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Fold and fault interactions during the development of an elongated narrow basin: The Almanzora Neogene-Quaternary Corridor (SE Betic Cordillera, Spain)

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[1] Elongated corridors grow in different tectonic settings, mainly in areas deformed by fold and fault sets parallel to the borders. The Almanzora Corridor, however, is a good example of an E-W elongated asymmetrical narrow basin developed in a changing stress scenario, generated by the interaction of fold and fault sets oriented parallel and oblique to the corridor borders. The initial crustal thickening process was mainly related to the development of the E-W oriented Sierra de Los Filabres large antiform, which constitutes a major heterogeneity. During the Tortonian, a NW-SE convergent tectonic setting, oblique to this already emerged antiform, gives rise to a large dextral simple shear band that determines: the development of a major fold (Las Estancias antiform), the asymmetrical location of minor tectonic structures (faults and minor folds), and the distribution of sedimentation/denudation areas that finally configure the Almanzora Corridor synform. Furthermore, development of NW-SE oriented normal faults points to NE-SW orthogonal extension in a new stress field oblique to the corridor borders. This region illustrates that the elongated character of the corridors may persist, inherited from the orientation of previous crustal rheological heterogeneities. In addition, marine transgression may be produced in compressional settings, favored by the synform development during initial stages of crustal thickening, finally led to the relief uplift. **Citation:** Pedrera, A., J. Galindo-Zaldívar, C. Sanz de Galdeano, and Á. C. López-Garrido (2007), Fold and fault interactions during the development of an elongated narrow basin: The Almanzora Neogene-Quaternary Corridor (SE Betic Cordillera, Spain), *Tectonics*, *26*, TC6002, doi:10.1029/2007TC002138.

1. Introduction

[2] Long elongated valleys are common in different tectonic frameworks, where faults or folds with dominant trends occur. Fold-and-thrust belts develop orthogonal to the trend of compression and produce a succession of highs and valleys [e.g., *Clarke and Carver*, 1992; *Ferrière et al.*, 2004]. The depressed areas correspond to the synforms, and are generally filled by sediments. In extensional contexts, the geometry of the elongated depressions is usually controlled by normal fault sets that grow perpendicular to the minimum stress axis, as in the Basin and Range province [e.g., *Varga et al.*, 2004], the African rift zone [e.g., *Ebinger*, 1989; *Chorowicz*, 2005] and the Aegean region [e.g., *Armijo et al.*, 1996; *Pavlides et al.*, 2006]. In areas deformed by transcurrent faults, elongated valleys are oriented parallel to the fault traces that constitute the basin boundaries, for instance in the California region [e.g., *Howell et al.*, 1980]. In areas of overprinted faults and folds with different trends, however, the basins become discontinuous and irregularly shaped [e.g., *Matenco and Schmid*, 1999; *Pedrera et al.*, 2006]. The development of large folds during the initial stages of crustal thickening may point to rheological discontinuities that determine the geometry of the later tectonic deformations. When stresses rotate, faults will occur preferentially subparallel to the previous elongated reliefs owing to the inherited anisotropy; yet other structural associations take place as well, determining the development of complex elongated corridors.

[3] The relief of the Betic Cordillera, located in the westernmost part of the Alpine Chain, is produced by the interaction of folds and faults that accommodate the N-S to NW-SE convergence between the Eurasian and African plates [*DeMets et al.*, 1990] (Figure 1). Several domains can be distinguished in the Cordillera on the basis of lithological and tectonometamorphic features: the Internal Zones, mainly formed by three major complexes that include metamorphic rocks, some of them of Paleozoic age: the Nevado-Filábride, Alpujárride and Maláguide complexes (generally not affected by Alpine metamorphism); the Flysch Units, which are Tertiary detritic sedimentary rocks, mainly represented in the western Betics [*Egeler*, 1963; *Egeler and Simon*, 1969]; and the External Zones, essentially made up of Mesozoic and Cenozoic sedimentary rocks.

[4] During the Middle Miocene, fission-track data indicate the extensional exhumation of the metamorphic complexes related to the activity of low-angle normal faults [*Johnson*, 1997; *Johnson et al.*, 1997]. On the other hand, the first sedimentary evidence of emerged Internal Zones subjected to important denudation processes is a red con-

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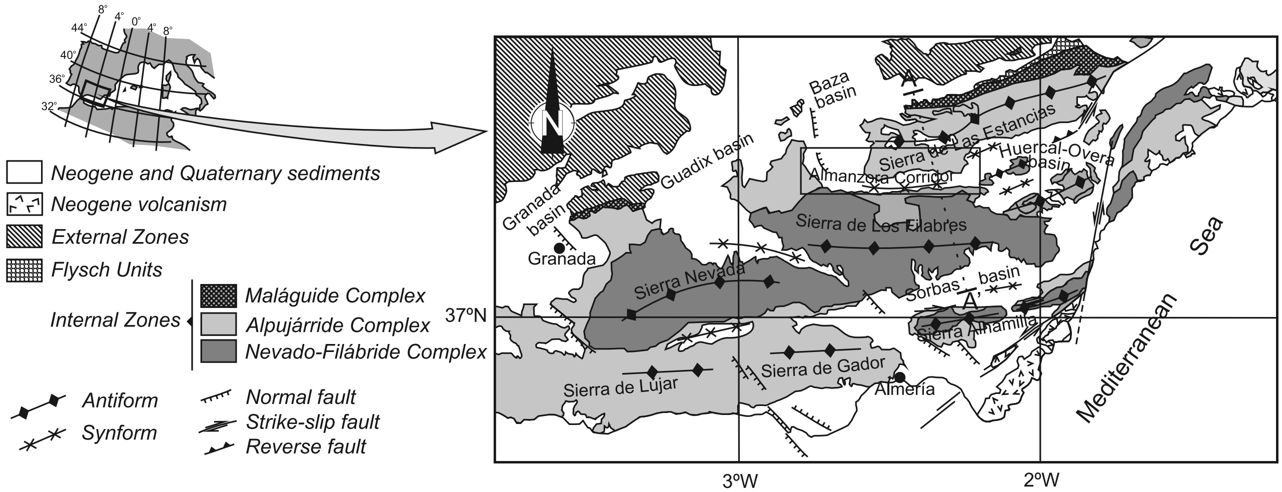

Figure 1. Geological map of the central eastern Betic Cordillera, showing different domains and the main folds and faults developed since Tortonian times. Note that the synforms coincide with the Neogene-Quaternary basin position. The position of the topographic profile Figure 7a is marked.

glomerate alluvial and fan-delta unit [e.g., *Braga et al.*, 2003]. Later, during the Tortonian, E-W and ESE-WNW ranges and basins started to develop, coinciding with large antiforms and synforms [*Weijermars et al.*, 1985; *Galindo-Zaldívar et al.*, 2003; *Sanz de Galdeano and Alfaro*, 2004; *Augier et al.*, 2005]. During the late Miocene, faults developed coeval with folds, thus interacting during the basin formation [*Estévez et al.*, 1982; *Ott d'Estevou and Montenat*, 1985; *Stapel et al.*, 1996; *Booth-Rea et al.*, 2004; *Marín-Lechado et al.*, 2006]. The Neogene-Quaternary sedimentary basins generated on the previously structured metamorphic basements are situated in different tectonic frameworks within the Betic Cordillera: they are generally transcurrent in the Eastern Betics [*Bousquet and Montenat*, 1974; *Bousquet and Philip*, 1976; *Bousquet*, 1979; *Sanz de Galdeano*, 1983; *Montenat et al.*, 1987; *Weijermars*, 1987; *Huibregtse et al.*, 1998], while related to normal faults and folds in the central and western Betics [*Ruano et al.*, 2004; *Rodríguez-Fernández and Sanz de Galdeano*, 2006].

[5] The Almanzora Corridor is an E-W elongated depression (average 35 km long and 6 km wide) situated in the eastern part of the Betic Cordillera. The northern border of the basin is the Sierra de Las Estancias range, consisting of Alpujárride rocks. The southern border is the Sierra de Los Filabres, formed by Alpujárride and Nevado-Filábride rocks (Figure 1). The basin sedimentary infill is characterized by siliciclastic sediments from the Serravallian–early Tortonian up to Quaternary, including marine and continental deposits that are strongly controlled by different tectonic events and have been the subject of previous research [*Braga and Martín*, 1988; *Martín et al.*, 1989; *Guerra-Merchán and Serrano*, 1993].

[6] In the Almanzora Corridor, the fold and fault interaction configures the basin geometry and deforms the sediments since Serravallian–early Tortonian. In the adjacent sedimentary basins, such as Huercal-Overa, some geological studies have focused on active tectonics [*García-Meléndez et al.*, 2003; *Soler et al.*, 2003; *Masana et al.*, 2005a, 2005b] and neotectonic aspects [*Mora*, 1993; *Augier*, 2004]. However, neotectonic studies are scarce in the Almanzora Corridor, having been undertaken only on a regional scale and focused on the basement deformation [*Augier et al.*, 2005].

[7] The aim of this paper is to study the tectonic evolution that finally determines the development of the narrow Almanzora basin. In addition, our contribution clarifies the regional stress evolution that is responsible for the great variability of tectonic structures generated from the Serravallian to the present in the eastern Betic Cordillera. The new insights obtained from this detailed analysis may improve knowledge of the simultaneous development of folds and faults in regimes of oblique convergence that are related to a regional changing stress field.

2. General Features of the Sedimentary and Chronostratigraphic Setting

2.1. Lithostratigraphic Sequence

[8] The Neogene infilling of the Almanzora Corridor is made up of several units separated by unconformities. The lithostratigraphic sequence considered in this study is based on the proposal of *Braga and Martín* [1988] and *Martín et al.* [1989], taking into account chronostratigraphic data from *Guerra-Merchán and Serrano* [1993]; and it agrees with the proposal of *Montenat et al.* [1987] regarding the Neogene history of the eastern Betic Cordillera (Figure 2).

