Quaternary International 401 (2016) 43–70

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Vertical land movements and sea level changes along the coast of Crete (Greece) since Late Holocene

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A R T I C L E I N F O

Article history:
Available online 29 October 2015

Keywords:
Crete
Relative sea level change
Tidal notches
Beachrocks
Archaeological indicators

A B S T R A C T

Geomorphological survey along the coasts of Crete revealed widespread evidence of uplifted and submerged tidal notches, different phases of beachrock formation, and many relics of ancient coastal constructions. About 1.6 ka BP, when the sea level was at −1.25 ± 0.05 m, the western tectonic block of the island uplifted by 9.15 ± 0.20 m in its westernmost extremity and by 2.00 m approximately in its eastern boundary and tilted southeastward. Repeated preceding episodes of subsidence submerged the western part of the island by 1.60 m in a period of 2300 years. Along the western coast, the younger phase of the submerged beachrocks was identified and measured at nineteen locations, together with the submerged tidal notches and archaeological remains. Land subsidence by 1.25 ± 0.05 m, subsequent to the uplift of the western part, occurred after the late Venetian occupation period (~AD 1600), coincident with the submersion of the eastern part of the island.

In central and eastern Crete, the relative sea level change evidence from tidal notches and beachrocks revealed five distinct sea level stands at −6.55 ± 0.55 m, −3.95 ± 0.35 m, −2.70 ± 0.15 m, −1.25 ± 0.05 m and −0.55 ± 0.05 m. The lowest sea level stand can be identified with the oldest dated tidal notch of western Crete between 4200 ± 90 B P and 3930 ± 90 B P. Two subsequent sea levels can be linked with the Protopalatial (1900–1700 B C or 1600 B C) and Neopalatial period (1600–1450 B C) of the Minoan civilization, according to submerged prehistoric morphologies and inundated Minoan constructions. The change of sea level from −2.70 ± 0.15 m to −1.25 ± 0.05 m is placed between 1450 B C and the fourth century BC. The dating of −1.25 ± 0.05 m sea level stand was based on the measurement and interpretation of ancient coastal installations built along the coast of central and eastern Crete during Classical, Hellenistic, Roman, Byzantine and Venetian periods. Historical sources report a relative sea level rise by 0.70 m during the AD 1604 paroxysmal event. Over the last 400 years, the relative sea level rose by 0.55 m. The uplift of the coast of western Crete and the submersion in its central and eastern coast indicate that during the AD 365 paroxysmal event the island was split along a tectonic boundary identified with the neotectonic graben of Spili and its northern and southern prolongation.

1. Introduction

The uplift of the western coast of Crete during Upper Holocene has been the subject of observation and study of many researchers for more than 100 years (Spratt, 1865; Raulin, 1869; Hafemann, 1965; Keraudren, 1971, 1979; Dermitzakis, 1973; Flemming, 1978; Laborel et al., 1979; Thommeret et al., 1981; Pirazzoli et al., 1982; Pirazzoli, 1986a; Kelletat, 1991). Since the first pioneering studies (Laborel et al., 1979; Pirazzoli et al., 1982; Pirazzoli, 1986a), at the SW edge of western Crete, at least nine uplifted fossil shorelines were recorded, declining in elevation towards the east. Using radiometric dating, it was estimated that the fossil shorelines formed during repeated subsiding events, occurred between 4200 ± 90 B P and 1550 ± 90 B P. Between 3870 ± 90 B P and 1550 ± 90 B P, the coast subsided by 1.60 m, falling progressively by 0.25 m approximately every 250 years. In the westernmost extremity of the island, after the formation of the uppermost

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http://dx.doi.org/10.1016/j.quaint.2015.08.008
1040-6182/

shoreline, a sudden uplift occurred during the AD 365 strong tsunamigenic earthquake (Pirazzoli, 1986a; Stiros and Drakos, 2006; Shaw et al., 2008) causing the uplift of the highest tidal notch at +7.90 ± 0.20 m and at +4.80 ± 0.50 m of the lowest one. The tectonic model proposed by Pirazzoli (1986a), considered a tectonic block some 100 km long that rose by 8 m approximately in its SW extremity and tilted northeastwards. Early studies assessed that the uplift occurred after 1685 B P (Hafemann, 1965) or during the last 1500 years (Flemming, 1978). Further studies estimated the age of the uplifting event at AD 63–75 ± 90 radiocarbon years BP (Dominey-Howes et al., 1998) or even later to the late fifth or early sixth century (AD 480–500) (Price et al., 2002). The latter consider that this large uplift did not occur simultaneously with a catastrophic earthquake. Neumeier et al. (2000) suggested a progressive instead of an abrupt uplift of the western coast by 0.50 m, as observed in the Damnoni coast. From radiocarbon dating performed on the HMC cement of beachrocks, they deduced that it started in the fourth century AD, from +1.80 m (sea level position at the beginning of the first millennium AD), to +1.30 m (sea level position around AD 585–835), until 1647–1895, when sea level was near to the present-day position.

The coast of central and eastern Crete displays abundant geomorphological and archaeological relative sea level indicators (Spratt, 1865; Marinatos, 1926; Evans, 1928; Blanc, 1958; Leatham and Hood, 1958/59; Boekschoten, 1962, 1963; Hafemann, 1965; Blackman, 1973; Dermitzakis, 1973; Blackman and Branigan, 1975; Kelletat, 1979, 1996; Pirazzoli, 1980; Pirazzoli et al., 1982; Nakasis, 1987; Mourtzas, 1988a, 1988b, 1990, 2012a, 2012b; Shaw, 1990; Mourtzas and Marinos, 1994), although interpretations sometimes lead to contradictory or doubtful conclusions on the intervening sea level changes (Blackman, 1973; Davaras, 1974, 1975; Flemming, 1978; Flemming and Pirazzoli, 1981; Kelletat, 1996; Blackman, 2011).

