Novel insights into the sea level evolution along the coast of Bozburun Peninsula (Turkey): A study on submerged Bronze Age harbor in Çamçalık



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# New insights on the sea-level evolution along the coast of Bozburun Peninsula (Turkey), from the submerged Bronze Age harbor in Çamçalık

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## Abstract

Recent discovery of a Bronze Age harbor site in Çamçalık provided new data for relative sea-level history along the coast of Bozburun Peninsula for the last 3600 years. The new data and the previously published data from the nearby sites were compared with the aim of understanding long-term relative sea-level changes. The further comparison of the observed sea-level data and newly produced glacial isostatic adjustment (GIA) models clarifies the tectonic contribution to the relative sea-level changes. Our results suggest a non-linear tectonic subsidence trend in the coastal zone since 3600 BP. An acceleration of the relative sea-level rise has occurred since the last 1400 years, mostly due to seismic events controlled by the tectonic regime of the southeastern Aegean Sea. As in the past, this active tectonic process will have a major impact on the future sea-level evolution of the coastal sector of the Bozburun Peninsula.

*Keywords:* Bronze Age harbor, relative sea-level change, archaeological sea-level indicators, tectonic subsidence, Bozburun Peninsula, Çamçalık

## 1 Introduction

The coastal areas of the Bozburun Peninsula, ancient Karian Chersonesos, in the southwestern Turkey have been inhabited for thousands of years. Most of the coastal sites are dated to the Late Roman-Early Byzantine Period, many to the Hellenistic Period, and only a few to earlier periods (Held, 2019). Due to relative sea-level (RSL) changes, the coastal archaeological remains are now partly or totally submerged in this shoreline. On the other hand, no evidence of the existence of a Bronze Age settlement has been found so far on this peninsula.

As a part of the Shipwreck Inventory Project of Turkey (SHIPT), which has been mapping and documenting the shipwrecks and submerged archaeological sites along the Turkish coasts since 2005 (Özdaş & Kızıldağ, 2013a), a recent coastal archaeological investigation has been initiated on the Bozburun Peninsula, focusing on the submerged archaeological remains on the coastal zone (Figure 1). During the 2019 survey, a Bronze Age coastal site was discovered on Çamçalık island, which is partially submerged due to RSL changes.

The RSL changes are the combined effect of eustatic, glacio-hydro-isostatic, and tectonic factors (Nakada & Lambeck, 1987; Peltier, 2004; Pirazzoli, 1997; 2005). The eustatic-isostatic contribution is associated with glacial meltwater inputs to the oceans and can be predicted by means of Glacio-Isostatic Adjustment (GIA) models, which require the spatio-temporal evolution of ice sheets and the Earth rheological profile (Stocchi & Spada, 2009) as inputs. Conversely, the tectonic contribution is less predictable and can be evaluated from the shoreline markers (Rovere et al., 2016). Since the meltwater input in the past 4000 years is small with respect to the deglaciation history in the last glacial cycle (Church et al., 2008; Lambeck et al., 2014; Peltier, 2004), any changes in RSL in this time frame are expected to stem from the sum of the GIA and tectonic movements rather than eustatic contribution.

Based on the data from archaeological sites of Fethiye, Anzidei et al. (2011) suggest that GIA contribution to the RSL changes plays a minor role and tectonic subsidence has a major contribution along the southwestern coasts of Turkey over the last 2300 years. GPS measurements and sea-level data obtained from Bodrum tide gauge (southwestern coasts of Turkey) confirm no significant vertical land motion between 1993 and 2009 in the region (Yıldız et al., 2013) and glacio-isostatic adjustment is suggested negligible (-0.01–0.16 mm/yr) (Yıldırım et al., 2022).

RSL changes can be inferred from the observations that have a direct relationship with sea levels in the past, which are called sea-level indicators, or sea-level index points. Those are defined as any archaeological, biological or geological feature that was constructed, formed, or deposited in connection with a former sea level (Morhange et al., 2001; Rovere et al., 2016). The current position of submerged coastal archaeological structures, which had a direct relationship with the shoreline during their operation, is used as a reliable indicator of past sea levels.

Previous studies indicated that the Mediterranean Sea has a great number of archaeological indicators of the sea-level variations of the last 4000 years (Anzidei et al., 2014; Auriemma & Solinas, 2009; Evelpidou et al., 2018; Flemming, 1978; Kolaiti & Mourtzas, 2016; Lambeck et al., 2018; Morhange et al., 2013; Pavlopoulos et al., 2012; Pirazzoli, 1976). The geoarchaeological assessment of submerged maritime and coastal constructions provided data on RSL changes along the coast of southwestern Turkey since Early Byzantine times (Anzidei et al., 2011; Flemming et al., 1973; Kızıldağ et al., 2012; Kızıldağ, 2019; Kızıldağ & Özdaş, 2021; Özdaş & Kızıldağ, 2013a; Stock et al., 2020). Nevertheless, no Bronze Age archaeological sea-level evidence could be obtained until now to provide data on the sea-level history of southwestern Turkish coasts.

In this study, sea-level data from a newly discovered Bronze Age site are presented to reconstruct the long-term sea-level evolution along the coast of the Bozburun Peninsula. Previously published data from two nearby sites, which were obtained under the SHIPT project, have been re-measured and re-evaluated in this study. A comparison of the observed data with sea-level predictions from GIA models provided an estimate for the tectonic component of the vertical displacement of the coastal sites.

## 2 Archaeological Framework

First settlers on the Chersonesos, modern Bozburun Peninsula, go back to the Chalcolithic Period (Gerber, 2019). For the following Bronze Age, no evidence has been found during the land surveys, except for two stone axes in Loryma (Gerber, 2019). This seemingly contradicts the Chersonesian place names which date back to the Bronze Age and indicate a continuity not yet visible in the archaeological record.

Archaeological surveys on Loryma, Bybassos, and Kastabos provided significant data on Chersonesos history (Held & Wilkening-Aumann, 2015; Held, 2019). In the first millennium BC, the Chersonesos has been inhabited by Karians. In the Geometric Period, they seem not to have been sedentary but rather nomadic shepherds who erected simple refuge forts on the top of hills and mountains, which were only used in case of emergency (Held, 2019). Around the late 8th or early 7th century BC, they became sedentary and settled down in about 15 small but well-fortified settlements. The Chersonesians had a decentral political organization and settlement pattern which considerably differs from the model of the Greek polis with one central city (*asty*) and a rural area (*chora*) around it, as in neighboring Knidos or Rhodos. This non-central pattern is typical Karian. In the 4th century BC, the Rhodians took possession of the mainland opposite their island to secure it and exploit it economically: the 'Rhodian Peraia' which initially comprised the Chersonesos.

There is plenty of evidence for the production of wine and the amphorae for the transport of the wine during the 3rd and 2nd centuries BC when the peninsula was part of the Rhodian Peraia (Held & Şenol, 2010). Shipwrecks found around the Bozburun Peninsula also provide evidence for maritime trade during the 3rd century BC (Özdaş & Kızıldağ, 2013b). A Hellenistic export harbor at Bybassos confirms this context (Held, 2014). Other harbors for small ships for local and regional trade, and installations for the production of marine goods like fish or possibly purple dye are located along the shore (Kızıldağ et al., 2012). They create a network of regional sea transport and connect the Chersonesian economy through large harbors like Bybassos with the Mediterranean world. In the first century BC, most of the peninsula was abandoned and resettled only in the 4th century AD, therefore mainly Archaic to Hellenistic and Byzantine Period contexts are found in the region.



## 3 Regional Setting

Bozburun Peninsula is located in the southeastern Aegean Sea, southwestern Turkey (Figure 1). The studied sites are situated along the western coast of the peninsula, whose shores are open to Yeşilova Gulf, opposite Symi Island. The gulf is characterized by a narrow shelf area, particularly in the southern part, and an indented coastline with numerous small islands and bays that provide sheltered anchorages for ships.

Bozburun Peninsula has a rocky coastal zone, mainly characterized by limestone. Mesozoic carbonates are generally exhibited, the oldest of which is the Upper Triassic-Lower Jurassic platform (Ersoy, 1993). These carbonates overlap the clastic units and are overlapped by offshore limestones.

Coastal evolution of the region is mainly affected by the active tectonic framework of the Aegean, which is controlled by the effects of subduction along the Hellenic Arc and of northward subduction of the African plate beneath western Turkey and the Aegean region (Nomikou et al., 2021; Taymaz et al., 2007). This motion causes a back-arc extension of the continental crust and southwestward movement of the Turkish plate in the Aegean extensional province (Taymaz et al., 2007). This movement has been produced significant volcanic activity on the Aegean Volcanic Arc since Pleistocene with several volcanic centers (e.g. Santorini, Kos, and Nisyros) (Nomikou et al., 2021). Bozburun Peninsula is situated in this tectonically active region of the interaction between the eastern end of the Aegean Volcanic Arc, Fethiye-Burdur Fault Zone (FBFZ), and the Pliny Trench (PT). This tectonic process caused numerous earthquakes during both historical and instrumental periods, affecting many archaeological sites. Significant clustered seismicity was recorded near the Yeşilova Gulf, and in the adjacent Gökova Gulf (Figure 1c).

Among the most destructive Rhodes earthquakes, it is worth mentioning: in 227 BC, which caused the collapse of the Colossus of Rhodes (Polybios 5,88); in AD 148, which caused a tsunami destroying many ships (Aelius Aristides, Rhodiakos 20–26); in 1481 ($I_0$=IX) with 30.000 fatalities; in 1609, which caused that over 10.000 people were reported to be drowned by a sea wave; and in 1874 ($I_0$=VIII), occurred very close to the study area (Guidoboni et al., 1994; Soysal et al., 1981). The earthquakes in the 6th and 7th century AD caused damage to several ancient cities in western Turkey (e.g. Sagalassos, Laodikeia and Hierapolis) (Similox-Tohon et al., 2005). The most recent earthquake activity occurred off the western Bozburun Peninsula between 24 to 28 November 2012, which had a mainshock of $M_L$=4.8 (Kandilli Observatory and Earthquake Research Institute, 2012) (Figure 1c). In total 582 earthquakes were recorded with a direction of about N-W, which are caused by local normal faults.

The most destructive and catastrophic event, the Santorini (or Thera) volcanic eruption, took place in the Late Bronze Age with accompanying subsequent major earthquakes and tsunamis. The chronology of the eruption is still disputable between earth scientists (1650-1600 BC) and archaeologists (1530-1500 BC) (Driessen, 2019). Based on radiocarbon analyses of catastrophe markers, the most probable date for the Minoan eruption was suggested as the late 17th century BC (Manning & Kromer, 2012), in particular, c. 1627–1600 BC (Friedrich & Heinemeier, 2009).



## 4 Methodology

A newly discovered submerged Bronze Age archaeological site in Çamçalık was investigated with the aim of estimating the RSL changes on the coast of the Bozburun Peninsula. Two adjacent sites in Hıdırlık and Kiseli (Kızıldağ et al., 2012), previously documented and dated to the Hellenistic and Early Byzantine periods, were also re-measured and re-evaluated to present a long-term sea-level evolution along the coast of Bozburun Peninsula. In addition to the archaeological sea-level indicators, geomorphological indicators, i.e. marine tidal notches, were also studied. To interpret the relative sea-level data, we made an approach for dating and an assumption for the minimum original elevation of the observational data (Auriemma & Solinas, 2009; Lambeck et al., 2004), and then a comparison with GIA models.

### 4.1 Survey methodology

The fieldwork was focused on measurements of the current elevations of archaeological (i.e. quay and breakwater) and geomorphological (tidal notch) structures, taking the photos and sampling the archaeological material. The first step of the fieldwork was to determine the distribution of the submerged remains by a photogrammetric survey based on taking aerial photos by using DJI Inspire 1 Pro with Zenmuse X5 16MP 30s camera. Then photomosaics were generated by using Agisoft Metashape software (Agisoft LLC., St. Petersburg, Russia). The subsequent stage of the survey was to measure the current elevations of the archaeological and geomorphological structures with respect to the present mean sea level. All the finds were located using a JRC model differential global positioning system (DGPS) receiver.

The upper surface depth from sea level, the height, and the width of the quays and breakwaters were measured (Table 1). As for tidal notch, the vertex depth from sea level, the inward depth and the height were measured. All measurements were taken during periods of low-energy waves. The observed data were reduced to mean sea level by applying tidal corrections at the time of surveys by calculating the residual sea level using a tide gauge dataset obtained from the nearest Marmaris station (https://tudes.harita.gov.tr). The local tide amplitude is ~0.3 m on the southwestern coast of Turkey (Yıldırım et al., 2022).

A vertical error was added to the measurements, which could be derived from the accuracy of measurements of the structures (Vacchi et al., 2016) and the condition of the measured surface. Although harbor constructions are good sea-level indicators, they have some limitations when determining whether the measured surface of the structures represents the original surface at the time of construction (Benjamin et al., 2017). The depths of particular functional features of the harbor installations were measured on the best-preserved original surface of the structures with consideration of the uncollapsed regular surfaces, both those extending for meters at almost the same level. Particularly in the Hıdırlık site, the uppermost surface of the breakwater clearly reflects the original surface used in the past since the wall remains can be followed throughout the entire structure. Since the sites are located on a low-energy coast that is sheltered from winds and waves, no measurement difficulties were encountered due to the wave effects. Therefore, a vertical error of ±0.1 m was added to the measurements taken from the preserved surfaces.



**4.2 Relative sea-level reconstruction**

The accuracy of the RSL reconstruction using archaeological sea-level markers depends on determining their association with the sea level in the past (Morhange & Marriner, 2015). Interface structures of harbors (e.g. quays and breakwaters) provide reliable data on the amount of sea-level change (Evelpidou & Karkani, 2018; Morhange & Marriner, 2015; Vacchi et al., 2016). The presence of fixed biological zonation on the archaeological structures significantly improves the reliability of sea-level index points (SLIP; indicators of former RSL) (Morhange & Marriner, 2015). In some cases, the construction technique can help to determine the amount of the functional height (the original elevation above the ancient MSL) (i.e. by detecting the concrete change between the areas in hydraulic concrete and the areas in concrete in a subaerial environment) (Aucelli et al., 2020). In case of the absence of bio-zonation or any other evidence, the assigning of functional height can have some difficulties since it differs by region, age and function of the structure. However, Antonioli et al. (2007) and Auriemma & Solinas (2009) suggested a functional height for harbor installations (e.g. piers, docks, and breakwaters) of 0.6 m above mean sea level taking into account the observations collected at many submerged archaeological sites along the coast of Mediterranean. This assumption was widely used in many sea-level studies in recent years (e.g. Aucelli et al., 2016; Kızıldağ & Özdaş, 2021; Kolaiti & Mourtzas, 2020).

We assigned 0.6 m of minimum original elevation for the quays and breakwaters with respect to the mean sea level during their operation, taking into consideration (i) the site conditions (e.g. the protection against wave action and shallow harbor basin), (ii) local tide amplitude (i.e. micro-tidal range); (iii) the draught of the ancient small boats for the landing to the quay (e.g. the Ravenna ship from 5th century AD had a draught about 0.5 m; Medas, 2003), (iv) the modern quays and breakwaters in the Bozburun town (e.g. their elevations of 0.6/0.8±0.1 m during the mean sea level); and (v) the relevant literature mentioned above. Taking into account the lack of precise sea-level index points (e.g. biological zonation) we added an error of ±0.2 m for the uncertainty of the original elevation approximation, which was assumed based on different interpretations presented by the abovementioned sea-level studies.

The breakwaters in the studied sites have a maximum height of 1.2 m. They have been built in small, shallow, and protected bays and must have been used by the small boats. If we add the error of -0.2 m and the high tide of 0.15 m to the presumed "minimum" original elevation of 0.6 m, the emerging segment of a breakwater has a height of 0.25 m and no less than 0.25 m was presumed for protection. The depth of harbor basin in front of the quay or breakwater was also considered for presumed original elevation and its error.

By determining a minimum original elevation, we estimated the paleo RSL position from the following equation (Shennan et al., 2015):

$$RSL_i = ME_i - OE_i$$

where ME is the measured elevation of the archaeological sea-level marker “i" and OE is the minimum original elevation value for the marker “i".

**4.3 Chronological setting**

To improve the chronology of RSL changes, we considered the time of the last use of archaeological constructions when they were still functional. Based on the fact that the sites were never used after they were abandoned, this study adopted the approach of the time of the last usage instead of construction time (Kızıldağ, 2019). This provides data on the earliest time of submergence and a more precise estimation. In other words, this approach constrained estimates of the magnitude of the vertical land movements. Archaeological material, i.e. ceramic findings among the submerged harbor structures and architectural remains on land, provided important chronological data. Furthermore, literature and historical records supplied information regarding the abandonment date.

**4.4 GIA predictions and contributions to the RSL**

The separation of glacio-hydro-isostatic signals from the observed sea-level data allows us to identify the amount of tectonic contribution to the RSL change and obtain the vertical tectonic rate (Anzidei et al., 2011; Karkani et al., 2019; Kolaiti & Mourtzas, 2020; Lambeck et al., 2004; Mattei et al. 2022; Vacchi et al., 2020). In order to identify the expected vertical land movements due to glacio-hydro-isostasy, we computed a set of GIA models for the study area. Then the predictions from GIA models were compared with the observational sea-level data to assess the vertical tectonic movements.

To evaluate the variations of RSL induced by GIA since 5000 BP, we obtained a suite of high-resolution solutions of the sea-level equation (SLE) using the SELEN4 solver (Spada & Melini, 2019). The SLE accounts for the gravitationally and topographically self-consistent response of the Earth to the melting of Late Pleistocene ice sheets, and its basic inputs are the spatio-temporal evolution of the ice load and the rheological profile of the Earth. We computed three solutions of the SLE by integrating into SELEN4 the ice chronologies and viscosity profiles assumed by ICE-6G (Peltier et al., 2015), ICE-7G (Roy & Peltier, 2015; 2017), and one of the iterations of the GIA models progressively developed by K. Lambeck and collaborators at the Australian National University (ANU; see e.g. Lambeck et al., 2003, 2014; Nakada & Lambeck, 1987). All our simulations are based on a global icosahedral grid with a spacing of ~40 km and include spectral terms up to harmonic degree L=512 that correspond to a wavelength of ~80 km on the Earth's surface. The boundary conditions for paleo-topography have been prescribed by assuming as a present-day topography the bedrock version of the ETOPO1 global topographic model by Amante & Eakins (2009), integrated with the Bedmap2 relief (Fretwell et al., 2013) in the Antarctic region (south of 60°S latitude).

