Introduction

The Western-Central Betic Cordillera (WCBC; Fig. 1) suffered a complex paleo-geographic evolution during late Neogene times (e.g., Guerra-Merchán et al., 2010). This evolution is closely related to the latest stages of development of the Gibraltar arc (e.g., Mattei et al., 2006) and involves (among other processes) the closure and desiccation of the Mediterranean basin during the Messinian Salinity crisis (MSC; Hsü et al., 1977) and the later catastrophic Zanclean flooding of the Mediterranean (Mialleff et al., 2018). In the central sector of the range (from Sierra de la Loja to the east, to El Torcal de Antequera and Serranía de Ronda) arcuate ridges elongated NE-SW are made up of Mesozoic Subbetic materials overthrust by the Flysch units (Fig. 1B). This ridge-line constituted the late Neogene water-divide between the Atlantic and Mediterranean basins (Fig. 1A; reconstructed from Martin et al., 2014, Fleckert et al., 2015 and Silva et al., 2011). One of the most significant aftermaths on the growing Betic Orogen caused by the desiccation of the Mediterranean basin was the triggering of an important headward fluvial incision in the Mediterranean slope (Silva et al., 2011) resulting in a significant north-westwards migration of the original water-divide (in some cases near 20 km) and the removal of...
The geophysical relief (g) is defined as the result in meters from dividing the total eroded volume by the total area of a single drainage basin ($q = m^3/m^2$) and is equivalent to the thickness (in meters) of the theoretical plate of denuded material by fluvial erosion (Small and Andersson, 1998). Consequently, the first step is to delimit the drainage divides (and calculate the basin area) in order to model the pre-incision surface and calculate the total eroded volume. This workflow has been applied to 48 basins in the WCBC (Fig. 1A), discarding the smallest ones (<15 km²). The study area is limited by the Guadalquivir basin to the North and the Sierra Nevada range to the East. A 40m/pixel DEM of the study area (Centro Nacional de Información Geográfica, CNIG -IGN) was used all along the modelling process.

From the ridgelines delimiting the individual drainage basins and to obtain a continuous raster-model of the pre-incision surface (i.e., “ridgeline surface”), we proceed to extract the nodes of the polylines defining the present ridgelines and transformed them to point features. The elevation of these point features come from the topographic DEM, and the calculation of a first model of the “ridgeline surface” is obtained using a tense spline interpolation, which offered the best results. The “ridgeline surface” must envelop, form fitting, the whole drainage basin and all its internal reliefs (e.g., Fig. 2), since it is intended to set the relative uniform slope-topography before fluvial incision. The obtained models should overlie all internal reliefs within individual basins, but typically some reliefs arise above the calculated “ridgeline surface” mainly in basins with complex morphology, geological evolution, recent volcanism and/or tectonics (e.g., Menéndez et al., 2008). In these cases, more elevation points must be added at these protruding areas to guide the modelling processes and to ensure that the final ridge surface model completely overlies all internal reliefs.

Typically this can take few iteration steps. This method assumes that the ridges have not been eroded, and hence the computed results are conservative. The GIS-based analysis offers two results (see Figs. 2 and 3). 1) The overall g value for each drainage basin from the computation of the total volume between the “ridgeline surface” and the present topography divided by the 2D area of the basin (Fig. 3C). 2) A g model from the subtraction of the “ridgeline surface” minus the present topographic DEM. The g model represents the continuous distribution of the geophysical relief (denuded rock-mass) in meters for spatial units of pixel size.

Surface uplift triggered by erosional unloading can be calculated applying elementary Airy-derived isostatic functions ($\rho_p/\rho_m$), were $\rho_p$ is the density of the crustal eroded material and $\rho_m$ the density at the depth of compensation around the Moho. The use of standard values for $\rho_p$ (2.67 g/cm³) and $\rho_m$ (3.33 g/cm³) indicates that the amount of uplift (i) per unit of denudation in meters is generally slightly less than the depth of fluvial dissection per unit area (Gilchrist et al., 1994).

**Methodology**

**Geophysical relief models for the Western-Central Betic Cordillera**

The g, model of the Guadalhorce basin (the more complex basin) evidence that major denudation (higher g values) is concentrated in the southern half of the basin (Fig. 2C), coinciding with its ancient Mediterranean slope exposed to the relevant sea-level fall occurred during the MSC (e.g. Fleckert et al., 2015). Those higher g values appear as NW-SE linear features in the g model (Fig. 2C). The computed values at these zones reach maximum of ca. 900 m (concentrated in the gorges zone), but mean g, values of ca. 400 - 500 m are widely extended in the southern half of the basin. On the contrary, the northern portion of the basin has lower mean g, values of ca. 250 m. This asymmetry in fluvial dissection within the basin clearly evidences the younger fluvial capture of this northern half of the basin. The g, mean value (denudation plane) for the Guadalhorce basin is 348.57 m (1151.55 km³ / 3442.89 km²). However denudation is asymmetrically distributed within the basin between its old Atlantic (northern sector) and Mediterranean (southern sector) slopes. In the nor-
them sector the denudation plate is of 281.16 m (538.51 km²/ 1972.70 km²), whilst in the south is of 442.06 m (611.99 km²/ 1465.95 km²). This asymmetry in the denudation values indicate that about 61% of fluvial erosion concentrated in the old Mediterranean slope of the basin.

