

Geometry and Late-Miocene to the Recent evolution of the western Betics external orogenic wedge

Geometría y evolución desde el Mioceno superior al Reciente de la cuña orogénica externa de las Béticas occidentales

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ABSTRACT

The external zones of orogens are frequently deformed into fold-and-thrust belts. Fold-and-thrust belts depict wedges in cross-section defined by the α angle, which is the slope of the syn-orogenic topography, and β angle, which is the basal detachment's dip. The aim of this work is to study the geometry and evolution of the western Betics wedge and to compare with the Central Betics. To do that, geological cross-sections, interpretation of seismic profiles and well data were used. The overall α angle is 1.34° , however, a sharp topographic drop coincides with a change in the structural style within the fold-and-thrust belt. Both fold-and-thrust belt segments analysed separately yield α angles lower than 0.6° . The angle β at the external wedge is ca. 3° . There are no evidences of steps in the basement top topography. Consequently, the western Betics wedge probably propagated since the Early Miocene to Recent without significant stagnation during its front propagation, unlike the central Betics wedge. Recent propagation of the deformation accreted the internal parts of the foreland basin (Serravallian to Quaternary sediments) to the Betics fold-and-thrust belt.

Key-words: fold-and-thrust belt, taper angle, wedge propagation, basement topography.

RESUMEN

Las zonas externas de los orógenos se deforman frecuentemente en cinturones de pliegues y cabalgamientos. Los cinturones dibujados en una cuña en cortes definidos por un ángulo α , o pendiente de la topografía sinorogénica, y un ángulo β , el buzamiento del despegue basal. El objetivo de este trabajo es estudiar la geometría y evolución de la cuña de las Béticas occidentales y compararla con las Béticas centrales. Para ello, se usan cortes geológicos, interpretación de perfiles sísmicos y sondeos. El ángulo α es 1.34° , sin embargo, una caída topográfica brusca coincide con un cambio del estilo estructural dentro del cinturón de pliegues y cabalgamientos. Si se analizan los dos segmentos por separado, se obtienen ángulos α de menos de 0.6° . El ángulo β en la cuña externa es de ca. 3° . No hay evidencias de escalones en el techo del basement. Por lo tanto, la cuña de las Béticas occidentales probablemente se propagó desde el Mioceno Inferior a Reciente sin paradas significativas en su propagación hacia el frente, a diferencia de las Béticas centrales. La propagación reciente de la deformación añadió las partes internas de la cuenca de antepaís (sedimentos serravalienses a cuaternarios) al cinturón de pliegues y cabalgamientos.

Palabras clave: cinturón de pliegues y cabalgamientos, ángulo de la cuña, propagación de la cuña, topografía del basement.

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Introduction

The external zones of orogens are frequently deformed into fold-and-thrust belts (FTBs) (Poblet and Lisle, 2015). The 2D geometry of active FTBs describes a wedge shape, which is defined by two angles: alpha (α) that is the slope of the syn-orogenic topographic forelandward-dipping surface and beta (β) that is the dip of the basal detachment. Both angles sum up the taper angle which is nearly constant when the wedge remain stable (Davis et al., 1983).

The Gibraltar arc is a collisional arc whose FTB exhibits an arcuate geometry seems to be still protuding (Balanyá et al., 2012). The interpretation of seismic profiles aided to constrain the geometry

of the Betics external orogenic wedge (northern lateral branch of the Gibraltar arc; Fig. 1A). In previous works, the central Betics wedge geometry was constrained and a basement threshold was detected (Jiménez-Bonilla et al., 2016). This work allows us to study the frontal wedge propagation from Langhian to Present in this fold-and-thrust belt segment. Nevertheless, little research about the wedge geometry and propagation has been made in the apical part of the Gibraltar arc.

