Miocene deformation front propagation and strain partitioning within the fold-and-thrust belt of the Central Betics

Propagación del frente de la deformación y reparto de la deformación miocena dentro del cinturón de pliegues y cabalgamientos de las Béticas Centrales

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ABSTRACT

The External Zones of migrating orogenic arcs can be deformed as fold-and-thrust belts where the advance of the deformation front toward the foreland is contemporary to the arc-lengthening. The Sierra de Cabra, in the Central Betics, is made up of Subbetic units surrounded by synorogenic, Middle to Upper Miocene rocks. The combined data from surface and seismic profiles show the presence of partially coetaneous structures during the Middle Miocene: (i) a NNW-verging thrust system detached within Triassic evaporites accommodating arc-perpendicular shortening, (ii) N-S, NW-SE and NNE-SSW normal faults accommodating WSW-ENE stretching and (iii) WSW-ENE normal faults. These results allow us to interpret the Sierra de Cabra as the Langhian Betic fold-and-thrust belt front. Additionally, the WSW-ENE stretching contributes to the structural and topographic segmentation along-strike the Betics. The Miocene strain partitioning here proposed is similar to that found in the Western Betics.

Key-words: *Thrust system, arc-parallel stretching, relief segmentation, Middle Miocene.*

RESUMEN

Las Zonas Externas de arcos orogénicos que migran pueden deformarse como cinturones de pliegues y cabalgamientos donde el avance del frente de la deformación hacia el antepaís es contemporáneo al estiramiento del arco. La Sierra de Cabra, en las Béticas Centrales, está formada por unidadesSubbéticas rodeadas de rocas Mioceno Medio a Superior. La combinación de datos de superficie y de perfiles sísmicos muestra la presencia de estructuras parcialmente coetáneas durante el Mioceno Medio: (i) un sistema de cabalgamientos vergente hacia el NNW cuyo despegue se localiza en las evaporitas Triásicas acomodando acortamiento perpendicular al arco, (ii) fallas normales N-S, NW-SE y NNE-SSW acomodando estiramiento WSW-ENE y (iii) fallas WSW-ENE. Estos resultados permiten interpretar la Sierra de Cabra como frente del cinturón de pliegues y cabalgamientos durante el Languiense. Adicionalmente, el estiramiento WSW-ENE contribuye a la segmentación estructural y topográfica a lo largo de las Béticas. El reparto de la deformación Mioceno aquí propuesto es similar al que se observa en las Béticas Occidentales.

Palabras clave: *Sistema de cabalgamientos, estiramiento paralelo al arco, segmentación del relieve, Mioceno Medio.*

Geogaceta, 59 (2016), 23-26
ISSN (versión impresa): 0213-683X
ISSN (Internet): 2173-6545

Fecha de recepción: 30 de junio de 2015
Fecha de revisión: 20 de octubre de 2015
Fecha de aceptación: 27 de noviembre de 2015

Introducción

Within the external regions of orogenic arcs, fold-and-thrust belts (FTBs) typically form as a result of orogen-subperpendicular shortening (Poblet and Lisle, 2011). At the same time, while the deformation front migrates toward the foreland, syn-orogenic sedimentary sequences are added to the FTB (DeCelles and Giles, 1996), and the orogenic arc generally lengthens along-strike, through arc-parallel stretching (Marshak, 1988).

This is the case of the External Zones of the Betics, situated in the northern branch of the Gibraltar Arc, as shown by Balanyá *et al*. (2007), Azañón *et al*. (2012), Expósito *et al*. (2012) and Jiménez-Bonilla *et al*. (2015).

This work focuses on the FTB of the Central Betics, in which: a) the main shortening took place close to the Aquitanian-Burdigalian transition, although tightening of the pre-existing structures occurred during Middle and/or Late Miocene (Crespo-Blanc, 2007) and b) an WSW-ENE stretching took place during the Middle Miocene (Azañón *et al*., 2012; Rodríguez-Fernández *et al*., 2013).

We present new and complementary structural data and seismic interpretations from the Sierra de Cabra area (Fig. 1), in order to (1) characterize the geometry, kinematics and the age of deformational structures and (2) assess the importance of the arc-parallel stretching in the Central Betics by comparison with that of the Western Betics.