[9] The first unit is a thick, red, continental conglomerate formation, which lies unconformably on the basement, and is well represented in the southern corridor border and in the eastern and western terminations. This unit can also be observed in other areas of the Cordillera and consistently contains coarse grained conglomerates from the metamorphic complexes grading into sandstones. The conglomerates are poorly sorted in general, but sometimes show inverted

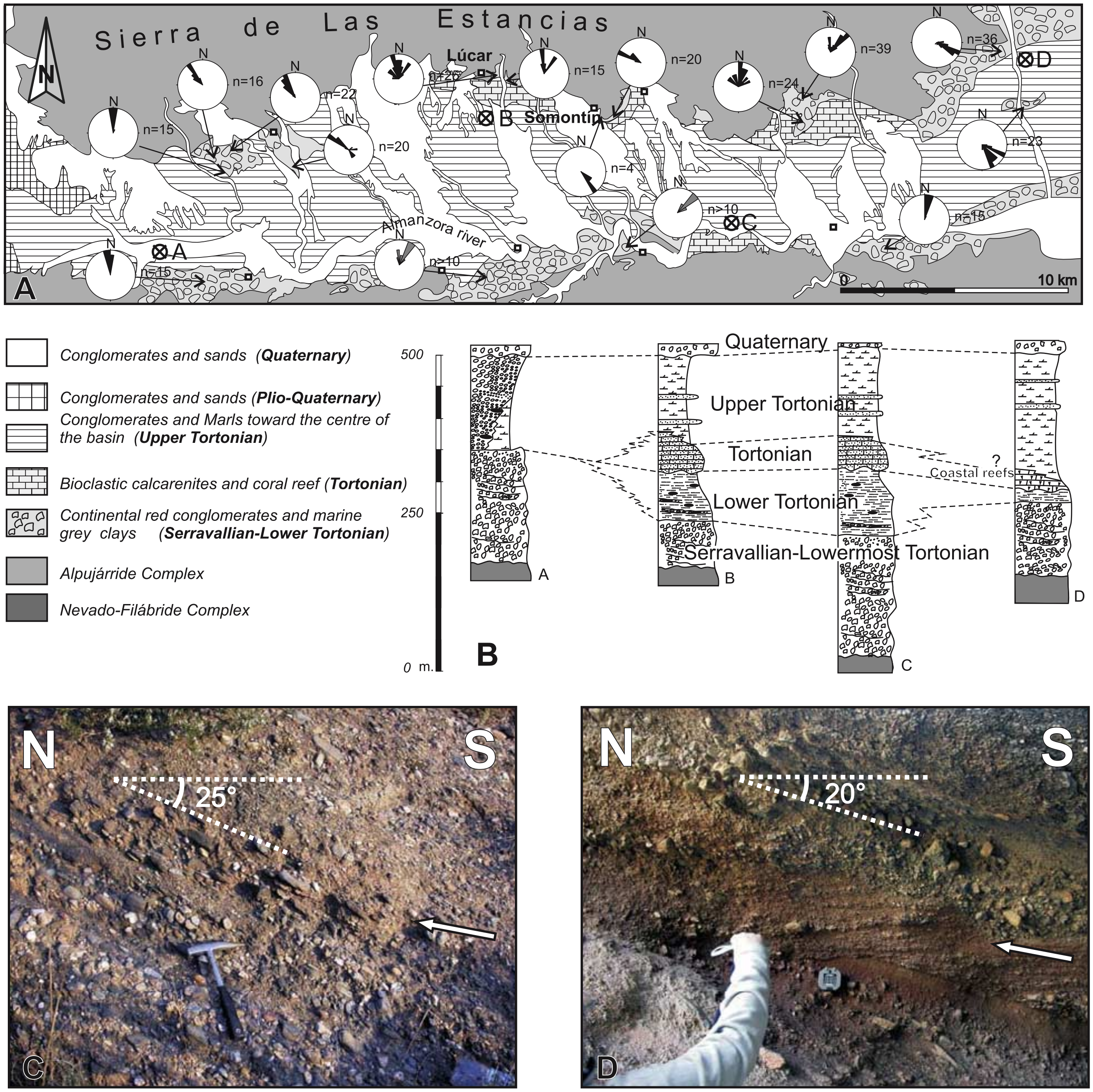

Figure 2. (a) Simplified geological map showing the Neogene infilling of the Almanzora Corridor. The rose diagrams show flow directions deduced from the dip of imbricate clasts. In grey diagrams from *Guerra-Merchán* [1992], only the diagrams with more than 10 measurements are plotted. (b) Lithostratigraphic sequences and correlation, modified from *Guerra-Merchán and Serrano* [1993] and based on the proposal of *Braga and Martín* [1988] and *Martín et al.* [1989], in agreement with *Montenat et al.* [1987] for the Neogene of the eastern Betic Cordillera. Field examples of sedimentary structures, (c) imbricate clasts and (d) cross bedding located in the north basin boundary, which indicate a flow direction to the north. Bedding is tilted by the growth of the Las Estancias antiform.

vertical clast distribution, coarsening upward. In the Granada basin, some fossils support a Serravallian age [*Martín-Suárez et al.*, 1993], although other authors suggest an early Tortonian age, at least for parts of the units [*Guerra-Merchán and Serrano*, 1993; *Doyle et al.*, 1996]. In the Almanzora Corridor, this unit is interpreted as continental alluvial fan deposits generated by the denudation of the mountain front.

[10] The continental Serravallian-lowermost Tortonian red siliciclastic deposits are overlain by grey marine clays [*Braga and Martín*, 1988] with intercalated patch reef limestones to the top of the sequence [*Guerra-Merchán*

and Serrano, 1993], dated as being from the early Tortonian by *Briend* [1981]. This unit corresponds to deltaic deposits mainly located near the northern boundary of the corridor, related to the distal areas of the previous unit. The relation between the base of the marine deposits and the top of the red conglomerates appears variable: in some outcrops the transition is progressive, whereas in others it is clearly unconformable.

[11] The relationship between the lower Tortonian sediments and the uppermost Tortonian sequence constitutes a main unconformity (Figure 2a and 2b). The grey clays are followed by yellowish bioclastic calcarenites with abundant remains of marine fossils, also from the Tortonian [*Braga and Martín*, 1988; *Martín et al.*, 1989; *Guerra-Merchán and Serrano*, 1993]. These deposits represent shallow platforms adjacent to the two basin borders, in transition to marls toward the centre of the corridor axis. The cross bedding in some outcrops indicates that the calcarenites were subjected to strong currents.

[12] The last unit onlaps the margins, comprising at its base greyish conglomerates with patch reef features that change laterally to silts and marls toward the center of the basin, dated by *Guerra-Merchán and Serrano* [1993] as the interval corresponding to the early and middle part of the late Tortonian. Above all these sediments is a thick deposit of yellow marls containing planktonic forams from the late Tortonian [*Briend*, 1981]. There are no Messinian marine sediments in the Almanzora Corridor, these being limited to the nearby Huercal-Overa basin [*Guerra-Merchán and Serrano*, 1993].

[13] Plio-Quaternary alluvial sediments pertain to the alluvial fan and to the river deposits, and are discordantly placed over the Miocene rocks. The alluvial fans, now inactive, are generally well developed in the north basin border, determining the topographic asymmetry of the basin.

2.2. Paleocurrent Analysis

[14] The coastal facies distribution of the sedimentary units (calcarenites, coral reefs, and proximal deltaic siliciclastic sediments) and the paleocurrent orientation allow us to reconstruct, with confidence, the palaeogeography from the Tortonian–late Tortonian onward. These deposits signal the presence of a narrow elongated basin since Tortonian times, with an emerged Sierra de Las Estancias and Sierra de Los Filabres (Figure 2a).

[15] Notwithstanding, the existence of an elongated basin during the early Tortonian, previous to the coastal sediments deposition, is a matter open to question. As a preliminary overview we can remark that the red alluvial fan conglomerates are preferentially at the base of the Sierra de Los Filabres (Figures 2a and 2b). In addition, the lower Tortonian deltaic deposits, related to the distal areas of the red conglomerate units, are mainly placed adjacent to the north corridor boundary (Figure 2b). In order to determine the clast provenance and the palaeogeography distribution during the early Tortonian, we carried out a detailed paleocurrent analysis (clast imbrications (Figure 2c) and cross bedding (Figure 2d)) of the red conglomerate beds, with special emphasis on the outcrops located close to the north basin border (Figure 2a). The bedding at the corridor boundaries is folded, as we will explain in the next section, and so the measurements have been restored to the horizontal.

[16] This study indicates that the Sierra de Los Filabres was the main source area, subjected to growth and to important denudation processes. Only the eastern corridor sediments show paleocurrents to the south, as does the nearby Huercal-Overa basin [*Mora*, 1993; *Augier*, 2004]. Consequently, the Almanzora Corridor developed after early Tortonian.

3. Main Tectonic Structures

[17] Brittle deformations and folds deform the Almanzora Corridor (Figures 3 and 4) and determine their configuration from the Serravallian–earliest Tortonian. A grasp of the tectonic event succession requires a detailed structural analysis.

3.1. Faults

[18] The faults that crop out in the study area have variable orientations and kinematics, as well as overprinted slickensides. Fault description is organized taking into account their kinematics.

3.1.1. Strike-Slip Faults

[19] Subvertical E-W to ESE-WNW strike-slip right-lateral faults deform the Tortonian sediments that crop out mainly in the south basin border. These faults are well exposed in the basement rocks and only deform the lower Tortonian conglomerates in the western sector, close to Serón. However, they displaced up to the Tortonian calcarenites in the central sector, close to Purchena (Figures 3 and 4).