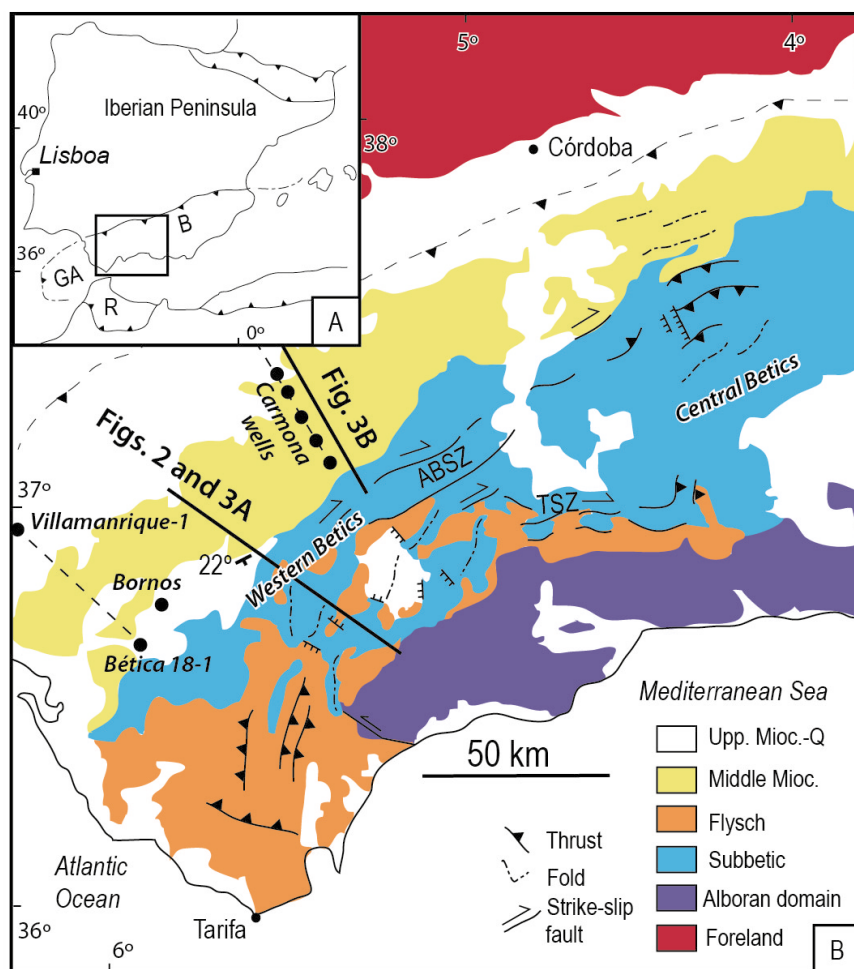
Upper Late Miocene to the Recent wedge evolution in the western Betics (apical part of the Gibraltar arc). We finally compare these results in the western Betics with those of the central Betics (Jiménez-Bonilla et al., 2016).

Methodology

Firstly, we have made a representative geological cross-section of the western Betics FTB (Figs. 2 and 3) constrained by surface geology field work, well data and seismic profiles.

Angle α is calculated by means of a least squares adjustment of equidistant points along the topographic profile. Measurements are taken every 2 km as in Jiménez-Bonilla et al. (2016).

Angle β is calculated in different ways: (A) the cross-section made along Betics FTB, (B) the identification of the basement top in the seismic profile S82A-9 and (C) the basement depth obtained in wells along the western Guadalquivir foreland basin (Lanaja, 1987; Jiménez-Bo-



and arc-parallel stretching (e.g. Balanyá *et al.*, 2012). Shortening was mainly accommodated by kilometric-scale folds and reverse faults of the FTB (e.g. Jiménez-Bonilla *et al.*, 2016), which is sharply interrupted along-strike by normal fault zones such as de Ronda Basin-related normal faults (Fig. 1).

The Betics FTB is composed of both Subbetic units and Flyschs Trough units which thrust onto the former. Flyschs Trough units are made up of claystones and sandstones deposited from the Paleogene to the Early Miocene ages (Martín-Algarra, 1987). Subbetics units deposited on the South Iberian paleo-margin and are made up of (1) Triassic evaporites, where the main detachment is located, (2) Jurassic dolostones and limestones and (3) Cretaceous to Paleogene marly limestones (Martín-Algarra, 1987). Recent works interpreted the frontal parts of the Betics FTB as a canopy of Triassic evaporites (Flich and Soto, 2022). The most recent deformation incorporated these allochthonous evaporites and Tortonian to Quaternary sediments into the external FTB (Jiménez-Bonilla *et al.*, 2017).

Western Betics orogenic wedge

The structural style of the western Betics FTB changes from its internal to its external parts.

The southeastern part of the FTB (0 to 40 km; Fig. 2) shows a tectonic stacking of Flyschs and Subbetic thrust sheets due to the Early to Middle Miocene main deformation event (Expósito *et al.*, 2012). The first 20 km of this segment (iFTB) are highly deformed by post-Serravallian events forming pop-up and pop-down structures (Fig. 2). Some reverse faults associated with fold limbs developed. From 20 to 40 km (mFTB), post-Serravallian folds are less frequent. Geomorphic analyses have proven the recent deformation in the iFTB and mFTB (Jiménez-Bonilla *et al.*, 2017).

