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Shoreline reconstruction of the submerged Minoan harbour morphology in the bay of Kato Zakros (Eastern Crete, Greece)

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ABSTRACT

The Minoan centre of Kato Zakros flourished in a favourable geographical location, naturally fortified, in a leeward bay providing a natural harbour morphology. The submerged geomorphological markers of former sea levels define four distinct sea level stands, at -4.00 ± 0.30 m, -2.85 ± 0.30 m, -1.25 ± 0.05 m, and -0.50 ± 0.05 m. The dating of these sea levels was based on the gradual rise of the brackish groundwater, observed at the building relics and the water supply installations of the Palace, as well as on submerged coastal rock-cut structures. The oldest change in sea level is associated with the violent seismic disaster of the old Palace that occurred around 1600 BCE. The destruction of the new Palace occurred around 1450 BCE and is related with a strong seismic event that hit all the Minoan centres of Crete, but it did not cause any change in the relative sea level. The following sea level change is most likely related with the demise of the Minoan centres of Crete around 1200 BCE. During the historical period, two changes in relative sea level occurred. The first change is linked with the 1604 CE earthquake, and the most recent with the period of the last 400 years. The palaeoshoreline reconstruction of the Kato Zakros bay revealed a natural morphology, shaped by an elongate beachrock slab on the northernmost part of the western coast. Coastal responses to sea level rise include: progressive shoreline retreat, submersion of the natural harbour morphology and coastal fishing installations, and flooding of the Palace relics.

1. Introduction

The imposing and inaccessible mountains of Sitia isolate the easternmost tip of Crete from the rest of the island. These mountain ranges end abruptly into the sea, forming sheltered coves with small alluvial valleys fed by the debris of impetuous torrents that flow into the coast crossing the deep gorges of the inland (Fig. 1a). In these sheltered bays, even from the early Minoan times, were developed the main Minoan settlements of Itanos, Palaikastro and Zakros that reached their zenith in the Neopalatial period as mercantile relationships between eastern Mediterranean and Egypt were intensified (Fig. 1a).

The valley of Kato Zakros, naturally fortified with the surrounding steep limestone slopes, and the bay protected from the prevailing NW winds (see wind rose in Fig. 2b) seems to be a very favourable location for installing a port base (Fig. 1a, b, 2b).

Captain Spratt sailed into the bay of Kato Zakros in 1852. He described vividly the stepped bedrock morphology, the tortuous gorge and the stream ending into the plain of Zakros, and the Cyclopean remains of a very ancient and very considerable city (Spratt, 1865). However, he erroneously believed this to be the ancient site of Itanos (Spratt, 1865).

At the close of the nineteenth century the archaeologist F. Halbherr, the explorer L. Mariani, and the excavator of Knossos A. Evans, based on Spratt's description visited Kato Zakros and reported the first archaeological evidence on it (Hogarth, 1901; N. Platon, 1974). The first systematic excavations of the site were made by D.G. Hogarth in 1901 (N. Platon, 1974). Sixty years later, the archaeologist N. Platon brought to light a Minoan Palace complex and a large part of the town surrounding it. The structure of the building remnants and rich mobile findings demonstrated that Kato Zakros was a very important harbour town and the starting point of the Minoan Thalassocracy connecting Minoan Crete with the great centres of the time in the Eastern Mediterranean (N. Platon, 1974).

Additionally, the discovery of the NE gateway and section of the harbour road from N. Platon (1974) led him to identify the location of mooring of the Minoan ships, in the NW part of the coast. The wide, slab-paved harbour road, originally built during the Protopalatial period, was the main road artery of Kato Zakros town (N. Platon, 1974). The high-level constructional features of the harbour road are indicative of the significant role in the economic and social life of the town (Salichou, 2012). Starting at the shore and following a western course led to the NE entrance of the Palace. It connected the harbour with the

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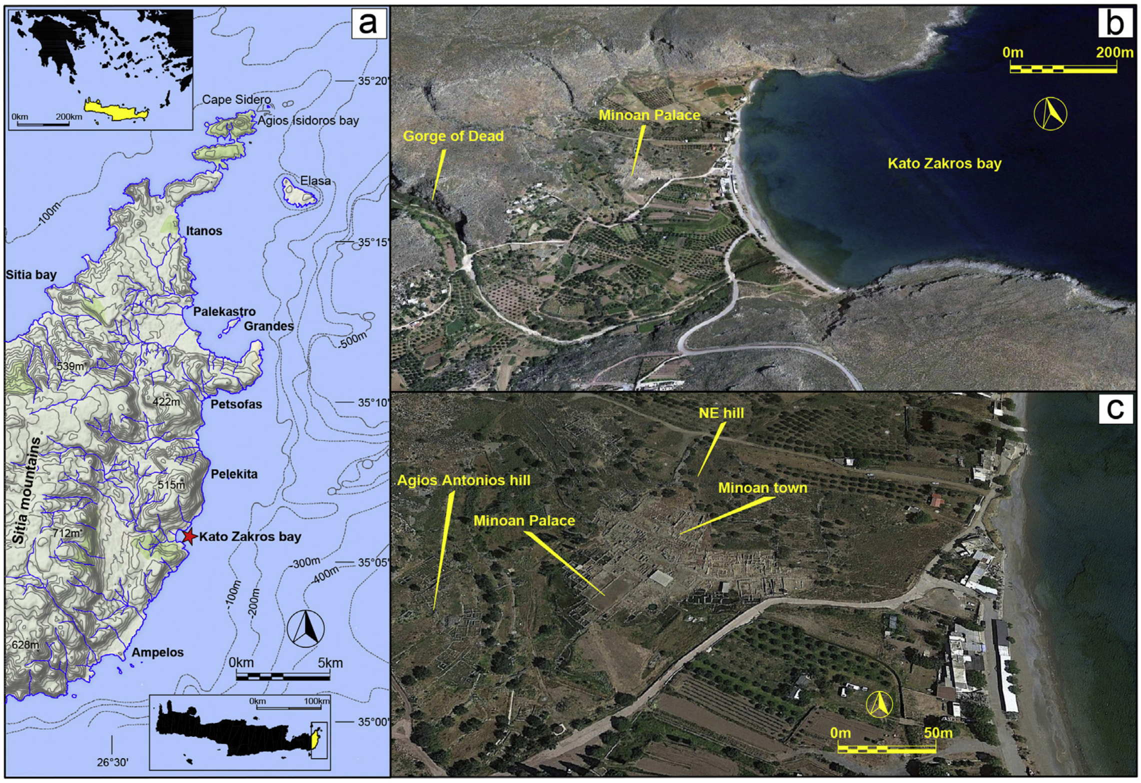

Fig. 1. (a): Location map of the eastern edge of Crete. (b): The bay and the valley of Kato Zakros. (c): The Palace of Kato Zakros between the NE hill and the hill of Agios Antonios to the south, and the relics of the surrounding Minoan town on the hillsides (images from Google Earth).

residential core of the site, being also the boundary between the town and the Palace (N. Platon, 1974) (Fig. 2a).

However, the supposed location of mooring where the harbour road led, today is a steep coast. The extensive sandy-gravely western coast would offer a shorter, evener and easier access to the Palace and the town (Fig. 1b, 2a). The answer was sought in the submerged palaeomorphology of the coast.

The sea transgression and shoreline alterations evolved together with the successive changes in sea level during the human presence and activity in the area over the last 4000 years. The underwater survey carried out in the present study recorded the submerged landforms and coastal archaeological constructions related to past sea levels, and after decoding them, the palaeoshoreline was reconstituted, in support of archaeological hypothesis.

2. Historical and archaeological context

The structure of the Minoan Palace of Kato Zakros points to a complex of internal, political, social, economic and religious organization. It was one of the major harbour-towns of the prehistoric antiquity, having trade relations with Asia and Africa, as deduced from large

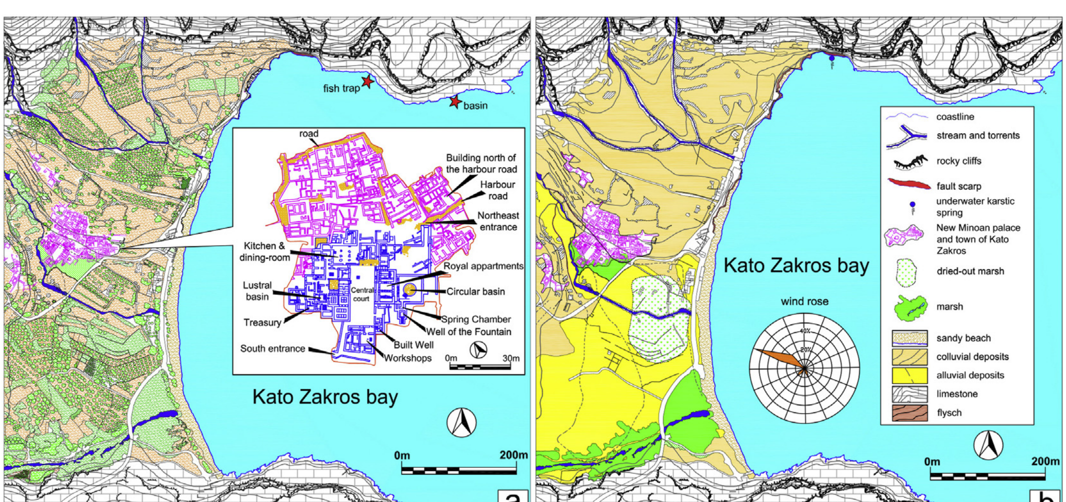

Fig. 2. (a): Location map of the bay and the valley of Kato Zakros. The general plan of the Kato Zakros Palace and the nearby houses of the town (after N. Platon, 1974) are shown in the box. (b): Geological sketch map of Kato Zakros. The wind rose diagram for the Kato Zakros bay is also given.

quantities of stored raw materials and artefacts from Cyprus, Egypt and Asia Minor (N. Platon, 1974).

The Minoan settlement developed on the southern margins of the northern elevated part of the depression of Kato Zakros, between two hills and the narrow valley that runs through them (Fig.1b, c). The palace complex covers an area of 4500 m^2 (Fig. 2a) and the visible ruins belong to the Neopalatial construction phase of Kato Zakros (ca. 1500 BCE–1450 BCE). The urban area covers roughly 8000 m^2 and expands upwards on the NW hill slope (Fig. 1c, 2a).

