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Neo-tectonic reactivation and relief rejuvenation in the western Betics foreland (Viar catchment)

Reactivación neo-tectónica y rejuvenecimiento del relieve en el antepaís de la Béticas occidentales (cuenca del Viar)

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ABSTRACT

We analyze the recent tectonic activity recorded in the Viar catchment (Betics foreland), combining structural and geomorphic tools. Our results indicate that recent, probably Quaternary, tectonic activity is responsible for relief segmentation, both parallel and perpendicular to the limit between the foreland of the Betics and the Guadalquivir foreland basin. Thus, uplift of the Viar catchment boundaries seems to be controlled by the presence of previous structures, reactivated as NW-SE oblique reverse faults at its NE boundary and oblique normal faults, close to E-W orientation, at its SW boundary. Additionally, SW-NE oblique normal faults are associated with the topographic escarpment that separates the Iberian Massif and the Guadalquivir foreland basin. They must have elevated the Iberian Massif before the subsidence of the Viar catchment occurred, given that the Neogene sediments of the Guadalquivir basin do not extend within the southernmost Viar catchment although its floor is at the same altitude as the Neogene outcrops in the northermost Guadalquivir basin. The contrasting kinematics accommodating relief rejuvenation point to the superposition of shortening, probably due to Alpine intraplate deformation, and extension related to forebulge flexion.

Key-words: *relief rejuvenation, geomorphic indices, tectonic reactivation, betic foreland.*

RESUMEN

En este trabajo, analizamos la actividad tectónica reciente en el entorno de la cuenca del Viar (antepaís bético) mediante herramientas estructurales y geomorfológicas. Nuestros resultados indican que la segmentación del relieve, tanto paralela como perpendicular al límite entre la cuenca de antepaís del Guadalquivir y el antepaís bético, se debe a actividad tectónica reciente, probablemente cuaternaria. El levantamiento de los relieves que bordean la cuenca del Viar parece estar controlado por la presencia de estructuras previas, reactivadas como fallas oblicuas inversas, de orientación NO-SE, en el NE, y fallas oblicuas normales, aproximadamente E-O, en el SO. Por otra parte, el escalón topográfico que asciende el antepaís bético sobre la cuenca de antepaís está relacionado con actividad reciente de fallas de componente normal dominante. Este ascenso relativo parece haber sido anterior a la subsidencia de la cuenca del Viar, ya que en su borde sur no entran los sedimentos neógenos que afloran en la cuenca del Guadalquivir a la misma cota. Las diferentes estructuras que acomodan el rejuvenecimiento del relieve sugieren la superposición de acortamiento, asociado a tectónica Alpina de intraplaca, y de extensión debida a la flexión del "forebulge".

Palabras clave: *rejuvenecimiento del relieve, índices geomorfológicos, reactivación tectónica, antepaís bético.*

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Introduction

Reactivation of pre-existing structures is a common mechanism for strain accommodation, which often occurs in preference to the generation of new structures (*e.g.*, Butler *et al.*, 1997). Thus, basement structures significantly control both strain localization and strain partitioning modes in orogenic forelands.

The Betics foreland (*i.e.*, the Iberian Massif) has undergone Neogene, or even younger uplift, as evidenced, for instance, by significant river incision and the presence of knickpoints along river longitudinal profiles. Furthermore, seismicity and faults affecting both basement and infill of the foreland basin (*i.e.*, Guadalquivir basin) have also been reported (Herraiz *et al.*, 1996; Vázquez-Vílchez *et al.*, 2015; Expósito *et al.*, 2016). Most of these evidences occur within a 50-70 km-wide band located just north of the Guadalquivir basin, which would correspond to the forebulge area (García-Castellanos *et al.*, 2002). In this work, we explore relief rejuvenation in the Viar catchment, and its potential relationship with reactivation of previous structures belonging to the Betics foreland. For such purpose, we have combined structural and geomorphic tools.

