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Active simultaneous uplift and margin-normal extension in a forearc high, Crete, Greece

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ABSTRACT

The island of Crete occupies a forearc high in the central Hellenic subduction zone and is characterized by sustained exhumation, surface uplift and extension. The processes governing orogenesis and topographic development here remain poorly understood. Dramatic topographic relief (2–6 km) astride the southern coastline of Crete is associated with large margin-parallel faults responsible for deep bathymetric depressions known as the Hellenic troughs. These structures have been interpreted as both active and inactive with either contractional, strike-slip, or extensional movement histories. Distinguishing between these different structural styles and kinematic histories here allows us to explore more general models for improving our global understanding of the tectonic and geodynamic processes of syn-convergent extension. We present new observations from the south–central coastline of Crete that clarifies the role of these faults in the late Cenozoic evolution of the central Hellenic margin and the processes controlling Quaternary surface uplift. Pleistocene marine terraces are used in conjunction with optically stimulated luminesce dating and correlation to the Quaternary eustatic curve to document coastal uplift and identify active faults. Two south-dipping normal faults are observed, which extend offshore, offset these marine terrace deposits and indicate active N–S (margin-normal) extension. Further, marine terraces preserved in the footwall and hanging wall of both faults demonstrate that regional net uplift of Crete is occurring despite active extension. Field mapping and geometric reconstructions of an active onshore normal fault reveal that the subaqueous range-front fault of south–central Crete is synthetic to the south-dipping normal faults on shore. These findings are inconsistent with models of active horizontal shortening in the upper crust of the Hellenic forearc. Rather, they are consistent with topographic growth of the forearc in a viscous orogenic wedge, where crustal thickening and uplift are a result of basal underplating of material that is accompanied by extension in the upper portions of the wedge. Within this framework a new conceptual model is presented for the late Cenozoic vertical tectonics of the Hellenic forearc.

1. Introduction

The Hellenic Subduction zone is the largest, fastest and most seismically active subduction zone in the Mediterranean, where the African slab subducts beneath Crete at a rate of ~36 mm yr^{-1} (Fig. 1; McClusky et al., 2000; Reilinger et al., 2006). Cenozoic subduction resulted in the construction of a large south-facing orogenic wedge spanning from the northern coastline of Crete to the surface expression of the subduction trench (e.g., Willett et al., 1993; Rahl et al., 2005; Wegmann, 2008; Jolivet and Brun, 2010). The leading edge of the subduction zone is obscured beneath a thick package of sediments and is often misidentified as the more inboard bathymetric depressions known as the Hellenic troughs, but it is actually located outboard of the Mediterranean Ridge accretionary complex, ~150 km south of Crete (Fig. 1; Ryan et al., 1982; Kastens, 1991; Chamot-Rooke et al., 2005). The topographic development of prominent forearc highs (e.g. Crete, Rhodes) is controlled by ongoing convergence and characterized by rapid, broad, sustained uplift with widespread upper-crustal

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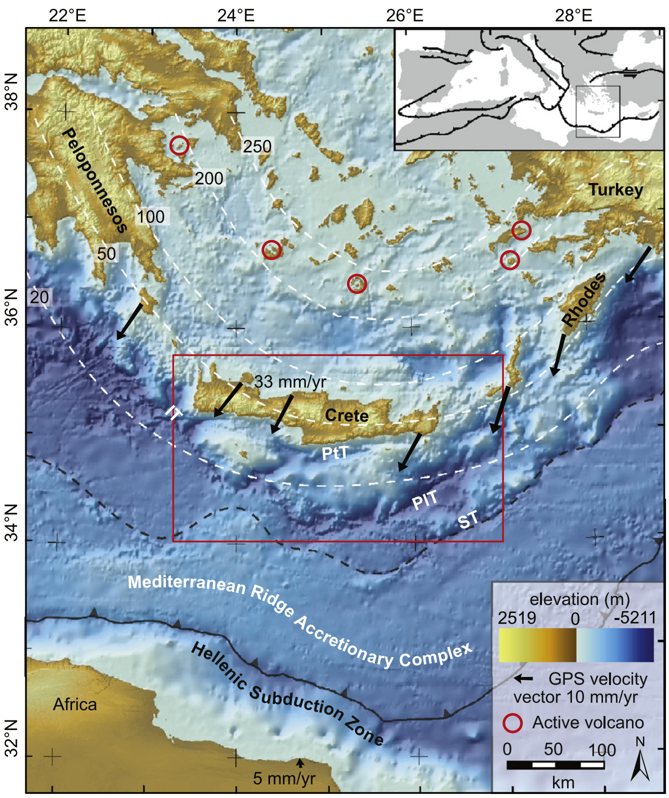

Fig. 1. Tectonic setting of the eastern Mediterranean in the vicinity of Crete, Greece. Inset: map of the major active and inactive convergent boundaries in the Mediterranean region and the North Anatolian Fault. The box highlights the area of the larger map. The Hellenic troughs, including the Ionian (IT), Ptolemy (PtT), Pliny (PlT), and Strabos (ST) are labeled. The location of the Hellenic Subduction zone in the south and back thrust (black dashed line) to the north that define the boundaries of the Mediterranean Ridge Accretionary complex is from Kreemer and Chamot-Rooke (2004). The GPS velocity vectors (black arrows) are resolvable into a total convergence rate of ∼36 mm/yr (Reilinger et al., 2006). Depth (km) to the subducting plate (dashed white lines) is from Benioff-zone seismicity (Papazachos et al., 2000), mico-seismicity (Meier et al., 2004; Becker et al., 2006), and an upper mantle seismic velocity model (Gudmundsson and Sambridge, 1998). The red box shows the location of Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

extension (Angelier et al., 1982; Knapmeyer and Harjes, 2000; Rahl et al., 2005). Despite more than 40-years of geologic and geophysical investigations in the eastern Mediterranean, the tectonic and geodynamic processes governing uplift and extension of the Hellenic forearc remain contentious.