The old Palace, a great structure underneath the East Wing of the new Palace, was established around 1900 BCE and it was destroyed around 1600 BCE (N. Platon, 1974; L. Platon, 2004, 2010) probably by an earthquake that preceded or followed the eruption of the Thera volcano. The new Palace and the town were built at least a century later (ca. 1500 BCE) and it seems that have suffered in turn a major disaster in the mid-15th century (ca. 1450 BCE) (N. Platon, 1974; L. Platon, 2010). This is perfectly represented by the finds of a destruction horizon spread throughout the settlement that seems to have been caused again by an earthquake followed by an extensive fire (N. Platon, 1974; L. Platon, 2010). After the second destruction, the Palace and the town were abandoned. A significant resettlement occurred during the period between 1400 BCE and 1320 BCE on the hill of Agios Antonios SW of the Palace and the hill NW of the Palace (N. Platon, 1961, 1962; Zoitopoulos, 2012). The area of the SW hill seems to be reinhabited once again during the 11th century BC, but to a very limited extent (L. Platon, 2010).

The new Palace complex (1500 BCE–1450 BCE) was accessible from four entrances (Fig. 2a). The main gate of the Palace was located at the NE side and was a magnificent, processional, entrance. There ended the paved road that connected the Palace with the harbour (Fig. 2a). The Palace consists of four wings, organized around the Central Court (Fig. 2a). The East Wing (Fig. 2a) contained the living apartments of the royal family and a great square hall with a central circular cistern, and two detached structures used for drawing underground water (N. Platon, 1974).

The town surrounds the Palace in a sophisticated town planning and with a complex network of stone paved roads (Salichou, 2012) (Fig. 2a). It comprises thirty buildings that were mostly private residences. Workshops and handicraft installations and equipment, as well as storerooms for agricultural products and various utensils, show a relative economic independence of a prosperous community contemporary with the Palace (L. Platon, 2010; Salichou, 2012).

3. Physiographic and geological features of the area

The Gorge of the Dead (Fig. 1b) is narrow, with steep and craggy sides and caves that were used as burial places during the Prepalatial and Protopalatial period. It crosses the limestone massif of the eastern margins of Sitia Mountains, following a winding path approximately 4 km long, which leads to the narrow longitudinal valley of Kato Zakros (Fig. 1a, b).

The northern topographically elevated part is composed by two hilly mounds of the flysch bedrock, at the southern slopes of which the Minoan settlement grows (Fig. 1b).

The main drainage system of the area is formed by the stream of the Gorge of the Death, which ends at the southernmost tip of the bay, following the southern margin of the valley. The periodic catastrophic floodings of the torrent inundate significant areas of the lowland and form a small marsh at the mouth of the stream (Fig. 1b). In ancient times, and until the beginning of the nineteenth century (Hogarth, 1901), the marsh seems to occupy a wider area, extending northwards to the margins of the northeast hill (Fig. 2b).

Hogarth (1901) located the marshy area north of the current estuary of the stream. A torrent that flows between the NE and SW hill bypassing the Minoan settlement from the south, appears to result in the marsh, as also shown in the drawing of Hogarth (1901). This torrent runs towards the SE with steep gradients, turns abruptly to the south just before the SW limits of the Minoan complex, thus bypassing it, and is then directed again towards the SE to its mouth (Fig. 1b, c, 2a, b). The sudden change of flow direction is most likely due to diversion works made by the Minoans, since the natural flow of the torrent seems to be passing through the settlement, ending at the marsh. Moreover, the experience of the Minoans in hydraulic works in Kato Zakros is well known (Angelakis & Spyridakis, 1996; Chryssoulaki, 2009). Another torrent of dendritic drainage pattern with a drainage basin roughly 135,000 m^2, flows in the northern part of the western coast of the bay, carrying sediments and accumulating in mouth, forming an alluvial fan (Fig. 2a, b).

The bay of Kato Zakros with a length of 680 m and a width of 320 m is bounded between two limestone promontories. The maximum depth does not exceed 10 m, is open to the east and is fully protected against the prevailing NW winds (Fig. 2a, b–wind rose). The north and south rocky coast has a Quaternary staircase morphology, with slightly inclined towards the sea terraces and steep palaeocoasts. The younger fossilized coastline is at an elevation of +5 m and is definitely dated to MIS 5.5 by Strombus bubonius (Angelier, 1980; Peters, 1985; Mourtzas, 1990). Fourteen even earlier fossilized coastlines are well incised on the limestone bedrock until the elevation of 473 m (Peters, 1985; Mourtzas, 1990).

At the NW edge of the northern coast the scrap of a normal fault dips southwestwards at 50° (dip direction/dip: 212°/50°, slip striations: 220°/50°) and brings the limestone into contact with the flysch bedrock (Fig. 2b). At least six apparent underwater springs were found here, detected by the temperature and turbidity of the water flowing from them (Fig. 2b). Fossilized dunes (aeolianites), covering partially the limestone bedrock of the northern coast, reach an elevation of up to 12 m and show intensive ancient quarrying traces on their surface.

The western coast of the bay stretches 800 m in a NNE-SSW direction. It consists mostly of sandy-gravely beach 20 m wide and steep cliffs up to 10 m high at the northern part (Fig. 1b, 2a, b).

4. History of the Late Holocene relative sea level changes on the coast of Crete

The Late Holocene history of the relative sea level change along the coast of Crete differentiated between the western and eastern part of the island in 365 CE (Pirazzoli, 1986; Stiros & Drakos, 2006; Shaw et al., 2008), when during a strong seismic event the island was split along the neotectonic graben of Spili and its northern and southern prolongation. Until then, the sea level throughout the coast of Crete was -1.25 ± 0.05 m lower than at present (Mourtzas, 2012a, b; Mourtzas et al., 2016). With fragmentation, the western part some 100 km long uplifted by 9.15 ± 0.20 m at its westernmost end and 2.00 ± 0.30 m at its eastern boundary, while rotating towards the SE. This significant tectonic event seems to have affected the entire Eastern Mediterranean as it was accompanied by tsunami, which devastated the Nile Delta and the ancient towns of west Cyprus and Libya (e.g. Stiros, 2001; Shaw, 2012).

During the period of 2600 years that preceded it, between 4200 BP and 1600 BP, the entire island was submerged as a single tectonic block. Nine to eleven successive subsidence coseismic episodes gradually submerged the western part of the island. In this time, the total subsidence of the southwest edge of the island reached 1.60 m (Pirazzoli et al., 1982; Mourtzas et al., 2016). During the same period, in the central and eastern part of Crete the submerged coastal landforms and the functional height of selected archaeological markers related to the sea level at the time of their construction revealed and dated three distinct sea level stands at -6.55 ± 0.55 m, -3.95 ± 0.35 m and -2.70 ± 0.15 m (Mourtzas et al., 2016). After the 365 CE earthquake, when the island was fragmented and the western tectonic block uplifted and tilted, the entire island was submerged by 1.25 m during two subsidence episodes, by -0.70 m the first and -0.55 m the second one.

The deeper sea level stand at −6.55 ± 0.55 m can be identified by the oldest dated tidal notch of western Crete between 4200 ± 90 BP and 3930 ± 90 BP. The change to the two subsequent sea levels can be linked with two out of three destruction phases of the Minoan civilization, in 1600 BCE and 1200 BCE.

The sea level stand of the eastern part at −3.95 ± 0.35 m seems to have remained stable between 1900 BCE and 1600 BCE. It is related to the tidal notch of the SW end of the island (cape Chrysoskalitissa) formed at −2.85 m during the initial subsidence and has been dated to 3870 ± 90 BP (Pirazzoli et al., 1982; Mourtzas et al., 2016).

The younger sea level stand at −2.70 ± 0.15 m of the eastern and central part has been dated between 1600 BCE and 1200 BCE (Mourtzas et al., 2016). Comparing it with the corresponding tidal notches of SW Crete that formed at the same depth and have been dated to 3330 ± 80 BP and 3290 ± 70 BP and considering their lowest limit (1250 BCE and 1220 BCE, respectively), we conclude that the change to the subsequent sea level stand at −1.25 ± 0.05 m should be attributed to the destructive coseismic tectonic events around 1250 BCE or 1200 BCE.

Dating of −1.25 ± 0.05 m sea level was based on the ancient Hellenistic and Roman coastal installations and mainly on the constructional features of the Roman fish tanks found along the entire coast of central and eastern Crete. Historical sources report a change by 0.75 m in the Hellenistic and Roman sea level in the 1604 CE paroxysmal event that is also confirmed by submerged Byzantine and Venetian coastal installations throughout the Cretan coast. The relative sea level rise from −0.55 m to the contemporary level concerns the period of the last 400 years (Mourtzas et al., 2016).

5. Approach methodology

The methodology for determining the palaeosea level changes and their dating, was based on the correlation between the submerged landforms associated with past sea level stands, such as the tidal notches and beachrocks, and the functional level of ancient inundated or submerged constructions (Anzidei et al., 2014). The same methodology has been used repeatedly in the Aegean to identify past sea levels, parallel shift of the shoreline over time and palaeogeographic reconstruction of sea fronts of ancient prehistoric and historic settlements (Mourtzas, 1988, 1990, 2010, 2012c; Mourtzas & Marinos, 1994; Mourtzas & Kolaiti, 2013, 2016, 2017; Mourtzas et al., 2014; Kolaiti & Mourtzas, 2016).

The palaeogeographic reconstruction of the natural submerged harbour morphology of the Kato Zakros bay was based on: (i) underwater mapping and accurate depth measurements of beachrocks, tidal notches and other sea abrasion features, such as abrasion platforms and potholes, associated with past sea levels, (ii) accurate depth measurements of characteristic construction features of ancient submerged structures related to a former sea level, (iii) accurate measurements of the level of brackish groundwater in specific constructions of the Minoan Palace, which were operating at a specific lower level, (iv) definition and dating of past sea levels by correlating geomorphologic and hydraulic data with archaeological and historical evidence, (v) correlation between past dated sea levels and the functional elevation of the ancient natural harbour features.

The various outcrops of beachrocks and detrital fans in the mouth of the torrents were mapped using satellite images (Google Earth, 2012) and high-resolution orthophotos at a scale of 1:500 (National Cadastre & Mapping Agency S.A.). The map was updated during undersea survey at positions where data accuracy was required to reconstruct past sea levels.

