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

Article *in* Quaternary International · May 2016

DOI: 10.1016/j.quaint.2015.08.008

3 authors:

Nikos Mourtzas
Gaiaergon S.A.

Eleni Kolaiti
AKTES - Society for the Study of Ancient Coastlines NPO

Marco Anzidei
National Institute of Geophysics and Volcanology

Quaternary International xxx (2015) 1–28

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

Nikos Mourtzas [a, *], Eleni Kolaiti [b], Marco Anzidei [c]

[a] GAIAERGON Ltd, Athens, Greece
[b] University of Peloponnese, GAIAERGON Ltd, Athens, Greece
[c] Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

ARTICLE INFO

Article history:
Available online xxx

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

ABSTRACT

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

* Corresponding author.
E-mail addresses: gaiaergon@gmail.com, nikosmourtzas@gmail.com (N. Mourtzas).

http://dx.doi.org/10.1016/j.quaint.2015.08.008
1040-6182/© 2015 Elsevier Ltd and INQUA. All rights reserved.

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.).

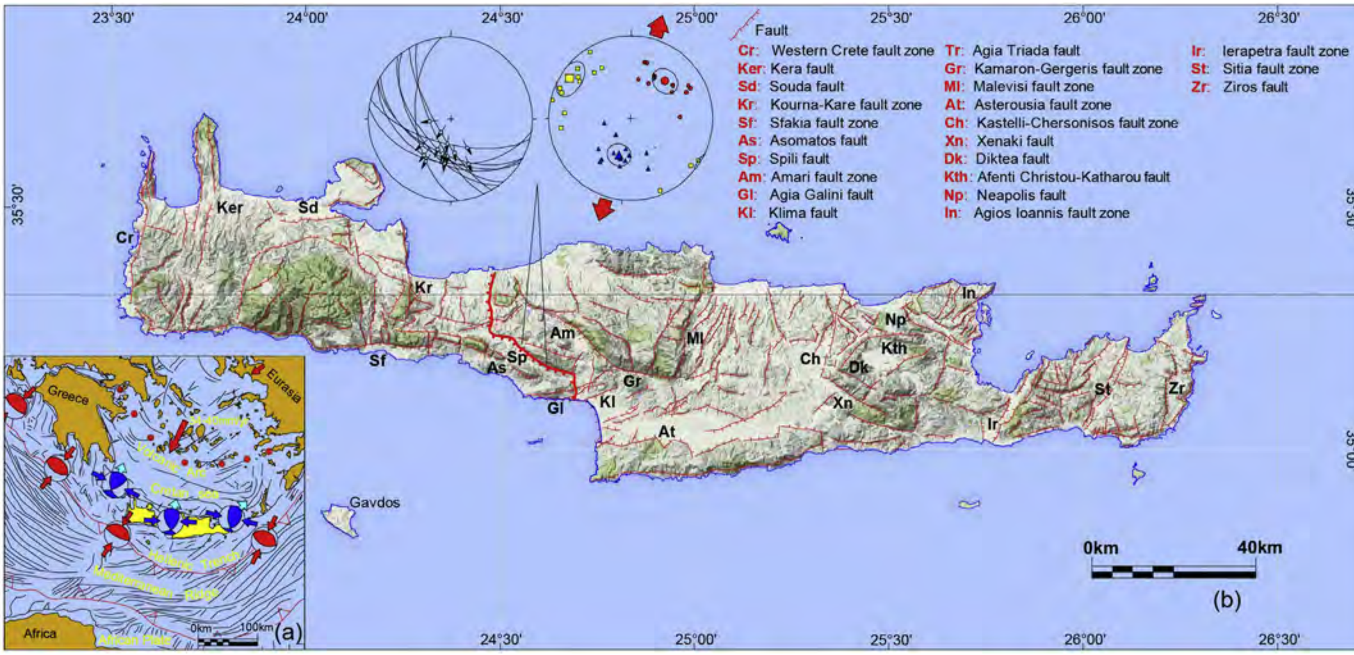

Fig. 2. Structural map of Crete. (a) The geodynamic frame of the Hellenic Arc. (b) The major fault zones and faults of Crete (red lines). Thick lines show the neotectonic fault of Spili and its extension across central Crete, thus separating the western from the eastern tectonic block. Structural analysis of the Spili fault is also presented. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

prevails in western Crete, while tectonic extension dominates in eastern Crete (Mercier et al., 1972, 1974; Sorel, 1976; Angelier, 1980; Fytrolakis, 1980). North of Crete the shortening and subductions of the crust forms the back arc depression of Cretan Sea (Makris and Stobbe, 1984) (Fig. 2a).

Within this complex tectonic framework, an abrupt change of sedimentation conditions occurred in Crete by the end of Pliocene, indicating an inversion of the vertical land movements that are now dominated by uplift. By the late Upper Miocene to early Pliocene, the conditions of deposition changed from open sea into coastal or subaerial environment (Meulenkamp et al., 1977, 1994). The island uplifted gradually during Quaternary, as evidenced by marine Pleistocene terraces and coastal deposits formed during the corresponding interglacial stages (Angelier, 1980; Peters, 1985; Mourtzas, 1990; Kelletat, 1996; Peterek and Schwarze, 2004; Wegmann, 2008; Tiberti et al., 2014). In this period, the island fragmented at least into six tectonic blocks delimited by NE–SW and E–W trending fault zones. These blocks have differential tectonic behavior in both time and space and are characterized by high velocities, different values of uplift rates with subsiding phases (Mourtzas, 1990; Tiberti et al., 2014). The fragmentation and uplift of the island continued during Pleistocene (Mourtzas, 1990). According to Angelier et al. (1982) the main mechanism inducing the rapid uplift of Crete since several million years is the continuous underplating of subducted sediments to the base of the crust beneath the island. This process, caused by lithospheric convergence in association with active extension, may involve the stacking of thrust sheets and duplex formation in the sedimentary rocks that are subducted underneath the island (Kokinou et al., 2009).

The transition from uplift to subsidence started after the formation of the younger Pleistocene terraces (Mourtzas, 1990). During Upper Holocene, subsidence affected all the island of Crete (Boekschoten, 1962, 1963; Hafemann, 1965; Kelletat, 1979; Mourtzas, 1990) without differential velocities that characterized the previous period (Mourtzas, 1990, 2012a, 2012b). The western tectonic block separated from the eastern one along the fault of Spili (Fig. 1) (Mourtzas, 2012a, 2012b), likely during a paroxysmal tectonic event occurred 1.6 ka BP. The western part uplifted of about 8 m in its SW extremity and tilted northeastwards (Pirazzoli et al., 1982, 1996).

Three subsequent phases of tectonic activity produced intense faulting (Fig. 2). During the first one, were formed E–W trending faults cutting and bounding the massive basement and sediments of Miocene. The second phase is characterized by N–S striking faults that cut the E–W faults previously formed. The third and younger phase includes NE–SW and NW–SE dipping faults (Le Pichon and Angelier, 1979; Ten Veen and Meijer, 1998). Arc-parallel (E–W) and arc-normal (N–S) extension faults are related to the Holocene tectonic activity and are possibly connected with large historical earthquakes and recent moderate seismicity (M = 6.0–6.5) (Fytrolakis, 1980; Caputo et al., 2006, 2010; Mouslopoulou et al., 2001, 2014).

3. Materials and methods

Data presented and discussed in this paper are partially based on the revision of previous studies by Mourtzas (1990). Most locations have been re-examined in detail during new surveys performed in 2012 and 2014 (Fig. 1), aiming:

(i) to map the geomorphological and archaeological indicators of sea level change;
(ii) to measure elevations, depths and morphological features of tidal notches;
(iii) to measure depths at the top and base of the seaward ends of each beachrock phase; thickness and width of each beachrock phase and their distance from the contemporary shoreline;
(iv) to measure the current elevation of uplifted and submerged coastal archaeological remains, to assess their functional elevations and interpret their relationships with geomorphological sea level indicators.

Table 1
Tidal notches along the coast of western Crete.

Location	Coordinates (Lat. North Long. East)	Tidal notch I′		Tidal notch I″		Tidal notch I		Tidal notch II		Tidal notch III	
		Elevation (m)	Dated age (BP)	Elevation (m)	Dated age (BP)	Elevation (m)	Dated age (BP)	Elevation (m)	Dated age (BP)	Elevation (m)	Dated age (BP)
Petri Geraniou	35°21′12.75″ 24°21′48.38″					+0.35 ± 0.05	non-dated				
Georgoupolis	35°22′00.00″ 24°16′00.00″										
Plaka	35°27′33.59″ 24°12′28.45″										
Stavros	35°35′29.08″ 24°05′43.80″			+0.35	544–396						
Agioi Theodoroi islet	35°32′00.00″ 23°56′00.00″									+3.10 ± 0.10	1850 ± 70
Rodopou-Menies	35°39′52.78″ 23°46′04.40″					+2.70 ± 0.10	non-dated				
Kasteli Kissamos	35°30′28.60″ 23°38′18.12″					+5.50 ± 0.10	non-dated	+5.10 ± 0.10	non-dated	+4.60 ± 0.10 +4.00 ± 0.10 +3.70 ± 0.10 +3.40 ± 0.10	non-dated
Cape Gramvousa	35°36′00.00″ 23°36′00.00″									+5.20 ± 0.20	1810 ± 70
Phalasarna	35°30′00.00″ 23°34′00.00″							+6.60 ± 0.30	1780 ± 90	+6.40 ± 0.30	1875 ± 100
Cape Karavoutas	35°23′00.00″ 23°33′00.00″							+7.00	1580 ± 70		
Cape Chrisoskalitissa	35°19′00.00″ 23°32′00.00″					+7.90 ± 0.20 +7.80 ± 0.30	1550 ± 80 1595 ± 70	+7.70 ± 0.20	1710 ± 80	+7.50 ± 0.20	1870 ± 80
Paleochora	35°14′17.03″ 23°40′0.52″					+8.80 m	1519–2652	+10.80	1707–2125		
Sougia	35°15′00.00″ 23°49′00.00″									+7.00 ± 0.30	1850 ± 70
Gavdos	35°51′54.12″ 24°06′28.87″							+3.50	1670 ± 110		
Agia Roumeli	35°13′24.75″ 23°56′27.70″									+4.20 ± 0.10	1860 ± 70
Agios Ioannis	35°12′00.00″ 24°01′00.00″										
Loutro	35°11′43.30″ 24° 3′27.60″										
Chora Sfakion	35°11′38.90″ 24°9′29.27″										
Timios Stavros	35°12′00.00″ 24°06′00.00″					+3.60 ± 0.10	non-dated				
Plakias	35°11′00.00″ 24°24′00.00″									+1.70 ± 0.10	1880 ± 70
Damnoni	35°09′55.84″ 24°25′14.34″									+1.70 ± 0.10	non-dated
Ammoudi	35°10′12.93″ 24°25′11.75″	−1.25 ± 0.10								+1.70 ± 0.10	non-dated
Preveli	35° 09′8.48″ 24°28′53.07″									+1.40 ± 0.10	non-dated
Agios Pavlos	35°06′08.66″ 24°33′54.83″									+1.40 ± 0.10	non-dated
Melambes	35° 05′50.16″ 24°39′02.91″									+1.00 ± 0.15	non-dated

The tidal marine notches carved on limestone or aeolianite coastal cliffs and on archaeological constructions are accurate indicators of sea level, particularly in areas of small tidal range, such as the central Mediterranean (Lambeck et al., 2010; Mourtzas and Kolaiti, 2013; Antonioli et al., 2015). Tidal notches formed in the intertidal zone during periods of eustatic and tectonic stability, in consequence of physicochemical and biological erosional processes. The intertidal erosion rate on calcareous cliffs is estimated between 0.20 mm/y and 1.0 mm/y (Torunski, 1979; Furlani et al., 2009, 2010). The inward notch depth permits to evaluate the sea level stability period while notch profiles support the reconstruction of relative sea level change in sheltered areas (Pirazzoli, 2007; Antonioli et al., 2015).

The formation of beachrocks in the intertidal zone along the coast of Crete suggests that these are indicative of specific sea level positions and consequently they are valid indicators of sea level change (Dermitzakis and Theodoropoulos, 1975; Neumeier, 1998; Neumeier et al., 2000). Cretan beachrocks are composed of sand and gravels (quartz, limestone lithoclasts, metamorphic and volcanic) with generally less than 10% of bioclasts. The intertidal cement is cryptocrystalline to microcrystalline, mainly Mg-calcite and in some cases pure calcite (Dermitzakis and Theodoropoulos, 1975; Neumeier, 1998).

The cementation process occurs with similar diagenesis in the intertidal and supratidal zone (Bernier and Dalongeville, 1996; Neumeier, 1998). For this reason, the outer (seaward) end of the

Please cite this article in press as: Mourtzas, N., et al., Vertical land movements and sea level changes along the coast of Crete (Greece) since Late Holocene, Quaternary International (2015), http://dx.doi.org/10.1016/j.quaint.2015.08.008

Tidal notch IV		Tidal notch IV′		Tidal notch V		Tidal notch VI		Tidal notch VII		Tidal notch VIII		References
Elevation (m)	Dated age (BP)	Elevation (m)	Dated age (BP)	Elevation (m)	Dated age (BP)	Elevation (m)	Dated age (BP)	Elevation (m)	Dated age (BP)	Elevation (m)	Dated age (BP)	
												present study
+1.50 ± 0.10	2030 ± 70											Pirazzoli et al. (1982)
+1.30 ± 0.20	non-dated											present study
												present study
												Pirazzoli et al. (1982)
												present study
												present study
												Pirazzoli et al. (1982)
						+5.90 ± 0.30	3400 ± 100 3420 ± 100	+4.80 ± 0.50	3930 ± 90	+4.00 ± 0.50	4200 ± 90	Pirazzoli et al. (1982)
												Pirazzoli et al. (1982)
+7.20 ± 0.20 +7.30 ± 0.30	2000 ± 70 2250 ± 70	+7.10 ± 0.20	2280 ± 70 2500 ± 70	+7.00 ± 0.30 +6.80 ± 0.20	3000 ± 70 3050 ± 70	+6.70 ± 0.30 +6.50 ± 0.20	3290 ± 70 3300 ± 80	+6.30 ± 0.20	3870 ± 90			Pirazzoli et al. (1982)
												Tiberti et al. (2014)
								+1.55 ± 0.10	non-dated			Pirazzoli et al. (1982)
												present study
												Wegmann (2008)
+2.50 ± 0.10	2400 ± 70											Pirazzoli et al. (1982)
+4.30 ± 0.10	1980 ± 70											Pirazzoli et al. (1982)
+4.40 ± 0.10	2030 ± 70											Pirazzoli et al. (1982)
		+2.75	non-dated									present study
+3.10 ± 0.10	2050 ± 70	+2.70 ± 0.10	2610 ± 70									Pirazzoli et al. (1982)
												Pirazzoli et al. (1982)
												Mourtzas (1990)
												present study
												present study
												Mourtzas (1990)
												present study

beachrock that forms in the intertidal zone can be used as an indicator of the mean sea level at the time of the beachrock formation. The depth of the seaward end of the beachrock base is therefore at the level of the low tide of the past sea level. The mean sea level can be identified from the depth of the beachrock base minus half the difference between the mean high tide and the mean low tide, which for Crete is 0.08 m (data from Hellenic Navy Hydrographic Service).

The rising and falling of relative sea levels can form sequences of beachrock outcrops, as reported by Neumeier et al. (2000) for Damnoni Bay. The submerged or uplifted current positions of the observed beachrocks reflect the different past sea levels and palaeo-shoreline positions. Beachrocks can be dated from archaeological findings incorporated into them or covered by them, or even from their relationships with nearby archaeological structures. Therefore can be defined an upper time limit for beachrock formation, not exceeding the age of the incorporated or related archaeological remains. The depths of top and base for each beachrock were measured at the best preserved parts of the seaward end of the beachrock, after checked for any fracturing, erosion or displacement from their original position.

The uplifted or submerged position of coastal archaeological sites, which had a direct or indirect relationship with past coastlines at the time of their function, are also used as indicators of past sea levels (Lambeck et al., 2010; Anzidei et al., 2011a, 2011b, 2014; Mourtzas, 2012a, 2012b; Mourtzas and Kolaiti, 2013; Mourtzas et al., 2014). These also allow the estimation of the vertical land motion during Late Holocene. The relationships between archaeological coastal installations and the former sea levels is a key issue to determine the past relative sea levels and rates of vertical land movements. In addition, the historical data derived from ancient literary sources and testimonies contribute to the definition of the functional elevations and of the timing of relative sea level change (Lambeck et al., 2004; Auriemma and Solinas, 2009; Mourtzas, 2012c; Mourtzas and Kolaiti, 2013; Mourtzas et al., 2014).

Measurements of archaeological and geomorphological sea level indicators were collected during calm sea conditions, using mechanical methods (i.e. invar rods). To account for tides that affect field measurements on the elevation of the observed sea level markers, data have been reduced for tide values at the time of surveys with respect to a mean sea level estimated from tidal data collected at the nearest tide-gauge stations of the Hellenic Navy Hydrographic Service. These are located at Kastelli, Souda and Iraklion, all in Crete (Fig. 1). Crete is characterized by a small tidal range environment, and therefore sea level corrections during surveys were in the range of 0.02 m–0.15 m.

4. Upper Holocene sea level indicators

We surveyed the coast of Crete to map and measure the available sea level indicators comprising tidal notches, beachrocks and maritime archaeological installations, which define distinct sea level stands (Fig. 1, Tables 1 and 2).

4.1. Tidal notches

Marine tidal notches are indentations or undercuttings, few centimetres to several metres deep, cut in steep calcareous cliffs at or near sea level (Carobene, 1972; Pirazzoli, 1986b; Kelletat, 2005; Antonioli et al., 2015). Several uplifted and submerged tidal notches were found. Only some were observed during previous studies (Laborel et al., 1979; Thommeret et al., 1981; Pirazzoli et al., 1982; Pirazzoli, 1986b; Mourtzas, 1990). In the central and eastern coast of Crete, these are largely submerged (Fig. 1, Tables 1 and 2).

4.1.1. Western coast

Along the western coast of Crete at least nine sea level lines (tidal and ripple notches) have been recognized (Fig. 3, Table 1). In the SW coast, these show a progressive increase in elevation towards the southwest, ranging from +1.00 ± 0.15 m in Melambes to +7.90 ± 0.20 m in Chrisoskalitissa Cape (Laborel et al., 1979; Pirazzoli, 1986a). Along the NW coast, a progressive northwest increase in elevation was observed, from +0.35 ± 0.05 m in Petri Geraniou to +6.60 ± 0.30 m in Phalasarna (Laborel et al., 1979; Pirazzoli et al., 1982). The most elevated tidal notch has been dated between 1550 ± 80 B P and 1595 ± 70 B P, whereas the lowest and highest of the underlying notches have been dated at 4200 ± 90 B P and 1710 ± 80 B P, respectively. The vertical succession of the uplifted notches in the SW extremity of Crete (Chrisoskalitissa) suggests the occurrence of several events of rapid subsidence of a total of 1.60 m. Afterwards, subsidence was followed by a large uplift event of 9.15 m, that can be attributed to the AD 365 earthquake (Pirazzoli, 1986a; Pirazzoli et al., 1996; Stiros and Drakos, 2006; Shaw et al., 2008) (Fig. 3).

We measured the uplifted tidal notches in six new locations, in addition to those already reported by previous studies (Laborel et al., 1979; Dalongeville, 1986; Pirazzoli, 1986a; Mourtzas, 1990). On the north coast, Petri Geraniou shows an uplifted fossil tidal notch at 0.35 ± 0.05 m above sea level (asl) (Fig. 4a) and in the aeolianite quarry of the Venetian period (1436–1456) at Stavros in Akrotiri Chanion, a well-shaped uplifted tidal notch is placed at

Table 2
Tidal notches along the coast of central and eastern Crete.

