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The Flysch Trough thrust imbricate (Betic Cordillera): A key element of the Gibraltar Arc orogenic wedge

María Luján,[1] Ana Crespo-Blanc,[1,2] and Juan Carlos Balanyá[3]

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[1] Within the Betic-Rif orogenic system, the Flysch Trough units are formed mainly by siliciclastic rocks, upper Jurassic to lower Miocene in age. In the Gibraltar Arc area, they are presently deformed as an accretionary prism, sandwiched between the fold-and-thrust belt derived from the South Iberian paleomargin sedimentary series and the metamorphic rocks of the Alboran Domain, on top. In the northern branch of the Gibraltar Arc, the main tectonic unit of the Flysch Complex is the Aljibe unit, which shows a well-organized structure of thrust imbricates, post lower Burdigalian in age. In this unit, various domains separated by major accommodation zones are characterized by their structural style and vergence. This change in structural style can be explained as a consequence of the variations of rock type along the basal décollement. Finally, these thrust systems were affected by extensional, low- to medium-angle faults and large-scale very open folds, successively. The organization of the Aljibe unit fits a push-from-behind mechanism for its emplacement, in which the relatively "rigid" back stop would be represented by the Alboran Domain. With the data presented in this paper, it is definitely shown that the Aljibe unit is not "chaotic" as claimed in previous papers and that the tectonic transport direction around the Gibraltar Arc swings from a northwestward to a westward direction along its northern branch, in the vicinity of the straits.

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1. Introduction

[2] The westernmost segment of the Alpine-Mediterranean orogenic belt is represented by the Betic and Rif chains, north and south of the Alboran Sea, respectively (Figure 1). They are linked by the Gibraltar Arc, which developed during and partly in response to the Cenozoic convergence between Africa and Iberia [e.g., *Dewey et al.*, 1989]. The Betic-Rif system is a key area for understanding the geodynamic processes which took place during the development of the western Mediterranean. in particular, the structural and kinematic evolution of its tectonic domains (known as the external zones, the Flysch Trough units and internal zones or Alboran Domain) is an essential prerequisite to propose any model of the geodynamic history of the western Mediterranean region as a whole.

[3] The aim of this paper is to shed light on the general architecture of the Flysch Trough units in the Betics, as a tectonic element of one of the tightest arc observed on Earth. Special attention is given to the structure of the Aljibe unit, the main unit of the Flysch Trough units. Indeed, in the Betic-Rif chain, these units are well known from a stratigraphic and sedimentologic point of view since the 1960s [*Didon*, 1960; *Chauve*, 1962; *Didon et al.*, 1973; *Wildi*, 1983; *Bouillin et al.*, 1986; *Stromberg and Bluck*, 1998; *Durand-Delga et al.*, 2000]. Nevertheless, from a structural point of view, they are almost unknown: In the northern branch of the Gibraltar Arc, a supposedly chaotic character has been attributed to most of the outcrops of the Flysch units [*Didon*, 1969; *Bourgois*, 1978; *Martín-Serrano*, 1985; *Moreno Serrano et al.*, 1988], meanwhile in Morocco, only preliminary studies have been made [*El Mrihi*, 2005].

[4] Detailed structural mapping permits to establish that the Aljibe unit shows a coherent structure of well-organized thrust imbricates, instead of a chaotic, gravitationally driven geometry. Moreover, the fan pattern of the tectonic transport trajectories shown in this paper represents a strong constraint for the Gibraltar Arc formation mode. Finally, the data presented herein will help establish the role of the Flysch Trough units as an accretionary prism associated with the western Mediterranean Subduction Zone, which extends from the northern Apennine to southern Spain [*Faccenna et al.*, 2004]. The mainly outward divergent thrusting observed in these units is coherent with asymmetrical westward propagating lithospheric models, either through mantle delamination or roll-back process, when framed into an evolutionary model of the westernmost segment of the western Mediterranean Alpine system.

2. Geological Setting

2.1. Tectonic Domains Around the Gibraltar Arc

[5] Three main tectonic domains are involved in the Gibraltar Arc (Figure 1b):

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[1] Departamento de Geodinámica de Granada, Universidad de Granada, Granada, Spain.

[2] Also at Instituto Andaluz de Ciencias de la Tierra, Consejo Superior de Investigaciones Científicas, Universidad de Granada, Granada, Spain.

[3] Departamento de Ciencias Ambientales, Universidad Pablo de Olavide, Seville, Spain.

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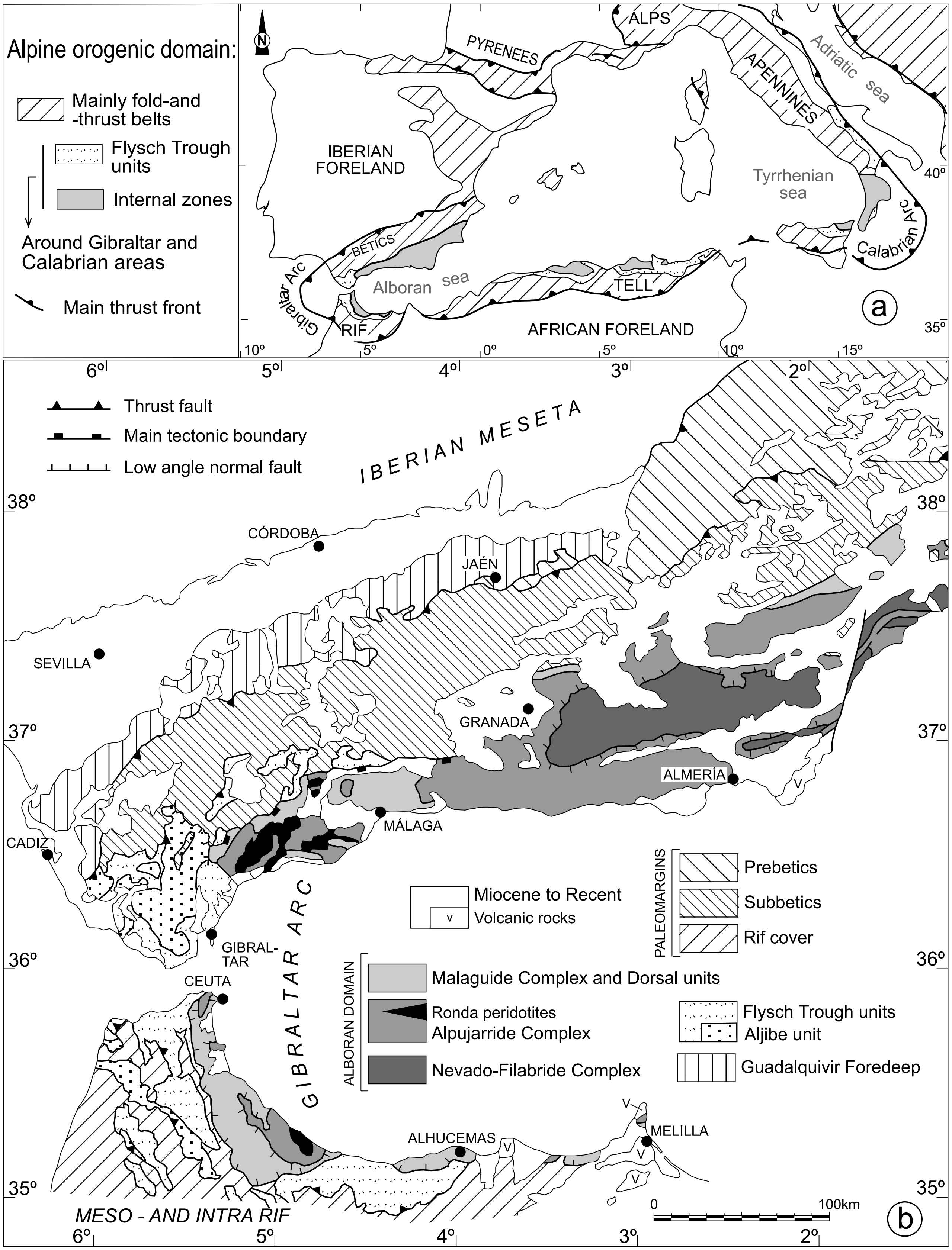

Figure 1. Tectonic sketch of the western Mediterranean area.

[6] 1. The Alboran Domain, a postmetamorphic thrust stack formed mainly by Paleozoic to Triassic rocks with a complex tectonometamorphic evolution, constitutes the internal zones of the Betic-Rif orogenic system [*Balanyá and García Dueñas*, 1988] (Figure 1b). The Alboran Domain forms currently lithospheric boudins deriving from the peri-Mediterranean Alpine metamorphic inner zones, which were drifted apart during the Neogene extensional episodes (Figure 1a). Such boudins are present not only in the Betic-Rif belt, but also in the Kabylies (Algeria) [*Bouillin et al.*, 1986; *Caby et al.*, 2001; *Michard et al.*, 2006] and in the Calabrian arc (Italy) [*Rossetti et al.*, 2001].

[7] 2. The external zone fold-and-thrust belts are represented by the South Iberian and Maghrebian Domains, which consist of sedimentary rocks, Triassic to Neogene in age, derived from their respective paleomargins [e.g., *García-Hernández et al.*, 1980; *Wildi*, 1983; *Chalouan et al.*, 2001]. They were separated by a transform fault that was active during the Upper Jurassic and Early Cretaceous [e.g., *Stampfli and Borel*, 2004].