Fig. 1.- (A) Location of the Gibraltar arc and (B) Geological map of the Betic chain. See color figure in the web.

Fig. 1.- (A) Localización del arco de Gibraltar y (B) mapa geológico de la cordillera Bética. Ver figura en color en la web.

nilla *et al.*, 2016). The seismic profile is displayed in km depth assuming an average seismic P wave velocity of 2500 m/s and constrained by well data (Jiménez-Bonilla *et al.*, 2016).

Tectonic setting

The Gibraltar arc built up during the Neogene because of the collision between the hinterland (Alboran domain) and the South Iberian and Maghrebian paleomargins, to the N and the S, respec-

tively. The western Gibraltar arc (west of longitude $4^{\circ}30'$) is defined as a major salient limited by two transpressional transitional zones (Balanyá *et al.*, 2012). The western Betics individualized and rotated clockwise more than 50° , whilst the central Betics rotated clockwise 12° during the last 9 My (Crespo-Blanc *et al.*, 2016).

The Betics FTB was detached at a décollement level located within a basal evaporitic, viscous substrate. During the FTB accretion, the strain was partitioned between arc-perpendicular shortening

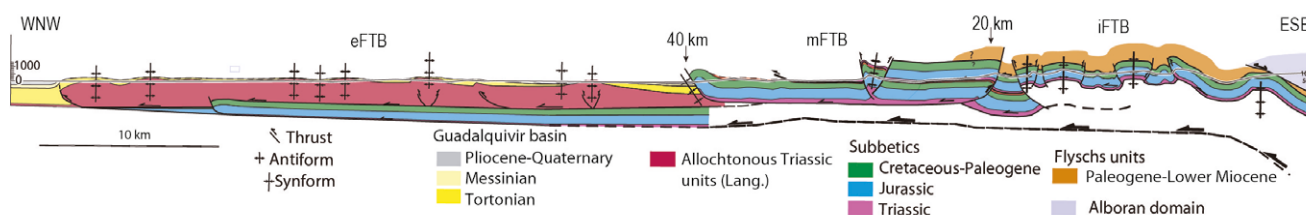


Fig. 2.- Cross-section parallel to the tectonic transport direction in the western Betics. Location in Fig. 1. See color figure in the web.

Fig. 2.- Corte paralelo a la dirección de transporte tectónico en las Béticas occidentales. Localización en Fig. 1. Ver figura en color en la web.

