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The ancient slipways and shipsheds of the Aegean: Accurate indicators of relative sea level change?

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Abstract
Ancient slipways are spread throughout the Aegean coastline, constitute an important part of Greek naval history and maritime tradition, and provide valuable evidence of the relative sea level (rsl) change from the period of their construction and use since their function required them to be situated at the water's edge. Geoarchaeological surveys of rsl changes in several coastal sites either revealed unknown slipways or offered some fresh insights into the functional features of sites previously published. The slipways here presented, albeit covering a wide chronological range from the Classical period to Modern times, follow similar construction and functional principles. The contemporary measured depths of the seaward end of the rock-cut sloping floors are interpolated into the curves of the rsl rise for the Aegean and allow us to conclude that slipways are good sea level indicators and suggest their functional height with an uncertainty not exceeding the tidal range.

Keywords Harbour works · Rock-cut slipways · Ancient shipsheds · Aegean Sea · Mediterranean Sea · Sea level rise · Rsl change indicator

1 Introduction

It was in 2013, when David Blackman, Boris Rankov and colleagues published a book, in which they gathered together and presented what was by then known about sites where shipsheds had been identified or proposed throughout the ancient Mediterranean (Blackman et al. 2013). Along with a catalogue of sites with summaries of the main features of shipsheds, they also provided detailed descriptions of the shipsheds, the way they functioned and how they were used, complementing the archaeological evidence with information from literary and epigraphic sources. Since then, only a few sites have been added to the Blackman, Rankov et al.'s catalogue [henceforth referred to as 'SSAM (2013)']: (a) Five rock-cut slipways at Boğsak in Isauria (Southern Asia Minor), which may include bollards for hauling small vessels out of the water (Harpster and Varınlıoğlu 2015; Jones et al. 2021, pp. 345–346). (b) A built slipway/shipshed of the Hellenistic period (second–second century BC) is reported by Sharvit et al. (2021, pp. 171–172) in the Hellenistic–Early Roman harbour of Akko (Israel). (c) Dündar and Koçak (2021, pp. 136–137) suggest that the evidence of four column shafts found in the inner harbour of Patara (Western Lycia), might indicate shipsheds, most probably built in the early Hellenistic period (forth–third century BC). (d) Höckmann and Öniz (2021) argue for a total of 294 slipways (of unknown date) on Dana Island (Rough Cilicia, Southern Asia Minor). These were first discovered by Varınlıoğlu in 2011, who hesitatingly suggested that they might represent ancient slipways. Now, however, Varınlıoğlu et al. (2017, pp. 53–55) question whether these features may have served either as slipways and building foundations and later as

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quarries or vice versa, though particular features could not definitely be identified as slipways for ships; Varınlıoglu and Esmer (2019) are also sceptical. Jones et al. (2021, pp. 353–7) has argued that the rock-cut inclined features lining the NW shore of Dana Island, probably dated to the Roman and Late Antiquity periods, rather resemble well-preserved quarries and building foundations found further inland, but it is conceivable that some of the sloped quarries were later used as improvised slipways for small boats. Öniz (2021) has a full discussion.

Ancient slipways are spread throughout the Greek coastline, geostrategically located on important sea routes. Slipways, covered slipways (shipsheds), *neosoikoi*, *neoria*, naval dockyard, base or station, *naustathmos*, or even *carenaggio*, regardless of their function, capacity and other—monumental or not—superstructures: they may have all used a sloping track for hauling out and launching various types of vessels (Blackman et al. 2013).

Geoarchaeological surveys of the relative sea level (rsl) changes in several coastal sites throughout the central and south Aegean either revealed unknown slipways or offered some fresh insights into the functional features of sites previously published. In this paper, new geoarchaeological data from nine sites of slipways and shipsheds are presented: four on the Island of Crete (Katholiko, Rethymno, Matala, Trypitos), three in the Cyclades (Keos Island: Poiiessa, Andros Island: Mandraki, Kimolos Island: Goupa and Remma) and two in the Saronic Gulf (Aegina Island, Lazareto Islet) (Fig. 1a, Table 1: columns A ÷ C). Of these, four sites (Katholiko, Mandraki, Kimolos and Lazareto) are now presented for first time. The rest of the sites (Rethymno, Matala, Trypitos, Poiiessa and Aegina) has been previously published and then included in the SSAM catalogue (2013, pp. 284–293, pp. 389–392, pp. 489–493, pp. 501–508, pp. 518–524 and related references therein).

The slipways here presented, albeit covering a wide chronological range from the Classical period to Modern times (Table 1: column D), follow more or less similar construction and functional principles. The rock-cut ramp of a slipway in most cases is well-preserved as no later additions or modifications have been made, and it provides therefore indisputable evidence of the slipway's position relative to the sea level at the time of construction.

The aim of this paper is to provide evidence on the relationship between slipways and sea level of the period of use, to stress the importance of shipsheds in determining and/or confirming former sea level stands, and to highlight why slipways are accurate index points of the rsl change.

2 Methods

The determination of the several sea level stands in the study areas was based on geomorphological indicators, i.e. marine tidal notches, marine terraces and various beachrock generations. The inferred sea level stands were dated using radiocarbon datings and good archaeological sea level markers and have been presented in previously published studies along with the curves of the mean rsl change for each study area (central and eastern Crete, eastern Peloponnese, and Cyclades) (Mourtzas et al. 2016; Kolaiti 2019; Kolaiti and Mourtzas 2020, 2023; respectively).

Ancient rock-cut slipways, although now partly submerged, were strictly related to the sea level at the time they were in use. The sloping floor of a rock-cut slipway was carved into the rock in dry conditions or probably slightly below mean sea level and its seaward end was within the intertidal zone of the sea level of the period of use in order to fulfil its function. Its contemporary position below the sea level provides robust evidence of the change in sea level and dates the former sea level.

The ancient shipsheds were mapped using satellite images (Google Earth Pro, v. 7.3.2) and high-resolution orthophotos at a scale of 1:500 (Ktimatologio S.A.). Plans were updated by field observations and supplemented by measurements of the depth of particular functional features (i.e. seaward and landward end of the sloping floor, slope gradient) of the ancient slipways (Table 1: columns E ÷ G). All measurements of depths were collected during calm sea conditions using mechanical methods (measuring tape and invar rod) and were repeated during different survey periods. To account for tides, observational data have been corrected for tide values at the time of the surveys with respect to mean sea level, using tidal data from the Hellenic Navy Hydrographic Service for the closest tide-gauge station for each study area (Table 1: columns H ÷ J). The effect of atmospheric pressure on the sea level was corrected using the meteorological data for the site at the time of the surveys (www.meteo.gr). Therefore, all measured depths reported herein correspond to depths below or above mean sea level (bmsl, amsl). Depths presented in previous studies and repeated herein are given without the above indication (bmsl, amsl), as it is not clear whether they have been corrected for tide and pressure at the time of surveys.

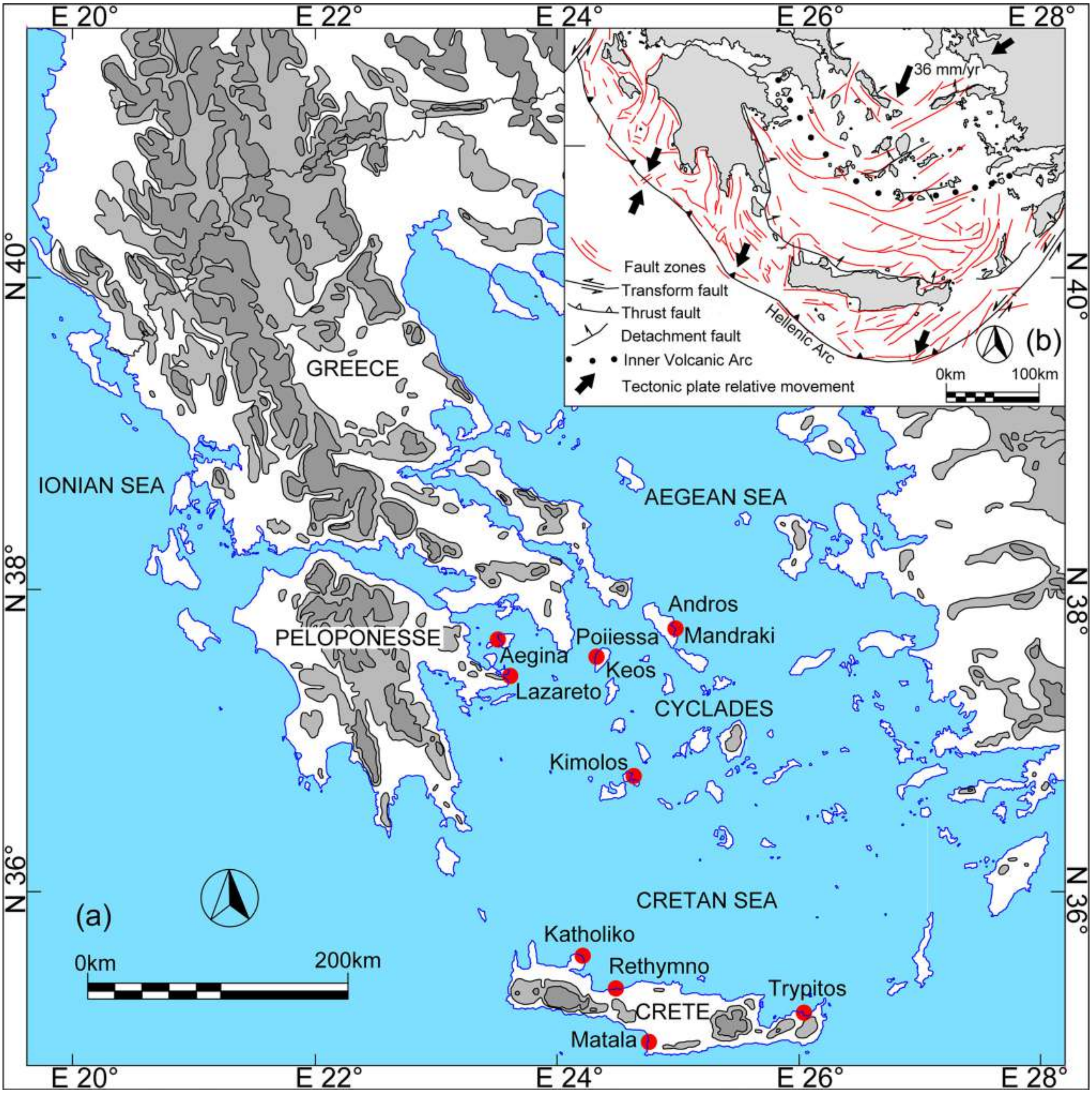


Fig. 1 **a** Location map of Greece with the locations of the shipsheds presented in this study. **b** Geodynamic framework of the Hellenic Arc depicting the main tectonic elements of the central and south Aegean region [after Le Pichon and Angelier (1979) and Jackson (1994), modified]

3 Geoarchaeological approach: results

3.1 Aegina shipsheds (Saronic Gulf)

At the southern smooth end of Kolona Hill (Aegina Island), in the northernmost of the three consecutive shallow embayments that comprise the southern part of the west coast of ancient Aegina's sea front, the closed harbour (*kryptos limen*) of ancient Aegina was shaped in *c*. 480 BC by the construction of a wall bounding its seaward sides (Welter 1938; Knoblauch 1972) (Fig. 2). The northern part of the wall starts at a distance of 20 m from the present coastline, after the remains of the walls of a parallelogram building, which is submerged up to a depth of 0.75 m bmsl, whilst a part of it protrudes above the sea about 0.23 m amsl (Fig. 3). The wall runs SW for 70 m and then turns at a right angle to the SE and ends after 140 m at an entrance-tower. Of the southeastern part of the wall, only the last part, about 60 m

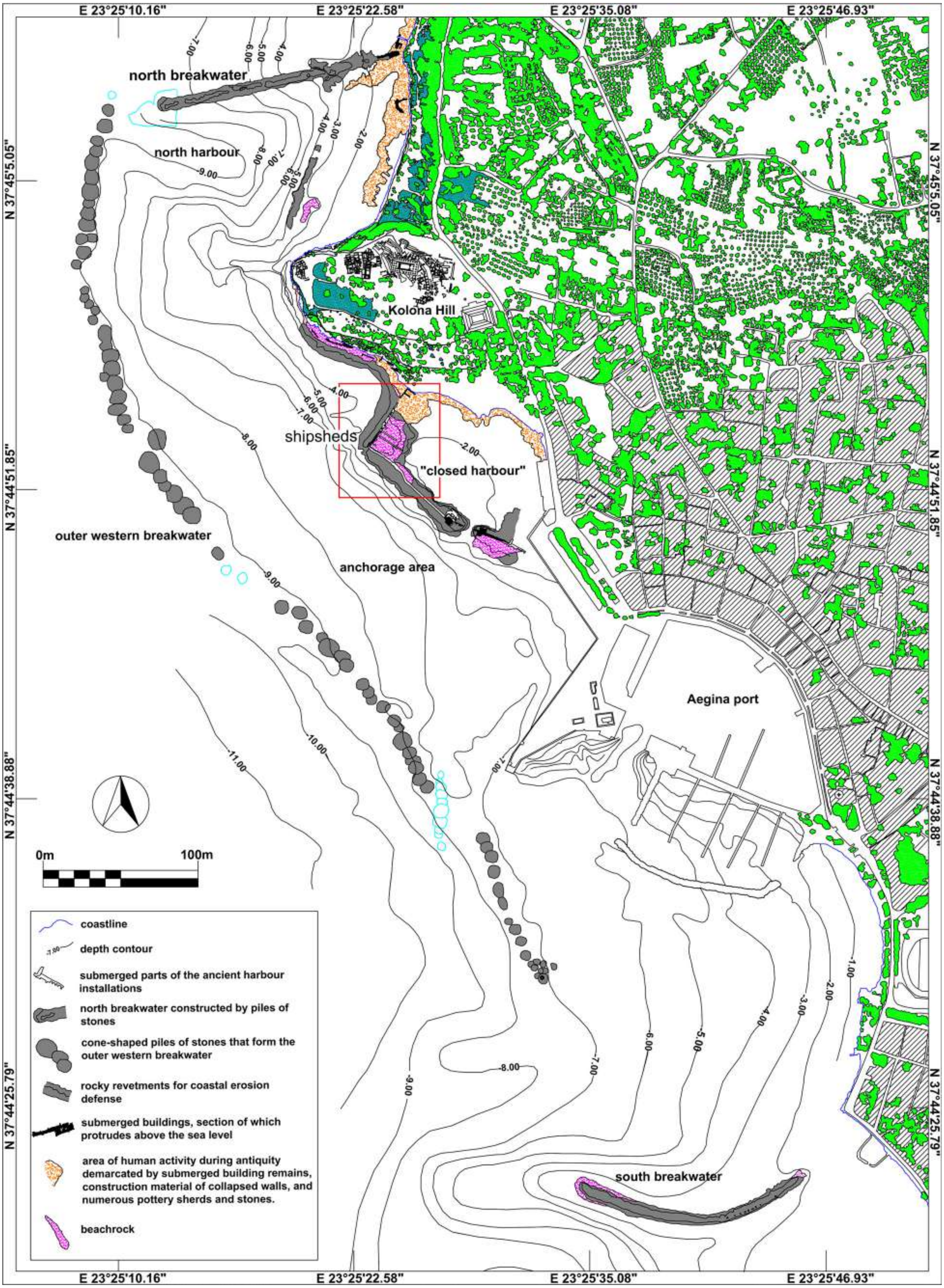
Table 1 List of the slipways presented herein and their details

Site		Type	Archaeological age	Sloping floor			Tide			Functional height (m)	Related sea level stand (m bmsl)	Flooded length at high tide (m)
Location	Coordinates			Gradient (°)	Depth of the seaward end (m bmsl)	Height of the underwater cliff (m)	Mean tidal range (m)	Maximum tidal range (m)	Spring tide (m)			
A	B	C	D	E	F	G	H	I	J	K	L	M
Aegina Island	37°44′54.02"N 23°25′23.86"E	Shipsheds	Early fifth century BC	5	−3.40	n/a	0.05	0.40	+0.58	0.00 ± 0.20	−3.60 ± 0.20	2.90
Trypitos (E Crete)	35°11′54.54"N 26°07′50.27"E	Slipway	Early 3rd to mid-second century BC	15	−1.20	2.10	0.15	0.40	+0.54	0.00 ± 0.20	−1.25 ± 0.05	0.75
Poiessa (Keos Island)	37°35′53.98"N 24°16′31.69"E	Slipway	Fourth century BC to probably 2nd or fourth century AD	6	−2.25	0.35	0.14	0.28	+0.51	0.00 ± 0.14	−2.40 ± 0.20	1.35
Matala (S–E Crete)	34°59′33.82"N 24°44′51.15"E	Slipway	1th to fifth century AD	13	−1.14	n/a	0.15	0.40	+0.54	0.00 ± 0.20	−1.25 ± 0.05	0.90
Mandraki (Andros Island)	37°50′23.73"N 24°56′29.58"E	*Carenaggio*	Late 14th to early fifteenth century AD	1	−1.18 to −1.42	0.50	0.14	0.28	+0.51	0.00 ± 0.14	−1.50 ± 0.20	8.00
Rethymno (N Crete)	35°22′16.33"N 24°28′07.63"E	Slipways	Late sixteenth century AD or even earlier (Classical/Hellenistic)	6	−1.20 to −1.55	n/a	0.13	0.25	+0.36	0.00 ± 0.12	−1.25 ± 0.05	2.90

Table 1 (continued)

Site		Type	Archaeo-logical age	Sloping floor			Tide			Functional height (m)	Related sea level stand (m bmsl)	Flooded length at high tide (m)
Location	Coordinates			Gradient (°)	Depth of the seaward end (m bmsl)	Height of the under-water cliff (m)	Mean tidal range (m)	Maximum tidal range (m)	Spring tide (m)			
A	B	C	D	E	F	G	H	I	J	K	L	M
Katholiko (NW Crete)	35°35′32.16"N 24°09′00.99"E	Shipshed	Seventeenth century AD	20	−0.60	2.00	0.13	0.25	+0.36	0.00 ± 0.12	−0.55 ± 0.05	0.35
Lazareto (E Pelopon-nese, Troezenia)	37°29′24.24"N 23°28′15.54"E	Slipway	Late sev-enteenth century AD	4	−1.20	1.00	0.05	0.40	+0.58	0.00 ± 0.20	−1.35 ± 0.15	0.90
Remma-Goupa (Kimolos Island)	36°47′23.84"N 24°34′58.93"E	Slipways	Early twenti-eth century	6–8	−0.40 ± 0.10	1.00	0.14	0.28	+0.51	0.00 ± 0.14	−0.45 ± 0.05	1.35

A: name of site. B: geographical coordinates (latitude, longitude). C: type of slipway (roofed: shipshed, unroofed: slipway). D: Archaeological age, which represents either the period of construction when this is known or the age/period of the ancient town for the needs of which the slipway was used. E: gradient of the sloping floor towards the sea. F: measured depth (m) of the seaward end of the sloping floor below mean sea level (bmsl). G: measured height (m) of the underlying underwater natural cliff, from the rock-cut boundary of the sloping floor to the sea bottom (n/a: not available). H, I, J: Tidal data for the closest tide-gauge station for each study area (from the Hellenic Navy Hydrographic Service). K: functional height of the sloping floor of the slipway. L: related sea level stand determined for each study area (m, bmsl). M: the length (m) of the sloping floor that was flooded by the sea at high tide when the slipway was in use


E 23°25'10.16"
E 23°25'22.58"
E 23°25'35.08"
E 23°25'46.93"
N 37°45'5.05"
N 37°44'51.85"
N 37°44'38.88"
N 37°44'25.79"
north breakwater
north harbour
Kolona Hill
shipsheds
"closed harbour"
outer western breakwater
anchorage area
Aegina port
south breakwater
0m
100m
coastline
depth contour
submerged parts of the ancient harbour installations
north breakwater constructed by piles of stones
cone-shaped piles of stones that form the outer western breakwater
rocky revetments for coastal erosion defense
submerged buildings, section of which protrudes above the sea level
area of human activity during antiquity demarcated by submerged building remains, construction material of collapsed walls, and numerous pottery sherds and stones.
beachrock

◂**Fig. 2** Plan of the ancient harbour installations of Aegina Island (after Mourtzas and Kolaiti 2013; Kolaiti 2019). The location of the ancient shipsheds is indicated by a red square

long, survives, ending at the entrance-tower. The masonry of the wall is from 2 to 2.80 m thick. The preserved superstructure, with a maximum visible height of 2 m above the top of the outer protective rip-rap, consists of three courses of ashlars, which in the area of the entrance were found to be connected with clamps. Today only sporadic sections of the wall protrude above the sea level, at a maximum elevation of 0.65 m amsl on its SW corner (Mourtzas and Kolaiti 2013; Kolaiti 2019).

