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# Neogene exhumation and relief evolution in the eastern Betics (SE Spain): insights from the Sierra de Gador

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## Abstract

The Betics are a key area to study an orogenic landscape disrupted by late-orogenic extension. New low-temperature thermochronology (LTT) data (AHe and AFT) coupled with geomorphic constraints in the Sierra de Gador (Alpujarride complex) are used to reconstruct the cooling history and evolution of relief during the Neogene. We document three stages: (1) a fast cooling event between 23 and 16 Ma associated with the well-known extensive tectonic exhumation of the Alpujarride unit, (2) a period of slow cooling between 16 and 7.2 Ma related to a planation event and (3) a post-7.2 Ma surface uplift associated with the inversion of the Alboran domain undetected by LTT. The planation event followed by this late uplift can explain the occurrence of inherited low-relief surfaces overlain by Tortonian-Messinian platform deposits at the top of the range. Finally, we propose that the Sierra de Gador is a more transient landscape than the nearby Sierra Nevada.

## Introduction

Exhumation of rocks and topographic evolution are two parameters that are closely related in orogenic systems (*e.g.* England and Molnar, 1990). In active orogenic wedges, uplift and exhumation of accreted rocks are generally associated with a pattern of high-elevation and high-relief topography (Willett and Brandon, 2002). Then, progressive removal of the lithospheric root together with surface erosion or tectonic unroofing leads to topographic decrease in post-orogenic settings. The final stage tends towards low-elevation and low-relief topographies associated to low-temperature plateaus in cooling paths (Calvet *et al.*, 2015). The occurrence of planar landforms at the top of mountain ranges illustrates a topographic transient stage linked to a large-scale tectonic perturbation or local base-level changes during orogenic evolution (*e.g.* Babault *et al.*, 2007; Calvet *et al.*, 2015). The Betics in southern Spain (Fig. 1) are an example of such orogenic disruption (*e.g.* Platt and Vissers, 1989; Lonergan and White, 1997; Jolivet *et al.*, 2008), where low-relief surfaces are described at the top of ranges (Farines *et al.*, 2015). The Eocene-Oligocene mountain building is disrupted by an Oligocene-Miocene extensional event associated with the collapse of the internal zones. Major detachments enabled the exhumation of metamorphosed stacked nappes as the Alpujarride complex and the underlying Nevado-Filabride complex (Fig. 1). The system has been inverted and the Betic crust shortened since the Late Tortonian, as demonstrated by the folding of Miocene deposits (*e.g.* Weijermars *et al.*, 1985; Sanz de Galdeano and Vera, 1992). Although the cooling event associated with the Miocene extensional event is well known, the late story, related to the final extensive stage and the following compressional event, remains poorly constrained, especially for the Alpujarride domain. Yet, this is the main basement area where surface uplift and topographic building can be constrained thanks to uplifted Miocene platform deposits (Braga *et al.*, 2003). This study is focused on the Sierra de Gador, which forms the largest antiform of the Alpujarride domain and

is still covered by remnants of Miocene platform deposits overlying a smooth topography. Thanks to low-temperature thermochronology (LTT) data (fission tracks and (U-Th)/He on apatite), we show that the current topography is inherited from a Middle-Upper Miocene planation event coeval with the late extensional stage of the eastern Betics. The post-Tortonian regional inversion, characterized by a strong surface uplift, is undetected by LTT data, suggesting that the Sierra de Gador topography is transient in nature.

## **Geological setting**

The Betics are located at the western edge of the peri-Mediterranean alpine ranges and form the northern part of the Betic-Rif arcuate mountain belt surrounding the Alboran Sea (Fig. 1). This orogenic arc results from the Meso-Cenozoic convergence between Africa and Iberia. The Betic ranges can be subdivided into non-metamorphic external zones and metamorphic internal zones. The external zones are composed of folded and deformed sediments of the Iberian paleo-margin thrust over the autochthonous Iberian platform, forming the Guadalquivir foreland basin, which is filled by Neogene sediments (Michard *et al.*, 2002; Frizon de Lamotte *et al.*, 2004). The internal zones (or Alboran domain) are composed of a stack of three nappes of different metamorphic grade; from bottom to top they are the Nevado-Filabride, the Alpujarride and the Malaguide complexes. These nappes were accreted during the pre-Miocene collisional stage and then mainly exhumed during a Miocene extensional event (Martínez-Martínez and Azañón, 1997; Azañón and Crespo-Blanc, 2000). During this period, the development of low-angle normal faults induced the separation of the three complexes, as observed currently. This extensional stage within the internal zones is coeval with thrusting and shortening in the external zones. This pattern can be explained by deep tectonic processes such as convective