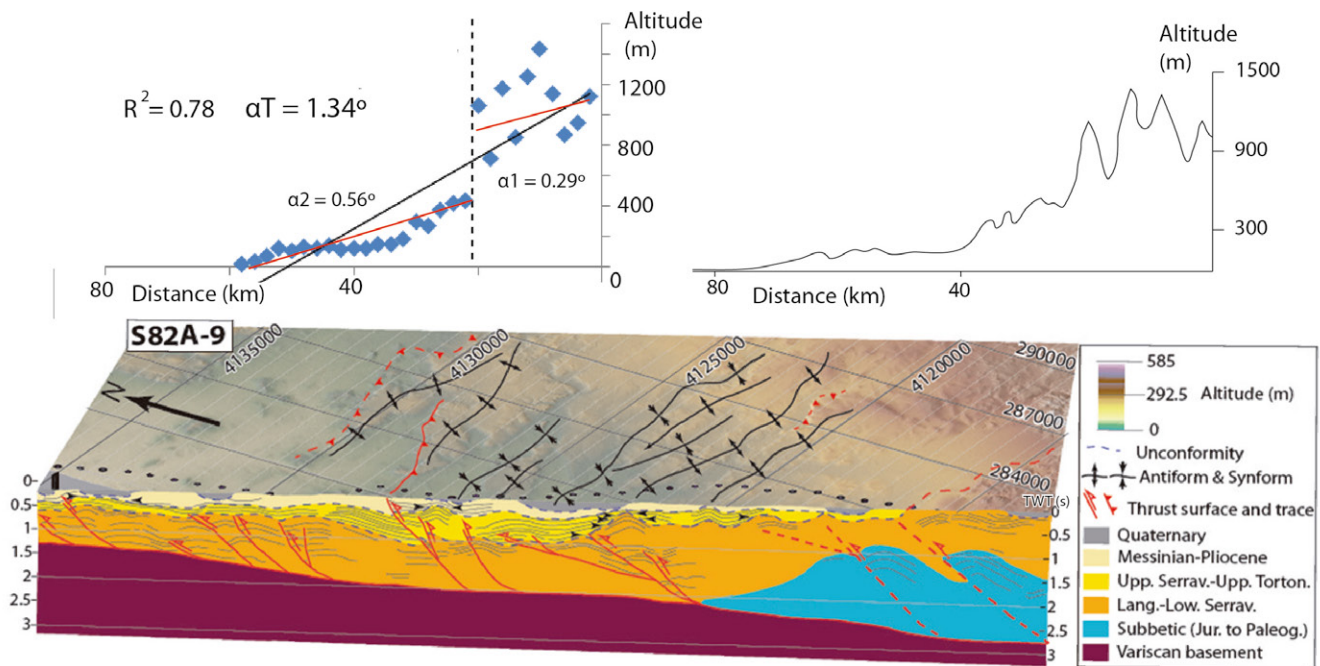


Fig. 3.- (A) Topographic profile of the western Betics FTB (B) Interpretation of seismic profile S82A-9. (See Fig. 1 for locations). See color figure in the web.

Fig. 3.- Corte topográfico del cinturón de pliegues y cabalgamientos de las Béticas occidentales. (B) Interpretación del perfil sísmico S82A-9. Localización en Fig. 1). Ver figura en color en la web.

The external FTB (eFTB) is composed of a thick allochthonous Triassic package (canopy; Flinch and Soto, 2022) and Middle Miocene to Quaternary sediments. The allochthonous Triassic package is sometimes more than 1 km thick (e.g. Bornos-1 well, Figs. 2 and 4B).

Overlying this allochthonous Triassic package, Middle Miocene to Quaternary sediments are deformed into non-cylindrical well Beticas 18-1 well; Fig. 4C), does not show large displacements. The

current Betics mountain front is not defined by a discrete fault but a complex fold tip line over ramping thrust.

Western Betics syn-orogenic topography (α)

The current Betics syn-orogenic topography also shows differences across strike the western Betics (Fig. 3A).

The iFTB, which is highly deformed by pop-up and pop-down structures (up to 20

km), shows a conformative relief (altitudes from 600 to 1,600 m) and a high stream incision (Fig. 3A). The topography sharply drops up to less than 500 m in the mFTB. The eFTB shows a smooth conformative relief. Altitudes range from 100 to 600 m (Fig. 3A). Depositional processes are dominant in both the mFTB and the eFTB.

When the overall syn-orogenic topography is analysed, the resulting α angle is 1.34° , especially due to the presence of a sharp topographic drop at ca. 20 km (i.e. between the iFTB and mFTB). This fact is related to both a less presence of post-Serravallian folds and an increase of their wavelength (Figs. 2 and 3B). When both FTB segments are analysed separately, α angles do not reach 0.6° (Fig. 3B).

Western Betics basement topography (β)

According to structural data, the Hercynian basement seems to dip 2° towards the ESE (Fig. 2).

Well data allowed us to analyse two sections in the western Betics FTB using the basement top (Lanaja, 1987). The westernmost section, in the apical part of the Gibraltar arc, is made from two wells: Villamanrique-1 and Bética 18-1 (Fig. 4C). The overall β is 3.1° in this section. To the E, we used the wells Carmona-2 to 6 and the outcropping basement. We made a least squares adjustment using the basement outcrop and wells Carmona 2 to 5

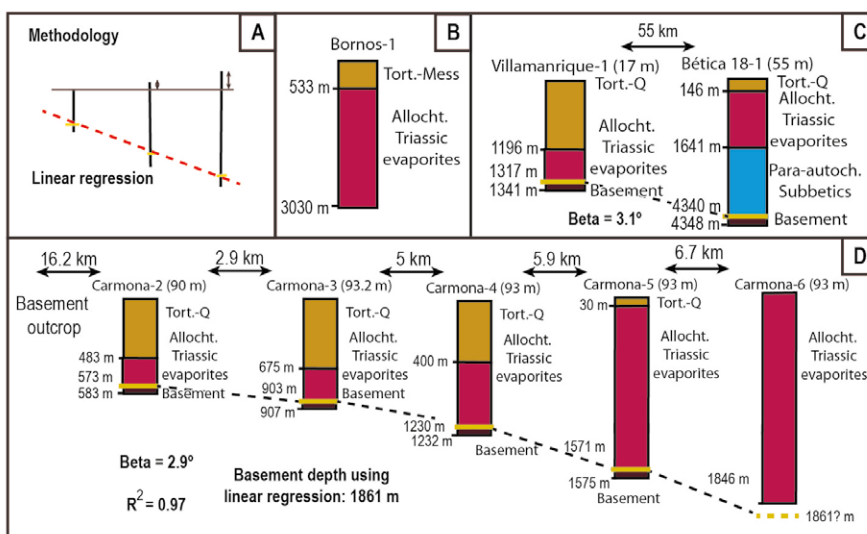


Fig. 4.- (A) Methodology used to calculate β from wells. (B) Interpretation of well Bornos-1. (C) Calculation of β using wells Villamanrique-1 and Bética 18-1. (D) Calculation of β using wells Carmona-2, 3, 4, 5 and 6. See color figure in the web.