On its outer side, the wall is surrounded by a protective rip-rap (Fig. 3) consisting of rubble up to 0.30 m × 0.15 m in size. In the entrance area, the rip-rap reaches 1.50 m in height and its width is up to 20 m. The top of the protective rip-rap is now at a depth of between 2.25 and 2.50 m, and its base between 3.50 and 4.20 m bmsl (Mourtzas and Kolaiti 2013; Kolaiti 2019).

The harbour entrance between the two towers on the SW side of the wall is 12 m wide on the top of the rip-rap and 6 m at its base. The depth of the entrance channel was measured at 2.95 m bmsl (Mourtzas and Kolaiti 2013), whilst Knoblauch (1969, 1972) measured a depth of 3.40–3.50 m. The observed difference is obviously due to silting processes during the last 50 years. The maximum measured depth in the central part of the harbour basin is 2.80 m bmsl, but a safe conclusion about the depth during the period of the harbour use cannot be drawn due to the siltation that it has undergone over the last 2500 years. A rockfill was also observed inside the harbour basin, all along the seaward sides of the wall and around the harbour entrances, up to 1 m high and 7–15 m wide, with the exception of the northern side that reaches 40 m in width and exceeds 1 m in height. The top of the rockfill is at a depth of 1.10–1.60 m bmsl and its base at 2.10–2.47 m bmsl (Mourtzas and Kolaiti 2013; Kolaiti 2019).

Four distinct former sea level stands have been determined for Aegina Island (Mourtzas and Kolaiti 2013; Kolaiti 2019): the sea level stand at 3.40 ± 0.10 m bmsl dated back between the seventh–sixth century BC and at least 250 AD, the sea level stand at 2.60 ± 0.10 m bmsl from *c.* 1400 to 1600 AD, and the sea level stand at 1.15 m bmsl between 1400 and 1820. The most recent sea level stand at 0.75 m bmsl dates back to the end of the eighteenth century.

On the NW side of the closed harbour eight rows of walls 5.75–6.17 m apart, with a maximum visible length of 42 m, were observed, parallel to each other and at a right angle to the outer NW wall (Fig. 3). The visible preserved height of their superstructure reaches 0.70 m. Their deepest trace is at a depth of 1.15 m bmsl. First Welter (1938) and then Knoblauch (1969, 1972) described these structures and interpreted them as shipsheds serving the military port of ancient Aegina, and their construction is integral with the city's wall and port (early fifth century BC). The site was presented by Gerding in SSAM (2013, pp. 284–293).

Knoblauch (1969, 1972) identified six shipsheds and assumed that there was room for three more on the NW side of the closed harbour, whilst Kolaiti (2019) mentioned the remains of nine shipsheds and suggested that along the north side where no remains are observed there was room for four more to develop. Knoblauch (1969, 1972) also reported that this area was covered by an artificial layer of bricks, potsherds and mortar, but it was difficult to interpret whether this was rubble from the shipsheds cemented together or the remains of a floor. Moreover, by assuming the latter he wonders why the keel slots are not preserved on the floor. Based on this assumption and measuring a depth of − 1.55 m at the base of the visible part of the NW wall and − 1.35 m at the lowest seaward part of the partition walls of the shipsheds, he suggested that the shipsheds were constructed when the sea level was 2 m lower than at present. It becomes clear that what Knoblauch (1969, 1972) describes as floor is in fact the beachrock formation (Figs. 3, 4), which formed by the cementation of the rockfill materials that were later placed there when the sea level was 1.15 m lower than at present (Mourtzas and Kolaiti 2013; Kolaiti 2019). The shipsheds would have originally been constructed on dry land or slightly below mean sea level with their sloping floor having a gradient of 5° seawards and their ending part located at the waterline of the period of use (Fig. 4). With the sea level at 3.40 m bmsl during the Classical period (Kolaiti 2019), the shipsheds could fulfil their function, that is hauling out and launching ships. When the sea level rose by 2.25–1.15 m bmsl (late 14th to early nineteenth century AD)—robust evidence of this sea level is tidal notch (I) incised on the wall (Fig. 4A)—the shipsheds were flooded (Fig. 4B) (Mourtzas and Kolaiti 2013; Kolaiti 2019). It was probably then that an extended rockfill was placed on the north side of the harbour basin in the shipsheds area (Kolaiti 2019), rendering the basin a suitable shelter for small vessels (Figs. 3, 4). Given that the siltation rate is estimated at 9 mm/yr over the last 50 years, the functional depth of the harbour basin when the sea level was at 3.40 bmsl during the Classical period, should be at least 1.50–2 m deeper than at present and has progressively silted up over the last 2500 years.

3.2 Trypitos Slipway (Sitia, NE Crete)

Trypitos is a small rocky peninsula, 2 km east of Sitia in NE Crete. It probably owes its modern name to the elongated trench cut into its eastern side. A Hellenistic town (early third century BC to mid-second century BC) has been excavated on top of the peninsula, built on terraces and protected

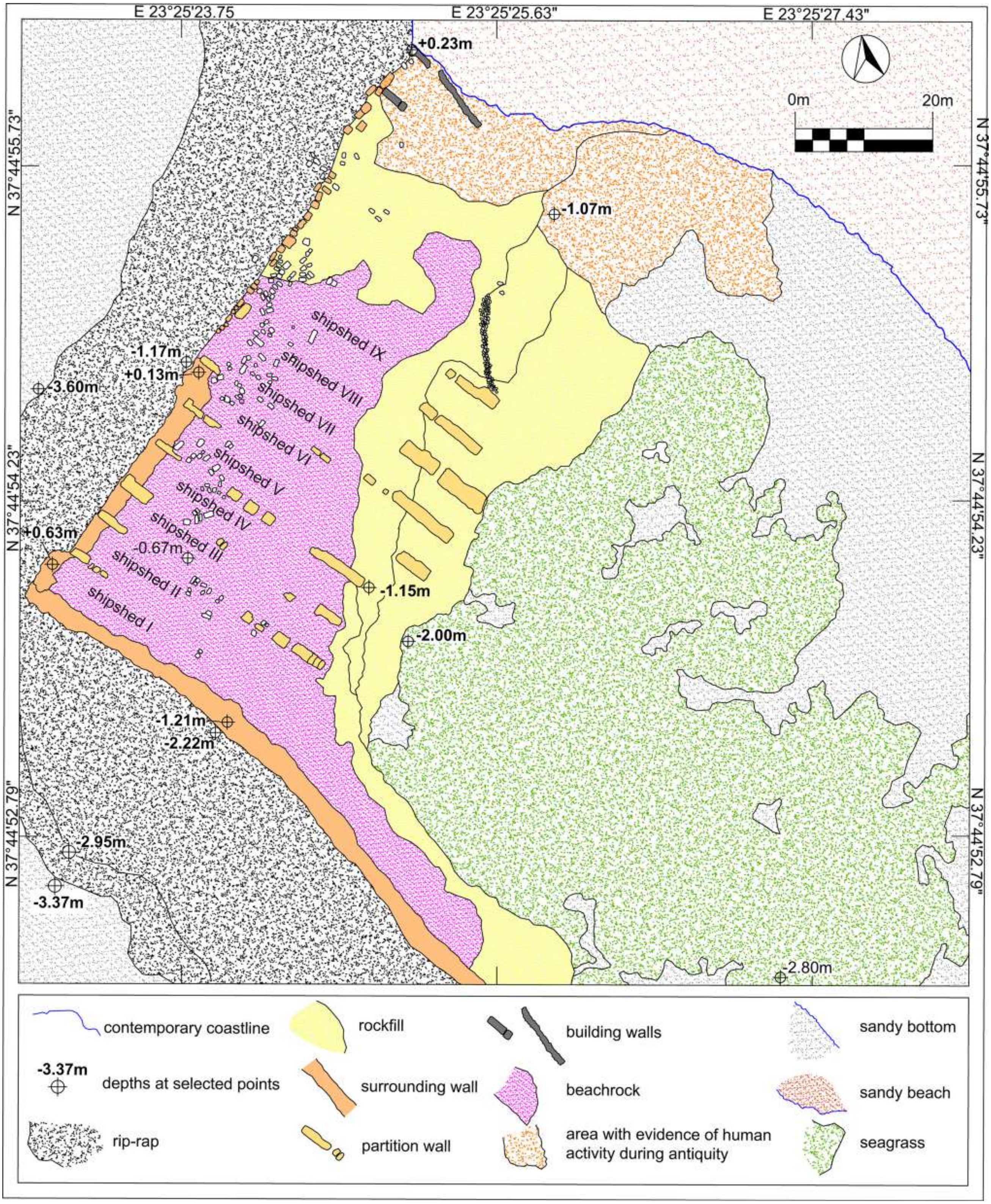


Fig. 3 Plan of the NW section of the ancient closed harbour of Aegina where the ancient shipsheds are located

from the South by a strong defensive wall, which cuts off the peninsula from the landward side (Papadakis 2000) (Fig. 5).

The Hellenistic rock-cut trench was first published by Davaras (1967). Davaras (1974) claimed that it was located at almost the same level as in the Hellenistic period or slightly higher, whilst Baika in SSAM (2013, p. 522) suggests that it was most probably slightly submerged.

It is an ancient slipway, 30 m long, 5.5 m wide and 7 m deep. Its sloping floor starts from an altitude of + 7.50 m and dipping towards the sea at an angle of 15° ends up at the depth of 1.10 m below the mean sea level, 2.50 m off the shoreline (Figs. 6, 7A, B). The rock-cut sloping floor is abruptly interrupted by a small underwater depression with steep slopes, 1–2 m high, and a rough bottom sloping towards the sea. On the north and south sides of the depression there are rock-cut grooves, opposite each other, with a length of 0.70–1 m and internal depth of 0.30 to 1 m (Fig. 7A, B). Wooden beams were placed into the grooves to bridge the depression up to the then shoreline, which is defined by a former sea level at − 1.25 ± 0.05 m (Mourtzas et al. 2016) (Fig. 7C, D).

3.3 Poiiessa Slipway (Keos Island, Cyclades)

The acropolis and the town of Poiiessa, built on the highest part of Phira Hill (Cape Tarsanas, a significant toponym), which borders the bay of the same name from the South, controls the west coast of Keos Island and the fertile valley of Poiiessa, with its agricultural facilities spreading throughout the hydrological basin. The town's economy was oriented towards both maritime trade and agricultural production. In the coastal zone to the south of the acropolis, the large concentration of sherds dates back to the Hellenistic (fourth century BC) and Roman periods (Papageorgiadou 1990), although it seems that according to ancient authors Poiiessa had declined in Roman times (second century AD) (Karnava et al. 2015).

The N–S-oriented Poiiessa Bay, at the end of the long valley, opens towards the West and is protected from the prevailing northerly winds. Along with Agios Nikolaos Bay it constitutes the safest shelter along the west coast of Keos (Mendoni and Mourtzas 1990). The bay is approached from the sea only by its sandy smooth east coast, whilst its northern and southern rocky steep shores are inaccessible. No remains of harbour installations have been found along the coast and in the nearshore zone of the bay, which indicates that ships approached the bay and were hauled ashore onto the sandy beach. The slipway is located at the eastern end of the cliff of the south coast of Poiiessa Bay, below the Hellenistic Acropolis, and it seems to be contemporary with it (Fig. 8). It was first reported by K. Manthos in his manuscript of 1868, which was edited and published 131 years later (1991). It is entirely cut into the rocky schist, with quarrying traces still visible on the sides of the trench. The maximum length of the slipway is 48 m and its width is 10 m in its central part, whilst at its northern seaward end it reaches 14.50 m. The maximum depth of the trench is 9.50 m at its landward end (Fig. 9A, B). The rock-cut ramp of the slipway starts at an elevation of 1.60 m amsl and inclines towards the sea with an average slope of 6°. It ends at a depth of 2.25 m bmsl, with the sea bottom at 2.58–2.60 m bmsl, thus creating a low cliff which clearly delimits the seaward end of the sloping floor. The continuation of the western seaward side of the sloping floor is interrupted by a depression—most probably natural—in the rock between the depths of 1.35 m and 1.90 m bmsl (Fig. 9A, B). Baika [2008, p. 39; in SSAM (2013), p. 490] traced the rock-cut sloping floor underwater to a depth of 1.924 ± 0.30 m on the eastern side and at 2.491 ± 0.30 m on the western side.

Just west of the submerged seaward end of the slipway there is a submerged rockfill, 13 m long and 16 m wide, consisting of sizeable stones (Fig. 9A, C). Its construction seems to have been contemporary with the slipway and was probably protecting the ramp against the waves and was preventing it from silting (Fig. 9C, D).

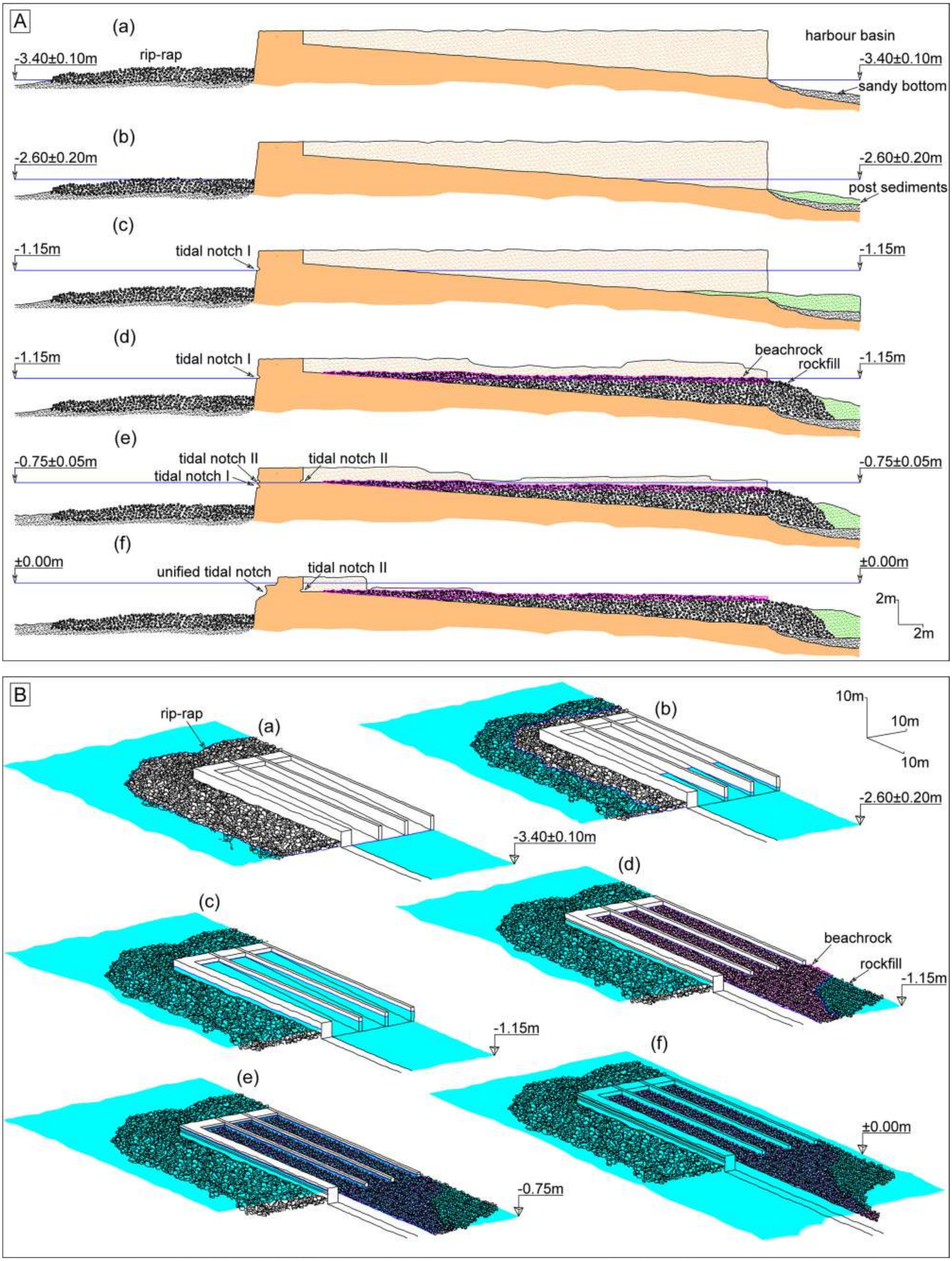
The rock-cut ramp is now located below the sea for a length of 27 m (Fig. 9A, B). Given that it was cut into the rock in dry conditions, the maximum measured depth of its seaward end at 2.25 m bmsl represents the intertidal zone of the sea level in the period that the slipway was in use (Fig. 9C, D). This depth matches the sea level stand at 2.40 ± 0.20 m bmsl, which has been determined for Keos Island and also the islands of northern and central Cyclades by many geomorphological indicators and has been dated back to the period between 180–30 BC and AD 1000 (Kolaiti and Mourtzas 2020, 2023).