Geological setting and morphostructural features of the Viar catchment

Our study is focused on the Viar catchment, a NW-SE elongated topographic depression located in the southernmost

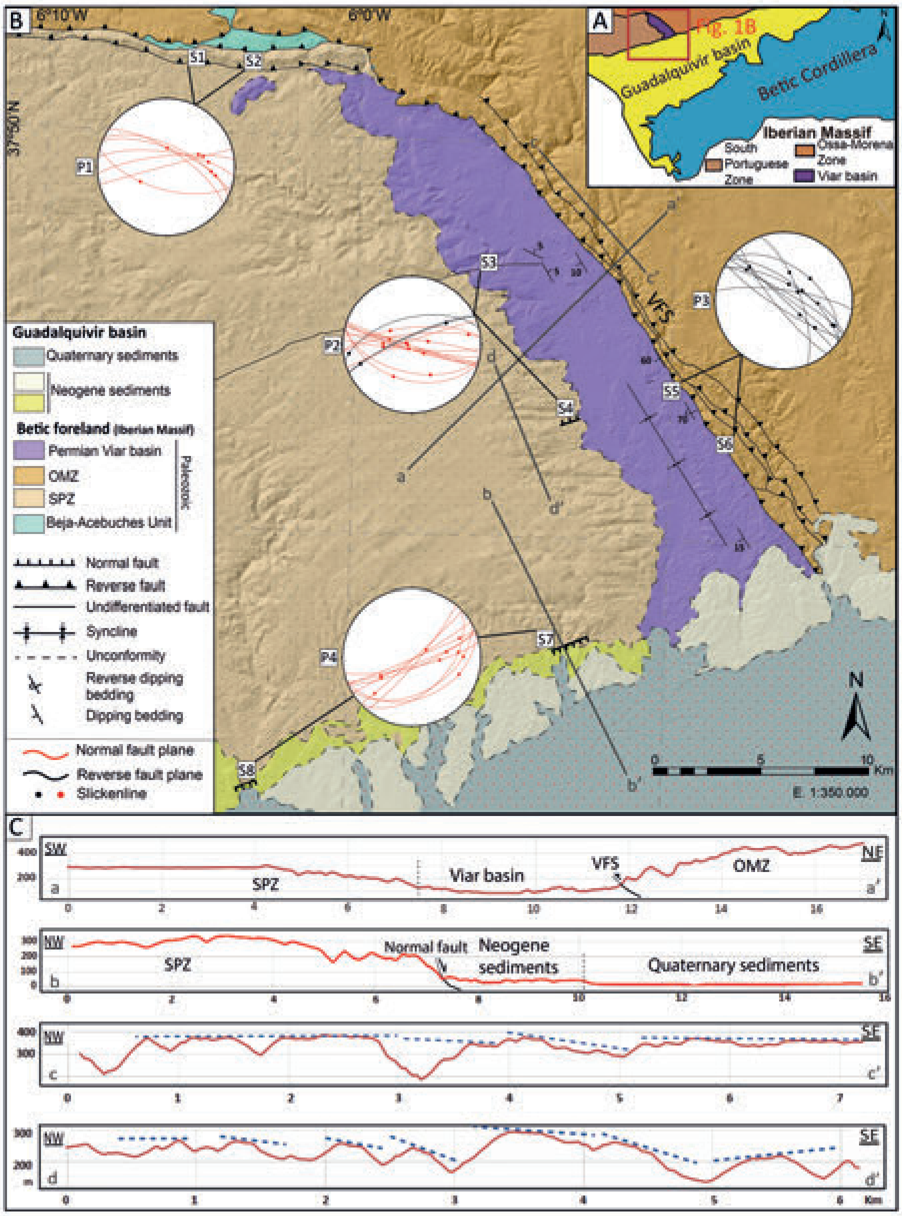

Fig. 1. - A) Location of the study area in SW Iberia. B) Simplified geological map of the Permian Viar basin area with the location of the structural measurement stations (S1, S2, S3, S4, S5, S6, S7 and S8), resulting stereograms (P1, P2, P3 and P4) and topographic profiles of figure 1C. VFS, Viar fault system; OMZ, Ossa-Morena Zone; SPZ, South Portuguese Zone. C) Topographic profiles; dashed lines represent the Neogene erosional paleosurface on top of the interfluves (see the text).

Fig.1.- A) Localización del área de estudio en el SO de Iberia. B) Mapa geológico simplificado de la zona de estudio con la localización de las estaciones de medidas estructurales (S1, S2, S3, S4, S5, S6, S7 y S8) cuyos resultados se representan agrupados en los estereogramas (P1, P2, P3 y P4). Se incluye la localización de los perfiles topográficos de la figura 1C; VFS: Sistema de fallas del Viar, OMZ: Zona de Ossa-Morena, SPZ: Zona Sudportuguesa. C) Perfiles topográficos. Las líneas discontinuas representan la paleosuperficie neógena de enrasamiento que culmina los interfluvios (véase el texto principal).