Flemming (1978), proposed a model with four evolution scenarios for the coast of central and eastern Crete over the last 2000 years. This model considers a crustal tilting that uplifted in the southeast and subsided in the northeast, which has been extensively discussed in Mourtzas (2012a; 2012b). In a following paper, Flemming and Pirazzoli (1981) modified the model and showed that the eastern part of Crete was subsiding gradually towards NE to a depth even larger than 4.0 m Mourtzas (1988a, 1988b, 1990, 2012a, 2012b) estimated that the relative sea level change of about 4.0 m observed in central and eastern Crete occurred at least in three subsiding phases over the last 4000 years.

In this paper, new data on relative sea level change along the coast of Crete are presented (Fig. 1), from the observations of geomorphological and archaeological indicators that suggest the occurrence of five distinct sea level stands and which are used to propose a new relative sea level curve for this region.

2. Geotectonic setting

The island of Crete is located in the central Mediterranean basin, along the transition zone between the African and Eurasian plates, in the fore-arc of the Hellenic Subduction Zone. The high seismicity of this area is triggered by the crustal shortening and subduction of the African oceanic lithosphere beneath the Aegean microplate. Here, the Wadati-Benioff seismic zone is dipping northwards beneath Crete up to a depth of 200 km (Le Pichon and Angelier, 1979; Knapmeyer and Harjes, 2000). Geodetic and seismic data indicate active crustal deformations with relative movements of the Aegean microplate with respect to Africa exceeding 3–4 cm per year (Le Pichon and Angelier, 1979; McCluskey et al., 2000; Kreemer and Chamot-Rooke, 2004; Serpelloni et al., 2013; Anzidei et al., 2014) (Fig. 2a).

The southern part of the Hellenic Trench (HT) includes a system of E–NE trending troughs that delimit Crete island from the Mediterranean Ridge (MR) complex. MR consists of sediment accumulations from the subducted African plate, 10–14 km thick approximately (Le Pichon et al., 2002). HT is characterized by compressive tectonics in its western part and normal or strike-slip faults delimiting the troughs to the east (Hsu and Ryan, 1973; Got et al., 1977; Stanley, 1977; Peters, 1985; Peters and Huson, 1985; Papazachos et al., 1991; Kiratzi and Louvari, 2003; Benetatos et al., 2004). The differential tectonic behavior of the two sectors of HT is also observed in the continental area of Crete: compression

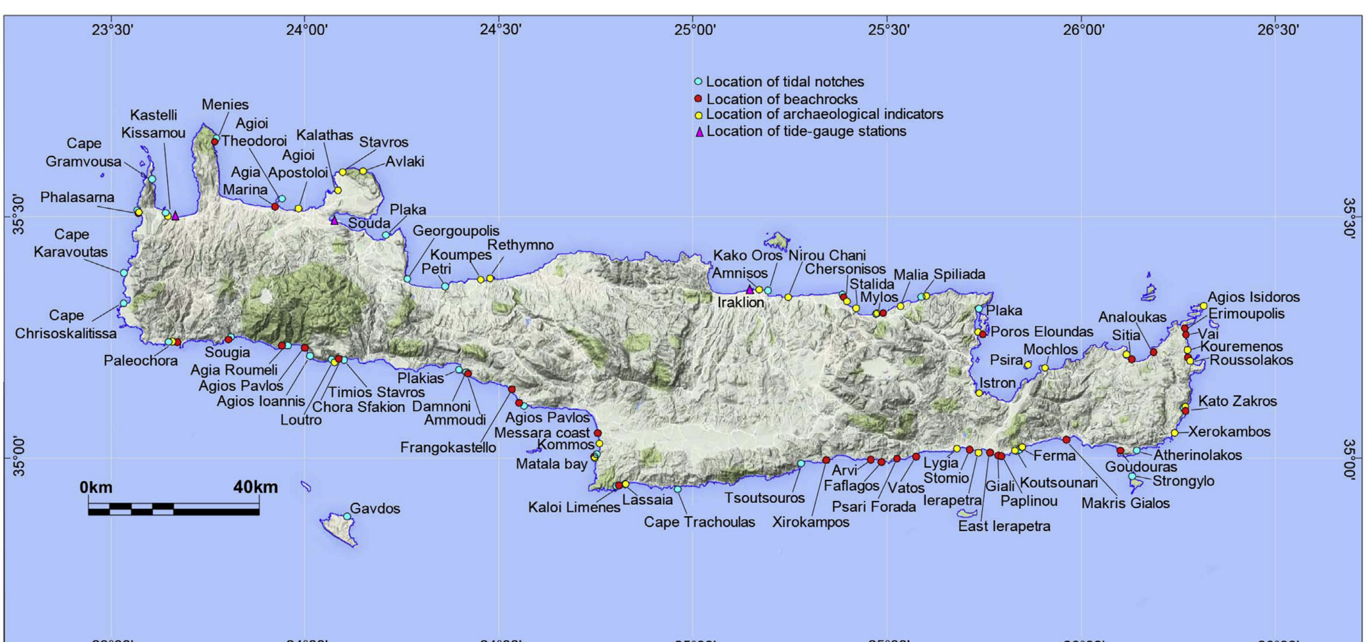

Fig. 1. Location map of Crete. Survey locations of tidal notches, beachrocks and archaeological indicators are shown by circle in different color. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).