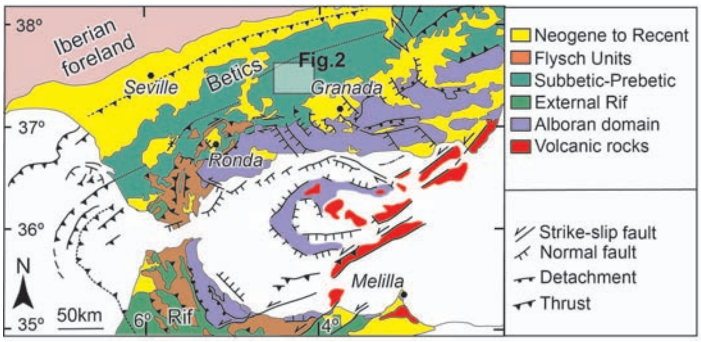

Fig. 1.- Tectonic map of the Gibraltar Arc.

Fig. 1.- Mapa tectónico del Arco de Gibraltar.

Tectonic setting

The Betics formed during the Miocene collision of a hinterland (Alboran Domain) and the South Iberian palaeomargin, initially separated by a deep Flysch Trough (Fig. 1). Both the palaeomargin and the Flysch Trough units formed the thin-skinned Betic FTB from Lower Miocene onwards (Crespo-Blanc, 2007; Expósito *et al.*, 2012).

Our work investigates the most external Subbetic outcrops of the FTB in the Central Betics (Sierra de Cabra area, Fig. 2). In this area, the Subbetic sequence is composed of Triassic Keuper facies, Jurassic dolostones and limestones and Cretaceous to early Miocene marly-limestones (Roldán *et al.*, 1988; Hernáiz *et al.*, 1992).

The Subbetic sequence is overlain by synorogenic sediments: (1) Aquitanian-Burdigalian marly-limestones and calcarenites, (2) Langhian to Serravallian marls wrapping around variably-sized palaeomargin blocks (the Olistostromic Unit), and (3) Tortonian to Messinian sandstones and marls (Roldán *et al.*, 2012)..

Structure and kinematics of the Sierra de Cabra area

The 3D geometry and kinematics of the Sª de Cabra structures have been studied by means of both surface data (geological cartography, 2 geological cross-sections and analyses of structural data; Figs. 2 and 3) and interpretation of one multichannel seismic reflection profile (Fig. 4).

Structures are grouped into those that produced (1) NW-SE to N-S directed shortening and (2) NE-SW to E-W directed stretching.

Shortening structures

The Sª de Cabra is internally structured in 3 or 4 Subbetic thrust sheets limited by roughly E-W striking thrusts and reverse faults (Fig. 2A). They merge at depth with a basal detachment located within the Triassic evaporites (Fig. 3A), and affect the Subbetic sequence as well as the Aquitanian to Burdigalian rocks, usually showing syn-sedimentary deformation. Langhian to Lower Tortonian sediments are thrusted by frontal thrust (Figs. 2A and 3A).

Thrust surfaces dip moderately SSE-ward, the steepest dips occurring in Jurassic limestones (see stereoplots B1 to B3 of Fig. 2). Cut-off lines in both footwall and hanging wall ramps trend around N070ºE (Fig. 2A). Some kilometric, NNW-vergent folds developed in the hanging walls (e.g. B3 thrust; Figs. 2A and 3A). The slickenlines typically show pitches > 45º both E-ward and W-ward (Fig. 2B), although smaller values are occasionally found (Fig. 2C). The slickenlines together with kinematic criteria always suggest a main reverse-slip component (Figs. 2B and C).

Stretching structures

Map-scale normal faults have been observed in the Sª de Cabra, affecting both the Subbetic sequence and the Langhian to Lower Tortonian sediments, the latter usually showing syn-sedimentary deformation (Figs. 2A and 4). These faults frequently cut and displace thrust traces and control both the W and the E current limits of the Sª de Cabra (Figs. 2A and 3B).

Most of these normal faults are roughly N-S striking (D1 and D2 in Figs. 2A and D). Nevertheless, NW-SE and NNE-SSW normal faults are also represented mostly outcropping in the W end of the Sª de Cabra (Figs. 2A and D3). These groups of normal faults display both planar and listric geometries and some rollovers structures can be observed in cross-section (Fig. 3B). The fault planes usually dip > 60º both to the W and to the E (D1 to D3 in Fig. 2D). The slickenline pitches are usually > 50º, which, together with kinematic criteria, indicate a dominant normal dip-slip component (stereoplots of Fig. 2D). Thus, the overall stretching direction accommodated by these faults is ca. E-W (X axis of the deformation ellipsoid around N064º/0).

