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Fish tanks of eastern Crete (Greece) as indicators of the Roman sea level

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A R T I C L E I N F O

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A B S T R A C T

The ancient fish tanks and fish traps of Crete are relics of the Roman domination of the island; they were usually constructed near the major urban centers of that period. The direct relationship of their various functional characteristics with past sea levels and the relatively accurate determination of their construction dates establish them as sensitive indicators of sea level change through space and time.

The fish tanks presented in detail in this study, namely those of Matala, Chersonissos, Mochlos and Sitia and the fish trap in the gulf of Zakros, have all been reported, recorded and/or interpreted in regard to their operation by previous researchers. In the absence of a comprehensive interdisciplinary approach to the issue, uneven methodologies, inaccurate data and wrong measurements have led to erroneous conclusions about sea level during their operation and about the size and direction of vertical tectonic movements in eastern Crete during the Upper Holocene.

The present study is based on a new underwater survey, in the course of which the architectural and functional features of the ancient constructions were reexamined precisely; their depth from modern sea level was measured and their relationship with coastal landforms, indicative of a past sea levels, was investigated.

A review of their manner of operation and their modern submerged position allowed the definition of a Roman mean sea level 1.24 m ± 0.09 m below the present one. The submersion of the central and eastern parts of Crete – included in the same tectonic block with a total length of at least 150 km – at an average tectonic rate of 0.65 mm/year during the last 1900 ± 100 years occurred, as is shown by historical evidence, during a paroxysmal tectonic event, probably related to the strong earthquake of 1604.

1. Introduction

Due to their strategic position in the center of the Eastern Mediterranean, the coasts of eastern Crete were a cradle of development and culture from prehistory until the late Roman period. The numerous cities, settlements and constructions along these shores were closely related to the sea level and to coastal morphology – any changes in those aspects had a direct impact on the coasts' socio-economic development. The world-famous ancient coastal settlements of Matala, Kommos, Lassaia, Tsoutsoura, Myrtos, Ierapetra, Koufonisi (Lefki), Ampelos, Zakros, Palaikastro, Istron, Mochlos, Malia, Chersonissos, Nirou Chani and Amnisos were submerged during paroxysmal tectonic episodes which accompanied strong seismic events.

Although since the mid-14th century, numerous scholars have referred to changes in the island's coastline since antiquity and more specifically to the submersion of coastal sites, linking the phenomenon to periods of decline in Cretan civilization, they failed to clearly determine the phasing and chronology of such changes. Instead, their diverse research methodologies and the lack of a unified interdisciplinary approach caused increasing confusion over the years. The determination of the older sea levels and their dating are essential both in reconstructing the ancient coastal morphology and in understanding the historical topography, the very setting in which ancient civilizations flourished over time. The fish tanks dating to the Roman occupation of Crete and scattered along the eastern coasts provide the possibility to accurately date an earlier sea level.

The various functional characteristics of Roman fish tanks, such as channels for sea water flow, entrances and sluice gates, walkways and compartment partitions, as described clearly by the Roman agricultural writers Varro and Columella, who specify details of their construction in "*de re rustica*", were necessarily in a direct relationship with the contemporary sea level. Their modern submersion constitutes a sensitive indicator of sea level change; as their construction period is estimated to range from the mid-1st

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century BC to the early 2nd century AD, the period during which that change occurred can be determined with relative accuracy.

As part of a short survey along the northern coasts of East Crete, Leatham and Hood (1959) located and sketched two submerged Roman fish tanks at Chersonissos and Mochlos. According to the authors, the theory that Crete rotated around an N–S axis, uplifting its western part and correspondingly submerging its east, is called into doubt by the dimensions of the submersion suffered by these two tanks. They recorded the Mochlos fish tank's floor at a depth of 1.50 m, and its counterpart at Chersonissos at a depth of 2.0 m. Thus, they concluded that the more easterly fish tank at Mochlos was submerged by 0.50 m less than that at Chersonissos to the west.

Further east, at the seafront of Sitia, Davaras (1974) reports ten almost totally destroyed Roman fish tanks. He describes part of the most southern one in detail, stating that its modern location proves coastal uplift by about 1.40 m over the last 2000 years. Most of its inclined floor is now located above the sea level, while their seaward part does not exceed a depth of 0.70 m. The channel on the eastern, seaward, side of the tank, which permitted sea water to enter and exit its interior, was found 0.25 m above the modern sea level. According to the author, for the tank to have been functional during antiquity, the depth of the channel floor should have been located at least 0.10 m to 0.20 m below its contemporary sea level. Assuming that the sea level rose by about 1.0 m from the Roman period until today, Davaras (1974) claims that the land–sea relation in the area changed by only 0.40 m during that period.

At the site of Ferma, to the east of Ierapetra, Davaras (1975) reports an uplift of the land by 0.50 m, which does not exceed the corresponding 1.0 m rise of the sea level from Roman times until today on the southern coast of Crete. Describing a Roman fish tank at this location, he estimates the sea level change on the basis of the modern depth of the upper surface of the partition between the two compartments of the tank.

In a brief report on the fish tanks at Chersonissos and Mochlos, Flemming and Pirazzoli (1981) suggest sea level changes of 1.0 m and 0.60–0.70 m, respectively, from Roman times until the present. According to the authors, during the same interval, Zakros tank has submerged for 1.0 m, while the one in Ierapetra shows a rise of the relative sea level at 0.20 m.

Nakassis (1987) identifies the "fish tank" in the Gulf of Zakros at the easternmost extremity of Crete as a fish trap, and argues that sea level there has not risen by more than 0.80 m.

Seven out of eleven known systems of fish tanks and traps located by the southern cliff of the Gulf of Matala on the southwest coast of Crete were investigated by the present author (Mourtzas, 2012b). On the basis of the modern depth of their functional features, a Roman sea level 1.20 m below the present one was determined here.

2. Methods of investigation

This study presents the following Roman fish tanks in Crete: a sequence of three tanks on the eastern side of the promontory of Chersonissos and the fish tank at the coast of Mochlos, both on the northern coast of East Crete, the fish tank at Ferma on the southern coast of East Crete, the fish trap set in the steep and rocky north coast of the gulf of Zakros on the eastern side of the island, and seven out of eleven systems of fish tanks and traps along the southern cliff of the Gulf of Matala on the SW shore of Central Crete (Fig. 1).

The ancient constructions were explored, surveyed and their depths measured by underwater diving using scuba equipment. Geographic coordinates were recorded using a GPS device (Mio P560 PDA Navigation). All measurements were collected during periods of low wave energy, vertical and horizontal accuracy was assured by the use of metal bars with cm subdivisions and an

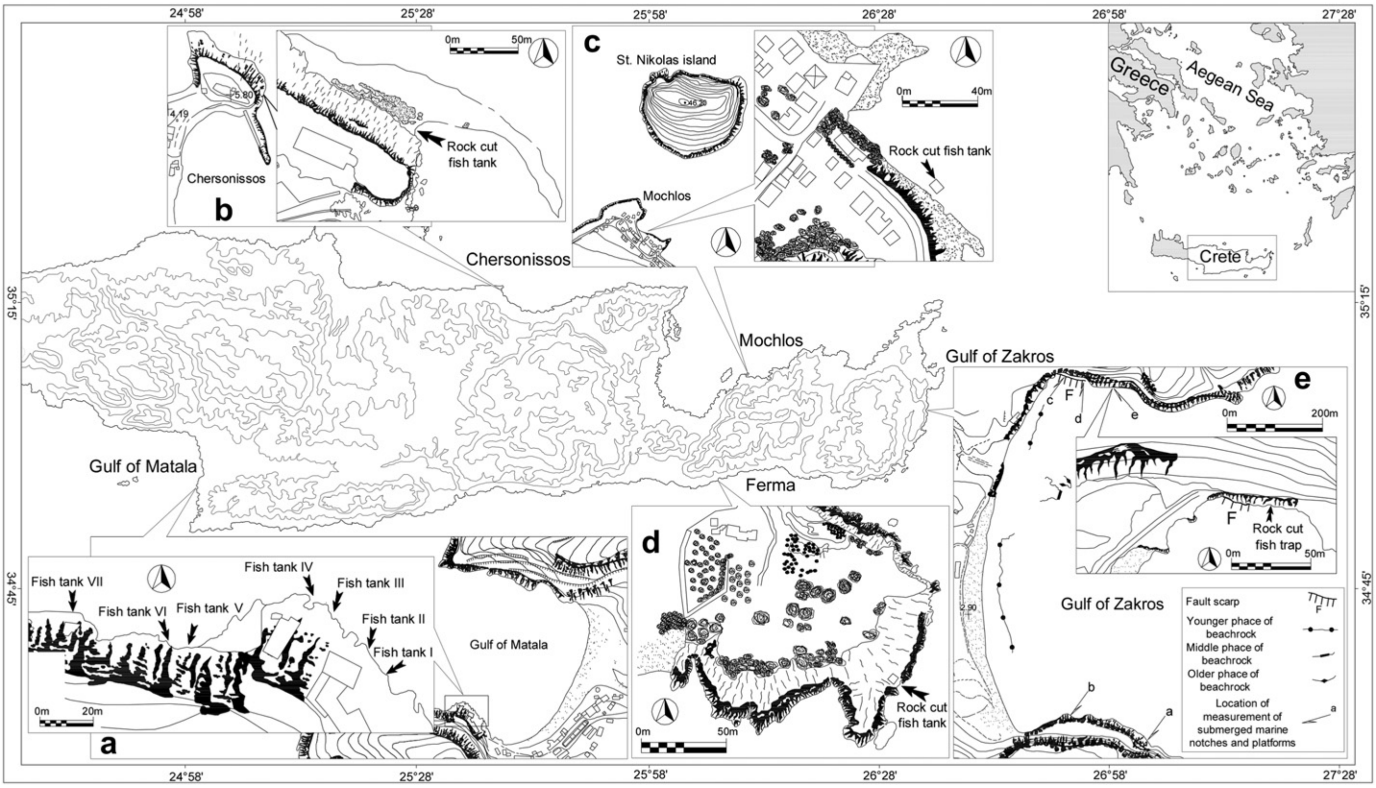

Fig. 1. Location map of the Roman fish tanks along the central and eastern coasts of Crete: (a) the fish tanks in the south cliff of the gulf of Matala, (b) the fish tank of Chersonissos, (c) the fish tank of Mochlos, (d) the fish tank of Ferma, (e) the fish trap in the gulf of Zakros.

inbuilt spirit level. Accuracy was further improved by multiple measurements. Records for tide effects were acquired from the database of Kasteli station (Eastern Mediterranean Tide Gauge Network – eMACnet).