[20] In addition, a set of N-S left-lateral strike-slip faults deforms only the Tortonian sediments, mainly located in the central and south corridor (Figure 3, near Olula del Río, and Figures 5b and 5c). These faults are conjugated with respect to the ENE-WSW right-lateral faults, and they likewise often have normal striations overprinted upon the horizontal ones. The above observations evidence that strike-slip faults started to develop during Tortonian and continued growing in post-Tortonian times, mainly toward the central corridor.

3.1.2. Normal Faults

[21] The normal faults can be grouped into two main sets: NW-SE and E-W to ESE-WNW. These faults show evi-

Figure 3. (a) Simplified geological map of the Almanzora Corridor, indicating the location of the main faults and folds. The position of cross sections of Figure 4 and the map of Figure 3b are marked. (b) Enlarged geological map of the easternmost sector of the Almanzora Corridor. The orientations of microfaults and mesofaults and the paleostress determinations are represented in stereographic projection, lower hemisphere.

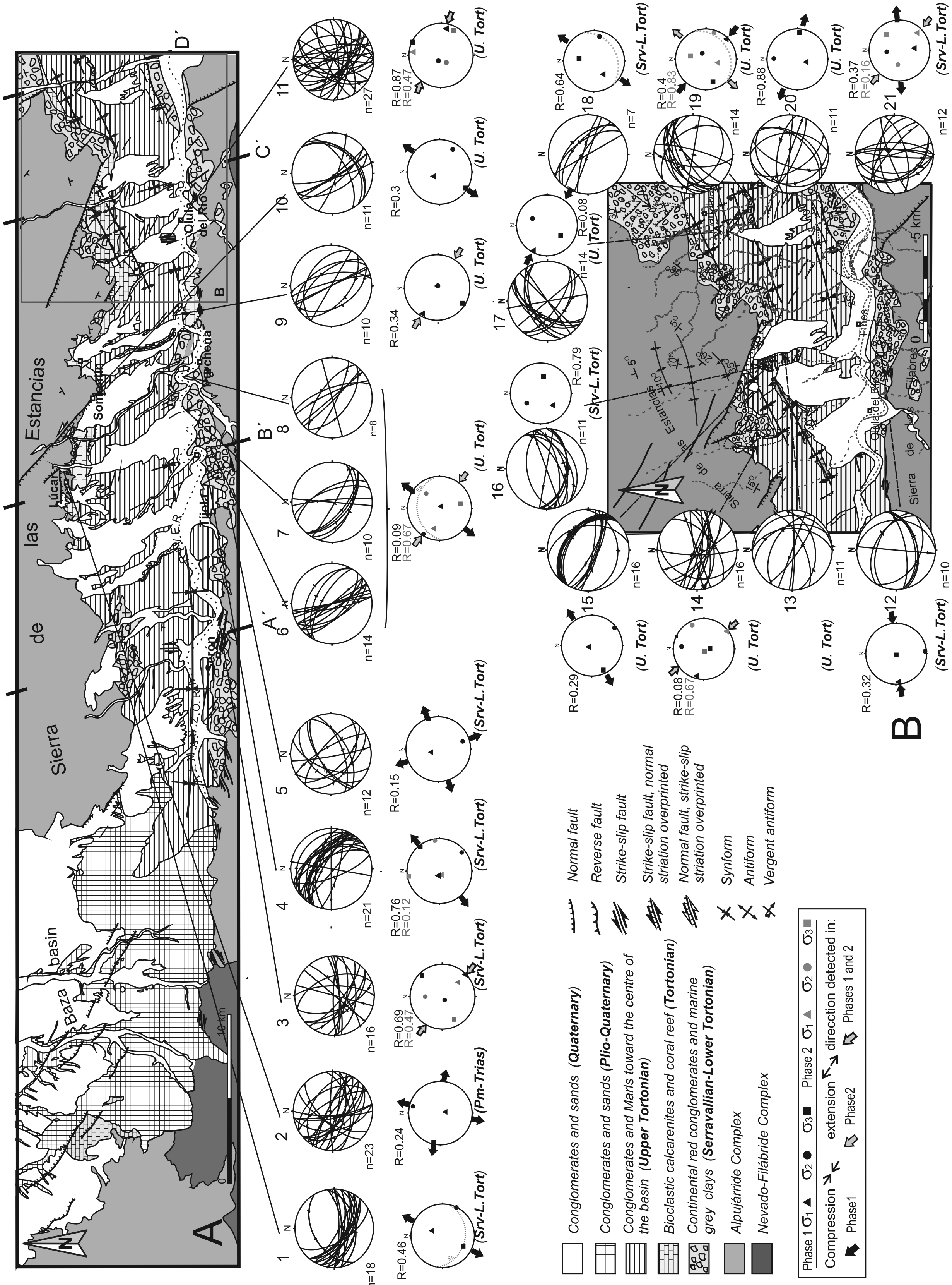
A
B
Sierra de las Estancias
Baza basin
Conglomerates and sands (Quaternary)
Conglomerates and sands (Plio-Quaternary)
Conglomerates and Marls toward the centre of the basin (Upper Tortonian)
Bioclastic calcarenites and coral reef (Tortonian)
Continental red conglomerates and marine grey clays (Serravallian-Lower Tortonian)
Alpujárride Complex
Nevado-Filábride Complex
Normal fault
Reverse fault
Strike-slip fault
Strike-slip fault, normal striation overprinted
Normal fault, strike-slip striation overprinted
Synform
Antiform
Vergent antiform
Phase 1 σ1 ▲ σ2 ● σ3 ■
Phase 2 σ1 ▲ σ2 ● σ3 ■
Compression / extension direction detected in:
Phase1
Phase2
Phases 1 and 2
(Srv-L.Tort)
(Pm-Trias)
(U. Tort)
10 km
5 km

Figure 3

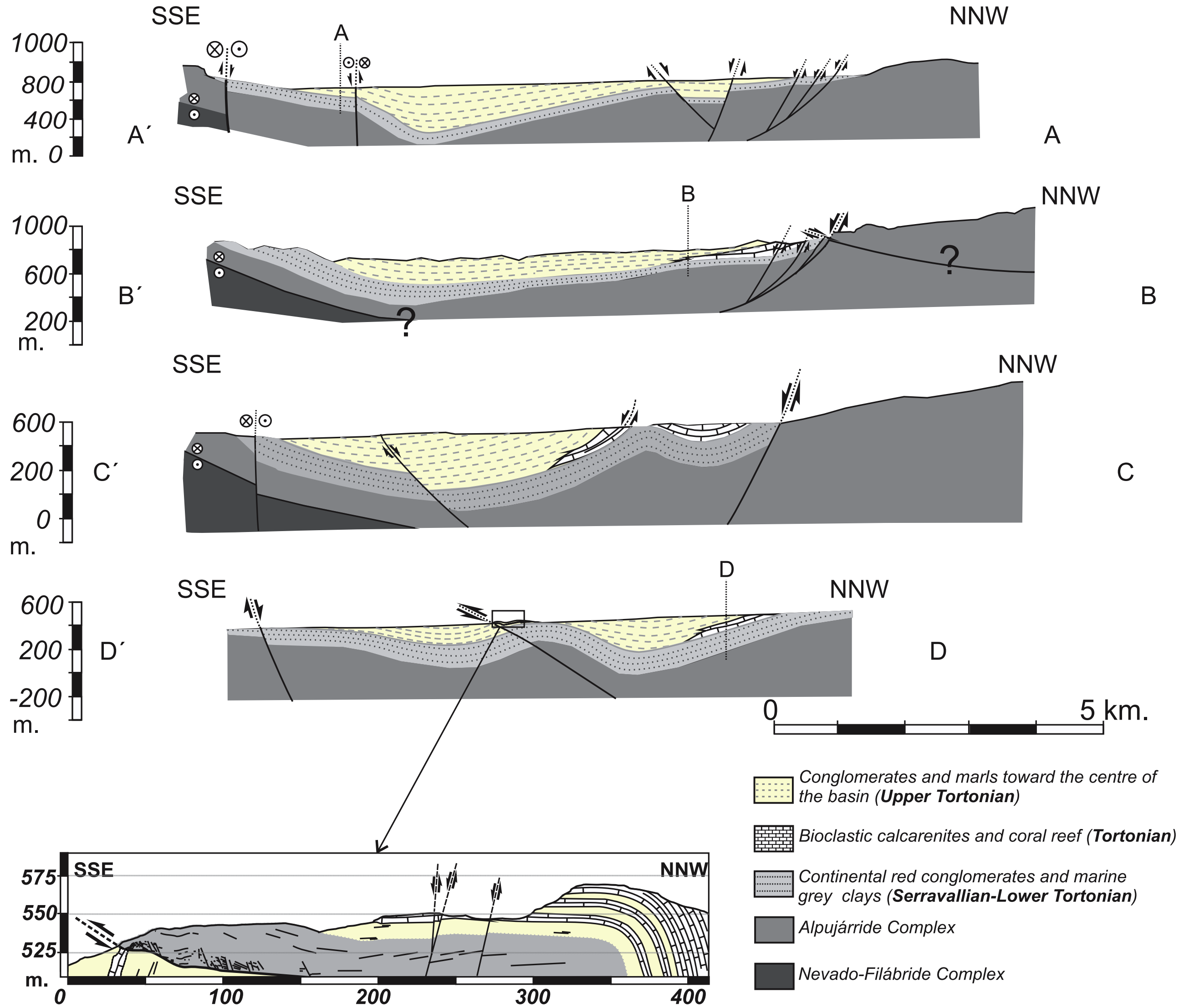

Figure 4. Simplified geological cross sections showing the Almanzora synform and the fault distribution. Their positions are marked in Figure 3. Note that the main structure of the basin is the kilometric-scale synform. The position of some lithostratigraphic sequences of Figures 2a, 2b, and 2d are marked in the cross sections. The enlarged blow-up of cross-section D′-D shows the structure of the main reverse fault that crops out in the basin (see also Figure 6c).

dence of activity in different periods, taking into account their relationships with the sediments.