A system of listric normal faults is interpreted W of Sª de Cabra in the seismic line of figure 4, sub-perpendicular to the normal faults. Both Langhian and Tortonian sediments show syn-sedimentary activity (Figs. 2A and 4). These normal faults converge onto a detachment at around 2 s Two Way Travel, TWT (Fig. 4). A reverse fault has also been drawn in the section, which we interpret as a result of the accommodation of a rollover structure (Fig. 4). The throw of the master fault zone is roughly estimated as 1-1.5 km utilizing a P-wave velocity of ca. 2000-3000 ms^{-1}. Based on both the cross-section of Fig. 3B and the seismic interpretation of Fig. 4, we estimated an overall extension within the Sª de Cabra of around 13%.

ENE-WSW faults (i.e. subparallel to shortening structures) have been identified toward the southern Sª de Cabra (Fig. 2A). Although sense criteria have not been observed on the NNW-dipping fault surfaces, their slickenlines pitches are > 45º and their dip-slip component must be normal, according to the ages of the involved rocks (Fig. 2E). The kinematic criteria in the SSE-dipping faults, which usually conserve a thrust geometry, show that they are normal faults (Fig. 2F). The latter are interpreted to have a listric geometry, merging at depth with a detachment within the Triassic (Fig. 3B). The estimated throw is up to 600 m (Fig. 3A).

Discussion

In the External Zones of the Central Betics, the Subbetics of the Sª de Cabra is deformed by a NNW-vergent thrust system detached within a viscous substrate, i.e. Triassic evaporites (Fig. 3A). This system would have belonged to the Aquitanian-Burdigalian Betic FTB front and nourished the Langhian, synorogenic foredeep (the Olistostromic Unit outcropping farther N; Roldán *et al.*, 2012), before the deformation progressed toward the foreland (to the NNW; Fig. 3A).

The geometries, the Miocene age and the throws of the normal faults suggest that they control the topographic relief drop E and W-ward of the Sª de Cabra. The along-strike structural segmentation,