Location	Coordinates (Lat. North Long. East)	Tidal notch I		Tidal notch II		Tidal notch III		Tidal notch IV		References
		Elevation (m)	Dated age (BP)	Elevation (m)	Dated age (BP)	Elevation (m)	Dated age (BP)	Elevation (m)	Dated age (BP)	
Matala	34°59′35.55″ 24°44′49.81″	−0.55		−1.25	1900 ± 100	−2.60		−3.90 ± 0.20	3900–3700	Mourtzas (1990) present study
Lassaia	34°56′13.91″ 24°49′29.53″	−0.60		−1.10	2300–1300	−2.80				Mourtzas (1990) present study
Cape Trachoulas	34°55′48.73″ 24°57′56.96″	−0.50		−1.20 ± 0.20				−3.80 ± 0.20		Mourtzas (1990)
Tsoutsouros	34°58′09.63″ 25°16′16.18″	+0.35								Mourtzas (1990)
Koutsounari	35°00′30.73″ 25°50′03.32″			−1.20	1900 ± 100					Mourtzas (1990)
Ferma	35°00′41.06″ 25°50′31.24″			−1.25	1900 ± 100					Mourtzas (1990)
Atherinolakos	35°00′42.72″ 26°09′13.81″	−0.50		−1.10		−2.60				Mourtzas (1990)
Strongylo islet	34°57′28.63″ 26°07′58.79″			+0.90	2200 ± 100					Montaggioni et al. (1981)
Kato Zakros bay	35°05′40.47″ 26°15′55.32″	−0.45 ± 0.05		−1.20 ± 0.05	1900 ± 100	−2.85	3600–3450			Mourtzas (1990) present study
Plaka	35°18′18.15″ 25°43′56.25″	−0.60	1650 ± 50	−1.35 ± 0.15		−2.90 ± 0.10				Mourtzas (1990)
Spiliada	35°19′05.86″ 25°32′23.42″	−0.55		−1.20				−3.80		Mourtzas (1990)
Mylos	35°17′49.94″ 25°29′08.18″			−1.15						Mourtzas (1990)
Chersonisos	35°19′24.02″ 25°23′35.87″			−1.20						Mourtzas (1990)
Kako Oros	35°20′05.16″ 25°13′31.42″	−0.65		−1.20		−2.60 ± 0.60				Mourtzas (1990)
	Average values	*−0.55 ± 0.05*		*−1.25 ± 0.05*		*−2.70 ± 0.15*		*−3.95 ± 0.25*		

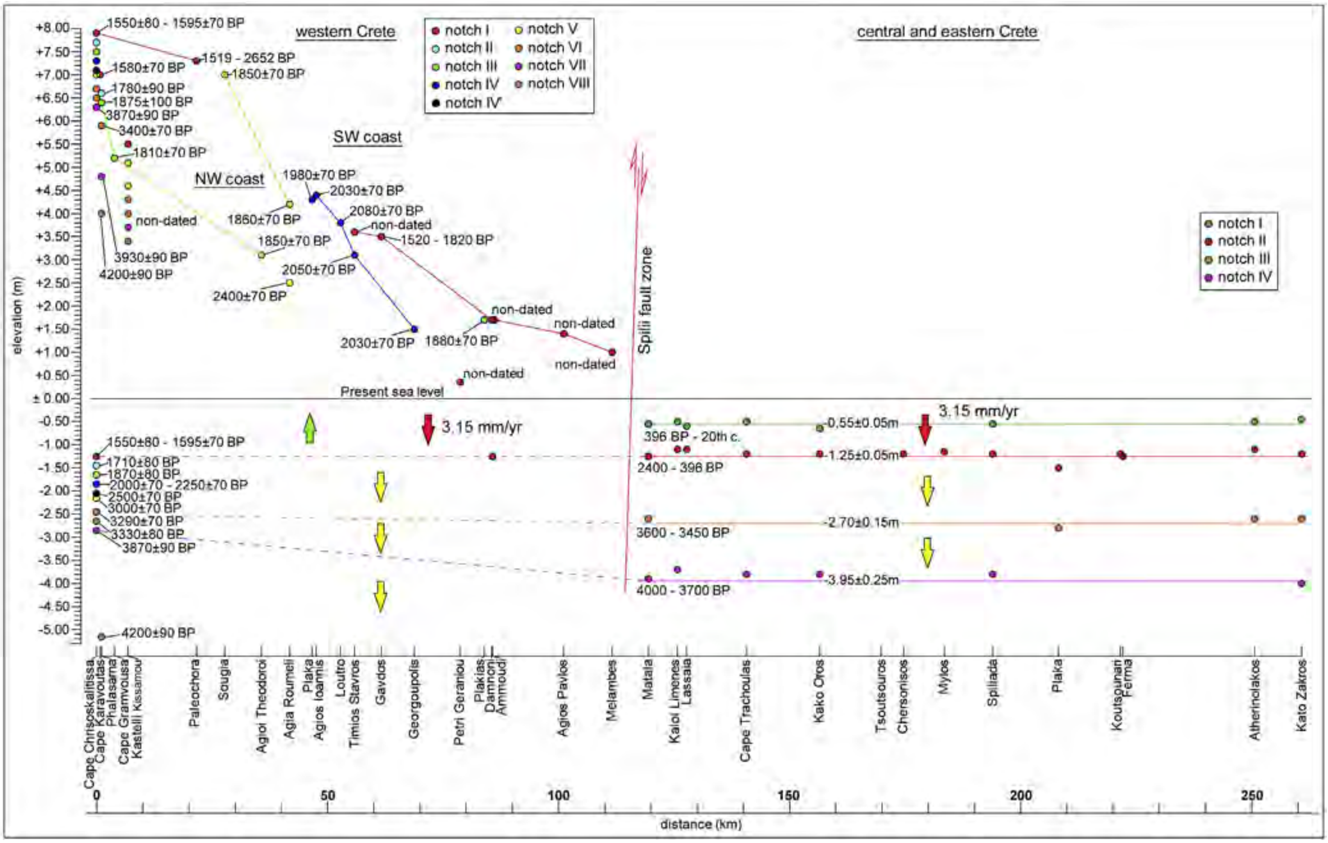

Fig. 3. Elevation of the tidal notches for each survey location. Color lines (right half) show the average depth of the four tidal notches (I, II, III, and IV) for central and eastern Crete and their dating. For western Crete (upper left) lines plot the gradual evolution of the elevation of the uplifted tidal notches on the NW and SW coasts. In the lower left the sea level stands have shifted for the continuous subsidence of western Crete, with reference level to sea level stand at −1.25 ± 0.05 m. The subsidence rates of westernmost Crete, according to Pirazzoli et al. (1982) data before the uplift episode of AD 365 (down left) is compared to the relative sea level change rate of central and eastern Crete bounded by the Spili neotectonic fault. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

0.35 m asl (Fig. 4b). To the west, at Kastelli Kissamou we found six uplifted tidal notches: the uppermost is placed at 5.50 ± 0.10 m asl (Fig. 4d). In Menies bay, on the northeastern tip of Rodopou peninsula, the uplifted tidal notch is at 2.70 ± 0.10 m asl (Fig. 4e). In the south part of Crete, on Preveli coast, the uplifted tidal notch is at 1.40 ± 0.10 m asl (Fig. 4r) while in the south-easternmost sector, along the Melambes coast, the uplifted tidal notch is at 1.00 ± 0.15 m asl (Fig. 4t).

A submerged tidal notch with an opening of 0.40 m and an inward depth of 0.10 m was found on the steep limestone cliff of Ammoudi bay. The depth of its base is at −1.25 ± 0.15 m and coincides with the depth of the top of the local beachrock (younger phase) that terminates in the rocky shore (Fig. 4q).

4.1.2. Central and eastern coast

The underwater geomorphological survey along the central and eastern coast of Crete includes the area from Messara Gulf to Heraklion, encircling the entire eastern section of the island. Here, four submerged fossil tidal notches below the present day notch have been identified at fourteen locations (Fig. 1, Table 2). From bottom to top, these are at −3.95 ± 0.25 m (notch IV), −2.70 ± 0.15 m (notch III), −1.25 ± 0.05 m (notch II) and −0.55 ± 0.05 (notch I) (Fig. 3, Table 2).

The tidal notches engraved on the coastal cliffs made of limestone are often continuous, and most show a well-developed base in the form of a small platform and a low roof. The average height ranges from 0.30 m to 0.35 m while the average inward depth is between 0.15 m and 0.25 m. The two deeper tidal notches formed in the sheltered locations of the Gulfs of Matala and Zakros have platforms from 2.0 m to 7.0 m wide, slightly dipping seawards. The shallower tidal notch at −0.55 m is not well-developed, and at some places it is just a faint trace (Fig. 4, Table 2).

All data on tidal notches for Crete (location, coordinates, elevation, dated age and references) are reported in Tables 1 and 2 for western and central-eastern Crete, respectively. Fig. 3 shows the elevation and age of the investigated tidal notches at each survey location with the resulting values of estimated relative sea level change, attempting to match the tidal notches for the different locations in Crete. For central and eastern Crete, the observed tidal notches correspond to four distinct sea level stands with a maximum variation of 0.35 m that can be attributed to rock hardness, chemical composition of water, hydrodynamical conditions, biological environment and local factors, including coast exposure and morphology. Fig. 4 shows the uplifted and submerged tidal notches surveyed along the coast of western and central-eastern Crete.

4.2. Beachrocks

Systematic measurements and mapping of beachrocks at forty-four locations along the Cretan coast (Fig. 1, Tables 3 and 4) defined four distinct beachrock phases that formed during different sea levels stands (Mourtzas, 1990; Kelletat, 1996; Neumeier, 1998; Neumeier et al., 2000).

Table 3
Beachrock phases along the coast of western Crete.

Location	Coordinates (Lat. North Long. East)	Phase I					Phase II				Phase IV			
		Elevation (m)		Width (m)	Uplifted landward extremity	Remarks	Elevation (m)		Width (m)	Remarks	Elevation (m)		Width (m)	Remarks
		Top	Base				Top	Base			Top	Base		
Stavros	35°35′29.08″ 24°05′43.80″	−1.25	−1.60	7.50										
Agia Marina	35°31′08.34″ 23°54′56.64″	−1.18	−1.28	13		uplifted notch at +3.10 m								
Rodopou-Menies	35°39′52.78″ 23°46′04.40″	−1.43	−2.20	15		uplifted notch at +2.70 m					−2.50	−3.10	10	uplifted notch at +2.70 m
Phalasarna	35°30′34.21″ 23°34′07.03″	−1.05	−1.20	10	0.20	uplifted notch at +6.60 m								
Paleochora	35°14′13.94″ 23°40′02.39″	−0.84	−1.90	40	1.80	uplifted notch at +8.65 m								
Sougia	35°14′44.60″ 23°48′15.34″										+3.80	+1.65	6.50	upper uplifted riple notch at +7.30 m and lower at +1.60 m
Agia Roumeli	35°13′44.96″ 23°57′35.46″	−1.20	−2.15	84	1.65									
Agios Pavlos Sfakion	35°13′22.76″ 24°00′00.97″										+2.50	+1.90	8	upper uplifted tidal notch at +4.20 m and lower at +2.50 m
Loutro	35°11′59.98″ 24°3′50.71″	−1.15	−2.20	20	0.30									
Chora Sfakion	35°11′38.36″ 24°09′26.17″	−0.25	−1.39	22	0.50	uplifted notch at +2.75 m								
Frangocastello	35°11′28.39″ 24°13′00.78″	−0.79	−1.21	15							−2.35	−2.75	140	uplifted notch at +3.10 m
Rodakino	35°10′54.07″ 24°17′51.42″										−2.22	−3.10	55	
Damnoni	35°10′27.38″ 24°24′53.68″	−1.55	−2.5	17	1.70	uplifted notch at +1.70 m					−5.15	−5.55	19	uplifted notch at +1.70 m
Ammoudi	35°10′14.82″ 24°25′12.14″	−1.25	−3.1	16	1.66	uplifted notch at +1.70 m								
Preveli	35°09′9.19″ 24°28′51.74″						+1.70	+1.60	20	uplifted notch at +1.40 m				
Gialopotamia	35°08′48.02″ 24°30′19.61″	−1.12	−1.77	12	1.40									
Xiromolia	35°07′40.46″ 24°32′13.40″	−1.25	−1.55	10										
Triopetra	35°07′31.39″ 24°32′30.19″	−1.35	−2.35	20										
Agios Pavlos	35°06′10.02″ 24°33′49.82″	−1.22	−1.54	12.5		uplifted notch at +1.40 m								
	Average value	*−1.25 ± 0.15*												

4.2.1. *Western Crete*

Along the coast of western Crete, nineteen beachrock locations have been identified (Fig. 1, Table 3) that have developed along uplifted coasts. The older well-developed beachrock phase was found at −3.00 ± 0.20 m on the north coast in Menies bay of Rodopou Peninsula and on the south coast at Frangokastello and Rodakino. Here, the maximum uplift resulting from the current elevation of tidal notches is between 2.70 m and 3.40 m asl (Fig. 5c and i).

On the southern coast, in the small bay of Sougia, the older beachrock phase is entirely uplifted. Its base is at 1.55 m asl, fitting the lowest elevated ripple notch, while the top is at 3.75 m asl, at the same elevation of an intermediate notch out of the eleven uplifted ripple notches (Fig. 5e). In the central part of the sandy shore of Damnoni bay, the uplifted notch is at 1.70 ± 0.10 m asl, while the older beachrock phase is placed at −5.55 m of elevation (Fig. 5k). This beachrock is most likely connected with the oldest sea level stand at Phalasarna (western Crete), dated by Pirazzoli et al. (1982) between 3900 B P and 4200 B P. The older beachrock submerged during the initial subsidence of the western coast of the island, and did not emerge in shores where uplift did not reach the maximum values.

Along the Preveli coast, the intermediate beachrock phase uplifted at 1.60 m asl and 2.40 m asl in the seaward and landward ends, respectively (Fig. 5m). The formation of the intermediate beachrock phase is contemporary with the uplifted tidal notch, which at this location was found at +1.40 ± 0.10 m and on the adjacent coast of Plakias was dated around 1900 B P (Pirazzoli et al., 1982).

In western Crete, the younger beachrock phase was found at fifteen coastal locations. Top and base of the seaward end of the beachrock are at −1.25 ± 0.15 m and −2.45 ± 0.40 m, respectively (Fig. 1, Table 3). The part of the beachrock on land between 1.40 m and 1.80 m asl is older than the seaward submerged part, and developed at a time just before the uplift of the island, at about 1.6–1.0 ka BP (Neumeier et al., 2000). The layer of algal

Table 4
Beachrock phases along the coast of central and eastern Crete.

Location	Coordinates (Lat. North Long. East)	Phase I				Phase II				Phase III				Phase IV		
		Elevation (m)		Width (m)	Dated age (BP)	Elevation (m)		Width (m)	Dated age (BP)	Elevation (m)		Width (m)	Dated age (BP)	Elevation (m)		Width (m)
		Top	Base			Top	Base			Top	Base			Top	Base	
Messara bay	35°01′47.98″ 24°45′28.00″	−1.35 ± 0.15	−1.95 ± 0.50	25		−1.90 ± 0.25	−2.80 ± 0.35	63		−3.00 ± 0.10	−4.30 ± 0.45	80	3900−3700			
Matala bay	34°59′38.18″ 24°44′56.26″	−1.35 ± 0.10	−3.55	26	1900 ± 100	−2.25	−3.20	13		−4.20	−4.50	30				
Kaloi Limenes	34°56′10.62″ 24°48′34.87″									−3.35 ± 0.15	−4.50 ± 0.30	55				
Lassaia	34°56′16.21″ 24°49′29.24″	−1.40 ± 0.30	−2.00 ± 0.15	50	2300−2067											
Xirokampos	34°58′55.91″ 25°18′50.50″													−6.10 ± 0.10	7.00 ± 0.35	69
Arvi	34°59′24.52″ 25°27′17.89″						−2.70 ± 0.15	68								
Faflagos	34°58′56.46″ 25°30′11.70″													−4.00	−7.20	67
Psari Forada	34°59′27.18″ 25°31′24.24″													−3.90 ± 0.10	−6.25 ± 0.15	37
Vatos	34°59′55.34″ 25°34′34.50″					−1.85	−3.30	100								
Gra-Lygia (W Ierapetra)	35°00′40.34″ 25°42′35.76″	−1.10 ± 0.40	−3.70	28						−3.30 ± 0.55	−4.20 ± 0.50	47		−4.90	−5.70	22
East Ierapetra	35°00′25.45″ 25°43′39.73″	−1.80 ± 0.30	−2.50 ± 0.35	50												
Giali	34°59′56.13″ 25°47′11.11″									−3.80	−4.25	70				
Stenaki-Paplinou	34°59′53.19″ 25°47′37.94″									−2.75	−3.90	65				
Ferma	35°00′54.21″ 25°50′38.50″									−3.40	−4.30	80				
Makris Gyalos	35°02′03.56″ 25°57′52.74″									−3.50	−4.50	60				
Goudouros	35°00′27.23″ 26°05′47.86″	−1.30	−2.10	16												
Kato Zakros bay	35°05′56.98″ 26°15′51.09″	−1.20 ± 0.20	−2.20 ± 0.20	40	1900 ± 100	−2.95 ± 0.25	−3.70 ± 0.20	90	3600−3450	−3.60	−4.20	37	3900−3700			
Kouremenos bay	35°12′17.72″ 26°16′20.37″	−1.35	−1.80	20										−6.20	−6.60	70
Vai bay	35°15′16.11″ 26°15′54.92″					−2.60	−3.40	70								
Erimoupolis bay	35°15′59.99″ 26°15′48.32″					−2.70	−2.90	15								
Agios Isidoros bay	35°18′51.20″ 26°18′40.58″	−1.35	−1.80	17		−1.90	−2.50	12.50								
Analoukas	35°12′43.69″ 26°11′09.59″	−1.00	−1.30	15												
Sitia bay	35°11′57.97″ 26°07′32.77″					−2.50	−3.40	35						−4.60	−6.40	68
Mylos bay	35°17′47.19″ 25°29′13.83″					−2.50	−3.00	22								
Chersonisos	35°19′23.91″ 25°23′25.06″	−1.40	−2.90	15	1900 ± 100	−1.90	−3.00	18								
	Average value	*−1.35 ± 0.20*					*−3.10 ± 0.30*				*−4.30 ± 0.20*				*−6.55 ± 0.55*	

