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An uplift history of Crete, Greece, from inverse modeling of longitudinal river profiles

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ABSTRACT

We jointly invert Cretan drainage networks to determine a temporal and spatial history of regional uplift. Our model assumes that longitudinal river profiles are controlled by uplift rate history and moderated by the erosional process. We have parameterized fluvial erosion using an advective–diffusive formulation. The inverse model recovers the smoothest uplift rate history that best fits a data set of ~250 longitudinal river profiles. Residual misfit between theoretical and observed river profiles decreases from 18 to 4 during optimization. Results suggest that Crete has been uplifted by 1–2 km during the last 4 Ma. The central Iraklion Ridge first became emergent at ~4 Ma, with eastern and western ends of Crete emerging ~1 Ma later. Maximum uplift rates of 1–1.2 mm/yr occurred in central and western Crete between 0 and 1 Ma. This calculated history of uplift is consistent with independent sedimentological, stratigraphic, and paleontological constraints.

1. Introduction

Crete is perched on the southern margin of the Aegean plate, beneath which Mediterranean seafloor is being subducted (Fig. 1A). It is generally accepted that the elevation and relief of this island developed in response to the history of subduction (e.g., Angelier, 1979; Le Pichon and Angelier, 1981; Ganas and Parsons, 2009; Shaw and Jackson, 2010). Le Pichon and Angelier (1979) suggested that the island has been uplifted in response to sedimentary underplating. Receiver function studies from Crete recognize a region that has low P- and S-wave velocities between 20 and 50 km depth, which is explained by subducted sediments or by serpentinised mantle (Knapmeyer and Harjer, 2000; Li et al., 2003; Endrun et al., 2004; Sodoudi et al., 2006). The isotopic composition of igneous rocks erupted from Santorini and Milos has no obvious sedimentary signature, suggesting that sediments have not been subducted to depths at which melting occurs (Fig. 1B). Buoyant sediments may have been partially scraped off to form the accretionary prism or subducted to shallow depths beneath Crete where they thicken the crust, generating uplift. The location of splay faults in the accretionary wedge above the subduction interface may control the growth of topography in Crete by uplifting the overriding Aegean plate (Shaw et al., 2010). Bohnhoff et al. (2001) carried out a wide-aperture seismic experiment in Crete and found P-wave velocities of 6.45–6.9 km/s at depths of 15–30 km, which may be diagnostic of compacted sediments. The island sits at the southern edge of a ~400 × 400 km region that is dynamically supported by 0.5–1 km (Fig. 1B; Faccenna et al., 2003).

Uplifted shorelines and marine terraces have been biostratigraphically and radiometrically dated along the Cretan coastline and have been used to establish an uplift history (e.g., Spratt, 1856; Angelier, 1979; Gaki-Papanastassiou et al., 2009; Shaw et al., 2010). Longer histories can be determined from the elevation of Calabrian (1.8–0.8 Ma) marine rocks, which occur at elevations of up to 1 km (Alexopoulos and Marcopoulou-Diacantoni, 1996).

We determine an uplift history of Crete for the last few million years. Our purpose is to show that uplift histories consistent with independent geological observations can be determined from drainage patterns on length scales of tens of kilometers and over timescales of hundreds of thousands of years.

2. Drainage patterns

Longitudinal river profiles, where elevation is plotted as a function of distance along a river, indirectly record uplift rate as a function of space and time (e.g. Whipple and Tucker, 1999; Roberts and White, 2010). We have extracted a drainage network from the ASTER GDEM data set (http://www.gdem.aster.ersdac.or.jp; Fig. 2). First, anomalous spikes and sinks were removed from the digital elevation model (DEM). Secondly, we determined a drainage network by calculating flow directions across the island. In western Crete, the fidelity of mapped drainage was checked using kinematic GPS surveys, which were