[22] The NW-SE oriented faults crop out in the entire basin and in the Sierra de Las Estancias range (Figures 3 and 4). The longest NW-SE normal faults, however, deform the westernmost corridor sector and the north corridor border. Although some faults of this set affect only the early Tortonian sediments and are covered by late Tortonian rocks, most deform all the Miocene rocks (Figure 5d), cutting into the previous sets of transcurrent faults (Figure 5c) and affecting even the Quaternary sediments in the westernmost corridor sector and in the Baza basin (Figure 6). Therefore these faults started to develop during Tortonian, continued growing in post-Tortonian times, and are still developing in the westernmost part of the study area.

[23] Several NW-SE normal faults that deform the central and eastern corridor sediments show left-lateral striation overprinted upon the ancient normal striae. In some outcrops, these faults also deform up to the Quaternary sediments (Figure 3, Somontín fault).

[24] The E-W to ESE-WSW normal faults deform the Alpujárride and Nevado-Filábride rocks in the southeastern corridor border, displacing the lower Tortonian sediments. In addition, some of the previously described strike-slip faults show overprinted normal striation. The normal faults are more abundant in the northwestern border, where they show variable dips ranging between 50°S and subvertical.

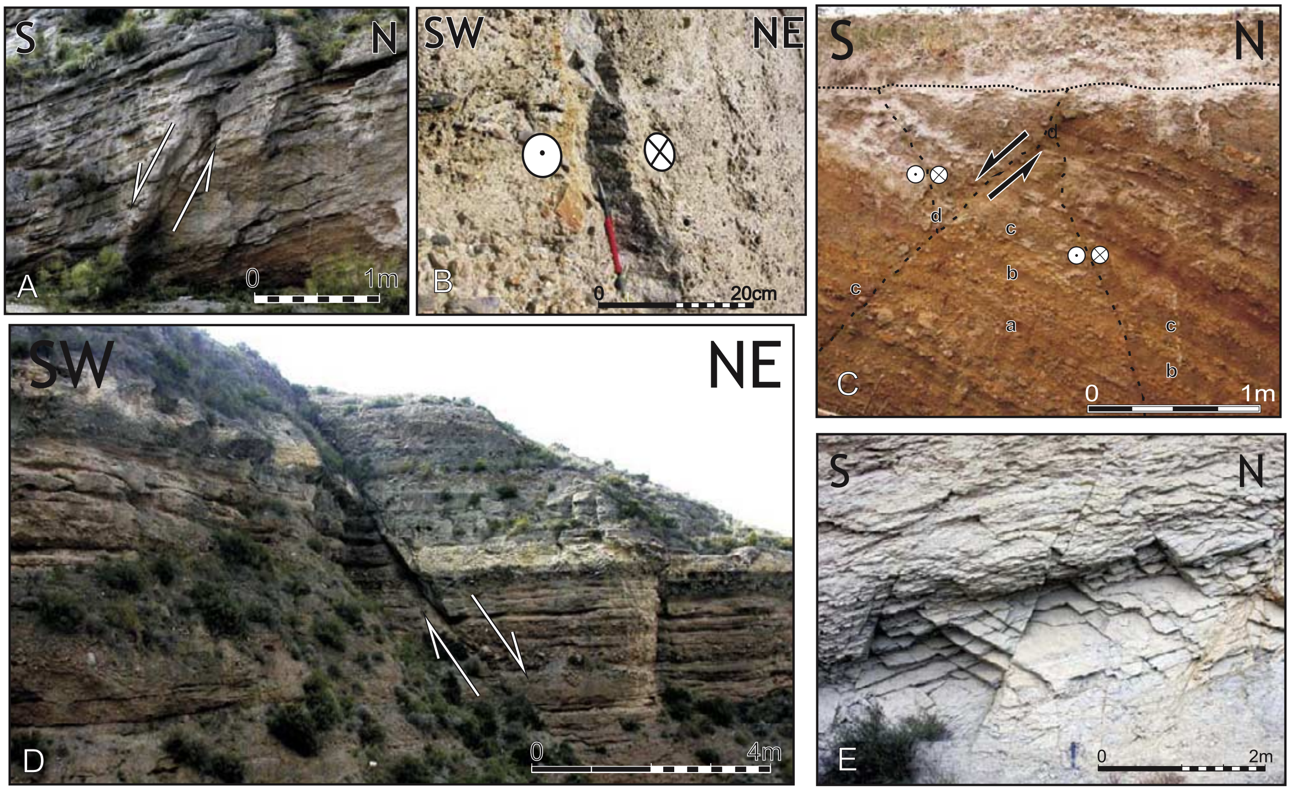

Figure 5. Field examples of faults. (a) E-W oriented and 65° south dipping fault that deforms the Tortonian sediments of the northwestern corridor border with a short normal slip displacement. (b) N-S left-lateral strike-slip faults deforming the Tortonian sediments in the central corridor. (c) NW-SE oriented normal fault cutting Serravallian–lower Tortonian sediments and a N-S strike-slip fault. (d) Example of NW-SE 50° northeast dipping normal fault that deforms the Tortonian sediments. (e) Conjugated normal faults tilted by minor folds in the eastern corridor.

In this sector, faults have short normal slip displacement and usually cut all Tortonian sediments appearing covered by the Plio-Quaternary deposits (Figures 3, 4, and 5a). Only one fault deforms up to the Plio-Quaternary sediments and generates topographic scarp (Figure 6, Lucar fault). Therefore the formation of the normal faults that belong to this set mainly occurred between the latest Tortonian and the Plio-Quaternary. In the nearby Huercal-Overa basin, some authors also identify E-W to ESE-WNW normal faults with activity during the Tortonian [*Augier*, 2004; *Mora*, 1993].

3.1.3. Reverse Faults

[25] The reverse faults are located in the eastern corridor (Figures 3, 4, and 7), near the Huercal-Overa basin [*Briend*, 1981; *Guerra-Merchán*, 1992; *García-Meléndez et al.*, 2003; *Masana et al.*, 2005a, 2005b]. These faults have orientations from N45°E to N90°E, and dips generally toward the NW, but also to the SE; kinematic analysis shows most striations to have directions comprised between N130°E and N140°E (Figure 7c). The reverse faults have short slips, in some cases of just a few cm in the central part of the basin (Figures 7a and 7b), though they may be greater than 40 m in the eastern sector (Figure 7d). These faults produced larger slips in Tortonian sediments than in the Quaternary alluvial sediments that crop out in the eastern corridor, indicating that they were active before Quaternary times, yet some of them continue to be active at Present (Figure 6).

3.2. Folds

[26] The main ranges and depressions of the central Betic Cordillera are related to kilometric-scale folds. In the study area these are as follows, from south to north (Figures 1 and 8a).

[27] 1. The north-vergent Filabres antiform has E-W average strike. The Nevado-Filábride rocks crop out in its crest, while in the northern limb rocks from the Alpujárride Complex are also exposed. This antiform is evidenced by the folding of the Alpujárride/Nevado-Filábride contact, the internal foliations of the metamorphic rocks, and the bedding of the Neogene sediments located at their flanks.

[28] 2. The Almanzora Corridor corresponds to a large north-vergent synform with E-W average strike. Its axial trace is located close to the south corridor border.- The Sierra de Las Estancias range also represents a large north-vergent fold that has an orientation changing from ENE-WSW in the eastern sector (outside the study area) to E-W in its western extreme, and constitutes the Almanzora Corridor north boundary. The rock outcrop distribution is