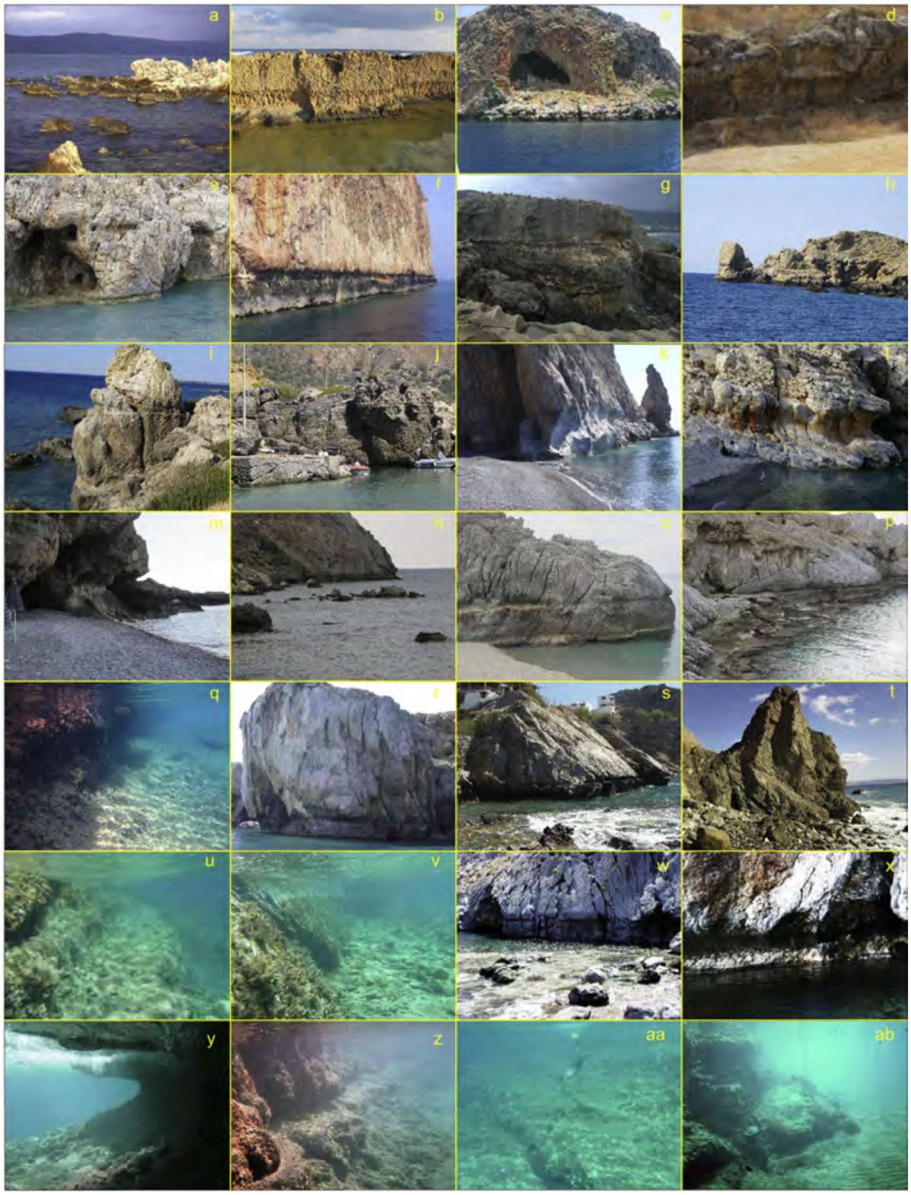

Fig. 4. Uplifted and submerged tidal notches along the coast of western (a–t) and eastern Crete (u – ab). (a) Petri Geraniou, +0.35 m, (b) Stavros quarry, +0.35 m, (c) Ag. Theodoroi islet, +3.10 m, (d) Rodopou-Menies, +2.70 m, (e) Kastelli Kissamou, +5.50 m, (f) Cape Gramvousa, +5.20 m, (g) Phalasarna, +6.60 m, (h) Cape Chrisoskalitissa, +7.90 m, (i) Paleochora, +8.80 m, (j) Sougia, +7.00 m, (k) Agia Roumeli, +4.20 m, (l) Loutro, +4.40 m, (m) Chora Sfakion, +2.75 m, (n) Plakias, +1.70 m, (o) Damnoni, +1.70 m, (p) Ammoudi, +1.70 m, (q) Ammoudi, −1.25 m, (r) Preveli, +1.40 m, (s) Agios Pavlos, +1.40 m, (t) Melambes, +1.10 m, (u) Matala, −0.55 m, −1.25 m, −2.60 m, (v) Lassaia, -0.60 m, −1.10 m, −2.80 m, (w) Cape Trachoulas, +2.20 m, +1.70 m, (x) Tsoutsouros, +0.35 m, (y) Ferma, −1.25 m, (z) Kato Zakros bay, south coast, −0.45 m, −1.20 m, −2.75 m, (aa) Kato Zakros bay, north coast, −0.80 m, −1.50 m, −2.85 m, (ab) Kato Zakros bay, south coast, −2.75 m, −4.30 m.

reef on the surface of the emerged part of the formation in Frangokastello, which is indicative of a former sea level, reinforces this view (Fig. 5i). The depth of the top and base of the seaward end of this younger phase coincides with the corresponding phase I, defined in the central and eastern coast of the island. It formed when sea level was at 1.25 ± 0.05 m lower than today, after the uplift of western Crete. Then, the coast of the entire island subsided, between 1415 and 1865, likely during the 1604 earthquake. This is also indicated by the beachrock formation placed at the entrance of the ancient harbor of Phalasarna that formed after the co-seismic uplift of AD 365 incorporating remains of the harbor, and then subsided at a depth of 1.0 m (Fig. 5d).

4.2.2. Central and eastern Crete

Along central and eastern Crete coast, beachrocks were found at twenty four locations in the area extending from Messara Gulf towards the east to Chersonisos on the northern coast (Fig. 1, Table 4). The lowest beachrocks of phase IV were identified at seven locations along the eastern coast, from Xirokampos to Sitia. The maximum underwater extension is about 70 m, while the maximum depths of the top and base are 6.20 m and 7.20 m, respectively. The average depths at the outer (seaward) end of the top and base are −4.95 ± 1.0 m and −6.55 ± 0.55 m, respectively.

The beachrocks of phase III were found at nine locations along the central and eastern coast of the island. The maximum widths

Please cite this article in press as: Mourtzas, N., et al., Vertical land movements and sea level changes along the coast of Crete (Greece) since Late Holocene, Quaternary International (2015), http://dx.doi.org/10.1016/j.quaint.2015.08.008

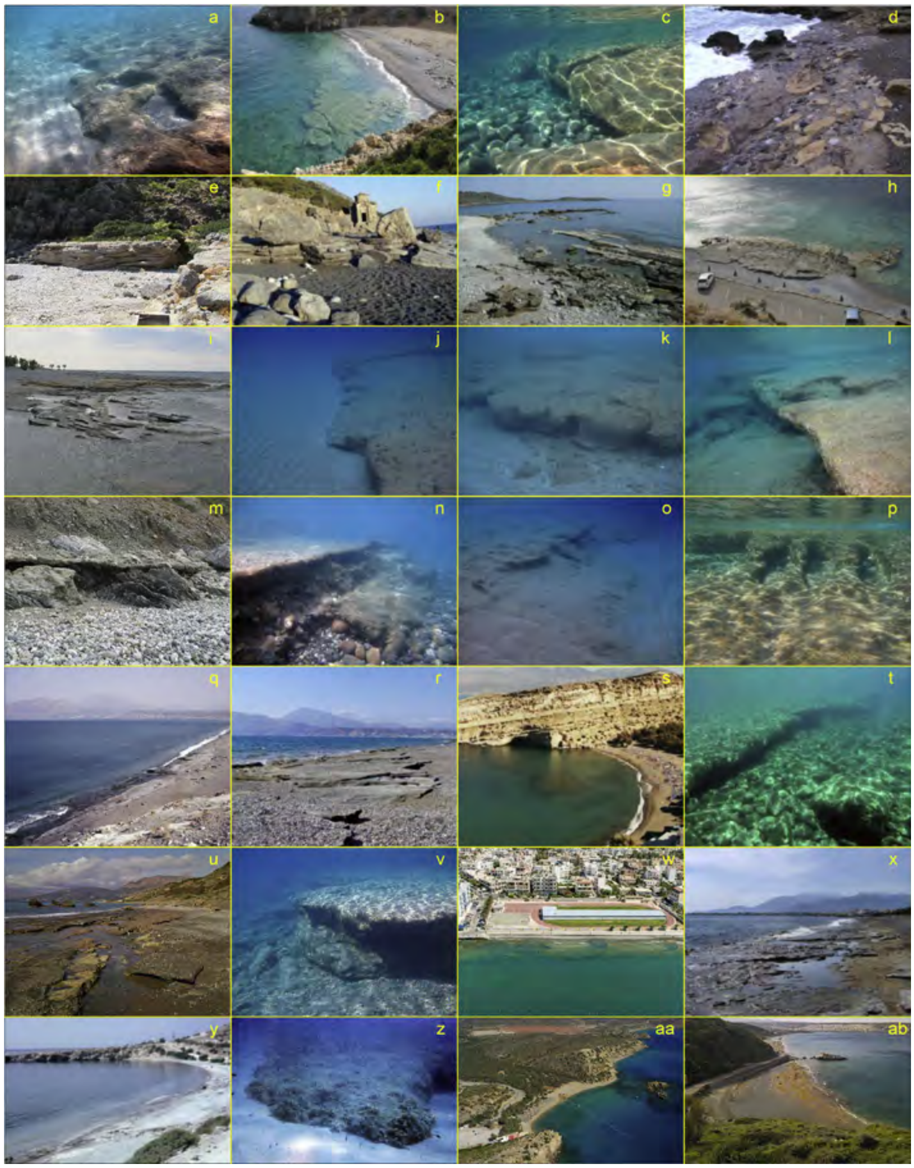

Fig. 5. Uplifted and submerged beachrocks along the coast of western (a–p) and eastern Crete (q – ab). (a) Agia Marina, (b) Rodopou-Menies, (c) Paleochora, (d) Phalasarna, (e) Sougia, (f) Agios Pavlos Sfakion, (g) Loutro, (h) Chora Sfakion, (i) Frangokastello, (j) Rodakino, (k) Damnoni, (l) Ammoudi, (m) Preveli, (n) Gialopotamia, (o) Triopetra, (p) Agios Pavlos, (q) Messara bay, Pachia Ammos, (r) Messara bay, Kalamaki, (s) Matala bay, (t) Lassaia, (u) Arvi, (v) Ierapetra port, (w) East Ierapetra, (x) Giali, (y) Ferma, (z) Kato Zakros bay, (aa) Vai bay, (ab) Sitia bay.

are about 80 m while their thickness ranges between 0.60 m and 1.30 m. The average depths of their top and base are at -3.45 ± 0.40 m and -4.30 ± 0.20 m, respectively.

The beachrocks of phase II were found at eleven locations. They display widths ranging from 13 m to 100 m and thickness from 0.60 m to 1.45 m. The average depth at the end of their tops and bases were identified at -2.35 ± 0.40 m and -3.10 ± 0.30 m, respectively.

The most elevated beachrocks of phase I were found at eleven locations. The average depths of their tops and bases are at -1.35 ± 0.20 m and -2.35 ± 0.60 m, respectively. Their width varies between 15 m and 50 m, and thickness are up to 2.0 m.

Data for each beachrock phase surveyed along the coasts of western and central-eastern Crete are presented in Tables 3 and 4. The features of uplifted and submerged beachrocks located along the western and central-eastern coast of Crete are given in Fig. 5. Figs. 6 and 7a–d show the average depths of the top and base of the seaward end of each beachrock phase (7a: I, 7b: II, 7c: III, 7d: IV) for each location of western and central-eastern Crete. Fig. 7e shows the average depths of the base of beachrock phases I, II and III and the top of phase IV found in the central and eastern coast of Crete. Error bars refer to the uncertainties in depths as estimated from multiple measurements at the same occurrence.

5. Archaeological indicators

Along the coast of Crete are available many archaeological relics (Fig. 1, Table 5). The valid archaeological indicators of relative sea level change can be divided into four main categories and can be

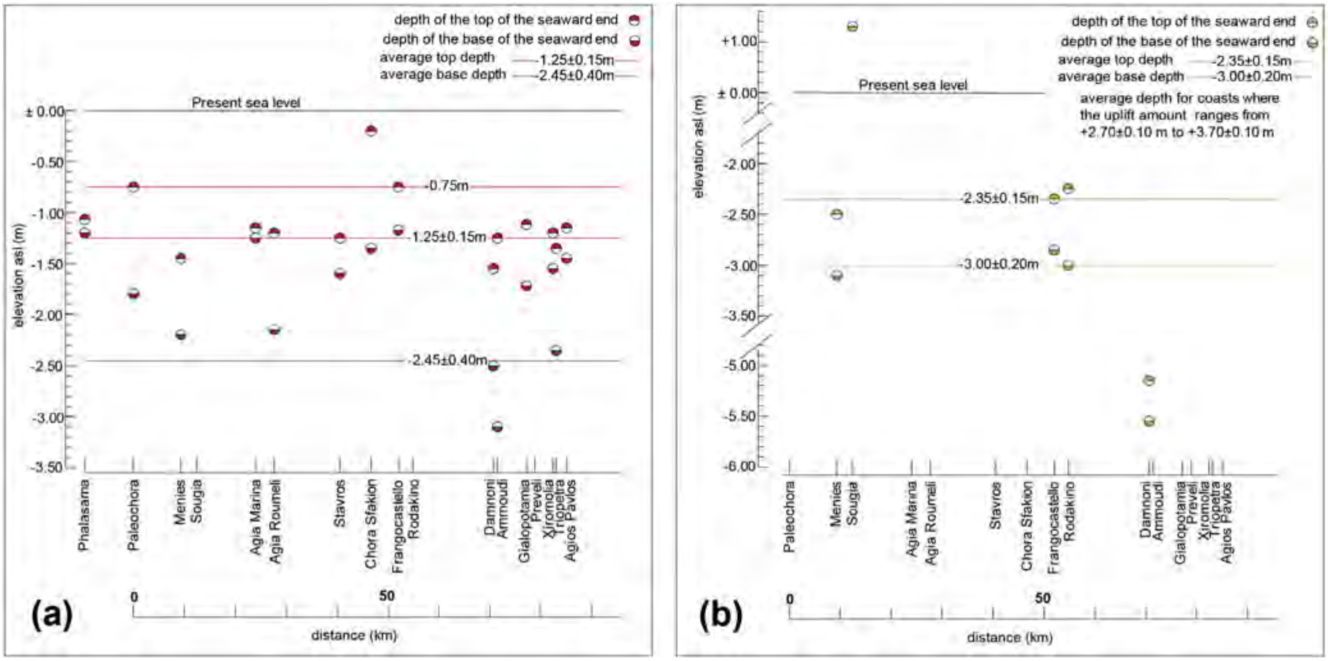

Fig. 6. Average depth of top and base of the seaward end of the (a) younger beachrock phase and (b) the older phases for each location along the coast of western Crete.

related to the present geomorphological indicators of sea level stands.

The first one, of low accuracy, includes coastal structures that were founded or constructed above sea level along the coast but without a known position in relation to the past shoreline. It comprises ancient coastal settlements and buildings whose age is often well known. Their present position provides only a quantitative indication of the intervening changes in their elevation with respect to former sea level, and therefore they cannot support estimates of precise relative sea level changes. This category comprises the submerged Minoan building relics at Amnissos (Fig. 8o and p), Nirou Chani (Fig. 8r), and Istron; the Classical Temple of Samonio Athena in Agios Isidoros bay, at Cape Sidero (Fig. 9o and p); the submerged Roman relics at Mochlos and Psira island; the

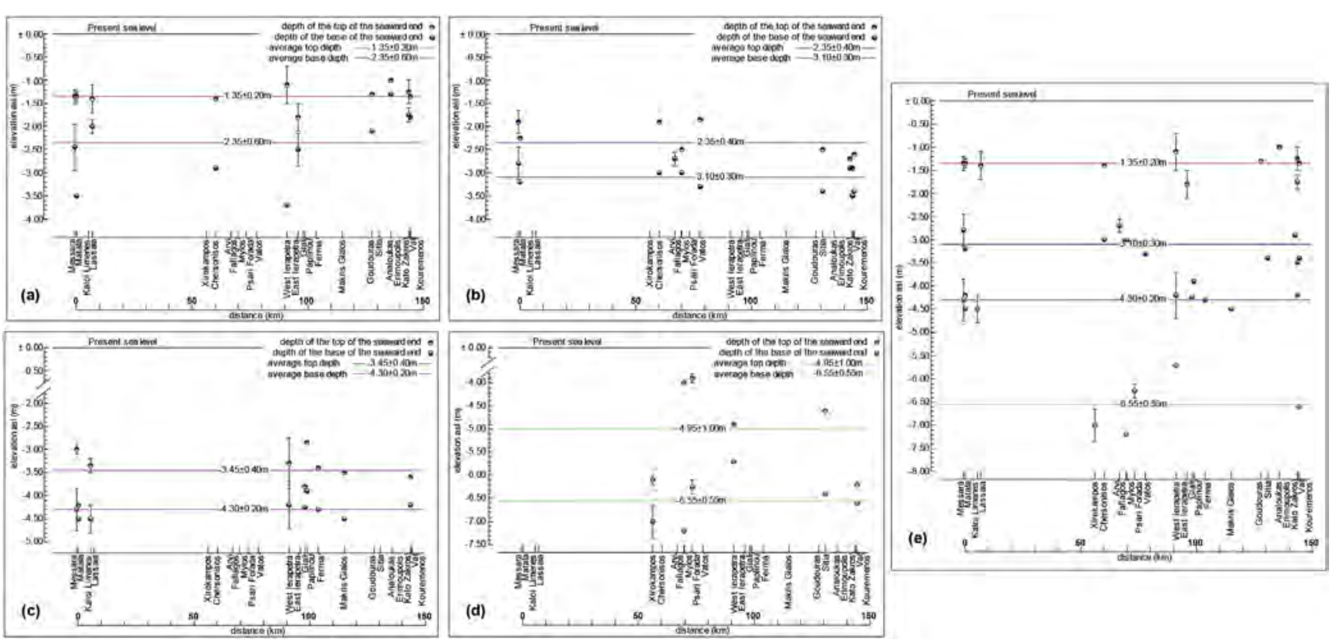

Fig. 7. Average elevation of top and base of the seaward end of each beachrock phase (7a: I, 7b: II, 7c: III, 7d: IV, 7e) for each location, along the coasts of central and eastern Crete. Error bars show the range of depth variation which can be attributed to erosion of the beachrock locally in the same occurrence.

Please cite this article in press as: Mourtzas, N., et al., Vertical land movements and sea level changes along the coast of Crete (Greece) since Late Holocene, Quaternary International (2015), http://dx.doi.org/10.1016/j.quaint.2015.08.008

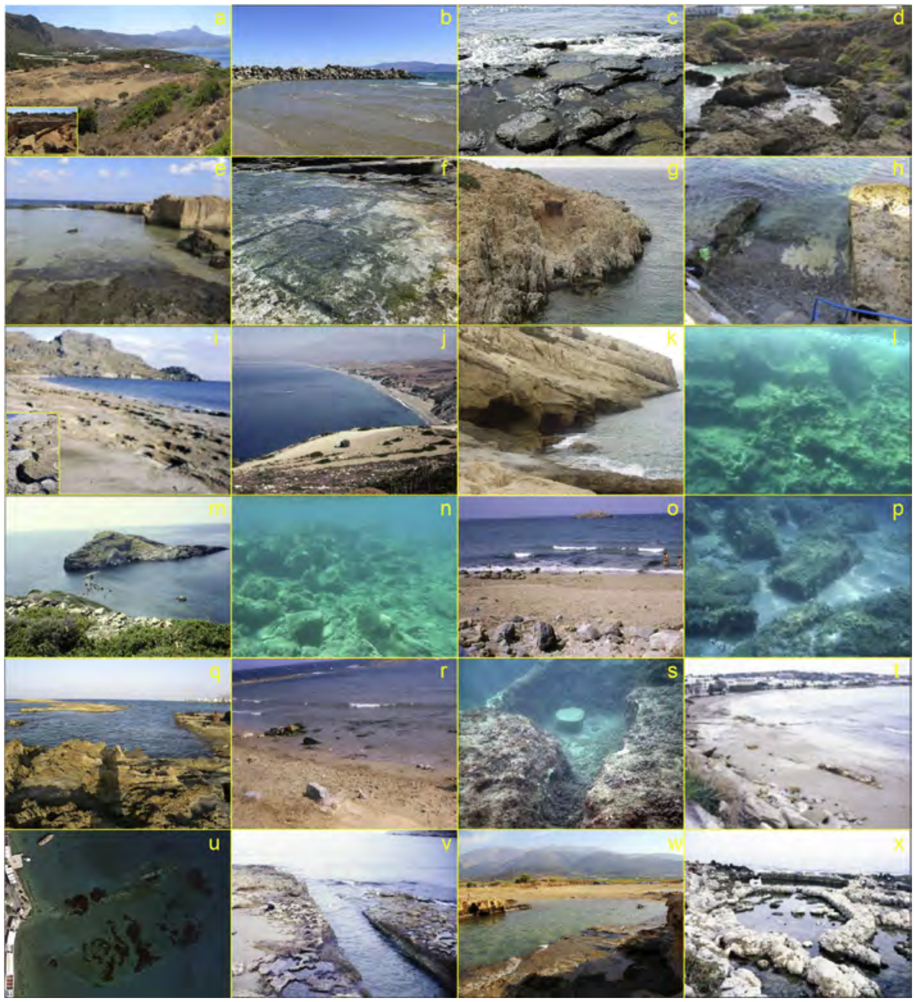

Fig. 8. Archaeological sea level indicators along the coast of western (a–i) and central Crete (j–x). (a) Phalasarna: uplifted harbour, (b) Kastelli Kissamou: uplifted breakwater, (c) Paleochora: millstone quarry (Theodoulou, 2011), (d) Kalathas: submerged quarry, (e) Stavros: submerged quarry, (f) Koumpes: submerged quarry (Manolioudis, 2013), (g) Avlaki: submerged slipway, (h) Rethymno: submerged slipway, (i) Damnoni: millstone quarry, (j) Kommos: submerged harbour morphology, (k) Matala bay: submerged carved fish tanks, (l) Matala bay: submerged fish tanks entrances, (m) Lassaia: submerged harbour morphology, (n) Lassaia: submerged breakwater, (o and p) Amnissos: submerged relics of walls, (q) Nirou Chani: submerged quarry, (r) Nirou Chani: submerged relics of walls, (s) Chersonisos: submerged fish tank, (t) Chersonisos: submerged relics of walls (u) Chersonisos: submerged harbour installations, (v) Mylos bay: submerged carved channel of a watermill, (w) Malia: submerged quarries, (x) Stalida: submerged construction for spring water collection.