Iberian Massif (Fig. 1A). It coincides with the Permian Viar basin developed between the Ossa-Morena Zone (OMZ) and the South Portuguese Zone (SPZ). It has been interpreted as a Late Variscan tardiorogenic intramontane basin whose infill is made up of Autunian detrital and volcanic rocks (Simancas, 1983; García Navarro and Sierra, 1998). According to previous interpretations, the basin would have been inverted since the end of the early Permian to the Middle Triassic (García-Navarro and Fernández, 2004). This inversion produced both an open N150ºE-oriented syncline and the NW-SE Viar reverse fault system (VFS, Fig. 1B) along its NE limit (Simancas, 1985; García-Navarro and Sierra, 1998).

The VFS hanging wall is mainly composed of Paleozoic metasedimentary and igneous rocks of the OMZ. In the footwall, the Permian Viar basin infill unconformably overlies the Devono-Carboniferous, volcano-detritic and plutonic rocks of the SPZ.

To the SSE, the Paleozoic rocks of the foreland form the basement of the Guadalquivir basin, being unconformably overlain by Neogene marine sediments as well as the Quaternary sediments of the Guadalquivir river.

The boundary between the Iberian Massif and the Guadalquivir basin coincides with a sharp topographic escarpment with a low-lying relief Guadalquivir basin, and a steeper relief Iberian Massif. The Viar catchment, with altitudes similar to the Guadalquivir basin is an exception within the Iberian Massif.

Approach and methods

To analyze the recent tectonic activity, we have carried out geomorphic analysis to test potential relief rejuvenation. On that purpose, we have applied both qualitative and quantitative methods by means of a digital elevation model (DEM) at 1:25000 scale. Based on such analysis, we have identified and characterized the nature and kinematics of the structures spatially related to this relief rejuvenation.

For the geomorphic qualitative description, we have generated relief and slope maps, topographic profiles, as well as longitudinal profiles of the four main rivers of the zone (Figs. 1C and 2).

Quantitative geomorphic indices have also been calculated to constrain the time span of the recent tectonic activity. These are:

- Mountain front sinuosity, Smf (Bull and McFadden, 1977): it has been applied to eight mountain fronts divided in segments of 2-10 km-long. The slope breakline has been established at slope values of 8º.

- Valley floor-to-height ratio, Vf (Bull and McFadden, 1977): calculated for the four main rivers, upstream and downstream of the mountain fronts associated with both the Viar catchment boundaries and the limit between the Iberian Massif and the Guadalquivir basin.

- Catchment hypsometric curve and hypsometric integral, HI (Keller and Pinter, 2002): applied to five tributaries of the Guadalquivir river and six tributaries of the Viar river.

Both qualitative and quantitative results have been carefully examined in order to discard those values controlled by lithological contrast.