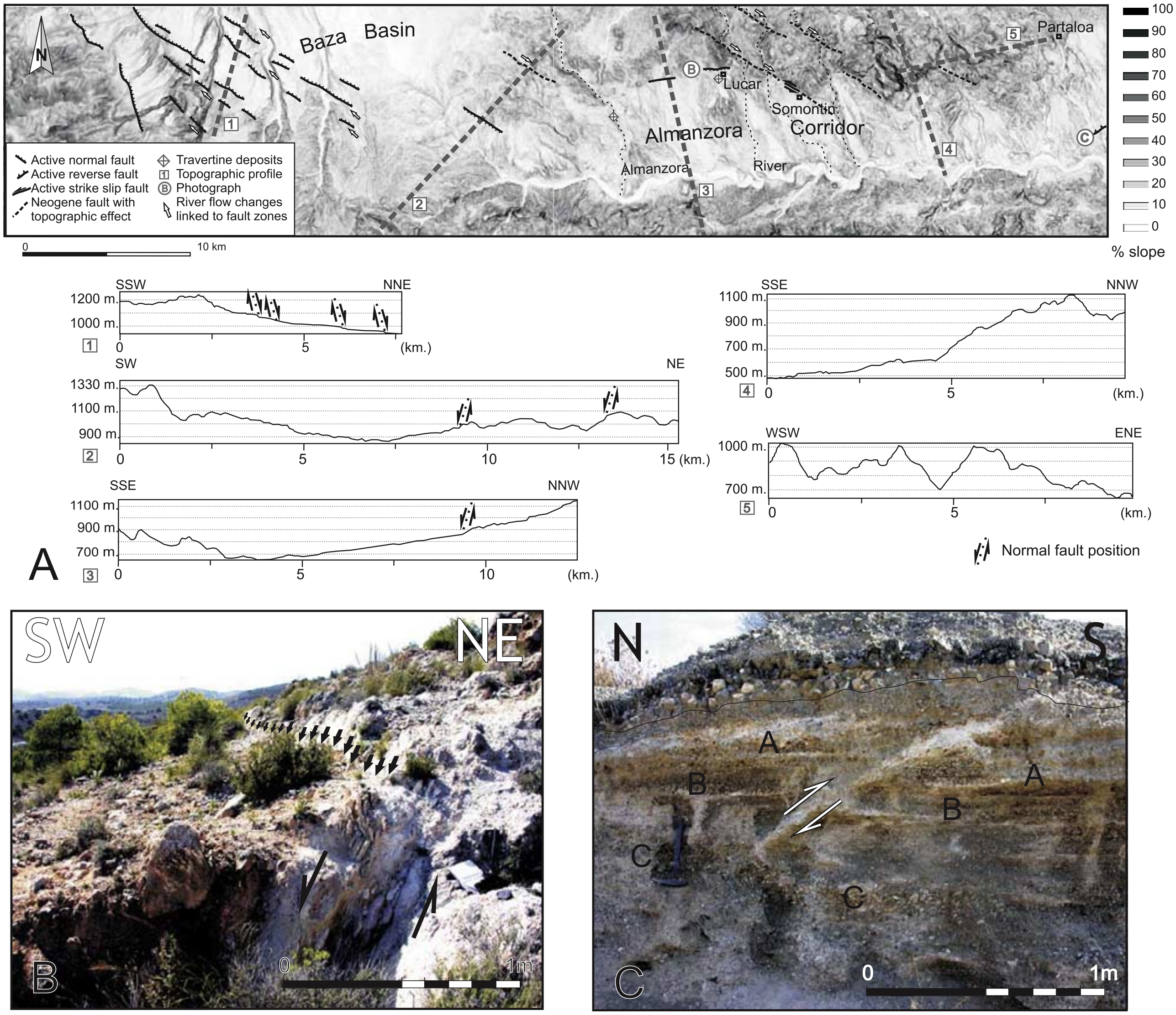

Figure 6. (a) Slope map and topographic cross section constructed from the digital elevation model with a 10-m-spaced cell grid. The slope percentage is indicated, and the areas with high slope are dark grey. Active tectonic structures are located in the map and in the cross section. The westernmost part of the corridor is affected by a set of active NW-SE faults and the north basin border shows three main steps that produce changes in the courses of rivers. (b) E-W segment of the normal Lúcar fault that deforms Quaternary sediments (UTM: 4140078 m, 550449 m). (c) ENE-WSW reverse fault that affects up to Quaternary sediments (UTM: 4137495 m, 569780 m).

asymmetrical, with a southern limb formed by Alpujárride rocks, and a northern limb that also includes rocks from the Maláguide Complex and the Flysch Units.

[29] The growth of these kilometric-scale folds was partially coetaneous to sedimentation in the Almanzora Corridor. Indeed, the sediments adjacent to the south basin border dip to the north, whereas the sediment closest to the north basin boundary dips to the south, revealing synsedimentary structures in both margins. The older sediments show higher dip than the recent ones, pointing to the synsedimentary character of folding (Figures 8a and 8b).

[30] Moreover, en echelon ENE-WSW oriented minor folds deform all the Tortonian sediments in the eastern part of the corridor (Figure 3b). These folds have variable wavelengths, comprised between 10 meters and several hundreds of meters, and tilt the previous faults (Figure 5e), though they may be affected by the most recent faults. Folds are generally open, yet in some cases produce very high dipping flanks, up to vertical (Figures 8c and 8d). The vergence of the folds is generally to the north, as is that of the large kilometer-scale folds. In addition, in the nearby Huercal-Overa basin, some ENE-WSW oriented minor folds deform up to Late Pleistocene sediments [*Soler et al.*, 2003;

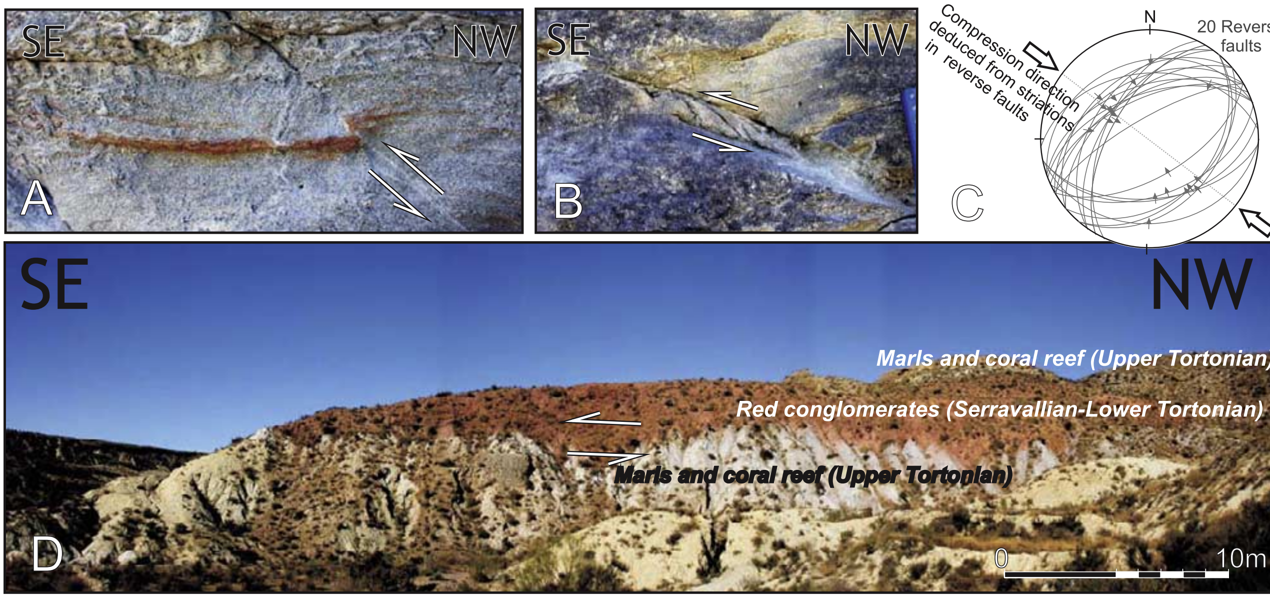

Figure 7. (a, b) Examples of ENE-WSW reverse faults showing a few centimeter slips, in the central part of the basin. (c) Orientations and kinematics of 20 reverse faults plotted in a stereographic projection, lower hemisphere. Note that reverse faults have orientations from N45°E to N90°E, while the striations have directions comprised between N130°E and N140°E. (d) The main reverse fault of the study area has a maximum slip greater than 40 m, is located in the eastern sector, and favored the imbrication of lower Tortonian conglomerates over upper Tortonian coral reefs.

Masana et al., 2005a, 2005b]. Within the hinge zone of the minor folds there develop: (1) coarse axial planar cleavage, (2) closed mesofolds, and (3) striations as a consequence of flexural slip deformation, when a multilayer of silts and calcarenites is folded.

4. Paleostress Analysis

[31] The paleostress ellipsoids were determined from microfaults and mesofaults using the method of *Galindo-Zaldívar and González-Lodeiro* [1988]. This method provides data on the main stress axes orientations and the axial ratios ($R = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$) of the overprinted deviatoric stress ellipsoids, considering that the striae on microfaults are parallel to the maximum shear stress [*Bott*, 1959] and that the stress field is homogeneous at the outcrop scale. The fault surface and the striae orientation were determined in the outcropping faults of each measurement station, and the regime was established essentially on the basis of displaced bedding, steps on fault surfaces and tails of microcrushed fault gauges. The overprinted striations on fault surfaces allow for an ordering of the stress superimposition.

[32] Along the Almanzora Corridor sedimentary infill, a total of 21 outcrops, including microfaults and metric size faults, were studied (Figure 3 and Table 1). The geographical proximity, rock homogeneity and low fault number allow for the grouping of stations 6, 7 and 8 for the statistical analysis. Other outcrops were discarded because of an insufficient number of faults (less than 10) or the fact that the faults were clearly deformed by late folds. Although the Quaternary sediment evidences the most recent deformation, it does not provide enough microfaults for determining paleostresses. Most measurement stations are located in the Tortonian sediments, though station number 2 is situated among marbles of the Alpujárride Complex (Figure 3 and Table 1).

[33] The paleostress ellipsoids determined in the region evidence at least two main tectonic events. The best represented set (type 1) is characterized by subvertical maximum stress axes, NE-SW extension, and variable axial ratios that are in transition to radial extension (stations: 1, 2, 4, 5; stations: 6, 7, 8 phase 1; station 10; station 15; station 18 and station 19 phase 2). This set is related to the development of normal faults with NW-SE orientations. The axis inclinations suggest that in several measurement stations the folds rotated some of the faults (stations: 6, 7, 8 phase 2, and 15).

[34] A second set (type 2) corresponds to paleostress ellipsoids characterized by a subhorizontal NW-SE maximum stress axis and high to medium axial ratios (station: 3; stations 6, 7 and 8 phase 2; stations 9, 11, 14 and 17; station 19 phase 1; station 21 phase 2) that may be related to the development of compressive structures, such as ENE-WSW reverse faults and folds. In this setting, when the intermediate stress axis becomes vertical, E-W to ESE-WNW dextral and N-S oriented sinistral faults develop. Other local paleostress ellipsoids are also found in the region. Station 20, located on the southern flank of a north vergent fold, evidences WNW-ESE extension related to an oblate stress ellipsoid. Station 12 and the first phase of