removal, delamination or slab rollback (*e.g.* Calvert *et al.*, 2000). Lithospheric imaging and volcanic data support a westward slab rollback model (Lonergan and White, 1997; Duggen *et al.*, 2004; Faccenna *et al.*, 2004; Spakman and Wortel, 2004). The extensional stage induced a major thinning of the Alboran domain and resulted in the formation of marine sedimentary basins including the Alboran basin (Sanz de Galdeano and Vera, 1992; Comas *et al.*, 1999). Since the Late Tortonian, the internal zones have undergone N-S to NW-SE compression, inducing large-scale folding and the emergence of a part of their overlying marine basins (Weijermars, 1985; Comas *et al.*, 1999; Marín-Lechado *et al.*, 2007; Iribarren *et al.*, 2009).

## **Exhumation and topographic features of the eastern Betics**

The topography of the Betics can be described by a succession of ranges separated by depressions where Miocene marine and continental basins are preserved (Fig. 1). The elevations of these ranges reach more than 3000 m in the Sierra Nevada and more than 2000 m in the Sierra de Gador. These ranges correspond to large E-W antiforms of the exhumed Alboran domain. The relief of the ranges corresponds to incised topographies, such as in the Sierra Nevada (Pérez-Peña *et al.*, 2010), or, more remarkably, to low-relief surfaces at the top of ranges, as in Sierra de Gador (Figs. 2 et 3; Farines *et al.*, 2015). In the Sierra Nevada, composed of Nevado-Filabride units, AFT and AHe ages range from  $2.7 \pm 0.6$  to  $10.5 \pm 0.9$  Ma (Fig. 2) and from  $6.2 \pm 0.4$  to  $8.8 \pm 0.5$  Ma respectively (Johnson *et al.*, 1997; Reinhardt *et al.*, 2007; Clark and Dempster, 2009; Vázquez *et al.*, 2011). AFT ages show a westward rejuvenation interpreted as the consequence of the top-to-the-WSW extension along the tectonic contact between the Nevado-Filabride and the Alpujarride complexes (Johnson, 1997; Johnson *et al.*, 1997). Thermal history indicates a rapid cooling (660 to 60°C) between ~16.5 and 6-8 Ma,

101 followed by a slow cooling to surface conditions, reached at around 3-5 Ma (Vázquez *et al.*,  
102 2011). Very young AFT ages in western Sierra Nevada are interpreted as the result of a fold  
103 core's late extensional collapse (Reinhardt *et al.* 2007). In the Sierra de Gador, composed of  
104 Alpujarride units, no thermochronological data are available except in the western valley where  
105 AFT ages of ~16 Ma have been reported (Fig. 2, samples PB365 and PB367 from Platt *et al.*,  
106 2005). A coupling with Ar/Ar data (~25 Ma) suggests a rapid cooling event during the early  
107 Miocene (Fig. 2, samples PB369 and PB533 from Platt *et al.*, 2005). The timing of the final  
108 exhumation of the Sierra de Gador cannot be determined due to the lack of LTT data (such as  
109 AHe). Remnants of inner-platform calcarenites deposited around 7.2 Ma (uppermost Tortonian-  
110 lowermost Messinian) now at high elevation (up to 1600 m) indicate that an important surface  
111 uplift has occurred since the end of the Tortonian (Braga *et al.*, 2003). This uplift results from  
112 the combination of a small-wavelength uplift induced by folding and a greater one induced by  
113 regional dynamic topography (Marín-Lechado *et al.*, 2007; Garcia-Castellanos and Villaseñor,  
114 2011). These deposits lie on a low-relief topography (<250 m; Figs. 2 and 3), and the whole  
115 area has been affected by a Late Tortonian-Early Messinian planation event (Farines *et al.*,  
116 2015). The low-relief summits now observed in the Sierra de Gador can be explained by this  
117 polygenic erosional process. Finally, although a Late Miocene-Early Pliocene exhumation in  
118 the Sierra Nevada associated with the post-Tortonian folding event has been proposed (Vázquez  
119 *et al.*, 2011), its equivalent has not been described in the Sierra de Gador.