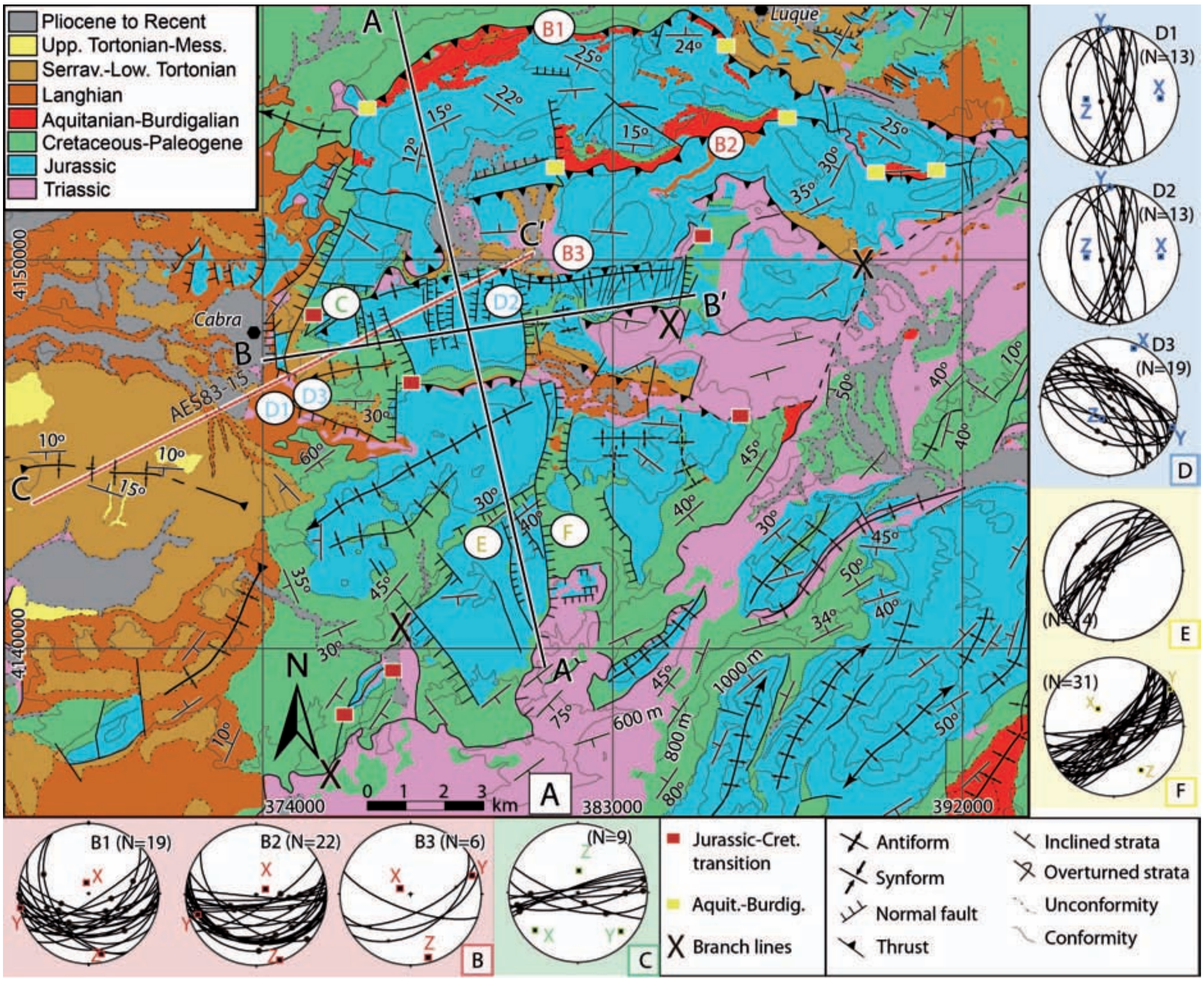

Fig. 2.- A) Structural map of the studied area including the recent rock formation dating from Roldán *et al.* (2012) and the locations of the cross-sections (A-A' and B-B') of figure 3 and the seismic line (C-C') of figure 4. Stereoplots: B) thrusts (B1, B2 and B3) within the Sierra de Cabra, C) sinistral strike-slip faults, D) N-S to NNE-SSW (D1 and D2) and NW-SE (D3) striking normal faults, E) faults NNW-dipping and F) SE-dipping ENE-WSW striking normal faults. In the stereoplots, the dots along the great circles indicate slickenline orientation; the XYZ denotes the axes of the deformation ellipsoid (Linked Bingham method).

Fig. 2.- A) Mapa estructural del área estudiada incluyendo las dataciones recientes procedentes de Roldán et al. *(2012) y la localización de los cortes (A-A' y B-B') de la figura 3 y la línea sísmica (C-C') de la figura 4. Stereoplots: B) cabalgamientos (B1, B2 y B3) dentro de la Sierra de Cabra, C) fallas de salto en dirección izquierda, D) fallas normales N-S a NNE-SSO (D1 y D2) y NW-SE (D3). E) Fallas buzantes hacia el NNW, y F) fallas normales orientadas ENE-WSW. En los stereoplots, los puntos a lo largo de los círculos mayores indican dirección de estrías, los XYZ denotan los ejes del elipsoide de deformación (método Linked Bingham).*

and the formation of intra-orogenic mini-basins currently preserve Middle to Upper Miocene deposits (Figs. 2A, D, 3B and 4). This interpretation is congruent with previous structural analyses (Azañón *et al.*, 2012).

ENE-WSW striking normal faults at the southern margin of the Sª de Cabra sometimes conserve its thrust geometry even though the kinematic criteria show a normal movement. We interpret these normal faults as local negative inversions of earlier S-dipping thrust surfaces (Figs. 2A, E, F and 3A). Taken together the roughly N-S and the WNW-ESE normal faults define a pattern similar to large-scale chocolate-tablet boudinage (Fig. 2A; Ghosh, 1988).

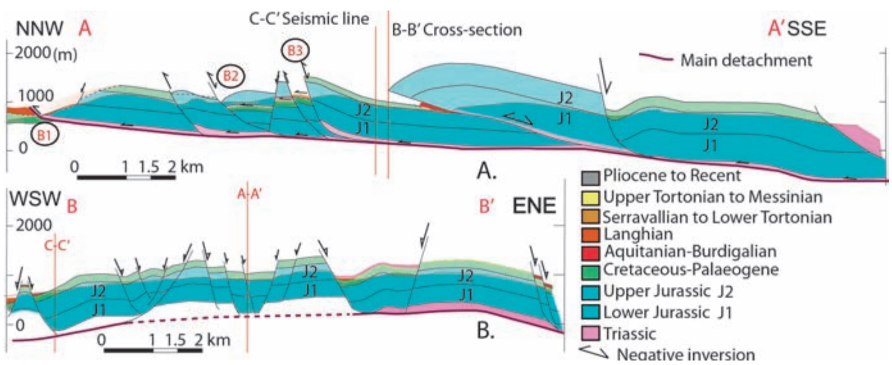

Fig. 3.- (A) Geological cross-sections sub-parallel to the FTB propagation (A-A') and (B) sub-parallel to the stretching direction (B-B') in the Sierra de Cabra.

Fig. 3.- (A) Corte geológico subparalelo a la dirección de propagación del FTB (A-A') y (B) sub-paralelo a la dirección de estiramiento (B-B') en la Sierra de Cabra.