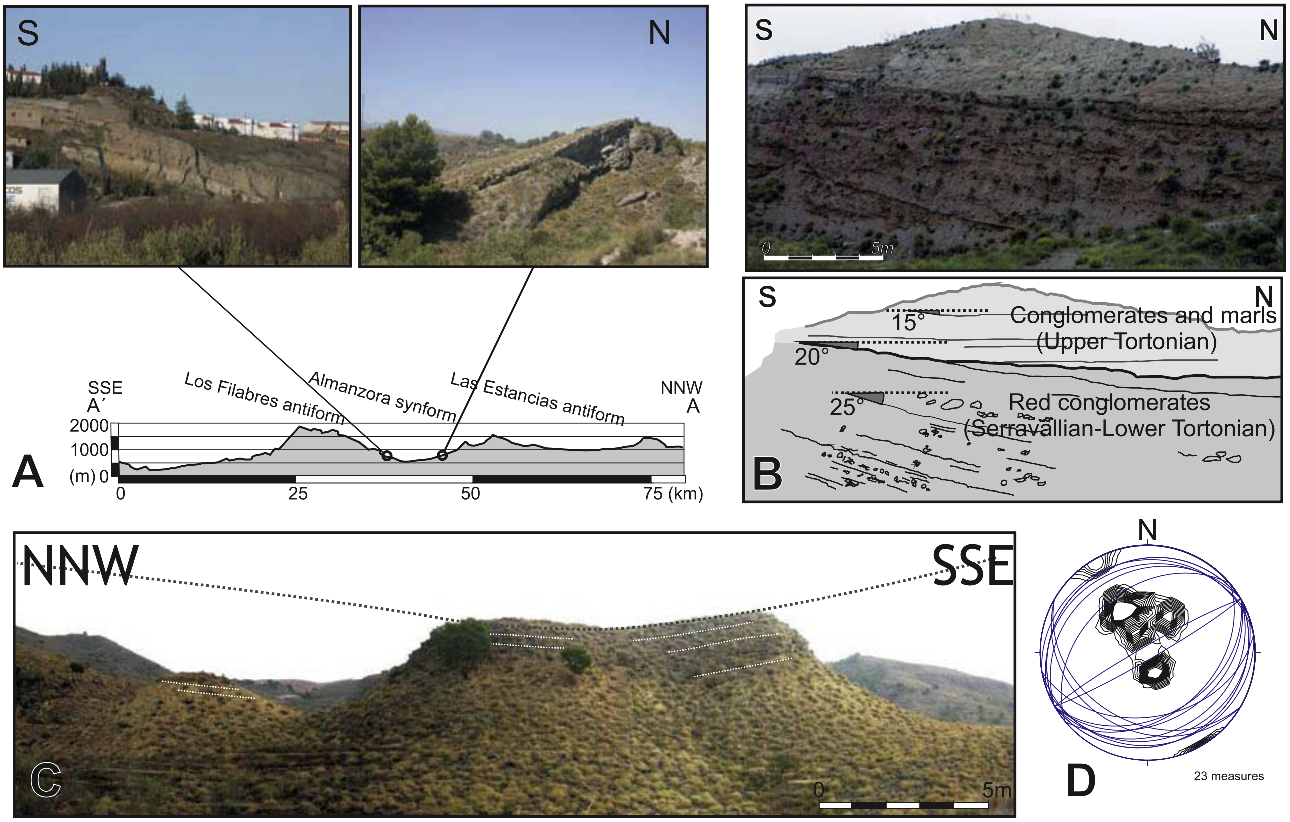

Figure 8. (a) Topographic profile where ranges and basin coincide with large antiforms and synforms (position in Figure 1). Indeed, the sediments adjacent to the south basin border of the Almanzora basin dip to the north and the sediments closest to the north basin boundary dip to the south. (b) Folded sediments showing structures synsedimentary to tilting, the older sediments having higher dip that the younger ones. (c) An ENE-WSW oriented minor fold that deforms the upper Tortonian sediments in the eastern part of the corridor. (d) Stereographic projection of bedding deformed by the ENE-WSW minor folds in the eastern corridor, lower hemisphere projection.

station 14 indicate a subhorizontal E-W maximum stress axis. Contrariwise, phase 2 of station 21 indicates a local E-W extension with a subvertical maximum stress axis, suggesting additional of the stress field.

5. Active Faults and Geomorphological Features

[35] Several tectonic structures are still active in the Almanzora Corridor, as indicated by structural features, drainage network position and incision. The westernmost part of the corridor is affected by a set of NW-SE faults that deforms up to the Quaternary glacis and produces the corridor's western termination (Figure 6a, profile 1).

[36] In the central part of the corridor, the Lúcar fault, formed by a set of E-W oriented and 40°–75° south dipping normal faults, locally deforms the Quaternary sediments, generating high dip in the calcretes and an average of 80 cm topographic scarp. In addition, the deposition of Quaternary travertines close to Lúcar is probably a consequence of the normal active faulting (Figure 6a, profile 3, and Figure 6b). The north basin border is irregular, but three main steps may be recognized. These steps are due to the presence of normal faults that also determine changes in the direction of the north Almanzora River tributary stream (Figure 6a). Close to Somontín, Quaternary sediments are deformed by a NW-SE oriented high-dipping fault that generates a steep scarp. The fault surface shows horizontal striation with a left-lateral regime overprinted on the normal old striae.

[37] The drainage network of the Almanzora River, along with the development and evolution of the corridor, was highly controlled by tectonics and reflects recent activity of the faults and folds. At present, the position of the ancient alluvial fan channels is taken up by most of the north Almanzora River tributary streams.

[38] Profile 3 shows a longitudinal section of alluvial fan (km 5 to 9) where the slope is very constant. Meanwhile, profile 4 shows a transverse section of an alluvial fan (km 1 to 4) along the folded Neogene sediments. The slope is variable due in part to the folding and the more intense erosion in this sector, associated with uplift. The Quaternary uplift is also evidenced by the presence of uplifted alluvial terraces [*García-Meléndez et al.*, 2003; *Soler et al.*, 2003]. These alluvial fan quaternary sediments are locally

Table 1. Paleostress Analysis Results[a]

Outcrop		Percent Data Used	R	σ_1		σ_2		σ_3	
1	Serv-L.Tort.	68	0.46	N25°E	62°	N116°E	1°	N207°E	28°
2	Pm-Trias	62	0.24	N167°E	77°	N14°E	12°	N283°E	6°
3	Serv-L. Tort.	67	0.69	N137°E	35°	N0°E	46°	N244°E	23°
		40	0.47	N136°E	2°	N237°E	80°	N46°E	10°
4	Serv-L. Tort.	65	0.12	N289°E	78°	N141°E	10°	N50°E	6°
		34	0.76	N233°E	81°	N80°E	8°	N349°E	4°
5	Serv-L. Tort.	69	0.15	N337°E	70°	N163°E	20°	N72°E	2°
6, 7, 8	U. Tort.	48	0.67	N122°E	84°	N302°E	6°	N32°E	0°
		32	0.09	N285°E	35°	N48°E	38°	N168°E	33°
9	U. Tort.	69	0.34	N302°E	3°	N51°E	82°	N211°E	8°
10	U. Tort.	82	0.3	N312°E	72°	N119°E	18°	N210°E	4°
11	U. Tort.	55	0.87	N116°E	16°	N296°E	74°	N26°E	0°
		31	0.47	N6°E	14°	N239°E	67°	N101°E	17°
12	Serv-L. Tort.	85	0.32	N45°E	88°	N175°E	1°	N265°E	2°
14	U. Tort.	59	0.08	N274°E	6°	N6°E	22°	N171°E	67°
		47	0.67	N150°E	2°	N60°E	6°	N258°E	84°
15	U. Tort.	71	0.29	N348°E	84°	N150°E	6°	N240°E	2°
16	Serv-L. Tort.	75	0.79	N215°E	30°	N334°E	40°	N100°E	35°
17	U. Tort.	80	0.08	N306°E	4°	N41°E	48°	N213°E	42°
18	Serv-L. Tort.	85	0.64	N224°E	43°	N122°E	13°	N19°E	44°
19	U. Tort.	60	0.4	N159°E	0°	N68°E	80°	N250°E	10°
		40	0.83	N202°E	48°	N109°E	3°	N16°E	42°
20	U. Tort.	75	0.88	N199°E	69°	N2°E	20°	N94°E	6°
21	Serv-L. Tort.	65	0.37	N176°E	30°	N356°E	60°	N86°E	0°
		35	0.16	N160°E	13°	N278°E	64°	N64°E	22°

[a]The main axes orientations are defined by their azimuth and plunge. In addition, the axial ratio values ($R = (\sigma 2 - \sigma 3)/(\sigma 1 - \sigma 3)$) are given for each station.

deformed by ENE-WSW oriented reverse faults, dipping 30° to the NE and having centrimetic slip (Figure 6c). Profile 5 shows the tributary stream incision in the Alpujárride rocks, which constitutes the most important one of the entire basin. The development of this stream incision, transverse to WSW-ENE fold axes that deform the sedimentary and metamorphic rocks, suggests a recent uplift of the Sierra de Las Estancias range and the headward erosion of the ancient fan channel. Such geomorphological features evidence recent tectonic activity in the area.

6. Discussion

[39] Although faults and folds may lead to the development of elongated topographies, including linear valleys, the overprinting structures in a changing stress scenario generally disrupt its elongated character. The changing stresses and strain, including rotation of tectonic elements, are very common in geodynamic settings characterized by oblique convergence [*Platt et al.*, 1995; *Platzman et al.*, 2000; *Platt et al.*, 2003]. In the Betic Cordillera, to date, corridor development has generally been related to strike-slip faulting [*Sanz de Galdeano et al.*, 1985; *Martínez-Martínez*, 2006]. Sedimentation areas in these tectonic settings are mainly located at pull-apart extensional zones.

[40] The new structural data reported in this paper encourage discussion of the genesis of the Almanzora Corridor, which is related to the progressive activity and interaction of faults and folds in a context of oblique shortening and dextral shear deformation. Its development allows us pinpoint two important implications for our knowledge of the narrow elongated basin growth: (1) the formation of narrow elongated basins under nonorthogonal convergence as a result of overprinted oblique tectonic structures and (2) the relationships between marine transgressions and fold development.

6.1. Narrow Elongated Almanzora Corridor Development

[41] Two different successive deformation stages are responsible for the corridor evolution: the initial development of the Los Filabres antiform during the Serravalian–earliest Tortonian, which will constitute its southern boundary, and the overprinting of other later structures.