Based on various estimates of the rsl change in Attica, Euboea, and the Cyclades, Baika [2008, pp. 39–40 and related references therein; 2010, pp. 73–74; in SSAM (2013), p. 490] suggested a rsl change between 2.50 and 2.80 m (± 0.30 m) since the Classical/Hellenistic period (500–30 BC), which in SSAM (2013, p. 492) was further reduced to at least 2 to 2.50 m in relation to the present sea level.

The slipway has been mostly covered by the debris of the excavations for the construction of the modern road just uphill, whilst part of its eastern seaward end has been covered by the modern concrete quay (Fig. 9A).

3.4 Matala Shipshed (S Crete)

The slipway on the SE side of the rocky coast of Matala (Fig. 10), east of the fish tank complexes (Mourtzas 2012a, b), is a deep cutting in the marly limestone bedrock, 38 m long and 5.50 m wide, with a maximum depth of 12 m (Fig. 11a). The rock-cut sloping floor of the trench starts at an altitude of 8 m amsl, slopes 13° seawards and ends


A
(a)
harbour basin
-3.40±0.10m
rip-rap
-3.40±0.10m
sandy bottom
(b)
-2.60±0.20m
-2.60±0.20m
post sediments
(c)
-1.15m
tidal notch I
-1.15m
(d)
-1.15m
tidal notch I
beachrock
rockfill
-1.15m
(e)
-0.75±0.05m
tidal notch II
tidal notch I
tidal notch II
-0.75±0.05m
(f)
±0.00m
unified tidal notch
tidal notch II
±0.00m
2m
2m
B
rip-rap
(a)
-3.40±0.10m
(b)
-2.60±0.20m
10m
10m
10m
(c)
-1.15m
(d)
beachrock
rockfill
-1.15m
(e)
-0.75m
(f)
±0.00m

◂**Fig. 4** Cross-sections of the ancient shipsheds of Aegina (**A**) and 3D reconstruction of the three westernmost ancient shipsheds (**B**): their evolution in relation to the rsl changes

underwater with its deepest trace at a depth of 1.14 m bmsl (Fig. 11b). According to Blackman (1973), who first described it, the slipway would have been covered with a gable roof with a sloping ridge-beam or a horizontal-ridged gable roof with two or three steps. However, no trace is now preserved. The seaward end of the sloping floor today is covered with concrete to form the floor of a modern tavern (Fig. 11a). The side walls of the slipway protrude from the modern fill and extend northward to the sea (Fig. 11b).

The underwater geoarchaeological survey revealed the sloping floor of the slipway underneath the concrete fill, projecting around 0.40 m above it towards the sea, with its lower end at a depth of 0.42 m bmsl (Mourtzas 1990; Mourtzas and Kolaiti 2020) (Fig. 11a). There, it is abruptly disrupted, apparently due to its destruction, but clear rock-cut lateral traces are preserved up to a depth of 1.14 m bmsl before it ends in the sandy bottom. This finding clearly indicates that the sloping floor would have continued to at least this depth (Fig. 11b/detail).

The measured depth of the visible lower end of the sloping floor of the shipshed, is clearly related with the Roman sea level of 1.25 ± 0.05 m bmsl, which represents the mean sea level of the Roman period and has been identified by the functional features (channels) of the adjacent eleven rock-cut complexes of fish tanks of Matala (Mourtzas 2012a, b; Mourtzas et al. 2016; Mourtzas and Kolaiti 2020), serving the fish needs of the Roman town of Gortyn in the period of its prosperity (first century AD) (Watrous et al. 1993, 2004; Di Vita 2010). Besides, this thriving productive activity developed on the southern rocky coast of the Matala Bay, on the steep northern cliff of the bay the Roman necropolis was established in the first and second century AD (Fig. 10). Blackman (1973) assumed that the shipshed would have been built when the sea level was very similar to what it is now, and believing that the fish tanks at Matala were tombs dated back from the 1st to second century AD with their floors up to 1.80 m under the sea, he suggested a possible succession of up and down ground movements making a total rise of about 2 m since that period, a view also repeated as a possibility by Gerding in SSAM (2013, p. 391). At the westernmost end of the south rocky coast, extensive quarrying activity is also observed: the carved bollards found there indicate the mooring and loading position of vessels for the sea transport of the extracted stone. At the same time, a large salt pan complex at Cape Nisi, just north of Matala Bay, produced salt for fish curing. According to Chatzi-Vallianou (1995) an extensive settlement developed in the coastal area of the valley of Matala (Fig. 10). Pottery and coinage date the upper buildings to the Early Christian times, whereas in deeper layers Roman ruins and pottery as well as a few remains of Hellenistic occupation have been found. The coastal port of Matala was probably not deserted until the end of the fifth century AD (Watrous et al. 1993, 2004). Consequently, the slipway can be safely dated back to the first century AD and may have been in use until the fifth century AD, with a functional sea level stand at 1.25 ± 0.05 m bmsl.

3.5 Mandraki *Carenaggio* (Andros Island, Cyclades)

Mandraki in Chora of Andros Island is located on the east side of the Chora Peninsula, in Nimporio Gulf, where the foot of the schist coastal cliff ends in the sea (Fig. 12). It is a rock-cut, parallelogram basin, around 800 m^2 in area, oriented NE–SW. It is 36 m long and 17 m wide, with an average depth of 2 m. Quarrying traces, still visible, indicate that a total rock volume of about 1650 m^3 was manually extracted. The rock-cut entrance of the basin is located on the SW leeward side and it is 18 m long and 7 m wide. The floor of the basin is now at a maximum depth of 0.50 m, whilst the floor of the entrance starts at 1.40 m bmsl and rises to 0.80 m bmsl towards the inside of the basin (Fig. 13).

Although there is no clear evidence linking the construction of the basin to a specific historic period of Venetian rule in Andros, it could be attributed to the period of the rule in Andros of Pietro Zeno. Andros was occupied in 1207 by Marino Dandolo, who remained until 1243. During his rule, the fortifications of Chora were built. Between 1384 and 1427, the fortifications were reconstructed and completed by Pietro Zeno, the Lord of Andros and Syros. Zeno was a prestigious diplomat and seems to have had his own fleet: probably Mandraki was then the *carenaggio* for ship repair (Polemis 1981, pp. 54–68).

Based on geomorphological and archaeological sea level indicators from the northern and central Cyclades, Kolaiti and Mourtzas (2020, 2023) identified and dated the sea level during the Venetian period (1207–1566) at 1.50 ± 0.20 m lower than at present. This change in the sea level has sunk the basin and the entrance of the *carenaggio* at 0.50 m and 1.40 m bmsl, respectively (Fig. 13), which during cutting both should be above the then sea level. The rock-cut base of a built sea wall on the northern coast of Nimporio, also attributed to the Venetian period, is now at the depth of 1.25 m and is a clear evidence of the sea level of that period (Mourtzas 2018).

In the late 19th–early twentieth century, the basin of Mandraki submerged and was used for leather processing. Then, it served as a place for bathers and a mooring for boats, as evidenced by two rusty davits for raising and lowering boats preserved there to this day.

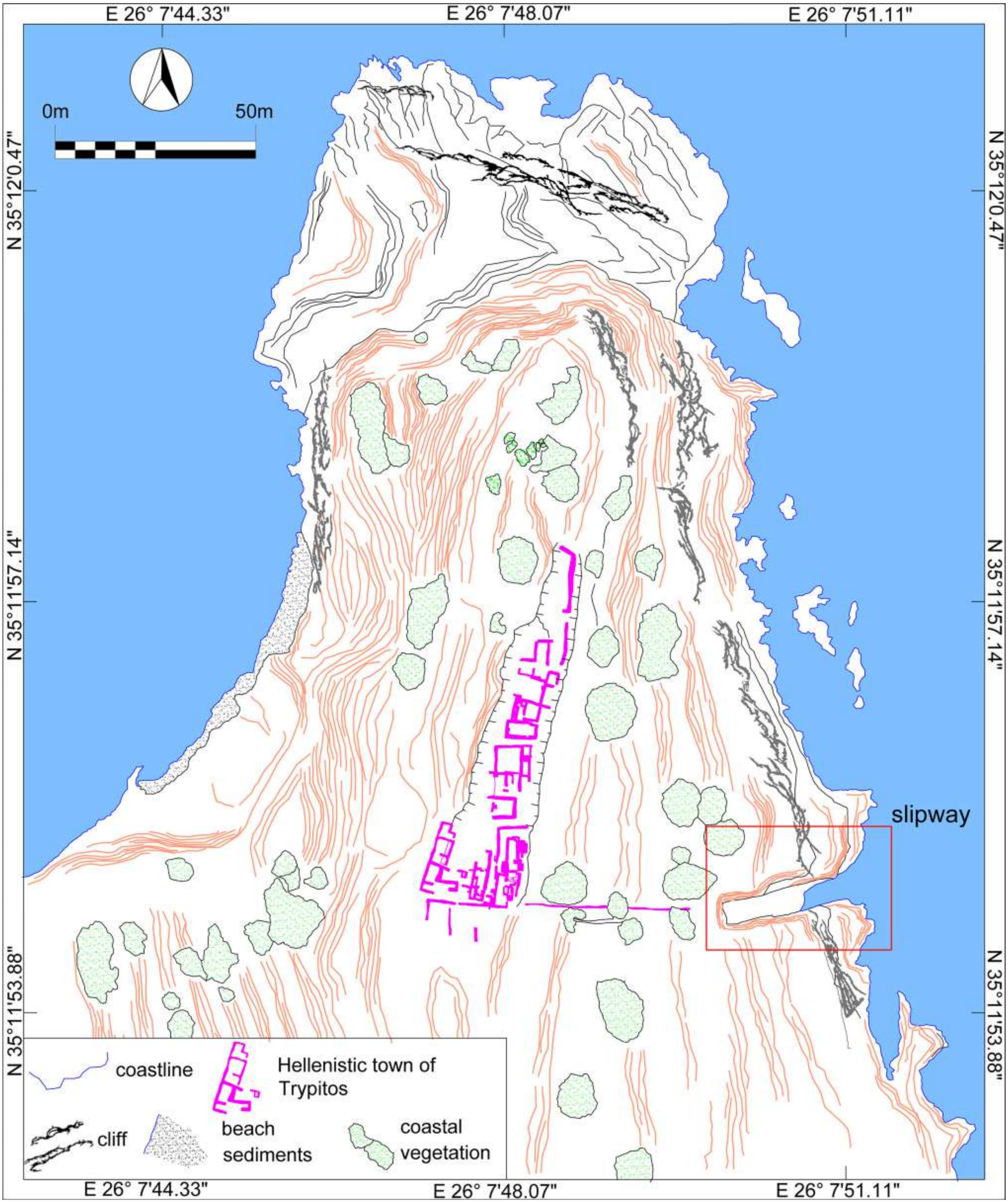


Fig. 5 Plan of Trypitos Peninsula. The location of the ancient slipway is indicated by a red square

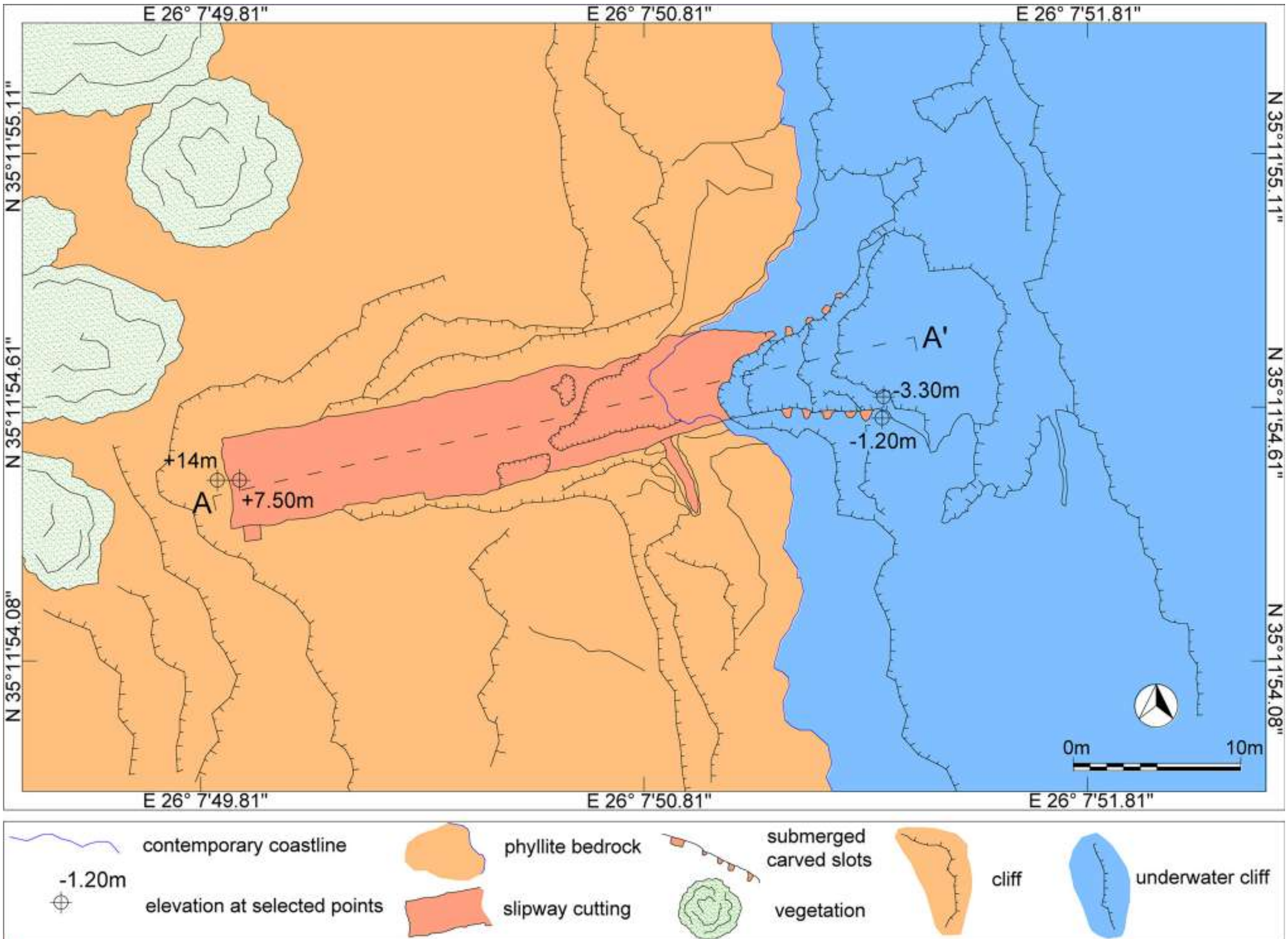


Fig. 6 Plan of the ancient slipway of Trypitos. A–A′: cross-section presented in Fig. 7A

3.6 Rethymno Slipways (N Crete)

The complex of the three shipways is located on the NW side of the peninsula of the Palaiokastro Hill where the Venetian fortress of Rethymno (Fortezza) was founded (Fig. 14). The slipways were cut into the marly limestone bedrock, with the two eastern ones following a NE–SW direction, whilst the western one in a NNE–SSW direction at an angle of 60° to the eastern slipways (Fig. 15).

The western slipway has a length of 29.50 m and a width of 6 m. Its internal depth is 0.50 m and 0.20 m at the eastern and western lateral sides, respectively. Its sloping floor starts at an elevation of 1 m amsl and inclines towards the sea with an average slope 6°, except for its landward end which reaches 13° (Fig. 15). Of its total length, 23 m are now on land and about 6.50 m underwater, reaching a depth of 1.20 m bmsl. The carved keel slot that runs lengthwise in the middle of the sloping floor has a length of 20 m, an average width of 0.30 m and an internal depth reaching 0.35 m. The slot continues underwater for about 6 m (Fig. 15).