Relative age of structures

According to the age of the rock formation involved, thrusting was active from Aquitanian to Burdigalian, accommodating most of the shortening. Nevertheless, younger sediments (dated as Langhian to Lower Tortonian; Roldán *et al.*, 2012) are involved in the frontal thrust of the Sª de Cabra (Fig. 2A), thus suggesting a post-Langhian NNW-ward progression of the deformation, probably coeval with tightening as proposed by previous works (Crespo-Blanc, 2007). N-S, NW-SE and NNE-SSW striking normal faults occurred simultaneously with Langhian sediments deposits and, occasionally, they also affect Quaternary sediments. This suggests that normal fault activity started presumably at the Upper Burdigalian or Lower Langhian but its activity lasted until the Quaternary (Figs. 2A and 3B).

Hence, in the Sª de Cabra area, during the Middle Miocene (from Upper Burdigalian to Lower Tortonian), the strain was partitioned into NNW-SSE, arc-perpendicular shortening and arc-parallel stretching. At the same time that the deformation migrated toward the NW, arc-parallel stretching continued and local thrust inversions occurred in the southern Sª de Cabra (Figs. 2A and 3).

This strain partitioning is comparable to that reported for the Western Betics, where (1) arc-perpendicular shortening (NW-SE in the Western Betics), was coetaneous to arc-parallel stretching (NE-SW in the Western Betics); (2) the extensional strain in the main Jurassic massifs of both areas is in the order of 10-15%; and (3) the stretching caused topographic and structural segmentation along-strike (the relief drop toward the Ronda intermontane basin in the Western Betics; Fig. 1; Balanyá *et al.*, 2007; Jiménez-Bonilla *et al.*, 2015) and the Subbetic outcrop segmentation in the Central Betics (Subbetic Extensional Complex; Azañón *et al.*, 2012; Rodríguez-Fernández *et al.*, 2013). However, this strain partitioning mode in the Western Betics seems to be active until more recent times (i.e. the last 5 Ma; Jiménez-Bonilla *et al.*, 2015).

Conclusions

The Sª de Cabra structure is defined by a NNW-verging thrust system, active during the Lower to Middle Miocene.

Middle Miocene and onwards, N-S, NW-SE and NNE-SSW striking normal faults accommodated arc-parallel stretching. These faults define the W and E boundaries of the Sª de Cabra, playing a key role on the along-strike structural and topographic relief segmentation.

After the Langhian, local thrust inversion in the southern part of the Sª de Cabra was coeval with NW-ward progression of the deformation.

Thus, during the Middle Miocene, the strain in the External Zones of the Central Betics is partitioned into arc-perpendicular shortening, broadly coetaneous with arc-parallel stretching, characteristic of the lateral branch of the Gibraltar Arc orogenic system. This strain partitioning is similar to that found in certain sectors located at the more frontal part of the Arc (Western Betics).

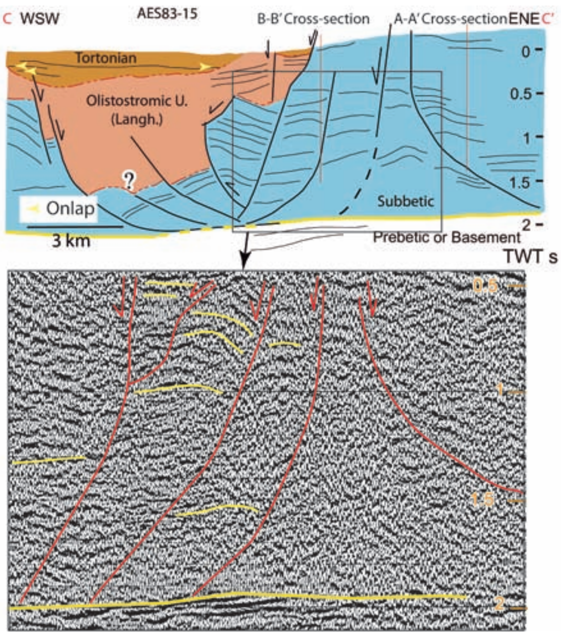

Fig. 4.- Seismic interpretation of a WSW-ENE oriented seismic line (C-C') and a detail from the seismic image.

Fig. 1.- Interpretación de una línea orientada WSW-ENE (C-C') y un detalle de la imagen sísmica.

Acknowledgements

This research is supported by grants RNM-0451 and CGL2013-46368. We thank the discussions provided by J.M. Azañón, F.J. Roldán and J. Rodríguez-Fernández and the revisions of J. Rodríguez-Fernández and Ruth Soto.

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