3. Geodynamic setting

The neotectonic evolution of the horst structure of Crete, located in the central fore arc, appears to be directly connected with the convergence, collision and subduction of the lithospheric plates along the southern part of the Hellenic Arc (Angelier, 1980; Angelier et al., 1982; Bohnhoff et al., 2001; De Chabalier et al., 1992; Delibasis et al., 1999; Dewey et al., 1973; Jackson and McKenzie, 1988; Jost et al., 2002; Knapmeyer and Harjes, 2000; Le Pichon and Angelier, 1979; Le Pichon et al., 1995; Makris and Yegorova, 2006; Makris and Stobbe, 1984; McKenzie, 1970, 1972; Meulenkamp et al., 1988; Papanikolaou, 2010; Papazachos and Comninakis, 1978; Papachazos et al., 2000; Ritsema, 1970; Taymaz et al., 1990; Ten Veen and Kleinspehn, 2003) (Fig. 2a).

The lithospheric convergence is responsible for continued uplift of Crete in association with active extension is consistent with a Platt (1986) wedge where deep underplating above the subduction thrust can cause upper crustal extension.

During the Upper Miocene to early Pliocene, after a period during which Crete had been part of a wide uplifted landmass, the area – now occupied by the island – fragmented into a mosaic of tectonic blocks that are delimited by three successive groups of high (Bohnhoff et al., 2005) and low angle large-scale extensional faults (Fassoulas et al., 1994): a large-scale E–W trending fault group, mainly cutting the basement rocks or bound basement rocks and Miocene sediments; a large- and moderate-scale N–S striking fault group cutting the previous one and a third group which comprises kilometer-scale faults striking NE–SW and NW–SE which appear to be the youngest faults occurring on Crete Island (Fytrolakis, 1980; Kokinou et al., 2009; Le Pichon and Angelier, 1979; Ten Veen and Meijer, 1998). With the exception of short periods of stability or uniform behavior, these blocks are governed by differential large-scale vertical movements, resulting on the one hand in the renewal of the relief, and on the other in constant regression and transgression of the sea (Drooger and Meulenkamp, 1973; Fortuin, 1978; Fortuin and Peters, 1984; Gradstein, 1973; Meulenkamp, 1969, 1982; Meulenkamp and Zachariasse, 1973; Meulenkamp et al., 1977).

The uplift of the island begins during Upper Pliocene–Lower Pleistocene after a phase of stability during the Middle Pliocene, the marine terraces and deposits of coastal Pleistocene terraces formed at the corresponding stages of uplift (Angelier, 1980; Peters, 1985; Mourtzas, 1990; Kelletat, 1996; Peterek and Schwarze, 2004; Wegmann, 2008). During this period, the central and eastern parts of the island are divided into at least eleven tectonic blocks which are 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 and unstable uplift rates. The fragmentation and uplift of the island continued throughout the Pleistocene, but apparently at reduced and more uniform speeds (Mourtzas, 1990).

The reversal of the vertical uplift tectonic movements and the gradual sinking of Crete begins after the formation and emergence of the younger Pleistocene terrace surfaces. This submersion is not uniform. The central and eastern part of the island, dismembered in different tectonic blocks, presents an overall increasing submersion rate of tectonic blocks from west to east, with larger values of sinking to be identified eastern of Ierapetra's fault zone. The tectonic block that comprises the northern coasts of eastern Crete shows higher submersion rates than the respective of the southern coasts (Mourtzas, 1990).

During the Upper Holocene the overall submersion of Crete continues (Boekschoten, 1962, 1963; Hafemann, 1965; Kelletat, 1979; Mourtzas, 1990) (Fig. 2b), as a single block without the differential activations of intermediate tectonic zones that characterize the previous period (Mourtzas, 1990 and 2012b). With the exception of the gradual uplift of the small cape of Trachoulas and the area of Tsoutsouras in the south coast (Mourtzas, 1990), as well as the islets Strongylo and Koufonisi constituting the western uplifted part of an undersea tectonic ridge with a different tectonic behavior from the opposite submerged SE end of Crete (Montaggioni et al., 1981), the island submerged 3.60 m to 3.90 m over the last 4000 years (Mourtzas, 1990).

The western tectonic block is separated from the eastern one along the active grabens of Spili and Amari (Mourtzas, 2012b) during a paroxysmal tectonic event that occurred 1530 ± 40 yr BP, was uplifted by about 10 m and inclined northeastwards (Pirazzoli et al., 1982, 1996), while the eastern block continued to sink (Fig. 2b).

The intense disruption of the island and the continuous reversals of the vertical tectonic movements throughout the Upper Cenozoic evolved, with small intervals of compression, into an extended regime of tensile stress that developed inside an environment of collision and subduction of the lithospheric plates. These contrasts further complicate the relationship between the generative stress and strain and permit speculation about the primary role of isostatic mechanisms in the process of deformation. In other words, the effort by the "small" tectonic blocks to regain a position of equilibrium disturbed the overall geodynamic environment.

4. The fish tanks of Matala

The submerged fish tanks on the southern cliff of the gulf of Matala are impressive monuments of Roman antiquity not only in terms of their use and functionality but also in regard to construction technique. A detailed survey of the seven – out of a total eleven – well preserved submerged fish tanks along a ca. 140 m stretch of coastline (Fig. 1a) was carried out by the present author (Mourtzas, 2012b).

The fish tanks are entirely carved from bedrock, on a plan approximating a parallelogram or trapezoid (Fig. 3). The length of their sides varies from 3.45 m to 5.85 m, their area from 11.50 m^2 to 20.50 m^2 and the total volume of the extracted rock is estimated at 360 m^3.

A partition of uncut rock, 0.30 m to 0.50 m in width and 1.35 m to 1.50 m in height, separates the fish tanks along their length into two compartments, each 1.50 m to 2.30 m wide. The depth of the tank cuttings below the natural surface of the surrounding rock varies from 1.0 m to 5.0 m. In areas where the floors are formed by ellipsoidal erosional holes, the total depth is greater, varying from an additional 0.40 m to 1.95 m.

On the northern seaward side of each compartment, two entrances for the sea water were cut, with dimensions from 0.55 m × 0.70 m to 1.70 m × 0.80 m. Two channels, one at each entrance, from 1.40 m to 7.80 m in length, 0.60 m to 1.0 m in width and with a depth of 0.20 m to 0.60 m at their seaward northern ending and 0.90 m to 1.50 m at the entrance were also cut (Fig. 3b). At some entrances, pairs of carved grooves are preserved, 0.20 m to 0.40 m wide; they served to slide in and out sluice gates which prevented fish from escaping (Fig. 3b).

All around or along certain sides of the fish tanks, walkways are preserved, measuring 0.45 m to 0.70 m in width and 1.35 m to 1.50 m in height above the tank floor. Along with the partitions, they permit access at any point.

The fish tanks are covered by rock-carved roofs protecting the interior from the elements; the height of the tank from floor to roof varies from 2.70 m to 3.80 m (Fig. 3b).

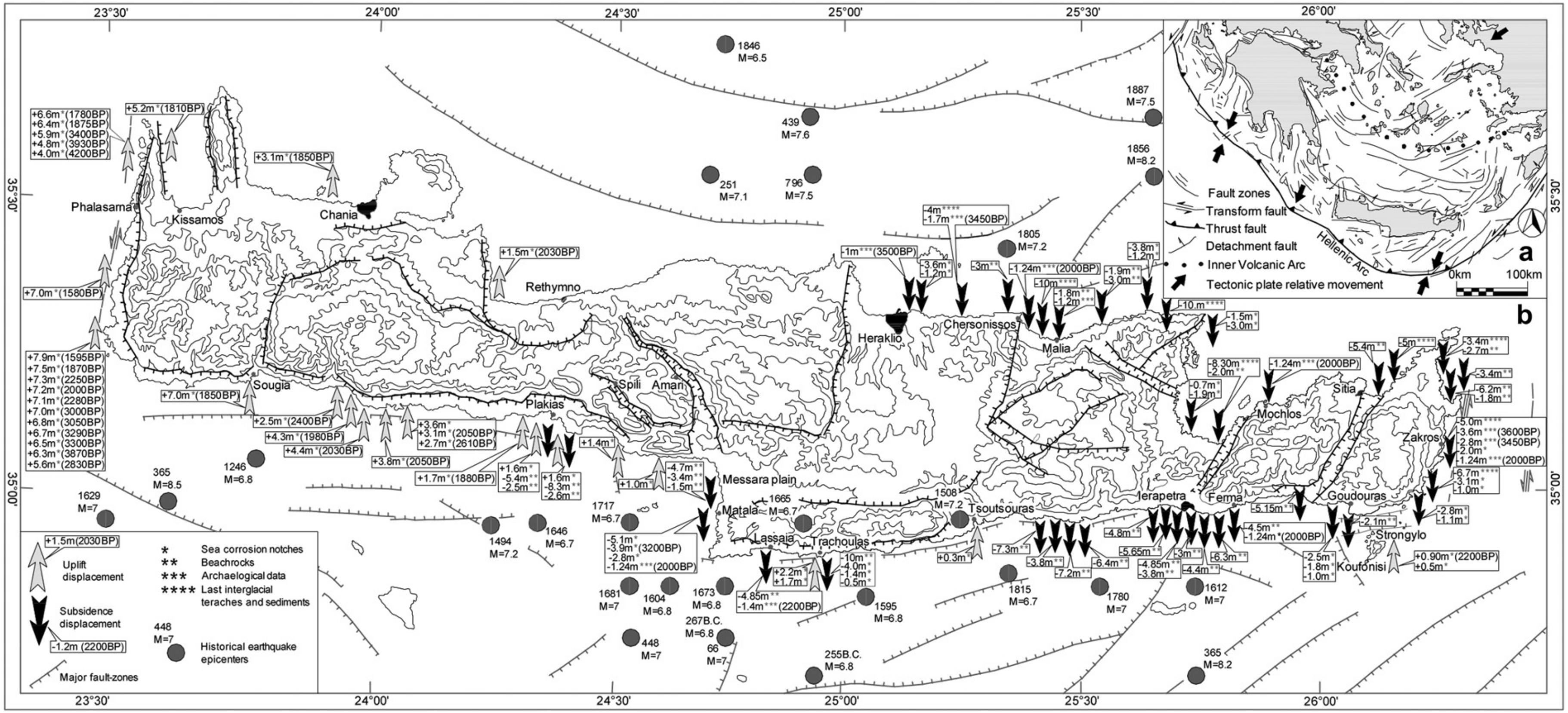

Fig. 2. (a) Tectonic sketch of the Hellenides and the actual Hellenic Arc and Trench system, according to Papanikolaou (2010). (b) Seismotectonic map of Crete, showing the main neotectonic structures of land and sea, the dating, size and direction of the vertical tectonic movements during the Holocene, according to Mourtzas (1990) and Pirazzoli et al. (1982), the epicenters of historic earthquakes according to Papazachos and Papazachou (1989) and the type of sea level indicator.