6.1.1. N-S Compression During the Earliest Tortonian: Sierra de Los Filabres Growth

[42] The age of development of the recent reliefs in the Internal Zones of the Cordillera is not precisely determined, although most authors agree that it would have begun at Middle Miocene times [e.g., *Braga et al.*, 2003; *Rodríguez-Fernández and Sanz de Galdeano*, 2006]. The fission track data in the Las Estancias range and Sierra Nevada [*Johnson*, 1997; *Johnson et al.*, 1997; *Platt et al.*, 2005] indicate Early to Middle Miocene ages for the uprising of Alpujárride and Nevado-Filábride metamorphic rocks. The oldest conglomerates that clearly include Nevado-Filábride rocks are of early Miocene age [e.g., *Guerra-Merchán*, 1992], suggesting the presence of emerged areas undergoing erosion. In the Almanzora Corridor, paleocurrent directions and facies distribution deduced from the lower Tortonian sediments indi-

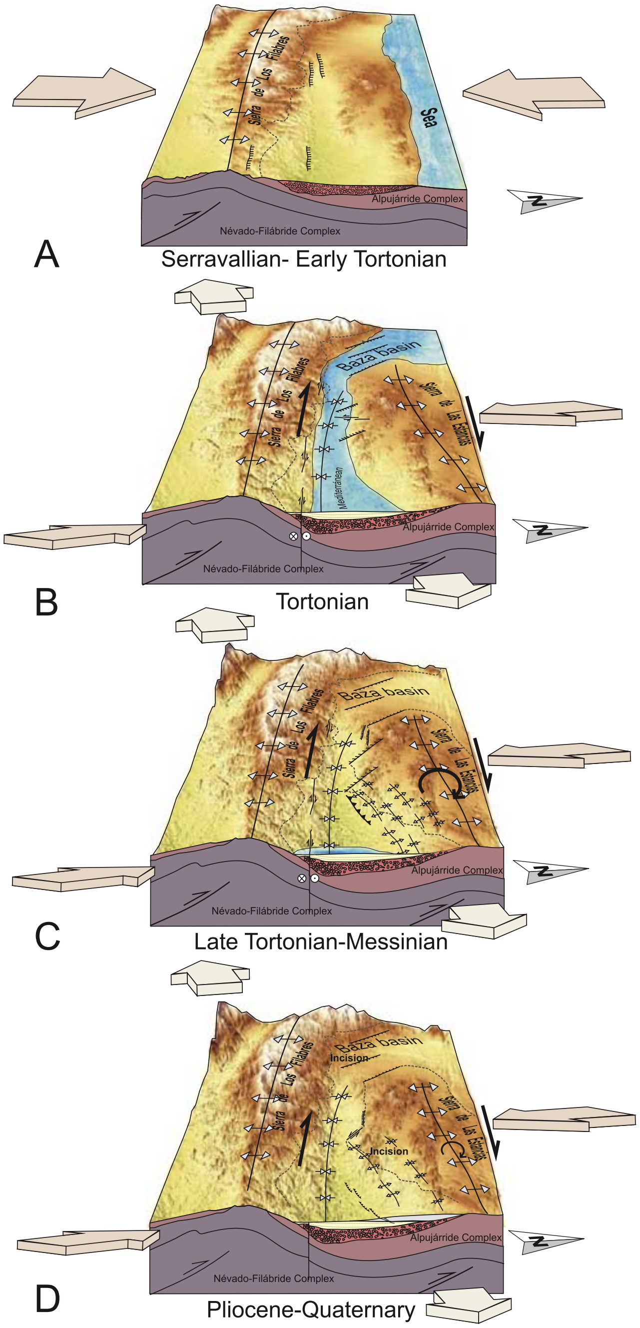

Figure 9. Block diagrams that represent the evolution of the main structures and the regional stress field in the Almanzora Corridor. The tectonic evolution is analyzed in four stages, showing the interaction of the faults and folds during Serravallian–early Tortonian, Tortonian, late Tortonian–Messinian, and Plio-Quaternary times.

cate the presence of an E-W uplifted Sierra de Los Filabres, which provided coarse sediments to the north, where the paleocoast was located. The uplift of the Sierra de Los Filabres may be related with the onset of an E-W antiform that started to grow during the earliest Tortonian producing unconformities in the sedimentary infill (Figure 8b). At any rate, in the Huercal-Overa basin, east of the study area, there should be other emerged sectors dating from this time period and determining a different pattern of paleocurrents, including southward directions [*Mora*, 1993; *Augier*, 2004].

[43] Although the lower Tortonian conglomerates that crop out in the Almanzora basin are tilted and show well developed brittle deformation, it is difficult to determine the deformation age and the synsedimentary paleostress. Nevertheless, the onset of growth of the E-W oriented Sierra de Los Filabres north-vergent fold suggests that the maximum stress axis was subhorizontal and N-S oriented during this period (Figure 9a). The Sierra de Los Filabres, together with Sierra Nevada, formed a large island at the end of middle Miocene [*Braga et al.*, 2003].

6.1.2. NW-SE Oriented Compression From Tortonian: Dextral Shear Deformation

[44] Our structural analysis indicates a change in the stress field during the Tortonian, with shortening direction changing up to NW-SE (stress ellipsoids type 2), accompanied by local NE-SW extension (stress ellipsoid type 1). The maximum stress axis became oblique to the previous E-W oriented Sierra de Los Filabres fold producing dextral shear deformation along a wide band located to the north. The activity and distribution of different tectonic structures evidenced the dextral simple shear deformation component.

[45] During the Tortonian, the Sierra de Las Estancias ENE-WSW antiform and E-W right-lateral and N-S left-lateral strike-slip faults started to grow, linked to the shortening. The NE-SW associated extension developed NW-SE normal faults that started to open the Baza basin in the westernmost sector of the corridor (stress ellipsoid type 1). In between the Los Filabres and Las Estancias antiform, the Almanzora synform developed. Its growth favored Tortonian marine transgression in this area, observed on a regional scale and traditionally linked with extensional events (Figure 9b).

[46] According to the sedimentological studies carried out by *Guerra-Merchán* [1992] in the Almanzora Corridor and by *García-García* [1993] in the southern border of the Baza basin, fast uplift linked to a tectonic event took place during the late Tortonian. Our stress analyses point out that the regional maximum stress axis continues NW-SE during the latest Tortonian–early Messinian (stress ellipsoid type 2), oriented obliquely to Sierra de Los Filabres (Figure 9c). Under a regional dextral shear deformation framework, extensional tectonics prevailed in the western corridor and a compressional setting controlled the eastern end. The related deformations may have produced the progressive clockwise rotation, from ENE-WSW to E-W, of the westernmost sector of Sierra the Las Estancias antiform. As a result of the eastern corridor narrowing, the sediments were subjected to a contractional deformation that produced ENE-WSW minor folds and reverse faults. Simultaneously, NW-SE normal faults deformed the Baza basin, the Almanzora Corridor and the Las Estancias range; while E-W dextral faults deformed the south basin border (Figure 9c). Furthermore, the corridor uplift took place as a consequence of the interaction between the kilometric-scale fold growth and a

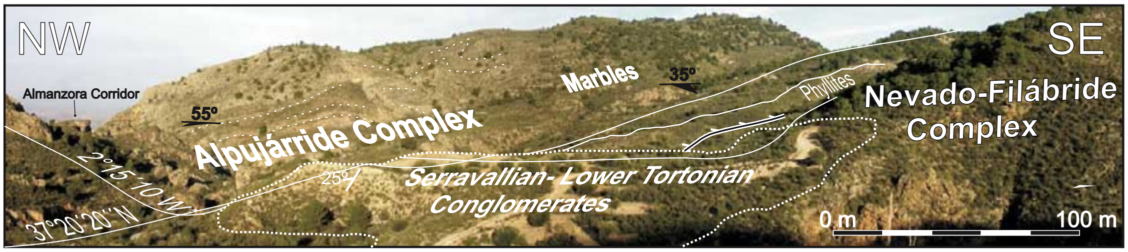

Figure 10. Lower Tortonian sediments covering the Alpujárride/Nevado-Filábride contact close to Fines, suggesting that the fault was active mainly prior to basin development (UTM: 4132647 m, 566103 m).

regional crustal thickening produced by plate convergence. The uplift effects (basin continentalization and river base level changes) are not only observed in the Almanzora Corridor, but also in all the Neogene basins of the Betic Cordillera.

6.1.3. Present-Day Setting

[47] The kilometric-scale Almanzora synform is responsible for the asymmetrical basin shape characterized by: alluvial fan development only in the northern border, high incision of the north tributary rivers, and the southward position of the Almanzora River. The south basin border is rectilinear and mainly controlled by the strike of inherited Miocene structures (mainly the foliation of the metamorphic rocks), and there are no active faults, as evidenced by undisturbed Quaternary sediments that crop out in this border. The north border geometry is more irregular, mainly because of the interaction between NW-SE normal faults as well as the lower dip of the northern limb of the synform. In this context, the stress field continues to be characterized by NE-SW extension, permitting the activity of the NW-SE normal faults in the Baza basin (stress ellipsoid type 1), and a NW-SE directed compression (stress ellipsoid type 2), detected only in the eastern corridor, along with the growth of small ENE-WSW reverse faults (Figure 9d).

6.2. Mechanism of Basin Growth

[48] The Almanzora Corridor and its terminations constitute an example of elongated asymmetric narrow basin development in an oblique convergence framework since the Tortonian. Previous authors propose extensional models for the basin development based on the growth of large E-W normal faults coetaneous to sedimentation [*Guerra-Merchán*, 1992; *Augier et al.*, 2005]. The new data presented in this paper may improve understanding of the tectonic evolution, as certain aspects contradict previously proposed models.