[8] 3. The Flysch Trough units (or Flysch Complex) derived from a basin underlain by very attenuated continental crust or oceanic crust, and are composed by Upper Jurassic to Miocene deep-water sediments [*Biju-Duval et al.*, 1978; *Dercourt et al.*, 1986; *Durand-Delga et al.*, 2000; *Stampfli and Borel*, 2004]. These units, now deformed in an accretionary prism presently located in the western Betics, along the northern part of Africa, in the Calabrian Arc and the Apennines, demonstrate the existence of a long oceanic basin fringing the North African paleomargin (Figure 1a) [*Durand-Delga and Fontboté*, 1980; *Bouillin et al.*, 1986; *Dercourt et al.*, 1986; *Balanyá and García Dueñas*, 1988; *Stampfli and Borel*, 2004]. Together with both paleomargins, the Flysch Trough units are involved in the Gibraltar Arc fold-and-thrust belt.

[9] It is generally acknowledged that shortening in this fold-and-thrust belt was due to the westward migration of the Alboran Domain from the Early Miocene [e.g., *Andrieux et al.*, 1971; *Bourgois*, 1978; *Durand-Delga*, 1980; *Leblanc and Olivier*, 1984; *Martín Algarra*, 1987; *Balanyá and García Dueñas*, 1988; *García-Dueñas et al.*, 1992; *Royden*, 1993; *Lonergan and White*, 1997; *Crespo-Blanc and Campos*, 2001; *Michard et al.*, 2002].

2.2. Flysch Trough Units

[10] The Flysch Trough units can be followed from one part to the other of the Gibraltar Straits. In its northern branch, *Didon* [1969] distinguished three mains units, called Aljibe, Algeciras, and Bolonia units (Figure 2), whose equivalent in Morocco are the Numidian, Beni-Ider, and Tala Lakraa units, respectively [*Didon et al.*, 1973]. The general map of Figure 2 illustrates the distribution of the Flysch Trough units in Spain. The large-scale cross section which accompanies the map of Figure 2, based on the work by *Crespo-Blanc and Frizon de Lamotte* [2006] shows the internal structure of the Flysch Trough units and its relationship with the Subbetic Domain [see also *Balanyá and Garća Dueñas*, 1988; *García de Domingo et al.*, 1994; *Crespo-Blanc and Campos*, 2001; *Michard et al.*, 2002; *Frizon de Lamotte et al.*, 2004]. Along this cross section, constrained in its eastern part by wells and commercial seismic profiles [e.g., *Crespo-Blanc and Luján*, 2002], the structural trend varies, from a NE-SW to an E-W direction, and the corresponding change in the direction of the section line has been made.

[11] It should be clear, according the large-scale cross section of Figure 2, that in the vicinity of the Gibraltar Arc, the Flysch Trough Domain is situated structurally over the Internal Subbetic units. In turn, the Flysch Trough units is overlain by the Alboran Domain (Figure 1) [e.g., *Balanyá and García Dueñas*, 1988; *García de Domingo et al.*, 1994; *Crespo-Blanc and Campos*, 2001; *Frizon de Lamotte et al.*, 2004] (see also Figure 10 in section 7.1). In the southern branch of the Gibraltar Arc, the structural relationships between the Alboran Domain and Flysch Trough units, including Predorsalian units, are similar. Nevertheless, the Flysch units have also been locally observed on top of the Alboran Domain (Rif area [see *Durand-Delga et al.*, 1962; *Feinberg et al.*, 1990; *García-Dueñas et al.*, 1990]). This relationship has been recently interpreted as due to late, low-angle normal faults [*Chalouan et al.*, 1995; *El Mrihi*, 2005].

[12] In this paper, special attention is paid to the structure of the Aljibe unit, a thrust imbricate fan [*Boyer and Elliot*, 1982], post lower Burdigalian in age, due to an approximately E-W shortening [*Luján et al.*, 1999; *Luján*, 2003]. Indeed, this unit represents most of the Flysch outcrops north of the Gibraltar Straits (Figure 2) and the outcrops of the other Flysch units are very poor.

3. Structural Relationships of the Aljibe Unit With the Surrounding Units

[13] The structural relationships of the Aljibe unit with the surrounding units are illustrated in Figure 2. Subbetic rocks appear as an alignment of tectonic windows below the Flysch Trough Domain, and in the northeastern part of the study area, the Aljibe thrust imbricate is cut by a low- to middle-angle normal fault (El Colmenar fault [*Luján et al.*, 2000]), whose footwall is occupied by the Subbetic units. Toward the west, the boundary with the Subbetic domain is very complex: Kilometric-scale outcrops of Aljibe unit are embedded within Triassic evaporites and clayey formations whose attribution either to Flysch or to Subbetic units is unclear. Huge blocks composed by a few thrust slices of Aljibe unit formations are bent in plan view, perhaps due to vertical axis rotations [*Moreno Serrano et al.*, 1988]. Moreover, various systems of middle- to high-angle normal faults which individualized outcrops of Aljibe unit have been evidenced. In fact, up-to-date, is has not been possible to reconstruct a coherent structure from one outcrop to the other.

[14] Concerning the Aljibe-Algeciras unit boundary, when this latter is N-S oriented (in the northern part of the map of Figure 2), it can be observed that Aljibe unit is situated structurally on top of Algeciras unit (see also cross section of Figure 2), meanwhile toward the south, when this boundary turns to an E-W direction, the structural relation-

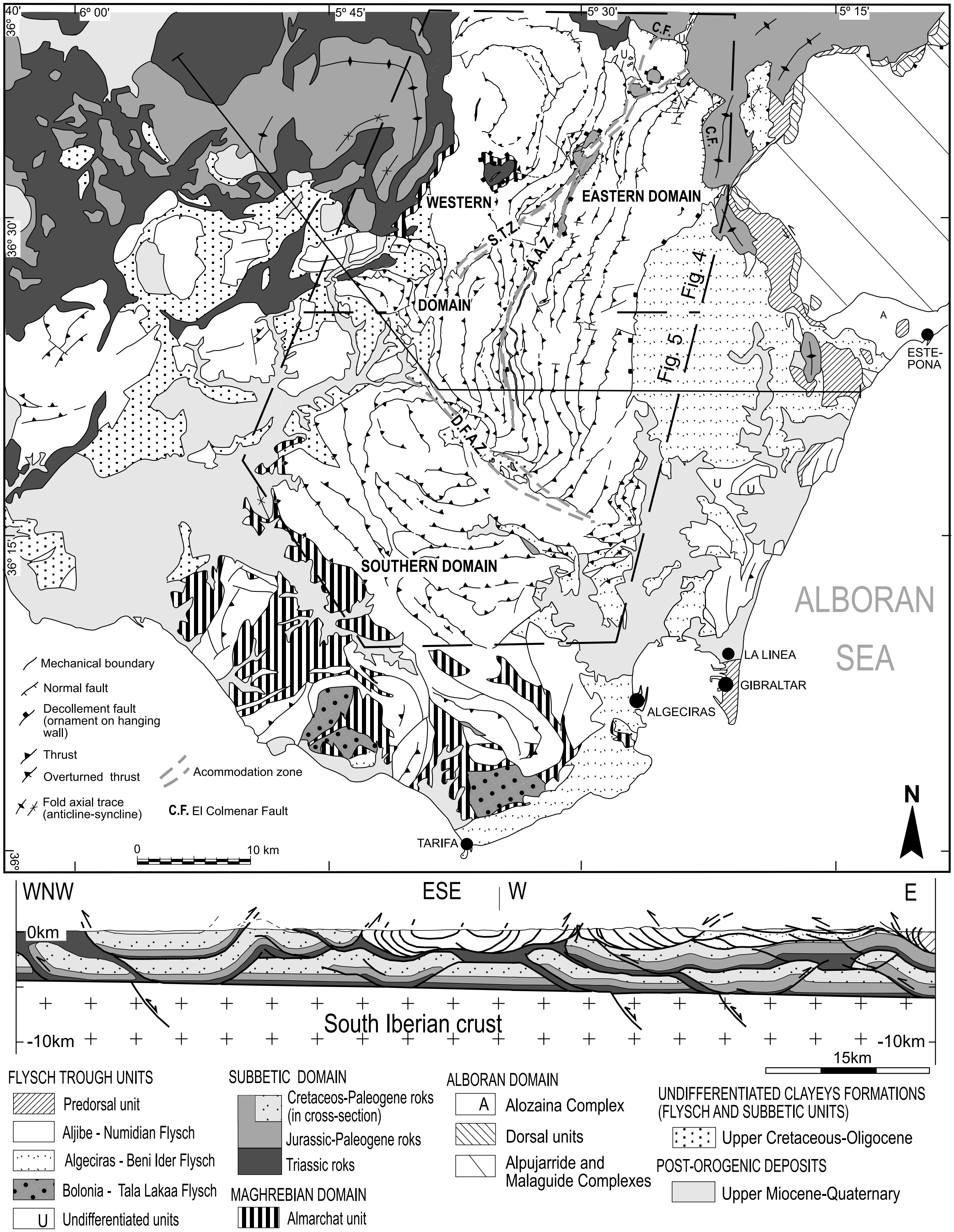

Figure 2. Simplified structural map of the northern branch of the Gibraltar Arc, showing the distribution of the main units which belong to the Flysch Trough Complex.