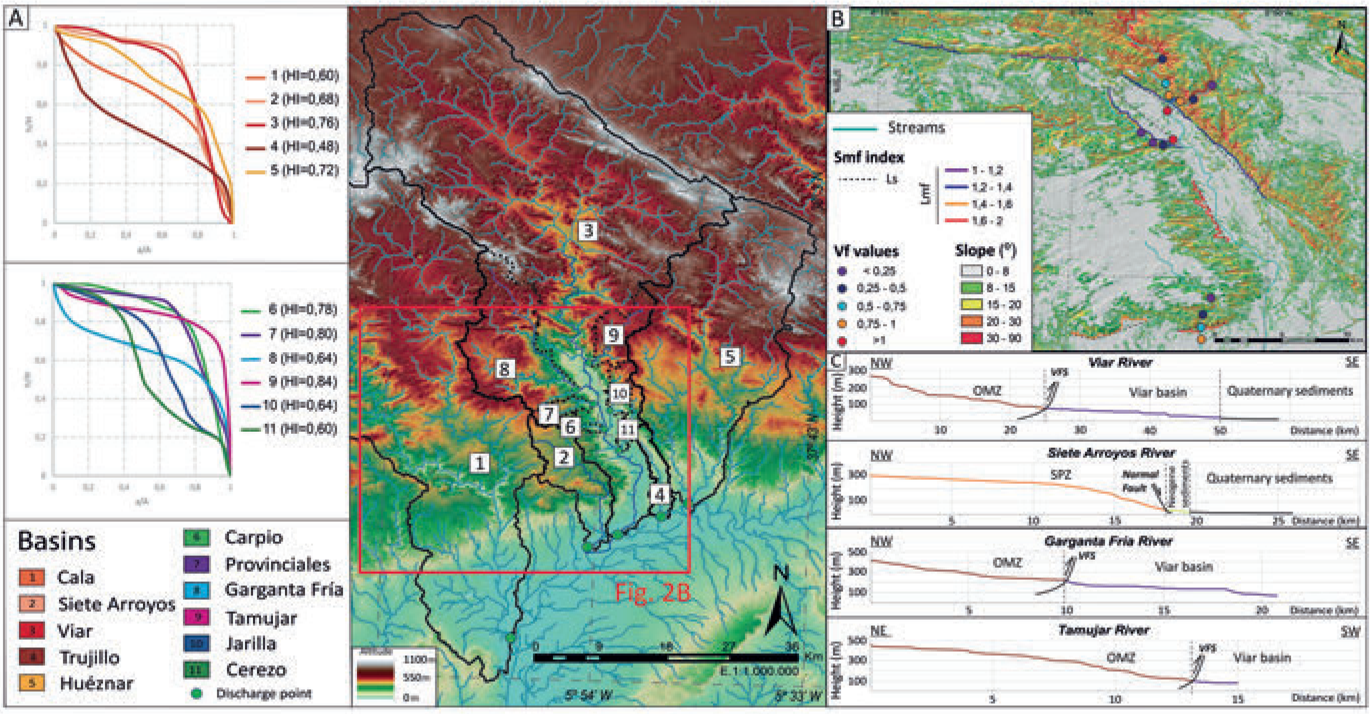

Fig. 2. - A) Drainage catchments (1 to 5) and sub-catchments (6 to 11) distribution map on a bottom relief map with hypsometric curves and hypsometric integral values (HI). B) Slope map and hillshade map (location on Fig. 2A) showing the mountain fronts segments; Ls, length measured along a straight line; Lmf, length of mountain front; Smf values are shown by the gradation of colors in the Lmf line, Vf values are pointed by the color. C) Longitudinal river profiles; materials and structures along them are presented.

Fig. 2.- A) Mapa de distribución de las cuencas (1 a 5) y sub-cuencas (6 a 11) de drenaje sobre el mapa de relieve. Curvas hipsométricas y valores de la integral hipsométrica (HI) de cada cuenca y sub-cuenca. B) Mapa de pendientes y mapa de sombras que muestran los segmentos de los frentes montañosos; Ls, longitud medida a lo largo de una línea recta; Lmf, longitud del frente montañoso; los valores de Smf se muestran por la gradación de colores en la línea Lmf, los valores de Vf están señalados por el color. C) Perfiles longitudinales de los ríos donde se presentan los materiales y las estructuras por las que fluye el cauce.

Geomorphic results

The Viar catchment is flanked by roughly NW-SE-oriented ranges (Figs. 1C and 2B) that exhibit smooth summits, whose slopes rarely exceed 8°; steep topographic drops with slopes of up to 30° mark the boundary with the Viar river valley. The flat summits, which probably represent remnants of a erosional surface previously dated as Paleogene (Rodríguez Vidal and Díaz del Olmo, 1994), are cut by incised tributaries of both Viar and Guadalquivir rivers (Fig. 1C). The resulting flat interfluves are mostly sub-horizontal or slightly SSE inclined and display often a stepped geometry, particularly to the SW (profile d-d', Fig. 1C), with decametric vertical offsets, as well as different degree of tilting, mainly toward the SSE. This erosional paleosurface is located in the VFS hanging wall (*i.e.*, OMZ) at a higher topographic level than in its footwall (*i.e.*, SPZ).

The drainage network follows a mainly dendritic pattern, whose main rivers (Guadalquivir tributaries) have a NNW-SSE average orientation, conditioned by the topographic gradient between the Iberian Massif and the Guadalquivir basin. However, secondary streams orientations are often tectonically controlled, particularly in the igneous rock outcrops of the SPZ, which are intensely fractured.

Rivers often display features associated with relief rejuvenation such as incised meanders, pearched terraces or fluvial elbows due to river capture and fault-related stream deflections. The stream segments that flow into the Viar catchment flanks have convex longitudinal profiles (Fig. 2C), with knickpoints spatially related to the NE and SW boundaries of the Viar catchment as well as to the contact between the Iberia Massif and the Guadalquivir basin.