The two eastern slipways were cut into the rock parallel to each other at a distance of 1.20 m (Fig. 15). They are mostly covered by the passing ring road of the fortress. Only the seaward part of both slipways and the landward end of the southern one are now visible (Fig. 15). The southern slipway has a total length of 55 m and is submerged for 25 m below the sea up to a depth of 1.55 m bmsl (Figs. 15, 16). It has an average internal depth of 0.50 m and a width of 3.80 m at its landward, visible, end that gradually increases to 5.80 m at its seaward end. Its sloping floor starts at an elevation of 5 m amsl and slopes 6° towards the sea, except for its landward visible part that reaches 22°. A keel slot, 0.25 m wide and 0.30 m deep, is only preserved in the landward visible section, whilst there are no traces of it in the submerged section of the slipway. Alongside the keel slot on both sides, small rectangular holes were cut, used for the insertion of wooden beams to support the boat keel when on land (Fig. 16). Of the northern of the two eastern slipways, only the seaward 5.50 m-wide part is now preserved. Its sloping floor is

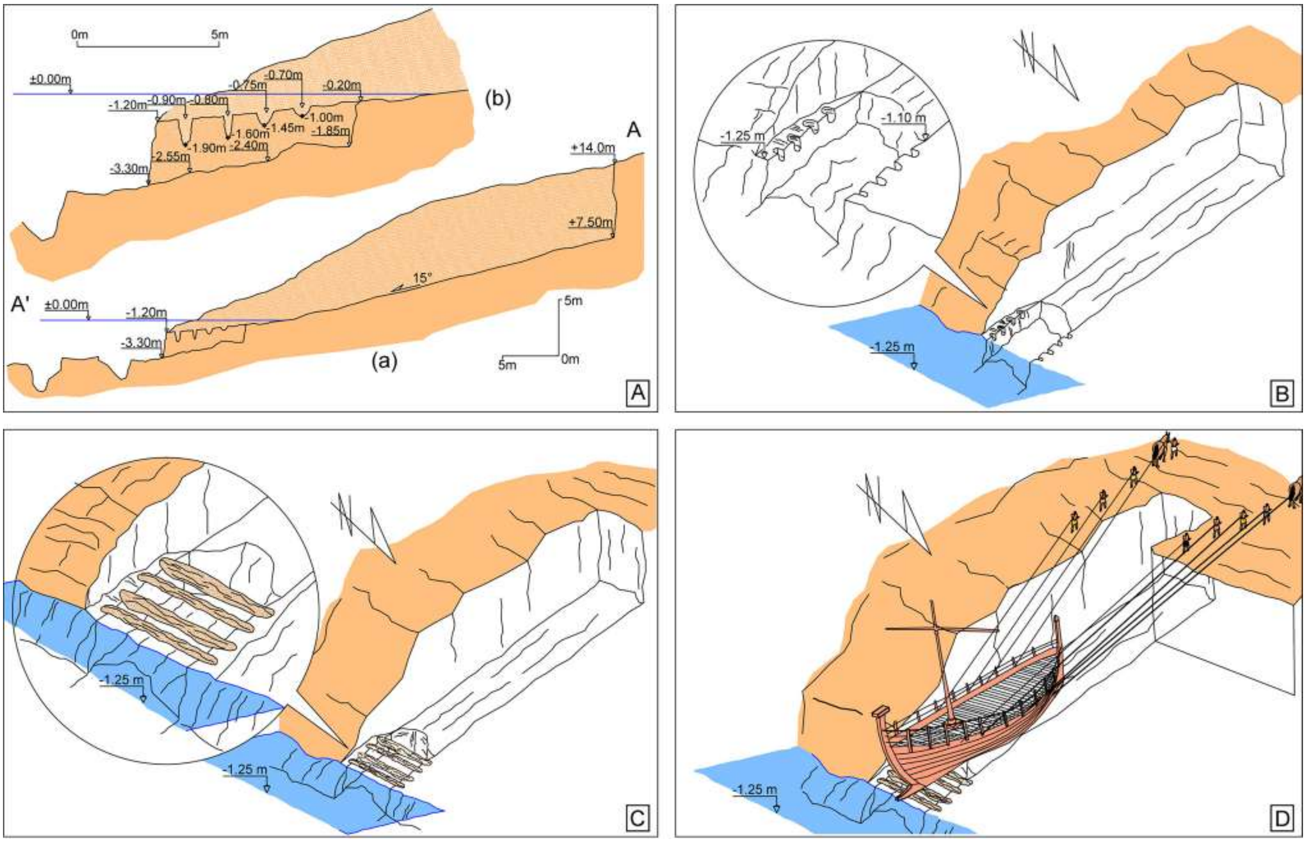


Fig. 7 The ancient slipway of Trypitos. **A** Cross-section of the slipway as it now stands (**a**) and of its seaward end (**b**) today submerged. **B** 3D reconstruction of the slipway during the Hellenistic period when the sea level was at 1.25 m bmsl. The inset shows its seaward end with the rock-cut grooves in more detail. **C** 3D reconstruction of the slipway with the wooden beams placed into the rock-cut grooves when the sea level was at 1.25 m bmsl. The inset shows its seaward end with the wooden beams in more detail. **D** 3D schematic representation of the hauling-out of a ship onto the slipway

covered for a length of 3 m with sand from the retaining wall of the ring road and then is submerged for 24 m below the sea up to a depth of 1.55 m bmsl (Fig. 15). It dips 6° towards the sea in its submerged part and 10° in its small visible part on land. At a distance of 2.50 m from the shore and a depth of 0.50 m bmsl, the sloping floor is overlaid by a thin beachrock slab (Fig. 15). An eroded trace left by the keel of ships dragged along the sloping floor is preserved on the submerged section of the slipway.

Regarding the slipways' chronology, although the fortress may correspond to the acropolis of ancient Rhithymna, there is no evidence of construction or use of the slipways during the Classical or Hellenistic period. Instead, they are shown on mediaeval maps and locals report them as part of a traditional *carenaggio* operating until the early twentieth century, following the Venetian naval arsenal installations there [Baika in SSAM (2013), pp. 505–506]. Moreover, their location in relation to the Venetian fortification circuit (not connected to this but following its outline), which was erected between 1573 and 1580 to protect the city and the harbour (Steriotou 1997), suggests that the slipways might be contemporary to this. Baika accepts this is possible, but Blackman finds it difficult, despite lack of evidence, to believe that there was nothing there in Classical/Hellenistic times.

Flemming et al. (1973), who first discovered the Rethymno slipways, and Flemming and Pirazzoli (1981) suggested a change in the sea level not exceeding 0.20 m, whilst Baika in SSAM (2013, p. 501, p. 506) assumed that they were located within ± 10 cm of present sea level. However, the rock-cut sloping floors should end up at the shoreline of the period that the slipways were in use or slightly below it, but now are submerged at 1.20–1.55 m bmsl (Fig. 16). Therefore, their use can be related to the sea level at 1.25 ± 0.05 m bmsl, which lasted from *c.* 1200 BC (and definitely confirmed by archaeological indicators as the sea level from the Classical period onwards) until the 1604 earthquake, when it rose by 0.70–0.55 m lower than at present (Mourtzas et al. 2016). This period of rsl stability, definitely since Classical times, allows for an earlier date for the construction of the slipways. Clear evidence of the 0.55 m sea level stand in the site is the beachrock slab that

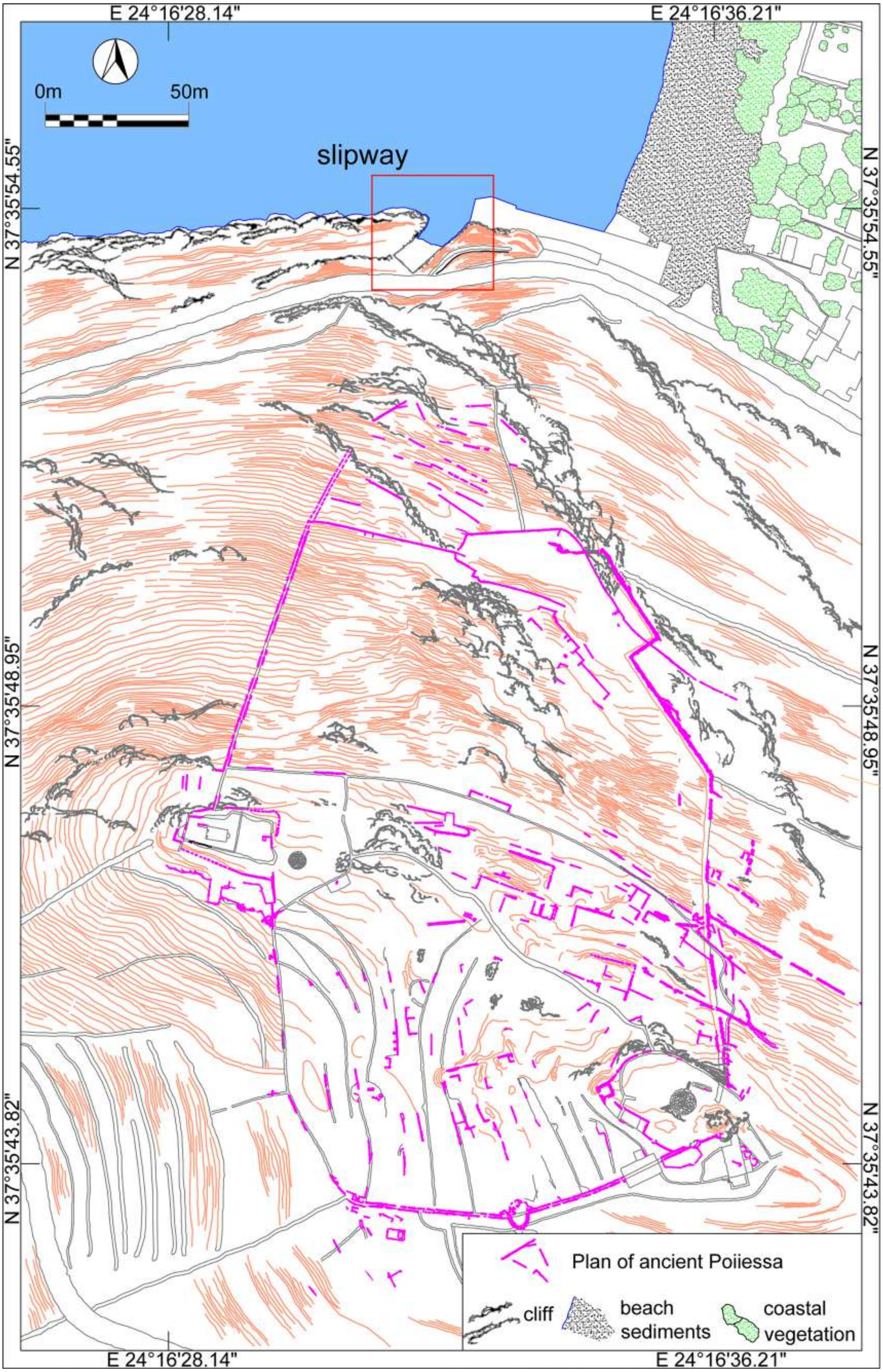


Fig. 8 Plan of ancient Poiiessa [after Svolos and Apergis (2002, p. 32), modified]. The location of the ancient shipshed is indicated by a red square

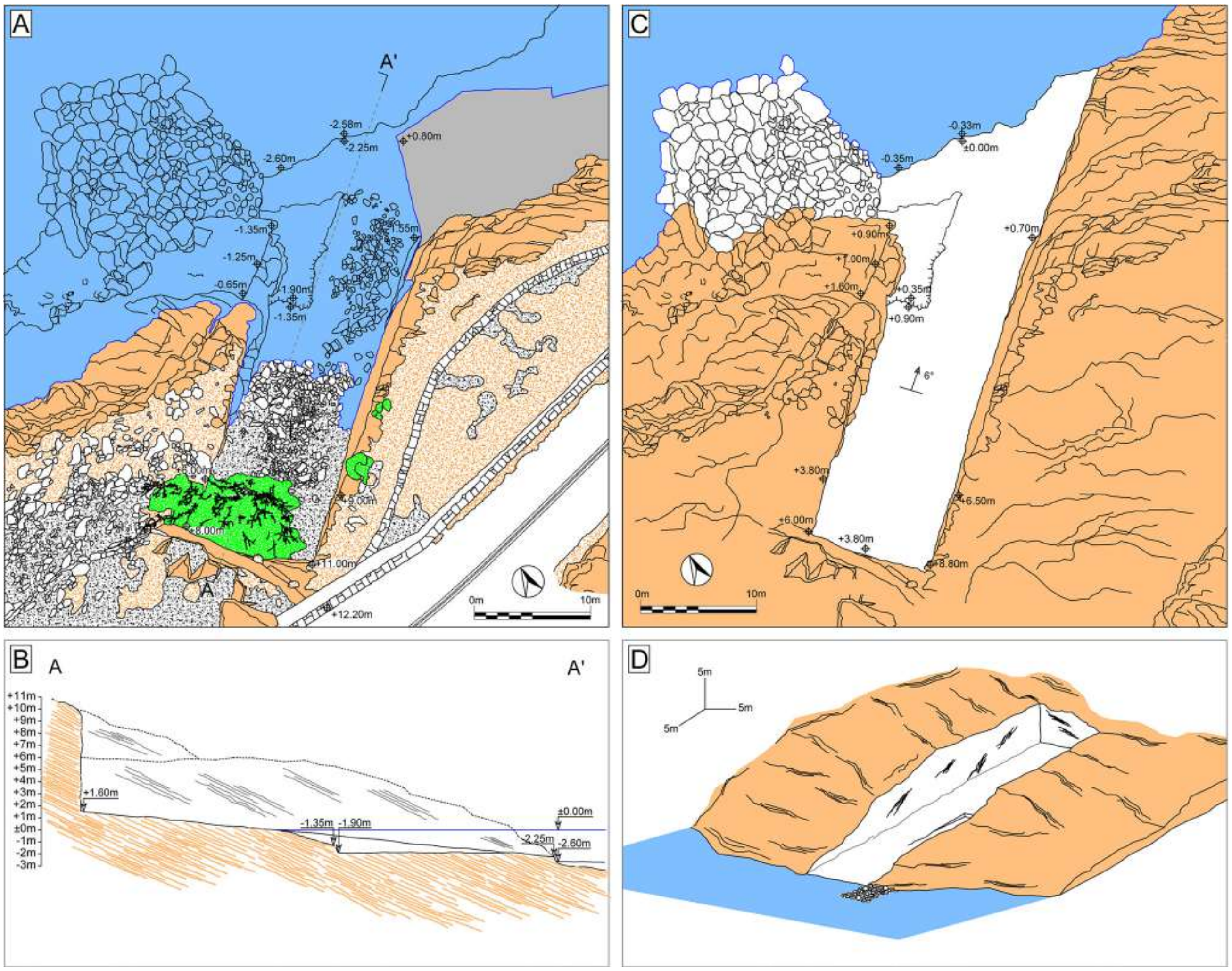


Fig. 9 **A**, **B** Plan and cross-section A–A′ of the ancient shipshed of Poiiessa as it now stands. **C**, **D** Plan and 3D reconstruction of the ancient shipshed during the Hellenistic period when the sea level was at 2.40 ± 0.20 m bmsl

covers the floor of the northern of the two eastern slipways and is now submerged at that depth.

3.7 Katholiko Shipshed (NW Crete)

The monastery of Katholiko, 20 km east of Chania, is located in the mountainous area of Arkoudovounia, at the Avlaki gorge, near the northern shore of Cape Akrotiri and at a short distance from the sea. The gorge ends in the rocky coast of the narrow, picturesque, fjord-type cove, of serpentine shape, to which it owes the name Avlaki (Fig. 17). There, apart from the impressively extensive sandstone quarry that was used for the building of the monastery, the remains of the monastery's harbour facilities are preserved (Fig. 17).

The monastery was founded in the area of the cave where Saint John the Hermit or Xenos died during the eleventh century AD and became one of the most important ascetic centres of Crete. In the seventeenth century, an extensive construction project designed by Sebastiano Serlio was carried out under the supervision of Jeremiah Tzagarolo. It was then that the monastery complex acquired its current form, with a bell tower and a magnificent bridge over the stream connecting the two walls of the gorge. The deck of the bridge shapes a large area ('a square'), whilst in the bridge abutments there are large vaulted storage spaces. A two-storey building and a small series of vaulted rooms were built on the walls of the gorge to house the pilgrims. When Crete became a target for pirates, who spread fear all along its shore, the monastery was deserted and the monks were forced to move to a safer place, so they went to the adjacent sixteenth century AD-monastery of Gouverneto (Cretanbeaches.com, n.d.).

The slipway that served the monastery is a parallelogram cutting in the limestone bedrock, 16 m long and 2.50 m wide, with a maximum depth of 2 m at its landward end

Fig. 10 Location map of Matala Bay. The location of the ancient shipshed is indicated by a red square

(Fig. 18A). The rock-cut sloping floor of the cutting starts at an altitude of 5.50 m amsl, has a gradient of 20° seawards, and ends underwater at a depth of 0.60 m bmsl, with the sea bottom at 2.60 m bmsl (Fig. 18A). Two walls on either side of the slipway, 0.40 m high and 0.70 m thick, retained an arched roof covering the cutting for a length of 8.30 m (Fig. 18B). Most of the roof, made of 0.30 m-thick sandstone blocks, has now collapsed and only a small part of it, approximately 1.50 m long, is preserved at the landward end of the cutting. A parallelogram cutting, measuring 1.5 m × 1 m with a depth not exceeding 0.40 m, is observed on the sloping floor some 2 m before its seaward end (Figs. 18A, 19).

The sloping floor of the slipway, which is now submerged to a depth of 0.60 m for a length of more than 1 m, points to a 0.60 m relative sea level rise from the seventeenth century AD to date (Fig. 19). This is consistent with the relative sea level rise by 0.55 m during the last 400 years throughout the coast of Crete, which followed the 0.70 m submergence during the AD 1604 paroxysmal seismic event (Mourtzas et al. 2016).

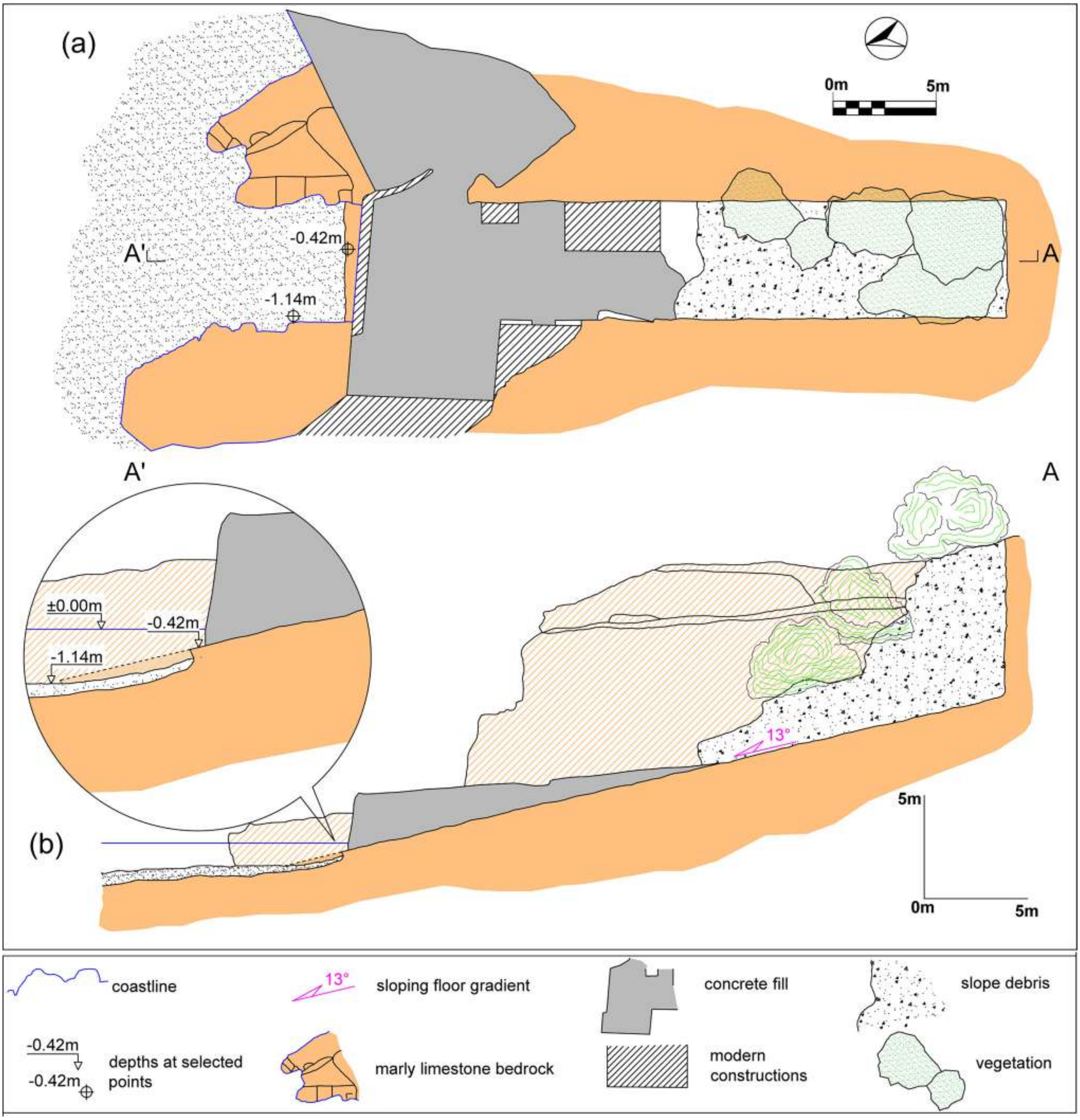


Fig. 11 **a** Plan of the ancient shipshed of Matala [after Blackman (1973), modified]. **b** Cross-section A–A′ of the shipshed. The inset shows its seaward end in more detail