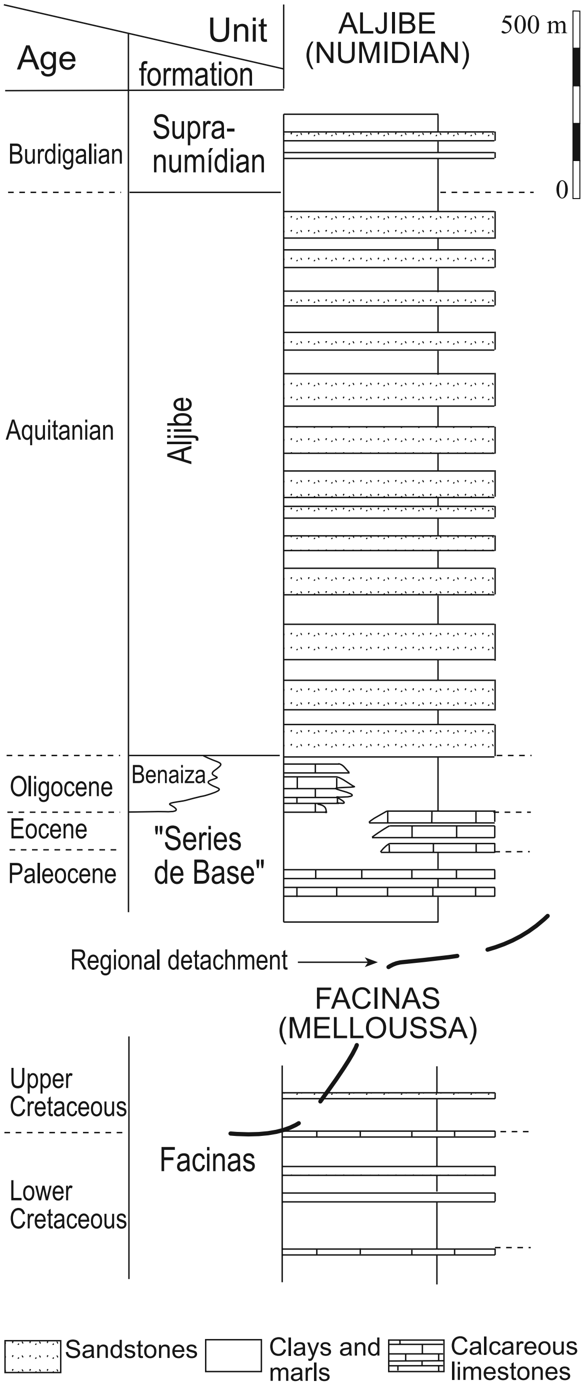

Figure 3. Simplified lithostratigraphic sequence of the Facinas and Aljibe units.

ship between both units is the opposite, due to out-of-sequence thrusts [*Luján*, 2003].

[15] Part of the Maghrebian cover appears north of the Gibraltar Straits (Almarchal unit [*Didon*, 1960; *Thurow*, 1987]). It lies structurally below the Aljibe unit, although most of the boundaries are severely folded and presently appear as overturned thrusts [*Esteras et al.*, 1988]. For example, southwest of the studied area, the whole imbricate thrust was verticalized and even overturned. Actually, the thrust surface is dipping toward the northeast, and the Almarchal unit appears over the Aljibe unit.

4. Lithostratigraphic Sequences of the Flysch Trough Units

[16] Most of the lower Cretaceous to lower Miocene sedimentary rocks of the Flysch Trough units around the Gibraltar Arc, show a turbiditic character. They are constituted by clayeys and sandy formations, of detritic (siliciclastic) and/or carbonated (calciturbiditic) character, deposited by gravitational flow in a deep marine basin [*Guerrera et al.*, 1993; *Esteras et al.*, 1995; *Stromberg and Bluck*, 1998]. Because the Upper Cretaceous to Paleogene sequence of Flysch units show remarkable similarities, the main difference between the units concern the provenance of the detritus which filled the Trough during the lower Miocene: Meanwhile. the detritic elements of the Algeciras unit originated from the erosion of the metamorphic rocks of the Alboran Domain; those of the Aljibe unit derived from the African craton. Consequently, the Neogene sequence of the Aljibe unit, is composed of a characteristic quartzite formation with minor marly levels, meanwhile turbiditic graywackes represent the Miocene rocks of the Algeciras unit. The lower Miocene turbidites of Bolonia unit (Tala Lakraa in Morocco) show an intermediate character, with both detritic provenance [*Didon and Hoyez*, 1978].

[17] Concerning the Cretaceous formations of both Aljibe and Algeciras units, it must be stressed that they appear as discontinuous slices beneath a continuous sequence of Paleogene to Miocene formations. In consequence they have been considered as tectonic units [e.g., *Didon*, 1969; *Martín Algarra*, 1987] (Figure 2).

[18] The lithostratigraphy of Aljibe unit, together to that of Facinas unit, its complementary detached Cretaceous formation, will be described briefly. Four sedimentary formations constitute both units (Figure 3):

[19] 1. The Facinas formation, Cretaceous in age, is formed mainly by clayey and marly materials. Scarce intercalations of limestones and very fine grained sandstones can appear. The detachment which bound this unit and the Aljibe unit can be located either at the top of this formation, or within it.

[20] 2. The "Serie de base" formation [*Esteras et al.*, 1995], Paleocene to Oligocene in age, is constituted by reddish-greenish clays, with fossils as Tubotomaculum. Some intercalations of calciturbidites are present. Locally, it is possible to differentiate the Benaiza formation [*Blumenthal*, 1936], Oligocene in age, in which the calciturbidites prevail.

[21] 3. The Aljibe formation [*Gavala*, 1924] is the thickest (up to 1500 m) and the most characteristic formation of the Aljibe unit. It has been dated as Aquitanian [e.g., *Esteras et al.*, 1995] and is composed by quartzites, whose detritic elements originated from the erosion of the African craton [e.g., *Guerrera et al.*, 1990]. Scarce intercalations of claystones appear between quartzites.

[22] 4. The Supranumidian formation, defined by *Esteras et al.* [1995], has been dated by these authors as lower Burdigalian. It is constituted by marls, clays and quartzitic micaceous sandstones.

[23] It must be stressed that sedimentary structures in the Aljibe unit formations, such as laminations (convolute, cross-stratified and trough cross), flute and groove casts, ripples and load structures permit to have a good control over the strata polarity.

5. Structural Style of the Aljibe Unit

[24] The simplified structural map of the Aljibe unit (Figure 2) shows three structural domains, hereafter referred as eastern, western and southern domains. Each of these domain has distinctive geometric and kinematic features, although all the three are characterized by an imbricate thrust structure, rooted at the lower part of the Serie de base formation or, occasionally, atop of the Facinas formation (see Figure 3). Both the eastern and western domains show approximately NNE-SSW striking thrusts systems. In the eastern domain, thrusts and folds systematically verge toward the west, whereas they verge toward the east in the western domain (Figure 4). The accommodation zone between the eastern and western domains, the so-called Arnao accommodation zone (AAZ), roughly coincides with the alignment of tectonic windows composed by Subbetic marly limestones (Late Cretaceous to Paleogene in age). Toward the south, the structural trend of both domains is curved, and the thrust systems abruptly terminate against a second main accommodation zone, the Dehesa de Fatigas accommodation zone (DFAZ).This latter bounds the southern domain (Figures 2 and 5), which is characterized by imbricated thrust slices that show a westward to southwestward tectonic transport.

[25] The youngest rocks affected by these structures are lower Burdigalian marls and brown clays (Figure 3). No penetrative structures have been found in the thrusted and folded rocks of the Aljibe unit. This indicates that rocks within the Aljibe thrust imbricate underwent a negligible amount of internal strain.

5.1. Eastern Domain

[26] In the eastern domain, the Aljibe unit is composed by an imbricate thrust system (Figures 2, 4, and 5). The slices show a large lateral continuity (up to 35km long) and their width varies between 1 and 2 km. Cutoff, branch and tip lines of the thrusts are N-S to NNE-SSW directed. The cutoff points between the stratification of the sandstones and the thrusts show that the fault ramps ascend toward the west to NW, as illustrated by the eastern part of the geological maps of Figures 4 and 5 According to these crosscut relationships, the transport direction swings slightly from a northwestward to a westward direction, from north to south, respectively. The substrate of this thrust fan is represented by the upper Cretaceous to Paleogene marls or marly limestones (Penibetic "red beds") which crop out below this domain.

[27] The cross sections drawn in the eastern domain illustrate the described geometry (Figure 4, section A and eastern part of section B, and Figure 5, eastern part of section E and section F). Estimations of shortening along these cross sections are comprised between 0.54 and 0.43. These estimations have been calculated through line balancing, by using the boundary between the Serie de base and the Aljibe formations. Similar results have been obtained along successive cross sections in this domain [*Luján*, 2003].

[28] The internal structure of the slices is tabular or draws hectometric to kilometric scale, west to NW vergent folds. Some folds are fault propagation folds whereas others developed as accommodation folds over footwall ramps (e.g., eastern part of cross section A of Figure 4). The axial traces of both types of folds are drawn in the map of Figure 4. A decametric-scale propagation fold can be observed in Figure 6. It affects sandstones and marls belonging to Aljibe formation and is associated with a ramp ascending toward the west.

[29] Near of the boundary with the southern domain, a few kilometers south of Castillo de Castellar (eastern border of Figure 5), it can be observed how the thrust slices are folded, verticalized and even overturned (see the eastern part of cross section F of Figure 5). The west vergent thrust system is folded and actually appears dipping toward the west, although the cause and significance of this late inversion is unknown.

[30] In the less competent Serie de base formations, as the Benaiza formation (Figure 3), metric-scale west vergent folds can be observed. In the same formations, E-W stretching associated with boudinage in the levels situated at the vicinity of the thrusts has also been observed. This indicates layer parallel stretching.