Roman building at Stomio (Fig. 9b) whose operation was directly connected with the shoreline (Mourtzas, 1988b); and the submerged Byzantine building relics at Poros Eloundas (Fig. 9c). In this category can also be included the coastal Minoan quarries at Nirou Chani (Fig. 8q) and Malia (8aa), the Roman quarries at Sitia (Fig. 9j), and the Venetian quarries at Agioi Apostoloi, Kalathas (Fig. 8d), Stavros (Fig. 8e), and Koumpes (Fig. 8f). The functional elevation of quarries have been previously estimated by Mourtzas (1990), Lambeck et al. (2004), Anzidei et al. (2013), and Auriemma and Solinas (2009) from the elevation of the lowest carved areas, above the sea level at the time they were excavated, at a minimum functional elevation of 0.60 m above high tide.

The second category, of intermediate accuracy, includes constructions that were partially founded below sea level, such as maritime constructions (harbours, piers, quays etc.). Their dating is usually relatively accurate and based on ancient literature and constructional features. The upper surface of these constructions was above sea level at a minimum elevation of 0.30 m above high tide, such as the Roman harbour installations of Chersonisos (Fig. 8u), Kouremenos, Ierapetra (Fig. 9a), and Lassaia (Fig. 8m and n), but often at about 1.0 m asl, such as the harbour installations at Minoan Kommos (Fig. 8j), Classical Phalasarna (Fig. 8a), and Roman Kastelli Kissamou (Fig. 8b).

The third category, which is the most precise, includes ancient maritime constructions whose function was strictly related to past sea levels, and their dating is quite well known. Their present position with respect to the estimated original position at the time of their construction provides precise information on the amount and timing of relative sea level change. An excellent case-study is provided by the seventeen fish tanks and fish traps located along the coast of Crete at Phalasarna, Matala (Fig. 8k and l), Ferma (Fig. 8h), Kato Zakros, Mochlos (Fig. 9g), and Chersonisos (Fig. 8s). Ancient shipsheds are also valid sea level markers, as the seaward end of the carved sloping floor is flush with the then sea level (Fig. 8g and h, Fig. 9k).

The fourth category refers to coastal water tables and their changes in response to sea level changes. Usually coastal aquifers are in hydraulic connection with the adjacent sea. Therefore, sea level rise may result in the flooding of archaeological sites built on land near the shore (Mourtzas, 1990, 2010; Pagliarulo et al., 2013).

Please cite this article in press as: Mourtzas, N., et al., Vertical land movements and sea level changes along the coast of Crete (Greece) since Late Holocene, Quaternary International (2015), http://dx.doi.org/10.1016/j.quaint.2015.08.008

Table 5
Archaeological indicators along the coast of Crete.

Location	Coordinates (Lat. NorthLong. East)	Type of archaeological indicator	Archaeological age	Elevation	Functional height	Sea level change	Related sea level stand	References
Phalasarna	35°30'38.80'' 23°34'8.91''	Uplifted closed harbour.	The harbour operation is dated to the second half of the 4th c. BC. It was probably destroyed in 67 BC by the Romans. The port was abandoned in the late 1st c. AD and its basin was filled with terrestrial sediments.	In AD 365 the port rose by 6.60 m	In the 4th c. BC the depth of the harbour basin is estimated at 1.10 ± 0.10 m with the quays edges 0.40 m above the then sea level. In 67 BC the harbor entrance was blocked and the basin silted up.	+6.60 m	+6.60 ± 0.30 m	Hadjidaki (1996, 2001) Pirazzoli et al. (1992) Frost (1997) Dominey-Howes et al. (1998)
	35°30'32.31'' 23°34'8.96''	Rock-cut basin which later was probably used as fishpond. A crack, formed in the AD 55 or 66 earthquake which sank the region by 0.20 m, was permitting sea water to enter into the tank.	1st century AD	+6.60 m	± 0.00 m	+6.60 m	+6.60 ± 0.30 m	Flemming & Pirazzoli (1981) Pirazzoli et al. (1992)
Kastelli Kissamou	35°30'4.49'' 23°38'45.83''	Uplifted breakwater constructed by accummulated rubble blocks.	Probably Roman, as concluded by the adjacent relics of a masonry (67 BC – 395 AD).	+3.00 m to +5.50 m	+0.30 m to +1.20m	+2.70 m to +4.30 m	+2.50 ± 0.30 m to +4.30 ± 0.30 m	Flemming & Pirazzoli (1981) present study
Paleochora	35°14'13.94'' 23°40'2.39''	Millstone quarry, carved on the surface of the younger beachrock generation.	Middle to late 19th century.	−0.25 m	+0.30 m	−0.55 m	−0.55 ± 0.05 m	present study
Agioi Apostoloi	35°30'53.30'' 23°58'33.94''	Submerged quarry floor.	The quarries were operating in the Venetian domination of Crete, more likely during the construction of the defensive works of Chania town (1436 – 1456).	−0.10 m	+1.00 m	−1.10 m	−1.25 ± 0.05 m	present study
Kalathas	35°33'9.64'' 24° 5'4.58''			−0.30 m	+1.00 m	−1.30 m	−1.25 ± 0.05 m	present study
Stavros	35°35'35.58'' 24°05'45.03''			−0.35 m	+1.00 m	−1.35 m	−1.25 ± 0.05 m	present study
Avlaki	35°35'32.13'' 24° 09'01.17''	Slipway: the seaward edge of the sloping floor is submerged.	Avlaki is the seaport of the Katholikon monastery (11th c. AD – 1548).	−0.60 m	± 0.00 m	−0.60 m	−0.55 ± 0.05 m	present study
Damnoni	35°10'27.38'' 24°24'53.68''	Millstone quarry carved on the surface of the younger beachrock generation.	Middle to late 19th century.	−0.20 m	+0.30 m	−0.50 m	−0.55 ± 0.05 m	present study
Koumpes	35°21'56.70'' 24°27'09.22''	Submerged quarry floor.	The quarries were operating in the Venetian domination of Crete, more likely during the construction of the	−0.80 m	+0.50 m	−1.30 m	−1.25 ± 0.05 m	present study

			defensive works of Rethymno town (1571 – 1580).					
Rethymno	35°22'11.81" 24°28'07.13"	A small rectangular pond cut into the rock, whose edges are submerged.	Venetian period (1204 – 1669)	−0.05 m	+0.30 m	−0.35 m	−1.25 ± 0.05 m	Flemming and Pirazzoli (1981)
	35°22'16.19" 24°28'07.69"	Slipway: the seaward edge of the sloping floor is submerged.		−1.55 m	± 0.00 m	−1.55 m		Flemming and Pirazzoli (1981) Blackman et al. (2014) present study
Kommos	35°00'47.74" 24°45'29.87"	Submerged harbour morphology. An islet was protruded from the sea for a length of 165 m protecting the shore in front of the prehistoric settlement.	The settlement was founded in MM IA and MM II periods (2000 – 1800 BC). It was probably destroyed by an earthquake and abandoned in 1700 BC. In the Neopalatial Period (1700 – 1425 BC) the town was rebuilt and extended. Building and rebuilding continued throughout LM II and LM III periods (1425 – 1200 BC).	The islet is submerged at max depth −4.50 m	the islet was protruded from the sea 0.50 m to 4.20 m	−4.00 m	−3.95 ± 0.35 m	Mourtzas (1988a, 1990) Shaw (1990, 2006) present study
Matala bay	34°59'35.55" 24°44'49.81"	Eleven submerged complexes of carved fish tanks and traps.	Roman period: constructed between AD 1 and 200.	−1.25 ± 0.05 m	± 0.00 m	−1.25 ± 0.05 m	−1.25 ± 0.05 m	Buondelmonti (1415) Mourtzas (1988a, 1990, 2012a) 2
Lassaia	35°00'44.91" 25°40'29.22" 35°00'44.91" 25°40'29.22" 35°00'44.91" 25°40'29.22"	Submerged breakwater.	Hellenistic period (300 BC – AD 67)	−0.90 m	+0.30 m	−1.20 m	−1.25 ± 0.05 m −1.25 ± 0.05 m −1.25 ± 0.05 m	Blackman and Branigan (1975) Mourtzas (1990) Mourtzas and Marinos (1994) present study Blackman and Branigan (1975) Mourtzas (1990) Mourtzas and Marinos (1994) present study Blackman and Branigan (1975) Mourtzas (1990) Mourtzas and Marinos (1994) present study
Amnissos	35°19'57.17" 25°12'15.37" 35°19'57.17" 25°12'15.37" 35°19'57.17" 25°12'15.37"	Submerged relics of walls of a Minoan villa.	The villa had been built in early MM III (1700 BC). The first architectural phase ended with damage caused by an earthquake destruction at the end of MM III (1700) with a second earthquake and tsounami destruction and accompanying fire, caused in LM IA (1600 BC).	−1.00 m	> +2.00 m	−3.00 m	−2.75 ± 0.25 m −2.75 ± 0.25 m −2.75 ± 0.25 m	Evans (1928) Marinatos (1934) Flemming and Pirazzoli (1981) Mourtzas (1990) Schafer (1991) present study Evans (1928) Marinatos (1934) Flemming and Pirazzoli (1981) Mourtzas (1990) Schafer (1991) present study Evans (1928) Marinatos (1934) Flemming and Pirazzoli (1981) Mourtzas (1990) Schafer (1991) present study
Nirou Chani	35°19'58.93" 25°14'38.22" 35°19'58.93"	Submerged ruins of Minoan buildings.	The luxurious house was probably built in the MM III period (1700 BC) and after	−1.20 m	> +2.00 m	−3.00 m	−2.75 ± 0.25 m −2.75 ± 0.25 m −2.75 ± 0.25 m	Marinatos (1926) Frost (1963) Flemming and Pirazzoli (1981) Mourtzas (1990) present study

(*continued on next page*)

Table 5 (*continued*)

Location	Coordinates (Lat. NorthLong. East)	Type of archaeological indicator	Archaeological age	Elevation	Functional height	Sea level change	Related sea level stand	References
	25°14'38.22'' 35°19'58.93'' 25°14'38.22''		its destruction by fire in the LM IB period (1450 BC) was finally abandoned.					Marinatos (1926) Frost (1963) Flemming and Pirazzoli (1981) Mourtzas (1990) present study Marinatos (1926) Frost (1963)
	35°20'01.40'' 25°14'36.00'' 35°20'01.40''	Submerged coastal Minoan quarry.	It was probably operating in the period between 1700 BC and 1450 BC.	−1.70 m to −2.10 m −1.70 m to −2.10 m −1.70 m to −2.10 m	> +1.00 m	−2.10 m	−2.75 ± 0.25 m −2.75 ± 0.25 m −2.75 ± 0.25 m	Flemming and Pirazzoli (1981) Mourtzas (1990) present study
Chersonisos	25°14'36.00'' 35°20'01.40'' 25°14'36.00''	35°19'11.33'' 25°23'31.41'' 35°19'11.33'' 25°23'31.41'' 35°19'11.33'' 25°23'31.41''	Submerged Roman quay.	Roman period (67 BC to AD 395)	−1.00 m	+0.30	−1.30 m	−1.25 ± 0.05 m −1.25 ± 0.05 m −1.25 ± 0.05 m
	Leatham and Hood (1958/1959) Flemming and Pirazzoli (1981) Mourtzas	35°19'24.09'' 25°23'36.23'' 35°19'24.09'' 25°23'36.23'' 35°19'24.09'' 25°23'36.23''	Submerged fish tank.	Roman period (AD 1 to 200)	−1.20 m	± 0.00	−1.20 m	
35°19'23.16'' 25°23'24.30'' 35°19'23.16'' 25°23'24.30'' 35°19'23.16'' 25°23'24.30''	(1990, 2012a, b) Leatham and Hood (1958/1959) Flemming and Pirazzoli (1981) Mourtzas (1990, 2012a, b) Leatham and Hood (1958/1959) Flemming and Pirazzoli (1981) Mourtzas (1990, 2012a, b)	Submerged relics of walls and a natural breakwater.	Probably of Roman period (67 BC to AD 395)	−1.00 m to −1.80 m −1.00 m to −1.80 m −1.00 m to −1.80 m	+0.30	−1.30 m		
Stalida	35°18'22.33'' 25°25'11.41'' 35°18'22.33'' 25°25'11.41'' 35°18'22.33'' 25°25'11.41''	Ellipsoid buildings surrounding the coastal karstic springs, for water collection and improvenent of its quality. Sea level change resulted in lowering of the discharge point and inflow of sea water into the constructions.	Venetian period (1206 to 1669)	−0.30 m to −0.50 m −0.30 m to −0.50 m −0.30 m to −0.50 m	+0.30 m to +0.50 m	−1.00 m	−1.25 ± 0.05 m −1.25 ± 0.05 m −1.25 ± 0.05 m	Mourtzas (1990)
Mylos bay	35°17'49.61'' 25°29'08.04'' 35°17'49.61'' 25°29'08.04''	Circular cistern and partially submerged carved channel of a watermill.	Probably of Byzantine or Venetian period (961 AD – 1669) Probably of Byzantine or Venetian period (961	−0.30 m to−0.70 m−0.30 m to−0.70 m−0.30 m to−0.70 m	+0.50 m	−1.20 m	−1.25 ± 0.05 m −1.25 ± 0.05 m −1.25 ± 0.05 m	Mourtzas (1990)

	35°17'49.61" 25°29'08.04"		AD – 1669) Probably of Byzantine or Venetian period (961 AD – 1669)					
Malia	35°17'48.01" 25°29'01.60" 35°17'48.01" 25°29'01.60" 35°17'48.01" 25°29'01.60"	Submerged coastal Minoan quarries.	It was probably operating in the period between 1900 BC and 1450 BC.	−1.20 m	> +1.00 m	> +2.20 m	−2.75 ± 0.25 m −2.75 ± 0.25 m −2.75 ± 0.25 m	Mourtzas (1990)
Spiliada	35°18'46.29" 25°31'48.29" 35°18'46.29" 25°31'48.29" 35°18'46.29" 25°31'48.29"	Submerged relics of walls and foundations of a coastal Minoan settlement and rock cuttings.	Early Minoan IIB (2550 BC – 2300 BC)	−2.33 m	> +1.00 m	> +3.33 m	−3.95 ± 0.35 m	Simosi (2003) present study Simosi (2003) present study Simosi (2003) present study
Stomio	35°00'44.91" 25°40'29.22" 35°00'44.91" 25°40'29.22" 35°00'44.91" 25°40'29.22"	Submerged Roman building. Probably was an artisanal construction (baths or tanks), having a direct relationship with the then shoreline.	Roman period (67 BC to AD 395)	−1.20 m	± 0.00 m	−1.20 m	−1.25 ± 0.05 m −1.25 ± 0.05 m −1.25 ± 0.05 m	Mourtzas (1988a, 1990) present study Mourtzas (1988a, 1990) present study Mourtzas (1988a, 1990) present study
Ierapetra harbour	35°00'21.85" 25°44'25.35" 35°00'21.85" 25°44'25.35" 35°00'21.85" 25°44'25.35"	Submerged Roman breakwater.	Roman period (67 BC to AD 395)	−0.30 m to −1.30 m−0.30 m to −1.30 m−0.30 m to −1.30 m	+0.30 m	−1.00 m to −1.60 m	−1.25 ± 0.05 m −1.25 ± 0.05 m −1.25 ± 0.05 m	present study
Poros Eloundas	35°15'21.68" 25°44'4.47"	Submerged ruins of building walls.	The constructions must be contemporaneous to the Christian basilica, the ruins of which are located 100 m further north. The temple belongs to the first Byzantine period (AD 395 – 824) and their construction dates to the late 5th c. AD.	−1.00 m	+0.30 m	−1.30 m	−1.25 ± 0.05 m −1.25 ± 0.05 m −1.25 ± 0.05 m	present study
	35°15'21.51" 25°44'9.32"	Submerged protective breakwater.		−3.25 m (foundations) and −1.30 m (surface)	+0.30 m	−1.60 m	−1.25 ± 0.05 m −1.25 ± 0.05 m −1.25 ± 0.05 m	present study
	35°15'22.14" 25°44'10.77"	Submerged ruins of building walls.		max depth −1.32 m	+0.30 m	−1.60 m	−1.25 ± 0.05 m −1.25 ± 0.05 m −1.25 ± 0.05 m	present study
	35°15'19.89" 25°43'56.62" 35°15'19.89" 25°43'56.62"	Venetian saltpans: large square tanks for sea water evaporation, bordering by stone walls, today entirely submerged.	They were operating in the Venetian period (1579 – 1601). The southern part was repaired and reorganized between 1631 and 1644. The floor of the salt pans was higher than the then sea level and partition walls protruded above the sea level during high tide.	The surface of the partition walls is at −0.18 m to −0.27 m and their bottom at −0.48 m to −0.60 m.	+0.10	−0.60 m	−0.55 ± 0.05 m	Makrakis (2006) present study Makrakis (2006) present study
Istron	35°07'49.79" 25°43'35.12" 35°07'49.79" 25°43'35.12"	Priniatikos Pyrgos: submerged ruins of walls of a Minoan settlement.	Early and Late Minoan settlement (3rd and 2nd millennium BC). A large Roman settlement was also built over the Minoan ruins.	−1.00 m	> +2.00 m	> +3.00 m	−3.95 ± 0.35 m	Mourtzas (1990)
Koutsounari	35°00'30.91" 25°50'03.18"	Submerged rock-cut salt pan.	Roman period: constructed between AD 1 and 200.	−1.20 m	± 0.00 m	−1.20 m	−1.25 ± 0.05 m −1.25 ± 0.05 m	Mourtzas (1988a, 1990)

(*continued on next page*)

Table 5 (*continued*)