3.8 Lazareto Slipway (E Peloponnese, Saronic Gulf)

In the gulf of Alyki in Troezenia (East Peloponnese), east of the Poros channel, on the NE side of Lazareto Islet, a rock-cut trench was first reported by Kolaiti (2019) (Fig. 20). The privately owned Lazareto Islet had been granted in 1912 to S.P. Deimezis. There are no buildings on it and is one of the four uninhabited limestone islets of the Bourtzi–Lazareto–Arvanitis–Limani complex located at the strategic position of the east entrance of the Poros channel. The Bourtzi Islet was probably used as a naval base by the Byzantine Fleet during the seventh century AD. A Venetian fort is also reported there, which would have been used by Morosini and his fleet between 1687 and 1693, and later a Christian church

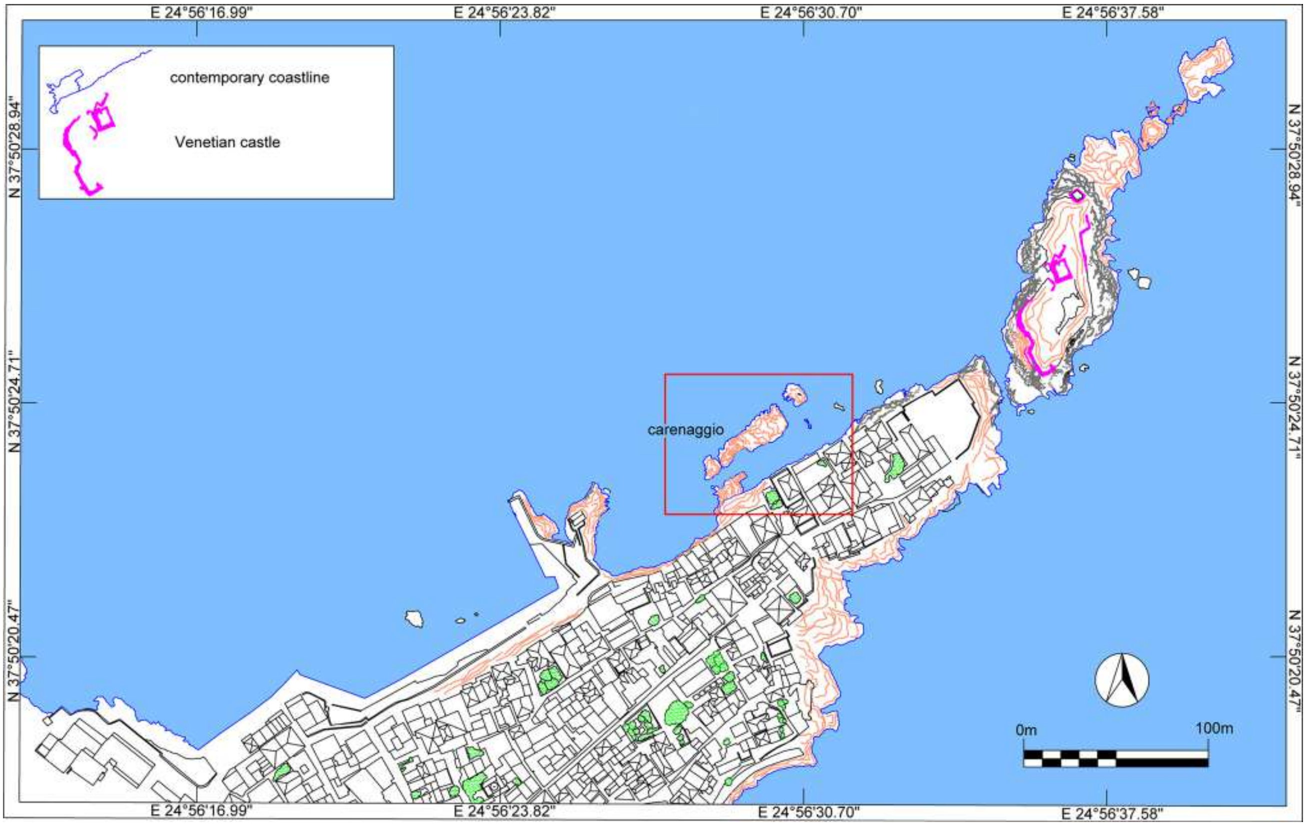


Fig. 12 Plan of Chora of Andros. The location of the Mandraki *carenaggio* is indicated by a red square

of Agios Constantinos. A small castle was built in 1826 on the Bourtzi Islet by the Bavarian military officer C.W. v. Heideck for the control of the channel and the port of Poros (Kastrologos-Castles of Greece, n.d.). The fort was then linked to a sad page in Greek history, as it was the stronghold of Admiral Miaoulis and the Hydriot rebels in the civil conflict with the Governor Ioannis Kapodistrias, who was supported by the Russian fleet, culminating in the blowing up of the newly built flagship *Hellas* and the corvette *Hydra* on 13.8.1831 by Miaoulis after his defeat (Kordatos 1957; Vournas 1997; Stamelos 2003).

The trench is cut into the limestone bedrock, runs S–N for 25 m along the NE rocky coast of Lazareto Islet and has a maximum width of 6 m (Fig. 21). The sloping floor is roughly cut, slopes 4° towards the sea, and is now mostly flooded by the sea: from a depth of 0.10 m bmsl at its landward end it gradually descends to 0.75 m bmsl at its seaward end (Fig. 21). The final, 5 m-long, part of the sloping floor abruptly deepens and is now located at a depth of 1.20 m bmsl. Given that the trench was cut in dry conditions and was ending at the waterline of the period of construction and use, its current depth points to a sea level at 1.20 ± 0.15 m bmsl, with the estimated error representing the local tidal range.

No archaeological dating is provided for the site. The seaward depth of the slipway at 1.20 ± 0.15 m can be related to the sea level stand at 1.35 ± 0.15 m bmsl, which has been determined for the Saronic Gulf and is dated back to between First Venetian Occupation/First phase of the Ottoman domination (*c*. 1389) and two decades after the Greek War of Independence (*c*. 1840) (Kolaiti and Mourtzas 2016; Kolaiti 2019, 2020). Since it is very difficult to provide a chronology for ancient rock-cut structures as the same cutting methods were diachronically used, based on the dating of the related sea level, it is assumed that the slipway would have been constructed in the early nineteenth century opposite the entrance of the Eidek Fort on the harbourless Bourtzi Islet.

3.9 Remma and Goupa Slipways (Kimolos Island, Cyclades)

The small bays of Goupa and Remma are located on the south part of the eastern coast of Kimolos and are separated by a tiny rocky islet in the shape of an elephant, to which it owes its name (Fig. 22). The *syrmata* (*σύρμα/σύρματα*, wires) and *magazakia* (*μαγαζάκι/μαγαζάκια,* little shops), which are located along the coast of the coastal settlements of Remma and Goupa, are spaces carved into the volcanic

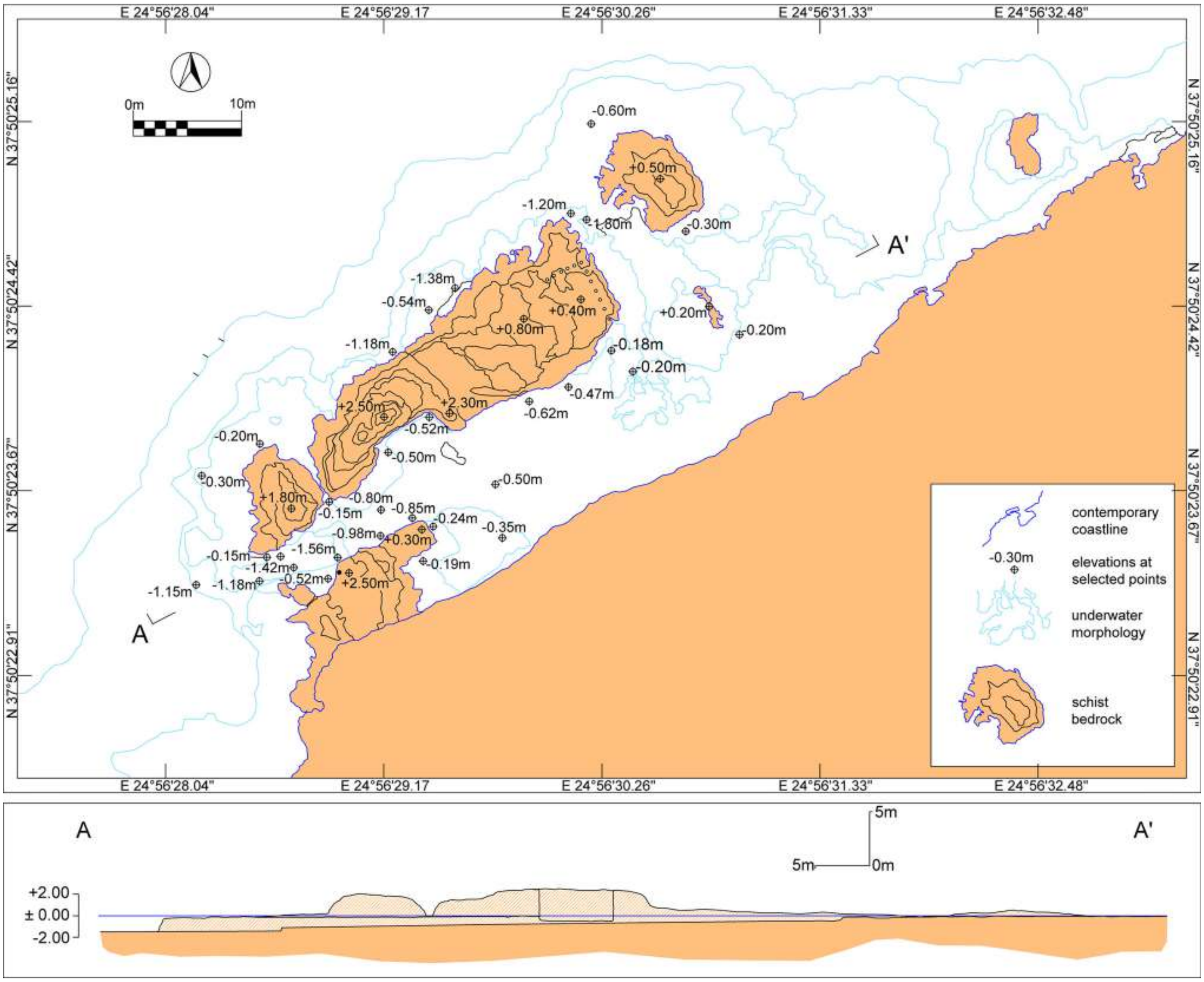


Fig. 13 Plan and cross-section A–A′ of the Mandraki *carenaggio* in Chora of Andros as it now stands

rock by the fishermen to house the wooden fishing boats and nets. Apart from their historical interest, they are a particular feature of the Cycladic architectural tradition. These rock-cut boathouses were called wires (mainly in Melos Island, whilst *magazakia* is more common in Kimolos Island), or haulage-ways, as at the end of the fishing season the fishermen dragged their boats ashore using wires. They consist of two parts, a rock-cut cave for the storage of boats along with the accompanying fishing tools and maintenance equipment, and the rock-cut ramp for hauling the boats out of the water. The storage spaces, of an area of approximately 15 m^2 each and a height of 2.80 m, are closed on the seaward front by multi-coloured wooden doors, giving them a picturesque aspect. The large wooden doors, about 2.50 m wide and 2 m high, cover the entire width of the cave and are equipped with a smaller door, which is used during the winter as the waves accumulate algae, stones and sand at the entrance. When the spring comes, the ramps are cleaned, the wooden doors are opened and the boats are hauled down into the sea.

The ramps on the coast of the Remma Bay are 15 m long and 3.50 m wide and slope 6° towards the sea. In the Goupa Bay, on the other hand, the length and width of the sloping floor is 3 m and 2 m, respectively, and it slopes 7–8° towards the sea. In the central part of some of the ramps, *phalangia* (*φαλάγγια*, short wooden beams) made of wild olive branches up to 0.10 m thick have been placed into rock-cut slots, on which the boats are towed (Fig. 23). Large bollards, are carved laterally on some of the ramps, to serve as a lever for the manual traction of the boats. On the coast of the Remma Bay, 19 *syrmata* or *magazakia* have been constructed in total, seven on the western coast and 12 on the northeastern, of which 12 are equipped with a ramp. In the adjacent Goupa Bay, there are 23 *syrmata* or *magazakia* in total, seven on the western coast and 16 on the eastern, 14 of which have a sloping floor (Fig. 22).

Fig. 14 Plan of the Venetian fortress of Rethymno. The location of the ancient slipways is indicated by a red square

In the Remma Bay, the rock-cut ramps are partly submerged for a length of 3.50–4 m, with their seaward end at 0.40 m bmsl on the western coast and 0.47 m bmsl on the northern coast. In the Goupa Bay, the seaward end of the sloping floor is submerged at 0.50 m bmsl on the western coast and 0.30 m bmsl on the eastern. On the submerged top of some of the ramps, carved slots for placing *phalangia* were observed, and also submerged bollards. The rock-cut seaward end of each ramp is abruptly interrupted, with the sea bottom being at a depth of 1.50–1.80 m. The lower parts of the rock-cut steps and carved drainage ditches of rock-cut tanks found between the *magazakia* are submerged to a depth of 0.40 m.

The construction period of the *magazakia* has not been precisely determined since there is no relevant literary documentation. According to oral testimonies and narrations from the locals, they are dated back to just before or at the beginning of the twentieth century. The rock-cut ramps and the *phalangia* slots, as well as the rest of the cuttings (steps, tanks, ditches, bollards, built wall) should have been cut on dry land and their current submerged position indicates a change of 0.40 ± 0.10 m of the sea level during the last 120 years.

Images of all the slipways presented in this study, with details of the features examined, are given in Figs. 24 and 25.

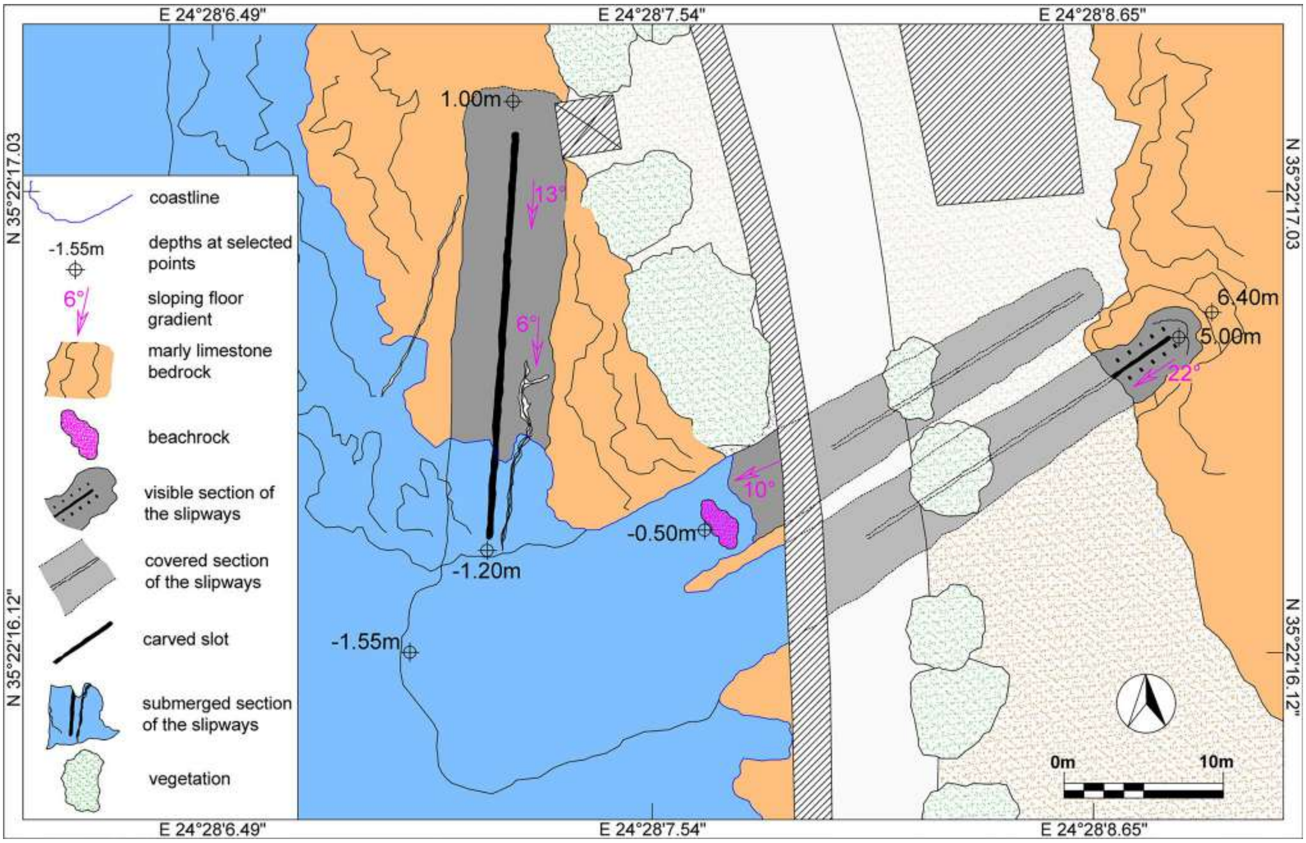


Fig. 15 Plan of the ancient slipways of Rethymno as they now stand

4 Discussion

Ancient coastal structures directly related to a former sea level stand are good indicators of rsl change and can be used for the dating of past sea levels, which are identified by geomorphological sea level markers (i.e. tidal marine notches, beachrocks, marine terraces). The determination of their archaeological age along with the understanding and interpretation of their function in relation to the sea level at the time they were in use is a prerequisite for rendering them precise and reliable indicators of the rsl change. Both the pioneering geoarchaeological and oceanographic surveys of N.C. Flemming in the late 1950s and then those by P.A. Pirazzoli, demonstrated the importance of shipsheds (and also fish tanks) in providing measurable evidence of the rsl change (e.g. Flemming 1972, 2021; Pirazzoli 1979; Flemming and Pirazzoli 1981). Blackman (1982) highlighted the value of harbourworks, including shipsheds, in establishing the evidence of rsl change and in dating precisely the former sea levels, and remaining faithful to this view, any evidence of the rsl change was presented in the catalogue of the Mediterranean shipsheds (SSAM 2013), aiming at determining the seaward end and thus the length of the slipway. Baika in SSAM (2013, p. 249) highlighted the contribution of rock-cut slipways to the study of rsl change in Mediterranean, mostly reflecting the complexity of the geoarchaeological landscape to which they belong.