As discussed by Melini & Spada (2019), GIA models are affected by different sources of uncertainties, stemming from imperfect knowledge of the model parameters and by different approaches to the numerical solution of the SLE. This is of particular relevance in regional-scale GIA models, since local rheological structure may be significantly different from average profiles suitable for global GIA models. Following Spada & Melini (2022), through an ensemble approach, we have evaluated a range of uncertainties associated with RSL predictions of models ICE-6G and ANU, arising from imperfect knowledge of the regional-scale rheological structure of the Mediterranean basin. In particular, since hydro-isostatic effects are mostly controlled by lithospheric flexure, we considered variations of the modeled

RSL curves corresponding to a range of plausible values of the thickness of the lithosphere and evaluated the corresponding 1-sigma uncertainties on the model predictions.

## 5 Results

In this study, sea-level data from a new submerged Bronze age site (Çamçalık) and previously discovered and re-surveyed and re-measured two submerged archaeological sites (Hıdırlık and Kiseli) were analyzed to reconstruct the long-term RSL changes occurred along the Bozburun Peninsula in the last 3600 years.



### 5.1 Çamçalık Bronze Age site

A submerged platform structure containing a large number of archaeological materials was found at the Çamçalık Bronze Age site (Figure 2). The platform extends about 150 m parallel to the shoreline, with a maximum width of 10 m at the northern side of the Çamçalık island, which is connected to a submerged isthmus to the mainland. The upper surface of the structure is located at -2.5±0.1 m, while the bottom goes down in an abrupt vertical sheer to the natural seafloor at -4.9±0.1 m depth. The archaeological materials in this artificial platform are naturally concreted and cemented with rocky materials (Figure 2d, e).

Among the archaeological finds, hundreds of loom weights, conical cups, carinated cups, stone axes and tools, and a large number of ceramic fragments of pithoi, beak-spouted jugs, oval-mouthed amphorae, tripod legs of cooking pots, etc. were recorded, most of them homogeneous in type and date (Figure 3). While most loom weights and conical cups are intact, all other ceramic vessels are in poor condition. Removing the cemented archaeological material during the archaeological excavation, some well-preserved loom weights, conical cups, and pottery fragments were uncovered as uncemented and surrounded by rock pieces.

Some wall remains are visible on the top of the eastern section of the platform, extending to the land, which are submerged today (Figure 2b, c). With only one layer of stones, they are barely distinguishable among the debris from a modern fish farm and coastal erosion, partly remaining under modern masonry. The wall remains, which have been constructed by using rubble and roughly-cut stones without mortar, form rectangular structures with a maximum width of 8 m.

During the complimentary survey carried out on land, we obtained only a few finds, scattered over the whole island, and showing the same spectrum. The whole island, despite its uncomfortably steep and rocky slopes, has been inhabited as attested by many small terraces built from rough boulders and up to the peak of the island. The plainer eastern part of the island near the submerged isthmus connecting it to the mainland, which was most suitable for construction, has been destroyed by service buildings and installations of a recent fish farm.

In addition to archaeological materials, we observed geomorphological indicators along the limestone rocky coastline of the site. A distinctive submerged tidal notch structure is identified along the southwestern limestone cliff of the island (Figure 4a). The vertex depth of the notch, which corresponds to the former mean sea level, is approximately 0.6±0.1 m lower than the modern shoreline. The inward depth was measured as 0.8±0.1 m.

**5.2 Hıdırlık Hellenistic site**

Previous studies carried out in the submerged sites on the coast of Bozburun Peninsula provide a data set for long-term sea-level evaluation (Kızıldağ et al., 2012). A submerged breakwater located in the Hıdırlık Harbor on the southern coast of Yeşilova Gulf was re-investigated during the fieldwork. Rubble-mound breakwater has a length of 36 m and maximum width of 10 m (Figure 5). The well-preserved top layer, which has been made up of large rough stones, lies at -1.5±0.1 m (Figure 5b, c). The bottom depth reaches 2.7±0.1 m at the inner basin and 3.5±0.1 m at the outer basin. The foundations of a rectangular building were observed in the inner harbor; whose floors are measured at -0.7±0.1 m.

This small harbor is linked to a Hellenistic farm by a path, and the breakwater must have served the farm. An architectural remain dated to the Late Classical/Early Hellenistic Period (4th-3rd century BC) is located on the coastline, which is most probably associated with harbor activities (Figure 5a, inset). Additionally, the shipwrecks in the surrounding area confirm a date of 3rd century BC for the time of the usage of the harbor.

A well-developed submerged tidal notch structure was observed along the coast at a depth of 0.5 to 0.55 m with a maximum inward depth of 0.4 m (Figure 4b).

**5.3 Kiseli early Byzantine site**

A submerged breakwater is located off Kiseli Island, close to Tymnos ancient city and modern Bozburun town, which was previously documented by Kızıldağ et al. (2012) (Figure 6a, b). The surface of a rubble mound breakwater is now located at -1.0±0.1 m below present mean sea level. The depth at the base of 16 m long and 6 m wide breakwater was measured at -1.8±0.1 m at its seaward end. The breakwater is associated with the adjacent partly submerged church remains dated to the early Byzantine period (Figure 6a).

A submerged quay consisting of rough-cut ashlar blocks is located on the western coast of Kiseli Island (Figure 6c). The upper surface of the quay lies at -1.0±0.1 m below present sea level, while the bottom level lies at -2.40±0.1 m. The foundations belonging to rectangular buildings on the quay platform are partly submerged. Based on the fact that the building foundations are located directly upon the quay platform and the quay blocks are preserved and not collapsed, the current surface of the quay is considered to represent the original surface.

The adjacent buildings and churches on land are dated to the early Byzantine times, which were in use until the 7th century AD. The abundance of LR1 amphora sherds, dated to the 5–7th century AD (Opait, 2004), near the breakwater and along the coasts provide evidence for the time of the last usage of the site.

Similar to other sites, a clear tidal notch structure is located at -0.6 m with a maximum inward depth of 0.3 m that continuous along the entire rocky coast (Figure 4c). No present-day notch is observed.

## 6 Discussion

### 6.1 A Bronze Age quay

The investigation of Bronze Age harbors in the Aegean Sea is a major challenge for researchers since most of them are submerged or buried due to geomorphological changes like sea-level changes, siltation, marine erosion, and tectonic movements, which have occurred since that time (Tartaron, 2013). Before coastal geomorphological studies accelerated, the problem of long-term coastal change was widely ignored as it was assumed that Bronze Age coastal morphology remained unchanged until today.

The known Bronze age harbors (e.g. the Minoan harbors of Gournia, Pseira, Kommos, Amnissos, Malia, and Mochlos) exhibit some common characteristics, including natural protection from the prevailing wind; a promontory or bay where ships can moor; an installation for winter storage of ships; storage facilities for goods; and a location near trade activity (Blackman, 1982; Watrous, 2012). According to Shaw (1990), the preferred topography was peninsulas with sandy beaches on both sides as landing places. Tartaron et al. (2003) successfully used this "double harbor arrangement" pattern to detect Bronze Age harbors by reconstructing the shoreline.

According to most scholars, the Aegean harbors of the Bronze Age were not supplied with maritime installations (e.g. quays and piers); instead, sandy beaches were used for landing, where the ships could be dragged on land (e.g. Loizou, 2016; Shaw, 1990; Tartaron et al., 2003). After geomorphological reconstruction of the harbor of Zakros in Crete, Guttandin et al. (2011) suggested that the harbor was originally located in a bay that since then has been silted up and had a jetty at its entrance and probably quays erected from large boulders along the shore. Similar quays may be recognized on the ship fresco from Akrotiri, where–next to the mentioned bay with small ships on the beach–in a neighboring bay two ships are depicted, berthing with their sterns perpendicular to the shore or a quay (Blackman, 2011; Guttandin et al., 2011).

The most recent discussion was presented by Hadjidaki (2021) about the Minoan natural or artificial harbors. To construct a harbor at Kapetaniana (Crete), the top of the small reef was flattened, and lines of stones were placed on top of it, thus producing a mole of 40 m in length. Furthermore, in the region where the coast was flat enough, an artificial installation was provided, which was created from pottery concreted within the boulders and sherds, for additional protection and landings of the ships. A man-made mole or breakwater is located in the harbor of Cape Plaka (Crete), built on top of a natural reef with some lines of large boulders (Hadjidaki, 2004).

The artificial platform of Çamçalık must have provided a quay function in the Bronze Age topography of the site (Figure 7). Associated with some Minoan harbor works in Crete, it seems to have been a construction of rough boulders producing a slightly sloping quay, rather than a vertical masonry stone wall. This yet is not an obstacle for the use as a quay, provided that the ships docked with the bow towards the quay, and an anchor at the stern-or the other way round. This is the usual system of berthing in the Mediterranean, even today ships are using a quay of rough boulders. The presence of the wall stones on the platform provides evidence for its function as a quay. The platform must have provided a dry area for the landing of ships and cargo transfer. With an average width of 10 m, the platform has offered sufficient space for the erection of small buildings.



**6.2 Cultural context of Çamçalık**

The spectrum of the Çamçalık pottery, which contains conical cups, three-legged cooking pots, spherical loom weights, etc., is culturally associated with the household pottery of Minoan, Bronze Age Aegean culture (Momigliano, 2012). In particular, the use of Linear A script on three loom weights provides clear evidence of Minoan culture (Silvia Ferrara, Bologna, pers. comm.). The closest finds of pottery are dated between Middle Minoan III (MM III) to Late Minoan I (LM I) phases, i.e. to the Neopalatial Period in Crete (Watrous, 2021). In addition, the pottery shows the typical range of Minoanising settlements in Anatolia such as Iasos or Miletos. There was a network between the Aegean islands and the Anatolian mainland (Momigliano, 2009). The MM III to LM I periods are well attested in Anatolia and correspond to phase IV at Miletos (Niemeier, 2005; 2007). Çamçalık pottery is very similar to that of Miletos IV, with 95% of the pottery determined as Minoan types, most of it locally produced, and only 5% local western Anatolian types (Niemeier, 2005; 2007).

Since no other period is attested in the finds, the submerged platform of Çamçalık can be dated to the MM III/LM IA period (1600 BC). Since material from later periods is absent, the occupation at Çamçalık had only one phase before its destruction and abandonment. The end of the settlement may have been caused by the Santorini eruption, accompanied by co-seismic tectonic movements. The eruption also caused a period of decline at Iasos (Momigliano, 2012; Niemeier, 2007).

Çamçalık is unique in terms of providing the largest collection of Bronze Age finds ever found underwater in Anatolia. One of the puzzling results of the previous land or underwater surveys on the Bozburun Peninsula was the almost complete lack of evidence for Bronze Age coastal settlements. Nevertheless, Bronze Age finds from the underwater survey in the Hisarönü Bay and at Loryma (Özdaş & Kızıldağ, 2016; Özdaş & Kızıldağ, 2017) proved that the area has been used in the Bronze Age by ships. The discovery of the Çamçalık Bronze Age site complemented and explained the underwater finds filling a gap in the literature in this region.

**6.3 Relative sea-level evaluation**

The submersion of the harbor structure of the Çamçalık site led to the identification of a sea-level stand during the Bronze Age. Taking into consideration the assumed original elevation for the quay and the last time of use for the site, the RSL change was determined by using the equation RSLi to be at least 3.1±0.3 m during the last 3600 years.

Data from nearby submerged sites on the coast of the Bozburun Peninsula provide a data set for long-term sea-level evaluation (Kızıldağ et al., 2012). The breakwaters in Hıdırlık and Kiseli sites are well-dated based on the architectural remains on land and ceramic findings among the submerged architectural remains. In particular, the abandonment history of the Early Byzantine site provides a more precise date for submergence. Taking into account the assumed minimum original elevation of 0.6±0.2 m for the breakwaters at the time of their use, two different sea-level stands can be inferred from Hıdırlık and Kiseli sites by using the equation RSLi: at -2.1±0.3 m during the Hellenistic Period (~2300 BP) and -1.6±0.3 m during the Early Byzantine Period (~1400 BP) respectively.

Sea-level studies carried out in the Mediterranean present comprehensive RSL data for Bronze Age. Henderson et al. (2011) suggest that the foundations of the buildings at Bronze Age Pavlopetri have been submerged by c. 4–5 m during the last 5000 years, due largely to tectonic factors. The submerged Early Bronze Age (EBA) settlement building walls at Platiyali extend to a depth of at least 5 m below present sea level. Another submerged EBA settlement, Salanti, is found at a depth of 4 m below present sea level. Over a hundred bronze axes from EBA were found at a depth of 3.5 m below present sea level in the Glyfada-Mesi site. Moreover, Evelpidou et al. (2018) identified a submerged shoreline at -2.8 m based on a tidal notch in Naxos Island (the Cyclades in the Aegean Sea), which must have been developed at least before 3350 to 4200 BP. Kolaiti & Mourtzas (2016) determined a sea-level stand of 3.3 ± 0.15 m during the Middle Bronze Age in the west Saronic Gulf. The beachrock formations located in the Mykonos–Delos–Rhenia region in Cyclades, Greece, indicate a sea-level stability at −3.6 m around 2000 BC (Desruelles et al., 2009). Based on beachrock data, Karkani et al. (2017) suggested that the relative sea level rose by at least 3.8 m in the last 4000 years in the central Cyclades. Although Çamçalık has different tectonic characteristics comparable with other Mediterranean tectonically active areas, sea-level data seem to be compatible with the other sites.

Antonioli et al. (2011) suggested a RSL rise of 2.3 m and tectonic subsidence of about 1.48±0.3 mm/yr since the last 2300 years for the southwestern Turkish coasts. RSL rise of at least 2.8 m over the past 1400 years is suggested for Kekova (Özdaş & Kızıldağ, 2013). Recent detailed studies demonstrated that Fethiye coasts have a greater amount of RSL rise of 3.1-4.6±0.3 m in the Gulf of Fethiye (Kızıldağ, 2019) and 2.2-3.1±0.3 m on the eastern coast of Fethiye (Kızıldağ & Özdaş, 2021) over the last 1400 years. This remarkable difference in RSL changes between the regions confirms that the local scale tectonic processes have an important effect on the submergence of coastal sites.

Relative sea-level variations in the Mediterranean basin, which is in the far-field of the former Late Pleistocene ice sheets, are mostly controlled by hydro-isostatic effects due to meltwater load and associated with vertical land movements stemming from the combined effect of tectonics and GIA (Spada & Melini, 2022). Figure 8 shows modeled relative-sea level in the study area according to the GIA models ICE-6G, ICE-7G and ANU; the range of 1-sigma epistemic uncertainties associated with ICE-6G and ANU, obtained through the ensemble approach outlined above, corresponds to shaded areas. Taking into account the amplitude of uncertainties, ICE-6G indicates a substantially stable sea level since 3600 BP, and a slow RSL rise for earlier epochs, while ICE-7G predicts a highstand of about 0.2m between 2000 and 3600 BP, with the modeled RSL curve according to ICE-7G being at the upper boundary of the 1-sigma confidence interval of the ICE-6G RSL prediction. Conversely, the ANU model predicts a much faster RSL rise between 3600–1400 BP, followed by a slower rise up to the present sea level. The qualitative difference between predictions from ICE-X and ANU reflects different eustatic curves as well as different rheological profiles assumed by the models considered.

The maximum GIA contribution to the vertical land movement is 0.9±0.2 m for the last 3600 years; 0.3±0.1 m for the last 2300 years; and 0.1±0.05 m for the last 1400 years. In comparison with the GIA curves, our archaeological index points remained at a lower position. The difference between predictions from GIA models and archaeological sea-level index points allows us estimating the magnitude of local vertical tectonic displacement in the study area. Removing the maximum GIA component, we estimate a tectonic subsidence rate of at least 0.6±0.5 mm/yr over the last 3600 years. Nevertheless, GIA calculations indicate that there is a remarkable increase in vertical tectonic movement after Early Byzantine times.

The comparison of the current positions of the Early Byzantine remains at -1.0±0.1 m with the tidal notch at -0.6±0.1 m verifies that the sea level has remained stable at -0.6±0.1 m and a tidal notch has developed after the submersion of Early Byzantine remains. In other words, a most recent vertical displacement has occurred in the last 1400 years. The inward depth of a notch is related to the duration of sea-level stability. Evelpidou et al. (2014) suggested that notches can develop at rates of bioerosion between 0.2 and 1.0 mm/yr in the Mediterranean coastline. Nevertheless, the rock lithology and the contribution of several processes (e.g. fresh-water springs, wave energy and bioerosion rate) have important roles in notch formation (Antonioli et al., 2015). Anyhow, the inward depth of about 0.8±0.1 m indicates long-term sea-level stability in a timespan between the Early Byzantine times and modern times.

The fact that the presence of one prominent tidal notch structure, which is almost fixedly observed throughout the western part of the Bozburun Peninsula, and the absence of the deeper ones may confirm sudden submergence in a timescale after the Early Byzantine Period and gradual submergence between the Late Bronze Age and Early Byzantine Period. When the rate of RSL change is greater than the rate of bioerosion, a tidal notch does not form (Evelpidou et al., 2014). The fact that the absence of any biologic or geomorphologic sea-level indicator on the vertical surface of the 150 m long and 2.4 m thick monolithic platform, which exhibits a homogeneous formation from top to bottom, may support the assumption of gradual submergence after the Bronze age occupation, mostly associated with ANU model.

The presence of present-day development of tidal notches is still debatable. Based on studies carried out along tectonically active Greek coastlines, Evelpidou et al. (2012) suggested that the modern tidal notch is disappearing because the bioerosion rate remained lower than the rate of sea-level rise during the last century (~1.4 mm/yr). Conversely, Antonioli et al. (2015) proposed that the current notch is present in the vast majority of tectonically stable carbonate coasts in the central Mediterranean. However, the global rise in sea level at a rate of ~1.4 mm/yr since the late 19th century should not be ignored at this point (Church et al., 2008).

The proposed date of the archaeological finds in Çamçalık corresponds to the period shortly before the Santorini eruption, which may have caused the end of the settlement. The Çamçalık quay must have lost its function after the Late Bronze Age, with catastrophic events accompanying the Bronze Age eruption of Santorini. This assumption fits with the proposed date for archaeological finds. The absence of later layers can confirm that life must have been interrupted by an earthquake and the eruption of Santorini.

The Late Bronze Age Minoan eruption of Santorini is one of the most powerful volcanic eruptions known to have occurred during the Holocene (Eastwood et al., 2002). The eruption must have been triggered by one or more earthquakes ($I_0$=X) (Soysal et al., 1981), which caused damage in Rhodes, Kos, and Crete (Driessen, 2019). The fact that there are no archaeological remains from the Bronze Age to the Hellenistic Period in the site indicates that Çamçalık was abandoned as a result of one or more catastrophic events. Similarly, there is a gap between Early Byzantine and modern times in the surrounding region, which can be explained by ongoing seismic events, causing the coastal changes.