Location	Coordinates (Lat. NorthLong. East)	Type of archaeological indicator	Archaeological age	Elevation	Functional height	Sea level change	Related sea level stand	References
	35°00'30.91" 25°50'03.18"							
Ferma	35°00'40.80" 25°50'30.82" 35°00'40.80" 25°50'30.82"	Submerged fish tank.	Roman period: constructed between AD 1 and 200.	−1.30 m	± 0.00 m	−1.30 m	−1.25 ± 0.05 m −1.25 ± 0.05 m	Davaras (1975) Flemming and Pirazzoli (1981) Mourtzas (1990, 2012a, b) Davaras (1975) Flemming and Pirazzoli (1981) Mourtzas (1990, 2012a, b)
Psira island	35°11'07.29" 25°51'48.71" 35°11'07.29" 25°51'48.71"	Submerged blocks of concrete masonry, probably remains of a Roman water front.	Dated between 67 BC and AD 395.	he upper surface of the wharf is at −1.00 m.	+0.30 m	−1.30 m	−1.25 ± 0.05 m −1.25 ± 0.05 m	Leatham and Hood (1958/1959)
Mochlos	35°11'09.63" 25°54'20.63" 35°11'09.63" 25°54'20.63"	Submerged isthmus joined the Minoan settlement on the islet to the mainland and submerged relics of Minoan walls.	First settled in the Final Neolithic – Early Minoan I period (3650 – 3000 BC). Evidence of a MM IA destruction (2160 – 1900 BC). The town was destroyed by fire at the end of LM IB (1450 BC).	−1.50 m to −2.00 m in the edges, −3.80 ± 0.20 m in the central section	+0.50 m	−4.30 m	−3.95 ± 0.35 m	Leatham and Hood (1958/1959) Mourtzas (1990) Soles (2007) present study Leatham and Hood (1958/1959) Mourtzas (1990) Soles (2007) present study
	35°11'09.63" 25°54'20.63" 35°11'09.63" 25°54'20.63"	Submerged concrete wall of the Roman or Byzantine period.	67 AD to AD 824	< −1.50 m	+0.50 m	−1.50 m	−1.25 ± 0.05 m −1.25 ± 0.05 m	Leatham and Hood (1958/1959)
	35°11'00.77" 25°54'22.02" 35°11'00.77" 25°54'22.02"	Submerged fish tank.	Roman period: constructed between AD 1 and 200.	−1.10 m to −1.40 m	± 0.00	−1.25 ± 0.15 m	−1.25 ± 0.05 m −1.25 ± 0.05 m	Leatham and Hood (1958/1959) Mourtzas (1990, 2012a, b) Leatham and Hood (1958/1959) Mourtzas (1990, 2012a, b)
Sitia	35°12'37.54" 26°06'31.74" 35°12'37.54" 26°06'31.74"	Submerged quarry floor.	It was probably operating in the Roman period between 67 BC and AD 395.	−0.30 m	+1.00 m	−1.30 m	−1.25 ± 0.05 m −1.25 ± 0.05 m	Davaras (1974) Mourtzas (1990, 2012a, b) Davaras (1974) Mourtzas (1990, 2012a, b)
	35°11'54.79" 26°07'50.91" 35°11'54.79" 26°07'50.91"	Slipway. The seaward edge of the sloping floor is today submerged.	Hellenistic period (300 BC to AD 69).	> −0.40 m to −0.80 m	±0.00 m±0.00 m	> −0.80 m	−1.25 ± 0.05 m −1.25 ± 0.05 m	Davaras, (1968) Blackman et al. (2014) present study Davaras, (1968) Blackman et al. (2014) present study
Farmakokefalo – Xerokambos – Ancient Abelos	35°02'57.05" 26°14'23.97" 35°02'57.05" 26°14'23.97"	Salt pans, 5 m from the shoreline on land, consisting of a system of canals and reservoirs for sea water evaporation.	Classical and Hellenistic Period (500 – 67 BC).	+0.20 m	> +1.00 m	−1.20 m	−1.25 ± 0.05 m −1.25 ± 0.05 m	Montaggioni et al. (1981) Peters (1985) Mourtzas (1990) Montaggioni et al. (1981) Peters (1985) Mourtzas (1990)
Kato Zakros bay	35°05'52.26" 26°15'40.45" 35°05'52.26" 26°15'40.45"	Rise of groundwater table in the water supply system of the Palace, > 4.0 m from the Protopalatial period and 2.85 m from the Neopalatial period.	The palace was constructed around 1900 BC and was rebuilt after the earthquake destruction of 1700 BC or 1600 BC. Finally was destroyed by an earthquake around 1450 BC.	−2.85 m	±0.00 m	2.85 m	−2.75 ± 0.25 m −2.75 ± 0.25 m	Flemming and Pirazzoli (1981) Mourtzas (1990) present study Flemming and Pirazzoli (1981) Mourtzas (1990) present study

	35°05'57.04" 26°15'52.53" 35°05'57.04" 26°15'52.53"	Submerged harbour morphology. An islet was protruded from the sea for a length of 165 m protecting the shore in front of the prehistoric settlement.	Neopalatial period (1600 – 1450 BC).	−2.90 m	+0.30 m	+3.20 m	−2.75 ± 0.25 m −2.75 ± 0.25 m	present study
	35°05'52.26" 26°15'40.45" 35°05'52.26" 26°15'40.45"	Submerged fish trap.	Roman period: constructed between AD 1 and 200.	−1.00 m to −1.30 m	± 0.00 m	−1.30 m	−1.25 ± 0.05 m −1.25 ± 0.05 m	Nakasis (1987) Mourtzas (1990, 2012a, b) Nakasis (1987) Mourtzas (1990, 2012a, b)
Palaikastro	35°11'48.86" 26°16'43.80" 35°11'48.86" 26°16'43.80"	Submerged ruins of Late Minoan walls and a submerged carved structure.	The town established around 1900 BC, damaged by earthquake around 1700 BC, suffered the effects of the Theran eruption, reconstructed and abandoned after a earthquake around 1300 BC (LM IIIB).	−1.80 m	> +1.00 m	−2.80 m	−2.75 ± 0.25 m −2.75 ± 0.25 m	Pirazzoli (1980) Flemming and Pirazzoli (1981) Mourtzas (1990) Pirazzoli (1980) Flemming and Pirazzoli (1981) Mourtzas (1990)
Kouremenos	35°12'55.84" 26°16'18.98" 35°12'55.84" 26°16'18.98"	Roman breakwater.	Roman period (69 BC to AD 400).	−1.25 m to −1.30 m	+0.30 m	−1.60 m	−1.25 ± 0.05 m −1.25 ± 0.05 m	Simosi (1988) present study Simosi (1988) present study
Agios Isidoros bay	35°18'51.20" 26°18'40.58"	Submerged foundation and parts of columns from the ruined Temple of the Samonio Athena, incorporated into the beachrock formation.	4th century BC	The walls relics at −0.65 m are incorporated into a beachrock submerged at −1.35 m.	+0.70 m	−1.35 m	−1.25 ± 0.05 m	Spratt (1865) Chalikiopoulos (1903) Papadakis (1989) Mourtzas (1990) present study

Fig. 9. Archaeological sea level indicators along the coast of eastern Crete. (a) Ierapetra: submerged Roman harbour, (b) Stomio: submerged Roman building, (c) Poros Eloundas: submerged ruins, (d) Poros Eloundas: submerged buildings (e) Poros Eloundas: submerged saltpans, (f) Mochlos: submerged isthmus, (g) Mochlos: submerged fish tank, (h) Ferma: submerged fish tank, (i) Koutsounari: submerged rock-cut salt pan, (j) Sitia: submerged quarry, (k) Sitia: slipway, (l) Kato Zakros: inundated ruins of the Minoan palace, (m) Kato Zakros: inundated cistern of the Minoan palace, (n) Kato Zakros: submerged harbour morphology, (o and p) Agios Isidoros bay: submerged relics of the Temple of Samonio Athena.

The Minoan coastal settlement at Kato Zakros (Eastern Crete) is a typical example. The rise of the aquifer by 2.85 m in the water supply systems of the palace, caused the inundation of the southern section of this site (Fig. 9l and m), indicating a rise of sea level over the last 3450 years (Mourtzas, 1990). The timing of this change is in agreement with the elevation of the nearby tidal notches and beachrocks, which can be therefore tentatively dated.

The uplift by 5.0 m of the Roman breakwater located at Kastelli Kissamou and the uplift by 6.60 m harbor of the fourth century BC and the Roman age fishtank in Phalasarna, are likely the most

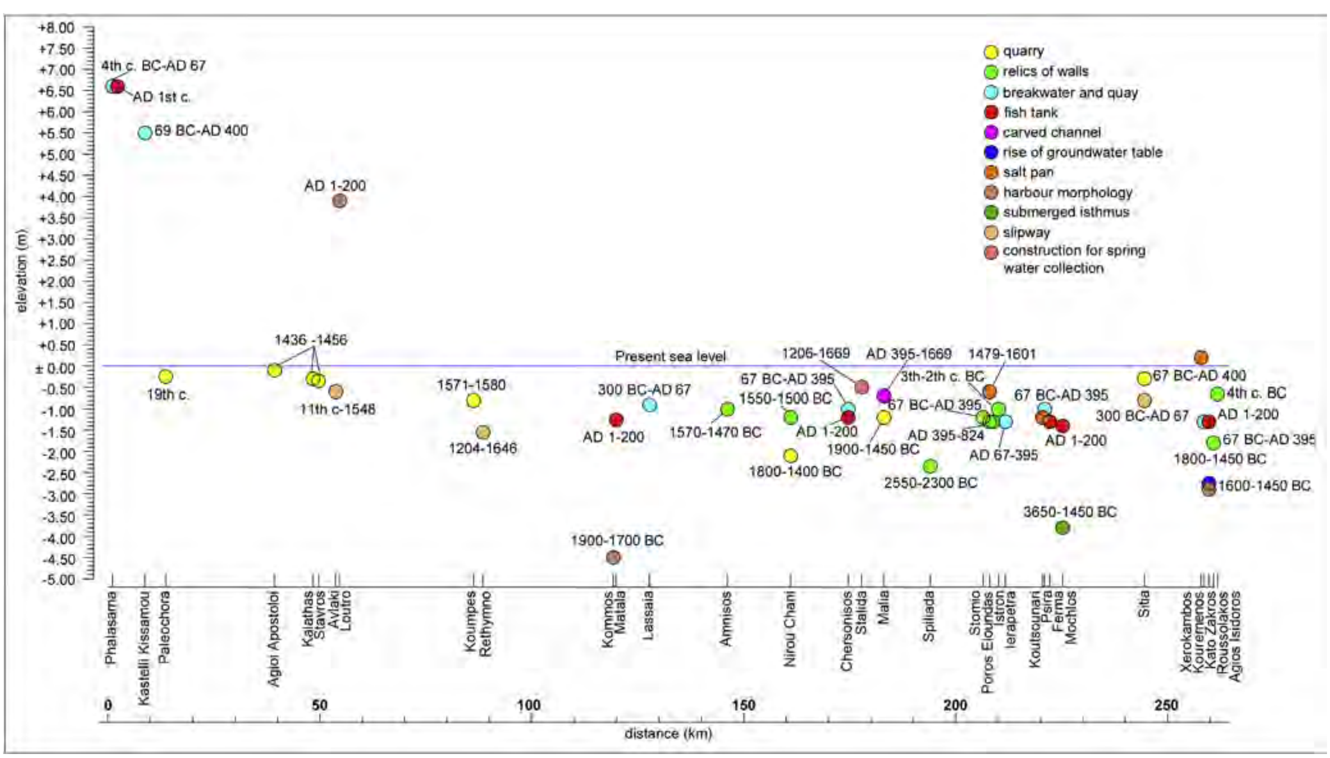

Fig. 10. Elevation and age of the archaeological indicators for each location. Circles in different solid color show each type of archaeological markers (breakwater, carved channel, fish tank, quarry, building, slipway etc.). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

typical archaeological indicators of the recent uplift along the western coast of Crete. The submerged quarry floors between 0.10 m and 0.80 m below sea level at Paleochora, Agioi Apostoloi, Kalathas, Stavros, Koumpes, and Damnoni, all dated between the Venetian period and the nineteenth century, as well as the submerged slipways of the Venetian period at a depth between 0.60 m and 1.55 m, show and date the, subsequent to the uplift, subsidence events of Crete in at least two phases.

All the archaeological indicators of relative sea level change along the central and eastern coast of Crete are below the present sea level. Those connected with the Protopalatial Minoan phase of Crete (1900–1700 B C) are at −4.30 ± 0.45 m, including the submerged harbor morphology of the Protopalatial phase of Kommos (Mourtzas, 1988a) and the submerged isthmus at Mochlos that joined the Minoan settlement on the islet to mainland (Leatham and Hood, 1958/59; Mourtzas, 1990; Soles, 2007). The archaeological markers associated with the Neopalatial Minoan phase of Crete (1600–1450 B C), such as the Neopalatial phase of the Palace of Kato Zakros, refer to a submersion at −2.85 m. The Roman harbor installations and the fish tanks and fish traps of the Roman period (AD 1–200) and the coastal constructions and installations of the Byzantine and middle Venetian period show a submersion at −1.25 m to −1.30 m. Finally, the late Venetian saltpans at Poros Eloundas and the late Venetian slipway at Avlaki rocky coast, that were operational between 1631 and 1644 and the nineteenth century, show a submergence of the coast of about 0.60 m.

In Table 5, data on archaeological indicators (location, coordinates, type of marker, archaeological age, elevation, functional height, sea level change and references), are reported. Some views of uplifted or submerged archaeological markers along the coast of western and central Crete are shown in Fig. 8, while in Fig. 9 are provided for eastern Crete. Fig. 10 shows the elevations and age of the archaeological indicators for each location. Circles refer to different types of archaeological markers (breakwater, carved channel, fish tank, quarry, relics of building, slipway etc.).

6. Comparison between geomorphological indicators

In comparing the depths of the seaward end of beachrocks with those of tidal notches that formed at the same sea level stand, a good correlation is observed. The mean depth of the submerged tidal notches and beachrock phases observed along the western and central-eastern Crete are shown in Fig. 11. Depths are well-matched, and correlation of geomorphological indicators suggests five distinct sea levels. In central and eastern Crete, the beachrock level at 4.30 ± 0.20 m below sea level (bsl) (phase III) corresponds to the tidal notch of 3.95 ± 0.25 m bsl (tidal notch IV), the beachrock level at 3.10 ± 0.30 m bsl (phase II) is in agreement with the position of the tidal notch at 2.70 ± 0.15 m bsl (tidal notch III). The elevation of the beachrock at 1.35 ± 0.20 m bsl (phase I) is consistent with the tidal notch at 1.25 ± 0.05 m bsl (tidal notch II). Although the depths of the base of the seaward end of the two deeper beachrock phases (III, II) coincide with the respective depths of the tidal notches IV and III, only the top of the seaward end of the shallower beachrock phase (I) is comparable with the depth of the tidal notch II, whereas the depth of its base is in agreement with the depth of the top of the preceding beachrock phase (III).

From the comparison of the mean depths of the younger beachrock phase (I) of the central-eastern (1.35 ± 0.20 m bsl) and western (1.25 ± 0.15 m bsl) Crete with the elevation of the tidal

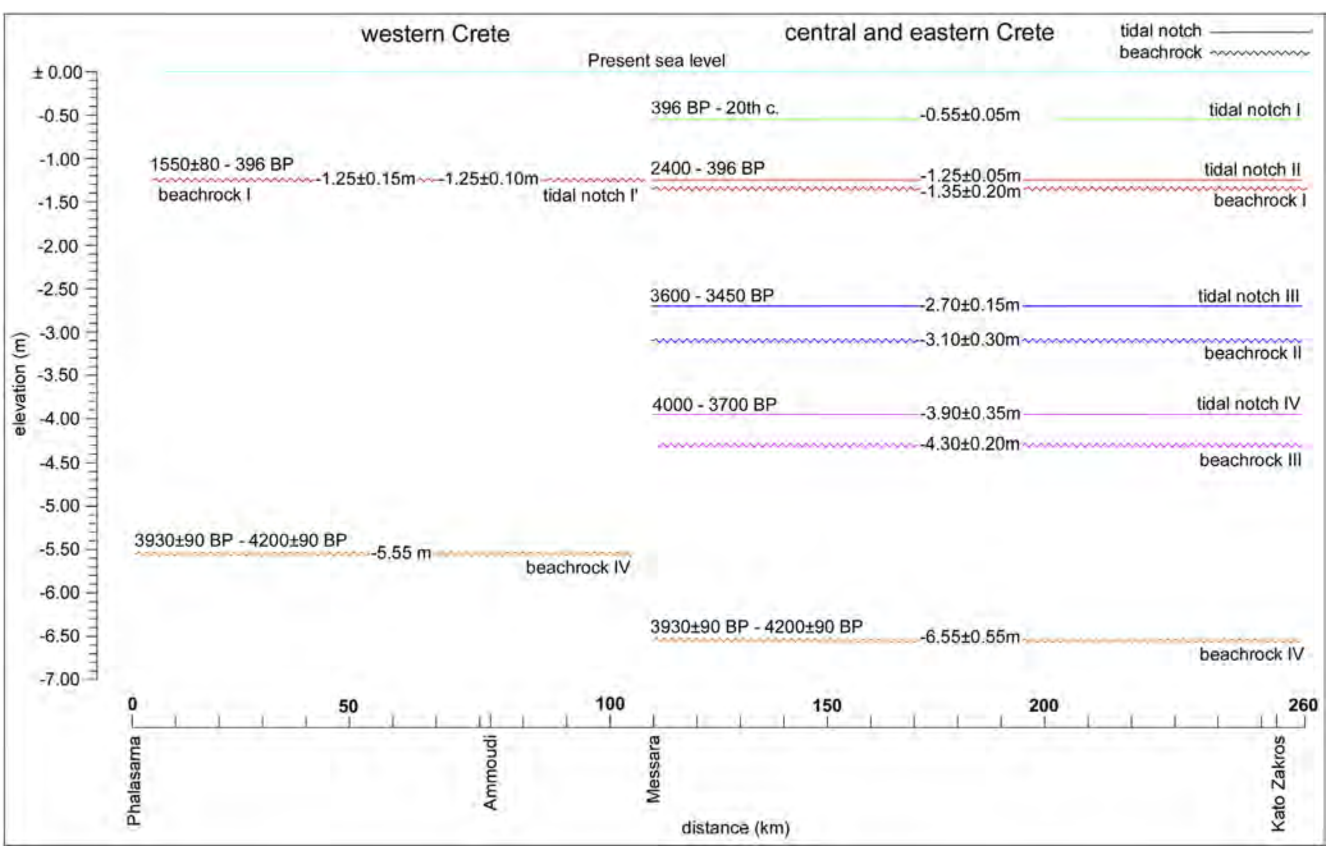

Fig. 11. Average elevations of submerged tidal notches and beachrock phases of western, central and eastern Crete. Elevations are in good agreement and geomorphological indicators infer five distinct relative sea levels.

notches II (1.25 ± 0.05 m bsl) and I (1.25 ± 0.10 m bsl), we found a good fit for the respective elevations. When we add the subsequent uplift of 1.70 m of the tidal notch III found in Damnoni to the depth of the older beachrock phase IV at 5.55 m bsl, the resulting elevation of 7.25 m corresponds to the maximum uplift of the tidal notch III (+7.50 m) found in the most uplifted westernmost extremity of the island. Therefore, it is reasonable to assume that the older beachrock phase at Damnoni formed between 4200 ± 90 B P (Phalasarna) and 3930 ± 90 B P (Chrisoskalitissa).

From the comparison between the maximum submersion (−7.25 m) of the older beachrock phase IV in Damnoni (before the uplift of the coast by 1.70 m), the corresponding submersion of the westernmost beachrock on the east coast in Xirokampos (−7.00 ± 0.35 m) and Faflago (−7.20 m), and the average depth of beachrock phase IV in central and eastern Crete (−6.55 ± 0.55 m), it is reasonable to deduce that they formed during the same sea level stand.

7. Dating of relative sea level stands

The older relative sea level stand at −6.55 ± 0.55 m in central-eastern Crete can be correlated to the sea level stands at 4200 ± 90 B P to 3930 ± 90 B P, in western Crete. The beachrock level at −4.30 ± 0.20 m that corresponds to the tidal notch of −3.95 ± 0.25 m (relative sea level stand, rsls IV) can be dated at 3900 B P to 3700 B P or 3600 B P, on the basis of the Protopalatial period of the Prehistoric settlement of Kommos (Mourtzas, 1988a, 1990), the submerged Minoan quarry at Nirou Chani (Mourtzas, 1990), the submerged Prehistoric settlement at Spiliada (Simosi, 2003), and the submerged isthmus of Minoan Mochlos (Leatham and Hood, 1958/59; Mourtzas, 1990; Soles, 2007), all of about the same age. The elevation of the beachrock at 3.10 ± 0.30 m bsl, which fit the tidal notch at 2.70 ± 0.15 m bsl (rsls III), is dated at 3600 B P to 3450 B P, based on the rise of groundwater level in the Neopalatial water basins and wells of the Minoan palace of Kato Zakros (Mourtzas, 1990).