All measurements were collected during calm sea conditions using mechanical methods. To account for tides, observational data have been reduced for tide values at the time of surveys with respect to average sea level, using tidal data from the nearest tide-gauge stations. All records were corrected for tides using data from the Hellenic Navy Hydrographic Service for the closest tide-gauge station at Iraklion (mean tide range 0.15 m and mean maximum tide range 0.40 m). The effect of atmospheric pressure on sea level corrected using the meteorological data for the site at the time of surveys (www.meteo.gr). All measurements were made during high-water periods, with sea level from 0.10 m to 0.18 m higher than the mean sea level.

The various beachrocks bands consisting of cemented beach sediments (e.g. Bernier & Dalongeville, 1996), are used as indicators of past sea levels. Dermitzakis & Theodoropoulos (1975), Neumeier (1998), and Neumeier et al. (2000) argued for the intertidal zone diagenetic process of the Cretan beachrocks. Mourtzas et al. (2016) comparing the elevations and depths of the seaward end of the various beachrock generations throughout the coast of Crete with the respective elevations and depths of the uplifted and submerged tidal notches and the functional height of ancient coastal installations, ascertained a remarkable match, thus proving that beachrocks can be considered as reliable RSL markers. Beachrock cementation occurs in the intertidal and supratidal zone, both presenting a similar, indistinguishable diagenesis (Bernier & Dalongeville, 1996; Neumeier, 1998). Therefore, the intertidal zone may be difficult to determine on the basis of the cement alone (Hopley, 1986). For this reason, the seaward end of the beachrock constitutes the undeniable section of the slab that is formed in the intertidal zone and can be used as a reliable indicator for the definition of a former mean sea level. The depth of the base of the seaward end of the beachrock slab coincides with the low tide of the respective sea level in which it was cemented.

The submerged tidal marine notches and the accompanying sea abrasion platforms are incised on the limestone and aeolianite underwater cliffs in the intertidal zone during periods of eustatic and tectonic stability, as a result of physicochemical and biological erosional processes (De Waele & Furlani, 2013; Antonioli et al., 2015).

Groundwater level change in coastal aquifers observed in ancient constructions combined with the changes in sea level has been used as an accurate indicator of sea level change (Sivan et al., 2004; Toker et al., 2012; Mourtzas, 2010; Pagliarulo et al., 2013a, b), taking into account limitations on their use (Milella et al., 2006; Morhange et al., 2013; Mastronuzzi et al., 2016). At the coastal margin, fresh groundwater flowing from inland areas meets with saline groundwater from the sea in a transition zone where mixing occurs through dispersion and diffusion. Sea level change affects the water table height and significantly disturbs the hydraulic gradient, which establishes an equilibrium position, the salt – fresh water interface. As saltwater is heavier, it tends to move landward underneath the freshwater layer, into coastal aquifers in a wedge shape. Therefore, saltwater wedge causes salt intrusion into aquatic ecosystems. Consequently, sea level changes affect the local hydrogeological parameters and the change in coastal phreatic water table has the same trend as in sea level.

Water wells and cisterns in the Neopalatial phase of the Minoan Palace of Kato Zakros, whose functionality depends on the height of the fresh water table, are at present flooded with brackish water, below mean sea level. Accurate measurements of the elevation of various functional features of the houses, the cisterns, and the well, such as floors, stairways, and pumping level of the water in the well, from the mean height of the phreatic water table, give a clear picture of the change in phreatic groundwater in parallel with sea level over the last 4000 years.

Ancient coastal constructions, such as the fish trap and the pool on the north coast of the bay, whose function was related to a past sea level and their dating is relatively accurate, were surveyed and the depths of their functional parts were measured. Their contemporary position provides precise information on the dating of sea level change (Mourtzas, 2012a, b).

6. Geomorphological sea level markers

Four tidal notches and sea abrasion platforms incised on the carbonate basement and three beachrock generations were surveyed and recorded along the coast of the Kato Zakros bay (Fig. 4a, b).

6.1. Tidal notches

In the western extremity of the northern coast, two submerged tidal notches situated on the fault scrap, form horizontal grooves with lateral continuity (Fig. 3a, b, 4a). The bottom of the uppermost notch is at −0.45 m and the deepest at −1.25 m. The seabed is located at a depth of 1.80 m to 2.10 m (Fig. 4 a-a). Their aperture ranges from 0.30 m to 0.35 m and the inward depth of the uppermost is 0.15 m and the lowest 0.25 m.

In a section of the northern coast, where aeolianites cover the carbonate bedrock, tidal notches are formed as sea abrasion platforms (Fig. 3c, 4 a-b). The uppermost platform, 4 m wide, reaches −0.80 m and the subsequent one, 6 m wide, develops between −1.40 m and −2.20 m. The seabed is at −2.85 m.

Further east, the tidal notches have been incised on the limestone coast in the form of horizontal grooves accompanied by sea abrasion platforms (Fig. 4 a-c). The uppermost platform is 3.40 m wide and develops between the depths of 0.55 m and 0.75 m, the intermediate is 1.80 m wide and develops between −1.25 m and −1.35 m, and the deepest is 5.80 m wide and develops between −2.55 m and −2.70 m. The seabed is at a depth of 4 m.

At the easternmost extremity of the northern coast, the two shallower tidal notches are horizontal grooves at the depths of 0.50 m and 1.25 m. The lowermost notch is at −2.80 m with the accompanying

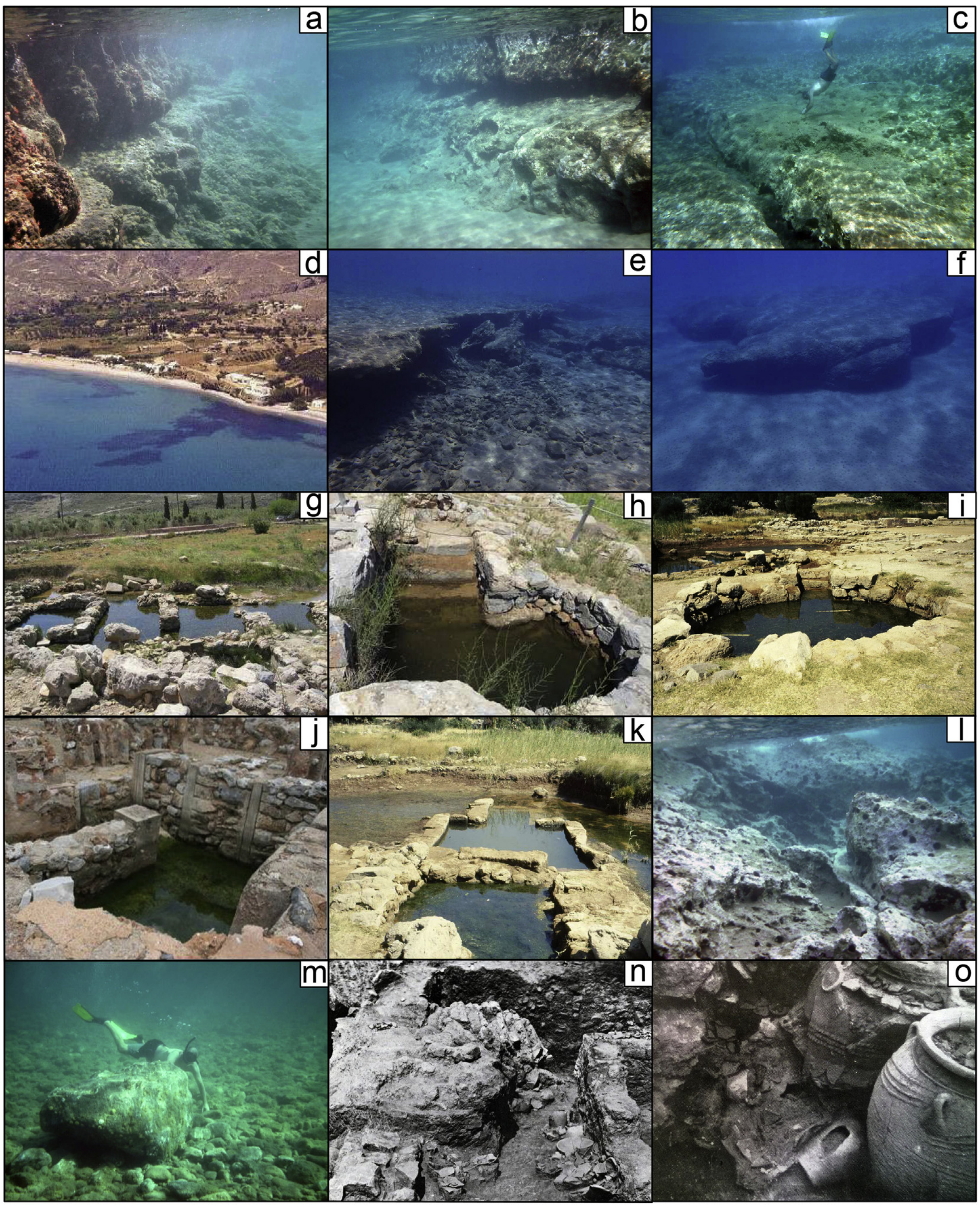

Fig. 3. (a) The well-developed tidal notch incised on the rocky northern coast at −1.25 ± 0.05 m. (b) The tidal notch at −1.25 ± 0.05 m on the rocky southern coast. (c) Sea abrasion platforms formed in the aeolianites on the northern coast. (d) The elongate underwater development of the various beachrock bands that form the submerged natural harbour morphology. (e) The landward end of the submerged beachrock elongate intrusion. (f) The seaward end of the earlier beachrock band at −4.00 ± 0.30 m. (g) Groundwater rise in the building complex south of the NE gate. (h) The Built Well after inundation. (i) The Circular Cistern flooded. (j) The Lustral Basin flooded. (k) The Well of the Fountain and the surrounding area inundated. (l) View of the entrance of the submerged fish trap from the west. (m) The underwater boulder deposits in the southern end of the western coast. (n) & (o) Seismic disasters of the Protopalatial and Neopalatial phase of the Minoan Palace and town of Kato Zakros (from N. Platon, 1974).