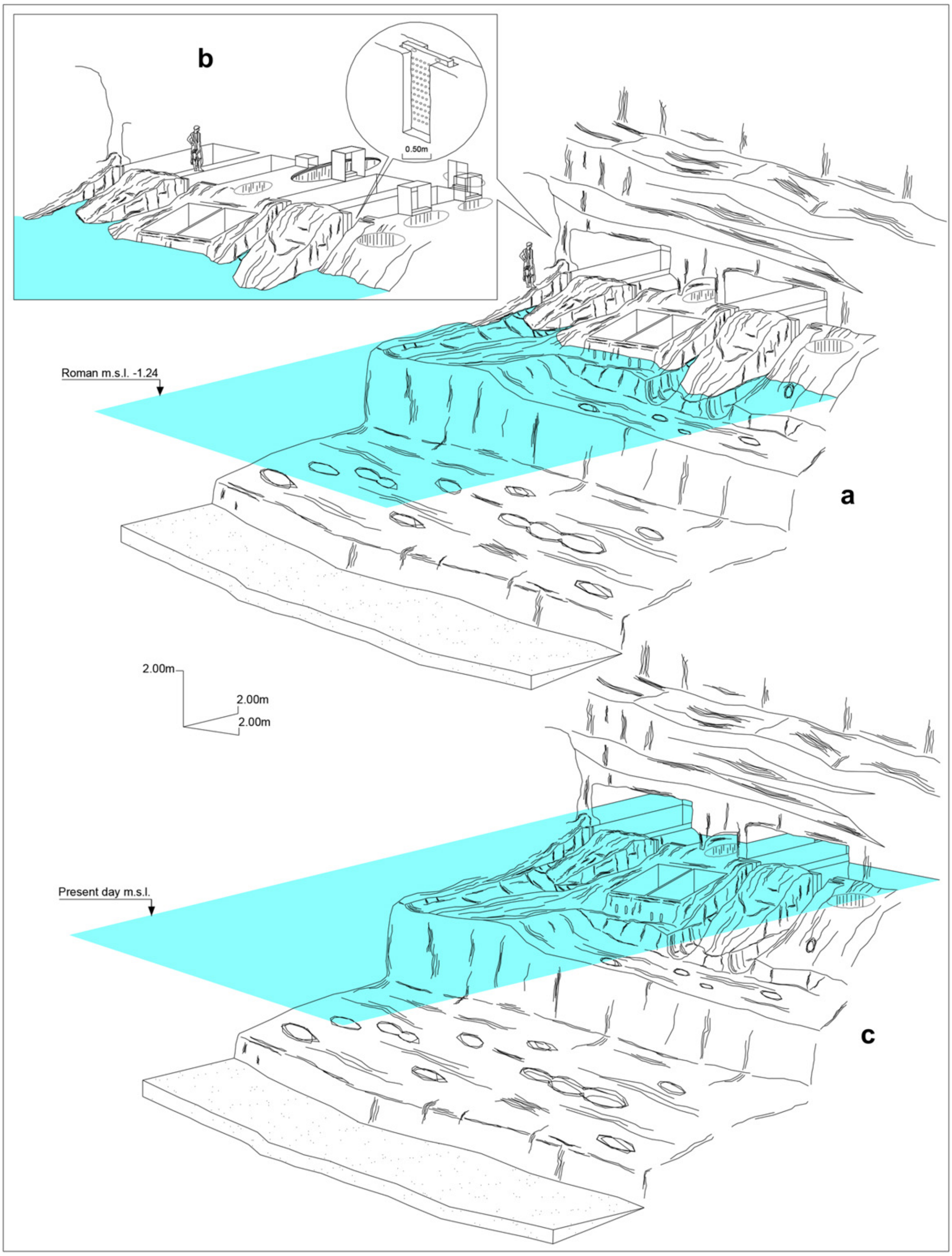

Fig. 3. Perspective plan of fish tanks V and VI on the south cliff of the gulf of Matala. (a) sea level during the Roman period, (b) detail of the fish tanks' internal, the carved grooves served to slide in and out sluice gates, (c) present sea level.

Openings carved into the west and east sides of some fish tanks slightly above the height of the walkways probably originally held wooden beams.

Rock-cut storage areas are either interposed between the fish tanks or cut along their southern and western sides. They are ellipsoidal cuttings measuring ca. 1.50 m × 1.0 m; their height from floor to roof is about 2.50 m. They communicate with the fish tanks through carved parallelogram-shaped openings with dimensions of ca. 0.70 m × 0.50 m (Fig. 3b).

The fish traps that accompany the fish tanks, and in some cases communicate with them, are ellipsoidal or rhomboidal erosional holes, their shapes slightly enhanced, measuring about 2.0 m × 1.50 m, and equipped at their northern seaward side with carved channels providing communication with the sea (Fig. 3b).

The depth of the fish tank floors varies from 1.55 m to 1.90 m below modern sea level. The upper surfaces of the rock-cut partitions and walkways are today at depths of 0.20 m to 0.65 m under the sea. The floors of the channels facilitating the flow of water into the interior of the tanks, cut into the marine terrace, are now from 1.45 m to 1.60 m below sea level (Mourtzas, 2012b).

On the northern, seaward, side of the fish tanks, three different earlier sea levels have formed three erosional marine terraces and notches that are submerged at depths of 1.20 m to 1.30 m, 2.80 m and 3.90 m. The frontal channels of the fish tanks were cut into the highest of those terraces, located 1.20 m to 1.30 m below the modern sea level. The location of these channels directly relates to their contemporary mean sea level estimated at 1.25 m below the present sea level, which formed that terrace.

5. The fish tanks of Chersonissos

A system of fish tanks carved from the rocky and compact diagenetic Miocene clays and conglomerates is preserved at the northeastern side of the Chersonissos promontory. It consists of three rhomboidal tanks, carved into the interior of a well-protected undersea recess set between an elongated reef and the modern shore, 80 m to the north of the Chersonissos breakwater (Fig. 1b).

The reef stretches in an SE direction for a length of 120 m, its surface located 0.10 m to 0.50 m below sea level, its perimeter forming a low but steep undersea escarpment. A sea notch −today submerged − was formed along the reef; its aperture is ca. 0.90 m and its bottom is located 1.15 m to 1.20 m below sea level.

The fish tanks are aligned along that escarpment, orientated towards the east and reaching a length of 11 m at a distance of 2.50 m from the modern shoreline. They were cut into the marine erosional terrace which is situated at a depth varying from 0.10 m to 1.0 m below sea level, while to the west of them small morphological elevations protrude above modern sea level to a height of 0.50 m–1.0 m.

The southern, larger fish tank consists of a trapezoidal cutting; its eastern seaward side is 5.0 m in length, the western one 4.60 m, the northern one 3.70 m and the southern one 3.60 m. The depth of the cutting from the rock surface varies from 1.70 m to 1.90 m in the southern and eastern parts, but reduces to 0.70 m in the eastern and northern parts. The fish tank communicated with the sea via two rock-cut channels: one at its southern end, 1.70 m long, 1.40 m wide and with a depth varying from 1.45 m at its central part to 1.65 m at its ending; the other to the north, 3.0 m in length, 0.70 m in width and 1.80 m in depth (Fig. 4).

An intermediate and smaller fish tank, measuring 2.30 m × 2.20 m and cut ca. 1.0 m into the rock, is separated from the previous one by a rock partition 0.25 m in width. A rock-cut channel at the northern ending of the tank, with a length of 2.30 m, width of 0.70 m and depth of 1.80 m connected it with the sea (Fig. 4).

The northernmost fish tank is today the most distant from the (modern) shoreline, as well as the most ill-preserved: its eastern, seaward part has been destroyed by marine erosion. It is separated from the intermediate one by a rock-cut partition 1.20 m wide and with a height of 0.65 m–1.0 m above the tank floor. The partition may originally have been even higher by ca. 0.25 m, as indicated by a preserved taller section with a width of 0.40 m (Fig. 4).

Leatham and Hood (1959) claimed that this narrower section of the partition was part of a wall, built of triangular tiles bonded with cement. It is more probable that this part of the partition was carved from the conglomerate bedrock, thus producing the visual impression of an artificial wall. The dimensions of the tank cutting are 2.30 m × 2.20 m with a depth of 0.80 m below the rock surface. At its southwest end is a carved extension measuring 0.80 m × 0.70 m. The fish tank communicates with the sea via a rock-cut channel located in the middle of its eastern, seaward side, 1.50 m long, 0.60 m in wide and 0.30 m deep (Fig. 4).

An almost circular erosional hole, 3.50 m in diameter and 1.0 m in depth from the rock surface, at a distance of 5 m east of the southern fish tank, is connected with the extension of the northern fish tank via a rock-cut channel (Fig. 4).

The depth of the fish tanks' floors varies from 1.80 m to 2.10 m below modern sea level; the depth of the erosional hole is at 2.0 m. The depth of the upper surfaces of the partitions between the fish tanks varies from 1.0 m to 1.20 m. The floor of the channels is located at depths of 1.80 m–2.0 m, with the exception of the channel floor at the SE edge of the southernmost tank, which is today located at a depth of 1.45 m (Fig. 4).