In the Guadalhorce basin this differential erosional unloading occurs mainly during the MSC (Elez et al., 2016). Later, Pliocene to Quaternary fluvial incision reshaped the late Neogene landscape in the old Mediterranean slope generating impressive gorges and the eventual capture of the old Atlantic slope of the basin (Elez et al., 2016).

A comparable N-S asymmetric distribution of g values also occurs in the Vélez river basin (Nº 31 in Fig. 1A) and other minor basins, likewise crossed by the ancient Atlantic-Mediterranean water divide. In this case, values for the denudation plates are of 186.89 m in the northern sector and 407.55 m in the southern one. The value of the denudation plate for the entire basin is of 357.95 m, similar to that computed for the Guadalhorce basin.

Figure 3 illustrates the spatial distribution of the computed g values for the whole WCBC from the overall “ridgeline surface” model (Fig. 3A). The regional picture clearly shows a different distribution of g values at both sides of the ancient water-divide (Fig. 3B), with wide areas exceeding values of 500 m and maximum values of about 1200-1500 m in the ancient Mediterranean slope while values near 100-400 dominate in the Atlantic side. Figure 3C illustrates the denudation plates for each analyzed basin. The basins located at the ancient Mediterranean slope display quite significantly greater g values (328 - 465 m for the largest basins) than those located at the Atlantic slope (< 235 m). This asymmetric distribution is noticeable even in the case of the smaller basins and evidences (and is interpreted here as) the influence of the ancient late Neogene water divide in the differential denudation triggered by the MSC in the emergent orogeny.

**Isostatic uplift caused by erosional unloading: The example of the Guadalhorce basin**

The computed surface uplift due to the erosional unloading (p / p₀ = 0.874) is 233 ±20 m for the whole studied sector of the Betics (WCBC) since the onset of the MSC. However, the values of uplift computed for the Mediterranean (c. 291 ±20 m) and Atlantic (c. 179 ±20 m) slopes are significantly different resembling the spatial distribution of g, illustrated in figures 3B and C. A similar scenario occurs in the case of the Guadalhorce basin (Figs. 2 and 3). The computed uplift for the entire basin is of 304 ±20 m, but the values for its northern (245.79 ±20 m) and southern (386.44m ±20 m) sectors differ.

In the case of the Guadalhorce basin is possible to compare the g data with the palaeotopographic and paleogeoid models developed by Elez et al. (2016), in detail, it is especially valuable the comparison with the late Messinian sea level surface (paleogeoid) deformation model (PDM). This is obtained from proxy elevation data of stratigraphic (late Tortonian to early Messinian) littoral sediments in the zone presently located at elevations between 400 and 700 m Sanz de Galdeano and Alfaro (2004) and geomorphologic nature uplifted about 650-700 m, (Elez et al., 2016). These PDM models also show an approximation to the accumulated uplift from late Messinian to Recent (discounting the eustatic component). Although both kind of models (g, and paleogeoid uplift) result from different conceptual approaches, the thickness of the denudation plate computed here (gᵣ = 348 m) is similar to the uplift computed from paleogeoid models (345 m) since the MSC obtained by Elez et al. (2016). Comparing the computed values of uplift obtained here (ca. 350 m) with the bulk uplift of the area coming from upraised late Neogene stratigraphic markers and landforms in the zone seems evident that near the 45-50% of the uplift was triggered by erosional unloading.

Since sea level is supposed to be uniform after the Zanclean refilling (e.g., Micallef et al., 2018), the asymmetry in uplift values for the entire WCBC is a clear consequence of the stronger erosional rock removal caused by the sea-level fall during the MSC. Then, the difference of isostatic uplift between the Mediterranean (291 ±20 m) and Atlantic (179 ±20 m) slopes corresponds only to the uplift generated during the MSC, about 112 ±20 m, indicating uplift rates about 0.18 mm/yr in the Mediterranean slope and around null in the Atlantic one during the MSC.

**Conclusions**

For the WCBC, a transect of more than 200 km along the Betics Cordillera, the spatial distribution of the geophysical relief (Figs. 3A and B) and subsequent isostatic uplift is strongly constrained by the ancient Messinian Atlantic-Mediterranean water divide (Fig. 1A), with the higher values to the ancient Mediterranean slope. Results indicate that uplift triggered by erosional unloading can achieve near 45% of the total...
recorded uplift. Consequently, isostatic uplift caused by erosional unloading is identified as one of the main processes controlling the landscape evolution during and after the MSC in the WCBC.

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