## 7 Conclusions

By producing new data from the recently discovered Bronze Age site, the relative sea-level history along the coast of Bozburun Peninsula in the last 3600 years was reconstructed for the first time with this study. The comparison of the observed RSL data with predictions from recently published GIA models allowed us to evaluate the impact of the vertical tectonic movement. Precise chronological data provided evidence to determine an accurate timespan (e.g. archaeological material mixed with harbor constructions and abandonment history) and then to constrain the magnitude of the vertical land movement.

Our results suggest that observed sea-level change is due to equal contributions of GIA and tectonic factors (ANU model) or only to tectonics (ICE-X models) between 3600-1400 BP, while the tectonic contribution is considerably dominant after 1400 BP. A rapid acceleration in the submergence of the coastline was defined between Early Byzantine and modern times. This indicates that the seismic activity in the study area produced vertical land movement during this period. Geomorphological sea-level markers confirmed that a long-term sea-level stand occurred after Early Byzantine archaeological remains had submerged. On the contrary, the absence of deeper tidal notches or biological layers on the Bronze Age quay platform can be attributed to a gradual RSL rise.

The results obtained in this study highlight the complex history of sea-level changes in the coastal sector of the Bozburun Peninsula, which is located in the active tectonic segment of the southeastern Aegean Sea. The tectonic regime due to interaction between the Hellenic Arc subduction zone and Aegean Volcanic Arc is responsible for the submersion of coastal archaeological sites, predominantly in the last 1400 years. A recent earthquake activity that occurred in 2012 verifies that the western coast of the Bozburun Peninsula is still under the influence of ongoing seismicity.



This study demonstrates that RSL changes had a significant impact on the past cultures that were living in the coastal zone of the Bozburun Peninsula. Further studies would improve our understanding to produce future scenarios regarding the impact of relative sea-level rise on coastal occupation by considering both local tectonic estimates and the projections of 21st century sea-level rise.

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**References**

Amante, C., & Eakins, B. W. (2009). ETOPO1 Global Relief Model converted to PanMap layer format. *NOAA-National Geophysical Data Center, PANGAEA*. https://doi.org/10.1594/PANGAEA.769615.

Antonioli, F., Anzidei, M., Lambeck, K., Auriemma, R., Gaddi, D., Furlani, S., Orrù, P., Solinas, E., Gaspari, A., Karinja, S., Kovačić, V., & Surace, L. (2007). Sea-level change during the Holocene in Sardinia and in the northeastern Adriatic (central Mediterranean Sea) from archaeological and geomorphological data. *Quaternary Science Reviews, 26*(19-21), 2463-2486.

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

Anzidei, M., Antonioli, F., Benini, A., Lambeck, K., Sivan, D., Serpelloni, E., & Stocchi, P. (2011). Sea level change and vertical land movements since the last two millennia along the coasts of southwestern Turkey and Israel. *Quaternary International, 232*(1-2), 13-20.

Anzidei, M., Lambeck, K., Antonioli, F., Furlani, S., Mastronuzzi, G., Serpelloni, E., & Vannucci, G. (2014). Coastal structure, sea-level changes and vertical motion of the land in the Mediterranean. *Geological Society, London, Special Publications, 388*(1), 453-479.

Aucelli, P., Cinque, A., Mattei, G., & Pappone, G. (2016). Historical sea level changes and effects on the coasts of Sorrento Peninsula (Gulf of Naples): New constrains from recent geoarchaeological investigations. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *463*, 112–125.

Aucelli, P. P., Mattei, G., Caporizzo, C., Cinque, A., Troisi, S., Peluso, F., Stefanile, M., & Pappone, G. (2020). Ancient coastal changes due to ground movements and human interventions in the Roman Portus Julius (Pozzuoli Gulf, Italy): Results from photogrammetric and direct surveys. *Water, 12*(3), 658.

Auriemma, R., & Solinas, E. (2009). Archaeological remains as sea level change markers: a review. *Quaternary International, 206*(1-2), 134-146.

Benjamin, J., Rovere, A., Fontana, A., Furlani, S., Vacchi, M., Inglis, R. H., Galili, E., Antonioli, F., Sivan, D., Miko, S., Mourtzas, N., Felja, I., Meredith-Williams, M. Goodman-Tchernov, B., Kolaiti, E., Anzidei, M., & Gehrels, R. (2017). Late Quaternary sea-level changes and early human societies in the central and eastern Mediterranean Basin: An interdisciplinary review. *Quaternary International, 449,* 29-57. https://doi.org/10.1016/j.quaint.2017.06.025.

Blackman, D. (1982). Ancient harbours in the Mediterranean. Part 1. *International Journal of Nautical Archaeology, 11*(2), 79-104.

Blackman, D. (2011). Minoan Shipsheds. *Skyllis, 11*(2), 4-11.

Church, J. A., White, N. J., Aarup, T., Wilson, W. S., Woodworth, P. L., Domingues, C. M., Hunter, J.R., & Lambeck, K. (2008). Understanding global sea levels: past, present and future. *Sustainability Science, 3*(1), 9-22.

Desruelles, S., Fouache, É., Ciner, A., Dalongeville, R., Pavlopoulos, K., Kosun, E., Coquinot, Y., & Potdevin, J. L. (2009). Beachrocks and sea level changes since Middle Holocene: comparison between the insular group of Mykonos–Delos–Rhenia (Cyclades, Greece) and the southern coast of Turkey. *Global and Planetary Change*, *66*(1-2), 19-33. https://doi.org/10.1016/j.gloplacha.2008.07.009.

Driessen, J. (2019). The Santorini eruption. An archaeological investigation of its distal impacts on Minoan Crete. *Quaternary International*, *499*, 195-204.

Eastwood, W. J., Tibby, J., Roberts, N., Birks, H. J. B., & Lamb, H. F. (2002). The environmental impact of the Minoan eruption of Santorini (Thera): statistical analysis of palaeoecological data from Golbisar, southwest Turkey. *The Holocene, 12*(4), 431-444.

Ersoy, S. (1993). Transgresif platform karbonat istifine Bozburun (Marmaris, Muğla) yarımadasından bir örnek. *Türkiye Jeoloji Bülteni*, *36*(2), 171-177.

Evelpidou, N., & Karkani, A. (2018) Archaeology and sea-level change. In C.W. Finkl, & C. Makowski (Eds.), *Encyclopedia of Coastal Science* (pp.1-7). Cham: Springer.

Evelpidou, N., Melini, D., Pirazzoli, P. A., & Vassilopoulos, A. (2014). Evidence of repeated late Holocene rapid subsidence in the SE Cyclades (Greece) deduced from submerged notches. *International Journal of Earth Sciences, 103*(1), 381-395.

Evelpidou, N., Tziligkaki, E., & Karkani, A. (2018). Submerged Antiquities on Paros and Naxos Islands, Aegean Sea, Greece. New evidence for the mean sea level during the late Bronze Age and the Roman period. *Bulletin of the Geological Society of Greece, 52*(1), 71-9.

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

Flemming, N. C., Czartoryska, N. M. G., & Hunter, P. M. (1973). Archaeological evidence for eustatic and tectonic components of relative sea level change in the South Aegean. *Marine Archaeology, 23*, 1-63.

Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., Bianchi, C., Bingham, R. G., Blankenship, D. D., Casassa, G., Catania, G., Callens, D., Conway, H., Cook, A. J., Corr, H. F. J., Damaske, D., Damm, V., Ferraccioli, F., Zirizzotti, A. (2013). Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere, 7,* 375–393, doi:10.5194/tc-7-375-2013.

Friedrich, W. L., & Heinemeier, J. (2009). The Minoan eruption of Santorini radiocarbon dated to 1613+13 BC-geological and stratigraphic considerations. *Monographs of the Danish Institute at Athens*, *10*, 57-63.

Galanidou, N., Dellaporta, K., & Sakellariou, D. (2020). Greece: Unstable landscapes and underwater archaeology. In G. Bailey, N. Galanidou, H. Peeters, H. Jöns & M. Mennenga, (Eds.), *The Archaeology of Europe's Drowned Landscapes* (pp.371-392). Springer, Cham.

Gerber, C. (2019). Die Karische Chersones in prähistorischer Zeit. Ergebnisse der Begehungen in Loryma 2001 und Bybassos 2006. In W. Held (Ed.), *Die Karische Chersones vom Chalkolithikum bis in die byzantinische Zeit. Beiträge zu den Surveys in Loryma und Bybassos* (pp. 11–66). Eigenverlag des Archäologischen Seminars der Philipps-Universität.

Guidoboni, E., Comastri, A., & Traina, G. (1994). *Catalogue of ancient earthquakes in the Mediterranean area up to the 10th century (Vol. 1).* Rome: Instituto Nazionale di Geofisica.

Guttandin, T., Panagiotopoulos, D., Pflug, H., & Plath, G. (2011). *Inseln der Winde. Die maritime Kultur der bronzezeitlichen Ägäis.* Institut für Klassische Archäologie Universität Heidelberg.

Hadjidaki, E. (2004). A Possible Minoan Harbor on South Crete. In L. Preston Day, M.S. Mook & J.D. Muhly (Eds.), *Crete Beyond the Palaces: Proceedings of the Crete 2000 Conference* (pp. 53-60). INSTAP Academic Press.

Hadjidaki, E. (2021). *The Minoan Shipwreck at Pseira, Crete (Vol. 65)*. INSTAP Academic Press.

Held, W. (2014). Häfen der Rhodischen Peraia. In S. Ladstätter, F. Pirson & T. Schmidts (Eds.), *Häfen und Hafenstädte im östlichen Mittelmeerraum von der Antike bis in byzantinische Zeit: neue Entdeckungen und aktuelle Forschungsansätze, Byzas 19, vol. 1* (pp. 357-375). Ege Yayınları.

Held, W. (Ed.) (2019). *Die Karische Chersones vom Chalkolithikum bis in die byzantinische Zeit. Beiträge zu den Surveys in Loryma und Bybassos.* Forschungen auf der Karischen Chersones 1. Eigenverlag des Archäologischen Seminars der Philipps-Universität.

Held, W., & Şenol, K. (2010). Rhodian Wine' from Karia. The Production of 'Rhodian Wine' on the Karian Chersonesos in the Hellenistic Period. In Ü. Aydınoğlu & A. K. Şenol (Eds.), *Olive Oil Production in Anatolia during Antiquity / Antik Çağda Anadolu'da Zeytinyağı ve Şarap Üretimi* (pp. 175–183). Ege Yayınları.

Held, W., & Wilkening-Aumann, Ch. (2015). Vom Karischen Bund zur Griechischen Polis. Archäologischer Survey in Bybassos und Kastabos auf der Karischen Chersones. In A. Matthaei & M. Zimmermann (Eds.), *Urbane Strukturen und bürgerliche Identität im Hellenismus, Die hellenistische Polis als Lebensform 5* (pp. 74–98). Brill Deutschland GmbH.

Henderson, J. C., Gallou, C., Flemming, N. C., & Spondylis, E. (2011). The Pavlopetri Underwater Archaeology Project: investigating an ancient submerged town. In J. Benjamin, C. Bonsall, C. Pickard & A. Fischer (Eds.), *Underwater Archaeology and the Submerged Prehistory of Europe* (pp. 207-218). Oxbow Books.

Kandilli Observatory and Earthquake Research Institute. (2012). Press Bulletin on the Earthquake Event on 24-28 November 2012 off Bozburun-Muğla (Mediterranean). http://www.koeri.boun.edu.tr/sismo/Depremler/onemliler/

Kandilli Observatory and Earthquake Research Institute. (2022, June 16). Earthquake Catalog Search System. B.U. KOERI-RETMC. Retrieved June 6, 2022, from http://www.koeri.boun.edu.tr/sismo/2/earthquake-catalog/

Karkani, A., Evelpidou, N., Giaime, M., Marriner, N., Morhange, C., & Spada, G. (2019). Late Holocene sea-level evolution of Paros island (Cyclades, Greece). *Quaternary International*, *500*, 139-146.

Karkani, A., Evelpidou, N., Vacchi, M., Morhange, C., Tsukamoto, S., Frechen, M., & Maroukian, H. (2017). Tracking Shoreline Evolution in Central Cyclades (Greece) using Beachrocks. *Marine Geology, 388*, 25–37.

Kızıldağ, N. (2019). Late Holocene sea level change along the coast of Fethiye Gulf in southwestern Turkey. *Geoarchaeology, 34*(3), 295-310.

Kızıldağ, N., & Özdaş, H. (2021). Relative sea-level changes along the Fethiye coast (SW Turkey) based on recent archaeological data. *Geoarchaeology, 36*(3)*,* 474-489.

Kızıldağ, N., Özdas, A. H., & Uluğ, A. (2012). Late Pleistocene and Holocene Sea Level Changes in the Hisarönü Gulf. Southeast Aegean Sea. *Geoarchaeology, 27*(3), 220–236.

Kolaiti, E., & Mourtzas, N. D. (2016). Upper Holocene Sea Level Changes in the West Saronic Gulf. Greece. *Quaternary International, 401*, 71–90.

Kolaiti, E., & Mourtzas, N. D. (2020). New insights on the relative sea level changes during the Late Holocene along the coast of Paros Island and the northern Cyclades (Greece). *Annals of Geophysics, 63*, 669.

Lambeck, K., Antonioli, F., Purcell, A., & Silenzi, S. (2004). Sea-level change along the Italian coast for the past 10,000 yr. *Quaternary Science Reviews, 23*(14-15), 1567-1598.

Lambeck, K., Anzidei, M., Antonioli, F., Benini, A., & Verrubbi, V. (2018). Tyrrhenian sea level at 2000 BP: evidence from Roman age fish tanks and their geological calibration. *Rendiconti Lincei. Scienze Fisiche e Naturali, 29*(1), 69-80.

Lambeck, K., Purcell, A., Johnston, P., Nakada, M., & Yokoyama, Y. (2003). Water-load definition in the glacio-hydro-isostatic sea-level equation, *Quaternary Science Reviews, 22*(2), 309–318.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., & Sambridge, M. (2014). Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *Proceedings of the National Academy of Sciences, 111*(43), 15296-15303.

Loizou, E. (2016). Late Bronze Age Harbours in the Aegean. *Skyllis, 16*(2), 118–125.

Manning, S.W., & Kromer, B. (2012). Considerations of the scale of radiocarbon offsets in the East Mediterranean, and considering a case for the latest (most recent) likely date for the Santorini eruption. *Radiocarbon,* 54*(3–4)*, 449–474.

Mattei, G., Caporizzo, C., Corrado, G., Vacchi, M., Stocchi, P., Pappone, G., Schiattarella, M., & Aucelli, P. C. (2022). On the influence of vertical ground movements on Late-Quaternary sea-level records. A comprehensive assessment along the mid-Tyrrhenian coast of Italy (Mediterranean Sea). *Quaternary Science Reviews, 279*, 107384.

Medas, S. (2003). The Late-Roman ‘‘Parco di Teodorico’’ Wreck, Ravenna, Italy: preliminary remarks on the hull and the shipbuilding. In C. Beltrame (Ed.), *Boats, Ships and Shipyards. Proceedings of the Ninth International Symposium on Boat and Ship Archaeology* (pp. 42–48). Oxford: Oxbow Books.

Melini, D,. & Spada, G. (2019). Some remarks on Glacial Isostatic Adjustment modelling uncertainties, *Geophysical Journal International, 28*(1)*,* 401–413.

Momigliano, N. (2009). Minoans at Iasos?. In C.F. Macdonald, E. Hallager, & W-D. Niemeier (Eds.), *The Minoans in the central, eastern and northern Aegean – new evidence* (pp. 121–140). Aarhus University Press.

Momigliano, N. (2012). *Bronze Age Carian Iasos. Structures and Finds from the Area of the Roman Agora (c. 3000–1500 BC).* Giorgio Bretschneider.

Morhange, C., & Marriner, N. (2015). Archeological and biological relative sea-level indicators. In I. Shennan, A.J. Long & B.P. Horton (Eds.), *Handbook of sea-level research* (pp. 146-156). John Wiley & Sons.

Morhange, C., Laborel, J., & Hesnard, A. (2001). Changes of relative sea level during the past 5000 years in the ancient harbor of Marseilles, Southern France. *Palaeogeography Palaeoclimatology Palaeoecology, 166,* 319-329.

Morhange, C., Marriner, N., Excoffon, P., Bonnet, S., Flaux, C., Zibrowius, H., Goiran, J-P., & Amouri, M. E. (2013). Relative sea-level changes during Roman times in the Northwest Mediterranean: The 1st century AD fish tank of Forum Julii, Fréjus, France. *Geoarchaeology, 28*(4), 363-372.

Nakada, M., & Lambeck, K. (1987). Glacial rebound and relative sea-level variations: a new appraisal, *Geophysical Journal International, 90*(1)*,* 171–224.

Niemeier, W.-D. (2005). The Minoans and Myceneans in Western Asia Minor: Settlement, Emporia or Acculturation?. In R. Laffineur & E. Greco (Eds.), *Emporia. Aegeans in the Central and Eastern Mediterranean. 10th International Aegean Conference Athens 2004*, (pp. 199–204 pl. 48–49). Liege.

Niemeier, W.-D. (2007). Milet von den Anfängen menschlicher Besiedlung bis zur Ionischen Wanderung / Westkleinasien und Ägäis von den Anfängen bis zur Ionischen Wanderung: Topographie, Geschichte und Beziehungen nach dem archäologischen Befund und den hethitischen Quellen. In J. Cobet, V. von Graeve, W.-D. Niemeier & K. Zimmermann (Eds.), *Frühes Ionien. Eine Bestandsaufnahme. Panionion-Symposion Güzelçamlı 1999* (pp. 3–19). Philipp von Zabern.

Nomikou, P., Krassakis, P., Kazana, S., Papanikolaou, D., & Koukouzas, N. (2021). The volcanic relief within the Kos-Nisyros-Tilos tectonic graben at the eastern edge of the Aegean Volcanic Arc, Greece and Geohazard Implications. *Geosciences, 11*(6), 231.

Opait, A. (2004). The eastern Mediterranean amphorae in the province of Scythia. In J. Eiring & J. Lund (Eds.), *Transport amphorae and trade in the eastern Mediterranean: Acts of the international colloquium at the Danish Institute at Athens* (pp.293–308). Aarhus: Aarhus University Press.

Özdaş, H., & Kızıldağ, N. (2013a). Archaeological and geophysical investigation of submerged coastal structures in Kekova, southern coast of Turkey. *Geoarchaeology, 28*(5), 504-516.