Based on the functional characteristics of the fish tanks in relation with the sea level of that period, for the fish tank to be operational, two conditions had to be met:

(a) In order for the southern rock-cut channel to be functional, i.e. permitting the flow of water into the southern, larger fish tank, the sea level of that period must clearly have been higher than 1.45 m below modern sea level, which corresponds to the modern depth of the channel floor.
(b) The sea level during the period of operation of the fish tank must have been more than 1.20 m below modern sea level, which corresponds to the modern depth of the upper surface of the partition between the southern and the intermediate fish tank.

According to the above, it results that the sea level during the period of the fish tanks' operation was lower than the present, namely by between 1.20 m and 1.45 m (Fig. 9).

6. The fish tank of Mochlos

The Mochlos fish tank is located in the sea, at a distance of 7.0 m off the coast, about 60 m SE from the modern jetty of Mochlos village (Fig. 1c). It is entirely carved into the red-colored Pleistocenic sandstone formation that lies beneath the breccia and conglomerate deposits on the nearby land. The sandstone formation gradually submerges below the sea level to a depth of 1.80 m at a distance of 23.0 m from the shoreline. At its end, it terminates abruptly, forming a steep escarpment, 1.0 m in height. At the deeper end, above the fish tank, the sandstone bears the marks of intense coastal erosion (Fig. 5).

The fish tank is a rhomboidal cutting with dimensions of 7.70 m × 4.60 m; its depth from the surface of the surrounding rocky sea floor varies from 1.10 m to 1.30 m. Its interior is divided into two compartments, each 4.60 m long, the western one with a width of 2.30 m and the eastern one of 4.20 m. They are separated by a partition of uncut rock with a width of 0.80 m at the base but only 0.30 m in the upper part. At the southern end of the partition is a carved recess with dimensions of 1.0 m × 0.70 m and a depth of 0.70 m; this was probably used for the temporary placement of fish or fishing equipment (Fig. 5).

The fish tank communicated with the sea via three carved channels, their width ranging between 0.90 m and 1.10 m. Two channels with a depth of 1.20 m below the surface of the rocky floor start at the NW side of each compartment and converge at a distance of 2.90 m into a unified channel 2.70 m long, 2.60 m wide and with a floor depth of 0.60 m. A third channel, 0.60 m deep, starts at the NE side of the eastern compartment and follows an NE direction for a length of 12.50 m (Fig. 5).

The floor of the fish tank is located at the depth of 1.90 m–2.10 m below modern sea level, with the exception of its shallower southern part, located at 1.60 m to 1.70 m. Those parts

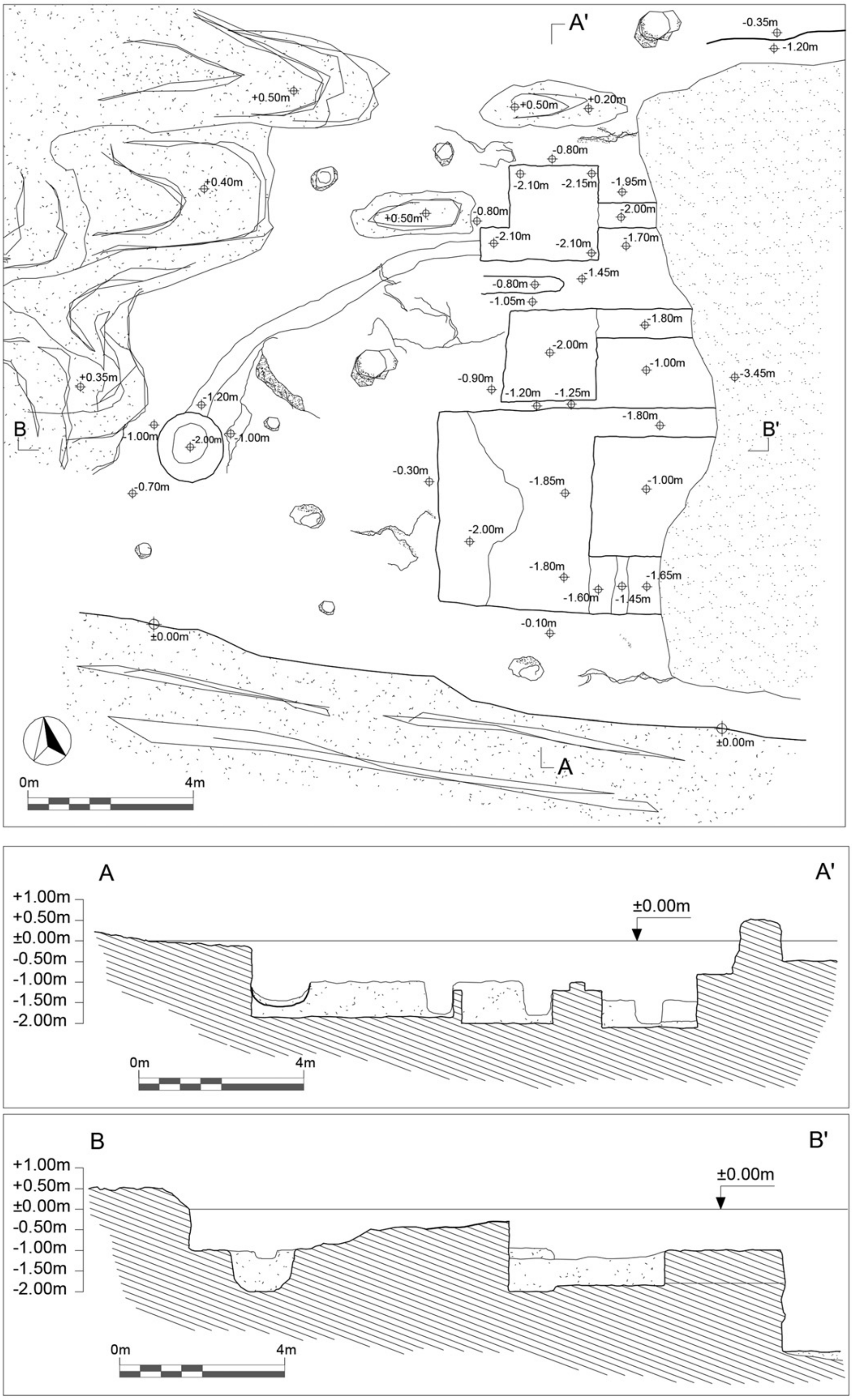

Fig. 4. Plan and cross-sections of the fish tank at Chersonissos. Depths at selected points are indicated.

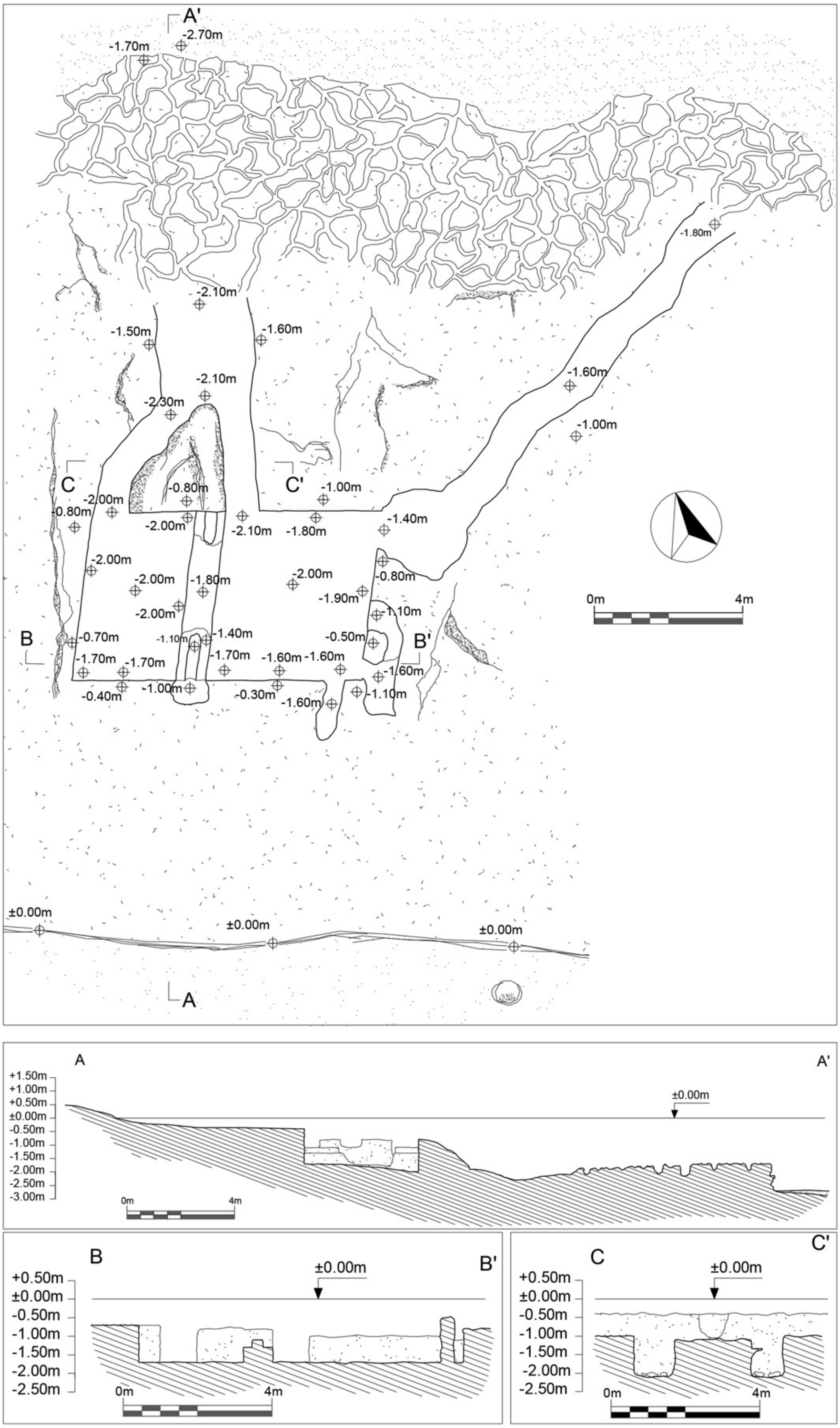

Fig. 5. Plan and cross-sections of fish tank of Mochlos. Depths at selected points are indicated.

of the upper surface of the internal partition that have not been eroded are located at a depth of 1.10 m. The floor of the recess at the southern end of the partition is located 1.0 m below modern sea level. The floors of the two frontal channels are located at depths from 2.10 m to 2.30 m. The depth of the floor of the third channel below today's sea level is 1.40 m where it enters the tank and 1.80 m at its far end (Fig. 5).