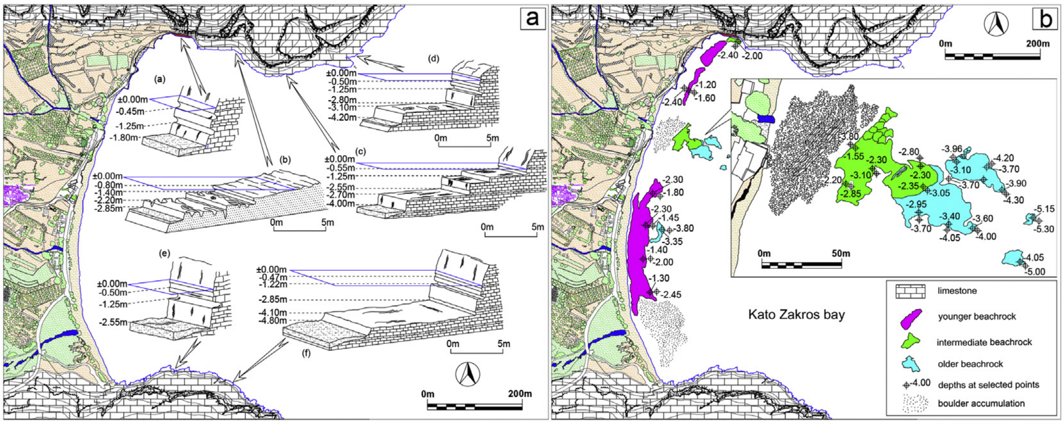

Fig. 4. Location maps of: (a) the various tidal notches and sea abrasion platforms incised on the rocky coast of the Kato Zakros bay, (b) the three distinct beachrock generations.

sea abrasion platform to reach a depth of 3.10 m. The sea bed is at −4.20 m (Fig. 4 a-d).

The tidal notches incised on the southern, steep, carbonate coast appear in the form of continuous horizontal grooves. The shallower notch at a depth of 0.47 m to 0.50 m is not well developed and at places is presented as a faint trace. The tidal notch at a depth of 1.22 m to 1.25 m is well developed, with an aperture ranging from 0.30 m to 0.45 m and inward depth from 0.25 m to 0.60 m. The lowermost notch at −2.85 m is accompanied by an extended platform 10 m wide, and dips slightly towards the sea up to a depth of 4.10 m (Fig. 3b, c, 4 a-e, a-f).

From the detailed survey of the submerged tidal notches it is deduced that they are continuous over the entire length of the rocky coast of the bay and are found at −0.50 ± 0.05 m, −1.25 ± 0.05 m, and −2.85 ± 0.30 m (Fig. 7a).

6.2. Beachrocks

Systematic mapping and measurement of beachrock slabs along the western coast of the bay allowed to define three distinct beachrock bands, each one of them was formed in different sea levels (Fig. 3d, e, f, 4b).

The two older beachrock generations are confined to the northern section of the western coast and are mainly cemented detrital materials accumulated in the mouth of the northern stream. They consist of sands and coarse gravels to large boulders that cover the thin-bedded limestone bedrock.

Two distinct slabs in a sturgeon shape, the first 38 m long and 20 m wide, and the second 40 m long and 30 m wide, with their seaward ends at a distance of 160 m from the shoreline, constitute the oldest and deepest beachrock band. At the seaward end the base is at −4.00 ± 0.30 m and the top at −3.65 ± 0.30 m. Located some 20 m from the end of the seaward beachrock slab, were found two beachrock relics that are probably cemented remnants of the tongue-shaped ends of the alluvial fan. A small beachrock slab was found in the central part of the western coast some 75 m from the shoreline. The depth of the top and base at its seaward end is at −3.80 m and −3.35 m, respectively (Fig. 4b).

The intermediate beachrock band consists of an elongated slab, 50 m long and maximum 65 m wide. It starts 45 m approximately from the shoreline and develops in NW-SE direction. It overlays the thin-bedded limestone bedrock. The depths of the top and base at the seaward end are 2.25 ± 0.05 m and 2.95 ± 0.15 m, and at the landward end −1.25 m and −1.55 m, respectively. The seabed is located at −3.80 m. A beachrock slab was identified at the northwest extremity of the northern rocky coast, in front of the fault scrap, where underwater springs flow. The depths of its top and base are −2.0 m and −2.40 m, respectively (Fig. 4b).

The younger beachrock band grows on the major part of the western coast except for its southern extremity. It consists of a slab with a minimum width of 6 m and maximum 33 m. The distance of their seaward end from the shoreline ranges from 25 m to 35 m, and the depths of the top and base are 1.20 ± 0.20 m and 2.20 ± 0.20 m, respectively (Fig. 4b).

In summary, three distinct beachrock bands were identified (Fig. 7a). Their seaward ends are at −3.65 ± 0.30 m (top) and −4.00 ± 0.30 m (base) of the oldest band, −2.25 ± 0.05 m (top) and −2.95 ± 0.15 m (base) of the intermediate band, and −1.20 ± 0.20 m (top) and −2.20 ± 0.20 m (base) of the younger band.

6.3. Correlation between geomorphological markers

Comparing the depths of the seaward end of beachrocks with those of tidal notches, a good morphological correlation between them can be recognized that refers to same sea level stands during their formation (Fig. 7a). Previous studies with a similar approach in coastal areas have proven to be successful (e.g. Mastronuzzi et al., 2014 and references therein).

The beachrock level at −4.00 ± 0.30 m appears to meet the deepest part of the sea abrasion platform and the seabed at the foot of the limestone cliff at −4.10 ± 0.10 m. The shallow depth of the sea bottom surrounding the rocky shores of the bay has prevented the formation of the deeper tidal notch, which is detected all around the central and eastern coast of Crete at −3.95 ± 0.25 m (Mourtzas et al., 2016).

The depth of the top of the intermediate beachrock of 2.95 ± 0.25 m agrees with the tidal notch at −2.85 ± 0.30 m. The depth of the top of the younger beachrock band of 1.20 ± 0.20 m is consistent with the tidal notch at −1.25 ± 0.05 m. The tidal notch at −0.50 ± 0.05 m does not correspond to any beachrock formation.

Based on geomorphological indicators and comparing them, we arrive at four distinct sea levels, at −4.00 m ± 0.30 m, −2.85 ± 0.30 m, −1.25 ± 0.05 m, and −0.50 ± 0.05 m (Fig. 7a). The evolution of geomorphological markers and the relationship between them is demonstrated in Fig. 8.

7. Archaeological markers

The rise of the brackish phreatic water table in the water supply installations and the ruins of the Palace, and the submerged rock-cut coastal constructions on the north coast of the bay are accurate indicators of sea level change and contribute to the dating of the various levels. The hydraulic communication of the alluvial aquifer of the south part of Kato Zakros valley with the sea was found through the increased content of dissolved salts in freshwater, and the saltwater intrusion into the water supply wells. A sea level rise results in reduction of the aquifer's capacity to store freshwater and shifts landwards the fresh-salt water interface. The rise of the brackish water table and flooding of the southern part of the Palace (Fig. 3g) caused great difficulties during the excavations and is one of the major problems for the restoration and promotion of the monument.

7.1. Protopalatial constructions

N. Platon (1974) pointed out the difficulty of the excavation of Protopalatial constructions that were found beneath the establishments of the new phase of the Palace, because of the constant seepage of water through the soil. During the reconstruction of the East Wing of the new Palace, around 1500 BCE, after the complete destruction of the Protopalatial complex, the new floors were made of lime concrete, at a higher level than the previous ones that was reaching in places 3 m to 3.5 m. N. Platon (1974) also described the filling of the Spring Chamber, the elevated floor of the Hall of the Cistern, below which was found a bathtub of the earlier phase of the Palace, as well as the constant changes and additions to the drainage system after repeated destructions and reconstructions.

The rise of water table flooded the floors of the buildings of the new Palace by at least 1 m at the southern lower part. Consequently, the level of the water table 3600 years ago must have been at least 4 m lower, in order for the floors not to be inundated.

7.2. Neopalatial constructions

The water supply installations of Kato Zakros can be linked with the artisanal activities in the Palace and religious practices on the site. These include the Spring Chamber, the Well of the Fountain, the Built Well, the Circular Cistern, and the Lustral Basin (Fig. 3h, i, j, k and 5a, b, c).

7.2.1. The Spring Chamber

The Spring Chamber was situated in the SW side of the Hall of the Cistern. It was the main chamber in which the water sprang up and collected, supplying the royal apartments with water. It was also used for sacred offerings. The spring water was channelled into the Well of the Fountain, which was constructed south of the Spring Chamber (N. Platon, 1974). The Spring Chamber is flooded by brackish water, because of the groundwater level rise by approximately 3 m.

7.2.2. The Well of the Fountain

The Well of the Fountain was a rectangular structure, which was connected to the Spring Chamber. The upper part of the walls was carefully built of ashlar poros stones, whereas the lower interior was narrower and made roughly, thus reducing the size of the basin. The bottom of the well was paved with irregular slabs. A staircase of fifteen steps, eleven of which are perfectly preserved, led down to the drawing level of the well. Spring water flowed through an opening at the base of the north wall. A smaller opening at the base of the east wall channelled water from another underground source (N. Platon, 1974). The significant increase of the groundwater level by 2.75 m from the bottom of the Well of the Fountain causes flooding of the staircase (Fig. 3k and 5b).

7.2.3. The Built Well

The Built Well is situated in the southeast corner of the Central Court of the Palace and close to the major workshop unit of the South Wing. It was reached by eight steps leading down to a platform from where water could be drawn. The bottom of the well was at a depth of about 2 m from the drawing platform. It was paved with slabs and through them water, probably deriving from a spring, seeped out. The installation was equipped with an overflow, which was a conduit for water to drain away. The water drawing was done by means of a wooden hoist, fixed to the pier of the balustrade and the south wall of the room (N. Platon, 1974). Hoists were previously necessary to draw water from relatively deep wells. The rise of the water table to 2.90 m from the bottom of the well causes not only filling of the well but also inundates five out of eight steps of the staircase (Fig. 3h and 5a).