Özdaş, H., & Kızıldağ, N. (2013b). Marmaris Bozburun Peninsula Shipwrecks. *TINA, 1*, 49-57.

Özdaş, H., & Kızıldağ, N. (2016). Hisarönü Bronze Age Shipwreck Excavation, 2016 Campaign. *TINA, 6*, 102–107.

Özdaş, H., & Kızıldağ, N. (2017). Campaign of the Bozburun Underwater Excavations in Marmaris, *TINA, 8*, 40–45.

Pavlopoulos, K., Kapsimalis, V., Theodorakopoulou, K., & Panagiotopoulos, I. P. (2012). Vertical displacement trends in the Aegean coastal zone (NE Mediterranean) during the Holocene assessed by geo-archaeological data. *The Holocene, 22*(6), 717-728.

Peltier, W. R. (2004). Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G (VM2) model and GRACE. *Annual Review of Earth and Planetary Sciences, 32,* 111-149.

Peltier, W.R., Argus, D.F., & Drummond, R. (2015). Space geodesy constrains ice-age terminal deglaciation: The global ICE-6G_C (VM5a) model. *Journal of Geophysical Research: Solid Earth, 120,* 450-487.

Pirazzoli, P.A. (1976). Sea level variations in the northwest Mediterranean during Roman times. *Science, 194,* 519-521.

Pirazzoli, P. A. (1997). Sea-level changes: the last 20 000 years. *Oceanographic Literature Review, 8*(44), 785.

Pirazzoli, P.A. (2005). A review of possible eustatic, isostatic and tectonic contributions in eight late-Holocene relative sea-level histories from the Mediterranean area. *Quaternary Science Reviews, 24,* 1989-2001.

Rovere, A., Stocchi, P., & Vacchi, M. (2016). Eustatic and relative sea level changes. *Current Climate Change Reports*, *2*(4), 221-231.

Roy, K., & Peltier, W. R. (2015). Glacial isostatic adjustment, relative sea level history and mantle viscosity: reconciling relative sea level model predictions for the US East coast with geological constraints. *Geophysical Journal International, 201*(2)*,* 1156-1181.

Roy, K., & Peltier, W. R. (2017). Space-geodetic and water level gauge constraints on continental uplift and tilting over North America: regional convergence of the ICE-6G_C (VM5a/VM6) models. *Geophysical Journal International, 210*(2)*,* 1115-1142.

Shaw, J.W. (1990). Bronze Age Aegean Harboursides. In C. Gillis, C. Risberg & B. Sjöberg (Eds.), *Thera and the Aegean World III vol. 1: Archaeology. Proceedings of the Third International Congress, Santorini 1989* (pp. 420–436). The Thera Foundation.

Shennan, I. (2015). Handbook of sea-level research: framing research questions. In I. Shennan, A.J. Long, B.P. Horton (Eds.), *Handbook of Sea-Level Research* (pp. 3–25). John Wiley & Sons.

Similox-Tohon, D., Sintubin, M., Muchez, P., Vanhaverbeke, H., Verhaert, G., & Waelkens, M. (2005). Identification of a historical morphogenic earthquake through trenching at ancient Sagalassos (SW Turkey). *Journal of Geodynamics, 40,* 279-293.

Soysal, H., Sipahioğlu, S., Kolçak, D., & Altinok, Y. (1981). *Türkiye ve çevresinin tarihsel deprem kataloğu (MÖ 2100-MS 1900)*. TUBITAK, Istanbul.

Spada, G., & Melini, D. (2019). SELEN4: a Fortran program for solving the gravitationally and topographically self-consistent Sea Level Equation in Glacial Isostatic Adjustment modeling. *Geoscientific Model Development Discussions*, 1-37.

Spada, G., & Melini, D. (2022). New estimates of ongoing sea level change and land movements caused by Glacial Isostatic Adjustment in the Mediterranean region, *Geophysical Journal International, 229*(2), 984–998.

Stocchi, P., & Spada, G. (2009). Influence of glacial isostatic adjustment upon current sea level variations in the Mediterranean. *Tectonophysics, 474*(1-2), 56-68.

Stock, F., Seyer, M., Symanczyk, A., Uncu, L., & Brückner, H. (2020). On the geoarchaeology of Limyra (SW Anatolia)—new insights into the famous Lycian city and its environs. *Geoarchaeology, 35*(4), 487-502.

Tartaron, T. F. (2013). *Maritime networks in the Mycenaean world*. Cambridge University Press.

Tartaron, T. F., Rothaus, R. M., & Pullen, D. J. (2003). Searching for Prehistoric Aegean Harbors with GIS. Geomorphology and Archaeology. *Athena Review, 3-4*, 27-36.

Taymaz, T., Yilmaz, Y., & Dilek, Y. (2007). The geodynamics of the Aegean and Anatolia: introduction. *Geological Society, London, Special Publications, 291*(1), 1-16.

Turkish National Sea Level Monitoring System. (2022, June). *Tide Gauge Data.* https://tudes.harita.gov.tr/

Vacchi, M., Ermolli, E. R., Morhange, C., Ruello, M. R., Di Donato, V., Di Vito, M. A., Giampaola, D., Carsana, V., Liuzza, V., Cinque, A., Boetto, G., Poveda, P., Boenzi, G., & Marriner, N. (2020). Millennial variability of rates of sea-level rise in the ancient harbour of Naples (Italy, western Mediterranean Sea). *Quaternary Research, 93*, 284-298.

Vacchi, M., Marriner, N., Morhange, C., Spada, G., Fontana, A., & Rovere, A. (2016). Multiproxy assessment of Holocene relative sea-level changes in the western Mediterranean: Sea-level variability and improvements in the definition of the isostatic signal. *Earth-science Reviews, 155,* 172-197.

Watrous, L. V. (2012). The harbor complex of the Minoan town at Gournia. *American Journal of Archaeology, 116*(3), 521-541.

Watrous, L. V. (2021). *Minoan Crete: an introduction*. Cambridge.

Yıldırım, C., Aksoy, M. E., Özcan, O., İşiler, M., Özbey, V., Çiner, A., Salvatore, P., Sarıkaya, M.A., Doğan, T., İlkmen, E., & Schneiderwind, S. (2022). Coseismic (20 July 2017 Bodrum-Kos) and paleoseismic markers of coastal deformations in the Gulf of Gökova, Aegean Sea, SW Turkey. *Tectonophysics, 822*, 229141.

Yildiz, H., Andersen, O. B., Simav, M., Aktug, B., & Ozdemir, S. (2013). Estimates of vertical land motion along the southwestern coasts of Turkey from coastal altimetry and tide gauge data. *Advances in Space Research, 51*(8), 1572-1580.

**Figure Captions**

Figure 1. (a) the location map of studied submerged sites (red icon); (b) tectonic setting of the Aegean Sea (modified from Taymaz et al., 2007) and the submerged Bronze Age sites (black icon) along the Aegean coastline (compiled from Galanidou et al., 2020); (c) Seismotectonic map of the study area and its surrounding region. Epicenters of earthquakes in historical and instrumental periods (between 1950-2022) were obtained from the seismicity catalogue of Kandilli Observatory and Earthquake Research Institute (KOERI). The focal mechanism solutions of earthquakes in 2012 and 2017 were reported by KOERI

Figure 2. (a) Aerial photo of Çamçalık island and its vicinity, (b) and (c) submerged wall stones upon the quay surface, (d) front view of the quay platform, (e) vertical surface of the quay exhibiting calcareous structure mixed with limestone and pottery sherds

Figure 3. The artifacts from Çamçalık: beak-spouted jug, loom weight with Linear A, conical cup, oval-mouthed amphora

Figure 4. Submerged tidal notch structures in (a) Çamçalık; (b) Hıdırlık; and (c) Kiseli. Measurements were taken on 08/26/2019 at 13.00 (from Çamçalık and Kiseli) and 08/27/2019 at 14.30 (from Hıdırlık). (d) Trend-removal tidal amplitude in the study area. Data obtained from nearest tide gauge station located at Marmaris. The red icons indicate the tide levels during the measurements of sea-level indicators

Figure 5. (a, b) Aerial photos from Hıdırlık harbor with Hellenistic building on the coast (inset photo) and (c) underwater photo of Hıdırlık breakwater.

Figure 6. (a) Aerial photo from Kiseli breakwater and church remains; (b) underwater photo of breakwater; and (c) aerial photo of quay with the position of sea level during survey (inset photo)

Figure 7. Representative section of the Çamçalık quay platform

Figure 8. Comparison of observed sea-level data with newly modeled GIA curves. Sea-level index points were displayed with vertical error bar for depth and horizontal error bar for age. The RSL curves for ICE-6G (red), ICE-7G (green) and ANU (blue) have been obtained through a high resolution numerical solution of the SLE. Shaded areas correspond to uncertainties on GIA predictions of ICE-6G and ANU associated to possible variations of the rheological parameters and have been estimated through a mini-ensemble approach

Table 1. Archaeological data used to reconstruct the relative sea-level evolution of the Bozburun Peninsula. AI: archaeological indicator, C: chronology based on time of the last use, MD: measured depth of archaeological remains, ME: the error estimate derives from measurement uncertainties, TL: tide level according to mean sea level during the survey, CD: corrected depth for tide with measurement error

# New insights on the sea-level evolution along the coast of Bozburun Peninsula (Turkey), from the submerged Bronze Age harbor in Çamçalık

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## Abstract

Recent discovery of a Bronze Age harbor site in Çamçalık provided new data for relative sea-level history along the coast of Bozburun Peninsula for the last 3600 years. The new data and the previously published data from the nearby sites were compared with the aim of understanding long-term relative sea-level changes. The further comparison of the observed sea-level data and newly produced glacial isostatic adjustment (GIA) models clarifies the tectonic contribution to the relative sea-level changes. Our results suggest a non-linear tectonic subsidence trend in the coastal zone since 3600 BP. An acceleration of the relative sea-level rise has occurred since the last 1400 years, mostly due to seismic events controlled by the tectonic regime of the southeastern Aegean Sea. As in the past, this active tectonic process will have a major impact on the future sea-level evolution of the coastal sector of the Bozburun Peninsula.

*Keywords:* Bronze Age harbor, relative sea-level change, archaeological sea-level indicators, tectonic subsidence, Bozburun Peninsula, Çamçalık

## 1 Introduction

The coastal areas of the Bozburun Peninsula, ancient Karian Chersonesos, in the southwestern Turkey have been inhabited for thousands of years. Most of the coastal sites are dated to the Late Roman-Early Byzantine Period, many to the Hellenistic Period, and only a few to earlier periods (Held, 2019). Due to relative sea-level (RSL) changes, the coastal archaeological remains are now partly or totally submerged in this shoreline. On the other hand, no evidence of the existence of a Bronze Age settlement has been found so far on this peninsula.

As a part of the Shipwreck Inventory Project of Turkey (SHIPT), which has been mapping and documenting the shipwrecks and submerged archaeological sites along the Turkish coasts since 2005 (Özdaş & Kızıldağ, 2013a), a recent coastal archaeological investigation has been initiated on the Bozburun Peninsula, focusing on the submerged archaeological remains on the coastal zone (Figure 1). During the 2019 survey, a Bronze Age coastal site was discovered on Çamçalık island, which is partially submerged due to RSL changes.

The RSL changes are the combined effect of eustatic, glacio-hydro-isostatic, and tectonic factors (~~Khan et al., 2015;~~ Nakada & Lambeck, 1987; Peltier, 2004; Pirazzoli, 1997; 2005). The eustatic-isostatic contribution is associated with glacial meltwater inputs to the oceans and can be predicted by means of Glacio-Isostatic Adjustment (GIA) models, which require the spatio-temporal evolution of ice sheets and the Earth rheological profile (Stocchi & Spada, 2009) as inputs. Conversely, the tectonic contribution is less predictable and can be evaluated from the shoreline markers (Rovere et al., 2016). Since the meltwater input in the past 4000 years is small with respect to the deglaciation history in the last glacial cycle (~~Khan et al., 2015;~~ Church et al., 2008; Lambeck et al., 2014; Peltier, 2004), any changes in RSL in this time frame are expected to stem from the sum of the GIA and tectonic movements rather than eustatic contribution. A procedure was recently proposed by Mattei et al. (2022) in order to evaluate vertical displacements and tectonic behaviors of Italian coasts by comparing bibliographic and new sea-level data and GIA. Based on the data from archaeological sites of Fethiye, Anzidei et al. (2011) suggest that GIA contribution to the RSL changes plays a minor role and tectonic subsidence has a major contribution along the southwestern coasts of Turkey over the last 2300 years. GPS measurements and sea-level data obtained from Bodrum tide gauge (southwestern coasts of Turkey) confirm no significant vertical land motion between 1993 and 2009 in the region (Yıldız et al., 2013) and glacio-isostatic adjustment is suggested negligible (-0.01–0.16 mm/yr) (Yıldırım et al., 2022).

Since tectonically active coasts are exposed to ongoing relative sea-level changes, those areas need to be examined very sensitively to generate future scenarios for inundation. RSL changes can be inferred from the observations that have a direct relationship with sea levels in the past, which are called sea-level indicators, or sea-level index points. Those are defined as any archaeological, biological or geological feature that was constructed, formed, or deposited in connection with a former sea level (Morhange et al., 2001; Rovere et al., 2016). The current position of submerged coastal archaeological structures, which had a direct relationship with the shoreline during their operation, is used as a reliable indicator of past sea levels.

Previous studies indicated that the Mediterranean Sea has a great number of archaeological indicators of the sea-level variations of the last 4000 years (Anzidei et al., 2014; Auriemma & Solinas, 2009; Evelpidou et al., 2018; Flemming, 1978; Kolaiti & Mourtzas, 2016; Lambeck et al., 2018; Morhange et al., 2013; Pavlopoulos et al., 2012; Pirazzoli, 1976). The geoarchaeological assessment of submerged maritime and coastal constructions provided data on RSL changes along the coast of southwestern Turkey since Early Byzantine times (Anzidei et al., 2011; Flemming et al., 1973; Kızıldağ et al., 2012; Kızıldağ, 2019; Kızıldağ & Özdaş, 2021; Özdaş & Kızıldağ, 2013a; Stock et al., 2020). Nevertheless, no Bronze Age archaeological sea-level evidence could be obtained until now to provide data on the sea-level history of southwestern Turkish coasts.

In this study, sea-level data from a newly discovered Bronze Age site are presented to reconstruct the long-term sea-level evolution along the coast of the Bozburun Peninsula. Previously published data from two nearby sites, which were obtained under the SHIPT project, have been re-measured and re-evaluated in this study. A comparison of the observed data with sea-level predictions from GIA models provided an estimate for the tectonic component of the vertical displacement of the coastal sites.

## 2 Archaeological Framework

First settlers on the Chersonesos, modern Bozburun Peninsula, go back to the Chalcolithic Period (Gerber, 2019). For the following Bronze Age, no evidence has been found during the land surveys, except for two stone axes in Loryma (Gerber, 2019). This seemingly contradicts the Chersonesian place names which date back to the Bronze Age and indicate a continuity not yet visible in the archaeological record.

Archaeological surveys on Loryma, Bybassos, and Kastabos provided significant data on Chersonesos history (Held & Wilkening-Aumann, 2015; Held, 2019). In the first millennium BC, the Chersonesos has been ~~certainly~~ inhabited by Karians. In the Geometric Period, they seem not to have been sedentary but rather nomadic shepherds who erected simple refuge forts on the top of hills and mountains, which were only used in case of emergency (Held, 2019). Around the late 8th or early 7th century BC, they became sedentary and settled down in about 15 small but well-fortified settlements. The Chersonesians had a decentral political organization and settlement pattern which considerably differs from the model of the Greek polis with one central city (*asty*) and a rural area (*chora*) around it, as in neighboring Knidos or Rhodos. This non-central pattern is typical Karian. In the 4th century BC, the Rhodians took possession of the mainland opposite their island to secure it and exploit it economically: the 'Rhodian Peraia' which initially comprised the Chersonesos.

~~In 305 BC, Demetrios Poliorketes, one of the Diadochi fighting for the heritage of Alexander's Macedonian Empire, attacked Rhodos, starting from Loryma on the Chersonesos. After the siege of Rhodos which lasted for a whole year, Demetrios left Rhodos without success but leaving behind a devastated island. The Rhodians subsequently took possession of the mainland opposite of their island to secure it and to exploit it economically: the 'Rhodian Peraia' which initially comprised the Chersonesos, its neighboring region to the north 'Apeiros', and Physkos (modern Marmaris). In the first century BC, most of the peninsula was abandoned and resettled only in the 4th century AD, so that mainly Archaic to Hellenistic and Byzantine Period contexts are found in the region.~~

There is plenty of evidence for the production of wine and the amphorae for the transport of the wine during the 3rd and 2nd centuries BC when the peninsula was part of the Rhodian Peraia (Held & Şenol, 2010). Shipwrecks found around the Bozburun Peninsula also provide evidence for maritime trade during the 3rd century BC (Özdaş & Kızıldağ, 2013b). A Hellenistic export harbor at Bybassos confirms this context (Held, 2014). Other harbors for small ships for local and regional trade, and installations for the production of marine goods like fish or possibly purple dye are located along the shore (Kızıldağ et al., 2012). They create a network of regional sea transport and connect the Chersonesian economy through large harbors like Bybassos with the Mediterranean world. In the first century BC, most of the peninsula was abandoned and resettled only in the 4th century AD, therefore mainly Archaic to Hellenistic and Byzantine Period contexts are found in the region.

## 3 Regional Setting

Bozburun Peninsula is located in the southeastern Aegean Sea, southwestern Turkey (Figure 1). The studied sites are situated along the western coast of the peninsula, whose shores are open to Yeşilova Gulf, opposite Symi Island. The gulf is characterized by a narrow shelf area, particularly in the southern part, and an indented coastline with numerous small islands and bays that provide sheltered anchorages for ships.



Bozburun Peninsula has a rocky coastal zone, mainly characterized by limestone. Mesozoic carbonates are generally exhibited, the oldest of which is the Upper Triassic-Lower Jurassic platform (Ersoy, 1993). These carbonates overlap the clastic units and are overlapped by offshore limestones.

Coastal evolution of the region is mainly affected by the active tectonic framework of the Aegean, which is controlled by the effects of subduction along the Hellenic Arc and of northward subduction of the African plate beneath western Turkey and the Aegean region (Nomikou et al., 2021; Taymaz et al., 2007). This motion causes a back-arc extension of the continental crust and southwestward movement of the Turkish plate in the Aegean extensional province (Taymaz et al., 2007). This movement has been produced significant volcanic activity on the Aegean Volcanic Arc since Pleistocene with several volcanic centers (e.g. Santorini, Kos, and Nisyros) (Nomikou et al., 2021). Bozburun Peninsula is situated in this tectonically active region of the interaction between the eastern end of the Aegean Volcanic

Arc, Fethiye-Burdur Fault Zone (FBFZ), and the Pliny Trench (PT). This tectonic process caused numerous earthquakes during both historical and instrumental periods, affecting many archaeological sites. Significant clustered seismicity was recorded near the Yeşilova Gulf, and in the adjacent Gökova Gulf (Figure 1c).