Based on the functional characteristics of the fish tank in relation to the past sea level, the sea level during its period of operation must have been at least 1.10 m lower than at present, as indicated by the depth of the upper surface of the internal partition, but not more than 1.40 m, the floor depth of the eastern side channel; in short, the ancient sea level was between 1.10 and 1.40 m below its modern counterpart (Fig. 9).

7. The fish tank of Ferma (Ierapetra area)

This fish tank is located at the steep SE of the Ferma promontory, the southward extension of a rocky ridge at the western edge of the gulf of the same name (Fig. 1d).

It is a deep trapezoidal cutting in the massive, thick-layered, post-Tortonian limestone, which dips towards the SE with an inclination of 40°. Cavities in the limestone have been filled with strongly lithified, terrestrial and coastal, Pleistocenic deposits of breccia and conglomerate. Davaras (1975) interpreted these deposits as a small artificial wall on the edge of the cutting, built to support a covering. The tank's SE, NW and SW sides are 5.50 m long, the NE side only 4.80 m. The maximum depth from the rock surface to the fish tank floor, at the southern side of the cutting, is 6.20 m (Fig. 6).

At the SE seaward side of the tank, two entrances were cut; their openings have lost their original shape and size due to intense sea erosion and rock failures. During the undersea survey, it was found that the entrances were not symmetrical. The initial width of the northern entrance seems to not exceed 0.50 m, its length is 1.20 m or less; the respective maximums for the southern entrance are 1.0 m and 1.40 m. On the opposite, NW side of the cutting a stairway of eleven steps with a total height of 2.40 m was cut into the rock to facilitate descent into the interior. A walkway is preserved around the fish tank's perimeter, 0.40 m to 0.50 m wide on the NE and SW sides and up to 0.80 m on the SE and NW ones (Figs. 6 and 7).

The interior of the tank is divided into two compartments of equal size, each 3.40 m × 2.10 m, separated by a 0.40 m wide rock-cut partition. The undersea survey revealed an additional 0.50 m wide partition, perpendicular to the main one, separating the SW compartment into two smaller compartments with dimensions of 2.10 m × 1.90 m to the NE and 2.10 m × 1.20 m to the NW (Figs. 6 and 7).

The underwater survey also revealed that the tank floor and the inner wall surfaces below the top of the partition and the perimeter walkways had not been finished, with the exception of the NW part of the NE compartment where vertical sides and a flat floor have been carved. Therefore, the depths of the compartments below the upper surface of the partition vary.

The depth of the NE compartment is 1.20 m and its floor is today located 1.55 m below sea level in its SE part; the respective depths in its NW part are 0.45 m and 0.80 m. The depths of the sub-rooms of the SW compartment are 1.05 m and 0.65 m, while their floors are 1.40 m and 1.0 m below modern sea level, respectively (Fig. 6).

The upper surface of the fish tank partition, where preserved, lies 0.35 m below present sea level. The upper surface of the perimeter walkway is between 0 m and 0.50 m underwater. The entrances of the fish tank are also submerged below the modern sea level, their floors located at a depth of 0.50 m.

To the SE, seaward side of the fish tank, a well-developed marine terrace with the corresponding notch at its edge was formed by a past sea level. A 5.0 m wide marine terrace lies at depths between 1.0 m and 1.40 m. This is followed by an undersea slope inclined by about 20° for a length of ca. 10 m. At its bottom and a depth of 5.10 m, the relief smoothens, forming the present sandy sea bottom (Fig. 6).

The lower parts of the two fish tank entrances, located today at a depth of 0.50 m below sea level, are about 0.50 m above the shallower NW edge of the marine terrace. This height difference indicates that there was no direct relationship between the entrances and the past sea level that created the terrace (Figs. 6 and 7). The flow of water in the interior of the fish tank was ensured by the continuous intense waves prevailing at the exposed and steep SE cliff of the Ferma promontory.

8. The fish trap in the Gulf of Zakros

The Zakros fish trap is an entirely submerged rock-cut structure located off the steep northern shores of the gulf of Zakros (Fig. 1e). It is cut into a coastal deposit of red sandstone of Pleistocene age that covers the coast's underlying limestones; at a distance of 10 m from the shoreline they are submerged under 3.10 m of water. Davaras (1974), as well as Flemming and Pirazzoli (1981) noted the structure's existence but interpreted it as a fish tank, whereas Nakassis (1987) describes and characterizes it as a fish trap.

The Zakros fish trap, today in a poor state of preservation, consists of a roughly carved rhomboidal cutting. The cutting was based on the enlargement and shaping of preexisting marine erosional cavities. Two elongated open fissures were used as a basic starting point for forming its western side, the entrance and the access channel. The cutting's overall dimensions are 3.50 m × 2.80 m; its depth from the surface of the adjacent rocky sea bottom varies between 1.60 m and 1.75 m. The width of the southern and western sides of the tank is 0.35 m and 0.60 m, respectively. Their height from the floor, assessed from preserved sections is 0.75 m on the southern and 1.0 m on the western side (Fig. 8).

The western side of the tank is equipped with a narrow entrance, 0.90 m wide and 0.65 m deep. From it extends a trapezoidal rock-cut channel, ca. 7.0 m in length, its width increasing from 1.0 m near the entrance to 3.20 m at its westward end. The channel's floor dips strongly towards the S and its depth from the surrounding sea bottom does not exceed 0.50 m (Fig. 8).

The tank floor is located at a depth between 1.70 m and 1.75 m under the modern sea level, with the exception of its central part where the floor of the erosional holes is at depths from 1.85 m to 2.0 m. The upper surface of the southern and western sides of the tank is located at depths of 0.95 m and 0.90 m, respectively. The upper surface of the southern side of the channel, where preserved, is located at depths ranging from 0.90 m to 1.0 m. The depth of the channel is 0.50 m to 0.60 m in the northern part, but its southern part, the floor of the expanded natural fissure, is 1.45 m below the present sea level (Fig. 8).

The fish trap is carved into a ca. 4.0 m wide marine erosional terrace, submerged to a maximum depth of 0.80 m below modern sea level.

Based on the functional characteristics of the fish trap and their necessary relationship with the contemporary sea level, three conditions had to be met for the trap to function:

(a) For the rock-cut channel to be functional, permitting water to flow into the tank interior, the sea level at its time of operation must have been less than 1.40 m below the present one, as that is the depth of the channel floor at its entrance.
(b) The sea level during the trap's period of operation must have been above the level of the tank entrance, located at 1.30 m below the present sea level.

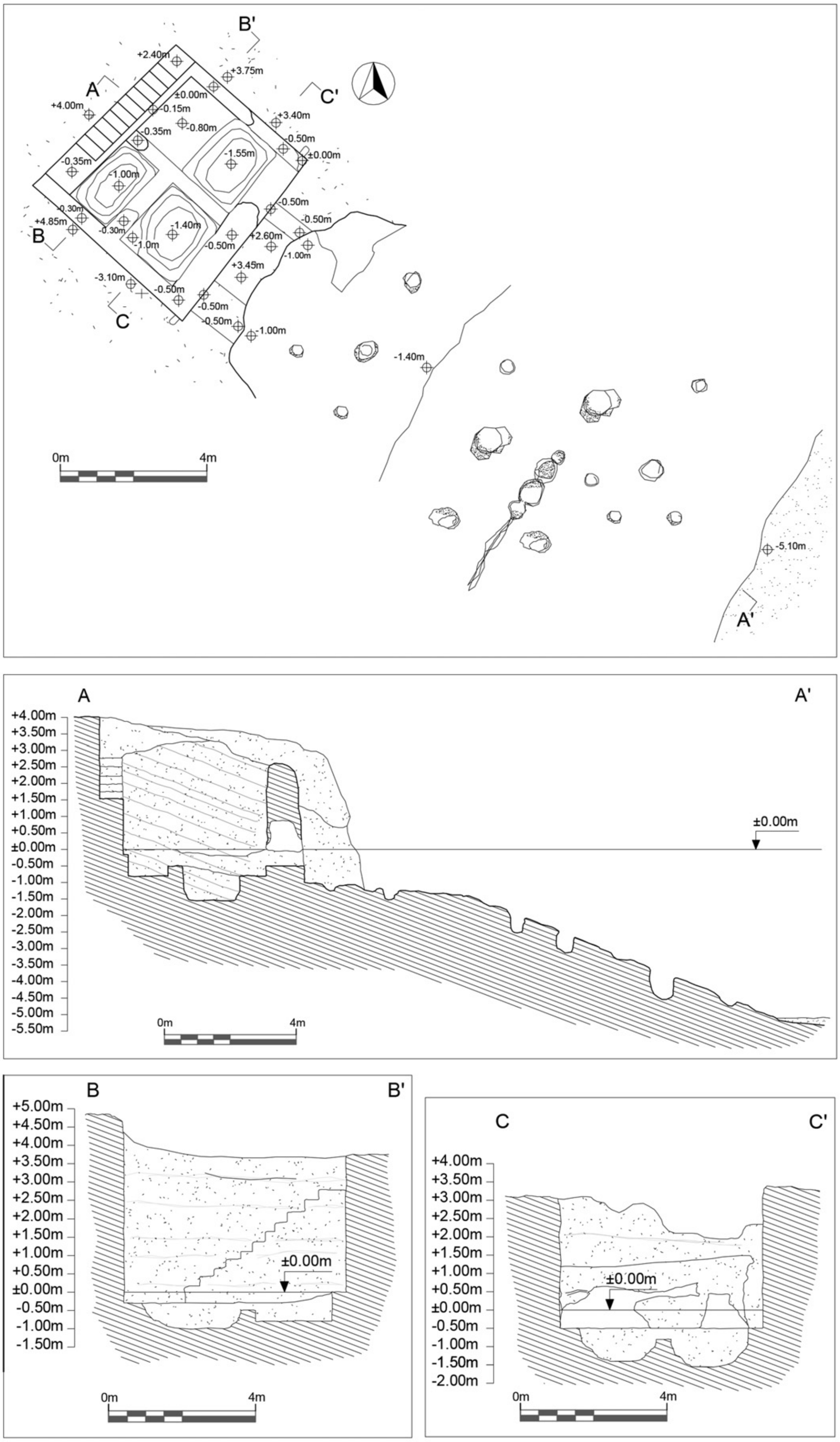

Fig. 6. Plan and cross-sections of fish tank of Ferma. Depths at selected points are indicated.