7.2.4. The Circular Cistern

The Circular Cistern is situated in the centre of the Hall of the Cistern, directly to the east of the royal apartments. The inner diameter is less than 5 m and the depth is 1.70 m. The walls are thick and are lined with hydraulic plaster. According to N. Platon (1974) it could have served as a private swimming pool or an aquarium for local and exotic fish. A staircase with eight steps led down to the slab-paved bottom of the Cistern. N. Platon (1974) described how, in front of the lowest step, was placed a large poros slab through which the water gushed up and was automatically filtered. However, lining with hydraulic plaster indicates that it was a water retaining structure, thus excluding the spurt of water from the bottom. The rise of the groundwater level in the Cistern appears to exceed 1.50 m, covering seven out of eight steps descending into it (Fig. 3i and 5c).

7.2.5. The Lustral Basin

The Lustral Basin is situated in the West Wing of the Palace, next to the small shrine room. Those participating in religious ceremonies should be purified by taking bath in sanctified water before entering the shrine. Eight steps descended into the basin. To ensure water tightness, the inside of the basin was covered by hydraulic mortar. Today, the rise of the water table by about 1 m inundates the lower part of the basin (Fig. 3j).

The rise of the brackish water table, as recorded in the water supply systems of the Palace, indicates a change in sea level by 2.80 ± 0.10 m from the Neopalatial period of the Palace (1500 to 1450 BCE) to date.

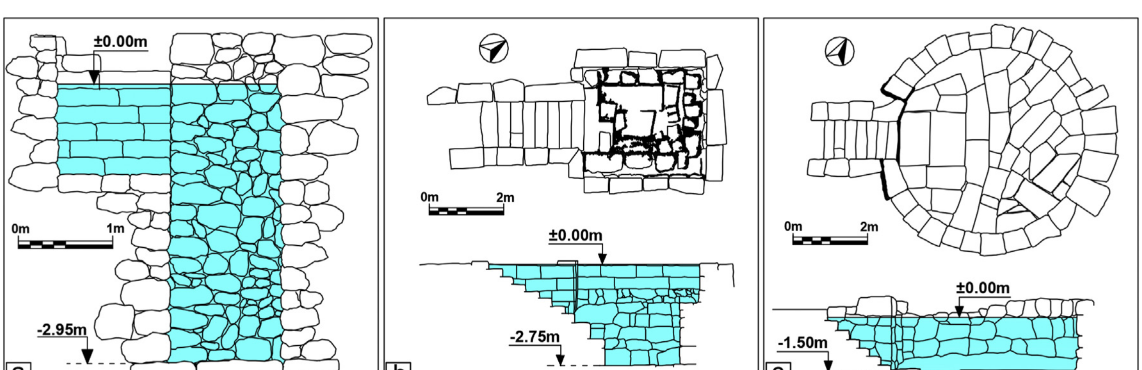

Fig. 5. Plan and cross-sections of the water supply systems of the Palace showing the rise of brackish groundwater in them: (a) Built Well, (b) Well of the Fountain, (c) Circular Cistern.

7.3. Submerged ancient coastal fishing installations

The submerged fish trap and the pool, which has probably been used for the same purpose at a later period, found on the northern rocky coast of Kato Zakros bay, serve as markers of past sea levels (Fig. 3l and 6).

7.3.1. The fish trap

The fish trap is carved into a marine erosional terrace, roughly 4.0 m wide, and is entirely submerged to a maximum depth of 0.80 m. Davaras (1975), Pirazzoli (1980), and Flemming and Pirazzoli (1981) interpreted it as a fish tank, whereas Nakassis (1987) characterized it as a fish trap. Mourtzas (2012b) described in detail the constructional characteristics and the relationship between the various functional features with a former sea level. It is roughly carved in a rhomboid shape, provided with a narrow entrance at the west side. A trapezoidal rock-cut channel starts from the entrance, with an increasing width to its westward end, dipping strongly towards the south (Fig. 3l and 6a, b). Mourtzas (2012b) dates it to the Roman times, and based on its functional height, considers that the sea level, when it was operating, was 1.0 m to 1.30 m lower than at present.

7.3.2. The pool

The pool is a natural cavity in the rock, 160 m east of the fish trap. It is egg-shaped with a long axis of 2.80 m and a depth of 2.50 m approximately. In the southern seaward side, a shallow channel 1.0 m long and 0.60 m wide is carved. The bottom of the pool is at −0.80 m and the channel at −0.75 m. It is assumed that this natural cavity was used by a local fisherman to capture fish at a later period, after the submersion of the fish trap when sea level was 0.50 ± 0.05 m lower than at present (Fig. 6c, d).

8. Dating of relative sea level stands

The sea level stand at −4.00 ± 0.30 m that corresponds to the oldest beachrock band, goes back to the Protopalatial period (ca. 1900 BCE–1600 BCE). The dating is based on the relationship between the floors of the Protopalatial buildings and the groundwater level of that period, at the southern low part of the old Palace (Fig. 7a). The beachrock level at −4.30 ± 0.20 m that corresponds to the tidal notch of −3.95 ± 0.25 m is dated between 3900 BP and 3600 BP for the entire coast of Crete, on the basis of the Protopalatial period of the Prehistoric settlement of Kommos (Mourtzas, 1988, 1990), the submerged Minoan quarry at Nirou Chani (Mourtzas, 1990; Mourtzas et al., 2016), the submerged Prehistoric settlement at Spiliada (Simosi, 1988; Mourtzas et al., 2016), and the submerged isthmus of Minoan Mochlos (Leatham & Hood, 1958/59; Mourtzas, 1990; Soles, 2007; Mourtzas et al., 2016), all sites belonging to almost the same period.

The sea level stand at −2.85 ± 0.30 m that corresponds to the tidal notch of −2.85 ± 0.30 m and the intermediate beachrock band of −2.95 ± 0.15 m is related with the rise of groundwater level by 2.85

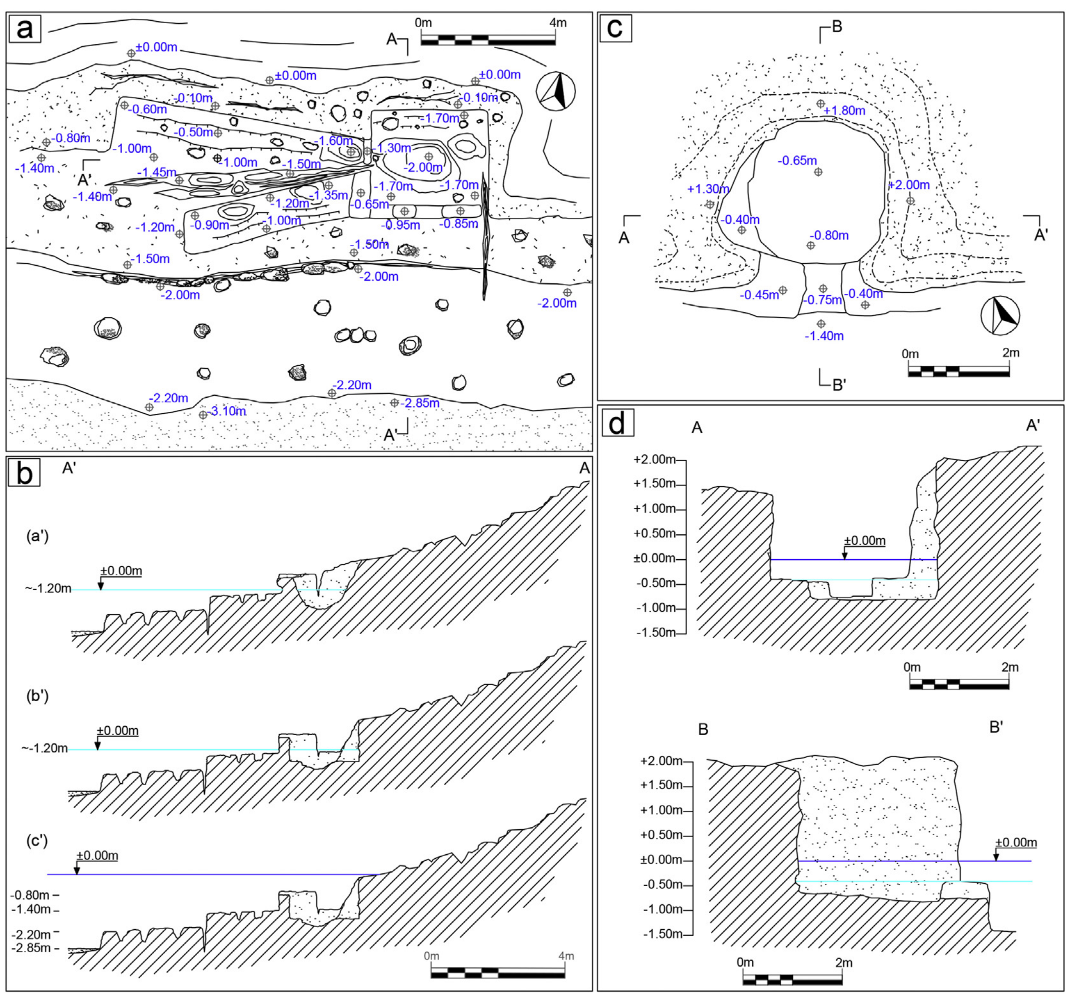

Fig. 6. (a) Plan of the fish trap. (b) Cross-sections of the fish trap. The construction progress and the change in sea level that caused its immersion are shown: (a′) as a natural cavity with a fissure in front, (b′) enlargement of the natural cavity and carving of the channel and the entrance of the fish trap, (c′) the sea level rise by 1.25 m immersed the fish trap. (c) Plan of the pool. (d) Cross-sections of the pool. The current sea level (blue line) in relation to the sea level at the time of operation (cyan line) is shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

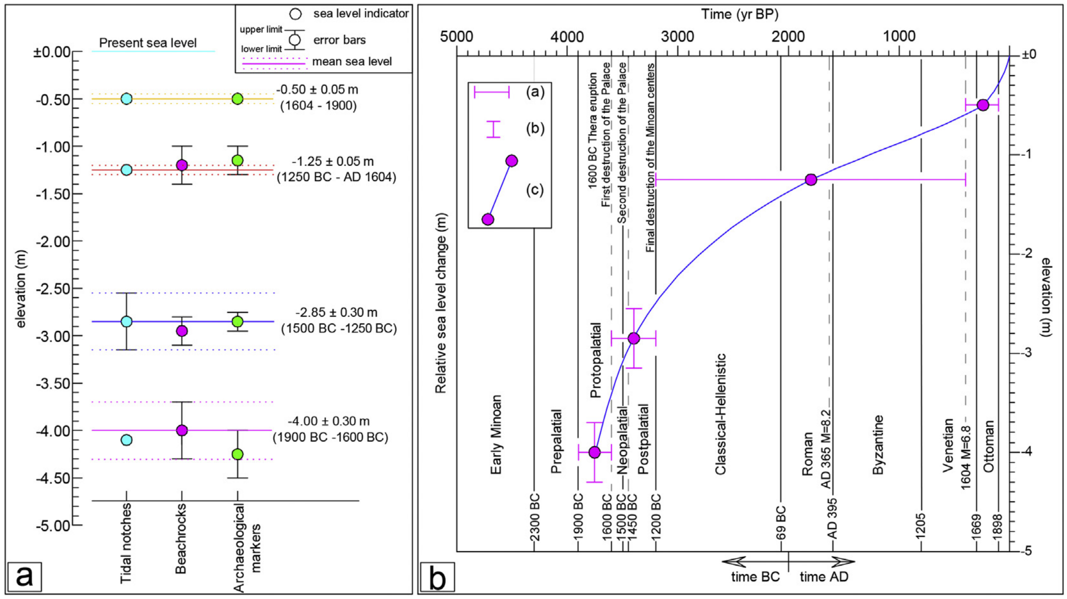

Fig. 7. (a) Correlation between the mean sea levels deduced from geomorphological (tidal notches and beachrocks) and archaeological markers. (b) Relative sea level change for the bay of Kato Zakros. In the top left box: (a) maximum estimated period of sea level stability, (b) sea level error bar, (c) mean relative sea level rise.