Essential to this debate are the kinematics and activity of a series of large arc-parallel faults and associated escarpments embedded in the forearc that are related to the construction of the Hellenic troughs and bound Crete's southern coastline (Figs. 1, 2). Two sets of faults dominate the central Hellenic margin; N–S striking extensional faults (Taymaz et al., 1990; Nyst and Thatcher, 2004; Bohnhoff et al., 2005; Shaw and Jackson, 2010) and much larger approximately E–W striking structures that are oriented subparallel to the high topographic and bathymetric relief (Figs. 1, 2; Angelier et al., 1982; Peterek and Schwarze, 2004). The N–S striking structures are unambiguously active normal faults as indicated by Holocene fault scarps and earthquake focal mechanisms (Bohnhoff et al., 2005; Caputo et al., 2006; Shaw and Jackson, 2010). However, a diversity of opinions exists as to the activity and kinematics of the larger E–W striking faults, with interpretations ranging from active to inactive, and including contractional, strike-slip and extensional; depending in part upon the dataset used to interpret displacement history (e.g. Angelier et al., 1982; Meulenkamp et al., 1988, 1994; Taymaz et al., 1990; Bohnhoff et al., 2001; Ring et al., 2001, 2003; ten Veen and Kleinspehn, 2003; Kreemer and Chamot-Rooke, 2004; Peterek and Schwarze, 2004; Rahl et al., 2005; Meier et al., 2007; Becker et al., 2010; Shaw and Jackson, 2010; Özbakır et al., 2013). The correctness of one model versus another has direct implications for the processes driving orogenesis above the Hellenic subduction zone as well as the potential seismic hazard posed by these faults.

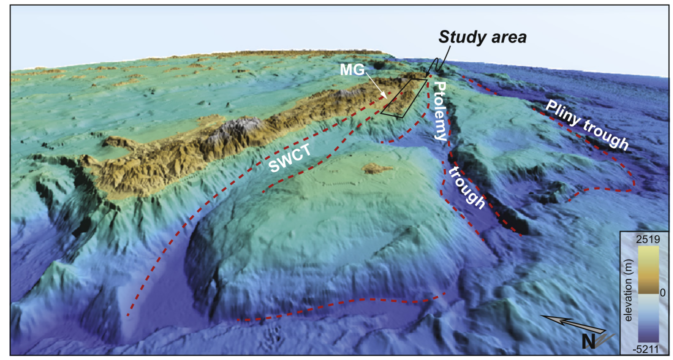

Fig. 2. Perspective view of digital topography (ASTER-topography, GEBCO-bathymetry) of the central Hellenic forearc highlighting the E–W striking structures that are the focus of this investigation, including the Southwest Cretan trough (SWCT) and Messara Graben (MG). Note the scale and dramatic topographic relief (2–6 km) associated with these faults. The N–S striking extensional faults are difficult to discern at the scale of the map and are thus not highlighted. The rectangle outlines the study area shown in Fig. 3.

Le Pichon and Angelier (1981) argued that Crete is a rigid backstop, and that uplift of the island was due to sediment underplating beneath this backstop. However, the presence of young, deeply exhumed high-pressure metamorphic rocks and active normal faults on the island are observations contrary to the hypothesis of a rigid backstop (e.g. Angelier et al., 1982; Fassoulas et al., 1994; Bohnhoff et al., 2001). Exhumation of the high-pressure metamorphic units is interpreted to have occurred by N–S (margin-normal) extension on E–W striking faults (Angelier et al., 1982; Fassoulas et al., 1994; Jolivet et al., 1996; Ring and Layer, 2003). Meulenkamp et al. (1988, 1994), Taymaz et al. (1990), and Shaw and Jackson (2010) posited that margin-normal extension has ceased and margin-normal shortening is now active on the Hellenic trough faults, resulting in the crustal thickening and uplift of Crete. Some researchers hypothesize that the E–W striking faults now accommodate sinistral strike-slip motion (ten Veen and Kleinspehn, 2003), while others argue that these structures continue to accommodate margin-normal extension (Angelier et al., 1982; Ring et al., 2001, 2003; Peterek and Schwarze, 2004). In these latter cases, upper crustal shortening is unlikely, requiring ongoing underplating to thicken the crust and raise Crete above the geoid as shown by Knapmeyer and Harjes (2000) and argued by Ring and Layer (2003).

Here we present new observations that show that margin-normal extension in the Hellenic forearc continues to the present and acts in concert with rapid, sustained uplift. Our study focuses on the tectonic geomorphology of the southern coastline of central Crete adjacent to the Ptolemy trough, one of the Hellenic troughs, where multiple sets of E–W striking faults extend offshore. South–central Crete is opportunistically situated to determine the activity and kinematics of these E–W striking faults and elucidate the processes that dictate ongoing orogenesis above the Hellenic subduction zone (Fig. 2). Pleistocene marine terraces are used in conjunction with optically simulated luminescence (OSL) and correlations to the Quaternary eustatic curve to document the rates and patterns of coastal uplift and identify active faults. Structural mapping, fault scaling properties and fault aspect ratios are used to determine the size of onshore faults and for testing hypothesized geometries and kinematics of the Ptolemy trough fault