[31] Evidences of slip parallel to the bedding within Aljibe sandstones are frequent. Distribution of striae and grooves marks define a N60°W directed great circle subperpendicular to the structural trend (see stereographic plot of Figure 4). This is coherent with a flexural slip folding mechanism.

5.2. Western Domain

[32] The western domain is characterized by eastward verging, irregularly spaced thrusts, moderate lateral continuity (5–14 km) of map structures and extensive upright folding within the imbricate slices (see maps and corresponding cross sections of Figures 4 and 5). In this domain, the substrate of the Aljibe thrust imbricate is composed by Triassic evaporites, which appear as a tectonic

Figure 4. Geological and structural map of the northern part of the Aljibe unit (modified from *García de Domingo et al.* [1991] and *del Olmo Sanz et al.* [1987]) and corresponding cross sections. Localization in Figure 2. Stereoplot of structures associated with flexural-slip folding: kinematic indicators (black circles) and fold axis (crosses). Stereoplot a, Eastern domain, and stereoplot b, western domain.

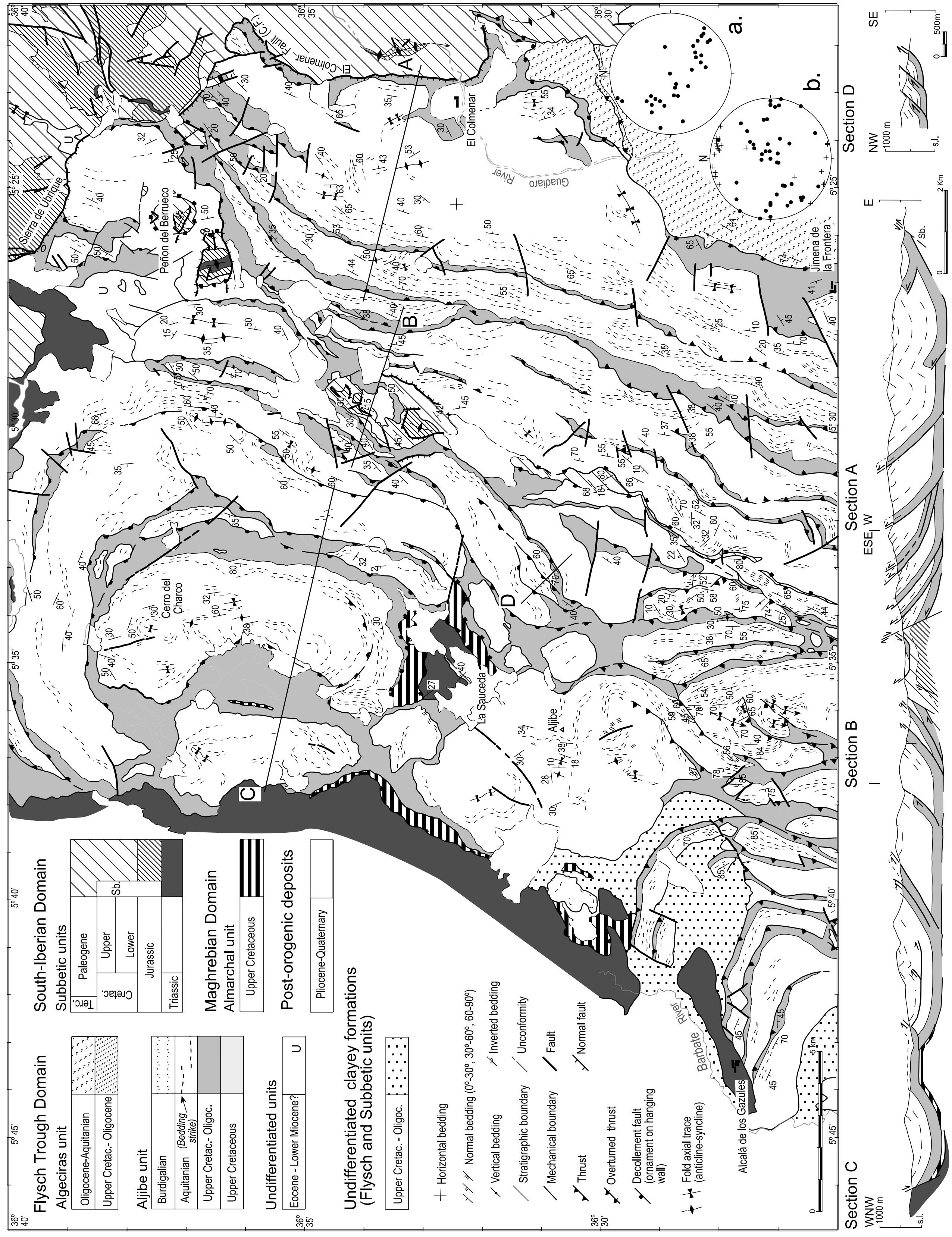
Flysch Trough Domain
Algeciras unit
Oligocene-Aquitanian
Upper Cretac.- Oligocene
Aljibe unit
Burdigalian
Aquitanian (Bedding strike)
Upper Cretac.- Oligoc.
Upper Cretaceous
Undifferentiated units
Eocene - Lower Miocene?
U
Undifferentiated clayey formations (Flysch and Subbetic units)
Upper Cretac. - Oligoc.
South-Iberian Domain
Subbetic units
Terc.
Paleogene
Cretac.
Upper
Lower
Sb.
Jurassic
Triassic
Maghrebian Domain
Almarchal unit
Upper Cretaceous
Post-orogenic deposits
Pliocene-Quaternary
Horizontal bedding
Normal bedding (0º-30º, 30º-60º, 60-90º)
Inverted bedding
Vertical bedding
Unconformity
Stratigraphic boundary
Fault
Mechanical boundary
Normal fault
Thrust
Overturned thrust
Decollement fault (ornament on hanging wall)
Fold axial trace (anticline-syncline)
Sierra de Ubrique
Peñon del Berrueco
El Colmenar
El Colmenar Fault (C.F.)
Guadiaro River
Jimena de la Frontera
Cerro del Charco
La Sauceda
Aljibe
Barbate River
Alcalá de los Gazules
A
B
C
D
a.
b.
N
Section A
Section B
Section C
Section D
WNW
ESE
W
E
NW
SE
1000 m
s.l.
500m
2 Km
5 Km
36º 40'
36º 35'
36º 30'
5º 45'
5º 40'
5º 35'
5º 30'
5º 25'

Figure 4

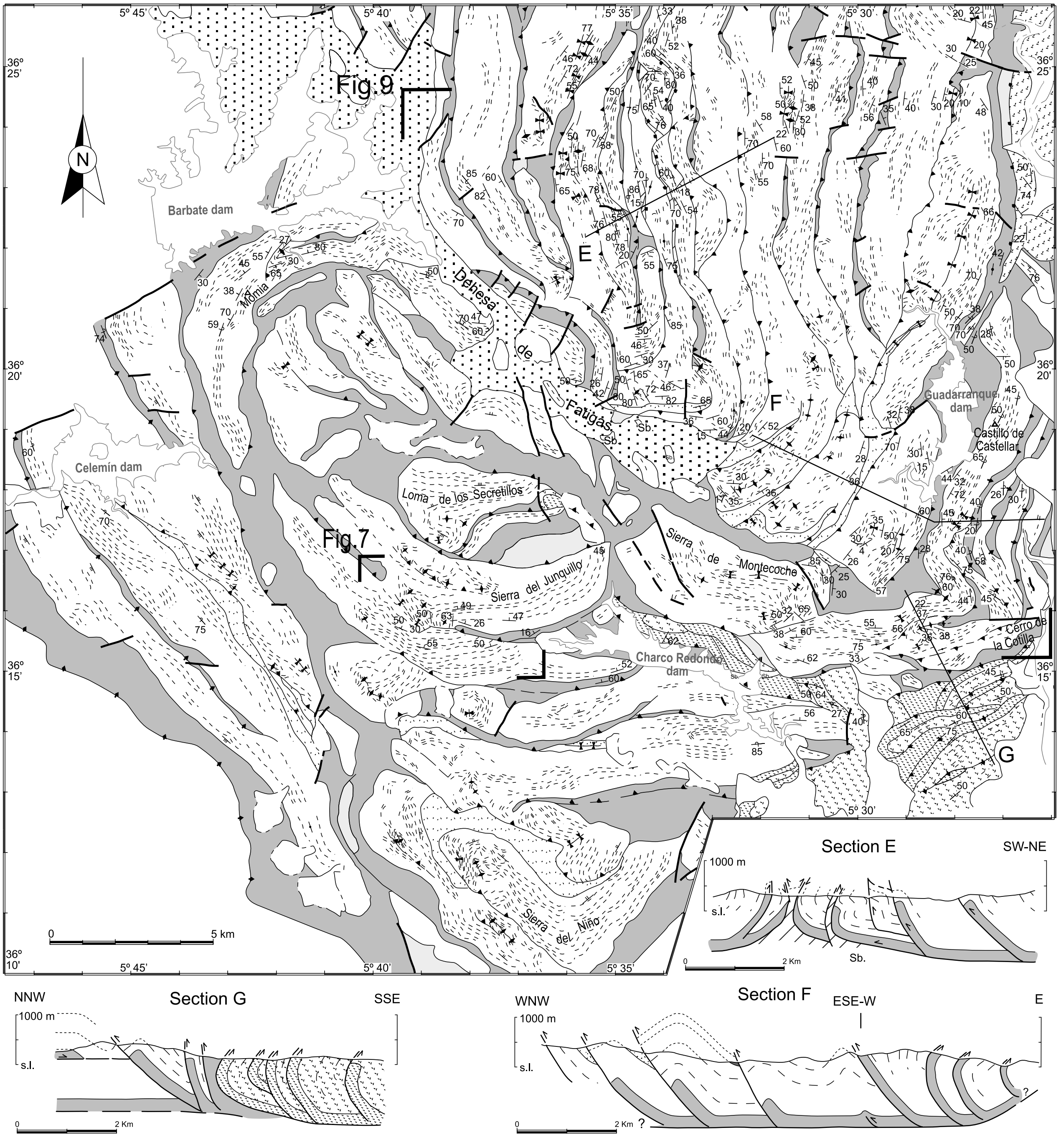

Figure 5. Geological and structural map of the Aljibe unit (modified from *Hernaiz Huerta et al.* [1991a, 1991b]) and corresponding cross sections. Localization in Figure 2. Same legend as Figure 4.