Fig. 4.- (A) Metodología usada para calcular β con sondeos. (B) Interpretación del sondeo Bornos-1. (C) Cálculo de β usando los sondeos Villamanrique-1 y Bética 18-1. (D) Cálculo de β usando sondeos Carmona-2, 3, 4, 5 y 6. Localización en Fig. 1. Ver figura en color en la web.

and we obtained a β of 2.9° (Fig. 4D). $R^2 = 0.97$ means that all points adjusted very well to the main line. Consequently, no steps on the basement topography can be inferred.

The interpretation of S82A-9 is congruent with β angles of ca. 3° and it also shows the absence of basement steps (Fig. 3B).

Discussion

The western Betics FTB is detached within the Triassic layer (Jiménez-Bonilla *et al.*, 2015; 2017 and this work). The evaporitic nature of the detachment level favours the development of post-Serravallian pop-up and pop-down structures (Fig. 2).

The Early to Middle Miocene, main deformation event probably built up a tectonic pile made up of Flyschs and Subbetics units (Expósito *et al.*, 2012). This stacking (partially eroded nowadays) may have provoked a tectonic load that favoured the emplacement of Triassic evaporites at the middle Miocene front of the FTB as a canopy (Flinch and Soto, 2022). These Triassic evaporites are overlaid by Tortonian to recent sediments, which deposited as mini-basins (Figs. 2 and Figs. 4B to 4D). The presence of a thicker viscous package favoured that the main detachment changed from the underlying autochthonous Triassic evaporites to the allochthonous package (Fig. 2). It is congruent with the low displacement observed in the underlying Subbetic units in the eFTB (Fig. 2). The deformation front propagated, adding Tortonian to Quaternary sediments to the FTB and it is currently active (Ruiz-Constán *et al.*, 2009). There is no evidence to interpret any step on the basement topography and any Triassic pinch-outs, thus the FTB deformation should have propagated without stagnation from the Early Miocene onwards. This fact would explain the absence of gravitational deposits made up of Jurassic blocks embedded in Middle Miocene sediments as it occurs in the Central Betics (Jiménez-Bonilla *et al.*, 2016).

The western Betics wedge shows $\alpha < 1.5$ and β ca. 3° (Figs. 2, 3 and 4). The basal friction angle seems to remain stable or

even it could have diminished when the main detachment progressed from the autochthonous Triassic evaporites to the allochthonous package.

This model sharply contrasts with the FTB development in the central Betics (Jiménez-Bonilla *et al.*, 2016). The central Betics wedge shows much higher β (4° to 13° vs <3°) and it shows a basement step. Moreover, a Triassic pinch-out is found. Both basement obstacles and/or the Triassic pinch-out probably conditioned the FTB stagnation during the Langhian and the deposition of gravitational deposits (the wedge reached the extensional deformation domain; critical taper theory; Jiménez-Bonilla *et al.*, 2016).

Consequently, the central Betics deformation front slowed down during the Langhian, whilst the western Betics deformation propagated at a constant speed. This difference on the propagation of deformation fronts could explain the differences on vertical axis rotations between the western and the central Betics FTB (Crespo-Blanc *et al.*, 2016). Both FTB segments show Quaternary tectonic activity.

Conclusions

1. The post-Serravallian deformation in the western Betics provoked the development of pop-up and pop-down structures in the internal FTB and the propagation of the deformation towards the Guadalquivir foreland basin, adding Tortonian to Quaternary sediments to the FTB.

2. The western Betics orogenic wedge is defined by a syn-orogenic topography (α angle) of < 1.5° and a basement topography without any significant step and a slope (β) of approximately 3°.

3. Our results suggest that while the central Betics deformation slowed down during the Langhian, provoking the deposition of gravitational deposits, the western Betics front continued propagating. It could have favoured the differences on vertical axis rotations between the western and central Betics, in their turn linked to the shaping of the Western Gibraltar Arc.

Author contributions

Díaz-Azpiroz and Jiménez-Bonilla compiled the data, Jiménez-Bonilla conceived the idea and all authors contributed to the writing.

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