The beachrock level at 1.35 ± 0.20 m bsl related to the tidal notch of −1.25 ± 0.05 m (rsls II) is dated after 1450 B C. Archaeological markers and historical records assign it to the period between 400 B C and AD 1604 (Mourtzas, 2012a, 2012b). Dating was based on the submerged classical temple of Samonio Athena (NE Crete) and the submerged Hellenistic harbour of Lassaia (Blackman and Branigan, 1975; Mourtzas, 1990; Mourtzas and Marinos, 1994). In addition, the interpretation is reinforced by the Roman fish tanks and other coastal installations, placed along the coast of eastern Crete. Historical testimonies aided in matching the paroxysmal event of 1604 with the change of 0.70 m in the Classical to Venetian sea level (Mourtzas, 2012a, 2012b). The submerged Byzantine and Venetian coastal (AD 500–1580) installations at Poros Eloundas and Rethymno, and the inundated floors of Koumpes, Stavros, Kalathas and Agioi Apostoloi Venetian quarries in northwest Crete support this hypothesis. During the last 400 years, sea level rose from −0.55 m (rsls I) to the present level causing the submersion of the salt pans of the late Venetian and Ottoman period at Poros Eloundas and the submerged late Venetian slipway of Avlaki, in Akrotiri Chanion peninsula.

8. Earthquake contribution to the observed relative sea level changes

Crete is subjected to intense seismicity, even of large intensity (Guidoboni et al., 1994). Around 1700 B C, a large earthquake destroyed the major centers of the Protopalatial phase of the Minoan civilization, such as the Palaces of Knossos, Phaestos, Malia, Kato Zakros, and the harbor town of Kommos (Evans, 1928; Fiandra, 1963, 1980; Platon, 1974; Levi, 1976; Pelon, 1980, 1983; Detorakis, 1990; La Rosa, 1995; MacDonald, 2003; Monaco and Tortorici, 2004; Shaw, 2006). This event is also confirmed by the traces of huge fires, rubble of collapsed buildings, a human skeleton in the Minoan Temple of Anemospilia, and the destruction of the Prehistoric palace and town of Archanes in central Crete (Sakellarakis and Sapouna-Sakellaraki, 1981, 2002). Another destructive earthquake struck the Neopalatial phase of the Palaces in 1450 B C, which was rebuilt after the 1700 B C event (Georgalas, 1931; Sieberg, 1932; Platakis, 1950; Pendlebury, 1954; Platon, 1974; Pichler and Schiering, 1980; Vallianou, 1996; Monaco and Tortorici, 2004).

Based on data from archaeological excavations, were identified two episodes of earthquake effects that struck the Minoan centers of Knossos and Phaestos before 1700 B C (Evans, 1928; Fiandra, 1963, 1980; Levi, 1976; Detorakis, 1990; La Rosa, 1995). The theory that tried to link the eruption of Thera volcano with the destruction of the Neopalatial Minoan settlements in Crete (Marinatos, 1939; Platon, 1974), has been widely disregarded, as the eruption appears to have occurred at least 100–150 years earlier (LaMarche and Hirschboeck, 1984; Baillie and Munro, 1988; Hammer et al., 2003; Manning et al., 2006; Friedrich and Heinemeier, 2007) than the traditional archaeological dating of the destruction of the Neopalatial Minoan phase (Michael, 1976; Betancourt, 1987, 1998; Manning, 1988; Friedrich et al., 1990; Housley et al., 1990; Manning and Ramsey, 2003). However, seismic effects are recognizable in several Minoan settlements around 1600 B C. This earthquake and tsunami that accompanied Thera eruption and hit the central Aegean seem to be associated with archaeological destruction layers of the Minoan palaces (Driessen and Macdonald, 1997; Soles, 2007; Bruins et al., 2008; Hardman, 2009). Recent pottery-based studies date the first destruction of the Protopalatial phase of Kato Zakros Palace to around 1600 B C (Platon, 2004), linking it with the Thera eruption and its attendant neotectonic upheavals in the area of the southern Aegean.

Nur and Cline (2000) and Nur and Burgess (2008) suggested that a seismic event in the Eastern Mediterranean during the years 1225–1175 B C could have been responsible for the partial or the entire destruction of a number of Eastern Mediterranean settlements, including late Minoan sites in Crete (Jusseret and Sintubin, 2012). Evidence for earthquake related damage was identified at the sites of Malia and Sissi, dated to 1300–1200 B C (Jusseret et al., 2013).

While there is a broad agreement on the seismic destruction of Minoan centers at the end of the Protopalatial period (~1700 B C) (Evans, 1928; Fiandra, 1963; 1980; Platon, 1974; Levi, 1976; Sakellarakis and Sapouna-Sakellaraki, 1981, 2002; La Rosa, 1995; Macdonald, 2003; Monaco and Tortorici, 2004; Shaw, 2006) and the impact on the Minoan communities of Crete that have had the phenomena accompanying the eruption of Thera, such as earthquakes, tsunami and ash diffusion (Antonopoulos, 1992; Driessen and Macdonald, 1997; Soles, 2007; Bruins et al., 2008; Hardman, 2009), there is a serious disagreement about the causes of the destruction of the Minoan sites by the end of the Neopalatial period (~1450 B C). It is attributed to natural phenomena, such as earthquakes (Evans, 1928; Pichler and Schiering, 1980; Vallianou, 1996; Nur and Cline, 2000; Puglisi, 2003; Monaco and Tortorici, 2004; Pelon, 2005), long-term effects of the eruption decisive for the decline of Minoan civilization (Driessen and Macdonald, 1997; Hardman, 2009), external military events such as the Mycenaean invasion in Crete (Hood, 1985; Popham, 1990), social upheavals and internal troubles (Furumark, 1950; Niemeier, 1984), and climate change affecting agricultural production (Riley, 2004) and water resources (Gorokhovich, 2005). Recently, was even suggested that the climate change may have been responsible for the slow demise of Minoan civilization, when El Nino causes drier conditions in the area of Crete (Tsonis et al., 2010).

The sea level rise by 1.20 m between the Minoan Protopalatial and Neopalatial phase could be associated with a large seismic event that most likely occurred around 1700 B C. The change by 1.45 m between the sea level stand of the Neopalatial phase (−2.70 ± 0.15 m) and the sea level stand with un upper age dated to the fourth century BC (−1.25 ± 0.25 m), would be either contemporary with the second destruction of the Minoan centers (~1450 B C) or in one or more paroxysmal events between 1450 B C and 400 B C.

After the Roman conquest of Crete and during the subsequent centuries, 35 earthquakes from moderate to large magnitude (M = 6.5–8.2), are reported in this region, causing the destruction of the major cities of Crete (Perrey, 1848; Mallet, 1854; Schmidt, 1862; Sathas, 1867; Raulin, 1870; Stavrakakis, 1890; Xanthoulidis, 1925; Sieberg, 1932; Maravelakis, 1939; Platakis, 1950; Papazachos and Papazachou, 1989; DiVita, 1995, 1996; Spyropoulos, 1997; Ambraseys, 2009; Papadopoulos, 2011). Remarkable are the earthquakes of AD 46, 55 (M = 7.2), 66 (M = 7.0), 168, and 365 (M = 8.2). Particularly, the latter split the island and caused crustal uplift in western Crete. The tsunami triggered by this event struck the coasts of most parts of the Mediterranean basin (Guidoboni et al., 1994; Stiros and Drakos, 2006; Stiros, 2010). Additional remarkable earthquakes occurred between 527 and 565 and in 666 (M = 6.5). In more recent times, the earthquake of 8 August 1303 is likely one of the largest events in the seismic history of the Mediterranean. The epicenter was located southeastwards of Crete and had similar effects to the 365 earthquake (Evangelatou-Notara, 1993; Guidoboni and Comastri, 1997; Papadopoulos, 2011).

Based on Buondelmonti (1415) and Spratt (1865) historical reports, Mourtzas (2012a,b) concluded that the submersion of the Roman (AD 1 to AD 200) fish tanks in the Gulf of Matala occurred during an interval of 450 years (Mourtzas, 2012a,b). In this period, 74 earthquakes of magnitude (Ms) 5 to 6.9 struck Crete, although coastal subsidence can be attributed to the 1604 earthquake (Ms = 6, intensity VII–VIII) (Giannaris, 1889; Stavrakakis, 1890; Georgiades, 1904; Zoudianos, 1960).

9. Discussion

Geomorphological and archaeological data allowed us to reconstruct the history of the relative sea level change along the

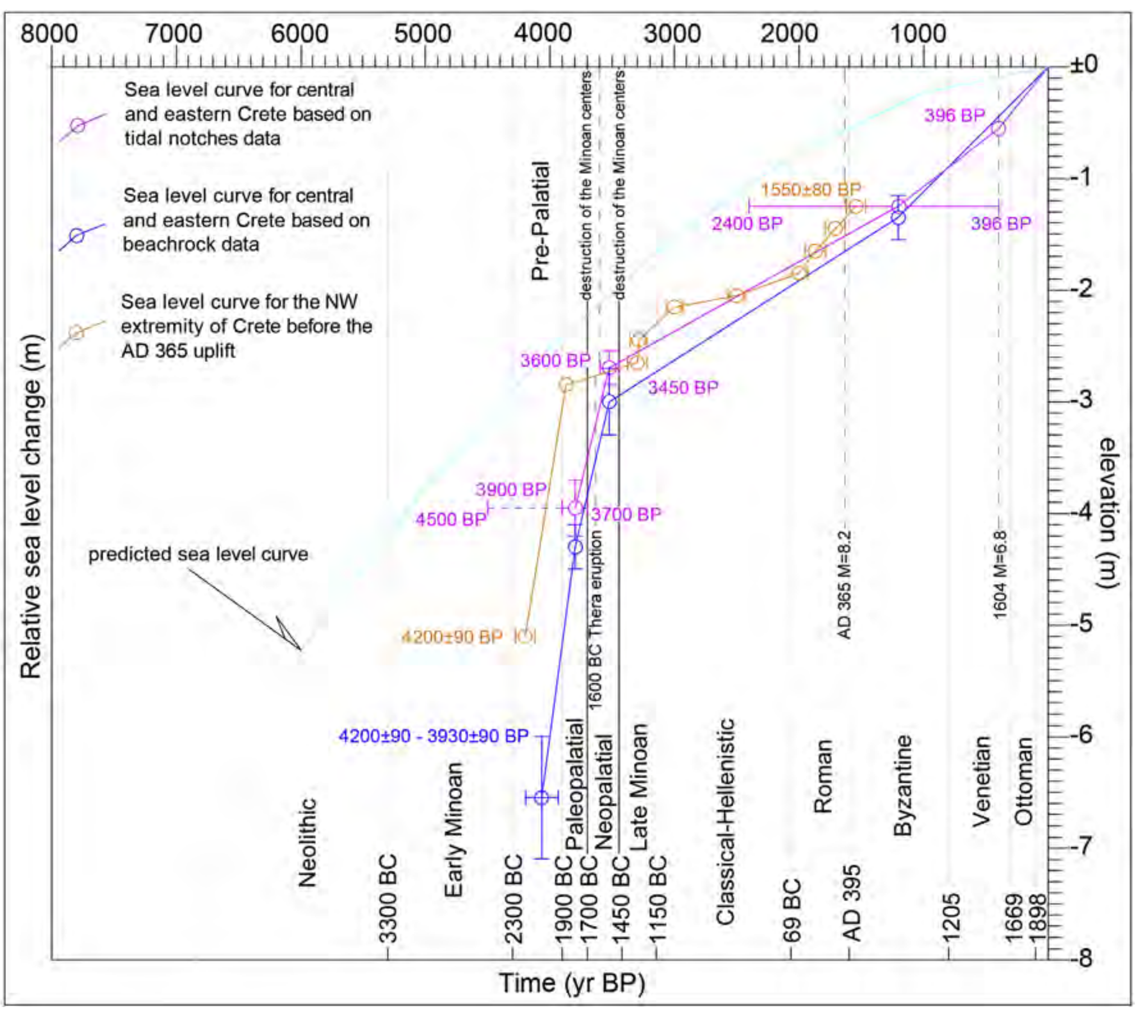

Fig. 12. Relative sea level change in western and central-eastern Crete during Upper Holocene. Blue line is the relative sea level change curve from beachrock data; magenta line is the relative sea level change curve estimated from tidal notch data. Orange line is the land subsidence in the NW extremity of Crete before the AD 365 uplift that clearly shows the coincidence between the higher uplifted tidal notch and a sea level stand at −1.25 ± 0.05. Cyan line is the predicted sea level curve for Crete, according to the glacio-hydro-isostatic model (Lambeck and Purcell, 2005). Error bars are the time span (horizontal) and the depth uncertainties (vertical). Historical periods and major catastrophic events are also reported. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

coast of Crete during the Upper Holocene. The correlation between elevations of the seaward end of submerged and emerged beachrocks and tidal notches support the hypothesis that their formation occurred during the same sea level positions (Fig. 11). Our observations support the observations of Neumeier (1998) on the intertidal cementation of beachrocks along the coast of Crete, but are in contrast with Kelletat (2006), who concluded that beachrocks of Crete cannot be used as valid sea level indicators. Kelletat (2006), analyzing the uplifted formation in Paleochora, did not consider the relative sea level fluctuations affecting this area, suggesting that beachrocks were characterized by a former supratidal environment.

In addition, the relationship between the functional elevations of ancient constructions and geomorphological markers, taking into account the limitations of the technique, allow their dating and the timing of the corresponding sea level. The submersion by −1.25 ± 0.05 m that followed the uplift of the western part of Crete occurred at the same time in the central and eastern part of the island, in two phases. The first subsidence of 0.70 m occurred the period between 1415 and 1865, but most likely in the 1604 earthquake (Mourtzas, 2012a, 2012b), while the second one of 0.55 m occurred over the last 400 years.

A second finding is that the sea level during the split and emergence of the western part of the island, around AD 365, was lower than today by −1.25 ± 0.05 m, hence the size of the maximum uplift in the NW extremity of the island is even greater than reported (7.90 ± 0.20 m) by Laborel et al. (1979), and reaches 9.15 ± 0.20 m. The uplift observed in the eastern tectonic boundary of the western block is 1.60 m at Petri Geraniou on the north coast and 2.00 m at Melambes on the south coast.

Fig. 12 shows the relative sea level change prediction for central-eastern Crete during Upper Holocene and the relative sea level change in the NW sector of the island before the uplift, as reported by Laborel et al. (1979) and Pirazzoli et al. (1982). Sea level stands and the respective sea level curves are discerned from geomorphological indicators.

The relative sea level curves (Fig. 12) indicate in the western and central-eastern part of the island sea level rose rapidly in the prehistoric period (4200 − 3450 B P), but with a significant reduction between 3450 B P and 396 B P, when the western part was split and uplifted. The subsequent subsidence of the entire island occurred in two different phases: the first by 0.70 m and the second by 0.55 m, at a rate of 3.15 mm/y (Fig. 3).

Comparing observed sea levels with predicted sea levels for the same periods using the Lambeck and Purcell (2005) predictions, we found that relative sea level indicators always fall below the past sea levels. In addition, sea level changes are variable in their rates, indicating that tectonics play a key role in changing the land − sea relationship along the coast of Crete (Lambeck, 1995).

The easternmost evidence of uplift along the western block of Crete in Petri Geraniou and Melambes, on the north and south coast, respectively, and the subsidence of the coast easternmost on the coast of Messara and Rethymnon, define a NW−SE trending tectonic boundary, corresponding to the neotectonic graben of Spili and its north−south prolongation. The structural analysis in three different sections of the fault indicates that this is a normal fault SW dipping, with at least three events of slickenside striations. The two older are SSW trending while the younger is SW trending, revealing subsequent fault reactivations, under a NNE−SSW tensile stress regime (Fig. 2). Five large-magnitude earthquakes occurred in the last 16.5 ka, accommodating two earthquakes within the last millennium, accruing a total of 3.5 m of throw, having remained quiet for the preceding 6.5 ka (Mouslopoulou et al., 2014).

The islets of Strongylo and Koufonisi uplifted by 0.90 m at 2200 B P (Montaggioni et al., 1981), representing the western uplifted part of a large tectonic ridge opposite the SE coast of Crete. The gradually uplifted Cape Trachoulas up to 5.0 m (Mourtzas and Fytrolakis, 1988), the uplifted western rocky coast of Tsoutsouros by 0.35 m (Mourtzas, 1990), and the uplifted northern coast of Akrotiri Chanion peninsula by 0.35 m that occurred after 1500, can be attributed to local tectonic events.

10. Conclusions

Geomorphological observations performed on tidal notches and beachrocks combined with archaeological data from coastal

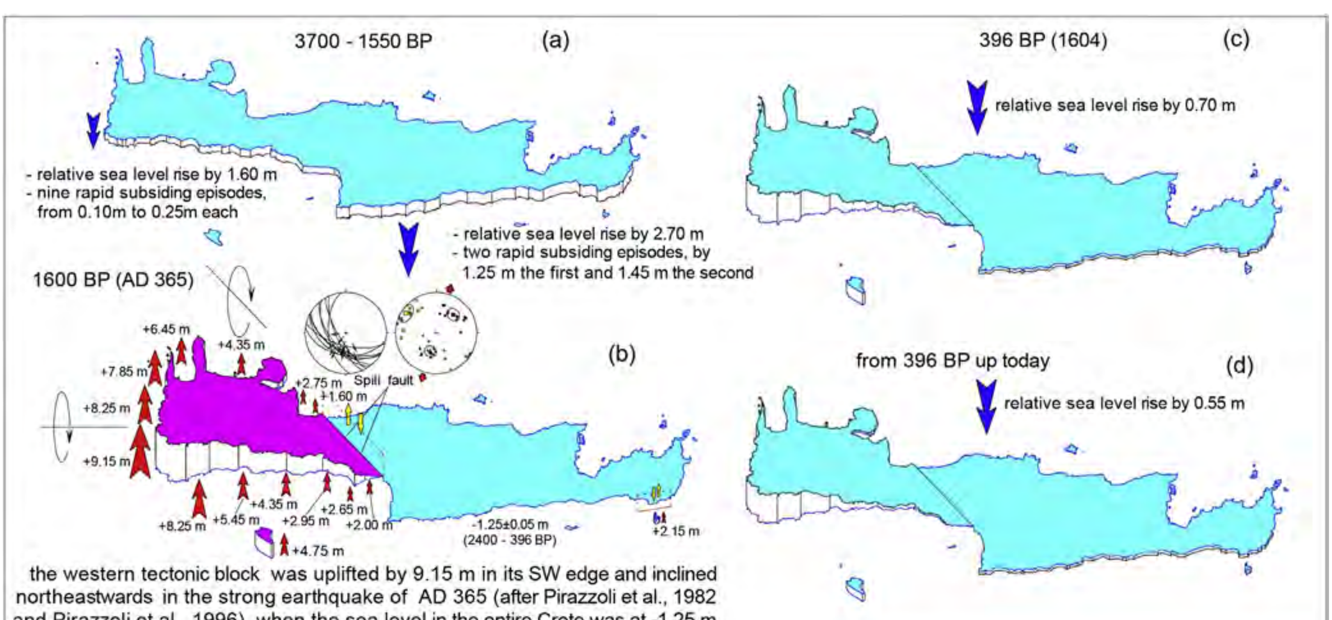

Fig. 13. Cartoon showing the history of land uplift and subsequent relative sea level changes along the coast of Crete.

Please cite this article in press as: Mourtzas, N., et al., Vertical land movements and sea level changes along the coast of Crete (Greece) since Late Holocene, Quaternary International (2015), http://dx.doi.org/10.1016/j.quaint.2015.08.008

installations located along the coast of Crete, have shown overall submersion by 1.60 m and by 2.65 m in western and central-eastern Crete, respectively (Fig. 13). This submersion occurred between 4000 B P and 396 B P. Around AD 365, when the sea level was 1.25 m lower than today, the western tectonic block split off the eastern block in a paroxysmal tectonic event. During this event, the western block uplifted by 9.15 m and 7.90 m in its SW and NW extremities, respectively, and between 1.60 m and 2.00 m in its easternmost boundaries, whereas the eastern block remained stable. After that, the coast of the entire island submerged by 1.25 m during two subsiding episodes: the first by 0.70 m in the 1604 earthquake and the second by 0.55 m during the last 400 years.

Acknowledgments

We are thankful to Kurt Lambeck who supported this research providing sea level predictions for Crete. The last stages of this study (2012, 2014) have been partially carried out under the umbrella of the MEDFLOOD project, funded by INQUA (project 1202P). Fieldwork in summer 2012 has been funded by the project MIUR 2010–2011 (project no. D81J12000430001), *Response of morphoclimatic system dynamics to global changes and related geomorphological hazard*, funded by the Italian Ministry of Education, University and Research.