window (around La Sauceda, Figure 4). A second-order narrow transpression zone (STZ of Figure 2) running N50°E disrupts the continuity of the thrust imbricates (southwestern part of the map shown in Figure 4). North of this transpression zone a group of slices, which show fault ramp ascending toward the east, draw a basin-type interference pattern (around El Charco area), with opposite immersion of the structures from north to south. Blind lateral ramps could be responsible for this geometry, although late folding cannot be ruled out. In the southern flank of this interference a small duplex with a northeastward transport direction can be observed (cross section D of Figure 4). South of the second-order transpressional zone, the slices are N-S striking, 5 to 12 km long, and show fault ramps ascending toward the east.

[33] The western part of the composite cross section of Figure 4 shows the characteristic geometry of a thrust imbricate. Thrust distribution is irregular and large-scale

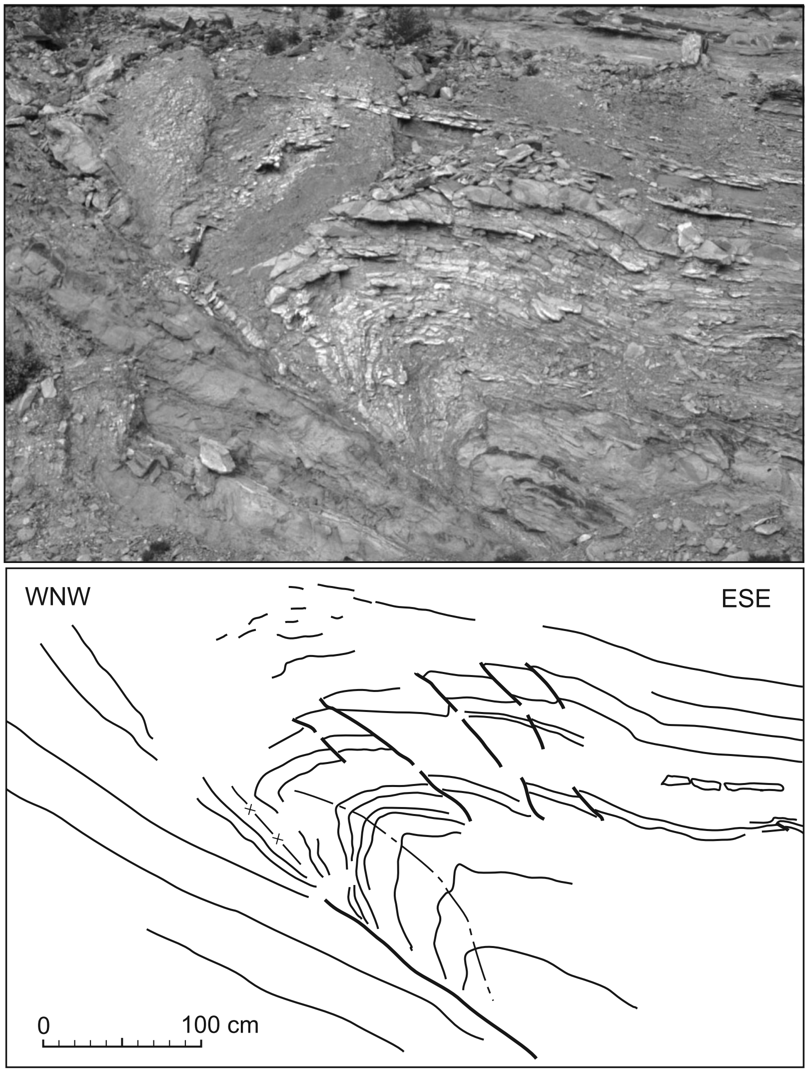

Figure 6. Photograph and interpretative sketch of a decametric-scale propagation fold belonging to the eastern domain (see Figure 2). This fold is drawn by sandstones and marls belonging to Aljibe formation.

décollement folds are observed. These latter are identified within the Aljibe formation sandstones, meanwhile some decametric-scale, east vergent décollement folds also affect the marly and clayey rocks of Benaiza formation. The stereoplot b of Figure 4 shows an approximately N-S directed maximum for the axes of décollement folds observed in both sedimentary formations (crosses). The kinematic indicators associated with folding (e.g., calcite or quartz slickenfibers, S-C fabric) are coherent with a flexural slip folding mechanism, although the indicators are dispersed around a mean E-W direction (solid circles). Scarce kinematic indicators show a tectonic transport toward the east, that is, roughly subperpendicular to the fold axes.

5.3. Southern Domain

[34] At a first glance, the southern domain seems to be more chaotic than the other ones, but a careful mapping shows that its structure corresponds to an approximately westward verging thrust stack, although out-of-sequence thrust and late folding can be evidenced (Figure 5).

[35] In the central part of this domain (from the Loma de los Secretillos to the Sierra del Niño), an immersion of the whole structure of about 40° toward the north-northeast is observed. Consequently, the erosion of the strata permits to observe an oblique profile of the central group of slices, which makes possible a direct observation of their main geometric features. In particular, westward ramps and west verging hectometric-to kilometric-scale fault propagation folds (almost cylindrical) can be recognized. A spectacular example of such structure appears on the aerial view of a small area, west of Sierra Junquillo, with its corresponding structural map (Figures 5 and 7).

[36] The profile of the central part of this domain has been restored by using the "grid method" (Figure 8) [*Roberts*, 1982; *Ragan*, 1985]. Moreover, a smooth folding,

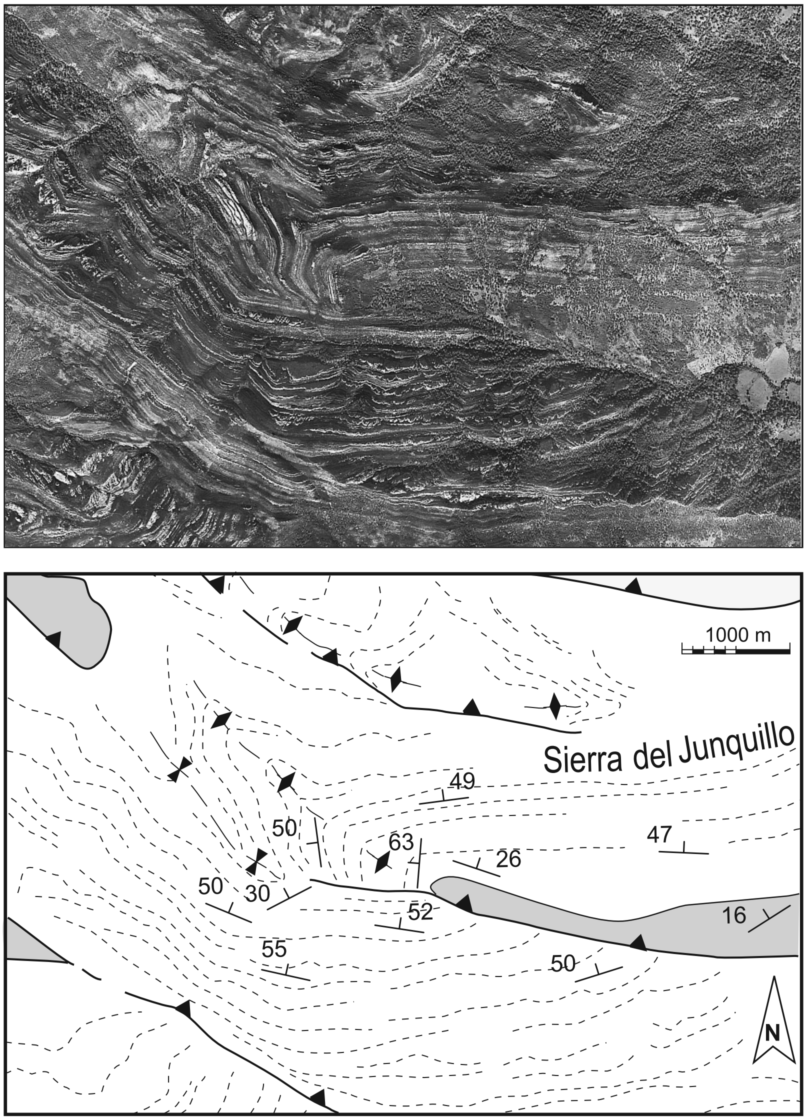

Figure 7. Aerial view of a fault propagation fold belonging to the southern domain of the Aljibe unit, and structural map of the same area. The hinge line of this fold shows a moderate immersion toward the NNW. Localization in Figure 5.

evidenced in the Sierra del Niño slice, has been removed. The structure consists of an imbricate thrust stack, with associated fault bend and fault propagation folds. Out-of-sequence thrusts are present in the upper part of the thrust stack, and bound the Algeciras unit, which appears sandwiched between two slices of Aljibe unit. By restoring this cross section and using the boundary between the Serie de base and the Aljibe formations, a minimum shortening of 0.7 has been estimated for the in-sequence thrust stacking. Finally, the presence of upper Aquitanian to Burdigalian formation only in the lowermost slice can argue for a piggyback sequence of thrusting.