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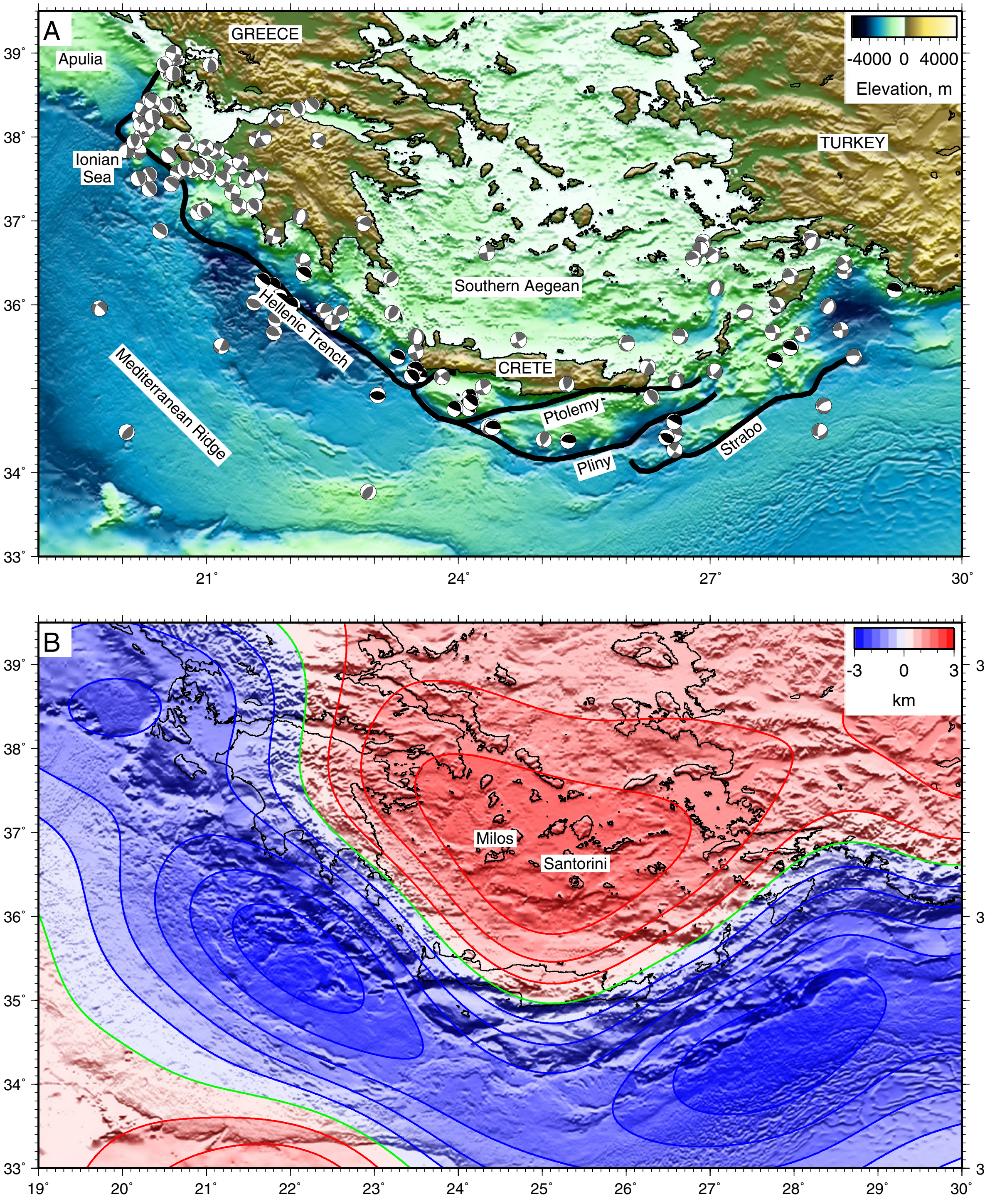

Fig. 1. (A) Regional topographic and bathymetric map (Smith and Sandwell, 1997: v11.1). Thick black lines = south-facing bathymetric scarps and trenches. Black focal mechanism = thrust faults (Shaw et al., 2010). (B) Dynamic topography calculated using an admittance of 40 mgal/km and GRACE free-air gravity anomalies filtered between 400 and 2500 km (Tapley et al., 2005). Contour interval = 0.5 km; green contour = 0 km. Shading = topographic and bathymetric relief. Note that volcanic islands Santorini and Milos sit within the +1.5-km contour. Loading of African plate produces negative anomalies.

acquired in September 2008 (Fig. 3). Elsewhere, Landsat imagery was used to check extracted networks (Fig. 4). Many Cretan rivers, especially those draining southward, flow through steep and narrow (few tens of meters wide) gorges. In these gorges, coarse-grained alluvium drapes bedrock (Fig. 3; Caputo et al., 2010). Away from gorges, extracted drainage networks have a resolution of ~30 m. Crete is drained by ~270 rivers with Strahler order >2 (Strahler, 1957). We extracted 237 river profiles from this data set (Appendix A). Profiles have a variety of shapes ranging from strongly convex upward to smoothly concave upward. River profiles from the highlands of Crete are often convex upwards and many rivers have 10–20 km long knickzones (Fig. 5). Along each river, we have plotted substrate lithology (Andronopoulos, 1993). We have then compared river profile slope and curvature to changes in substrate within a 1.5-km moving window. Substrate strength, σ_t, is gaged using Sklar and Dietrich's (2001) parameterization. At wavelengths of ~1.5 km, 90% of changes in