Nevertheless, the ancient rock-cut slipways are, perhaps, inadequately recognised sea level indicators, which can, however, prove to be *archaeodetic* proxies of the rsl change. In a review of the archaeological sea level markers by Auriemma and Solinas (2009), the slipways were not included. On the other hand, Baika in SSAM (2013, p. 249) characterised slipways as 'precious archaeological markers of local and regional rsl changes', provided that their landward and seaward ends are 'firmly established' paying attention to 'methodological grounds'. Morhange and Marriner (2015, p. 148) classify slipways as a type of archaeological remains that 'yield quite precise RSL data because their function is directly related to sea level' and therefore can be used 'to reconstruct sea-level changes' with a 'vertical error usually speculated from present-day analogs'. Benjamin et al. (2017, p. 47 and related references therein) included slipways in the broad category of those structures that need to be at or partially below sea level in order to function properly. Moreover, in the same publication, Benjamin et al. based on Mourtzas et al.'s (2016) classification of the archaeological sea level markers along the Cretan coast,

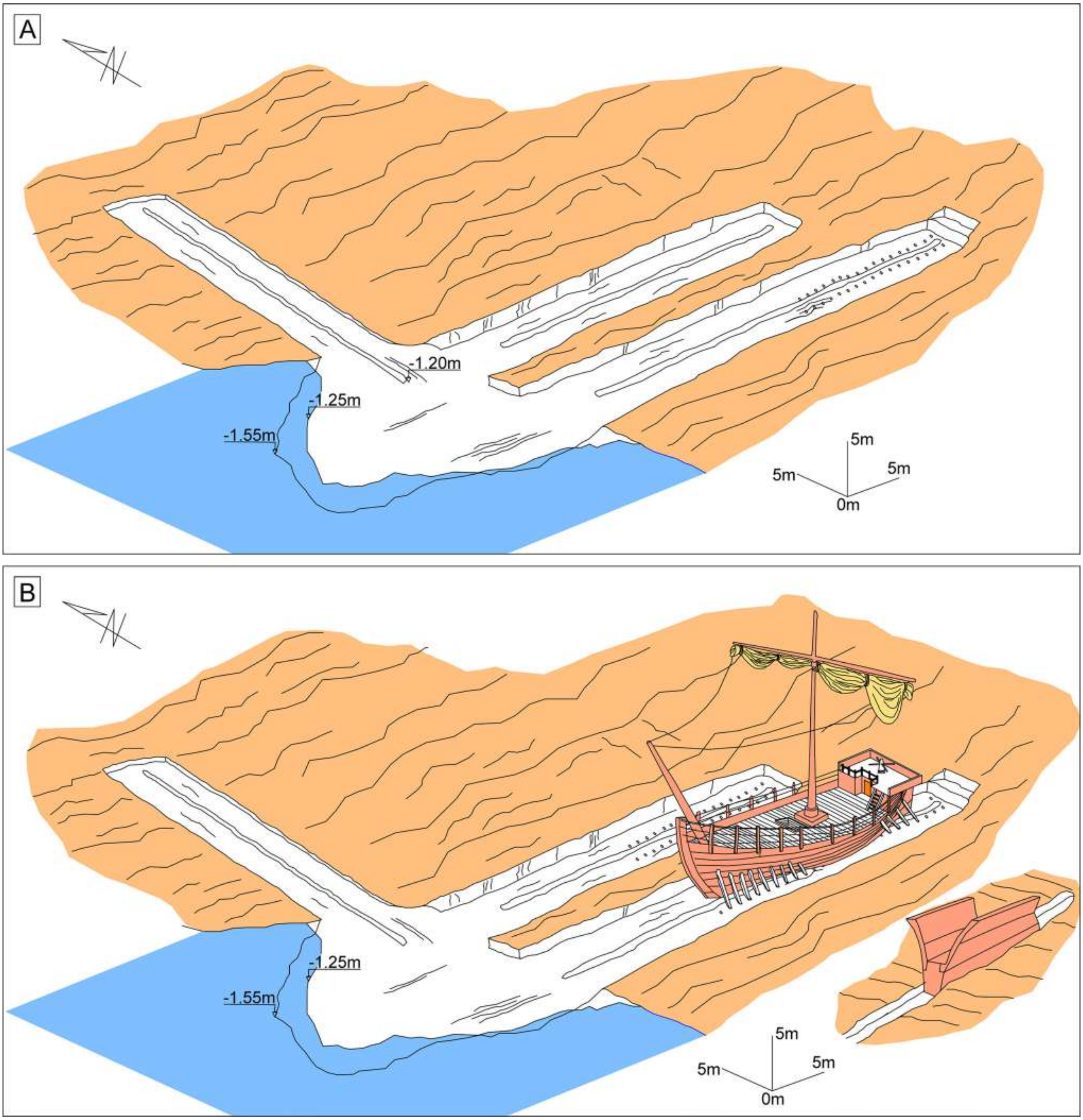


Fig. 16 3D reconstruction (**A**) and 3D schematic representation (**B**) of the slipways of Rethymno when the sea level was at 1.25 m bmsl

put the slipways along with fish tanks in the same category of maritime constructions, whose function was strictly related to past sea levels, and may offer reliable data on the rsl change provided that their age and spatial proximity to the contemporary shore can be determined. Kolaiti (2019) thoroughly described the archaeological sea level indicators, introducing a protocol for their use, and based on comparative depth observations throughout the Aegean suggested that slipways and fish tanks are precise sea level indicators, falling in the first category of archaeological indicators with high accuracy and sufficient reliability. It, therefore, becomes clear that determining the relationship between the seaward end of the rock-cut sloping floor and a former sea level is the crucial factor for slipways to be considered as precise archaeological sea level indicators.

The decisive feature of a rock-cut slipway is the border between its seaward end and the underlying natural rock. In most of the study sites, after the seaward end follows a low

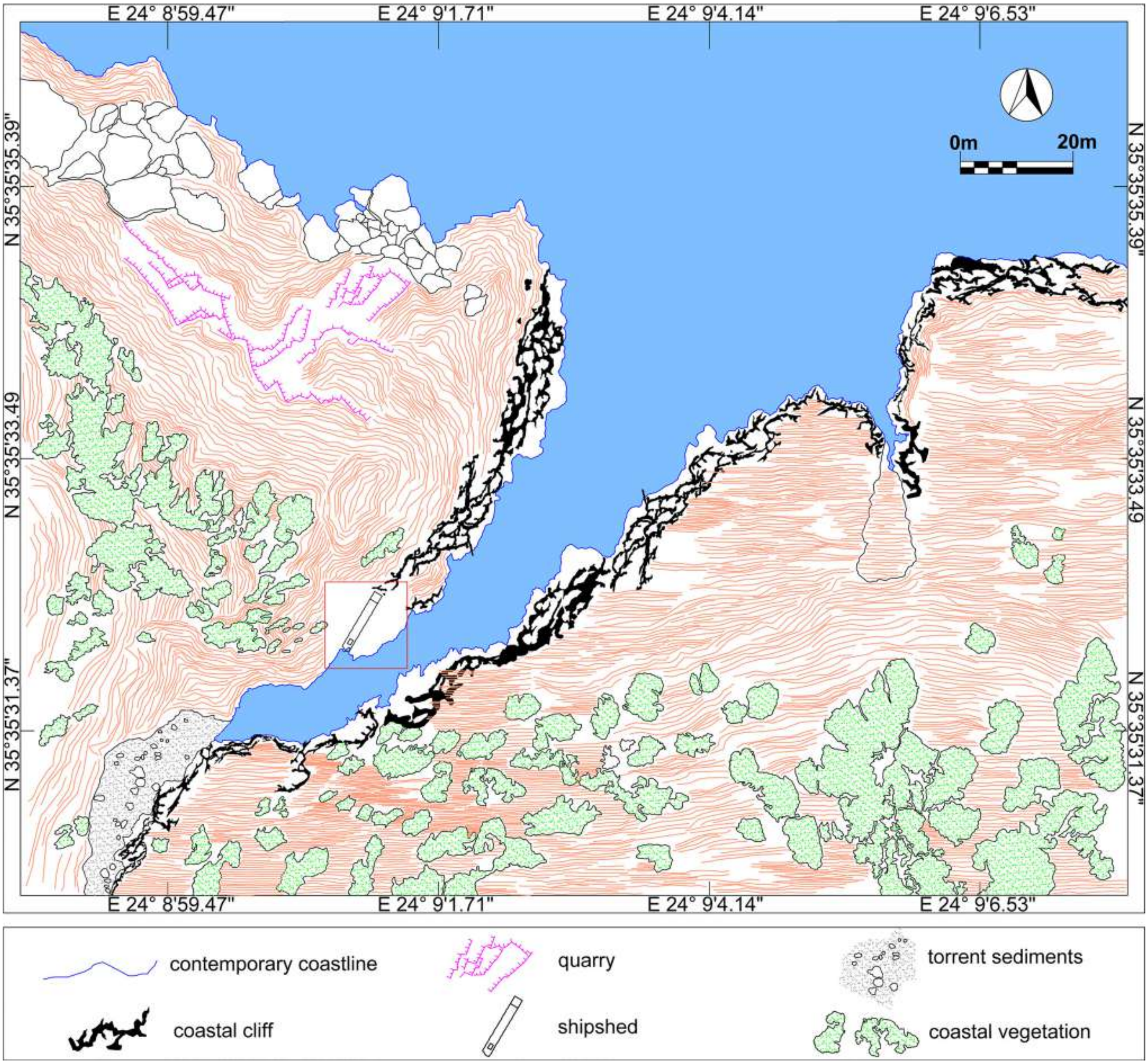


Fig. 17 Location map of Avlaki Cove. The location of the shipshed of Katholiko is indicated by a red square

cliff that ends at the sea bottom. The measured height of the underwater cliff is 2.10 m in Trypitos, 0.35 m in Poiiessa, 0.50 m in Mandraki, 2 m in Katholiko, and 1 m in Lazareto, Remma and Goupa (Table 1: column G). Later filling in Aegina, Matala and Rethymno slipways, does not allow such an observation. It becomes apparent that the cutting, following a particular gradient dictated by the coastal landscape, ended at a clear morphological erosional boundary that coincided with the then sea level. In Trypitos, where the rock surface was imperfect, due to the existence of an erosional cavity located 1 m amsl and 10 m from the then shoreline, slots were carved on the lateral sides of the cavity for placement of wooden beams in order to bridge the gap and fill the missing upper part up to the then waterline. In Aegina, due to the lack of excavation data and the existence of the later filling, no secure conclusions can be drawn about the slope gradient and the relationship of their seaward end to the mean sea level of the Classical period. Moreover, Aegina's shipsheds, like other major shipshed complexes of ancient times, with rock-cut foundations and ramps built up upon them, would have been subject to a more complicated constructional technique supported by availability of resources, than the small, entirely rock-cut, slipways, and must therefore be robustly corroborated by other evidence in order to be accepted as accurate indicators of ancient sea level.

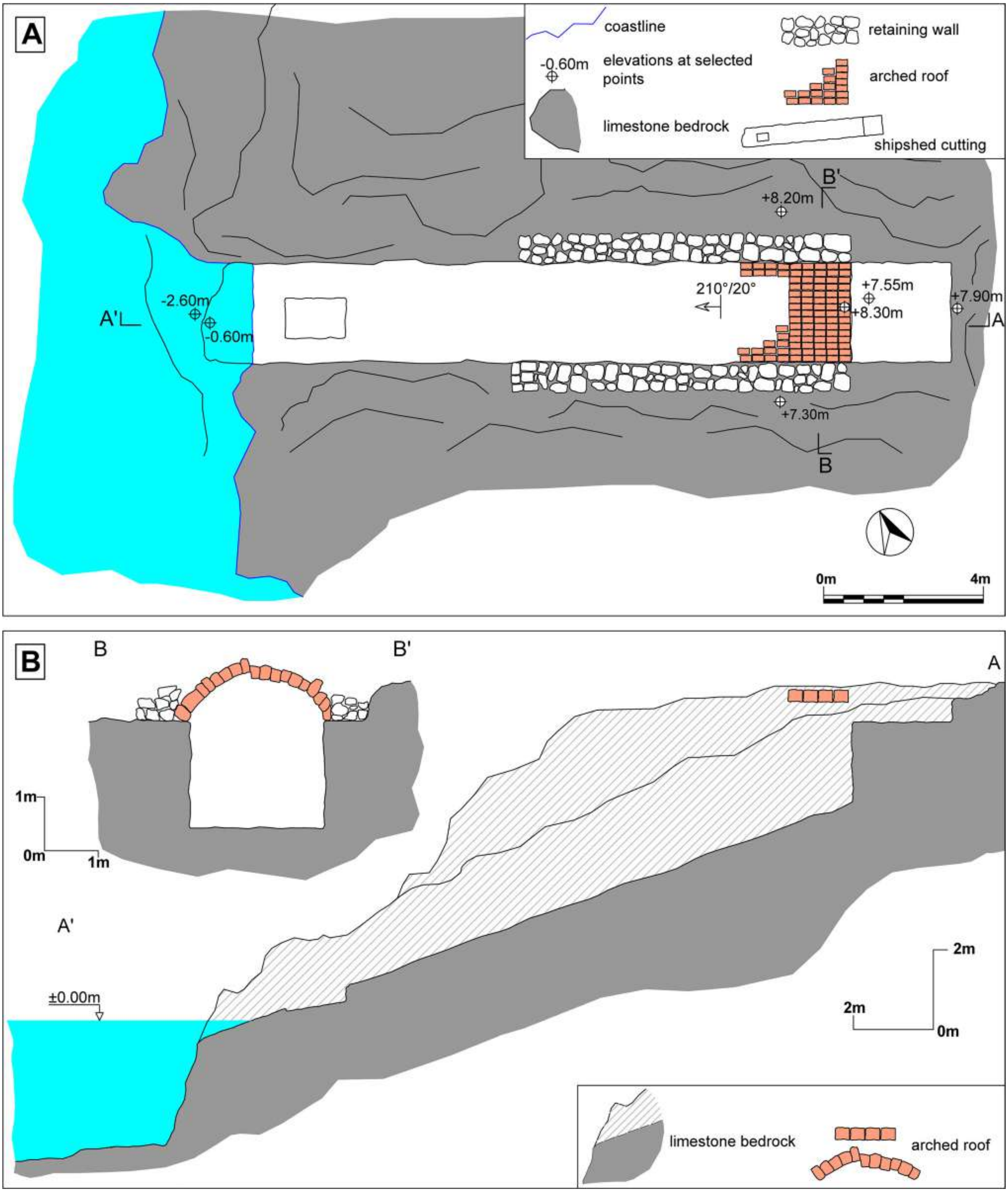


Fig. 18 Plan (**A**) and cross-sections A–A′ and B–B′ (**B**) of the Katholiko shipshed as it now stands

The difficulty of cutting part of the slipping floor underwater is another argument that slipways were entirely cut in dry land and the rock-cut surface ended up at the then sea level. Although in the ancient literary sources underwater activities are mentioned, with divers mainly involved in vandalism missions during naval conflicts or in shipwreck salvage