[37] The western part of this domain is characterized by steeply dipping structures. Both the thrust plane and the bedding within the slices are subvertical or even overturned. In particular, the three slices of the southwestern corner of the map of Figure 5 are NW-SE oriented and show overturned basal thrust with a southwestward transport direction, when restored to a subhorizontal position.

[38] Finally, in the Momia Sierra, near of Barbate dam, the Aljibe quartzite formation draws a closed arcuate structure, with a propagation fold in its eastern part, plunging a few degrees toward the west (Figure 5). Four slices are present within this arc, and it can be described as a bend thrust imbricate.

5.4. Accommodation Zones

5.4.1. Arnao Accommodation Zone (AAZ)

[39] The western and eastern domains are juxtaposed along the Arnao accommodation zone (AAZ), without important

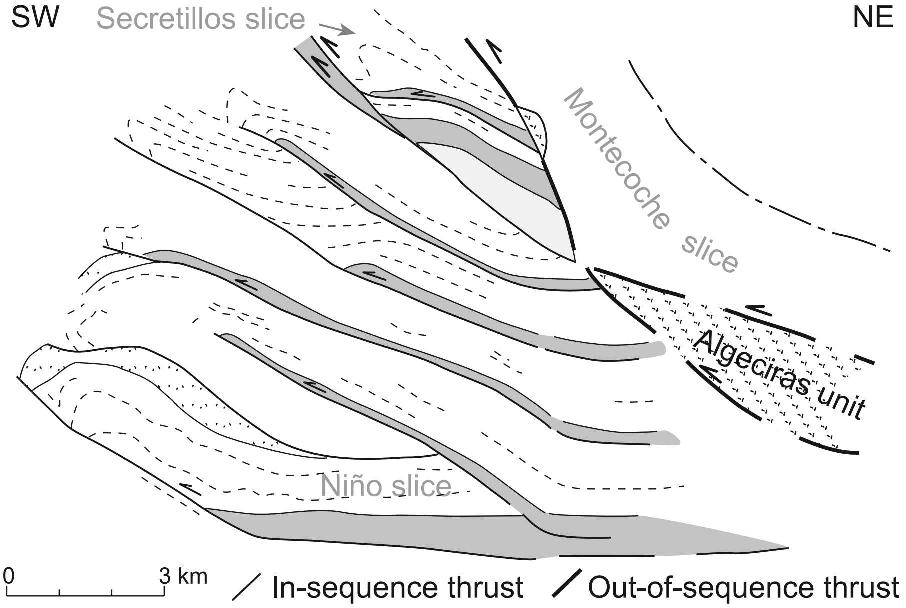

Figure 8. Restored section, by using the "grid method" of the central part of the southern domain of the Aljibe unit, from Loma del Secretillo to Sierra del Niño slice. Same legend as Figure 4.

overlapping (Figures 4 and 5). This accommodation zone is broadly NNE-SSW trending, and shows a slightly arcuated geometry in map view, convex toward the west (Figure 2). It coincides with an alignment of tectonic windows of Subbetic units. In the northern part of the accommodation zone, the Subbetic rocks draw an antiform (see central part of the composite cross section of Figure 4). Southward, this antiform is relayed by one or two narrow bands of upper Cretaceous to Paleogene marls (Penibetic red beds), bounded by two opposite reverse faults, defining a pop-up structure (Figure 5, section E) These latter facilitate the extrusion of the marly rocks, and overturned the Aljibe unit slices in the vicinity of the accommodation zone (see cross section E of Figure 5). Accordingly, this part of the AAZ is a triangle zone, as defined by *Price* [1986].

5.4.2. Dehesa de Fatigas Accommodation Zone (DFAZ)

[40] In the maps of Figures 2 and 5, it can be observed how the Arnao accommodation zone come to the end against the Dehesa de Fatigas accommodation zone, although none of them displaced the other. Accordingly, both structures probably developed simultaneously. From NW to SE, both the character of the DFAZ and the geometry of the adjacent structures north of this accommodation zone vary. The northwestern section of the DFAZ is constituted by a broad fault zone developed on clayey materials whose attribution to Subbetic or Flysch Trough domain is uncertain. It includes hectometric-scale fragments of various lithologies (mainly Aljibe formation quartzite and Subbetic limestones) and none coherent kinematic criteria have been detected in the clayey material. In the western domain adjacent to this segment of the DFAZ, an inflexion of the thrusts trend can be observed, from N-S to NW-SE, meanwhile in the eastern domain, this inflexion took place in an opposite sense, that is, from N-S to NE-SW (Figures 5 and 9a). The inflexion of the structures trend in the eastern domain continues in the next segment of the DFAZ, where this latter is narrower and consists of a fault zone within the Paleogene claystones and intercalations of calcareous limestones belonging to the Aljibe unit (Serie de base formation). Finally, in the easternmost part of the DFAZ, the thrusts slices of the eastern domain are continuous through the accommodation zone: They curve from a N-S to an E-W direction and can be continued until the Sierra de Montecoche slice of the southern domain (Figure 5). This segment of the DFAZ shows a complex geometry of overturned slices, belonging either to the Aljibe unit (cross section F of Figure 5), or to Algeciras unit (cross section G, of Figure 5).

5.5. Late Deformations

[41] The general architecture of imbricate thrust fan, characteristic of all the structural domains of the Aljibe unit, can locally be affected by late deformations. These are successively (1) extensional faulting and (3) very open upright folding.

[42] The most spectacular extensional structure is a low- to medium-angle normal faults which cut the Aljibe unit thrust imbricate, the El Colmenar fault, which bounds the Aljibe unit with the Subbetic unit (NE of Figure 2) and shows a tectonic transport toward the west or SW [*Luján et al.*, 2000]. In turn, this fault and all the previous structures are folded by very open upright folds, with N-S to NE-SW trending hinge lines axes, which developed locally. For example, because of this late folding, the El Colmenar fault shows a sinuous geometry, as the fault plane is N-S to E-W directed, and is dipping toward the west or the south, respectively (Figures 2 and 4).

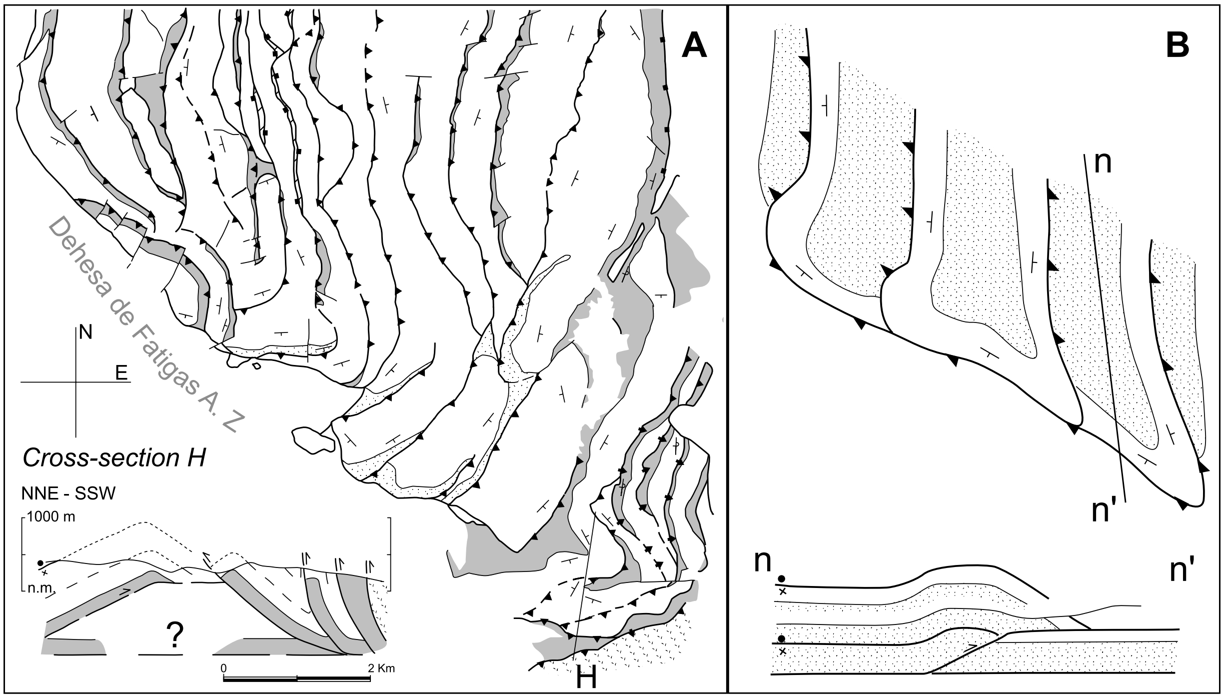

Figure 9. (a) Simplified structural map of the Dehesa de Fatigas Accommodation Zone and its geometrical relationships with the structural trend observed in the Aljibe unit imbricate thrust fan. Cross section showing a blind ramp dipping toward the north (localization in Figure 5). (b) Comparison with a similar idealized situation and corresponding cross section inspired from the sketch of *Boyer and Elliot* [1982].

