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# Late Miocene to present-day exhumation and uplift of the Internal Zone of the Rif chain: Insights from low temperature thermochronometry and basin analysis

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A B S T R A C T

Located on the margin of the west Alboran basin, the Gibraltar Arc (Betic-Rif mountain belt) displays post-Pliocene vertical movements evidenced by uplifted marine sedimentary basins and marine terraces. Quantification of vertical movements is an important clue to understand the origin of present-day relief generation in the Betic-Rif mountain chain together with the causes of the Messinian Salinity Crisis. In this paper, we present the results of a pluridisciplinary study combining an analysis of low temperature thermochronology and Pliocene basins evolution to constrain the exhumation history and surface uplift of internals units of the Rif belt (Northern Morocco). The mean (U-Th)/He apatite ages obtained from 11 samples are comprised between 14.1 and 17.8 Ma and display a wide dispersion, which could be explained by a great variability of apatite chemistries in the analyzed samples. No correlations between altitude and age have been found along altitudinal profile suggesting a rapid exhumation during this period. Thermal modeling using our (U-Th)/He apatite ages and geochronological data previously obtained in the same area ($^{40}Ar/^{39}Ar$ and K/Ar data on biotite, zircon and apatite fission track) allow us to propose a cooling history. The rocks suffered a rapid cooling at 60–100 °C/Ma between 22.5 and 19 Ma, then cooled to temperatures around 40 °C between 19 and 18 Ma. They were re-heated at around 110 °C between 18 and 15 Ma then rapidly cooled and exhumed to reach the surface temperature at around 13 Ma. The re-heating could be related to a renewal in thrusting and burying of the inner zones. Between 15 and 13 Ma the cooling resumed at a rate of 50 °C/Ma indicating an exhumation rate of 0.8 mm/y considering an average 40 °C/km geothermal gradient. This exhumation may be linked to the extension in the Alboran Sea. Otherwise biostratigraphic and sedimentological analysis of Pliocene basins of the internal Rif provided informations on the more recent events and vertical movements. Pliocene deposits of the Rifian coast represent the passive infilling of palaeo-rias between 5.33 and 3.8 Ma. The whole coastal area was uplifted at slow average rates (0.01–0.03 mm/y) in relation with a northeastward tilting of 0.2–0.3° since the Lower-Pliocene. A late Pliocene to present extensional tectonics associated to uplift has been identified all along the coastal ranges of the Internal Zone of the Rif chain. This extension was coeval with the major late Pliocene to Pleistocene extensional episode of the Alboran Sea and appears to be still active nowadays. No significant late Messinian uplift was evidenced, thus calling into question the geodynamic models relating the closure of the marine gateways and the MSC to slab roll back.


## 1. Introduction

The Rif chain culminates at 2400 m on the margin of the west Alboran basin located at the westernmost tip of the western

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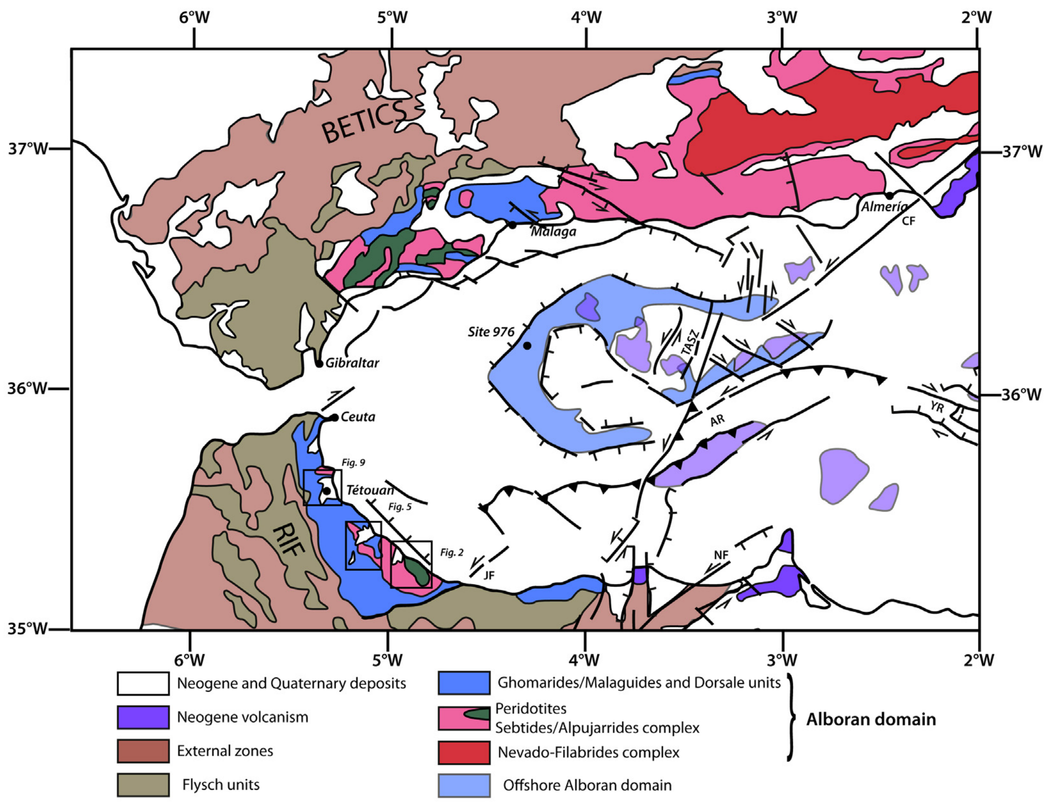