Regarding the quantitative results, most of them point to recent, probably Quaternary activity. The hypsometric curves of most catchments and sub-catchments (Fig. 2A) are convex with HI values > 0.6, related to weakly eroded catchments. The exception are sub-catchments 4, 10 and 11, which develop mainly on the Viar catchment or Guadalquivir basin. The Smf index yields low values, associated with relative recent or active tectonics (Fig. 2B). These values are particularly low (1-1.4) in the mountain front that coincides with the VFS trace. The lowest Vf values (Fig. 2B), related to down-cutting streams, have been obtained in all cases upstream from the mountain front. Values become progressively higher downstream from the mountain fronts.

Structural results

The relief rejuvenation features of the Viar catchment are spatially related to fractures than can be grouped according to its orientation and kinematics (Fig. 1B).

The mountain front that limits the Viar catchment to the NE coincides with the VFS. It consists of mainly steeply, NE-dipping fault surfaces (P3, Fig. 1B), whose slickenlines indicate a dominant reverse slip component and a variable lateral slip, though the left-lateral displacement prevails. To the north, the VFS turns west, also coinciding with a topographic high that constitutes the northern limit of the Viar catchment. In this segment, we have found fault planes oriented close to E-W-and dipping steeply either to the north or south (P1, Fig. 1B), being most of them right-lateral normal faults.

Faults of similar orientation (P2, Fig. 1B) are spatially related to the N-S relief segmentation exhibited by the western boundary of the Viar catchment, being probably responsible for the tilting and displacement of the Paleogene erosional paleosurface on top of it (Fig. 1C, profiles c-c' and d-d'). They show a dominant normal slip component and a minor lateral one, either right- or left-lateral. In igneous rocks outcrops of both the SPZ and the Viar catchment, these faults are evenly distributed with a m-scaled spacing, and seem to have formed due to reactivation of previous joints.

Finally, SW-NE to WSW-ENE- oriented, SE-dipping, oblique normal faults (P4, Fig.1B) have been measured at the contact between the foreland (*i.e.*, the Iberian Massif) and the Guadalquivir basin, west of the Viar catchment (Fig. 2A). They are associated with the topographic escarpment that separates both domains. Some patches of Neogene, Guadalquivir basin-derived sediments found on the footwalls of these faults (*i.e.*, the Iberian Massif), permit to estimate a minimum throw of around 30 m. Recent activity in faults of similar kinematics have been described at the same contact in sectors located east of the Viar catchment (Expósito *et al.*, 2016).

Discussion and conclusions

Our qualitative and quantitative geomorphic analysis, combined with our structural results, reveal that the current Viar catchment relief seems to be controlled by the recent reactivation of previous structures. This recent activity is consistent with the topographic discontinuity that the erosional paleosurface on top of interfluves exhibits between the ZOM and the ZSP, as well as with the N-S stepped geometry of such paleosurface within each zone. As mentioned above, this paleosurface has been previously interpreted as Paleogene. Nevertheless, it could be even younger if it had formed at the base level of the foreland basin (*i.e.*, Guadalquivir basin) whose subsidence occurred during the middle-upper Miocene.

The topographic drop between the Viar catchment and the NE range is related to the reactivation, as mainly reverse, left-lateral faults, of the NO-SE-oriented VFS, thus being the relief rejuvenation significantly localized along its trace. Conversely, the relief rejuvenation that raises the SW range above the Viar catchment is rather distributed. This recent activity seems to be related to the reactivation, as oblique normal faults, of previous joint surfaces in igneous rocks, also producing N-S relief segmentation of the range. The different relief rejuvenation mode observed to the SW and NE of the Viar catchment explains that, although Vf and HI yield similar values for both boundaries, Smf values are higher in the SW (*i.e.*, the SPZ), where relative uplift is accommodated by distributed faults of limited extend.

According to our results, all the structures above described seem to have been active during the Quaternary. Furthermore, the distribution of Neogene sediments along the boundary between the Iberian Massif and the Guadalquivir basin permits to stablish a relative timing for the relief segmentation. Thus, whereas the Viar catchment floor is currently at the same altitude as the northernmost Neogene outcrops of the Guadalquivir basin, the sediments do not extend to the North into the catchment. This fact may indicate that the uplift of the forebulge region (Viar and surrounding areas located to the N-NW of the Guadalquivir basin), accommodated by the NE-SW faults was prior to the Viar catchment subsidence, due to the structures reactivation on both catchment flanks.

The contrasting kinematics of the structures accommodating relief rejuvenation suggest the superposition of two different deformational fields in the Viar catchment. The VFS reactivation would be due to regional shortening, associated with the propagation of Alpine recent intraplate deformation. On the other hand, normal faulting would accommodate extension in response to flexion in the foreland forebulge.

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