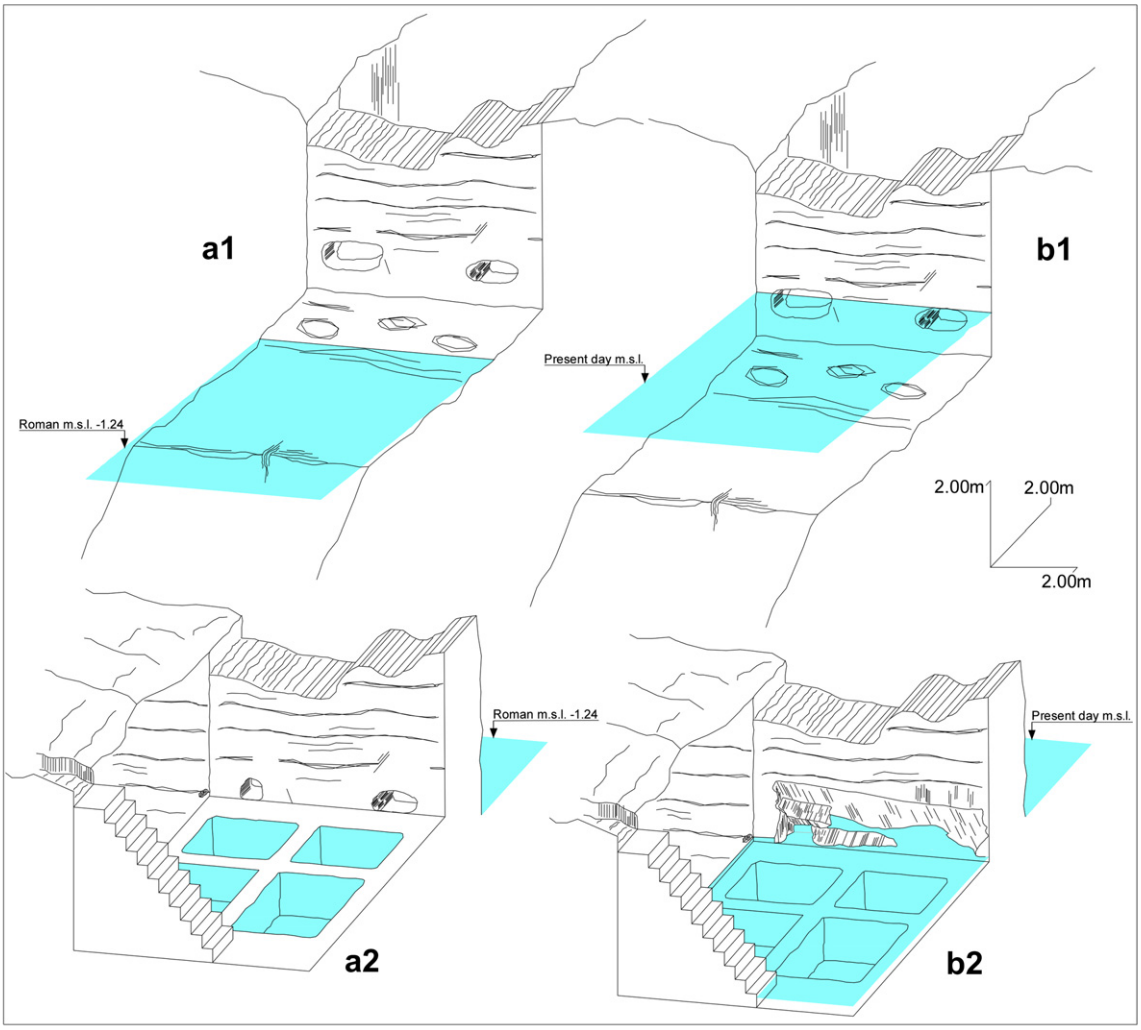

Fig. 7. Perspective plans of fish tank of Ferma. (a) sea level during the Roman period, (b) present sea level. (a1), (b1) external view and (a2), (b2) interior view.

(c) For the tank or trap to operate properly, the sea level must have been lower than the upper surfaces of its southern side and of the channel, which today are located at depths between 0.95 m and 1.0 m.

According to the above, it can be concluded that the sea level during the fish trap's period of operation was lower than at present, at a level between 1.0 m and 1.30 m (Fig. 8).

A correlation of the fish trap itself with marine landforms created by an older sea level shows that the western part of the north coast of the gulf of Zakros, formed by an extended E–W mirror of fault, has undergone local deformation. On the steep and rocky southern and northern coasts of the gulf, marine terraces and notches have been formed from past sea levels. On the southern limestone coast, a well-developed marine notch has been created at a depth of 1.0 m (Fig. 1e, sites a and b); on the western part of the northern coast the same notch can be observed along the mirror of fault at a depth of 1.45 m (Fig. 1e, site c). Further east, two marine terraces are located at depths of 1.40 m and 2.0 m, respectively (Fig. 1e, site d). They have been created in cohesive coastal deposits of Pleistocene age which cover the fault surface; it is these deposits into which the fish trap was cut. Even further east, along the northern coast and beyond the influence zone of the fault, the marine notch is located at depth of 1.10 m (Fig. 1e, site e, Table 1). In addition, the beachrocks of the western sandy shore of the gulf are developed at depths analogous to those of the marine erosional landforms (Fig. 1e, Table 2).

9. Archaeological data for the dating of fish tanks

Roman fish tanks and fish traps in Crete were constructed close to important urban centers of that period, such as Gortyna, the capital of the province of Crete, Chersonissos, a key port on the northern coast, and Ierapetra, enjoying a similar position on the southern coast. As these cities flourished during the Roman period, they were equipped with extensive harbors, impressive public buildings, aqueducts and public baths, all accompanied by the growth of numerous secondary settlements in their surroundings. The fish tanks appear to have served the needs of smaller settlements, e.g. Mochlos, a fortified small Late Roman settlement on the north coast (Sanders, 1982), or a Roman villa several kilometers inland from the gulf of Zakros (Sanders, 1982) on the eastern extremity of the island.

The dating of the fish tanks derives indirectly from the age of the towns they served, as well as from other contemporaneous activities and installations in their broader vicinity.

The fish tanks of Matala appear to be contemporary with the Roman settlement, the quarry, the slipway and the rock-carved tombs submerged at depth of 1.80 m below present sea level on the

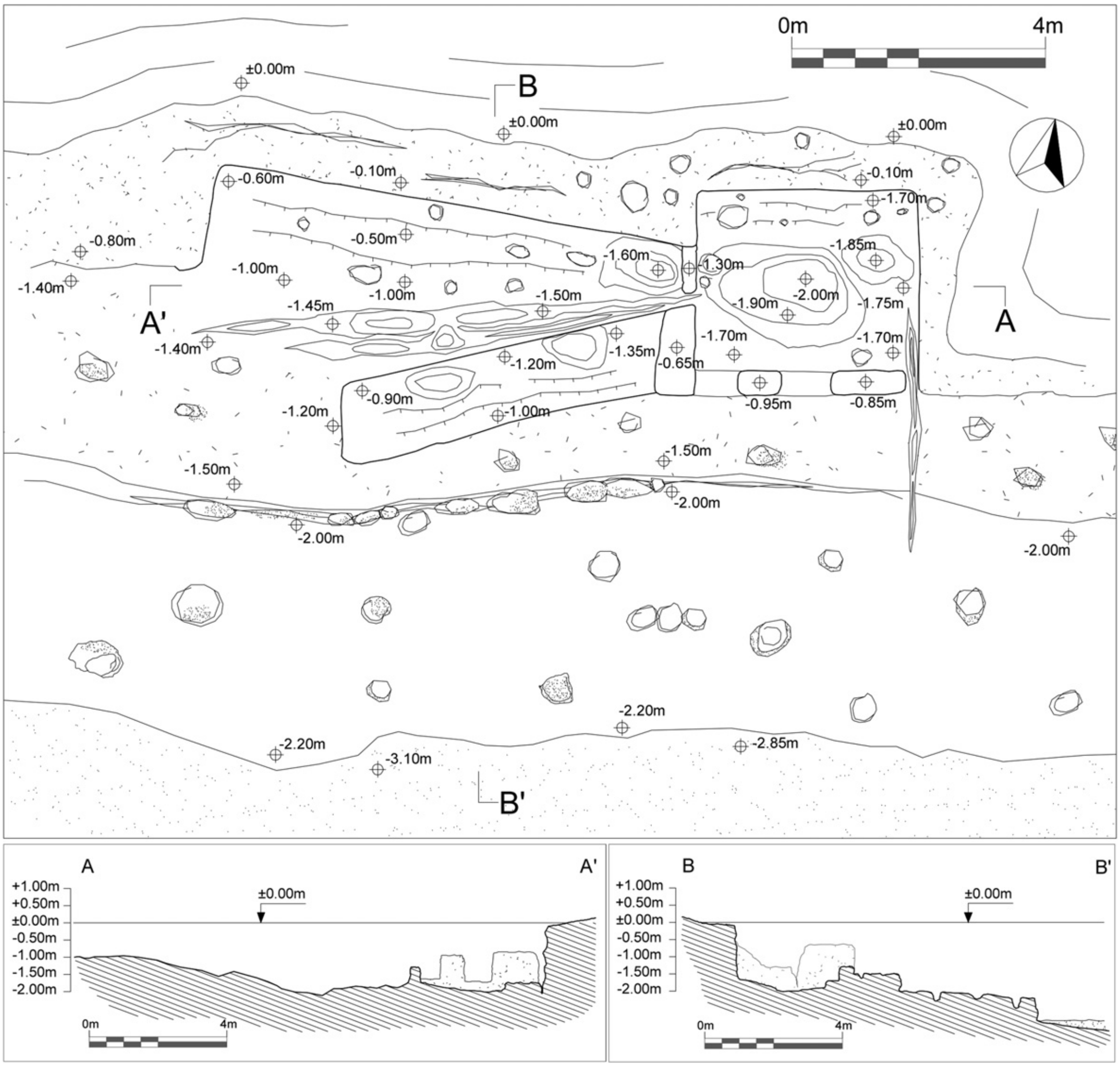

Fig. 8. Plan and cross-sections of fish trap in the gulf of Zakros. Depths at selected points are indicated.

northern coast of the gulf, all dated to the 1st and 2nd centuries AD (Blackman, 1973; Lembesi, 1969). The fish tank at Chersonissos is located at the terminal of the ancient city, on the NE side of the promontory of Kastri and at a short distance from the Roman defensive walls, the early Christian basilica, the now partially submerged Roman port, the ruins of residential houses and the pyramidal Roman marble fountain with mosaics of fishing scenes. In the area surrounding the Ferma site, 8 km east of Ierapetra, extensive Greco-Roman quarrying activity (Davaras, 1975) and the rock-carved salt pan located on a conglomerate projection into the sea 1 km to its east (Mourtzas, 1988b) indicate various small-scale industrial activities in the area during the Roman period. A large quantity of salt might have been required for the preservation of produce in the form of salt fish. The fish tank of Mochlos is just a few dozen meters from the boundaries of the Roman settlement. Finally, the isolated and coarsely constructed fish trap in the gulf of Zakros seems to have simply served the needs of a local fisherman.