References

Ambraseys, N., 2009. Earthquakes in the Mediterranean and Middle East. A Multidisciplinary Study of Seismicity up to 1900. Cambridge University Press, Cambridge.

Angelier, J., 1980. Thèse de Doctorat d'Etat, Societé Geologique du Nord. Néotectonique de l'arc Égéen, vol. 3 (Lille).

Angelier, J., Lyberis, N., Le Pichon, X., Barrier, E., Huchon, P.H., 1982. The tectonic development of the Hellenic arc and the sea of Crete: a synthesis. Tectonophysics 86, 159–196.

Antonioli, F., Lo Presti, V., Rovere, A., Ferranti, L., Anzidei, M., Furlani, S., Mastronuzzi, G., Orru, P.E., Scicchitano, G., Sannino, G., Spampinato, C.R., Pagliarulo, R., Deiana, G., de Sabata, E., Sanso, P., Vacchi, M., Vecchio, A., 2015. Tidal notches in Mediterranean Sea: a comprehensive analysis. Quaternary Science Reviews 119, 66–84.

Antonopoulos, J., 1992. The great Minoan eruption of Thera volcano and ensuing tsunami in the Greek archipelago. Natural Hazards 5, 153–168.

Anzidei, M., Antonioli, F., Lambeck, K., Benini, A., Soussi, M., 2011a. New insights on the relative sea level change during Holocene along the coasts of Tunisia and western Libya from archaeological and geomorphological markers. Quaternary International 232, 5–12.

Anzidei, M., Antonioli, F., Benini, A., Lambeck, K., Sivan, D., Serpelloni, E., Stocchi, P., 2011b. Sea level change and vertical land movements since the last two millennia along the coasts of southwestern Turkey and Israel. Quaternary International 232, 13–20.

Anzidei, M., Antonioli, F., Benini, A., Gervasi, A., Guerra, I., 2013. Evidence of vertical tectonic uplift at Briatico (Calabria, Italy) inferred from Roman age maritime archaeological indicators. Quaternary International 288, 158–167.

Anzidei, M., Lambeck, K., Antonioli, F., Furlani, S., Mastronuzzi, G., Serpelloni, E., Vannucci, G., 2014. Coastal structure, sea-level changes and vertical motion of the land in the Mediterranean. In: Martini, I.P., Wanless, H.R. (Eds.), Sedimentary Coastal Zones from High to Low Latitudes: Similarities and Differences. Geological Society, London, p. 388. Special Publications. http://dx.doi.org/10.1144/SP388.20.

Auriemma, R., Solinas, E., 2009. Archaeological remains as sea level change markers: a review. Quaternary International 206, 134–146.

Benetatos, C., Kiratzi, A., Papazachos, C., Karakaisis, G., 2004. Focal mechanisms of shallow and intermediate depth earthquakes along the Hellenic Arc. Journal of Geodynamics 37, 253–296.

Baillie, M., Munro, M., 1988. Irish tree rings, Santorini and volcanic dust veils. Nature 332, 344–346.

Bernier, P., Dalongeville, R., 1996. Mediterranean coastal changes recorded in beach-rock cementation. Zeitschrift für Geomorphologie N.F., Suppl.-Bd 102, 185–198.

Betancourt, P.P., 1987. Dating the Aegean Late Bronze Age with radiocarbon. Archaeometry 29, 45–49.

Betancourt, P.P., 1998. The chronology of the Aegean Late Bronze Age: unanswered questions. In: Balmuth, M.S., Tykot, R.H. (Eds.), Sardinian and Aegean Chronology: towards the Resolution of Relative and Absolute Dating in the Mediterranean. Studies in Sardinian Archaeology, vol. 5. Oxbow Books, Oxford, pp. 291–296.

Blackman, D.J., 1973. The neosoikos at Matala. In: Proceedings of the 3rd Cretological Congress (1971), Athens, pp. 14–21.

Blackman, D., 2011. Minoan shipsheds. Skyllis 11, 411–422.

Blackman, D.J., Branigan, K., 1975. An archaeological survey on the south coast of Crete, between the Ayiofarango and Chrisostomos. Annals of the British School at Athens (BSA) 70, 17–36.

Blackman, D., Rankov, B., Baika, K., Cerding, H., Pakkamen, J., 2014. Shipsheds of the Ancient Mediterranean. Cambridge University Press, New York.

Blanc, J.J., 1958. Recherches géologiques et sédimentologies -Résultats scientifiques des campagnes de la Calypso, III, vol. 34. Ann. de l'Institut Oceanographique, pp. 157–211.

Boekschoten, G.J., 1962. Beachrock at Limani, Chersonisos, Crete. Geologie en Mijnbouw 41, 3–7.

Boekschoten, G.J., 1963. Some geological observations on the coasts of Crete. Geologie en Mijnbouw 42, 241–247.

Bruins, J.H., Mac Gillivray, A., Synolakis, E.C., Benjamini, C., Keller, J., Kisch, J.H., Klugel, A., Van der Plicht, J., 2008. Geoarchaeological tsunami deposits at Palaikastro (Crete) and the Late Minoan IA eruption of Santorini. Journal of Archaeological Science 35, 191–212.

Buondelmonti, C., 1415. Descriptio Insule Crete (M. Aposkitis, Trans., 1983). Association of Cultural Development of Heraclion, Heraklion.

Caputo, R., Monaco, C., Romagnoli, G., Tortorici, L., 2006. Multiseismic cycle deformation rates from Holocene normal fault scarps on Crete (Greece). Terra Nova 18, 181–190.

Caputo, R., Catalano, S., Monaco, C., Romagnoli, G., Tortorici, G., Tortorici, L., 2010. Active faulting on the island of Crete (Greece). Geophysical Journal International 183, 111–126.

Carobene, L., 1972. Osservazioni sui solchi di battente attuali ed antichi nel Golfo di Orosei in Sardegna, vol. 9. Memorie della Società Geologica Italiana, pp. 641–649.

Chalikiopoulos, L., 1903. Sitia die Osthalbinsel Kretas: Eine geographische Studie. E. S. Mittler und Sohn, Berlin.

Dalongeville, R., 1986. Formes de corrosion et de construction organogène des littoraux actuels calcaires de Méditerranée. Thèse doct. d'État. Univ. Bretagne occidentale, Brest.

Davaras, C., 1974. Rock-cut fish tanks in Eastern Crete. Annals, British School at Athens 69, 87–93.

Davaras, C., 1975. A rock-cut fish tank near Hierapetra. Archaeologica Deltion 30A, 149–154.

Dermitzakis, M., 1973. Recent tectonic movements and old strandlines along the coast of Crete. Bulletin, Geological Society of Greece 10, 40–46.

Dermitzakis, M., Theodoropoulos, D., 1975. Study of beach-rocks in the Aegean Sea. Observations on occurrences in SE Crete, Rhodes and Metopi. Annales Géologiques des Pays Helléniques 1 (26), 275–305 (in Greek).

Detorakis, Th, 1990. History of Crete. Irakleio, Mystis Editions (in Greek).

DiVita, A., 1995. Archaeologists and earthquakes: the case of 365 AD. Annali di Geofisica 38, 971–976.

DiVita, A., 1996. Earthquakes and civil life at Gortyn (Crete) in the period between Justinian and Constant II (6–7th century AD). In: Stiros, S., Jones, R. (Eds.), Archaeoseismology, vol. 7. British School at Athens, Fitch Laboratory, pp. 45–50. Occasional Paper.

Dominey-Howes, D., Dawson, A., Smith, D., 1998. Late Holocene coastal tectonics at Phalasarna, western Crete: a sedimentary study. In: Stewart, I.S., et al. (Eds.), Coastal Tectonics, vol. 146. Geological Society of London Special Publication, pp. 343–352.

Driessen, J., Macdonald, C.F., 1997. The Troubled Island. Minoan Crete Before and After the Santorini eruption. Aegaeum, 17, Austin-Liège. Université de Liège.

Evangelatou-Notara, F., 1993. Earthquakes in Byzantium from the 13th to 15th Century. Historical Research, Athens.

Evans, A.J., 1928. The Palace of Minos: a Comparative Account of the Successive Stages of the Early Cretan Civilization as Illustrated by the Discoveries at Knossos, Part I: Fresh Lights on Origins and External Relations: the Restoration in Town and Palace after Seismic Catastrophe towards Close of M. M. III and the Beginnings of the New Era, vol. 2. Macmillan and Co, London.

Fiandra, E., 1963. I periodi struttivi del primo palazzo di Festos. Kritika Chronika 1961–1962, 112–126.

Fiandra, E., 1980. Precisazioni sul MM IIA a Festos. In: Atti IV Convegno Internazionale Studi Cretesi, Iraklion 1976, I, Atene 1980, pp. 169–196 (espec. 169-177).

Flemming, N.C., 1978. Holocene eustatic changes and coastal tectonics in the northeast Mediterranean: implications for models of crustal consumption. Philosophical Transactions, Royal Society of London, A 289, 405–458.

Flemming, N.C., Pirazzoli, P.A., 1981. Archéologie des côtes de la Crète. Historical Archaeology Dossiers 50, 66–81.

Friedrich, W.L., Heinemeier, J., 2007. The Minoan eruption of Santorini radiocarbon dated to 1613 ± 13 BC – geological and stratigraphic considerations. Time's Up! Dating the Minoan eruption of Santorini. In: Warburton, D.A. (Ed.), Acts of the Minoan Eruption Chronology Workshop, Sandbjerg, November 2007, Monographs of the Danish Institute at Athens, vol. 10, pp. 57–63.

Friedrich, W.L., Wagner, P., Tauber, H., 1990. Radiocarbon dated plant remains from the Akrotiri excavations on Santorini, Greece. In: Harder, D.A., Renfrew, A.C. (Eds.), Thera and the Aegean World III, Vol. III: Chronology. Thera Foundation, London, pp. 188–196.

Frost, H., 1963. Under the Mediterranean – Marine Antiquities. Routledge and Kegan Paul Ltd, London.

Frost, F.J., 1997. Tectonics and history at phalasarna. In: Swiny, S., Hohlfelder, R.L., Swiny, H.W. (Eds.), Res Maritimae: Cyprus and the Eastern Mediterranean from Prehistory to Late Antiquity. Scholars Press Atlanta, Atlanta, pp. 107–115.
Furlani, S., Cucchi, F., Forti, F., Sossi, A., 2009. Comparison between coastal and inland Karst limestone lowering rates in the northeastern Adriatic region (Italy and Croatia). Geomorphology 104, 73–81.
Furlani, S., Cucchi, F., Biolchi, S., Odorico, R., 2010. Notches in the Northern Adriatic sea: genesis and development. Quaternary International 232, 144–157.
Furumark, A., 1950. The settlement of Ialysos and Aegean history c. 1550-1400 B.C. Opuscula Atheniensia 6, 150–271.
Fytrolakis, N., 1980. The Geological Structure of Crete: Problems, Remarks and Conclusions. Thesis. Department of Minerology, Petrology, and Geology, National Technical University of Athens, Athens.
Georgalas, G., 1931. Crete (earthquakes). MEE 15, 157–158.
Georgiades, A.S., 1904. About Earthquakes and Construction of Antiseismic Buildings. S. Kousoulinou, Athens (in Greek).
Giannaris, A., 1889. On Erotokritos and the Poetry of Him: Historical Criticism and Linguistic Study with Glossary. Anemi, Athens, pp. 10–16 (in Greek).
Gorokhovich, Y., 2005. Abandonment of Minoan palaces on Crete in relation to the earthquake induced changes in groundwater supply. Journal of Archaeological Science 32, 217–222.
Got, H., Stanley, D.J., Sorel, D., 1977. Northwestern Hellenic arc: concurrent sedimentation and deformation in a compressive setting. Marine Geology 24, 21–36.
Guidoboni, E., Comastri, A., 1997. The large earthquakes of 8 August 1303 in Crete: seismic scenario and tsunami in the Mediterranean area. Journal of Seismology 1, 55–72.
Guidoboni, E., Comastri, A., Traina, G., 1994. Catalogue of Ancient Earthquakes in the Mediterranean Area up to the 10th Century. ING-SGA, Bologna.
Hadjidaki, E., 1996. The hellenistic harbour of phalasarna in western Crete: a comparison with the hellenistic inner harbour of Sraton's Tower. In: Raban, A., Holum, K.G. (Eds.), Caesarea Maritima: Retrospective after Two Millennia. University of Leiden, pp. 53–64.
Hadjidaki, E., 2001. The roman destruction of phalasarna. British Archaeological Reports International Series 940, 155–166.
Hafemann, D., 1965. Die Niveauveranderungen an den Kusten Kretas seit dem Altertum. Abhandlungen der Akademie der Wissenschaften und der Literatur Abhandlungen der Mathematisch-Naturwissenschaftliche Klasse 12, 608–688.
Hardman, A., 2009. A Look at the destruction and decline of a minoan town: Palaikastro. Totem. The University of Western Ontario Journal Of Anthropology 17 (1) article 9.
Hammer, C.U., Kurat, G., Hoppe, P., Grum, W., Clausen, H.B., 2003. Thera eruption date 1645 BC confirmed by new ice core data? In: Bietak, M. (Ed.), The Synchronisation of Civilisations in the Eastern Mediterranean in the Second Millennium B.C. Austrian Academy, Vienna, pp. 87–94.
Hood, S., 1985. Warlike destruction in Crete c. 1450 BC. In: Proceedings of the International Conference of Cretan Studies, 1981, Agios Nikolaos. Heraklion: Philological Society, pp. 170–178.
Housley, R., Hedges, R., Law, I., Bronk, C., 1990. Radiocarbon dating by AMS of the destruction of Akrotiri. In: Harder, D.A., Renfrew, A.C. (Eds.), Thera and the Aegean World, Vol. III: Chronology. Thera Foundation, London, pp. 207–215.
Hsu, K.J., Ryan, W.B.F., 1973. Extensional and Compressional Tectonics. in: Initial Report of Deep Sea Drilling Project, Part 2, vol. XIII. United States Government Printing Office, Washington D.C, pp. 1011–1019.
Jusseret, S., Sintubin, M., 2012. All that rubble leads to trouble: reassessing the seismological value of archaeological destruction layers in Minoan Crete and beyond. Seismological Research Letters 83, 736–742.
Jusseret, S., Langohr, C., Sintubin, M., 2013. Tracking Earthquake Archaeological Evidence in Late Minoan IIIB (~1300–1200 B.C.) Crete (Greece): a Proof of Concept. Bulletin of the Seismological Society of America 103, 1–18.
Kelletat, D., 1979. Geomorphologische Studien an den Kusten Kretas. Abhandlungen der Akademie der Wissenschaften zu Göttingen 32, 1–105.
Kelletat, D., 1991. The 1550 BP tectonic event in the Eastern Mediterranean as a basis for assessing the intensity of shore processes. Zeitschrift für Geomorphologie N.F., Suppl.-Bd 81, 181–194.
Kelletat, D., 1996. Perspectives in coastal geomorphology of Western Crete, Greece. Zeitschrift für Geomorphologie N.F., Suppl.-Bd 102, 1–19.
Kelletat, D.H., 2005. Notches. In: Schwartz, M.L. (Ed.), Encyclopedia of Coastal Science. Springer, Dordrecht, pp. 728–729.
Kelletat, D., 2006. Beachrock as sea-level indicator? Remarks from a geomorphological point of view. Journal of Coastal Research 22 (6), 1558–1564.
Keraudren, B., 1971. Le Quaternaire marin de la Grèce. Phd thesis. University of Paris.
Keraudren, B., 1979. Le Plio-Pleistocène marine et oligohalin en Grèce; stratigraphie et paleogéographie. Revue de Geologie Dynamique et de Geographie Physique 21, 17–28.
Kiratzi, A., Louvari, E., 2003. Focal mechanisms of shallow earthquakes in the Aegean Sea and the surrounding lands determined by waveform modelling: a new database. Journal of Geodynamics 36, 251–274.
Knapmeyer, M., Harjes, H.-P., 2000. Imaging crustal discontinuities and the downgoing slab beneath western Crete. Geophysical Journal International 143 (1), 1–21.
Kokinou, E., Vallianatos, Ph, Sarris, A., Moisidi, M., Tzanaki, I., Tzakalaki, E., Tziskaki, E., 2009. Spatial distribution of the near coast and onshore seismicity of Crete (South Greece) with special emphasis to Heraklion basin (Central Crete). In: Proceedings of the 3rd IASME/WSEAS International Conference on Geology and Seismology (GES'09), pp. 104–110.
Kreemer, C., Chamot-Rooke, N., 2004. Contemporary kinematics of the southern Aegean and the Mediterranean Ridge. Geophysical Journal International 157, 1377–1392.
La Rosa, V., 1995. A hypothesis on earthquakes and political power in Minoan Crete (Terremoti e civiltà abitative. In: Atti del Convegno, Roma 27-29 ottobre 1993), 38. Annali di Geofisica, pp. 881–891.
LaMarche Jr., V.C., Hirschboeck, K.K., 1984. Frost rings in trees as records of major volcanic eruptions. Nature 307, 121–126.
Laborel, J., Pirazzoli, P.A., Thommeret, J., Thommeret, Y., 1979. Holocene raised shorelines in western Crete (Greece). In: Suguio, K., Fairchild, T.R., Martin, L., Flexor, J.M. (Eds.), Proceedings 1978 International Symposium on Coastal Evolution in the Quaternary (Sao Paulo, 1979), pp. 475–501.
Lambeck, K., 1995. Late Pleistocene and Holocene sea-level change in Greece and south-western Turkey: a separation of eustatic, isostatic and tectonic contributions. Geophysical Journal International 122, 1022–1044.
Lambeck, K., Anzidei, M., Antonioli, F., Benini, A., Esposito, A., 2004. Sea level in Roman times in the Central Mediterranean and implications for recent change. Earth and Planetary Science Letters 224, 563–575.
Lambeck, K., Purcell, A., 2005. Sea-level change in the Mediterranean Sea since the LGM: model predictions for tectonically stable areas. Quaternary Science Reviews 24, 1969–1988.
Lambeck, K., Woodroffe, C.D., Antonioli, F., Anzidei, M., Gehrels, R.W., Laborel, J., Wright, A.J., 2010. Paleoenvironmental records, geophysical modeling, and reconstruction of sea-level trends and variability on centennial and longer timescales. In: Church, J.A., Woodworth, P.L., Aarup, T., Wilson, W.S. (Eds.), Understanding Sea-level Rise and Variability. Wiley-Blackwell, Oxford, pp. 61–121.
Le Pichon, X., Angelier, J., 1979. The Hellenic Arc and trench system: a key to the neotectonic evolution of the Eastern Mediterranean area. Tectonophysics 60, 1–42.
Le Pichon, X., Lallemant, S.J., Chamot-Rooke, N., Lemeur, D., Pascal, G., 2002. The Mediterranean Ridge backstop and the Hellenic nappes. Marine Geology 186, 111–125.
Leatham, J., Hood, S., 1958/59. Sub-Marine Exploration in Crete, 1955, LIII-LIV. Annals of the British School at Athens, pp. 263–273.
Levi, D., 1976. Festos e la civilta minoica. Edizioni dell'Ateneo, Roma.
Macdonald, C.F., 2003. The palaces at knossos. Athena Review 3.3, 36–43.
Makrakis, M., 2006. The saltworks of Elounda, Elounda. Trimestrial Magazine of the Cultural Association of Elounda 50, 12–25.
Makris, J., Stobbe, C., 1984. Physical properties and state of the crust and upper mantle of the Eastern Mediterranean Sea deduced from geophysical data. Marine Geology 55, 347–363.
Mallet, R., 1854. Report of the British Association Meeting. Catalogue of Recorded Earthquakes from 1606 BC to AD 1850, vol. 24, pp. 1–326.
Manning, S.W., Ramsey, C.B., 2003. A Late Minoan III absolute chronology for the Aegean—combining archaeology with radiocarbon. In: Bietak, M. (Ed.), The Synchronisation of Civilisations in the Eastern Mediterranean in the Second Millennium B.C. Austrian Academy, Vienna, pp. 111–133.
Manning, S.W., Ramsey, C.B., Kutschera, W., Higham, T., Kromer, B., Steier, P., Wild, M.E., 2006. Chronology for the Aegean Late Bronze Age 1700–1400 B.C. Science 312, 565–569.
Manning, S.W., 1988. The Bronze Age eruption of Thera: absolute dating, Aegean chronology and Mediterranean cultural interrelations. Journal of Mediterranean Archaeology 1 (1), 17–82.
Manolioudis, M.S., 2013. From the Ancient Quarries to the Monuments of Culture. Mythical heroes and riddles of technology, Rethymnon (Crete) personal edition (in Greek).
Maravelakis, M.I., 1939. Contribution to Knowledge of the History of Earthquakes in Greece and Neighboring Countries from Remembrances, 5. University of Thessaloniki, pp. 67–149.
Marinatos, S., 1926. Excavations at Nirou Khani Crete. Praktika (PAE), pp. 141–147 (in Greek).
Marinatos, S., 1934. Aminsos die Hafenstadt des Minos. Forschung Fortschrift 10 (28), 342.
Marinatos, S., 1939. The volcanic destruction of minoan Crete. Antiquity 13, 425–439.
McClusky, S., Balassanian, S., Barka, A., Demir, C., Ergintav, S., Georgiev, I., Gurkan, O., Hamburger, M., Hurst, K., Kahle, H., Kastens, K., Kekelidze, G., King, R., Kotzev, V., Lenk, O., Mahmoud, S., Mishin, A., Nadariya, M., Ouzounis, A., Paradissis, D., Peter, Y., Prilepin, M., Reilinger, R., Sanli, I., Seeger, H., Tealeb, A., Toksöz, M.N., Veis, G., 2000. Global positioning system constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus. Journal of Geophysical Research 105, 5695–5719.
Mercier, J., Bousquet, B., Delibasis, N., Drakopoulos, J., Keraudren, B., Lemeille, F., Sorel, D., 1972. Déformations en compression dans le Quaternaire des rivages ioniens (Céphalonie, Grèce): Données néotectoniques et séismiques, vol. 275. Comptes rendues, Academie des Sciences, Paris, pp. 2307–2310.
Mercier, J., Angelier, J., Delibassis, N., Gerard, P., Kerdiles, Y., 1974. Les déformations plio-quaternaires en extension en Crète méridionale (Ierapetra, Grèce). In: Coram. 2e réun. Ann. Sci. de la Terre, Pont-a-Mousson.
Meulenkamp, J.E., Jonkers, A., Spaak, P., 1977. Late Miocene to early Pliocene development of Crete. In: Proceedings, VI Colloquium. Geology of the Aegean Region, Athens, pp. 137–149.