Among the most destructive Rhodes earthquakes, it is worth mentioning: in 227 BC, which caused the collapse of the Colossus of Rhodes (Polybios 5,88); in AD 148, which caused a tsunami destroying many ships (Aelius Aristides, Rhodiakos 20–26); in 1481 ($I_0$=IX) with 30.000 fatalities; in 1609, which caused that over 10.000 people were reported to be drowned by a sea wave; and in 1874 ($I_0$=VIII), occurred very close to the study area (Guidoboni et al., 1994; Soysal et al., 1981). The earthquakes in the 6th and 7th century AD caused damage to several ancient cities in western Turkey (e.g. Sagalassos, Laodikeia and Hierapolis) (Similox-Tohon et al., 2005). The most recent earthquake activity occurred off the western Bozburun Peninsula between 24 to 28 November 2012, which had a mainshock of $M_L$=4.8 (Kandilli Observatory and Earthquake Research Institute, 2012) (Figure 1c). In total 582 earthquakes were recorded with a direction of about N-W, which are caused by local normal faults.

The most destructive and catastrophic event, the Santorini (or Thera) volcanic eruption, took place in the Late Bronze Age with accompanying subsequent major earthquakes and tsunamis. ~~Those events ruined the coastline of the Cycladic islands, Crete, southwestern Turkey, and the eastern Mediterranean.~~ The chronology of the eruption is still disputable between earth scientists (1650-1600 BC) and archaeologists (1530-1500 BC) (Driessen, 2019). Based on radiocarbon analyses of catastrophe markers, the most probable date for the

Minoan eruption was suggested as the late 17th century BC (Manning & Kromer, 2012), in particular, c. 1627–1600 BC (Friedrich & Heinemeier, 2009).

~~The presence of a sedimentary deposit off Israel revealed that tsunami waves from the Santorini eruption radiated throughout the eastern Mediterranean Sea, affecting the coastal sites (Goodman et al., 2009). A thick layer of debris left from a series of strong tsunamis related to the Santorini eruption was identified in Çeşme-Bağlararası, western Turkey (Şahoğlu et al., 2022).~~

## ~~4 Bronze Age shorelines in the Aegean Sea~~

## 4 Methodology

A newly discovered submerged Bronze Age archaeological site in Çamçalık was investigated with the aim of estimating the RSL changes on the coast of the Bozburun Peninsula. Two adjacent sites in Hıdırlık and Kiseli (Kızıldağ et al., 2012), previously documented and dated to the Hellenistic and Early Byzantine periods, were also re-measured and re-evaluated to present a long-term sea-level evolution along the coast of Bozburun Peninsula. In addition to the archaeological sea-level indicators, geomorphological indicators, i.e. marine tidal notches, were also studied. To interpret the relative sea-level data, we made an approach for dating and an assumption for the minimum original elevation of the observational data (Auriemma & Solinas, 2009; Lambeck et al., 2004), and then a comparison with GIA models.

### 4.1 Survey methodology

The fieldwork was focused on measurements of the current elevations of archaeological (i.e. quay and breakwater) and geomorphological (tidal notch) structures, taking the photos and sampling the archaeological material. The first step of the fieldwork was to determine the distribution of the submerged remains by a photogrammetric survey based on taking aerial photos by using DJI Inspire 1 Pro with Zenmuse X5 16MP 30s camera. Then photomosaics were generated by using Agisoft Metashape software (Agisoft LLC., St. Petersburg, Russia). The subsequent stage of the survey was to measure the current elevations of the archaeological and geomorphological structures with respect to the present mean sea level. All the finds were located using a JRC model differential global positioning system (DGPS) receiver.

The upper surface depth from sea level, the height, and the width of the quays and breakwaters were measured (Table 1). As for tidal notch, the vertex depth from sea level, the inward depth and the height were measured. All measurements were taken during periods of low-energy waves. The observed data were reduced to mean sea level by applying tidal corrections at the time of surveys by calculating the residual sea level using a tide gauge dataset obtained from the nearest Marmaris station (https://tudes.harita.gov.tr). The local tide amplitude is ~0.3 m on the southwestern coast of Turkey (Yıldırım et al., 2022).

A vertical error was added to the measurements, which could be derived from the accuracy of measurements of the structures (Vacchi et al., 2016) and the condition of the measured surface. Although harbor constructions are good sea-level indicators, they have some limitations when determining whether the measured surface of the structures represents the original surface at the time of construction (Benjamin et al., 2017). The depths of particular functional features of the harbor installations were measured on the best-preserved original surface of the structures with consideration of the uncollapsed regular surfaces, both those extending for meters at almost the same level. Particularly in the Hıdırlık site, the uppermost surface of the breakwater clearly reflects the original surface used in the past since the wall remains can be followed throughout the entire structure. Since the sites are located on a low-energy coast that is sheltered from winds and waves, no measurement difficulties were encountered due to the wave effects. Therefore, a vertical error of ±0.1 m was added to the measurements taken from the preserved surfaces.

### 4.2 Relative sea-level reconstruction

The accuracy of the RSL reconstruction using archaeological sea-level markers depends on determining their association with the sea level in the past (Morhange & Marriner, 2015). Interface structures of harbors (e.g. quays and breakwaters) provide reliable data on the amount of sea-level change (Evelpidou & Karkani, 2018; Morhange & Marriner, 2015; Vacchi et al., 2016). The presence of fixed biological zonation on the archaeological structures significantly improves the reliability of sea-level index points (SLIP; indicators of former RSL) (Morhange & Marriner, 2015). In some cases, the construction technique can help to determine the amount of the functional height (the original elevation above the ancient MSL) (i.e. by detecting the concrete change between the areas in hydraulic concrete and the areas in concrete in a subaerial environment) (Aucelli et al., 2020). In case of the absence of bio-zonation or any other evidence, the assigning of functional height can have some difficulties since it differs by region, age and function of the structure. However, Antonioli et al. (2007) and Auriemma & Solinas (2009) suggested a functional height for harbor installations (e.g. piers, docks, and breakwaters) of 0.6 m above mean sea level taking into account the observations collected at many submerged archaeological sites along the coast of Mediterranean. This assumption was widely used in many sea-level studies in recent years (e.g. Aucelli et al., 2016; Kızıldağ & Özdaş, 2021; Kolaiti & Mourtzas, 2020).

We assigned 0.6 m of minimum original elevation for the quays and breakwaters with respect to the mean sea level during their operation, taking into consideration (i) the site conditions (e.g. the protection against wave action and shallow harbor basin), (ii) local tide amplitude (i.e. micro-tidal range); (iii) the draught of the ancient small boats for the landing to the quay (e.g. the Ravenna ship from 5th century AD had a draught about 0.5 m; Medas, 2003), (iv) the modern quays and breakwaters in the Bozburun town (e.g. their elevations of 0.6/0.8±0.1 m during the mean sea level); and (v) the relevant literature mentioned above. Taking into account the lack of precise sea-level index points (e.g. biological zonation) we added an error of ±0.2 m for the uncertainty of the original elevation approximation, which was assumed based on different interpretations presented by the abovementioned sea-level studies.

The breakwaters in the studied sites have a maximum height of 1.2 m. They have been built in small, shallow, and protected bays and must have been used by the small boats. If we add the error of -0.2 m and the high tide of 0.15 m to the presumed "minimum" original elevation of 0.6 m, the emerging segment of a breakwater has a height of 0.25 m and no less than 0.25 m was presumed for protection. The depth of harbor basin in front of the quay or breakwater was also considered for presumed original elevation and its error.

By determining a minimum original elevation, we estimated the paleo RSL position from the following equation (Shennan et al., 2015):

$$RSL_i = ME_i - OE_i$$

where ME is the measured elevation of the archaeological sea-level marker "i" and OE is the minimum original elevation value for the marker "i".

### 4.3 Chronological setting

To improve the chronology of RSL changes, we considered the time of the last use of archaeological constructions when they were still functional. Based on the fact that the sites were never used after they were abandoned, this study adopted the approach of the time of the last usage instead of construction time (Kızıldağ, 2019). This provides data on the earliest time of submergence and a more precise estimation. In other words, this approach constrained estimates of the magnitude of the vertical land movements. Archaeological material, i.e. ceramic findings among the submerged harbor structures and architectural remains on land, provided important chronological data. Furthermore, literature and historical records supplied information regarding the abandonment date.

### 4.4 GIA predictions and contributions to the RSL

The separation of glacio-hydro-isostatic signals from the observed sea-level data allows us to identify the amount of tectonic contribution to the RSL change and obtain the vertical tectonic rate (Anzidei et al., 2011; Karkani et al., 2019; Kolaiti & Mourtzas, 2020; Lambeck et al., 2004; Mattei et al. 2022; Vacchi et al., 2020). In order to identify the expected vertical land movements due to glacio-hydro-isostasy, we computed a set of GIA models for the study area. Then the predictions from GIA models were compared with the observational sea-level data to assess the vertical tectonic movements.

To evaluate the variations of RSL induced by GIA since 5000 BP, we obtained a suite of high-resolution solutions of the sea-level equation (SLE) using the SELEN4 solver (Spada & Melini, 2019). The SLE accounts for the gravitationally and topographically self-consistent response of the Earth to the melting of Late Pleistocene ice sheets, and its basic inputs are the spatio-temporal evolution of the ice load and the rheological profile of the Earth. We computed three solutions of the SLE by integrating into SELEN4 the ice chronologies and viscosity profiles assumed by ICE-6G (Peltier et al., 2015), ICE-7G (Roy & Peltier, 2015; 2017), and one of the iterations of the GIA models progressively developed by K. Lambeck and collaborators at the Australian National University (ANU; see e.g. Lambeck et al., 2003, 2014; Nakada & Lambeck, 1987). All our simulations are based on a global icosahedral grid with a spacing of ~40 km and include spectral terms up to harmonic degree L=512 that correspond to a wavelength of ~80 km on the Earth's surface. The boundary conditions for paleo-topography have been prescribed by assuming as a present-day topography the bedrock version of the ETOPO1 global topographic model by Amante & Eakins (2009), integrated with the Bedmap2 relief (Fretwell et al., 2013) in the Antarctic region (south of 60°S latitude).

As discussed by Melini & Spada (2019), GIA models are affected by different sources of uncertainties, stemming from imperfect knowledge of the model parameters and by different approaches to the numerical solution of the SLE. This is of particular relevance in regional-scale GIA models, since local rheological structure may be significantly different from average profiles suitable for global GIA models. Following Spada & Melini (2022), through an ensemble approach, we have evaluated a range of uncertainties associated with RSL predictions of models ICE-6G and ANU, arising from imperfect knowledge of the regional-scale rheological structure of the Mediterranean basin. In particular, since hydro-isostatic effects are mostly controlled by lithospheric flexure, we considered variations of the modeled RSL curves corresponding to a range of plausible values of the thickness of the lithosphere and evaluated the corresponding 1-sigma uncertainties on the model predictions.

## 5 Results

In this study, sea-level data from a new submerged Bronze age site (Çamçalık) and previously discovered and re-surveyed and re-measured two submerged archaeological sites (Hıdırlık and Kiseli) were analyzed to reconstruct the long-term RSL changes occurred along the Bozburun Peninsula in the last 3600 years.

### 5.1 Çamçalık Bronze Age site

A submerged platform structure containing a large number of archaeological materials was found at the Çamçalık Bronze Age site (Figure 2). The platform extends about 150 m parallel to the shoreline, with a maximum width of 10 m at the northern side of the Çamçalık island, which is connected to a submerged isthmus to the mainland. The upper surface of the structure is located at -2.5±0.1 m, while the bottom goes down in an abrupt vertical sheer to the natural seafloor at -4.9±0.1 m depth. The archaeological materials in this artificial platform are naturally concreted and cemented with rocky materials, ~~similar to a large beachrock formation~~ (Figure 2d, e).

Among the archaeological finds, hundreds of loom weights, conical cups, carinated cups, stone axes and tools, and a large number of ceramic fragments of pithoi, beak-spouted jugs, oval-mouthed amphorae, tripod legs of cooking pots, etc. were recorded, most of them homogeneous in type and date (Figure 3). While most loom weights and conical cups are intact, all other ceramic vessels are in poor condition. Removing the cemented archaeological material during the archaeological excavation, some well-preserved loom weights, conical cups, and pottery fragments were uncovered as uncemented and surrounded by rock pieces.

Some wall remains are visible on the top of the eastern section of the platform, extending to the land, which are submerged today (Figure 2b, c). With only one layer of stones, they are barely distinguishable among the debris from a modern fish farm and coastal erosion, partly remaining under modern masonry. The wall remains, which have been constructed by using rubble and roughly-cut stones without mortar, form rectangular structures with a maximum width of 8 m.

~~Since this area has been used by a modern fish farm until ten years ago, a great number of dump materials are observed on the seafloor. In addition, due to pollution from the fish farm's waste, the seafloor and the remains are covered with a layer of slime. Most archaeological finds have been heavily damaged by the farm's activity.~~



During the complimentary survey carried out on land, we obtained only a few finds, scattered over the whole island, and showing the same spectrum. The whole island, despite its uncomfortably steep and rocky slopes, has been inhabited as attested by many small terraces built from rough boulders and up to the peak of the island. The plainer eastern part of the island near the submerged isthmus connecting it to the mainland, which was most suitable for construction, has been destroyed by service buildings and installations of a recent fish farm.

In addition to archaeological materials, we observed geomorphological indicators along the limestone rocky coastline of the site. A distinctive submerged tidal notch structure is identified along the southwestern limestone cliff of the island (Figure 4a). The vertex depth of the notch, which corresponds to the former mean sea level, is approximately 0.6±0.1 m lower than the modern shoreline. The inward depth was measured as 0.8±0.1 m.

### 5.2 Hıdırlık Hellenistic site

Previous studies carried out in the submerged sites on the coast of Bozburun Peninsula provide a data set for long-term sea-level evaluation (Kızıldağ et al., 2012). A submerged breakwater located in the Hıdırlık Harbor on the southern coast of Yeşilova Gulf was re-investigated during the fieldwork. Rubble-mound breakwater has a length of 36 m and maximum width of 10 m (Figure 5). The well-preserved top layer, which has been made up of large rough stones, lies at -1.5±0.1 m (Figure 5b, c). The bottom depth reaches 2.7±0.1 m at the inner basin and 3.5±0.1 m at the outer basin. The foundations of a rectangular building were observed in the inner harbor; whose floors are measured at -0.7±0.1 m.

This small harbor is linked to a Hellenistic farm by a path, and the breakwater must have served the farm. An architectural remain dated to the Late Classical/Early Hellenistic Period (4th-3rd century BC) is located on the coastline, which is most probably associated with harbor activities (Figure 5a, inset). Additionally, the shipwrecks in the surrounding area confirm a date of 3rd century BC for the time of the usage of the harbor.

A well-developed submerged tidal notch structure was observed along the coast at a depth of 0.5 to 0.55 m with a maximum inward depth of 0.4 m (Figure 4b).

### 5.3 Kiseli early Byzantine site

A submerged breakwater is located off Kiseli Island, close to Tymnos ancient city and modern Bozburun town, which was previously documented by Kızıldağ et al. (2012) (Figure 6a, b). The surface of a rubble mound breakwater is now located at -1.0±0.1 m below present mean sea level. The depth at the base of 16 m long and 6 m wide breakwater was measured at -1.8±0.1 m at its seaward end. The breakwater is associated with the adjacent partly submerged church remains dated to the early Byzantine period (Figure 6a).

A submerged quay consisting of rough-cut ashlar blocks is located on the western coast of Kiseli Island (Figure 6c). The upper surface of the quay lies at -1.0±0.1 m below present sea level, while the bottom level lies at -2.40±0.1 m. The foundations belonging to rectangular buildings on the quay platform are partly submerged. Based on the fact that the building foundations are located directly upon the quay platform and the quay blocks are preserved and not collapsed, the current surface of the quay is considered to represent the original surface.

The adjacent buildings and churches on land are dated to the early Byzantine times, which were in use until the 7th century AD. The abundance of LR1 amphora sherds, dated to the 5–7th century AD (Opait, 2004), near the breakwater and along the coasts provide evidence for the time of the last usage of the site.

Similar to other sites, a clear tidal notch structure is located at -0.6 m with a maximum inward depth of 0.3 m that continuous along the entire rocky coast (Figure 4c). No present-day notch is observed.

## 6 Discussion

### 6.1 A Bronze Age quay

The investigation of Bronze Age harbors in the Aegean Sea is a major challenge for researchers since most of them are submerged or buried due to geomorphological changes like sea-level changes, siltation, marine erosion, and tectonic movements, which have occurred since that time (Tartaron, 2013). Before coastal geomorphological studies accelerated, the problem of long-term coastal change was widely ignored as it was assumed that Bronze Age coastal morphology remained unchanged until today.

The known Bronze age harbors (e.g. the Minoan harbors of Gournia, Pseira, Kommos, Amnissos, Malia, and Mochlos) exhibit some common characteristics, including natural protection from the prevailing wind; a promontory or bay where ships can moor; an installation for winter storage of ships; storage facilities for goods; and a location near trade activity (Blackman, 1982; Watrous, 2012). According to Shaw (1990), the preferred topography was peninsulas with sandy beaches on both sides as landing places. Tartaron et al. (2003) successfully used this “double harbor arrangement” pattern to detect Bronze Age harbors by reconstructing the shoreline.

According to most scholars, the Aegean harbors of the Bronze Age were not supplied with maritime installations (e.g. quays and piers); instead, sandy beaches were used for landing, where the ships could be dragged on land (e.g. Loizou, 2016; Shaw, 1990; Tartaron et al., 2003). After geomorphological reconstruction of the harbor of Zakros in Crete, Guttandin et al. (2011) suggested that the harbor was originally located in a bay that since then has been silted up and had a jetty at its entrance and probably quays erected from large boulders along the shore. Similar quays may be recognized on the ship fresco from Akrotiri, where–next to the mentioned bay with small ships on the beach–in a neighboring bay two ships are depicted, berthing with their sterns perpendicular to the shore or a quay (Blackman, 2011; Guttandin et al., 2011).