## 122 **LT thermochronology and thermal modelling**

124 Eleven samples were initially collected for LT thermochronology analysis in the Alpujarride  
125 complex (sampled in quartzite and phyllite areas) and four AHe datings were performed (Ga-

04, Ga-07, Ga-09 and Ga-1; Fig. 4 and Supporting Information). In this area, the scarcity of apatites and their low uranium content (Johnson *et al.*, 1997; Platt *et al.*, 2005) led us to select Ga-04 (nearest sample from Tortonian calcarenites) for AFT dating to determine a Sierra de Gador cooling path (Fig. 4 and Supporting Information). Alpha-ejection-corrected AHe ages show apparent cooling AHe ages ranging from  $9.2 \pm 0.7$  to  $200 \pm 16.2$  Ma with no age-elevation relationship but a negative correlation between eU content and AHe apparent ages (Fig. 4). Spiegel *et al.* (2009) and Gautheron *et al.* (2012) have shown that the age-eU negative correlation can be interpreted as the result of He implantation from the surrounding material richer in U and Th than most of apatites. Murray *et al.* (2014) show also that implantation can affect AHe age even for a low U-content of the surrounding medium. Following this implantation model, the implantation-free age (or ‘true’ age) corresponds to the apparent age of the single grain with the highest eU content, which, in our study, corresponds to a AHe ‘true’ age of  $9.2 \pm 0.7$  Ma (Fig. 4; Supporting Information). Sample Ga-04 shows an AFT central age of  $16 \pm 2$  Ma corresponding to the AFT ages proposed for the Alpujarride complex in the western valley (PB365 dated at  $16.1 \pm 1.5$  Ma and PB367 dated at  $16.5 \pm 1.5$  Ma; Platt *et al.*, 2005; Figs. 2 and 4). We propose a common exhumation history for the Sierra de Gador and its western valley on the basis of the similar AFT ages without age-elevation correlation (Fig. 4), and the similar levels of erosion of the Alpujarride units partially covered by Tortonian sediments.

Thermal modelling was performed using QTQt software (Gallagher, 2012) to infer the Neogene cooling history of the Sierra de Gador. In addition to the new AHe data (age of  $9.2 \pm 0.7$  Ma) and AFT age ( $16 \pm 2$  Ma), published AFT (PB365 dated at  $16.1 \pm 1.5$  Ma; PB367 dated at  $16.5 \pm 1.5$  Ma) and muscovite Ar/Ar (PB369 dated at  $22.7 \pm 0.8$  Ma; PB533 dated at  $26.0 \pm 1.9$  Ma) data for the Alpujarride complex were used as a vertical profile (Platt *et al.*, 2005; Fig. 2). The resulting model (Fig. 5A) shows a polyphase thermal story with three clear stages: (1) a first

stage of very fast cooling between 23 and 16 Ma ( $\sim 45^{\circ}\text{C}/\text{Ma}$ ); (2) a second stage of strong cooling slowing down between 16 and 7.2 Ma ( $\sim 11.5^{\circ}\text{C}/\text{Ma}$ ); and (3) a third stage of near-surface conditions since 7.2 Ma without late reheating.