10. Historical seismicity and its probable correlation with the submersion of the coasts of Crete

The rich seismic history of the island is described in hundreds of reports on macroseismical effects of historic earthquakes that affected the island from 2100 BC up to the beginnings of the 19th cent.

From the Late Prepalatial period up to the end of Minoan civilization, during a period of approximately 650 years, seven strong seismic events are reported (ca. 2100 BC, 1890 BC, 1750 BC, 1650 BC, 1500 BC and 1400 BC); attributed to them is the partial or entire destruction of the two architectural phases of the palace of Knossos and the palaces of Phaistos and Malia (Evans, 1921–1936; Georgalas, 1931; Marinatos, 1938; Platakis, 1950; Pendlebury, 1954; Sieberg, 1932). The strong earthquakes of 368 BC, 267 BC and 255 BC ($M = 6.8–7.7$) had destructive effects on the whole island (Papazachos and Papazachou, 1989; Platakis, 1950; Sieberg, 1932; Stavrakakis, 1890) (Fig. 2b).

However, the aforementioned seismic events predate the submerged man-made constructions described in this article, all of which are dated to the 1st and 2nd centuries AD; thus, their submersion must definitely postdate that period. After the Roman conquest of Crete and during the historical periods that followed, 35 strong earthquakes are reported ($M = 6.5–8.2$), causing very serious damage and destruction to the major cities of Crete and in the countryside (Ambraseys, 2009; DiVita, 1995, 1996; Mallet, 1854; Maravelakis, 1939; Papazachos and Papazachou, 1989; Perrey, 1848; Platakis, 1950; Raulin, 1867–1869; Sathas, 1867;

Table 1
Depths of the submerged marine notches and erosional terraces in the gulf of Zakros (below present sea level).

	Depth of marine notch and erosional terrace I (m)	Depth of marine notch and erosional terrace II (m)	Depth of sea bottom (m)
Southern limestone coast (a)	1.00	2.80–6.60	7.00
Southern limestone coast (b)	1.00	3.00–3.60	4.80
Northern limestone coast (c)	1.45	–	2.20
Northern limestone coast (d)	1.40–1.50	2.00–2.20	2.85
Northern limestone coast (e)	1.10	2.80–3.50	4.90

Schmidt, 1867; Sieberg, 1932; Spyropoulos, 1997; Stavrakakis, 1890; Xanthoulidis, 1925). Among them are the earthquakes of 46 AD, 55 ($M = 7.2$), 66 ($M = 7.0$), 168, the huge earthquake of 365 ($M = 8.2$) that caused the total destruction of ten cities in the island and was followed by a tsunami hitting coasts around the entire Eastern Mediterranean (Guidoboni et al., 1994; Stiros, 2010; Stiros and Drakos, 2006), the earthquake between 527 and 565 and the less severe earthquake of 666 ($M = 6.5$), many of whom seems to have hit Gortyna (Fig. 2b). The earthquake which occurred on 8 August 1303 seems to be one of the largest events in the history of the Mediteranean area with its epicenter to be located southeastwards Crete and similar effects to those of the 365 earthquake (Evangelatou-Notara, 1993; Guidoboni and Comastri, 1997).

Based on reports by Buondelmonti (1415) and Spratt (1865), who had visited the gulf of Matala no less than 450 years apart, the present author (Mourtzas, 2012b) concludes that the submersion of the fish tanks in the gulf of Matala occurred during that interval, arguing that the ancient constructions were submerged during a paroxysmal tectonic event that is linked with the 1604 earthquake. There is significant testimony linking that event with vertical subsidence movements along the coasts (Mourtzas, 2012b).

The 1604 earthquake was very strong, with a magnitude of 6.8R and an epicenter located at the southern coast of the Messara trough on the SW coast of central Crete (Papazachos and Papazachou, 1989). According to Kriaris (1930–1935), the earthquake was destructive. Stavrakakis (1890) reports that it caused ground subsidence in the island and the city of Heraklion was abandoned by its inhabitants. However, the submersion of the coasts appears to have affected the entire eastern part of the island. The eastern coasts of Sitia province and specifically the coast of ancient Itanos, 10 km north of the gulf of Zakros, were lowered considerably (Platakis, 1950).

11. Mean relative sea level of the Roman time in the central and eastern Crete

The channels cut to provide communication between the Matala fish tanks and the sea are cut into the erosional marine platform located at a depth between 1.20 m and 1.30 m below modern sea level, indicating that during their operation the mean sea level was 1.25 m lower than today (Mourtzas, 2012b). Additionally, at Ferma the relationship between submerged coastal landforms at depths between 1.0 m and 1.40 m with the entrances of the fish tank suggests a Roman sea level between those depths.

The accepted conditions, necessary for the fish tanks to operate, at the other study locations defined an older sea level (1900 ± 100 yr BP) below than the present one, namely by 1.20 m to 1.45 m in Chersonissos, 1.0 m to 1.40 m in Mochlos and 1.0 m to 1.30 m in the gulf of Zakros.

A comparison of the modern depths of those functional features of the fish tanks (and fish traps) that were directly related to the contemporary sea level shows that the minimum and maximum depths of the tank and channel floors and of the upper surfaces of the fish tanks partitions in Chersonissos and Mochlos are relatively larger than the corresponding measurements in Matala and Zakros (Table 3).

Based on those above differences, and on the clear fact that the sea level during the operation of the fish tank of Chersonissos must definitely have been below the depth of 1.20 m, which corresponds to the depth of the top of its partition, it could theoretically be proposed that the submersion of the northern coast of East Crete was greater than that of the southern and eastern parts of the island by at least ca. 0.10 m.

However, since these differentiations concern the individual functional features of particular fish tanks, but are not confirmed by plentiful measurements, e.g. at the numerous fish tanks of Matala (Mourtzas, 2012b), they are probably due to other factors, such as the specific morphology of the study areas and to the coastal landforms that were exploited during antiquity for the cutting of the constructions, erosion or destruction of their functional characteristics, or even local deformation, as seen in the gulf of Zakros.

Taking into account the evidence and all relevant caveats, we can conclude average ancient sea levels at 1.25 m below modern in the gulf of Matala, 1.20 m in Ferma, at 1.25 m in Mochlos, at 1.33 m in Chersonissos and at 1.15 m in the gulf of Zakros (Fig. 9).

Consequently, the average sea level 1900 ± 100 yr BP was 1.24 m ± 0.09 m lower than at present and the average rate of relative vertical tectonic movement between land and sea surfaces is 0.65 mm/yr since Roman times (Fig. 9).

12. Discussion

The prevailing view that the degree of submersion along the NE coasts of Greece varies from location to location following a general rate of increase towards the east relies on measurements that differ strikingly from those the present study is based on. For example, Leatham and Hood (1959) state that in the Mochlos fish tank "the depth of the floors of the pools lie about 1.50 m below the modern sea level" and "the seaward edge of the rooms now stands only 1.10 m above the floors", while they report the respective functional features of the fish tank of Chersonissos at depths of 2.0 m and 1.0 m. The careful measurements carried out in the survey underlying the present text show that the respective depths in the fish tank of Mochlos are 0.50 m and 0.60 m greater and that they coincide with their counterparts in the fish tank of Chersonissos,

Table 2
Depths of the submerged beachrocks in the gulf of Zakros (below present sea level).

	Depth of the younger phase of beachrock (m)	Depth of the intermediate phase of beachrock (m)	Depth of the older phase of beachrock (m)	Depth of sea bottom (m)
Southern section of sandy coast	1.40–1.45	–	–	2.00–2.30
Northern section of sandy coast	1.00	2.90–3.20	3.60	3.90

Table 3
Depths of functional characteristics of the fish tanks of Crete (below the present sea level).

	Depth of fish tank floor (m)	Depth of channel floor (m)	Depth of the upper surface of partitions (m)
Fish tanks of Matala	1.50 m–1.90 m	1.30 m–1.70 m	0.20 m –0.65 m
Fish tank of Chersonissos	1.80 m–2.00 m	1.45 m–1.80 m	1.00 m–1.20 m
Fish tank of Mochlos	1.60 m–2.00 m	2.10 m–2.30 m, 1.40 m–1.80 m	1.10 m
Fish trap of Zakros	1.70 m	1.0 m–1.50 m	0.65 m–1.0 m

which also differ from Leatham's and Hood's (1959) measurements in the order of 0.10 m to 0.30 m.

Likewise, the new undersea survey at the seafront of Sitia completely overturns the views brought forward by Davaras (1974) regarding an uplift of that coast by ca. 1.40 m from the Roman period up to the present. Davaras' "completely destroyed Roman fish tanks", in his view placed above sea level by uplift, are clearly ancient quarries, with typical signs of quarrying activity which would have taken place above sea level, while part of them now lies below sea level as the result of submersion. The systematic row of holes with a regular distance of 0.30 m found at the southern side of the quarry, which Davaras (1974) considered as sockets for the wooden beams supporting the fish tank roof, are actually the marks of wooden wedges used for the detachment of the extracted blocks of rock (Papageorgakis et al., 1994).