The most recent discussion was presented by Hadjidaki (2021) about the Minoan natural or artificial harbors. To construct a harbor at Kapetaniana (Crete), the top of the small reef was flattened, and lines of stones were placed on top of it, thus producing a mole of 40 m in length. Furthermore, in the region where the coast was flat enough, an artificial installation was provided, which was created from pottery concreted within the boulders and sherds, for additional protection and landings of the ships. A man-made mole or breakwater is located in the harbor of Cape Plaka (Crete), built on top of a natural reef with some lines of large boulders (Hadjidaki, 2004).



The artificial platform of Çamçalık must have provided a quay function in the Bronze Age topography of the site (Figure 7). Associated with some Minoan harbor works in Crete, it seems to have been a construction of rough boulders producing a slightly sloping quay, rather than a vertical masonry stone wall. This yet is not an obstacle for the use as a quay, provided that the ships docked with the bow towards the quay, and an anchor at the stern-or the other way round. This is the usual system of berthing in the Mediterranean, even today ships are using a quay of rough boulders. The presence of the wall stones on the platform provides evidence for its function as a quay. The platform must have provided a dry area for the landing of ships and cargo transfer. With an average width of 10 m, the platform has offered sufficient space for the erection of small buildings.

**6.2 Cultural context of Çamçalık**

The spectrum of the Çamçalık pottery, which contains conical cups, three-legged cooking pots, spherical loom weights, etc., is culturally associated with the household pottery of Minoan, Bronze Age Aegean culture (Momigliano, 2012). In particular, the use of Linear A script on three loom weights provides clear evidence of Minoan culture (Silvia Ferrara, Bologna, pers. comm.). The closest finds of pottery are dated between Middle Minoan III (MM III) to Late Minoan I (LM I) phases, i.e. to the Neopalatial Period in Crete (Watrous, 2021). In addition, the pottery shows the typical range of Minoanising settlements in Anatolia such as Iasos or Miletos. There was a network between the Aegean islands and the Anatolian mainland (Momigliano, 2009). The MM III to LM I periods are well attested in Anatolia and correspond to phase IV at Miletos (Niemeier, 2005; 2007). Çamçalık pottery is very similar to that of Miletos IV, with 95% of the pottery determined as Minoan types, most of it locally produced, and only 5% local western Anatolian types (Niemeier, 2005; 2007).



Since no other period is attested in the finds, the submerged platform of Çamçalık can be dated to the MM III/LM IA period (1600 BC). Since material from later periods is absent, the occupation at Çamçalık had only one phase before its destruction and abandonment. The end of the settlement may have been caused by the Santorini eruption, accompanied by co-seismic tectonic movements. The eruption also caused a period of decline at Iasos (Momigliano, 2012; Niemeier, 2007).

~~Minoans were famous for their seafaring skills, which opened trade routes with Egypt, Anatolia, and the Levant. In the context of Minoan trade routes, Çamçalık marks the place where Minoan seafarers, sailing along the 'Eastern String' from Crete and passing the islands Karpathos and Rhodes, first reach the Anatolian mainland. The end of the settlement may have been caused by the Santorini eruption, accompanied by a sudden co-seismic tectonic subsidence. That might also be an explanation for a large amount of pottery scattered on the seafloor down to a depth of 30 m, which possibly indicates that a tsunami washed all this material away from the settlement. Those scattered potteries may be associated with the~~

following destructions by mostly human activity (modern fish tanks operations) and also natural events (erosion, further earthquake activity, etc.).

Çamçalık is unique in terms of providing the largest collection of Bronze Age finds ever found underwater in Anatolia. One of the puzzling results of the previous land or underwater surveys on the Bozburun Peninsula was the almost complete lack of evidence for Bronze Age coastal settlements. Nevertheless, Bronze Age finds from the underwater survey in the Hisarönü Bay and at Loryma (Özdaş & Kızıldağ, 2016; Özdaş & Kızıldağ, 2017) proved that the area has been used in the Bronze Age by ships. The discovery of the Çamçalık Bronze Age site complemented and explained the underwater finds filling a gap in the literature in this region.

**6.3 Relative sea-level evaluation**

The submersion of the harbor structure of the Çamçalık site led to the identification of a sea-level stand during the Bronze Age. Taking into consideration the assumed original elevation for the quay and the last time of use for the site, the RSL change was determined by using the equation RSLi to be at least 3.1±0.3 m during the last 3600 years.

Data from nearby submerged sites on the coast of the Bozburun Peninsula provide a data set for long-term sea-level evaluation (Kızıldağ et al., 2012). The breakwaters in Hıdırlık and Kiseli sites are well-dated based on the architectural remains on land and ceramic findings among the submerged architectural remains. In particular, the abandonment history of the Early Byzantine site provides a more precise date for submergence. Taking into account the assumed minimum original elevation of 0.6±0.2 m for the breakwaters at the time of their use, two different sea-level stands can be inferred from Hıdırlık and Kiseli sites by using the equation RSLi: at -2.1±0.3 m during the Hellenistic Period (~2300 BP) and -1.6±0.3 m during the Early Byzantine Period (~1400 BP) respectively.

Sea-level studies carried out in the Mediterranean present comprehensive RSL data for Bronze Age. Henderson et al. (2011) suggest that the foundations of the buildings at Bronze Age Pavlopetri have been submerged by c. 4–5 m during the last 5000 years, due largely to tectonic factors. The submerged Early Bronze Age (EBA) settlement building walls at Platiyali extend to a depth of at least 5 m below present sea level. Another submerged EBA settlement, Salanti, is found at a depth of 4 m below present sea level. Over a hundred bronze axes from EBA were found at a depth of 3.5 m below present sea level in the Glyfada-Mesi site. Moreover, Evelpidou et al. (2018) identified a submerged shoreline at -2.8 m based on a tidal notch in Naxos Island (the Cyclades in the Aegean Sea), which must have been developed at least before 3350 to 4200 BP. Kolaiti & Mourtzas (2016) determined a sea-level stand of 3.3 ± 0.15 m during the Middle Bronze Age in the west Saronic Gulf. The beachrock formations located in the Mykonos–Delos–Rhenia region in Cyclades, Greece, indicate a sea-level stability at −3.6 m around 2000 BC (Desruelles et al., 2009). Based on beachrock data, Karkani et al. (2017) suggested that the relative sea level rose by at least 3.8 m in the last 4000 years in the central Cyclades. Although Çamçalık has different tectonic characteristics comparable with other Mediterranean tectonically active areas, sea-level data seem to be compatible with the other sites.

Antonioli et al. (2011) suggested a RSL rise of 2.3 m and tectonic subsidence of about 1.48±0.3 mm/yr since the last 2300 years for the southwestern Turkish coasts. RSL rise of at least 2.8 m over the past 1400 years is suggested for Kekova (Özdaş & Kızıldağ, 2013). Recent detailed studies demonstrated that Fethiye coasts have a greater amount of RSL rise of

3.1-4.6±0.3 m in the Gulf of Fethiye (Kızıldağ, 2019) and 2.2-3.1±0.3 m on the eastern coast of Fethiye (Kızıldağ & Özdaş, 2021) over the last 1400 years. This remarkable difference in RSL changes between the regions confirms that the local scale tectonic processes have an important effect on the submergence of coastal sites.

Relative sea-level variations in the Mediterranean basin, which is in the far-field of the former Late Pleistocene ice sheets, are mostly controlled by hydro-isostatic effects due to meltwater load and associated with vertical land movements stemming from the combined effect of tectonics and GIA (Spada & Melini, 2022). Figure 8 shows modeled relative-sea level in the study area according to the GIA models ICE-6G, ICE-7G and ANU; the range of 1-sigma epistemic uncertainties associated with ICE-6G and ANU, obtained through the ensemble approach outlined above, corresponds to shaded areas. Taking into account the amplitude of uncertainties, ICE-6G indicates a substantially stable sea level since 3600 BP, and a slow RSL rise for earlier epochs, while ICE-7G predicts a highstand of about 0.2m between 2000 and 3600 BP, with the modeled RSL curve according to ICE-7G being at the upper boundary of the 1-sigma confidence interval of the ICE-6G RSL prediction. Conversely, the ANU model predicts a much faster RSL rise between 3600–1400 BP, followed by a slower rise up to the present sea level. The qualitative difference between predictions from ICE-X and ANU reflects different eustatic curves as well as different rheological profiles assumed by the models considered.

The maximum GIA contribution to the vertical land movement is 0.9±0.2 m for the last 3600 years; 0.3±0.1 m for the last 2300 years; and 0.1±0.05 m for the last 1400 years. In comparison with the GIA curves, our archaeological index points remained at a lower position. The difference between predictions from GIA models and archaeological sea-level index points allows us estimating the magnitude of local vertical tectonic displacement in the study area. Removing the maximum GIA component, we estimate a tectonic subsidence rate of at least 0.6±0.5 mm/yr over the last 3600 years. ~~Removing ANU-based GIA components, average rates of tectonic subsidence were estimated for three different timespans: 0.3±0.5 mm/yr during the period between 3600-2300 BP; 0.3±0.4 mm/yr between 2300-1400 BP, and 1.1±0.3 mm/yr from 1400 BP to the present. Based on ICE-6G and ICE-7G curves, tectonic subsidence rates were calculated as 0.8±0.6 mm/yr; 0.6±0.5 mm/yr; and 1.1±0.4 mm/yr for the same timespans.~~ Nevertheless, GIA calculations indicate that there is a remarkable increase in vertical tectonic movement after Early Byzantine times.

The comparison of the current positions of the Early Byzantine remains at -1.0±0.1 m with the tidal notch at -0.6±0.1 m verifies that the sea level has remained stable at -0.6±0.1 m and a tidal notch has developed after the submersion of Early Byzantine remains. In other words, a most recent vertical displacement has occurred in the last 1400 years. The inward depth of a notch is related to the duration of sea-level stability. Evelpidou et al. (2014) suggested that notches can develop at rates of bioerosion between 0.2 and 1.0 mm/yr in the Mediterranean coastline. Nevertheless, the rock lithology and the contribution of several processes (e.g. fresh-water springs, wave energy and bioerosion rate) have important roles in notch formation (Antonioli et al., 2015). Anyhow, the inward depth of about 0.8±0.1 m indicates long-term sea-level stability in a timespan between the Early Byzantine times and modern times.

The fact that the presence of one prominent tidal notch structure, which is almost fixedly observed throughout the western part of the Bozburun Peninsula, and the absence of the deeper ones may confirm sudden submergence in a timescale after the Early Byzantine Period and gradual submergence between the Late Bronze Age and Early Byzantine Period. When the rate of RSL change is greater than the rate of bioerosion, a tidal notch does not form (Evelpidou et al., 2014). The fact that the absence of any biologic or geomorphologic sea-level indicator on the vertical surface of the 150 m long and 2.4 m thick monolithic platform, which exhibits a homogeneous formation from top to bottom, may support the assumption of gradual submergence after the Bronze age occupation, mostly associated with ANU model.

The presence of present-day development of tidal notches is still debatable. Based on studies carried out along tectonically active Greek coastlines, Evelpidou et al. (2012) suggested that the modern tidal notch is disappearing because the bioerosion rate remained lower than the rate of sea-level rise during the last century (~1.4 mm/yr). Conversely, Antonioli et al. (2015) proposed that the current notch is present in the vast majority of tectonically stable carbonate coasts in the central Mediterranean. However, the global rise in sea level at a rate of ~1.4 mm/yr since the late 19th century should not be ignored at this point (Church et al., 2008).

The proposed date of the archaeological finds in Çamçalık corresponds to the period shortly before the Santorini eruption, which may have caused the end of the settlement. The Çamçalık quay must have lost its function after the Late Bronze Age, with catastrophic events accompanying the Bronze Age eruption of Santorini. This assumption fits with the proposed date for archaeological finds. The absence of later layers can confirm that life must have been interrupted by an earthquake and the eruption of Santorini.

The Late Bronze Age Minoan eruption of Santorini is one of the most powerful volcanic eruptions known to have occurred during the Holocene (Eastwood et al., 2002~~). It is proposed that one or more tsunamis accompanied Santorini eruption and the associated earthquakes, which was confirmed by the presence of sedimentary deposits attributed to tsunami waves off~~

Caesarea Maritima, Israel (Goodman et al., 2009) and in Çeşme-Bağlararası, western Turkey (Şahoğlu et al., 2022).The eruption must have been triggered by one or more earthquakes ($I_0$=X) (Soysal et al., 1981), which caused damage in Rhodes, Kos, and Crete (Driessen, 2019). The fact that there are no archaeological remains from the Bronze Age to the Hellenistic Period in the site indicates that Çamçalık was abandoned as a result of one or more catastrophic events. Similarly, there is a gap between Early Byzantine and modern times in the surrounding region, which can be explained by ongoing seismic events, causing the coastal changes.

Prevailing winds during the eruption carried volcanic ash from Santorini to Rhodes and southwestern Turkey rather than Crete and thus more volcanic dust must have fallen on the Turkish coasts. The analysis of volcanic ashes obtained from western and southwestern Turkey indicates that the tephra belongs to the Santorini Minoan eruption (Vardar & Öner, 2016). Marketou (1987) noted tephra layers that were discovered in many sites in Rhodes, probably from the Santorini eruption, in addition to that found at the Late Minoan site at Trianda in the northeastern island. Marketou (1990) also stated that a destructive earthquake occurred before the Santorini volcano awoke and then tephra fell.

## 7 Conclusions

By producing new data from the recently discovered Bronze Age site, the relative sea-level history along the coast of Bozburun Peninsula in the last 3600 years was reconstructed for the first time with this study. The comparison of the observed RSL data with predictions from recently published GIA models allowed us to evaluate the impact of the vertical tectonic movement. Precise chronological data provided evidence to determine an accurate timespan (e.g. archaeological material mixed with harbor constructions and abandonment history) and then to constrain the magnitude of the vertical land movement.

Our results suggest that observed sea-level change is due to equal contributions of GIA and tectonic factors (ANU model) or only to tectonics (ICE-X models) between 3600-1400 BP, while the tectonic contribution is considerably dominant after 1400 BP. A rapid acceleration in the submergence of the coastline was defined between Early Byzantine and modern times. This indicates that the seismic activity in the study area produced vertical land movement during this period. Geomorphological sea-level markers confirmed that a long-term sea-level stand occurred after Early Byzantine archaeological remains had submerged. On the contrary, the absence of deeper tidal notches or biological layers on the Bronze Age quay platform can be attributed to a gradual RSL rise.

The results obtained in this study highlight the complex history of sea-level changes in the coastal sector of the Bozburun Peninsula, which is located in the active tectonic segment of the southeastern Aegean Sea. The tectonic regime due to interaction between the Hellenic Arc subduction zone and Aegean Volcanic Arc is responsible for the submersion of coastal archaeological sites, predominantly in the last 1400 years. A recent earthquake activity that occurred in 2012 verifies that the western coast of the Bozburun Peninsula is still under the influence of ongoing seismicity.

This study demonstrates that RSL changes had a significant impact on the past cultures that were living in the coastal zone of the Bozburun Peninsula. Further studies would improve our understanding to produce future scenarios regarding the impact of relative sea-level rise on coastal occupation by considering both local tectonic estimates and the projections of 21st century sea-level rise.

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## References

Amante, C., & Eakins, B. W. (2009). ETOPO1 Global Relief Model converted to PanMap layer format. *NOAA-National Geophysical Data Center, PANGAEA*. https://doi.org/10.1594/PANGAEA.769615.

Antonioli, F., Anzidei, M., Lambeck, K., Auriemma, R., Gaddi, D., Furlani, S., Orrù, P., Solinas, E., Gaspari, A., Karinja, S., Kovačić, V., & Surace, L. (2007). Sea-level change during the Holocene in Sardinia and in the northeastern Adriatic (central Mediterranean Sea) from archaeological and geomorphological data. *Quaternary Science Reviews, 26*(19-21), 2463-2486.

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

Anzidei, M., Antonioli, F., Benini, A., Lambeck, K., Sivan, D., Serpelloni, E., & Stocchi, P. (2011). Sea level change and vertical land movements since the last two millennia along the coasts of southwestern Turkey and Israel. *Quaternary International, 232*(1-2), 13-20.

Anzidei, M., Lambeck, K., Antonioli, F., Furlani, S., Mastronuzzi, G., Serpelloni, E., & Vannucci, G. (2014). Coastal structure, sea-level changes and vertical motion of the land in the Mediterranean. *Geological Society, London, Special Publications, 388*(1), 453-479.

Aucelli, P., Cinque, A., Mattei, G., & Pappone, G. (2016). Historical sea level changes and effects on the coasts of Sorrento Peninsula (Gulf of Naples): New constrains from recent geoarchaeological investigations. *Palaeogeography, Palaeoclimatology, Palaeoecology, 463*, 112–125.

Aucelli, P. P., Mattei, G., Caporizzo, C., Cinque, A., Troisi, S., Peluso, F., Stefanile, M., & Pappone, G. (2020). Ancient coastal changes due to ground movements and human interventions in the Roman Portus Julius (Pozzuoli Gulf, Italy): Results from photogrammetric and direct surveys. *Water, 12*(3), 658.

Auriemma, R., & Solinas, E. (2009). Archaeological remains as sea level change markers: a review. *Quaternary International, 206*(1-2), 134-146.

Benjamin, J., Rovere, A., Fontana, A., Furlani, S., Vacchi, M., Inglis, R. H., Galili, E., Antonioli, F., Sivan, D., Miko, S., Mourtzas, N., Felja, I., Meredith-Williams, M. Goodman-Tchernov, B., Kolaiti, E., Anzidei, M., & Gehrels, R. (2017). Late Quaternary sea-level changes and early human societies in the central and eastern Mediterranean

Basin: An interdisciplinary review. *Quaternary International, 449,* 29-57. https://doi.org/10.1016/j.quaint.2017.06.025.

Blackman, D. (1982). Ancient harbours in the Mediterranean. Part 1. *International Journal of Nautical Archaeology, 11*(2), 79-104.

Blackman, D. (2011). Minoan Shipsheds. *Skyllis, 11*(2), 4-11.

Church, J. A., White, N. J., Aarup, T., Wilson, W. S., Woodworth, P. L., Domingues, C. M., Hunter, J.R., & Lambeck, K. (2008). Understanding global sea levels: past, present and future. *Sustainability Science, 3*(1), 9-22.

Desruelles, S., Fouache, É., Ciner, A., Dalongeville, R., Pavlopoulos, K., Kosun, E., Coquinot, Y., & Potdevin, J. L. (2009). Beachrocks and sea level changes since Middle Holocene: comparison between the insular group of Mykonos–Delos–Rhenia (Cyclades, Greece) and the southern coast of Turkey. *Global and Planetary Change*, *66*(1-2), 19-33. https://doi.org/10.1016/j.gloplacha.2008.07.009.