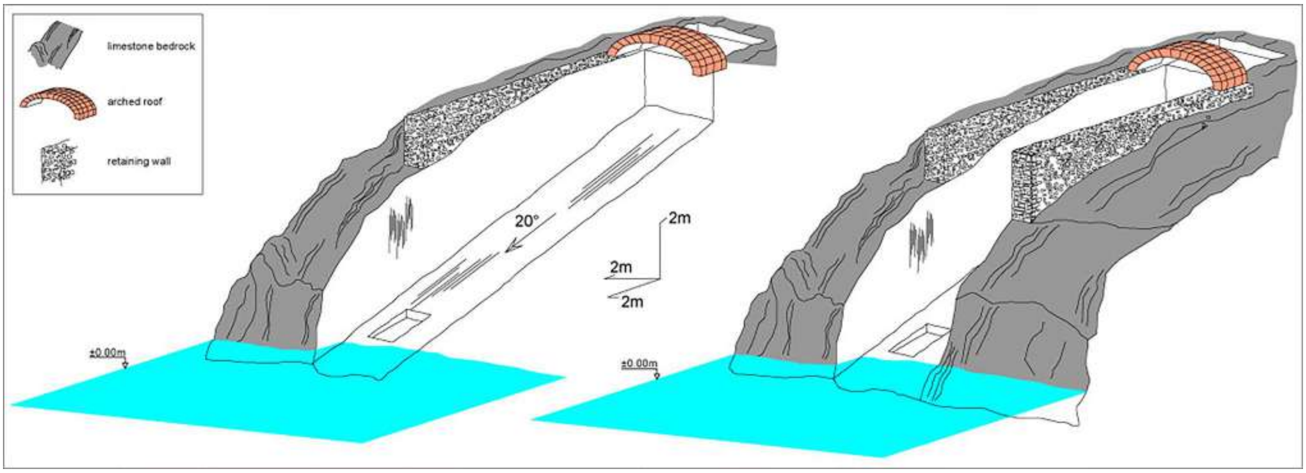


Fig. 19 3D reconstruction of the Katholiko shipshed as it now stands

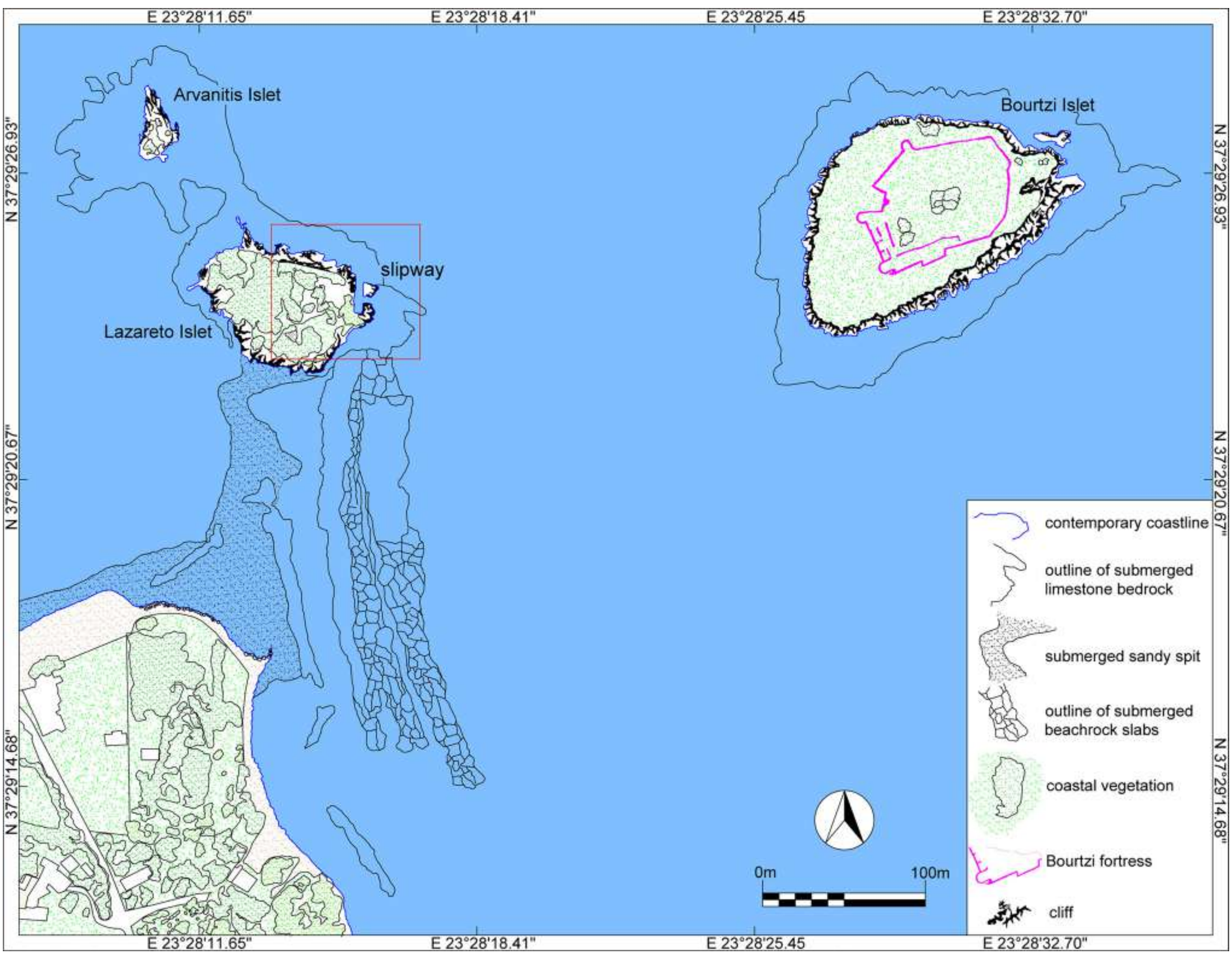


Fig. 20 Location map of Lazareto and Bourtzi Islets in the gulf of Alyki in Troezenia. The location of the Lazareto slipway is indicated by a red square

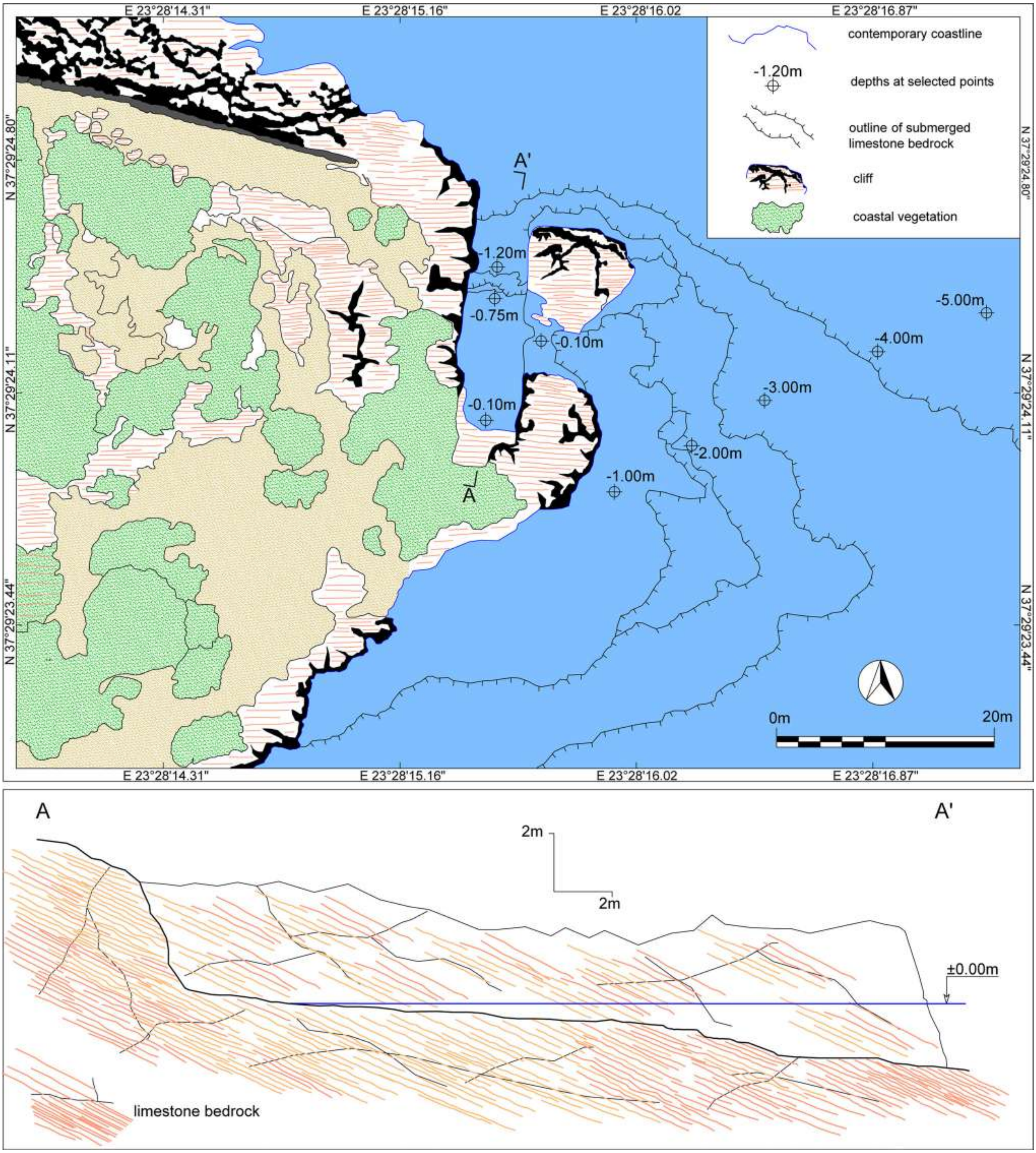


Fig. 21 Plan and cross-section A–A′ of the Lazareto slipway as it now stands

(Herodotus, 8.8; Thucydides, 7.25.5–6; Arrian, *Anabasis*, 2.21.6), there is no reference concerning underwater quarrying or cutting below the low tide sea level. Even if one single metre of the length of the seaward part of the sloping floor had been cut underwater, the area that would have had to be removed would have reached 5.50 m^2 in Trypito, 22 m^2 in Poiiessa, 8 m^2 in Matala, 2.50 m^2 in Katholiko, 20 m^2 in Rethymno, 17 m^2 in Mandraki, 6 m^2 in Lazareto, and 3.50 m^2 per slipway in Remma and Goupa on Kimolos. Underwater cutting of such extensive surfaces with even elaborated details (slots), whilst

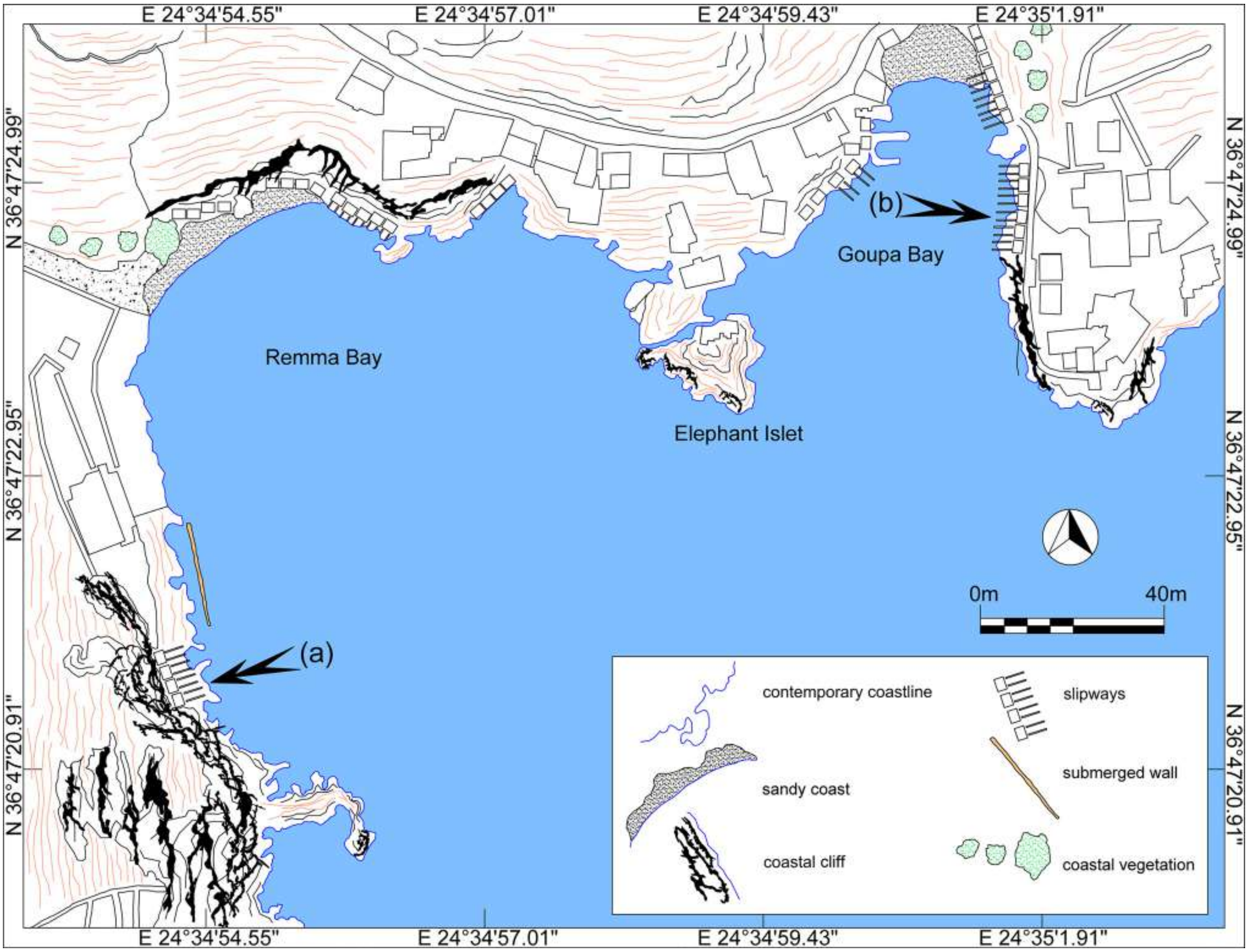


Fig. 22 Location map of Remma and Goupa Bays. Arrows **a, b** indicate the slipways that are presented in the cross-sections of Fig. 23

keeping the morpho-geometrical features of the sloping floor, would have been an extremely difficult and certainly a very demanding task. Moreover, an elderly owner of a *magazaki* in Kimolos reported that the cutting and maintenance of the rock-cut sloping floor were done in dry conditions during periods of low water (pers. comm., September 2021).

The Aegean region is one of the most seismically active and rapidly deforming regions in the world (Fig. 1b). It has complex structural features, mainly represented by lithospheric extension, convergence, and active subduction systems associated with active volcanoes within the Aegean Sea (Angelier and Le Pichon 1980; Angelier et al. 1982; Le Pichon et al. 1982; Papazachos et al. 2000; Jolivet et al. 2013; Brun et al. 2016; Mantovani et al. 2022). The larger Africa (Nubia) plate subducts beneath the Aegean microplate at 36 mm/yr along this margin (McKenzie 1972; Reilinger et al. 2006; Briole et al. 2021). Collision induces fragmentation of the lithosphere in tectonic blocks, continental block movements, active subduction system and mantle dynamics (McKenzie 1972, 1978; McKenzie and Jackson 1983, 1986; Taymaz et al. 1991; Le Pichon et al. 1995; McClusky et al. 2000; Goldsworthy et al. 2002; Nyst and Thatcher 2004; Kokkalas et al. 2006; Philippon et al. 2014; Confal et al. 2016). The Aegean has a complex tectonic history that has produced a strong heterogeneity in the crust. The bulk rheology of the continental lithosphere in the Aegean region is viscous and drives from below the motion of the various upper crustal blocks, where all displacements occur at the boundaries of the tectonic rigid blocks, involving frictional slip on faults. The asthenospheric flow also has a strong impact role in driving crustal deformation (Jolivet et al. 2013 and related references therein). In this complex strain context, a mosaic of large rigid blocks bordered by E–W and NNW–SSE strike-slip and oblique to normal faults was found in an active differential deformation process, directly affecting, and thus differentiating, the curves of the rsl change between the study areas. The contemporary measured depth of the seaward end of the rock-cut sloping floor

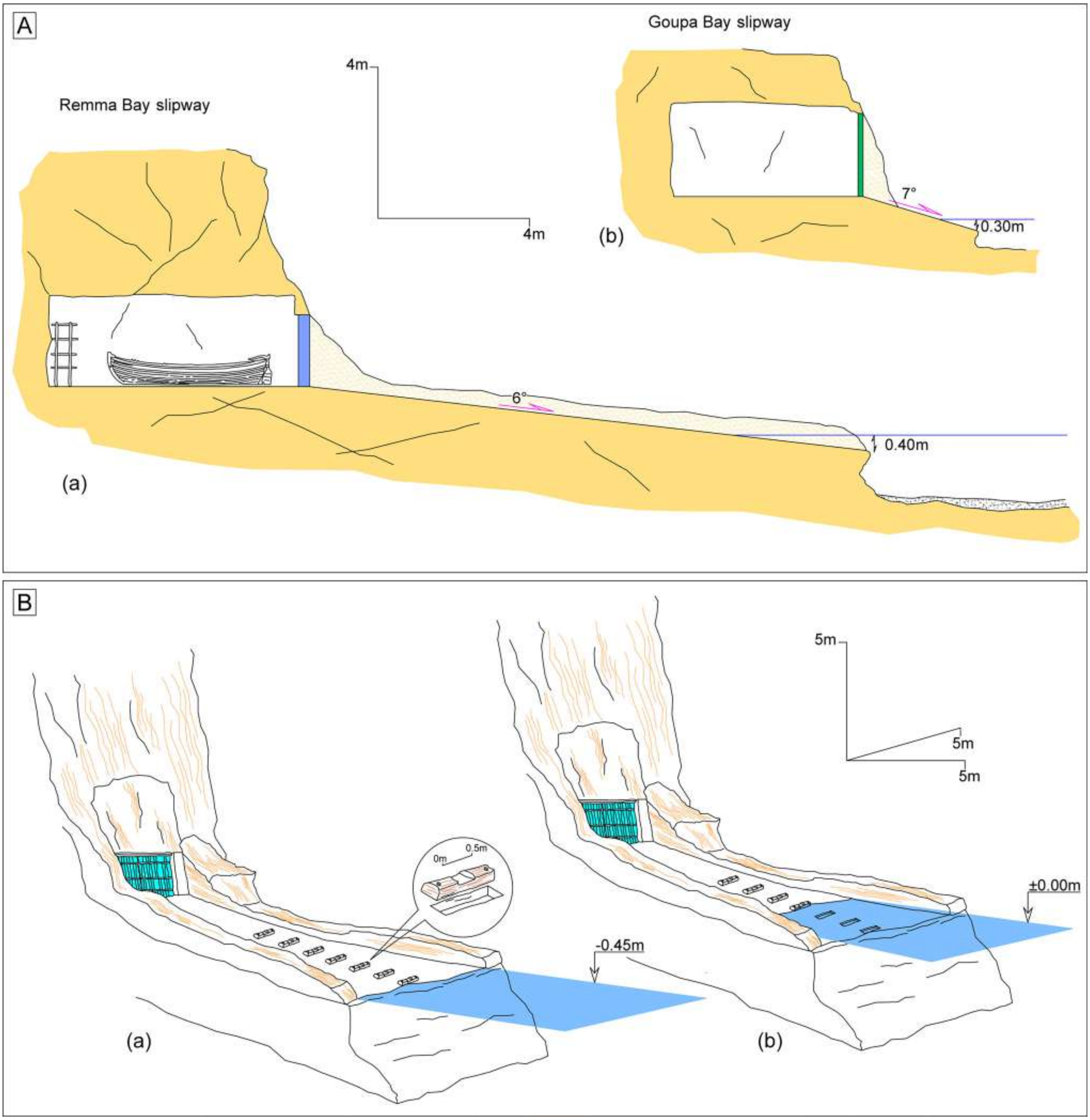
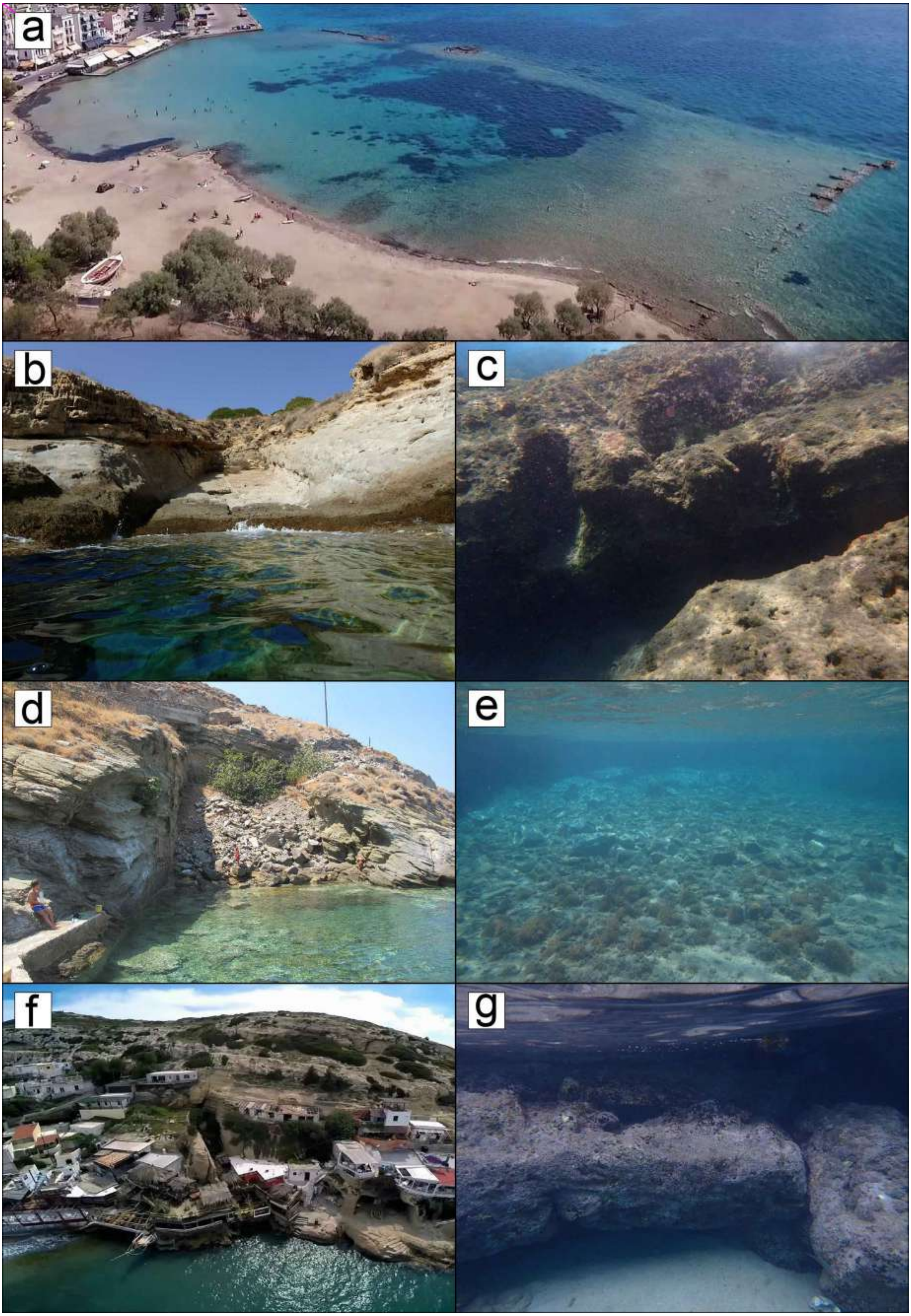


