres system. The two necks cross north of Charches, where the Lújar–Gádor unit (with a thickness of 5.6 km measured perpendicularly to the key surface) nearly disappears because of the combined effect of the extensional excisions.

In order to visualize the geometry of one of the fault systems, a 3D model of the main faults associated with the Filabres system is given in Fig. 7. It illustrates how the fan of listric faults and the Filabres detachment give rise to the wedge-shaped segments that can be seen in the cross-sections of Fig. 5. A detached rider has been sketched to represent those observed in the field (Fig. 3b). Note that the antithetic fault is tilted by two late

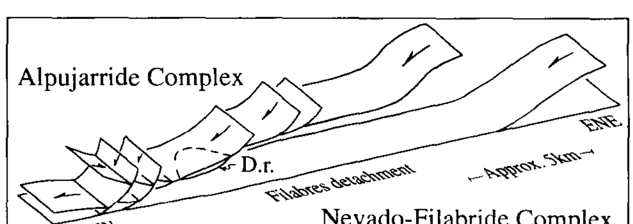

Fig. 7. Distribution model of the faults belonging to the Filabres extensional system. The small undulations due to the upper Miocene folds have been restored and a flat 'topography' has been attributed to the Filabres detachment. D.r.: detached rider at high extension (Gibbs 1984). An approximate vertical exaggeration of 1.5 was used.

listric faults. Because no transfer fault (Gibbs 1984) has been observed for this system, the faults probably die out laterally in zones of distributed strain.

As both extensional systems belong to the same structural level, it is likely that the south-southeastward system, before its segmentation by the Filabres extensional system, would have shown a similar fault distribution. Nevertheless, a striking difference exists between the Contraviesa system described south of Sierra Nevada and its antithetic system in the Sierra de Baza region; whereas in the Contraviesa area all the LANFs coalesce with a single detachment, the Turón detachment (García-Dueñas *et al.* 1992), situated at the top of the Lújar-Gádor unit and generally over the carbonate sequence, no single detachment of the south-southeastward system has been recognised in the Sierra de Baza. In any case, a hypothetical similar single detachment would have overlain the Filabres detachment. This means that the south-southeastward system northeast of Sierra Nevada is at a slightly deeper structural level where it penetrates the Lújar-Gádor unit than it is to the south of Sierra Nevada.

Bearing in mind the approximate character of extensional estimations, the calculations made by line restoration or by key surface-to-fault angles and amount of tilting gave comparable magnitudes for the Contraviesa, its antithetic system, and the Filabres system (β stretching factor approximately 1.4, Table 1). Both of the above methods probably underestimate extension; the line restoration method does not take into account the amount of small-scale faulting and brecciation, and in the case of high extension geometries with detached riders (Gibbs, 1984) such as those observed in the Sierra de Baza area, tilting is not necessarily modified by increased extension when the fault-bound riders move onto a flat detachment. García-Dueñas *et al.* (1992) established similar values for Filabres extension in the western Betics by carrying out approximate restoration along some cross-sections.

The described structures fit the geometric model for extension developing in more than one direction. The models for extension in the Alboran region based on Platt and Vissers' hypothesis (1989) of extensional collapse, where extension is considered to be roughly radial and centrifugal during the early to middle Miocene, and accommodated by shortening in the more external zones of the orogenic belt (e.g. Platzman 1992, Platzman *et al.* 1993), or those based on a single translation towards the west (e.g. Galindo-Zaldívar *et al.* 1989, Frizon de Lamotte *et al.* 1991, Jabaloy *et al.* 1992) or towards the north (Doblas & Oyarzun 1989), suggesting an evolution similar to that described for a core complex, are not consistent with the extensional episodes distinguished in the Sierra de Baza area and in the central Betics as a whole. The chocolate-tablet interference type must be taken into account in any analysis of the geometrical relationship between Alpujarride units. It can tentatively be considered representative of the early and middle Miocene tectonics of the entire Alboran domain in the Betics.

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