± 0.05 m in the Neopalatial water supply installations of the Minoan Palace and dated back between 1500 BCE and 1450 BCE (Fig. 7a).

The sea level stand at −1.25 ± 0.05 m that corresponds to the younger beachrock band of −1.20 ± 0.20 m and the tidal notch of −1.25 ± 0.05 m is dated according to the functional height of the Roman period (0–200 CE) fish trap (Fig. 7a). Archaeological markers all around Cretan coast and historical records allow to assign it to the period between 400 BCE and 1604 CE (Mourtzas, 2012a, b; Mourtzas et al., 2016). Historical testimonies aided in matching the paroxysmal event of 1604 with the change by 0.75 m in the Roman sea level (Mourtzas, 2012a, b; Mourtzas et al., 2016).

The sea level rise from −0.50 ± 0.05 m to the present level concerns the period of the last 400 years and is linked with the submersion of the pool on the north coast of the bay and the submerged coastal installations found throughout Crete of the late Venetian and Ottoman period (Fig. 7a).

The prediction of relative sea level change for the bay of Kato Zakros during Late Holocene is presented in Fig. 7b.

9. Causes and chronology of the destructions

According to N. Platon (1974), the old Palace of Kato Zakros was found to have undergone successive changes, probably due to repeated destructions and reconstructions, the last and longest to date around 1700 BCE.

N. Platon (1974) argued that the new Palace had been built around 1600 BCE and suffered two widespread destructions. After the first catastrophe around 1500 BCE, the Palace and the town were rebuilt with minor changes to the original plan, apart from sections that were filled in to rebuild on a higher level. The second and complete catastrophe according to N. Platon (1974) occurred around 1450 BCE and was associated with the eruption of the Thera volcano and the destructive consequences that followed: strong earthquakes, tsunami that destroyed harbour installations and buildings and other accompanying phenomena (N. Platon, 1974).

L. Platon (2011) concluded that the final destruction occurred in two stages and it had a geological origin, and most likely volcanic. Comparing the pottery of Zakros with that of Akroteri in Thera, he asserted that the eruption of the Thera volcano and the final destruction of Zakros were distant from some months up to two years or even zero. Between the start of volcanic activity and the great eruption, in a period of tranquillity, the inhabitants returned and tried to repair the Palace and the town. This activity shows that before the final abandonment the Palace had suffered damage, but to a degree not capable of forcing inhabitants to leave it. Nothing testifies concern, fear or worry of an impending danger. Sacrificial offerings of pumice and fruits, indicate that they were trying to appease the fury of natural phenomena that repeatedly hit the Palace during this period (L. Platon, 2011).

Although the concurrence of the final destruction of the Palace and town of Kato Zakros with the Minoan eruption of the Thera volcano looks exciting, it has proved completely wrong. Radiocarbon datings (Manning et al., 2006), tree-ring dating (Lamarche & Hirschboeck, 1984; Baillie, 1989; Grudd et al., 2000), and the Greenland ice cap dated frozen ash from the Thera eruption (Hammer et al., 1987; Zielinski & Germani, 1998; Hammer et al., 2003; Vinther et al., 2006) shift the eruption date 100 to 150 years earlier. Furthermore, the dating of an olive branch buried beneath a lava flow from the Thera volcano gave a date between 1627 BCE and 1600 BCE (Friedrich et al., 2006; Friedrich & Heinemeier, 2007).

Irrespective of the chronology of the catastrophe, the findings of the systematic excavation by N. Platon (1974) led to the conclusion that the final destruction of the new Palace and town of Kato Zakros was violent, sudden and complete (Fig. 3n, o). A severe earthquake caused the clay partitions to collapse, walls to deform, sections of the upper stories and the walls of the façade to fall down, huge stones to have been hurled to a distance filling the surrounding area and blocking the passages. The mud-brick walls of the kitchen and deep storerooms were detached. The southern approaches to the central court were blocked off by piles of stones, the masonry of the Circular Cistern fell inside it, and the walls surrounding the Well of the Fountain were dislocated and inclined from the vertical. The steps of the stairways were displaced, some pithoi found in the storerooms of the West Wing were compressed with a great force from east to west. The fire that followed was of large extent and of great intensity, it reduced everything to ashes, it burned out almost the entire building of the Palace and the houses of the town, carbonized the wooden parts, turned many stones into lime, distorted the columns, turned the clay pots into a shapeless mass, and melted the lead objects covering parts of the floors (N. Platon, 1974). Then, according to N. Platon (1974), a tsunami followed. Despite the sheltered topography and orientation of the bay, he assumed that the tsunami hit the shore with great vehemence, destroying the harbour installations and hurling the ships far inland. The sea invaded the land in a

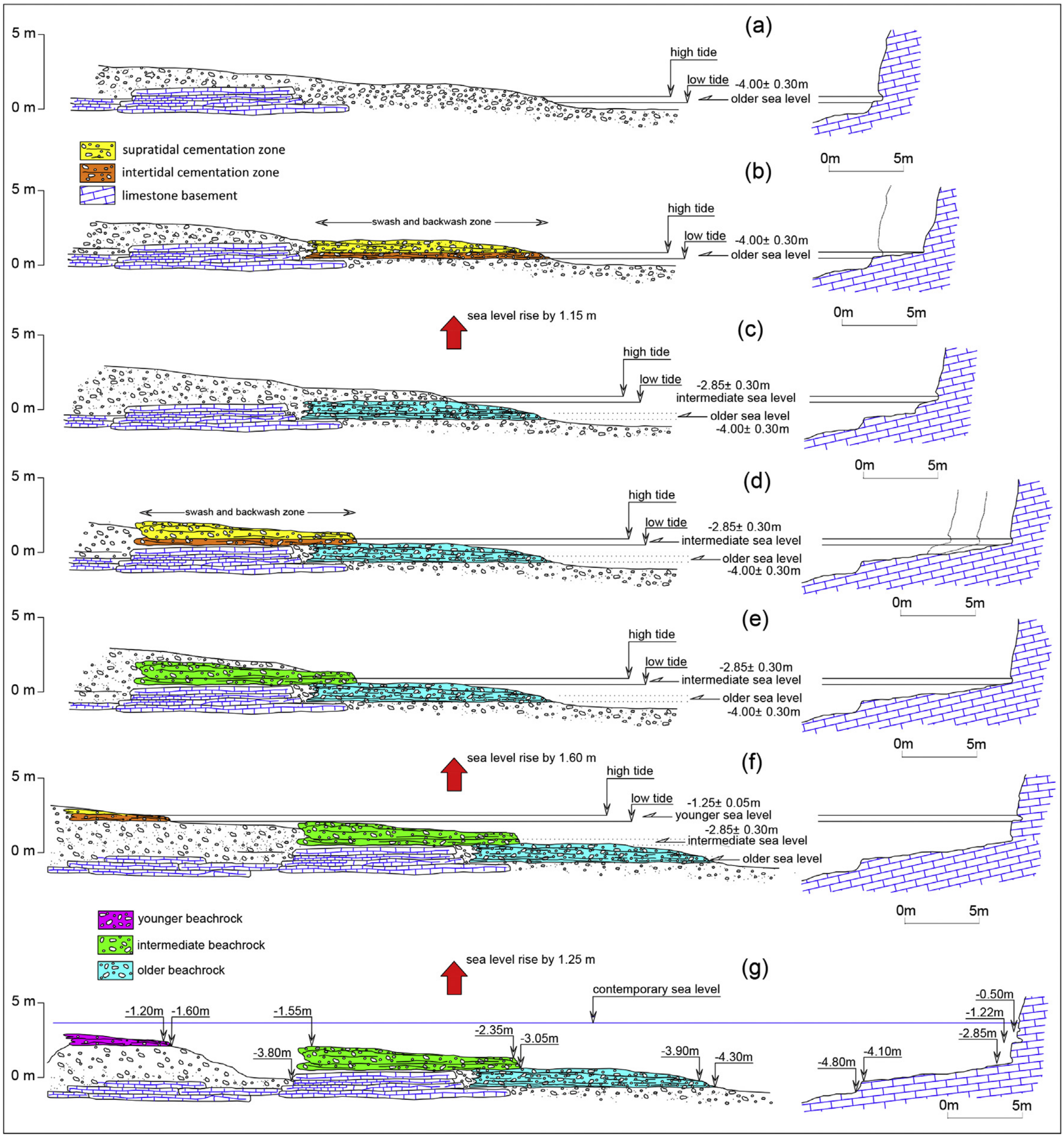

Fig. 8. (a) Sea level at -4.00 ± 0.30 m: detrital fans are accumulated on the palaeoshore covering the carbonate bedrock. A tidal notch begins to cut into the limestone coast in the intertidal range. (b) During the same period of sea level stability at -4.00 ± 0.30 m, the detrital fans are cemented between the low tide and the upper limit of swash and backwash zone. On the carbonate coast an increasing cliff retreat forms a sea abrasion platform. (c) Coast subsidence during a paroxysmal tectonic event by 1.15 m results in a new sea level at -2.85 ± 0.30 m. The recent detrital fans cover the older beachrock slab. In the intertidal range a new tidal notch is now incised on the limestone cliff. (d) Cementation of the overlaid detrital deposits occurs in the intertidal and supratidal zones of the new sea level. Increasing cliff retreat of the rocky coast widens the sea abrasion platform. (e) Two different beachrock slabs have been formed, the older and the intermediate, one partially over the other. By continuous supply of detrital material the intermediate beachrock slab is covered. (f) A new subsidence of the coast by 1.60 m during a paroxysmal tectonic event, forms a new sea level at -1.25 ± 0.05 m. On the limestone coast a new tidal notch is incised. By the cementation of the detrital deposits between the low tide and the upper limit of swash and backwash zone, a new beachrock band is formed. (g) Relative sea level rise by 1.25 m in two phases. Initially, by 0.75 m that formed the sea level of -0.50 m, in which a tidal notch is incised on the limestone coast. Then, sea level rose by 0.50 m to the present stand.

series of great waves and reached the town causing complete damage to the new Palace (N. Platon, 1974).