Fig. 23 **A** Cross-sections of the Remma (**a**) and Goupa (**b**) slipways. Their position is indicated by arrows on Fig. 22. **B** 3D reconstructions of the Goupa slipway when it was constructed with the sea level at 0.45 m bmsl (**a**) and as it now stands (**b**). The inset shows in more detail a carved slot for the placement of a wooden beam

(Table 1: column F) is interpolated into the curves of rsl rise as determined for each study area (Saronic Gulf/eastern coast of the Peloponnese, central Aegean/Cyclades, eastern and central coast of Crete) by geomorphological indicators and dated using good archaeological sea level markers and radiocarbon datings (Fig. 26). This comparison clearly indicates that the measured depths of all examined sites are either consistent with the corresponding sea level stands or fall within their range of depth uncertainty.

Specifically, the seaward end of the rock-cut lateral sides of the erosional cavity, on which have been formed the slots for placing wooden beams in the Hellenistic slipway of


a
b
c
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e
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g

◂**Fig. 24** **a** Aerial view of the closed harbour of Aegina: the submerged remains of the ancient shipsheds are shown on the northern side of the harbour (retrieved from: https://www.youtube.com/watch?v=vdb8JKkGRx8, accessed 26.7.2016). **b** View from the east of the Trypitos slipway (Sitia, NE Crete). **c** Underwater view of the grooves of the Trypitos slipway, into which wooden beams were placed to bridge the depression up to the then shoreline. **d** View from the north of the slipway of Poiiessa (Keos Island). **e** Underwater view of the rock-cut ramp of the Poiiessa slipway. **f** Aerial view of the shipshed and fish tanks in Matala Bay (S Crete). The modern taverns now overlying the ancient structures put their preservation at risk. **g** Underwater view of the visible lower end of the sloping floor of the Matala shipshed

Trypitos, is now at a depth of 1.20 m bmsl and coincides with the sea level at 1.25 ± 0.05 m bmsl dated to between 1200 BC and AD 1604 (Mourtzas et al. 2016). The rock-cut seaward end of the Hellenistic slipway of Poiiessa is at 2.25 m bmsl and is consistent with the sea level at 2.40 ± 0.20 m dated back to between 180–30 BC and AD 1000 (Kolaiti and Mourtzas 2020, 2023). At Matala, cutting traces are found up to a depth of 1.14 m bmsl and may have continued to a greater depth, reaching the Roman sea level of central and eastern Crete robustly determined at 1.25 ± 0.05 m bmsl by the adjacent Roman fish tanks (Mourtzas 2012a, b; Mourtzas and Kolaiti 2020). At Mandraki, the entrance of the rock-cut *carenaggio* of the Venetian period at Andros is now at 1.40 m bmsl, at the same depth as the sea level at 1.50 ± 0.20 m bmsl dated back to the Venetian period (Mourtzas 2018; Kolaiti and Mourtzas 2020, 2023). At Rethymno, the depth of the rock-cut seaward end of the slipway is at 1.20 m bmsl (western slipway) to 1.55 m bmsl (eastern slipways), the same as or some 0.25 m lower than the mean sea level of that period identified at 1.25 ± 0.05 m bmsl (Mourtzas et al. 2016). At Katholiko, the rock-cut seaward end of the slipway dated back to the last phase of the Venetian rule in Crete, is now at 0.60 m bmsl, the same as the sea level at 0.55 ± 0.05 m dated throughout Crete to between AD 1604 and the late nineteenth century (Mourtzas et al. 2016). The depth of the seaward end of the sloping floor of Lazareto slipway at 1.20 ± 0.15 m bmsl is associated with the sea level of the Saronic Gulf at 1.35 ± 0.15 m bmsl dated to between First Venetian Occupation/First phase of the Ottoman domination (*ca.* 1389) and two decades after the Greek War of Independence (*ca.* 1840) (Kolaiti and Mourtzas 2016; Kolaiti 2019, 2020). In the bays of Remma and Goupa in Kimolos, the rock-cut slipways, the slots and other cuttings, were made in dry conditions and their currently submerged position points to a rsl change by 0.40 ± 0.10 m over the last 120 years. This is consistent with the most recent sea level stand of the Cyclades at 0.45 ± 0.05 m that has been dated back to the late 19th–early twentieth century (Kolaiti and Mourtzas 2020, 2023) (Table 1: columns F and L).

A parallel worth mentioning to further substantiate our view on the coincidence of the seaward end of the ancient slipways with the sea level at the period of construction and use, is the uplifted slipway of the fortified town of Aigila, located on Kastro Hill, at the western cliff of the Potamos Bay, on the northern coast of Antikythera Island (Baika in SSAM 2013, pp. 277–283). Aigila is dated between the early fifth century BC (Waterhouse and Hope-Simpson 1961), late fifth century BC (Stais 1889) or the third quarter of the fourth century BC and the first half of the first century BC (Tsaravopoulos 2015). The current elevation at + 1.50 m of the seaward end of the slipway (Flemming and Pirazzoli 1981), which dates back to the same period as Aigila's *floruit*, is identical to the marine tidal notch at the same elevation, which has been dated around the island to 2970 ± 70 BP (788 BC to 389 BC) (Pirazzoli et al. 1982), thus providing strong evidence of the position of its seaward end at the sea level of the period of use.

Given that the depth of the seaward end of a slipway is consistent with the mean sea level of the period of construction and use, the sloping floor was flooded by the sea during high tide, whilst the sea conversely receded during low water. The flooded length of the ramp was different from site to site since it depends on the gradient of the sloping floor and the local tidal range, and it ranged from as much as 8 m in Mandraki to less than 1 m in Katholiko and Trypitos (Table 1: column M).

Finally, the Lazareto slipway is a paradigm of dating harbourworks of unknown age using evidence of the rsl change. The submerged position of the slipway and the interpolation of the measured depth of its seaward end into the rsl change curve for the eastern Peloponnese, provides evidence of the period when it was constructed. Besides, the suggested age is in agreement with the archaeological age of the adjacent Eidek Fort.

5 Conclusions

This study, based on geoarchaeological data from nine sites throughout the central and south Aegean where rock-cut slipways have been found, either previously known or first reported herein, attempts to establish the relationship between slipways and the former sea level. The spatial distribution of the examined slipways in the micro-tidal Aegean environment, along with their wide chronological range from the Classical period to Modern times, allowed us to make a correlation with the established sea level stands for the Aegean. It is evidenced that the seaward end of the sloping floor was positioned at the sea level of the period of use or just below it with an uncertainty not exceeding the tidal range, thus rendering slipways accurate indicators of the rsl change. The submerged or uplifted current position of the seaward end of their sloping floor represents the direction

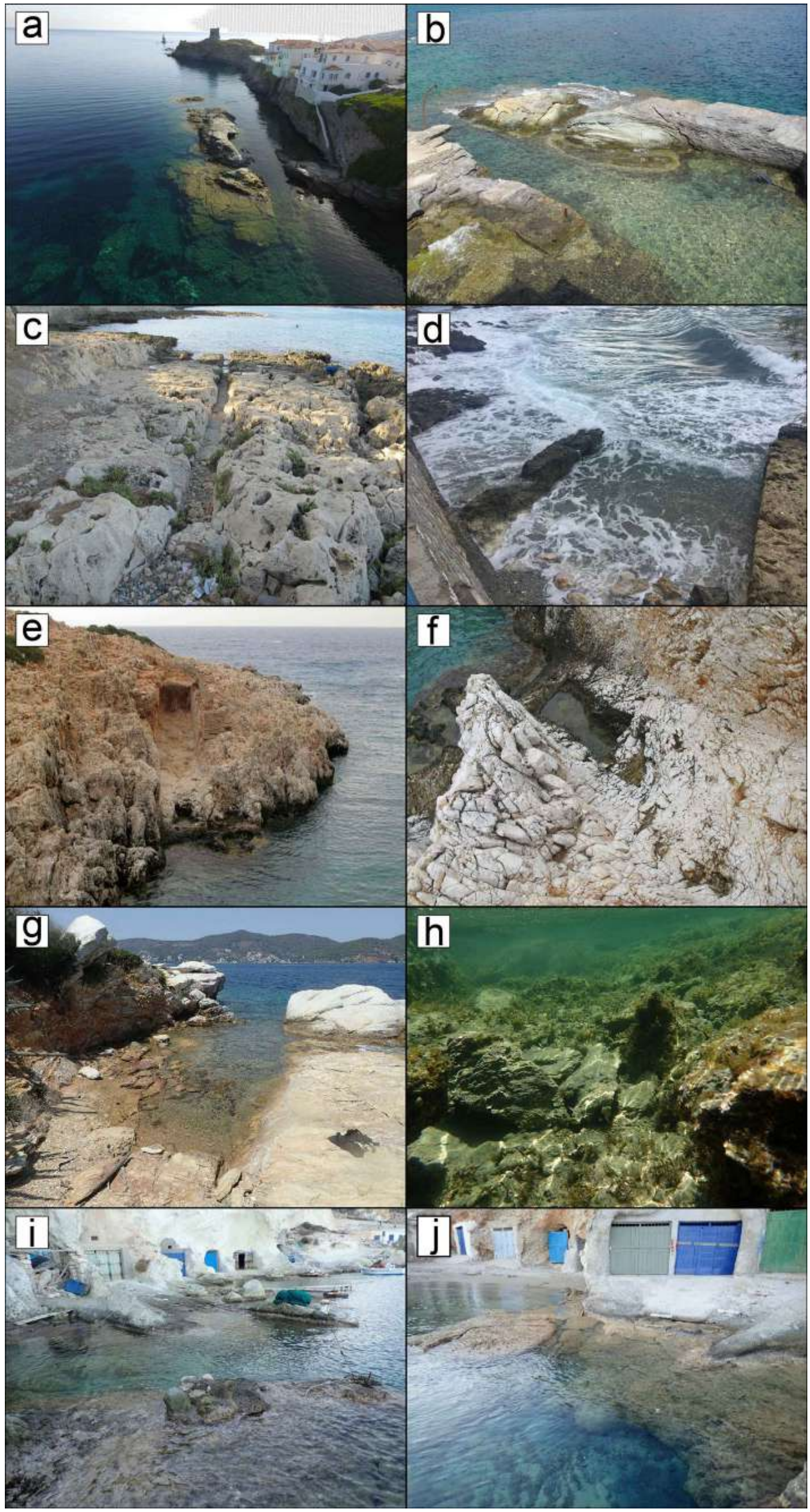

Fig. 25 **a** Aerial view of the Mandraki *carenaggio* (Andros Island). **b** View of the entrance and the central section of the Mandraki *carenaggio*. **c** The western slipway of the slipways complex in Rethymno (N Crete). The carved keel slot is preserved in the middle of the sloping floor of the slipway. **d** The seaward end of the two eastern slipways of Rethymno. **e** View from the south of the Katholiko shipshed (NW Crete). **f** The seaward end of the shipshed of Katholiko. **g** View from the south of the Lazareto slipway. **h** Underwater view of the sloping floor of the Lazareto slipway. **i**, **j** The sloping floors of the *magazakia* in Remma and Goupa Bays (Kimolos Island)

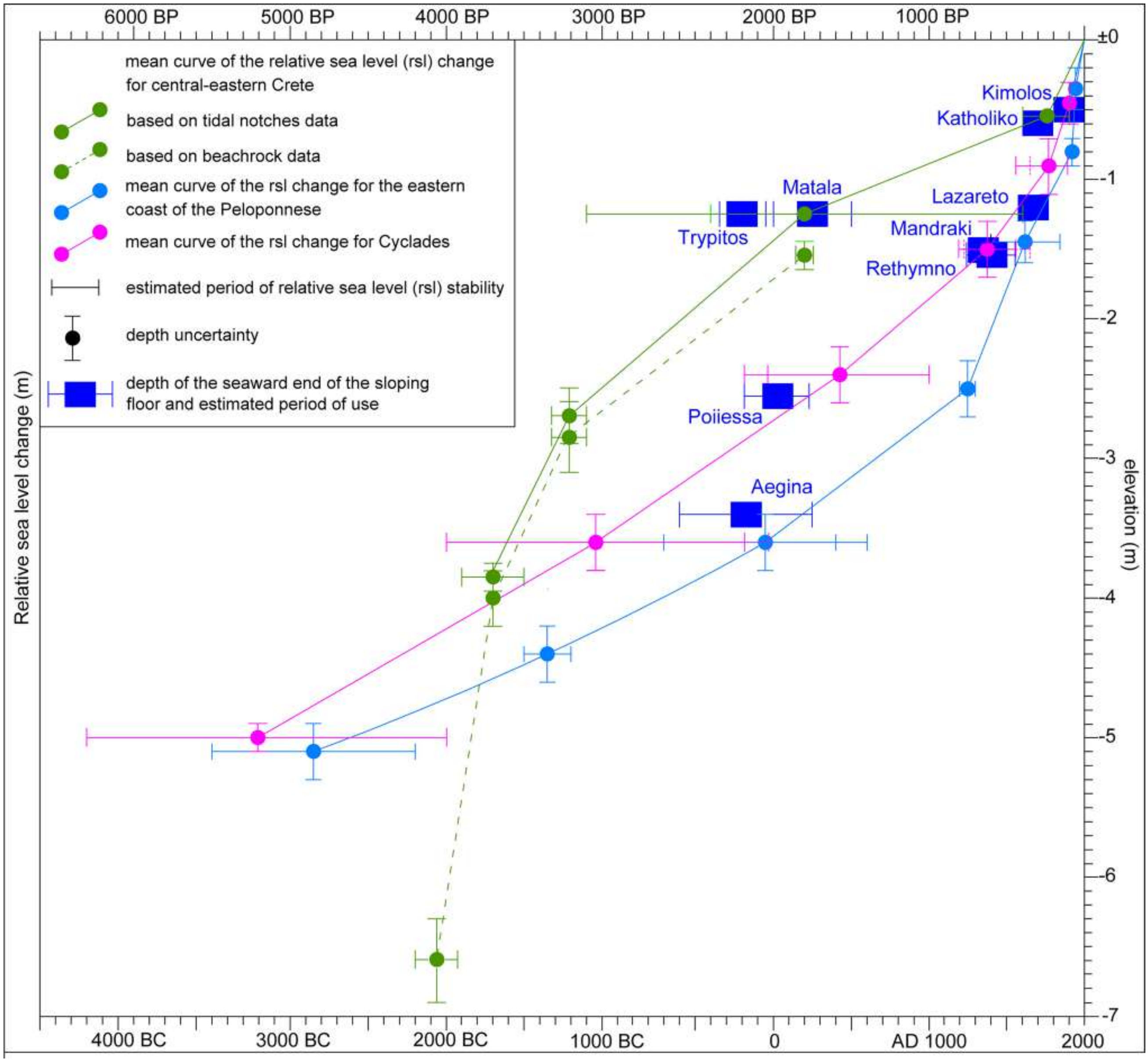

Fig. 26 Correlation of the contemporary depth of the seaward end of the sloping floor of the slipways presented in this study (blue square) with the sea level stands determined for each study area. Blue line: mean curve of the rsl change for the Saronic Gulf and the coast of eastern Peloponnese (after Kolaiti 2019). Magenta line: mean curve of the rsl change for the Cyclades (after Kolaiti and Mourtzas 2020, 2023). Green line: mean curve of the rsl change for eastern and central Crete (after Mourtzas et al. 2016)

and magnitude of the rsl change since the period when they were in use.

The value of slipways of certain age for determining and dating former sea levels is undoubtedly of great importance, as also for confirming already determined sea levels and their dating. Conversely, since their position relatively to the sea level at the period of use is established, then the archaeological dating of harbour works of unknown date, using the sea level determined for the particular area, will be proven equally useful. Moreover, slipways and shipsheds are not only accurate proxies of the rsl change, but also an important part of the Greek maritime history and tradition, highlighting the need to preserve and protect this vital cultural heritage.

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Data availability The authors declare that the data supporting the findings of this study are available within the paper.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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