**Fig. 1.** Structural map of the Alboran basin and Rif-Betic orogen (modified after Comas et al., 1999 and Martínez-García et al., 2011) showing the location of studied areas. AR: Alboran Ridge; CF: Carboneras Fault; JF: Jebha Fault; NF: Nekor Fault; TASZ: Trans-Alboran Shear Zone; YR: Yussuf Ridge.

Mediterranean (Fig. 1) in a very complex geodynamic setting (Chalouan et al., 2008 and references therein). The originality of this work is to tackle the question of vertical motions with two different approaches: the exhumation of the magmatic and/or metamorphic basement rocks recorded by low temperature thermochronometry and the surface uplift recorded by the sedimentary basins evolution.

Several previous works have addressed the exhumation history of the Internal Zones of the Rif chain (synthesis in Michard et al., 2006; Chalouan et al., 2008). All these papers focused on high temperature thermochronometry (Ar/Ar; U/Pb; U-Th/Pb) and solely Azdimousa et al. (2013) presented low temperature thermochronometric data (Apatite Fission Tracks; AFT). Whatever the geochronological method used in all these previous works, no age younger than ca. 15 Ma were obtained in the Internal Rif belt and thus, only the pre-15 Ma exhumation of the Rif was constrained. Consequently we focus in this paper on the evolution of the relief since 15 Ma with adapted tools to constrain the latest and shallowest stage of the exhumation history: apatite (U-Th)/He (AHe) thermochronometry and late Neogene basin study. Late Neogene basins from the Internal Zone of the Rif chain were previously studied and their uplift was evidenced early (e.g., Fallot, 1937; Feinberg and Lorenz, 1970; Wildi and Wernli, 1977; Wernli, 1988; Loget and Van Den Driessche, 2006). These basins recorded a general marine to continental transition followed by an ongoing uplift during the Quaternary as exemplified by uplifted marine terraces (Meghraoui et al., 1996). We present in this study new biostratigraphic and sedimentological data and some tectonic observations on the late Neogene basins that help to constrain the vertical movements of the Internal Zone of the Rif in late Neogene times.

The quantification of vertical movements for the 0–15 Ma interval is of importance because numerous geodynamic models have been proposed to explain the present-day relief generation in the Betic-Rif mountain chain together with the causes of the Messinian Salinity Crisis (e.g., Duggen et al., 2003, 2004). This work is a first attempt to evaluate these movements.

## 2. Geological and geodynamic setting

Localized at the westernmost tip of the Alpine belt and Cenozoic Mediterranean basin, the Betic-Rif arc form an orogenic system surrounding the Alboran Basin. Resulting of convergence between Africa and Eurasia since late Mesozoic, the complex tectonic evolution of this region is still a matter of debate.

The Betic-Rif orogenic system consists of stacked napes thrusted onto the Guadalquivir and Gharb foreland basins. It is divided into four major structural domains (Chalouan et al., 2008 and references therein) from external to internal (Fig. 1):

i. The External Zones correspond to Triassic to Miocene formations of the African and Iberian paleomargins. There are separated, from external to internal, into Prebetic and Subbetic in the Betic part and into Prerif, Mesorif and Intrarif in the Rif part. This domain was folded and thrusted during the Miocene collision and the Guadalquivir and Gharb areas became foreland basins.
ii. The Flyschs units, located in between External and Internal zones, originated from the Ligurian-Maghrebian Ocean which connected Central Atlantic and Alpine Oceans from Jurassic to Paleogene. There are composed of a nappe stack of predominantly turbiditic deposits. Upper formations were supplied early Miocene to late Burdigalian sediments from Internal Zone (De Capoa et al., 2007). A folding event affected these units after the late-Burdigalian and is associated with uplift-erosion in the Internal Zones probably constraining the onset of convergence