MacGillivray et al. (1987) and Driessen and Macdonald (1997) argued that the buildings of the nearby Minoan town of Palaikastro were probably destroyed by a tsunami ca. 1600 BCE triggered by the eruption of the Thera volcano, 150 years earlier than the chronology that N. Platon (1974) assumes that hit Zakros.

The discovery of an extensive geoarchaeological tsunami deposit on the shore of Palaikastro, consisting of various geological materials, volcanic ash from Thera and archaeological remains of the settlement, was associated with the Minoan eruption of the Thera volcano, on the grounds of geological, archaeological and radiocarbon-dating criteria. Field observations suggest that the tsunami waves in Palaikastro reached at least 9 m (Bruins et al., 2008).

However, there is no evidence of the contribution of a tsunami to the catastrophe of the Kato Zakros Palace. The extensive beachrocks, which clearly pre-existed the destruction phases, remained intact over time, whereas a tsunami of the intensity described should have dislocated and thrust them.

We examined if the extensive underwater deposits of boulders found in the southern end of the western coast of the bay result from the overwash process of a tsunami (Fig. 3m). The deposits cover an area of approximately 9000 m^2, the seaward end is in a distance of 100 m from the shore and about 40 m from the limestone cliffs of the south coast (Fig. 4b). The boulder size ranges from 0.35 m to 2.50 m. However, these deposits appear to be associated with stream mouth flood discharge deposits, as described by Hogarth (1901).

In conclusion, the archaeological survey revealed that the Palace and the city suffered two great destructions. The first catastrophe occurred around 1600 BCE and is associated with the eruption of the Thera volcano and the natural phenomena that preceded and followed it. The second seismic destruction around 1450 BCE marked the end of the Minoan centre of Kato Zakros and caused the destruction of almost all the Minoan centres of Crete but not their abandonment. The nearby Palaikastro, after the destruction, was reorganized and flourished until 1250 BCE, when a severe earthquake destroyed it. The harbour town of Kommos on the south coast, and Malia, Sissi and Mochlos on the north coast were rebuilt and continued to prosper until the mid LM IIIB period (ca. 1250 BCE–1200 BCE).

10. Discussion

The extensive different beachrock bands, the submerged tidal notches and sea abrasion platforms, the submerged rock-cut constructions, the underwater springs, and the rise of the groundwater provide clear evidence of large-scale landscape changes during the Late Holocene that could be attributed to sea transgression and human impacts.

*10.1. Prepalatial period (Early Minoan III, **ca.** 2000 BCE)*

During the Early Minoan III period, sea level was at -4.00 ± 0.30 m lower than at present and the western sandy coast of Kato Zakros bay was 80 m to 140 m wider than the current beach (Fig. 9a). Burials with funeral gifts found in the small natural caves of the Gorge of the Dead and in the clefts of the rocky coast, suggest the existence of a settlement there (N. Platon, 1974).

The northernmost stream crosses the hilly zone and erodes the bedrock depositing piles of coarse material in its mouth. The thick alluvial cone in the mouth of the stream ends in a swallow-tail shaped morphology. At the mouth of the two southern torrents develops an extensive marsh that covers almost the entire south lowland coastal zone. On the western edge of the northern rocky coast karstic springs discharge large amounts of water, feeding the early Minoan settlement.

10.2. Protopalatial period (Middle Minoan IA to Late Minoan IA, 1900 BCE to 1600 BCE)

At that time, when the sea level was at -4.00 ± 0.30 m and the western sandy coast 80 m to 140 m wider than at present, was established the old Palace and the settlement. The Palace was built in the low area, at the margin of the hilly zone. The settlement stretched to the successive terraces of the slope of the northeast hill. In this period the inhabitants probably made the first diversion works to bypass the Palace and draining of the northwest part of the marsh.

The earliest band of beachrock formed by cementation of coarse material accumulated in the swallow-tail shaped end of the alluvial cone in the mouth of the north stream (Fig. 9b). The natural morphology is used for approach and unloading of vessels, so that being lighter they could be hauled on the beach. The communication with the mooring area is likely achieved by a paved road, whose construction goes back to the Protopalatial phase and was discovered beneath the buildings of the northeast section of the Palace (N. Platon, 1974). The karstic springs of the northern coast continue to discharge large amounts of water.

10.3. End of the Protopalatial period (end of Late Minoan IA, 1620 BCE to 1600 BCE)

With the eruption of the Thera volcano and the neotectonic upheavals of the lithosphere that was caused in the area of the southern Aegean, appear to be linked the vertical tectonic movements that led the sea level to rise from -4.00 ± 0.30 m to -2.85 ± 0.30 m. As a consequence, the coastline has retreated towards the west about 70 m, submerging the earliest band of beachrock at -1.0 m simultaneously. The increase of the alluvial aquifer level that followed the rise of sea level, inundated the ruins of the already devastated Palace in the low elevation zone between the northeastern hill and the hill of Agios Antonios.

The northern stream still deposits large quantities of coarse material at its estuary. The mouth detrital deposits create an elongated morphology that goes into the sea for 50 m with a maximum of 30 m width (Fig. 9c).

10.4. Neopalatial period (Late Minoan IB) (1500–1450 BCE)

The new Palace is built in the low elevation zone between the northeastern hill and the hill of Agios Antonios over the remains of the old Palace, which were filled in. It was founded on a higher level of about 3.0 m to 3.50 m than this of the Protopalatial phase in order the new floors – sealed with lime concrete- to be above the groundwater level, which was inundating the ruins. The low elevation zone is selected again to ensure the adequacy of water through the water supply wells in the Palace for operational and ceremonial purposes. The stream crossing the narrow valley of the Palace is diverted to prevent flooding in the Palace's premises during flood periods, probably completing the diversion works of the Protopalatial period.

In this time, the sea level remains stable at -2.85 ± 0.30 m. The elongated intrusion of the mouth detrital deposits of the northernmost stream is cemented, thus forming the intermediate band of beachrock. The thick, hard, and flat slab of the formation constitutes a natural pier 50 m long and 30 m wide, which enters the sea (Fig. 9d). The depth of the sea bottom around the natural pier should not exceed 1 m.

The Minoan vessels could unload freight on the natural pier and then, being lighter, were hauled on the sandy beach. The paved harbour road leads from the mooring area to the main northeast gate and from there to the central court and the storerooms of the Palace.

10.5. The end of the Neopalatial period (Late Minoan IB) (1450 BCE)

The strong seismic sequence that hit Crete around 1450 BCE, destroyed the Neopalatial centres and settlements of eastern Crete. In the Palace of Kato Zakros the foreshocks remove inhabitants from their buildings. They return when the phenomena calm down and try to restore the damage. They attempt to propitiate the chthonic divinities by offerings of fruit and pumice. But earth tremors come back and force the inhabitants to abandon their activities and precious objects in the treasuries. The main earthquake is severe and sudden. The Palace buildings are completely destroyed, walls and floors collapsed, building blocks hurled a considerable distance, passages were impassable because of the large heaps of massive stones strewn there, culinary utensils hurled and accumulated at the base of the walls and crumbled, pithoi are compressed and squeezed along the west walls of the storerooms and break. All macroseismic data show that the horizontal seismic movements have a direction from east to west.

However, the coastal landscape does not seem to be affected, since the sea level remains stable and the natural harbour morphology unchanged. But the Palace and the town have suffered huge damage, are abandoned, and the site is deserted.

10.6. The Postpalatial period (Late Minoan IIIA to Late Minoan IIIB) (1450 BCE to 1200 BCE)

Thirty to forty years after the catastrophe, the inhabitants come back again and settle in the slopes of the northwest hill and the hill of Agios Antonios. They built ground-floor houses with few rooms, after cleaning the ruins and reusing the construction materials of the destroyed Palace (Zoitopoulos, 2012). However, in the nearby Minoan Palaikastro, 11 km to the north, life continues even after the LM IB destruction. The town