## Discussion and conclusions

Our results show an unsteady exhumation since the early Miocene. To infer exhumation rates, we used a mean geothermal gradient of  $49 \pm 11^{\circ}\text{C}/\text{km}$  following the range published for the Alpujarride complex exhumation (Argles *et al.*, 1999; Azañón and Crespo-Blanc, 2000). During the first cooling stage (23-16 Ma), rocks were exhumed at a rate of  $\sim 0.9$  mm/yr. Such a fast cooling event has been widely described for the Alpujarride complex (Sosson *et al.*, 1998; Comas *et al.*, 1999; Platt *et al.*, 2005) and interpreted as a late stage of post-orogenic thinning leading to the exhumation of a previously deeply buried metamorphic alpine-type nappe-stack (Fig. 5B). Then, during the second cooling stage (16-7.2 Ma), Alpujarride rocks from the Sierra de Gador kept exhuming but at a lower rate of  $\sim 0.2$  mm/yr, whereas the Nevado-Filabride units located further north, exhumed at a higher rate of  $\sim 1$  mm/y (Johnson *et al.*, 1997; Vázquez *et al.*, 2011) (Fig. 5A). During the 16-7.2 period, the Alpujarride topography decreased toward sea-level, whereas the Nevado-Filabride unit likely remained in a higher position, as suggested by the current difference in crustal thickness (Diaz *et al.*, 2016; Fig. 5B). These two units are separated by the Alpujarras corridor, which is mainly filled by Serravallian and Tortonian sediments eroded from Alpujarride-Malaguide and Nevado-Filabride units respectively (Rodríguez Fernández *et al.*, 1990; Farines *et al.*, 2015). However, the Sierra de Gador summit surfaces seem to have been formed during pre-Tortonian times (Farines *et al.*, 2015). According to our thermochronological results coupled with these surface and stratigraphic constraints, we



176 propose that the current low relief at the top of the Sierra de Gador started to be shaped 16 Ma  
177 ago (Fig. 5). Indeed, an important decrease in the exhumation rate coeval with topography  
178 decrease toward sea-level strongly suggests a levelling process. Some works have shown that  
179 an important decrease in the cooling rate tending towards a low-temperature plateau is often  
180 associated with planation processes, as in the Sierra de los Filabres (Calvet *et al.*, 2015; Farines  
181 *et al.*, 2015). At 7.2 Ma, surface temperatures were reached (Fig. 5A) and the low topography  
182 was then flooded and reworked by the sea, and inner-platform calcarenites were deposited (Fig.  
183 5B). Low-relief summits, described at a larger scale in the Betics, can be due to Miocene erosion  
184 events, as described in the Sierra de Gador (Farines *et al.*, 2015). After 7.2 Ma, the Sierra de  
185 Gador was uplifted and the Alpujarride rocks have remained at surface temperature conditions.  
186 This non-resetting of thermochronometers implies that the upper Tortonian cover was thin, in  
187 good agreement with the 100-200 m thickness depicted in the preserved Poniente basin further  
188 south (Pedrera *et al.*, 2015). We also cannot distinguish exhumation of rocks after 7.2 Ma,  
189 contrary to what has been described for the Sierra Nevada (Johnson *et al.*, 1997; Reinhardt *et*  
190 *al.*, 2007; Vázquez *et al.*, 2011). In particular, some authors have proposed a stage of accelerated  
191 exhumation around 4-5 Ma linked to a denudation affecting the western Sierra Nevada (Johnson  
192 *et al.*, 1997; Reinhardt *et al.*, 2007). This denudation could be the result of focused crustal  
193 folding accompanied by gravity sliding along surface detachments (Reinhardt *et al.*, 2007).  
194 Marín-Lechado *et al.*, (2007) proposed that the elevation decrease of the ranges southward is  
195 related to a decrease of the folding amplitude. Moreover, the dynamic topographic effect  
196 described in the eastern Betics (Garcia-Castellanos and Villaseñor, 2011) induces a  
197 superimposed uplift signal, which may be higher in the Sierra Nevada as it is located directly  
198 above the Iberian slab tear (Mancilla *et al.*, 2015). One can suppose that the resulting uplift in  
199 the Sierra de Gador was not high enough to induce important denudation after 7.2 Ma. The  
200 degree of fluvial erosion indicates roughly whether there has been equilibrium between uplift

and erosion of landscapes over the last million years (*e.g.*, Whipple, 2001). The presence of minimally dissected summit surfaces in the Sierra de Gador argues for a transient state of the range's topography, whereas equilibrium seems to have been reached for the Sierra Nevada (Azañón *et al.*, 2015). This difference could be explained either by a later uplift stage of the Sierra de Gador and/or by the resetting of the topography due to the Tortonian marine transgression. Indeed, the absence of initial topography increases the landscape response time following an uplift (Lague *et al.*, 2003). The current landscape of the Sierra de Gador results from inherited low relief, which was mainly initiated during Late Miocene, then uplifted and slightly dissected since 7.2 Ma. Finally, the topography of this range appears to be transient, indicating that transient landforms can develop and persist for several Myr during orogenic evolution.