[43] In a similar way, the tectonic window of Subbetic materials surrounded by Algeciras unit rocks, 10 km of Estepona along the coast, draws an antiform associated with this folding episode (Figure 2).

6. Aljibe Unit Structure: Key Observations for a "Push-From-Behind" Emplacement Model

[44] The structural characteristics of the Aljibe unit evidenced in this paper, together with some key data published previously, are summarized below:

[45] 1. The Aljibe unit shows a rather organized architecture of thrust imbricates, post-lower Burdigalian in age, characteristic of a thin-skinned type deformation. Its sole detachment is localized at the bottom of the Serie de base formation. Most of the folds recognized within individual imbricate slice are propagation folds.

[46] 2. The tectonic transport directions associated with the main shortening swing slightly from north to south of the studied area. They are ESE-WNW to NE-SW directed, respectively. Shortening produced structural domains separated by accommodation zones. In the eastern domain, the vergence is toward the west, meanwhile it is east directed in the western domain [see also *García de Domingo et al.*, 1994]. The southern domain also shows an approximately westward verging thrust stack, although dipping toward the north as a whole.

[47] 3. The superposition of structures shows that the Aljibe thrust imbricate has been cut by a low- to medium-angle normal fault [*Luján et al.*, 2000]. Finally, very open folds formed, mainly during the Tortonian-Messinian boundary in the Ronda basin, 30 km NE of the studied area, although the compression followed until the Pliocene [*Balanyá et al.*, 1995; *Rodríguez-Fernández et al.*, 1999; *Crespo-Blanc and Campos*, 2001]. This permits to constrain the age interval of the main shortening between the late Burdigalian and the late Tortonian.

6.1. Significance of the Accommodation Zones That Bound the Aljibe Unit Structural Domains

[48] The change of vergence from the western to the eastern domains through the Arnao accommodation zone (AAZ) may be related to the contrasting rheological properties of the substrate, constituted by brittle Subbetic marls and marly limestones (upper Cretaceous to Paleogene red beds) in the eastern domain and Triassic ductile evaporites in the western domain (Figure 4) [*Luján et al.*, 2003]. The boundary between frictional and viscous substrate is inferred to be located in the central part of the Aljibe thrust imbricate, immediately west of the alignment of tectonic windows. In the area of the structural map of Figure 4, the kinematic indicators show a west-northwestward transport direction in the eastern thrust imbricate, which is at a high angle (>75°) with respect to the main N30°E trending accommodation zone. *Luján et al.* [2003] suggested that

the shortening direction and the boundary between the marly limestones and the Triassic evaporites initially formed an angle of approximately 30°. Moreover, by similarity with their analogue experiments, the second-order transpressive zone observed in the western domain might be included in the variability range of structural trends developed above a viscous substrate in models where transport direction is oblique to the substrate boundary.

[49] In turn, the geometry observed along the accommodation zone of the Dehesa de Fatigas (DFAZ) suggests that this latter could be due to a blind ramp, WNW-ESE to NW-SE striking and dipping toward the north. It would have developed during the Aljibe unit thrusting, as it ends abruptly toward the east. Over this ramp the structures of both northernmost domain, verging either toward the foreland or toward the hinterland, would have accommodated with opposite sense flexure, as shown in Figure 9. Figure 9 compares the observed situation and its interpretation in depth (cross section H) with a sketch inspired form on figures of *Boyer and Elliot* [1982], who described a similar situation. Accordingly, this interpretation of the DFAZ is not coherent with that of *Moreno Serrano et al.* [1988], who invoked a dextral strike-slip fault ("La Cotilla" fault). These considerations lead us to define this accommodation zone as a compartment fault, as defined by *Brown* [1975], since this fault zone separates domains in which a similar shortening is solved with different structural style.

6.2. Organized Architecture Versus Chaotic Geometry

[50] The Aljibe unit organization described in this paper strongly differs from the chaotic geometry and the gravitational mode of emplacement proposed by previous authors [*Didon*, 1969; *Bourgois*, 1978]. It is also incompatible with the model proposed by *Moreno Serrano et al.* [1988] based on a very complex succession of compressional, extensional and gravitational events accompanied by blind strike-slip faulting. By contrast, the structural architecture of the Aljibe unit is coherent with a push-from-behind emplacement mechanism as proposed in other orogenic regions where detached covers show similar characteristics (e.g., see discussion by *Julivert and Arboleya* [1986]). In this scenario, the relatively rigid backstop is constituted by the metamorphic rocks of the Alboran Domain (Figures 1 and 2). Shortening transmitter from the backstop produced the detachment of detritic sedimentary series over a substrate with varying rheological properties [*Luján et al.*, 2003]. Indeed, the thrust imbricate system is regularly distributed within the Aljibe unit, and is not restricted to its frontal part (western domain), as it would in a gravitational process. When observed, normal faults systematically cut the thrust fan and show a dominant southwestward transport direction, that is oblique to the shortening direction [*Luján et al.*, 2000; *Luján*, 2003]. In the case of a gravitational mechanism of emplacement, we would have observed (1) thrusts in front of the Aljibe unit and (2) normal faults with a similar transport direction in its rear part [*Philip and Ritz*, 1999]. Moreover, a gravitational emplacement of the Flysch units implies that the basement of these detritic units, in order to be able to glide toward the west, would have been situated east of their present position and geometrically, in a higher position. In that case, the only possible solution would be that the Flysch units would have detached from the Alboran domain rocks. This is totally incoherent with the fact that the Flysch rocks proceed from a deep trough (see below, epigraph 7). The push-from-behind emplacement mechanism can explain most of the structural features of the Aljibe unit organization, also providing a plausible explanation for the emplacement of the Flysch Trough units as a whole. Notwithstanding, some observed geometries are still difficult to understand, as for example, the verticalization, and even overturning, of the thrust slices either in Castillo de Castellar area or in the southwestern part of the southern domain (Figure 5). Such geometry could be related with drag folds associated with eroded out-of-sequence thrust, or could be due to complex movements with associated tilting along lateral ramps. It also could represent the inverted frontal or rear part of an antiformal stack developed in the adjacent unit (Algeciras or Almarchal units).

[51] The significance of the arcuate structure of the Momia Sierra, which shows a bent thrust imbricate (see paragraph 4.3.), is also unclear at the moment. Although this particular structure of the southern domain could be due to the lateral movement along the Dehesa de Fatigas accommodation zone (see paragraph 5.4.), it must be stressed that it is not an isolated structure. Indeed, east of the studied area, not only in the Aljibe rock units but also in the Subbetic Domain, fold and thrust structures, associated with the main shortening, show arcuate geometry. This is the case of the spectacular 30 km long croissant-like structure, draw by an anticline of the Median Subbetic rock sequence (Figure 2). Triassic evaporites are surrounding these structure, and huge thicknesses of such materials have been drilled not very far (up to 2500 m of evaporites according to *Instituto Geológico Minero de España* [1987], 30 km northeast of the studied area). The ductile rheology of this type of substrate favors the formation of complex structures [*Cotton and Koyi*, 2000; *Costa and Vendeville*, 2002], but the detailed kinematics of the described arcuate structures is still unknown.

7. Tectonic Evolution of the Flysch Trough Units Within the Gibraltar Arc Orogenic Wedge

7.1. Present-Day Pattern of Transport Direction in the Northern Branch of the Gibraltar Arc

[52] The structural data presented in this paper, concerning the architecture of the Aljibe unit, the Flysch Trough main unit in the Betics, fill an important gap within the history of the tectonic evolution of the Gibraltar Arc system.

[53] The thin-skinned geometry of the Aljibe unit, revealed by a careful mapping, permits to establish the present-day pattern of the structural relationships and the transport direction in the northern branch of the Gibraltar Arc area. Together with the data of *Crespo-Blanc and Campos*