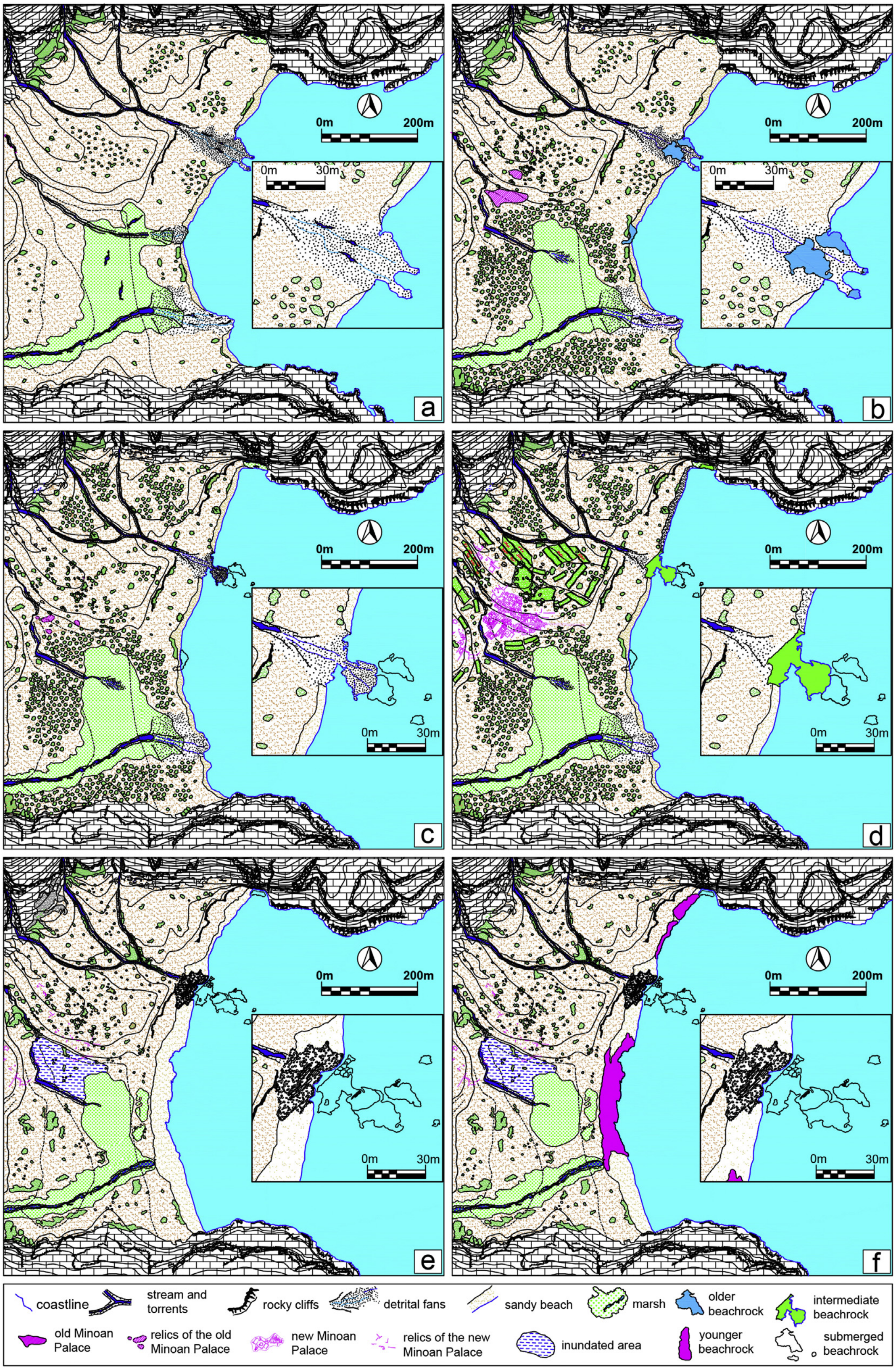

Fig. 9. Palaeoshoreline reconstruction of the Kato Zakros bay when: (a, b) sea level was −3.90 ± 0.30 m lower than at present: (a) Prepalatial period (ca. 2000 BCE) and (b) Protopalatial period (ca. 1900 BCE to 1600 BCE), (c, d) sea level was at −2.85 ± 0.30 m: (c) end of the Protopalatial period (ca. 1600 BCE) and (d) Neopalatial period (ca. 1500 BCE–1450 BCE), (e, f) sea level was at −1.25 ± 0.05 m: (e) end of the Postpalatial period (ca. 1200 BCE) and (f) from the end of the Postpalatial period to the late Venetian times (ca. 1200 BCE to 1604 CE).

was built during the LM II and LM IIIA1 periods (1450 BCE to 1400 BCE) and destroyed by fire in the beginning of the LM IIIA2 period (1400 BCE to 1320 BCE). An extensive reconstruction follows during the Lμ IIIA2 and LM IIIB periods. The town is entirely destroyed by earthquake in the middle of LM IIIB period (ca. 1250 BCE), and is abandoned forever (MacGillivray & Sackett, 2010). With this seismic event, the destruction and abandonment of many coastal Minoan sites on the north and east coast of eastern Crete is likely linked.

However, the main effects of this seismic sequence are the vertical subsiding movements and the change in sea level all along the coast of the island. The coast of Kato Zakros submerged by 1.60 m and the western coastline of the bay retreated inland by 15 m to 35 m. The natural harbour morphology in the northern part of the western coast of the bay disappeared below the sea. The sea level change caused the rise of the groundwater level, inundating the ruins of the deserted Palace (Fig. 9e).

10.7. From the late Postpalatial period to the late Venetian times (1200 BCE to 1604 CE)

Throughout this period sea level remains stable at −1.25 m and the younger beachrock band forms along the entire length of the western coast (Fig. 9f).

At the northernmost tip of eastern Crete, in the sheltered bay of Agios Isidoros, during the fourth century BC is founded the Sanctuary of Athena Samonio. The temple is at a distance of 10 m from the shoreline of that time and the sea level remained stable at −1.25 m.

The fish trap situated on the north coast of Kato Zakros was carved by a local fisherman, influenced by the manner of fish capture and preservation that was followed throughout Crete (Mourtzas, 2012a, b), in a period of the Roman domination of the island where eating of fish had become a passion (Davaras, 1975). The fish trap was probably supplying the Roman villa with remains of a hypocaust in Epano Zakros with fish, several kilometers inland from the gulf of Zakros (Sanders, 1982).

The coast of Kato Zakros bay seems to have subsided by 0.75 m, from 1.25 m to 0.50 m, during the 1604 seismic event (Mourtzas, 2012a, b). The devastating earthquake (34.9°N, 24.9°E) with maximum intensity VII–VIII and magnitude M = 6.0 (Papadopoulos, 2011) or M = 6.8 (Papazachos & Papazachou, 1989) is included in the seismic sequence of August and September 1604, which caused the ground settlement in Heraklion and noticeable subsidence of the east coast of Sitia region and mainly in Itanos, according to testimonies (Giannaris, 1889; Stavrakakis, 1890; Georgiades, 1904; Zoudianos, 1960).

The subsidence of the coast of Kato Zakros caused the younger beachrock band to submerge and the coast to shrink even more by 20 m to 35 m.

10.8. The last 400 years

In this period the sea level is 0.50 m lower than at present, most of the younger band of beachrock is submerged, the rock-cut fish trap lies below the sea level and is not used any more, the level of the groundwater is even higher, inundating a significant section of the southern lowland zone of the Palace, the coastal springs of the northwest edge of the bay discharge underwater, and the valley of Kato Zakros is occupied periodically by farmers who cultivate mainly in the lowland section. As the remains of ancient buildings hinder cultivation in the hilly area, they remove building materials for construction or retaining successive terraces. By digging a few wells and utilizing the scanty streams, the cultivated areas are gradually expanded, causing more damage to the Minoan ruins (N. Platon, 1974). During this period, it seems that the natural cavity of the northern coast is slightly shaped to be probably used as a fish trap, in memory of the rock-cut structure located a few meters to the west.

The last sea level change by 0.50 m is likely sudden. The morphology of the submerged tidal notch suggests a short period of stability of the sea level and an abrupt change to the present stand.

The topographic drawing of Hogarth (1901) depicts the area in the beginning of the last century. The position of the shoreline in 1901, as shown in the drawing in relation to buildings and cliffs of the northern part of the western coast, seems to coincide with the present coastline. This fact leads to the conclusion that most recent change in sea level occurred before the early twentieth century.

11. Conclusions

In this paper we have studied the geomorphological and archaeological markers encountered in the bay of Kato Zakros. The correlation between them and the comparison with the defined and dated sea levels of the entire coast of Crete during the Late Holocene (Mourtzas et al., 2016), highlighted the dynamic environmental changes during the human presence in the site.

The earliest sea level at −4.00 ± 0.30 m is related to the Protopalatial period of the Palace (ca. 1900 BCE–1600 BCE). The change in sea level from −4.00 ± 0.30 m to −2.85 ± 0.30 m that follows, is abrupt and is associated with the neotectonic upheavals in the area of the southern Aegean that accompanied the eruption of the Thera volcano around 1600 BCE.

The sea level stand of −2.85 ± 0.30 m seems to correspond to a short period of stability between 1600 BCE and 1450 BCE, assuming that the change is connected with the seismic disaster at the end of LM IB period (ca. 1450 BCE). The devastation of the Palace and the town during the Postpalatial period (ca. 1450 BCE–1200 BCE) could reasonably be attributed to the submersion of the natural harbour morphology, thus lacking its comparative advantage provided by the location. However, the sea level stand of −2.70 ± 0.30 m was dated in central and eastern Crete around 1220 BCE, by comparison with the corresponding 14C dated sea level of western Crete (Pirazzoli et al., 1982; Pirazzoli, 1986; Mourtzas et al., 2016). This chronology is consistent with the end of the LM IIIB period (ca. 1250 BCE–1200 BCE), which is largely coincided with the final demise of Minoan society, as defined and documented by potential earthquake archaeological effects at LM IIIB sites (Jusseret & Sintubin, 2012; Jusseret et al., 2013). At that time, a number of Minoan coastal sites, such as Kommos, Mallia, Sissi, Mochlos, and the nearby Palaikastro, were destroyed and abandoned forever. In Kato Zakros, the impact of the ca. 1200 BCE "earthquake storm" (Nur & Cline, 2000; Nur & Burgess, 2008) cannot be recognized, since around 1450 BCE that the Palace and the town were ruined and the site was desolated.

The new change in relative sea level around 1200 BCE is associated with the vertical coseismic subsidence by 1.60 m, from −2.85 ± 0.30 m to −1.25 ± 0.05 m. A long period of stability came after and lasted roughly 3000 years, until the 1604 CE earthquake. Because of this new coseismic vertical movement the land subsided by 0.75 m and the new sea level stabilized at −0.50 ± 0.05 m. The latest change of 0.50 m appears that occurred before 1900 when sea level rose to the present stand.

The palaeogeography of the seafront of the Minoan town of Kato Zakros revealed a natural harbour morphology, today submerged, in the northern part of the western coast. Minoan vessels could approach the natural 'pier' and unload, so that being lighter they could be hauled on the beach. Goods, following the paved, monumental, harbour road that ended in the mooring area, were transported through the main NE gate of the Palace to the central court and from there to the storerooms. The submersion of the natural morphology of the bay occurred around 1200 BCE, that means 200 years later than the destruction of the new Palace and the town, and is related to a coseismic event after which the Minoan centres petered out.

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