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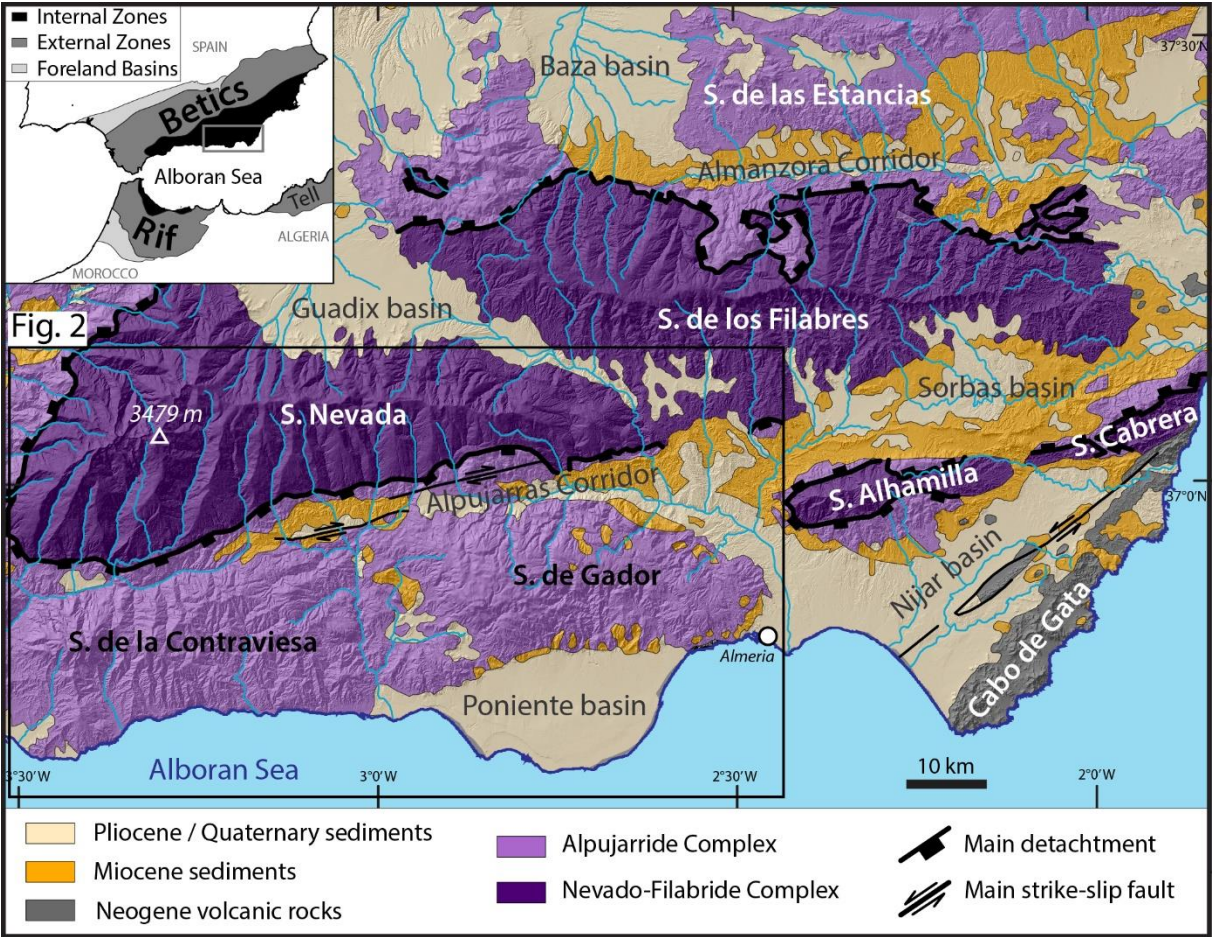
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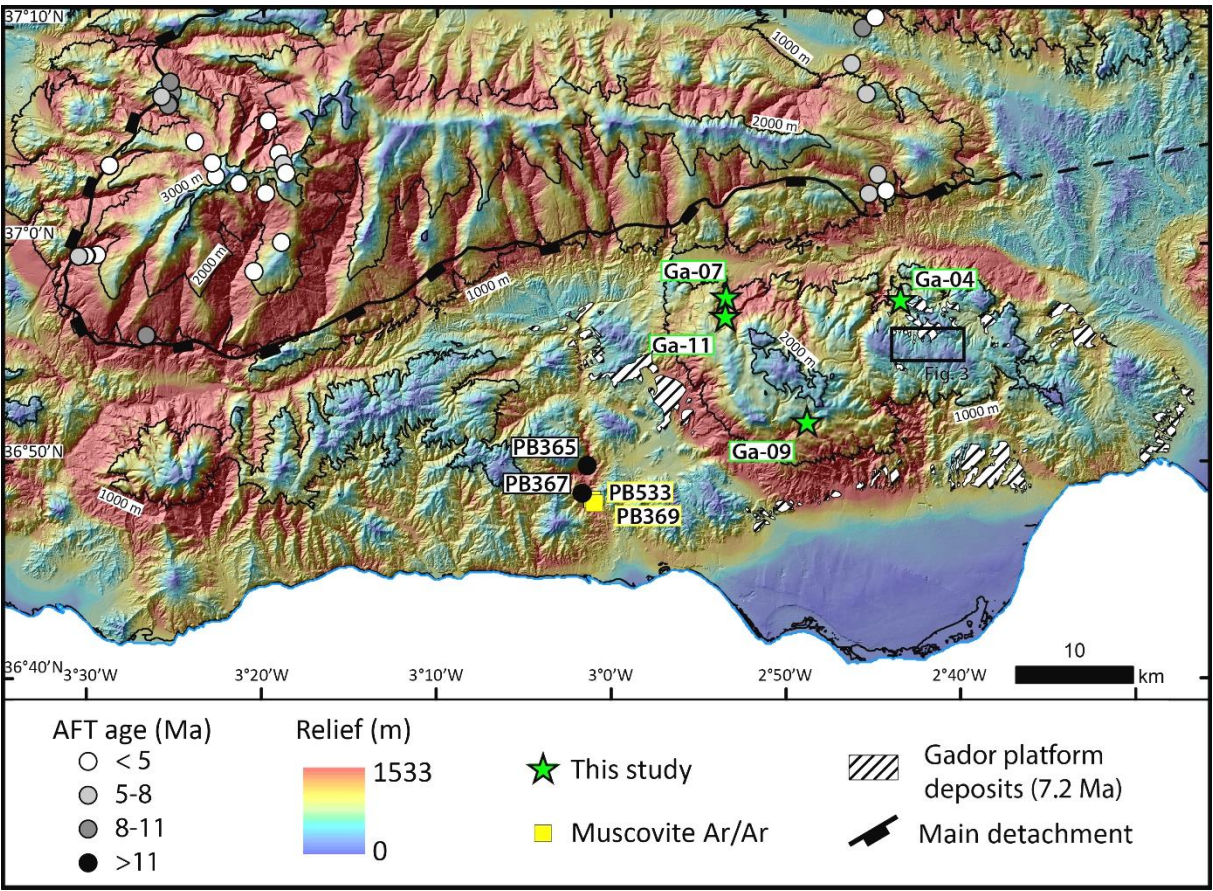
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**Figure 1.** Simplified geological map of the eastern Betics showing the main tectonic units and Neogene basins. Inset shows the main tectonic domains of the peri-Alboran orogenic system in western Mediterranean.