Driessen, J. (2019). The Santorini eruption. An archaeological investigation of its distal impacts on Minoan Crete. *Quaternary International*, *499*, 195-204.

Eastwood, W. J., Tibby, J., Roberts, N., Birks, H. J. B., & Lamb, H. F. (2002). The environmental impact of the Minoan eruption of Santorini (Thera): statistical analysis of palaeoecological data from Golbisar, southwest Turkey. *The Holocene, 12*(4), 431-444.

Ersoy, S. (1993). Transgresif platform karbonat istifine Bozburun (Marmaris, Muğla) yarımadasından bir örnek. *Türkiye Jeoloji Bülteni*, *36*(2), 171-177.

Evelpidou, N., & Karkani, A. (2018) Archaeology and sea-level change. In C.W. Finkl, & C. Makowski (Eds.), *Encyclopedia of Coastal Science* (pp.1-7). Cham: Springer.

Evelpidou, N., Melini, D., Pirazzoli, P. A., & Vassilopoulos, A. (2014). Evidence of repeated late Holocene rapid subsidence in the SE Cyclades (Greece) deduced from submerged notches. *International Journal of Earth Sciences, 103*(1), 381-395.

Evelpidou, N., Tziligkaki, E., & Karkani, A. (2018). Submerged Antiquities on Paros and Naxos Islands, Aegean Sea, Greece. New evidence for the mean sea level during the late Bronze Age and the Roman period. *Bulletin of the Geological Society of Greece, 52*(1), 71-9.

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

Flemming, N. C., Czartoryska, N. M. G., & Hunter, P. M. (1973). Archaeological evidence for eustatic and tectonic components of relative sea level change in the South Aegean. *Marine Archaeology, 23*, 1-63.

Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., Bianchi, C., Bingham, R. G., Blankenship, D. D., Casassa, G., Catania, G., Callens, D., Conway, H., Cook, A. J., Corr, H. F. J., Damaske, D., Damm, V., Ferraccioli, F., Zirizzotti, A. (2013). Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere, 7,* 375–393, doi:10.5194/tc-7-375-2013.

Friedrich, W. L., & Heinemeier, J. (2009). The Minoan eruption of Santorini radiocarbon dated to 1613+13 BC-geological and stratigraphic considerations. *Monographs of the Danish Institute at Athens*, *10*, 57-63.

Galanidou, N., Dellaporta, K., & Sakellariou, D. (2020). Greece: Unstable landscapes and underwater archaeology. In G. Bailey, N. Galanidou, H. Peeters, H. Jöns & M. Mennenga, (Eds.), *The Archaeology of Europe's Drowned Landscapes* (pp.371-392). Springer, Cham.

Gerber, C. (2019). Die Karische Chersones in prähistorischer Zeit. Ergebnisse der Begehungen in Loryma 2001 und Bybassos 2006. In W. Held (Ed.), *Die Karische Chersones vom Chalkolithikum bis in die byzantinische Zeit. Beiträge zu den Surveys in*

*Loryma und Bybassos* (pp. 11–66). Eigenverlag des Archäologischen Seminars der Philipps-Universität.

Goodman-Tchernov, B. N., Dey, H. W., Reinhardt, E. G., McCoy, F., & Mart, Y. (2009). Tsunami waves generated by the Santorini eruption reached Eastern Mediterranean shores. *Geology*, *37*(10), 943-946.

Guidoboni, E., Comastri, A., & Traina, G. (1994). *Catalogue of ancient earthquakes in the Mediterranean area up to the 10th century (Vol. 1).* Rome: Instituto Nazionale di Geofisica.

Guttandin, T., Panagiotopoulos, D., Pflug, H., & Plath, G. (2011). *Inseln der Winde. Die maritime Kultur der bronzezeitlichen Ägäis.* Institut für Klassische Archäologie Universität Heidelberg.

Hadjidaki, E. (2004). A Possible Minoan Harbor on South Crete. In L. Preston Day, M.S. Mook & J.D. Muhly (Eds.), *Crete Beyond the Palaces: Proceedings of the Crete 2000 Conference* (pp. 53-60). INSTAP Academic Press.

Hadjidaki, E. (2021). *The Minoan Shipwreck at Pseira, Crete (Vol. 65)*. INSTAP Academic Press.

Held, W. (2014). Häfen der Rhodischen Peraia. In S. Ladstätter, F. Pirson & T. Schmidts (Eds.), *Häfen und Hafenstädte im östlichen Mittelmeerraum von der Antike bis in byzantinische Zeit: neue Entdeckungen und aktuelle Forschungsansätze, Byzas 19, vol. 1* (pp. 357-375). Ege Yayınları.

Held, W. (Ed.) (2019). *Die Karische Chersones vom Chalkolithikum bis in die byzantinische Zeit. Beiträge zu den Surveys in Loryma und Bybassos.* Forschungen auf der Karischen Chersones 1. Eigenverlag des Archäologischen Seminars der Philipps-Universität.

Held, W., & Şenol, K. (2010). Rhodian Wine' from Karia. The Production of 'Rhodian Wine' on the Karian Chersonesos in the Hellenistic Period. In Ü. Aydınoğlu & A. K. Şenol

(Eds.), *Olive Oil Production in Anatolia during Antiquity / Antik Çağda Anadolu'da Zeytinyağı ve Şarap Üretimi* (pp. 175–183). Ege Yayınları.

Held, W., & Wilkening-Aumann, Ch. (2015). Vom Karischen Bund zur Griechischen Polis. Archäologischer Survey in Bybassos und Kastabos auf der Karischen Chersones. In A. Matthaei & M. Zimmermann (Eds.), *Urbane Strukturen und bürgerliche Identität im Hellenismus, Die hellenistische Polis als Lebensform 5* (pp. 74–98). Brill Deutschland GmbH.

Henderson, J. C., Gallou, C., Flemming, N. C., & Spondylis, E. (2011). The Pavlopetri Underwater Archaeology Project: investigating an ancient submerged town. In J. Benjamin, C. Bonsall, C. Pickard & A. Fischer (Eds.), *Underwater Archaeology and the Submerged Prehistory of Europe* (pp. 207-218). Oxbow Books.

Kandilli Observatory and Earthquake Research Institute. (2012). Press Bulletin on the Earthquake Event on 24-28 November 2012 off Bozburun-Muğla (Mediterranean). http://www.koeri.boun.edu.tr/sismo/Depremler/onemliler/

Kandilli Observatory and Earthquake Research Institute. (2022, June 16). Earthquake Catalog Search System. B.U. KOERI-RETMC. Retrieved June 6, 2022, from http://www.koeri.boun.edu.tr/sismo/2/earthquake-catalog/

Karkani, A., Evelpidou, N., Giaime, M., Marriner, N., Morhange, C., & Spada, G. (2019). Late Holocene sea-level evolution of Paros island (Cyclades, Greece). *Quaternary International*, *500*, 139-146.

Karkani, A., Evelpidou, N., Vacchi, M., Morhange, C., Tsukamoto, S., Frechen, M., & Maroukian, H. (2017). Tracking Shoreline Evolution in Central Cyclades (Greece) using Beachrocks. *Marine Geology, 388*, 25–37.

~~Khan, N.S., Ashe, E., Shaw, T.A., Vacchi, M., Walker, J., Peltier, W.R., Kopp, R.E., & Horton, B.P. (2015). Holocene relative sea-level changes from near-, intermediate-, and far-field locations. *Current Climate Change Reports, 1*(4), 247–262.~~

Kızıldağ, N. (2019). Late Holocene sea level change along the coast of Fethiye Gulf in southwestern Turkey. *Geoarchaeology, 34*(3), 295-310.

Kızıldağ, N., & Özdaş, H. (2021). Relative sea-level changes along the Fethiye coast (SW Turkey) based on recent archaeological data. *Geoarchaeology, 36*(3)*,* 474-489.

Kızıldağ, N., Özdas, A. H., & Uluğ, A. (2012). Late Pleistocene and Holocene Sea Level Changes in the Hisarönü Gulf. Southeast Aegean Sea. *Geoarchaeology, 27*(3), 220–236.

Kolaiti, E., & Mourtzas, N. D. (2016). Upper Holocene Sea Level Changes in the West Saronic Gulf. Greece. *Quaternary International, 401*, 71–90.

Kolaiti, E., & Mourtzas, N. D. (2020). New insights on the relative sea level changes during the Late Holocene along the coast of Paros Island and the northern Cyclades (Greece). *Annals of Geophysics, 63*, 669.

Lambeck, K., Antonioli, F., Purcell, A., & Silenzi, S. (2004). Sea-level change along the Italian coast for the past 10,000 yr. *Quaternary Science Reviews, 23*(14-15), 1567-1598.

Lambeck, K., Anzidei, M., Antonioli, F., Benini, A., & Verrubbi, V. (2018). Tyrrhenian sea level at 2000 BP: evidence from Roman age fish tanks and their geological calibration. *Rendiconti Lincei. Scienze Fisiche e Naturali, 29*(1), 69-80.

Lambeck, K., Purcell, A., Johnston, P., Nakada, M., & Yokoyama, Y. (2003). Water-load definition in the glacio-hydro-isostatic sea-level equation, *Quaternary Science Reviews, 22*(2), 309–318.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., & Sambridge, M. (2014). Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *Proceedings of the National Academy of Sciences, 111*(43), 15296-15303.

Loizou, E. (2016). Late Bronze Age Harbours in the Aegean. *Skyllis, 16*(2), 118–125.

Manning, S.W., & Kromer, B. (2012). Considerations of the scale of radiocarbon offsets in the East Mediterranean, and considering a case for the latest (most recent) likely date for the Santorini eruption. *Radiocarbon,* 54*(3–4)*, 449–474.

~~Marketou, T. (1987). Marine Style pottery from the Seraglio in Kos. Annual of the British *School at Athens, 82*, 165-169.~~

~~Marketou, T. (1990). Santorini tephra from Rhodes and Kos: some chronological remarks based on the stratigraphy. *Thera and the Aegean World III*, 100-113.~~

Mattei, G., Caporizzo, C., Corrado, G., Vacchi, M., Stocchi, P., Pappone, G., Schiattarella, M., & Aucelli, P. C. (2022). On the influence of vertical ground movements on Late-Quaternary sea-level records. A comprehensive assessment along the mid-Tyrrhenian coast of Italy (Mediterranean Sea). *Quaternary Science Reviews, 279*, 107384.

Medas, S. (2003). The Late-Roman ''Parco di Teodorico'' Wreck, Ravenna, Italy: preliminary remarks on the hull and the shipbuilding. In C. Beltrame (Ed.), *Boats, Ships and Shipyards. Proceedings of the Ninth International Symposium on Boat and Ship Archaeology* (pp. 42–48). Oxford: Oxbow Books.

Melini, D,. & Spada, G. (2019). Some remarks on Glacial Isostatic Adjustment modelling uncertainties, *Geophysical Journal International, 28*(1)*,* 401–413.

Momigliano, N. (2009). Minoans at Iasos?. In C.F. Macdonald, E. Hallager, & W-D. Niemeier (Eds.), *The Minoans in the central, eastern and northern Aegean – new evidence* (pp. 121–140). Aarhus University Press.

Momigliano, N. (2012). *Bronze Age Carian Iasos. Structures and Finds from the Area of the Roman Agora (c. 3000–1500 BC).* Giorgio Bretschneider.

Morhange, C., & Marriner, N. (2015). Archeological and biological relative sea-level indicators. In I. Shennan, A.J. Long & B.P. Horton (Eds.), *Handbook of sea-level research* (pp. 146-156). John Wiley & Sons.

Morhange, C., Laborel, J., & Hesnard, A. (2001). Changes of relative sea level during the past 5000 years in the ancient harbor of Marseilles, Southern France. *Palaeogeography Palaeoclimatology Palaeoecology, 166,* 319-329.

Morhange, C., Marriner, N., Excoffon, P., Bonnet, S., Flaux, C., Zibrowius, H., Goiran, J-P., & Amouri, M. E. (2013). Relative sea-level changes during Roman times in the Northwest Mediterranean: The 1st century AD fish tank of Forum Julii, Fréjus, France. *Geoarchaeology, 28*(4), 363-372.

Nakada, M., & Lambeck, K. (1987). Glacial rebound and relative sea-level variations: a new appraisal, *Geophysical Journal International, 90*(1)*,* 171–224.

Niemeier, W.-D. (2005). The Minoans and Myceneans in Western Asia Minor: Settlement, Emporia or Acculturation?. In R. Laffineur & E. Greco (Eds.), *Emporia. Aegeans in the Central and Eastern Mediterranean. 10th International Aegean Conference Athens 2004*, (pp. 199–204 pl. 48–49). Liege.

Niemeier, W.-D. (2007). Milet von den Anfängen menschlicher Besiedlung bis zur Ionischen Wanderung / Westkleinasien und Ägäis von den Anfängen bis zur Ionischen Wanderung: Topographie, Geschichte und Beziehungen nach dem archäologischen Befund und den hethitischen Quellen. In J. Cobet, V. von Graeve, W.-D. Niemeier & K. Zimmermann (Eds.), *Frühes Ionien. Eine Bestandsaufnahme. Panionion-Symposion Güzelçamlı 1999* (pp. 3–19). Philipp von Zabern.

Nomikou, P., Krassakis, P., Kazana, S., Papanikolaou, D., & Koukouzas, N. (2021). The volcanic relief within the Kos-Nisyros-Tilos tectonic graben at the eastern edge of the Aegean Volcanic Arc, Greece and Geohazard Implications. *Geosciences, 11*(6), 231.

Opait, A. (2004). The eastern Mediterranean amphorae in the province of Scythia. In J. Eiring & J. Lund (Eds.), *Transport amphorae and trade in the eastern Mediterranean: Acts of the international colloquium at the Danish Institute at Athens* (pp.293–308). Aarhus: Aarhus University Press.

~~Oreshko, R. (2019). Geography of the Western Fringes: Gar(a)giša/Gargiya and the Lands of the Late Bronze Age Caria. In O. Henry & K. Konuk (Eds.), *Karia Arkhaia. La Carie, des origines à la période pré-hékatomnide* (pp. 139–189). Institut Français d'Etudes Anatoliennes.~~

Özdaş, H., & Kızıldağ, N. (2013a). Archaeological and geophysical investigation of submerged coastal structures in Kekova, southern coast of Turkey. *Geoarchaeology, 28*(5), 504-516.

Özdaş, H., & Kızıldağ, N. (2013b). Marmaris Bozburun Peninsula Shipwrecks. *TINA, 1*, 49-57.

Özdaş, H., & Kızıldağ, N. (2016). Hisarönü Bronze Age Shipwreck Excavation, 2016 Campaign. *TINA, 6*, 102–107.

Özdaş, H., & Kızıldağ, N. (2017). Campaign of the Bozburun Underwater Excavations in Marmaris, *TINA, 8*, 40–45.

Pavlopoulos, K., Kapsimalis, V., Theodorakopoulou, K., & Panagiotopoulos, I. P. (2012). Vertical displacement trends in the Aegean coastal zone (NE Mediterranean) during the Holocene assessed by geo-archaeological data. *The Holocene, 22*(6), 717-728.

Peltier, W. R. (2004). Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G (VM2) model and GRACE. *Annual Review of Earth and Planetary Sciences, 32,* 111-149.

Peltier, W.R., Argus, D.F., & Drummond, R. (2015). Space geodesy constrains ice-age terminal deglaciation: The global ICE-6G_C (VM5a) model. *Journal of Geophysical Research: Solid Earth, 120,* 450-487.

Pirazzoli, P.A. (1976). Sea level variations in the northwest Mediterranean during Roman times. *Science, 194,* 519-521.

Pirazzoli, P. A. (1997). Sea-level changes: the last 20 000 years. *Oceanographic Literature Review, 8*(44), 785.

Pirazzoli, P.A. (2005). A review of possible eustatic, isostatic and tectonic contributions in eight late-Holocene relative sea-level histories from the Mediterranean area. *Quaternary Science Reviews, 24,* 1989-2001.

~~Raymond, A., Kaiser, I., Rizzotto, L. C., & Zurbach, J. (2016). Discerning Acculturation at Miletus: Minoanisation and Mycenaeanisation. In E. Gorogianni, L. Girella & P. Pavúk (Eds.), *Beyond Thalassocracies: understanding processes of Minoanisation and Mycenaeanisation in the Aegean* (pp. 58–74). Oxford.~~

~~Rechta, M. R. (2020). *Die bronzezeitliche Architektur von Tavşan Adası in ihrem ägäischen Kontext, Tavşan Adası 1.* Beier & Beran.~~

Rovere, A., Stocchi, P., & Vacchi, M. (2016). Eustatic and relative sea level changes. *Current Climate Change Reports*, *2*(4), 221-231.

Roy, K., & Peltier, W. R. (2015). Glacial isostatic adjustment, relative sea level history and mantle viscosity: reconciling relative sea level model predictions for the US East coast with geological constraints. *Geophysical Journal International, 201*(2)*,* 1156-1181.

Roy, K., & Peltier, W. R. (2017). Space-geodetic and water level gauge constraints on continental uplift and tilting over North America: regional convergence of the ICE-6G_C (VM5a/VM6) models. *Geophysical Journal International, 210*(2)*,* 1115-1142.

Shaw, J.W. (1990). Bronze Age Aegean Harboursides. In C. Gillis, C. Risberg & B. Sjöberg (Eds.), *Thera and the Aegean World III vol. 1: Archaeology. Proceedings of the Third International Congress, Santorini 1989* (pp. 420–436). The Thera Foundation.

Shennan, I. (2015). Handbook of sea-level research: framing research questions. In I. Shennan, A.J. Long, B.P. Horton (Eds.), *Handbook of Sea-Level Research* (pp. 3–25). John Wiley & Sons.

Similox-Tohon, D., Sintubin, M., Muchez, P., Vanhaverbeke, H., Verhaert, G., & Waelkens, M. (2005). Identification of a historical morphogenic earthquake through trenching at ancient Sagalassos (SW Turkey). *Journal of Geodynamics, 40,* 279-293.

Soysal, H., Sipahioğlu, S., Kolçak, D., & Altinok, Y. (1981). *Türkiye ve çevresinin tarihsel deprem kataloğu (MÖ 2100-MS 1900)*. TUBITAK, Istanbul.

Spada, G., & Melini, D. (2019). SELEN4: a Fortran program for solving the gravitationally and topographically self-consistent Sea Level Equation in Glacial Isostatic Adjustment modeling. *Geoscientific Model Development Discussions*, 1-37.

Spada, G., & Melini, D. (2022). New estimates of ongoing sea level change and land movements caused by Glacial Isostatic Adjustment in the Mediterranean region, *Geophysical Journal International, 229*(2), 984–998.