Beachrock is found along the eastern part of the coast of the gulf of Sitia along a length of 2 km, at a width of 12 m to 18 m on the sandy a further 70 m underwater, reaching a maximal depth of 6.30 m, thus revealing the continuous submersion of the coast throughout the duration of the Upper Holocene (Mourtzas, 1990).

Davaras (1975) suggestion of an uplift of the coast near Ierapetra by approximately 0.50 m since Roman times is based on an erroneous interpretation of the operation of the Ferma fish tank. Flemming's and Pirazzoli's (1981) estimate of a submersion by 0.20 m for the same fish tank is based on a similar misapprehension. The entry of water into the tank was ensured by intense wave action – there was no direct connection between the entrances of the fish tank and the ancient sea level. Continuous submersion in the area is indicated by two further factors: There is beachrock at a distance of 80 m from the modern shoreline in the gulf of Ferma, at a depth of up to 4.50 m below present sea level. Additionally, in the submerged part of the cohesive conglomerate protrusion at Koutsounari coast 1 km westwards, a Roman salt pan is submerged and notches associated with the sea level at its time of construction now lie 1.20 m below sea level (Mourtzas, 1988b, 1990).

Finally, the view held by Nakassis (1987), namely that the submersion of the fish tank at Zakros does not exceed 0.80 m, does not meet the conditions necessary to ensure the operation of that tank at the time of its construction.

Flemming (1978) assumes arbitrarily that the coast of Matala was initially uplifted by about 2 m after 100 AD and then submerged by 2 m, after 500 up to 1000 AD. On the contrary, all the data available indicate an overall submersion of the area by 5.10 m during Upper Holocene and by 1.24 m after 100 AD (Mourtzas, 1988b, 1990 and 2012b). Flemming (1978) also considers that the coast of ancient Lassaia on the southern coast of Crete remains stable after the Hellenistic period instead of a submersion by 1.0 to 1.40 m over the last 2200 years and an overall submersion of the area by 4.85 m during the Upper Holocene (Mourtzas, 1990; Mourtzas and Marinos, 1994); the coast of Ierapetra is submerged by 0.50 m over the last 1800 years instead of an overall submersion by 5.65 m during the Upper Holocene and by 1.24 m over the last 2000 years (Mourtzas, 1988a,b, 1990 and present study); the coast of Goudouras is uplifted by ca. 2.50 m instead of a continuous submersion to 2.50 m at least during the Upper Holocene (Mourtzas, 1990); the coast of the gulf of Zakros that remains stable over the last 1500 years instead of a submersion by at least 3.60 m from the Minoan period and 1.24 m from the Roman (Mourtzas, 1990 and present study). Finally, Flemming (1978) assumes that

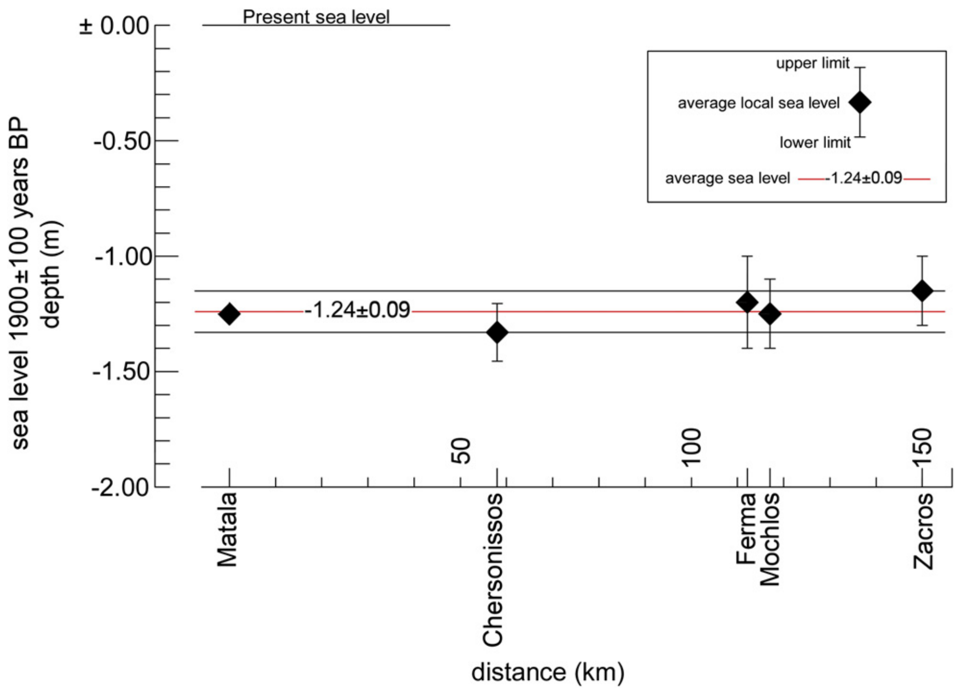

Fig. 9. Correlation between the average local sea levels, derived from the mean values of sea level conditions that should be met for the fish tanks to operate.

the coasts of Mochlos and Chersonissos are submerged by 0.25 m and 1 m, respectively, over the last 1900 years instead of a submersion by 1.24 m, as concluded by the present study.

The model suggested by Flemming (1978) for the eastern block of Crete indicates a tilting curved surface uplifted maximally in the southeast and submerged maximally in the northeast. This model is not consistent with the data presented above.

Lambeck (1995) attempting to demonstrate the significance of isostatic corrections in the change of the land–sea relationship in the Aegean region and examine quantitatively the contribution of vertical tectonic movements in this change, was based mainly on Flemming's (1978) erroneous data and model for central and eastern Crete. Using the nominal earth model and the eustatic sea level function estimates significant tectonic uplift at rates of up to 2 mm yr^{-1} in the SE part of Crete, while in a large part of the north coast east of Iraklion up to Sitia estimates tectonic uplift rates ranging between 0.7 mm yr^{-1} and 0.9 mm yr^{-1}. To justify the present submerged position of the ancient constructions along the north coast, at Amnisos, Nirou Hani, the coast of Malia and Mochlos claims that the north coast is also subject to tectonic uplift at rates smaller than the isostatic rates of opposite sign. As a result, according to Lambeck (1995), the result is a rising sea level relative to the land.

Fig. 2b, based both on previous studies (Boekschoten, 1962, 1963; Dermitzakis, 1973; Fytrolakis, 1980; Hafemann, 1965; Kelletat, 1979; Mourtzas, 1990; Pirazzoli et al., 1982) and the results of the present survey, illustrates both the continuous gradual submersion of the central and eastern part of Crete throughout Holocene to a depth of 10 m with tectonic rates of vertical submersion movements 0.65 mm/yr over the last 1900 ± 100 years. According to the glacio-hydro-isostatic sea level curve for the island of Crete (Lambeck, 1995, 1996), the relative sea level rise is over 1.50 m since 2000 years BP and over 6.0 m since 6000 years BP. This gradual sea level rise of ca. 1 mm/yr for the area is not consistent with the magnitude of submersion over the last 2000 years, the morphology of the stepped shorelines in front of the Roman fish tanks and the development in distinct phases of the extended beachrocks that require long periods of sea level stability and abrupt sea level changes between different phases (Pirazzoli, 1986; Furlani et al., 2010; Mourtzas, 1990 and 2012a). Moreover the prediction of the glacio-hydro-isostatic change of sea level in an intensively active tectonic area, such as central and eastern part of Crete, is overestimated 0.26 m at least, proving, as also Pirazzoli (2005) supports, that the rapid isostatic rates of glacio-isostatic models for active tectonic regions of central and eastern Mediterranean, are unrealistic.

Corresponding studies in the Central Mediterranean, concerning the Roman period and based on piscinae and other archaeological evidence, provide a mean sea level 0.58 ± 0.05 m below the present and an eustatic fluctuation not exceeding 0.15 m for the last 2000 years (Pirazzoli, 1976, 1979; Evelpidou et al., in press). This approach is contrasted with the results of Lambeck et al. (2004) that indicate a sea level rise of 1.35 ± 0.07 m on the Tyrrhenian coast and the conclusions of Antonioli et al. (2007, 2008) and Florido et al. (2010) that suggest a sea level rise of 1.60 ± 0.20 m from the Roman period up today in the Northeastern Adriatic area and on the Istrian and Dalmatian coasts, thus proving that also in this case, as well in Crete, the isostatic model seems to be impractical.

13. Conclusions

The dispersion of the coastal ancient rock-cut constructions for fishing and fish preservation along the coasts of central and eastern Crete, their construction and operation at a short historical period and their direct relationship with the sea level during the period of their operation, permit a straight comparison of their modern position, the direction and magnitude of the vertical tectonic movements and probable differentiations due to tectonic deformation from site to site.

During the Upper Holocene, the tectonic deformation at the front of the Hellenic Arc continues to be the main factor in the change of the land–sea relationship.

A paroxysmal tectonic event that occurred ca. 1530 ± 40 yr BP caused a massive uplift by some 10 m and tilted northeastwards a huge lithospheric block of 150 km–200 km length, including West Crete and the island of Antikythera (Pirazzoli et al., 1982, 1996). At the same time, the eastern part of Crete appears to have been under a different tectonic regime. Eastwards of the active tectonic grabens of Spili and Amari, the island submerged uniformly for 1.24 m ± 0.09 m during the past 1900 ± 100 yr, with an average tectonic rate of 0.65 mm/year. As the historical evidence shows, this submersion occurred during a paroxysmal tectonic event between 1415 and 1865 and is probably linked with the strong earthquake of 1604 (Mourtzas, 2012b). The total differential vertical tectonic movements at the ends of the adjacent tectonic blocks that delimit the active tectonic grabens of Spili and Amari during the Upper Holocene amount to 2.24 m (Mourtzas, 2012b).

The submersion of the eastern part of Crete is clearly smaller than its equivalent in the "aseismic" zone of the Central Aegean. In the area of the Cyclades, the coasts of Delos have submerged by a total of 2.15 m since the end of the Hellenistic period. This lowering occurred during two distinct successive phases of submersion, initially by 1.35 m and then by another 0.80 m (Mourtzas, 2012a).

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