[49] *Augier et al.* [2005], who describe the deformations of the southern border basement, have recently suggested this basin be interpreted as a half-graben structure in the hanging wall, related to the Alpujárride/Nevado-Filábride top-to-the-north low-angle normal fault. This model is contradictory with the W-NW extension direction deduced from the Alpujárride/Nevado-Filábride fault gauges [*Jabaloy et al.*, 1993; *Martínez-Martínez et al.*, 2002]. In addition, detailed analysis of the sedimentary infill reveals that the Alpujárride/Nevado-Filábride contact is buried in some sectors by sediments since the early Tortonian (Figure 10), suggesting that the fault was active mainly prior to basin development.

[50] Our structural data show that in both basin boundaries, the relation between the sediments and basement rocks is generally an unconformity, deformed only by some NW-SE normal faults in the north basin boundary and by dextral strike-slip faults in the south basin border. Indeed, the sediments adjacent to the south basin border dip to the north, whereas the sediments closest to the north basin boundary dip to the south, showing structures synsedimentary with respect to tilting in both margins. Even though abundant faults and folds deform the Almanzora basin, our data clearly indicate the greater significance of the folds than of the normal faulting during the corridor development. Thus the corridor development is mainly a consequence of fold growth, modified by a great variability of tectonic structures, including synsedimentary compressional deformations, in a regional stress field determined by NW-SE compression and orthogonal extension.

6.3. Implications for an Understanding of Narrow Elongated Basin Development Under Nonorthogonal Convergence

[51] In orogens developed in an oblique convergence framework, simple shear components appear as important deformation mechanisms [e.g., *Fabbri et al.*, 2004; *Velandia et al.*, 2005]. At a minor scale, the presence of crustal obstacles (e.g., large folds) or anisotropies (e.g., joint and faults) oblique to the compressional direction, favors the appearance of shear deformation bands [*Tchalenko*, 1970; *Jonk and Biermann*, 2002] that allow the development of transpressive and transtensive areas [*Ramsay and Huber*, 1970; *Ramsay*, 1980; *Sanderson and Marchini*, 1984].

[52] The Almanzora Corridor leads us to consider that, under simple shear component deformations, major folds and tectonic element rotations play an important role during a narrow basin development, controlling the local asymmetry of tectonic structures, with the extensional tectonic opening of the western corridor and the compressional setting controlling the eastern end. In addition, this tectonic setting is responsible for the denudation/sedimentation area distribution, and the final corridor's shape and longitude, which coincide with the extent of the dextral shear zone. The coalescence of extensive and compressive structures is a common feature of the Neogene-Quaternary basins of the

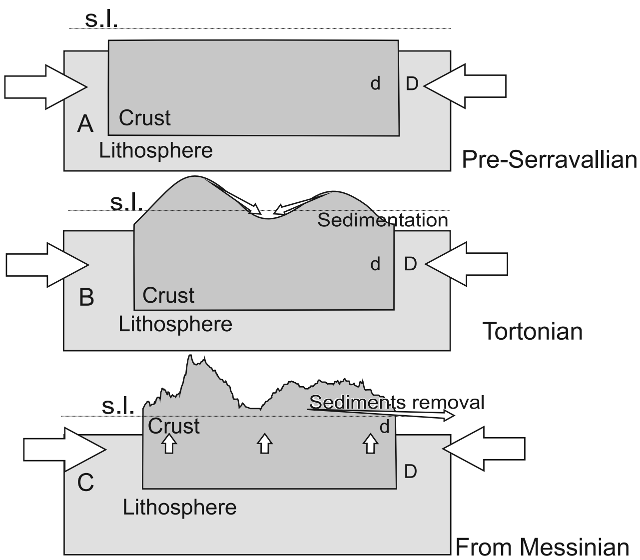

Figure 11. Relationships between folding and marine transgressions, considering as constant the sea level. (a) Unfolded crust. (b) Fold development. Although the average height of the cordillera increases, so does the difference between minimum and maximum heights, and the depressed areas allow a marine transgression and the onset of sediment deposition. (c) Final stage, with the compression continuing to produce crustal thickening while a regional and progressive emersion takes place until the marine basin continentalization.

Betic Cordillera, although the mechanisms that allow their coexistence are still under debate [e.g., *Galindo-Zaldívar et al.*, 1993, 2003; *Marín-Lechado et al.*, 2006; *Martínez-Martínez*, 2006; *Pedrera et al.*, 2006]. This setting is still actives at the cordillera scale, therefore the distribution of seismicity and the kinematics deduced from the focal mechanism solutions reveal an extensional setting in the upper crust that are in contrast with the NW-SE plate shortening [*Morales et al.*, 1997; *Galindo-Zaldívar et al.*, 1993; *Herraiz et al.*, 2000; *Muñoz et al.*, 2002; *Stich and Morales*, 2001; *Stich et al.*, 2003; *Buforn et al.*, 2004; *Martínez-Martínez*, 2006], that affected the lower crustal levels. In this sense, our geometric-kinematic model addresses the relationship between extension and shortening in one of these basins since the Tortonian.

[53] In the Almanzora Corridor, the presence of the large Sierra de Los Filabres antiform since the early Tortonian represents a rigid obstacle conditioning the stress distribution during its more recent evolution. A key question about the formation of the Filabres E-W oriented range is: Did it emerge with the present orientation, or has it rotated since the early Tortonian?

[54] 1. One possibility is to assume a consistent NW-SE direction of compression throughout Tortonian times. In this setting, the original orientation of the Los Filabres fold would be NE-SW (orthogonal to the shortening), and then subjected to a progressive dextral rotation. Paleomagnetic studies propose dextral rotations for tectonic elements located in the External Zones of the Cordillera during the indentation to the west of the Alboran Domain [*Platt et al.*, 1995; *Platzman et al.*, 2000; *Platt et al.*, 2003, 2005]. However, these rotations were previous to Tortonian times, probably being active during the early to middle Miocene [*Luján et al.*, 2003].

[55] 2. The other possibility is that the orientation of the range has remained unchanged since its initial stage of formation. Therefore most authors evoke the origin of E-W trending folds under a N-S contractional event (*Platt et al.*, 1983; *Weijermars et al.*, 1985; *Crespo-Blanc et al.*, 1994; *Martínez-Martínez et al.*, 1997, 2002; *Sanz de Galdeano and Alfaro*, 2004]. Following this assumption, we consider a counterclockwise rotation of the directed compression, from N-S (orthogonal to Sierra de Los Filabres antiform) to NW-SE (deduced from our data) during Tortonian. During the initial stages of the orogeny, large folds constitute examples of crustal barriers that favor the development of shear zones parallel to their boundaries where the crust is thinner. These ancient inherited characteristics, later emphasized during the basin evolution, strongly condition the final shape of the corridor.

6.4. Folds Development and Marine Transgression

[56] In convergent margins, contractional tectonic deformation produces crustal thickening and mountain development. Most of the sedimentary basins are a result of uprising sea level or extensional stages with related subsidence [*Keller and Pinter*, 2001]. However, the global sea level change curves [*Haq et al.*, 1987] cannot adequately explain the stratigraphical sequence of the Almanzora Corridor, meaning tectonic events conditioned the deposits and the morphology of the basin [*Guerra-Merchán*, 1992; *Guerra-Merchán and Serrano*, 1993; *García-García and Fernández*, 2006]. On the basis of our structural data, we can discard N-S extension of the Almanzora Corridor as the main mechanism responsible for the basin development. Could fold growth related to crustal thickening explain the Tortonian transgression in the basin?

[57] Folding related to crustal thickening increases the average height of the cordillera [*Keller and Pinter*, 2001]. However, it also augments the difference between minimum and maximum heights, respectively coinciding with synforms and antiforms. In the initial stages, the depressed areas may allow sea water penetration and become marine basins with sediment deposition from the adjacent antiformal mountains (Figure 11b). This mechanism may be responsible for the Almanzora basin Tortonian transgression. The Tortonian sediments lap onto the basal Tortonian red conglomerates and the basement rocks. The sediments located in the corridor border are deposited in coastal and very shallow marine environments, while a deep sedimentation fills in the corridor axis.

[58] In a second stage, compression continues producing crustal thickening and a regional and progressive emersion takes place, until marine basin continentalization (Figure 11c). In the Almanzora Corridor, the uppermost-latest Tortonian yellow marls [*Briend*, 1981] show a shallowing upward sequence that culminates in the basin continentalization. At

this point the erosion rates exceed the uplift and the sediments are removed out by the Almanzora River.

7. Conclusions

[59] Elongated depressions developed in geodynamic settings characterized by oblique convergence are often related to strike-slip faulting. However, the Almanzora Corridor growth is associated with a complex structural interaction developed in a changing stress scenario. (1) During the early Tortonian, a N-S directed compression allows deformation to advance to the north with a progressive fold growth, starting with the Sierra de Los Filabres antiform and then with the Sierra de Las Estancias antiform. (2) Later, since Tortonian, counterclockwise rotation in the stress field occurred, and the shortening direction changed to NW-SE (type 2) presenting an orthogonal associated extension (type 1). Therefore the maximum stress axis became oblique to the previous E-W oriented Sierra de Los Filabres fold, producing dextral shear deformation along a wide band located to the north. The westernmost sector of the Sierra de Las Estancias fold underwent progressive clockwise rotation, from ENE-WSW to E-W, producing the eastern corridor narrowing. As a result of the rotation, the deformation styles were clearly different in the Baza basin and western Almanzora Corridor (extensional) as compared to the eastern part of the Almanzora Corridor (compressional).

[60] The above regional observations give rise to four major conclusions about the evolution of a narrow and elongated basin. (1) The development of large mountain ranges represents crustal rheological heterogeneities that condition the growth of late structures. (2) A shortening direction oblique to these mountains may produce a deformation framework with an important simple shear component, including extension and compression directions that are oblique to the basin boundaries. Notwithstanding, the elongated character of the corridors may persist. (3) Under these conditions, fold development may play an important role during basin evolution, controlling the location of minor tectonic structures and the sedimentation/denudation areas. (4) In addition to the traditional extensional models, the Almanzora Corridor illustrates that the initial stages of synform growth could be responsible for local marine transgressions.

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