Meulenkamp, J.E., Van der Zwaan, G.J., Van Wamel, W.A., 1994. On Late Miocene to recent vertical motions in the Cretan segment of the Hellenic arc. Tectonophysics 234, 53–72.
Michael, H.N., 1976. Radiocarbon Dates from Akrotiri on Thera, 1. Temple University Aegean Symposium, pp. 7–9.
Monaco, C., Tortorici, L., 2004. Faulting and effects of earthquakes on Minoan archaeological sites in Crete (Greece). Tectonophysics 382, 103–116.
Montaggioni, L.F., Pirazzoli, P.A., Laborel, J., Thommeret, J., Thommeret, Y., 1981. Rivages tyrrhéniens et historiques a Strongilo et dans le Sud-Est de la Crète (Grèce): Implications néotectoniques. In: Actes du Colloque "Niveaux Marins et Tectonique Quaternaires dans l'aire Méditerranéenne (Paris, 29-XI-1980). CNRS et Univ, Paris I, pp. 65–76.
Mourtzas, N.D., 1988a. Neotectonic evolution of Messara's Gulf: submerged archaeological constructions and use of the coast during the prehistoric and historic periods. In: Marinos, P., Koukis, G. (Eds.), The Engineering Geology of Ancient Works, Monuments and Historical Sites. Balkema, , Rotterdam, pp. 1565–1573.
Mourtzas, N.D., 1988b. Archaeological constructions as indicators of the sea-level during the last 2000 years in the area of Ierapetra (SE Crete, Greece). In: Marinos, P., Koukis, G. (Eds.), The Engineering Geology of Ancient Works, Monuments and Historical Sites. Balkema, , Rotterdam, pp. 1557–1564.
Mourtzas, N.D., 1990. Tectonic Movement of the Coasts of Eastern Crete during the Quaternary. PhD thesis. National Technical University of Athens, Athens (in Greek).
Mourtzas, N.D., 2010. Sea level changes along the coasts of Kea island and paleogeographical coastal reconstruction of archaeological sites. In: Proceedings of the 12th International Congress of the Geological Society of Greece, 19-22 May 2010, Patras, Greece, vol. XLIII, pp. 453–463, 1.
Mourtzas, N., 2012a. Archaeological indicators for sea level change and coastal neotectonic deformation: the submerged roman fish tanks of the gulf of Matala, Crete, Greece. Journal of Archaeological Science 39, 884–895.
Mourtzas, N., 2012b. Fish tanks of eastern Crete (Greece) as indicators of the Roman sea level. Journal of Archaeological Science 39, 2392–2408.
Mourtzas, N.D., 2012c. A palaeogeographic reconstruction of the seafront of the ancient city of Delos in relation to Upper Holocene sea level changes in the central Cyclades. Quaternary International 250, 3–18.
Mourtzas, N.D., Fytrolakis, N., 1988. Neotectonic movements at the cape Trachoulas in the southern coasts of Iraklion district, Crete. Bulletin, Geological Society of Greece 20, 237–250.
Mourtzas, N.D., Marinos, P.G., 1994. Upper Holocene sea-level changes: Paleogeographic evolution and its impact on coastal archaeological sites and monuments. Environmental Geology 23, 1–13 (original paper).
Mourtzas, D.N., Kolaiti, E., 2013. Historical coastal evolution of the ancient harbor of Aegina in relation to the Upper Holocene relative sea level changes in the Saronic Gulf, Greece. Palaeogeography, Palaeoclimatology. Palaeoecology 392, 411–425.
Mourtzas, N.D., Kissas, C., Kolaiti, E., 2014. Archaeological and geomorphological indicators of the historical sea level changes and the related palaeogeographical reconstruction of the ancient foreharbor of Lechaion, East Corinth Gulf (Greece). Quaternary International 332, 151–171.
Mouslopoulou, V., Andreou, C., Atakan, K., Fountoulis, I., 2001. Paleoseismological investigation along the Kera fault zone, Crete: Implication for Seismic Hazard Assessment. Bulletin of the Geological Society of Greece 34, 1531–1537.
Mouslopoulou, V., Moraetis, D., Benedetti, L., Guillou, V., Bellier, O., Hristopulos, D., 2014. Normal faulting in the forearc of the Hellenic subduction margin: Palaeoerthquake history and kinematics of the Spili Fault, Crete, Greece. Journal of Structural Geology 66, 298–308.
Nakasis, Th, 1987. Quarry and Fish Trap in Kato Zakros Bay. Technical Journal. Ministry of Culture, pp. 85–98 (in Greek).
Neumeier, U., 1998. The Role of Microbial Activity in Early Cementation of Beachrocks (Intertidal Sediments). PhD thesis. University of Geneva (Terre et Environment).
Neumeier, U., Bernier, P., Dalongeville, R., Oberlin, Ch, 2000. Holocene sea-level changes underlined by beachrock features and diagenesis: example from Damnoni (Crete). Geomorphologie: relief, processes, environment 4, 211–220.
Niemeier, W.D., 1984. The end of the minoan Thalassocracy. In: Hägg, R., Marinatos, N. (Eds.), The Minoan Thalassocracy: Myth and Reality. Proceedings of the 3rd International Symposium at the Swedish Institute in Athens, 1982, SkrAth, vol. 4. Paul Åströms Forlag, Göteborg, pp. 205–215, 32.
Nur, A., Cline, E., 2000. Poseidon's horses: plate tectonics and earthquake storms in the late Bronze Age Aegean and Eastern Mediterranean. Journal of Archaeological Science 27, 43–63.
Nur, A., Burgess, D., 2008. Apocalypse: Earthquakes, Archaeology, and the Wrath of God. Princeton University Press.
Pagliarulo, R., Antonioli, F., Anzidei, M., 2013. Sea level changes since the Middle Ages along the coast of the Adriatic sea: the case of St. Nicholas Basilica, Bari, southern Italy. Quaternary International 288, 139–145.
Papadakis, N., 1989. Sitia, the Homeland of Myson and Cornaros (Guide to the History, Archeology, Culture). Sitia: Municipality of Sitia ed. (in Greek).
Papadopoulos, G.A., 2011. A Seismic History of Crete: the Hellenic Arc and Trench. Ocelotos, Athens.
Papazachos, V., Papazachou, K., 1989. The Earthquakes of Greece. Ziti, Thessaloniki.
Papazachos, B., Kiratzi, A., Papadimitriou, E., 1991. Regional focal mechanisms for earthquakes in the Aegean area. Pure and Applied Geophysics 136, 405–420.
Pelon, O., 1980. Le palais de Malia V. Études crétoises XXV. Paris/Limoges: École française d'Athènes-Bontemps.
Pelon, O., 1983. L'épée à l'acrobate et la chronologie maliote II. Bulletin de correspondance hellénique 107, 679–703.
Pelon, O., 2005. Les deux destructions du palais de Malia. In: Bradfer-Burdet, I., Detournay, B., Laffineur, R. (Eds.), KRHS TEXNITHS: L'artisan Crétois. Aegaeum, vol. 26. Université de Liège, Liège, pp. 185–198.
Pendlebury, J.D.S., 1954. A Handbook to the Palace of Minos. Dufour, New York.
Perrey, A., 1848. Mémoire sur les tremblements de terre ressentis dans la péninsule Turco-Hellénique et en Syrie. Mémoires couronnéset mémoires des Savants étrangers, vol. 23. Académie Royale de Belgique, pp. 1–73.
Peterek, A., Schwarze, J., 2004. Architecture and Late Pliocene to recent evolution of outer arc basins of the Hellenic subduction zone (south-central Crete, Greece). Journal of Geodynamics 38, 19–55.
Peters, J.M., 1985. Neogene and Quaternary Vertical Tectonics in the South Hellenic Arc and Their Effect on Concurrent Sedimentation Processes, vol. 1. Geologie, Universiteit van Amsterdam, Amsterdam, p. 23.
Peters, J.M., Huson, W.H., 1985. The Pliny and Strabo trenches (eastern Mediterranean): integration of seismic reflection data and Sea-beam bathymetric maps. Marine Geology 64, 1–17.
Pichler, H., Schiering, W., 1980. Der spätbronzezeitliche Ausbruch des Thera-Vulkans und seine Auswirkungen auf Kreta. Archäologischer Anzeiger, pp. 1–37.
Pirazzoli, P.A., 1980. Formes de corrosion marine et vestiges archeologiques submerges: interpretation neotectonique de quelques exemples en Grèce et en Yougoslavie. Annals, Institute of Oceanography 56 (S), 101–111.
Pirazzoli, P., 1986a. The early byzantine tectonic Paroxysm. Zeitschrift für Geomorphologie N.F., Suppl.-Bd 62, 31–49.
Pirazzoli, P.A., 1986b. Marine notches. In: Van de Plassche, O. (Ed.), Sea-level Research: a Manual for the Collection and Evaluation of Data. Geo Books, Norwich, pp. 361–400.
Pirazzoli, P.A., 2007. Geomorphological Indicators. Encyclopedia of Quaternary Science, Sea Level. Elsevier, pp. 2974–2983.
Pirazzoli, P., Thommeret, J., Thommeret, Y., Laborel, J., Montaggioni, F.L., 1982. Crustal block movements from hHolocene shorelines: Crete and Antikythira (Greece). Tectonophysics 86, 27–43.
Pirazzoli, P.A., Ausseil-Badie, J., Giresse, P., Hadjidaki, E., Arnold, M., 1992. Historical environmental changes at Phalasarna harbor, west Crete. Geoarchaeology 7 (4), 371–392.
Pirazzoli, P.A., Laborel, J., Stiros, S.C., 1996. Coastal indicators of rapid uplift and subsidence: examples from Crete and other eastern Mediterranean sites. Zeitschrift für Geomorphologie N.F., Suppl.-Bd 102, 21–35.
Platakis, E., 1950. The earthquakes of Crete. Kretika Chronika 4, 463–526 (in Greek).
Platon, N., 1974. Zakros: the New Minoan Palace. Archeologiki Eteria ed. (in Greek), Athens.
Platon, L., 2004. The Late Minoan palace of Zakros I: one "Knossos" out of Knossos. In: Cadogan, G., Hatzaki, E., Vassilakis, A. (Eds.), Knossos: Palace, City, State. Proceedings of the Conference in Herakleion Organized by the British School at Athens and the 23rd Ephoreia of Prehistoric and Classical Antiquities of Herakleion in November 2000, for the Centenary of Sir Arthur Evans's Excavations at Knossos), (BSA Studies 12), London, pp. 381–392.
Popham, M.R., 1990. Pottery styles and chronology. In: Hardy, D.A., Renfrew, C. (Eds.), Thera and the Aegean World III, Vol. III: Chronology, 27-28. The Thera Foundation, London.
Price, S., Higham, T., Nixon, L., Moody, J., 2002. Relative sea-level changes in Crete: reassessment of radiocarbon dates from Sphakia and West Crete. Annual of the British School at Athens 97, 171–200.
Puglisi, D., 2003. Il bastione Tardo Minoico I ad Haghia Triada: nuove osservazioni su cronologia e funzione. ASAtene 81 (2), 73–79.
Raulin, V., 1869. Description Physique et Naturelle de ille de Crète. A. Bertrand, Paris.
Raulin, V., 1870. Description physique de l'ile de Crète. Actes de la Société Linnéenne de Bordeaux 24, 353–770.
Riley, F.R., 2004. The olive Industry of Bronze Age Crete: evidence for volcanic damage to olive groves and property in Central and eastern Crete. Akroterion 49, 1–6.
Sakellarakis, Y., Sapouna-Sakellaraki, E., 1981. Drama of death in a Minoan temple. National Geographic 169, 204–222.
Sakellarakis, Y., Sapouna-Sakellaraki, E., 2002. Crete - Archanes. Athens: Ekdotiki Athenon S.A. (in Greek).
Sathas, K.N., 1867. Medieval earthquake catalogue of Greece and especially of Cephallonia and Leykada islands. Aion 1213–1215, 1246–1248 (in Greek).
Schmidt, J., 1862. Note sur le grand tremblement de terre qui a eu lieu en Grèce, le 26 décembre 1861. Comptes rendus hébdomadaires des séances 54, 669–671.
Serpelloni, E., Faccenna, C., Spada, G., Dong, D., Williams, S.D.P., 2013. Vertical GPS ground motion rates in the Euro-Mediterranean region: new evidence of velocity gradients at different spatial scales along the Nubia- Eurasia plate boundary. Journal of Geophysical Research Solid Earth 118. http://dx.doi.org/10.1002/2013JB010102.
Shaw, J.W., 1990. Bronze Age Aegean harboursides. In: Harder, D.A., Renfrew, A.C. (Eds.), Thera and the Aegean World III, vol. I. Thera Foundation, London, pp. 420–436.
Shaw, J.W., 2006. Kommos. A Minoan Harbor Town and Greek Sanctuary in Southern Crete. New Jersey: Princeton.
Shaw, B., Ambraseys, N.N., England, C.P., Floyd, A.M., Gorman, J.G., Higham, G.F.T., Jackson, A.J., Nocquet, J.-M., Pain, C.C., Piggott, D.M., 2008. Eastern Mediterranean tectonics and tsunami hazard inferred from the AD 365 earthquake. Nature Geoscience 1, 268–276.

Schafer, J., 1991. Amnisos - harbour town of Minos?. In: Laffineur, R., Basch, L. (Eds.), Thalassa: l' Egée Prehistorique et la Mer, Aegaeum, vol. 7. Université de Liège, Liège, pp. 111–116.
Sieberg, A., 1932. Erdbebengeographie. Handb. der Geophys., vol. 4, pp. 687–1005.
Simosi, A., 1988. Preliminary Underwater Research in Kouremenos Bay in Palekastro Sitia. Kritiki Estia. D.2, pp. 19–29 (in Greek).
Simosi, A., 2003. A Coastal Minoan Settlement in Speliada, Seision, Crete. Enalia, vol. VII, pp. 57–65.
Soles, J., 2007. The impact of the Minoan eruption of Santorini on Mochlos, a small Minoan town on the north coast of Crete. In: Warburton, D. (Ed.), Time's up: Dating the Minoan Eruption of Santorini, Acts of the Minoan Eruption Chronology Workshop, Sanbdjerg, vol. 10. Monographs of the Danish Institute, Athens, pp. 107–116.
Sorel, D., 1976. Etude néotectonique dans l'Arc égéen externe occidental; les iles ioniennes de Céphalonie et Zakynthos et l'Elide occidentale. Thesis 3e cycle. Geologie Structurale, Univ. Orsay.
Spyropoulos, P., 1997. Chronicle of the Earthquakes of Greece from Antiquity until Today. Athens: Dodoni.
Spratt, T.A.B., 1865. Travels and Researches in Crete. John Van Voorst, London.
Stanley, D.J., 1977. Post-Miocene depositional patterns and structural displacement in the Mediterranean. In: Nairn, A., Kanes, W., Stehli, F. (Eds.), The Oceans Basins and Margins, 4A. Plenum, New York, pp. 77–150.
Stavrakakis, N., 1890. Statistics on Population of Crete with Several Geographical, Historical, Archaeological, Ecclesiastic Etc News about the Island, pp. 107–117. Athens, (in Greek).
Stiros, S., 2010. The 8.5+ magnitude, AD365 earthquake in Crete: coastal uplift, topography changes, archaeological and historical signature. Quaternary International 216, 54–63.
Stiros, S., Drakos, A., 2006. A fault-model for the tsunami-associated, magnitude $\geq$ 8.5 Eastern Mediterranean, AD 365 earthquake. Zeitschrift für Geomorphologie 146, 125–137.
Ten Veen, J.H., Meijer, P.Th, 1998. Late Miocene to recent tectonic evolution of Crete (Greece): geological observations and model analysis. Tectonophysics 298, 191–208.
Theodoulou, Th, 2011. Geological changes and ancient remains on the coast of Crete. Building materials of the antiquity, geomorphological evolution of W Crete during the prehistorical and historical periods. In: Summer School Organized by: National and Kapodistrian University of Athens, Faculty of Geology and Geoenvironment, 25–29/8/2011, Crete, Kissamos, pp. 43–49.
Thommeret, Y., Thommeret, J., Laborel, J., Montaggioni, F.L., Pirazzoli, P., 1981. Late Holocene shoreline changes and seismo-tectonic displacements in western Crete (Greece). Zeitschrift für Geomorphologie N.F., Suppl.-Bd 40, 127–149.
Tiberti, M.M., Basili, R., Vannoli, P., 2014. Ups and Downs in Western Crete (Hellenic Subduction Zone). http://dx.doi.org/10.1038/srep05677. Scientific Reports, 4, No 5677.
Torunski, H., 1979. Biological erosion and its significance for the morphogenesis of limestone coasts and for nearshore sedimentation (Northern Adriatic). Senckenbergiana Maritima 11, 193–265.
Tsonis, A.A., Swanson, K.L., Sugihara, G., Tsonis, P.A., 2010. Climate change and the demise of Minoan civilization. Climates of the Past 6, 525–530.
Vallianou, D., 1996. New evidence of earthquake destructions in Late Minoan Crete. In: Stiros, S., Jones, R. (Eds.), Archaeoseismology, 7. British School at Athens, Fitch Laboratory, pp. 153–167. Occasional Paper.
Wegmann, W.K., 2008. Tectonic Geomorphology above Mediterranean Subduction Zones: Northeastern Apennines of Italy and Crete, Greece. PhD Thesis. Lehigh University.
Xanthoulidis, St, 1925. The Earthquake of 1856. Nea Ephimeris (Heraclion) (Article in the Newspaper of 27-4-1925, in Greek).
Zoudianos, N., 1960. History of Crete during Venetian Occupation, vol. 1. Athens (in Greek).