**Figure 2.** Shaded relief map of the eastern Betics showing the locations of the thermochronological samples and sedimentary markers used in this study. Elevation contours are plotted every 1000 m. Relief map was compiled with a 3 km-radius sliding window. Note the widespread presence of low relief (<250 m) extracted at high elevations (>1000 m) at the top of the Sierra de Gador. Samples plotted are from this study and from published data (Johnson *et al.*, 1997; Platt *et al.*, 2005; Reinhardt *et al.*, 2007; Clark and Dempster, 2009; Vázquez *et al.*, 2011)





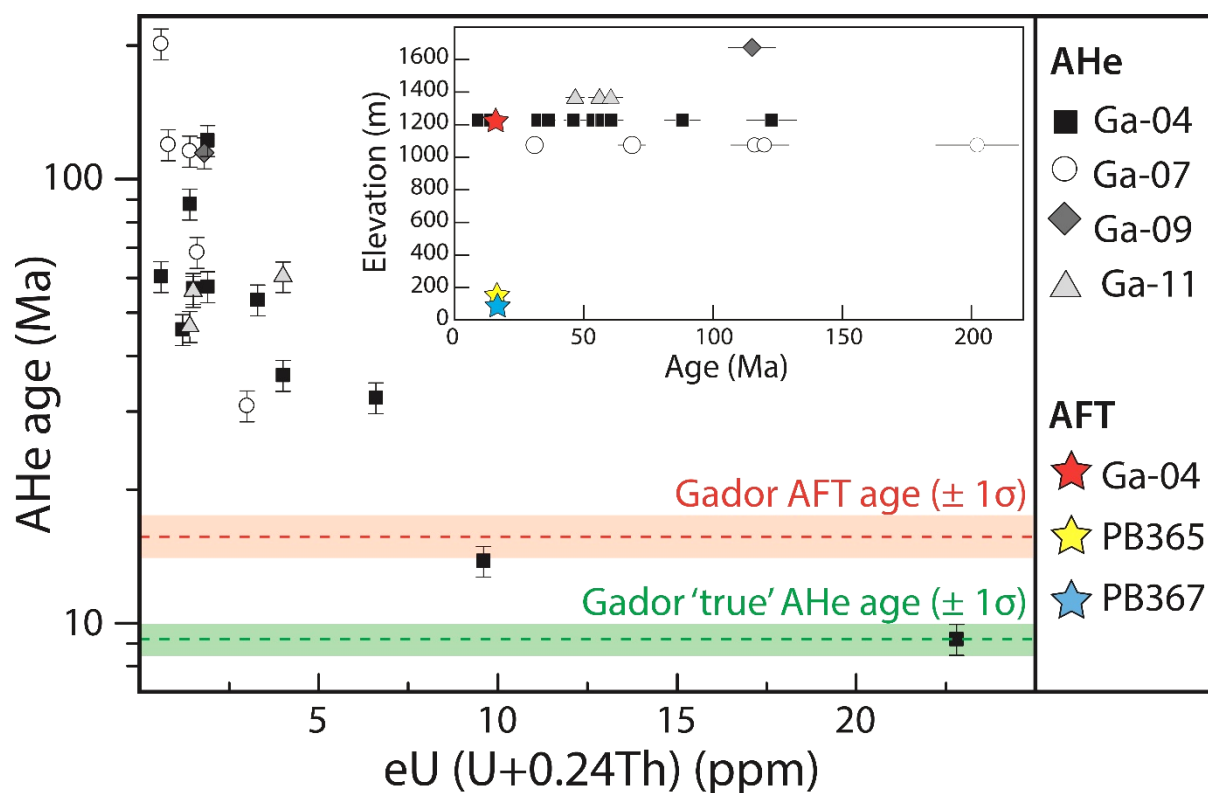
364 **Figure 3.** Photograph (looking north) showing low-relief surfaces overlain by thin calcarenite  
365 deposits at the top of the Sierra de Gador (~1600 m; see location in Fig. 2)

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**Figure 4.** AHe ages of the Sierra de Gador plotted against effective uranium (eU) content. The ‘true’ AHe age ( $9.2 \pm 0.7$  Ma) corresponds to the AHe age associated with the grain showing the highest eU content (see text for explanation). AFT ages from this study (Ga-04) and published data (PB365 and PB367 from Platt *et al.*, 2005) are also reported for comparison. Inset shows all of the LT-thermochronological data on an age-elevation profile



**Figure 5.** Exhumation story and landscape evolution of the Sierra de Gador domain during Neogene times. (A) Neogene cooling path obtained from inverse modelling: thick black line = expected model; thin black lines = the 95% confidence interval. Inset shows the comparison between the Sierra de Gador cooling path (black line) and the Sierra Nevada cooling paths published by Vázquez *et al.* (2011) (light and dark grey lines). (B) Sketch showing the main stages of tectonic and landscape evolution of the Sierra de Gador-Sierra Nevada domain (deduced from LT thermochronological data and geological constraints).