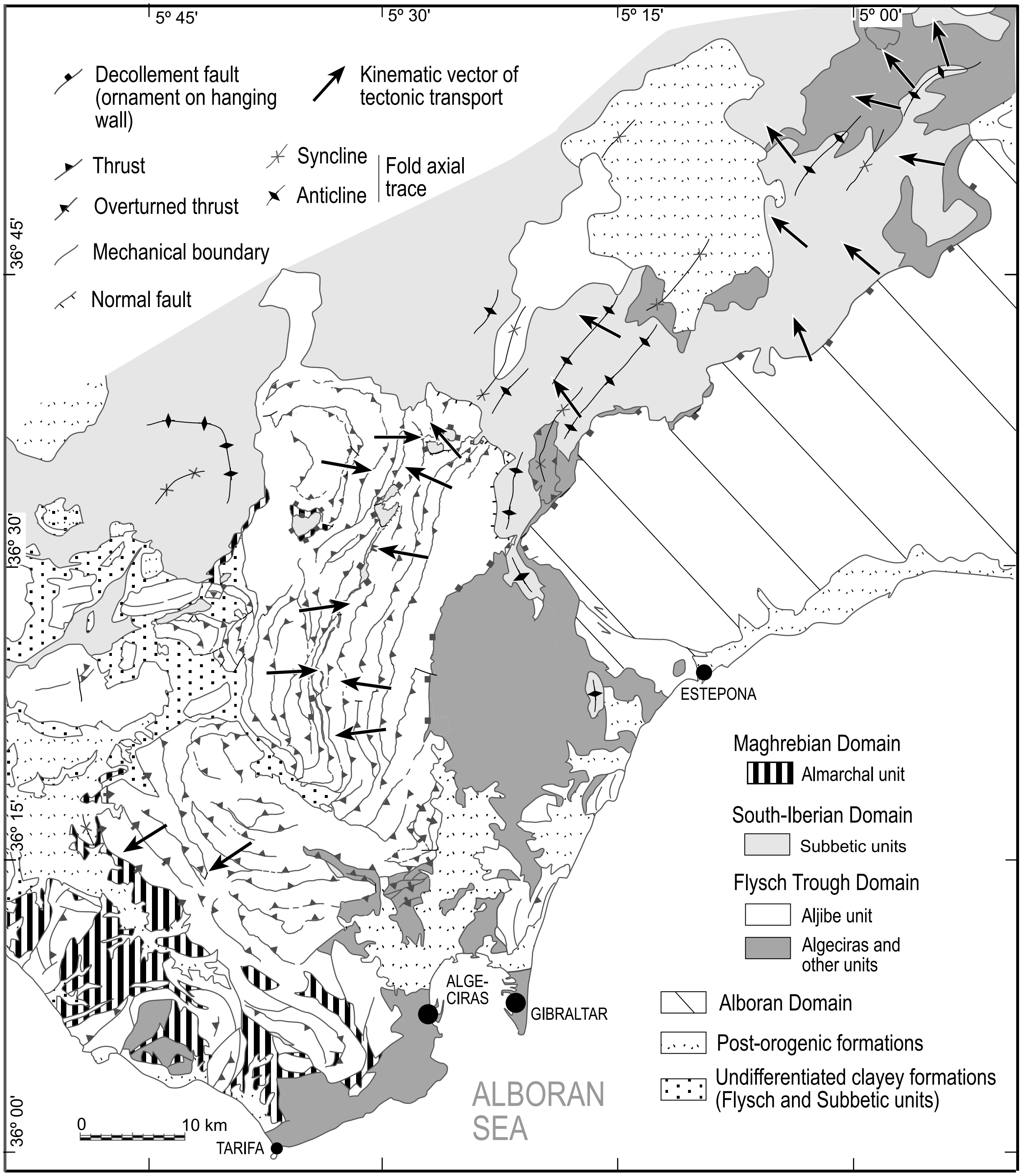

Figure 10. Present-day pattern of tectonic transport kinematic indicators around the northern branch of the Gibraltar Arc, according to the data presented in this paper for the Flysch Complex and those of *Crespo-Blanc and Campos* [2001] for the Subbetic units.

[2001] in the Subbetic units, a map of the kinematics indicators associated with the lower to middle Miocene main shortening event has been drawn (Figure 10). The pattern of the tectonic transport direction swings around the Arc, mainly from a northwestward direction to a southwestward one, although local variations are present. This image differs substantially from that of *Kirker and Platt* [1998], who assert that transport directions throughout the Gibraltar Arc are consistently WNW directed, regardless of the structural trend, or from that of *Platt et al.* [2003, paragraph 61], who claim that "slip vectors. . .have a remarkably consistent WNW trend from Granada. . .to Gibraltar." Moreover, their so-called "Ronda cross section," located a few kilometers NE of cross section of Figure 2, is incoherent with the geological mapping presented in our paper. Indeed, *Platt et al.* [2003] positioned the Flysch Trough units sandwiched in between South Iberian paleomargin-derived units [see *Platt et al.*, 2003, Figure 11].

[54] The fan pattern of kinematics indicators, together with the geometry of the detailed cross sections presented in this paper, in turn based on reliable structural maps, represents an important constraint for any paleotectonic reconstruction model of the Gibraltar Arc fold-and-thrust belt. As a matter of fact, our data are included in a companion paper which discusses the mode of formation of the western Gibraltar Arc at large scale. It shows how strain partitioning is distributed along the entire western Gibraltar Arc, resulting in arc-parallel stretching and arc-normal shortening (J. C. Balanyá et al., Structural trend line pattern and strain partitioning in the Gibraltar Arc accretionary wedge: Insights on the mode of orogenic arc building, submitted to *Tectonics*, 2005).

[55] The next step should be to analyze the structural cross sections and the kinematic data in the light of the paleomagnetically determined vertical axis rotations in the area [e.g., *Villalaín et al.*, 1994, 1996; *Platt et al.*, 1995; *Kirker and McClelland*, 1996]. Careful restoration, supported by the detailed work presented in this paper, of large-scale balanced cross section, as those proposed in TRANSMED project [*Frizon de Lamotte et al.*, 2004], should be made in order to make quantitative paleotectonic reconstructions.

7.2. Flysch Trough Units Architecture in Both Branches of the Gibraltar Arc and Geodynamic Models

[56] The structure of imbricate thrust fan of the Aljibe unit, developed during the lower to middle Miocene, is coherent with the paleotectonic evolution proposed in previous papers, in which the Flysch Trough units derived from a deep basin located between the Alboran Domain and the Mahgrebian margin, which connected the Ligurian Ocean and the Central Atlantic. [e.g., *Crespo-Blanc and Campos*, 2001; *Michard et al.*, 2002; *Faccenna et al.*, 2004; *Frizon de Lamotte et al.*, 2004]. The models proposed in these papers include the incorporation of both the Flysch Trough units and the South Iberian and Maghrebian paleomargin-derived units to the Betic-Rif orogenic wedge during the Miocene. This incorporation would have been coeval with the westward rollback and retreating of the lithosphere involved in the western Mediterranean Subduction Zone, which in turn provoked a drastic thinning in the back-arc area, mostly with a westward transport direction. Such scenario also fits with any asymmetrical lithospheric model, in particular those which evoke a westward delamination [*García-Dueñas et al.*, 1992; *Comas et al.*, 1999]. Within this frame, our results minimize the importance of northward translations advocated by some authors [e.g., *Bourgois*, 1978].

[57] Since the Flysch Trough units derive from a deep water infill located on a much attenuated lithospheric domain (Flysch Trough), they represent as a whole a particular case of accretionary prism nowadays emplaced onto their neighboring paleomargins. Additional questions arise when a comparison of the architecture of the Flysch Trough units north and south the Gibraltar Straits is made, in particular between the Aljibe and its southern equivalent, the Numidian unit (Figure 1) [*García-Dueñas et al.*, 1990]. Indeed, the most conspicuous differences are related with (1) the area distribution, as the Numidian Unit crop out over a much narrower area than the Aljibe Unit; (2) the lateral continuity, as the Numidian Unit shows a relative lack in continuity if compared with the Aljibe Unit; and (3) the structural style, as within the Numidian Unit, only a few thrust surfaces appear.

[58] The two first questions can be explained if it is assumed that the Moroccan branch of the Gibraltar Arc corresponds to a more deeply eroded thrust stack and/or that a depth change of the regional decollement level is present from one side to another of the Gibraltar Straits. The third difference is possibly related with the rheological properties of the substratum below the Flysch units, a key factor in controlling the structural style, including vergence, thrust spacing, and wedge surface slope [*Gutscher et al.*, 1996; *Cotton and Koyi*, 2000; *Luján et al.*, 2003]. The footwall of the fold-and-thrust Flysch Trough belt described in this paper, is constituted by units derived from two paleomargins with very different evolution [e.g., *Michard et al.*, 2002; *Crespo-Blanc and Frizon de Lamotte*, 2006]: The South Iberian paleomargin-derived units are mostly formed by carbonated rocks; meanwhile, the Maghrebian paleomargin-derived units are mostly composed of thick pelitic and marly sequences, that is, less frictional materials than those of the Spanish side.

[59] In the Betics, the paleomargin units are completely detached from their basement and are not imbricated within the Flysch units [e.g., *Balanyá and García Dueñas*, 1987]. It can be concluded that the external orogenic wedge formed by the Subbetic and Flysch Trough units fold-and-thrust belt, developed following multiple, gently dipping decoupling levels, strongly controlled by major paleogeographic boundaries. On the other hand, the absence of Flysch Trough basement situated over the South Iberian domain suggests that this basement was completely subducted.

[60] Once the Flysch Trough totally obliterated, the accretionary prism emplaced onto the South Iberian and Maghrebian paleomargins, and the complex geodynamic boundary conditions gave rise to a noncylindrical, arcuate orogenic wedge. At the moment, the available Oligocene to Present paleotectonic reconstructions of the westernmost Mediterranean region are merely qualitative [e.g., *Platt et al.*, 2003; *Faccenna et al.*, 2004, and references herein]. Since the Flysch Trough units have a special tectonic significance, as a suture marker between the Alboran Domain internal zones and the external zones deriving from two different paleomargins, the data presented in this paper provide important constraints to generate more refined reconstructions of the Betic-Rif orogenic building. Indeed, updated paleotectonic maps of the Gibraltar Arc including structural and kinematic data of the Flysch Trough units are

essential to test the reliability of any lithospheric models of the westernmost Mediterranean region, both the existing and the future ones.

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J. C. Balanyá, Departamento de Ciencias Ambientales, Universidad Pablo de Olavide, Cra. De Utrera km 1, E-41013 Seville, Spain. (jcbalrou@upo.es)

A. Crespo-Blanc, Instituto Andaluz de Ciencias de la Tierra, CSIC-Universidad de Granada, E-18071 Granada, Spain. (acrespo@ugr.es)

M. Luján, Departamento de Geodinámica de Granada, Campus Fuentenueva s/n, Universidad de Granada, E-18071 Granada, Spain. (mlujan@ugr.es)