Stocchi, P., & Spada, G. (2009). Influence of glacial isostatic adjustment upon current sea level variations in the Mediterranean. *Tectonophysics, 474*(1-2), 56-68.

Stock, F., Seyer, M., Symanczyk, A., Uncu, L., & Brückner, H. (2020). On the geoarchaeology of Limyra (SW Anatolia)—new insights into the famous Lycian city and its environs. *Geoarchaeology, 35*(4), 487-502.

~~Şahoğlu, V., Sterba, J. H., Katz, T., Çayır, Ü., Gündoğan, Ü., Tyuleneva, N., Tuğcu, İ., Bichler, M., Erkanal, H., & Goodman-Tchernov, B. N. (2022). Volcanic ash, victims, and tsunami debris from the Late Bronze Age Thera eruption discovered at Çeşme-Bağlararası (Turkey). *Proceedings of the National Academy of Sciences, 119*, 1-8. https://doi.org/10.1073/pnas.2114213118~~

Tartaron, T. F. (2013). *Maritime networks in the Mycenaean world*. Cambridge University Press.

Tartaron, T. F., Rothaus, R. M., & Pullen, D. J. (2003). Searching for Prehistoric Aegean Harbors with GIS. Geomorphology and Archaeology. *Athena Review, 3-4*, 27-36.

~~Taymaz, T., Jackson, J., & Mckenzie, D. (1991). Active tectonics of the north and central Aegean Sea. *Geophysical Journal International, 106*(2), 433-~~490.

Taymaz, T., Yilmaz, Y., & Dilek, Y. (2007). The geodynamics of the Aegean and Anatolia: introduction. *Geological Society, London, Special Publications, 291*(1), 1-16.

Turkish National Sea Level Monitoring System. (2022, June). *Tide Gauge Data.* https://tudes.harita.gov.tr/

Vacchi, M., Ermolli, E. R., Morhange, C., Ruello, M. R., Di Donato, V., Di Vito, M. A., Giampaola, D., Carsana, V., Liuzza, V., Cinque, A., Boetto, G., Poveda, P., Boenzi, G., & Marriner, N. (2020). Millennial variability of rates of sea-level rise in the ancient harbour of Naples (Italy, western Mediterranean Sea). *Quaternary Research, 93*, 284-298.

Vacchi, M., Marriner, N., Morhange, C., Spada, G., Fontana, A., & Rovere, A. (2016). Multiproxy assessment of Holocene relative sea-level changes in the western Mediterranean: Sea-level variability and improvements in the definition of the isostatic signal. *Earth-science Reviews, 155,* 172-197.

~~Vardar, S., & Öner, E. (2016). Investigation on Distribution of the Santorini (Thera) Tephra in West Anatolia and Paleogeographical-Geoarchaeological Features of the Çeşme-Bağlararası Mound. In İ. Gezgin & S. Ç. Cesur (Eds.), *Proceedings of III. International Çeşme-Chios History, Culture and Tourism Symposium* (pp. 105-128). Çeşme.~~

~~Voigtländer, W. (2004). *Teichiussa: Näherung und Wirklichkeit.* Verlag Marie Leidorf~~.

Watrous, L. V. (2012). The harbor complex of the Minoan town at Gournia. *American Journal of Archaeology, 116*(3), 521-541.

Watrous, L. V. (2021). *Minoan Crete: an introduction*. Cambridge.

Yıldırım, C., Aksoy, M. E., Özcan, O., İşiler, M., Özbey, V., Çiner, A., Salvatore, P., Sarıkaya, M.A., Doğan, T., İlkmen, E., & Schneiderwind, S. (2022). Coseismic (20 July 2017 Bodrum-Kos) and paleoseismic markers of coastal deformations in the Gulf of Gökova, Aegean Sea, SW Turkey. *Tectonophysics, 822*, 229141.

Yildiz, H., Andersen, O. B., Simav, M., Aktug, B., & Ozdemir, S. (2013). Estimates of vertical land motion along the southwestern coasts of Turkey from coastal altimetry and tide gauge data. *Advances in Space Research, 51*(8), 1572-1580.



**Figure Captions**

Figure 1. (a) the location map of studied submerged sites (red icon); (b) tectonic setting of the Aegean Sea (modified from Taymaz et al., 2007) and the submerged Bronze Age sites (black icon) along the Aegean coastline (compiled from Galanidou et al., 2020); (c) Seismotectonic map of the study area and its surrounding region. Epicenters of earthquakes in historical and instrumental periods (between 1950-2022) were obtained from the seismicity catalogue of Kandilli Observatory and Earthquake Research Institute (KOERI). The focal mechanism solutions of earthquakes in 2012 and 2017 were reported by KOERI

Figure 2. (a) Aerial photo of Çamçalık island and its vicinity, (b) and (c) submerged wall stones upon the quay surface, (d) front view of the quay platform, (e) vertical surface of the quay exhibiting calcareous structure mixed with limestone and pottery sherds

Figure 3. The artifacts from Çamçalık: beak-spouted jug, loom weight with Linear A, conical cup, oval-mouthed amphora

Figure 4. Submerged tidal notch structures in (a) Çamçalık; (b) Hıdırlık; and (c) Kiseli. Measurements were taken on 08/26/2019 at 13.00 (from Çamçalık and Kiseli) and 08/27/2019 at 14.30 (from Hıdırlık). (d) Trend-removal tidal amplitude in the study area.

Data obtained from nearest tide gauge station located at Marmaris. The red icons indicate the tide levels during the measurements of sea-level indicators

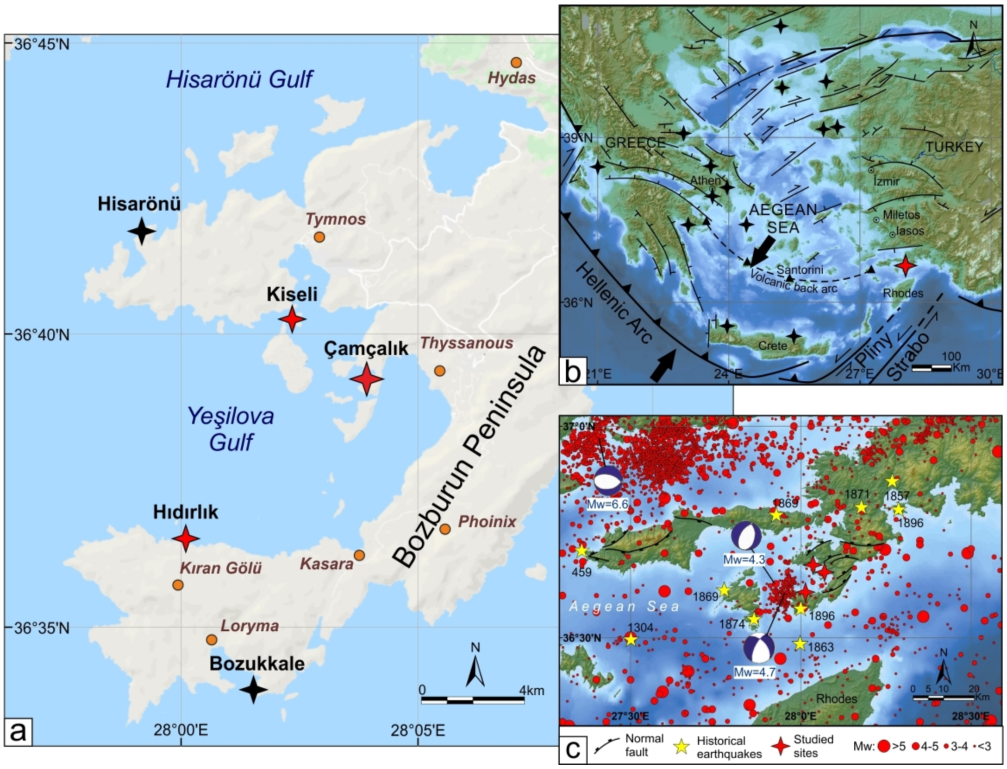
Figure 5. (a, b) Aerial photos from Hıdırlık harbor with Hellenistic building on the coast (inset photo) and (c) underwater photo of Hıdırlık breakwater.

Figure 6. (a) Aerial photo from Kiseli breakwater and church remains; (b) underwater photo of breakwater; and (c) aerial photo of quay with the position of sea level during survey (inset photo)

Figure 7. Representative section of the Çamçalık quay platform

Figure 8. Comparison of observed sea-level data with newly modeled GIA curves. Sea-level index points were displayed with vertical error bar for depth and horizontal error bar for age. The RSL curves for ICE-6G (red), ICE-7G (green) and ANU (blue) have been obtained through a high resolution numerical solution of the SLE. Shaded areas correspond to uncertainties on GIA predictions of ICE-6G and ANU associated to possible variations of the rheological parameters and have been estimated through a mini-ensemble approach

Table 1. Archaeological data used to reconstruct the relative sea-level evolution of the Bozburun Peninsula. AI: archaeological indicator, C: chronology based on time of the last use, MD: measured depth of archaeological remains, ME: the error estimate derives from measurement uncertainties, TL: tide level according to mean sea level during the survey, CD: corrected depth for tide with measurement error

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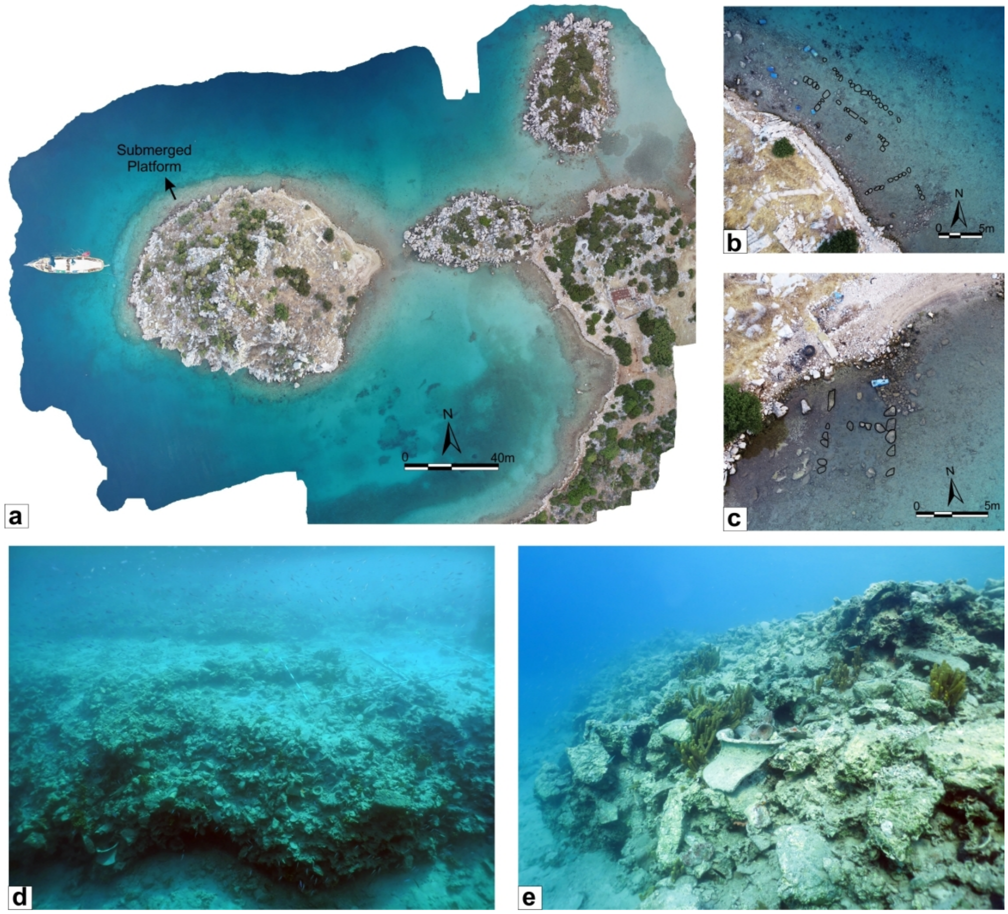


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180x164mm (300 x 300 DPI)


Figure 3. The artifacts from Çamçalık: beak-spouted jug, loom weight with Linear A, conical cup, oval-mouthed amphora

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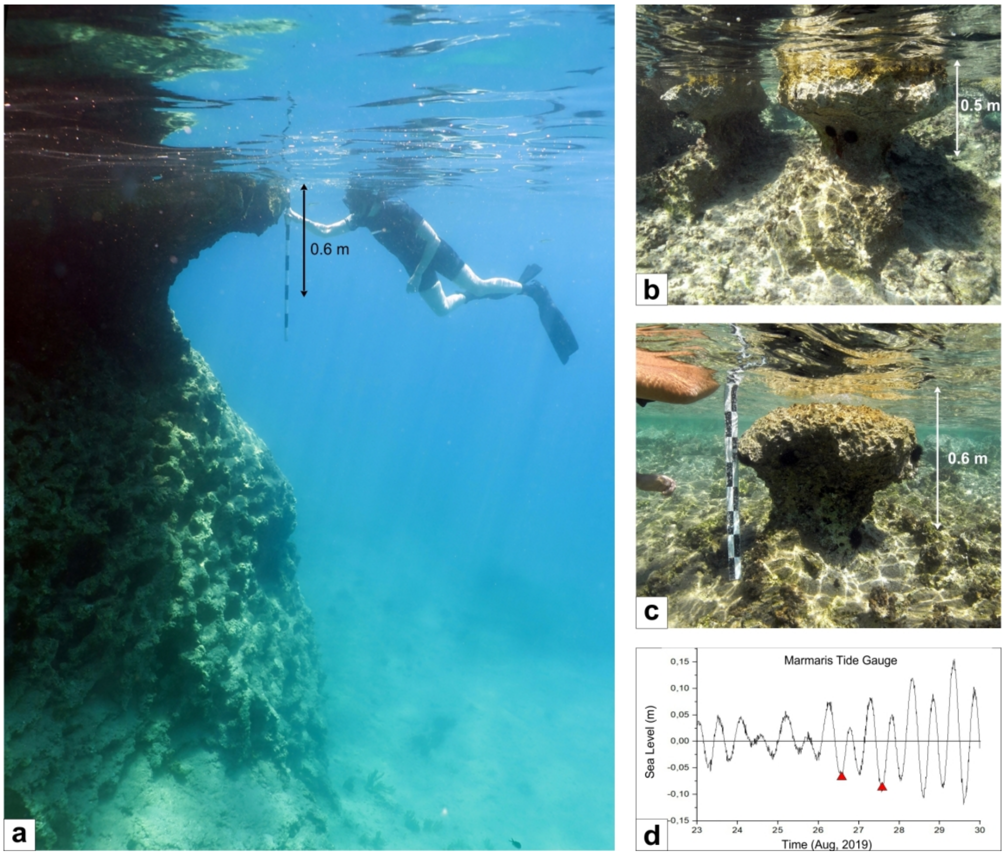


Figure 4. Submerged tidal notch structures in (a) Çamçalık; (b) Hıdırlık; and (c) Kiseli. Measurements were taken on 08/26/2019 at 13.00 (from Çamçalık and Kiseli) and 08/27/2019 at 14.30 (from Hıdırlık). (d) Trend-removal tidal amplitude in the study area. Data obtained from nearest tide gauge station located at Marmaris. The red icons indicate the tide levels during the measurements of sea-level indicators

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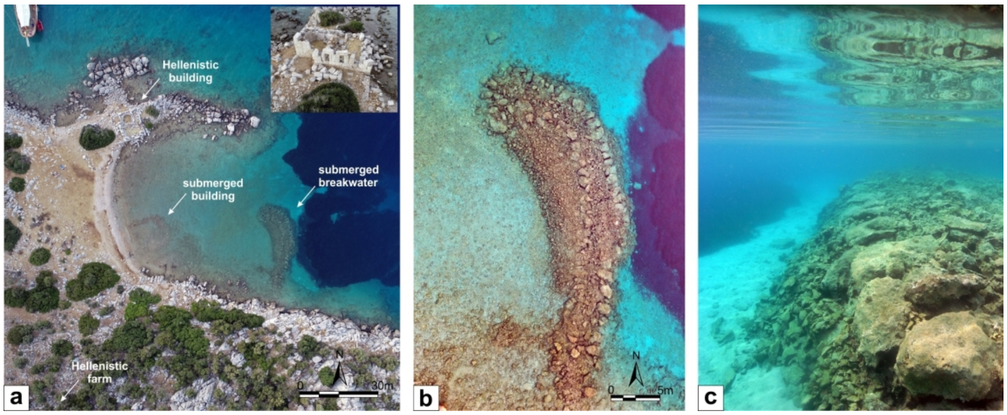


Figure 5. (a, b) Aerial photos from Hıdırlık harbor with Hellenistic building on the coast (inset photo) and (c) underwater photo of Hıdırlık breakwater.

157x64mm (300 x 300 DPI)

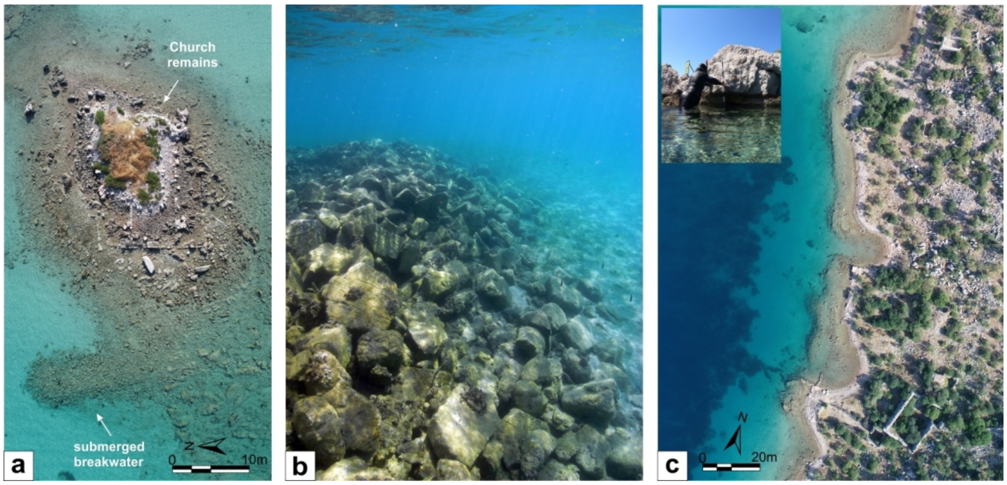


Figure 6. (a) Aerial photo from Kiseli breakwater and church remains; (b) underwater photo of breakwater; and (c) aerial photo of quay with the position of sea level during survey (inset photo)

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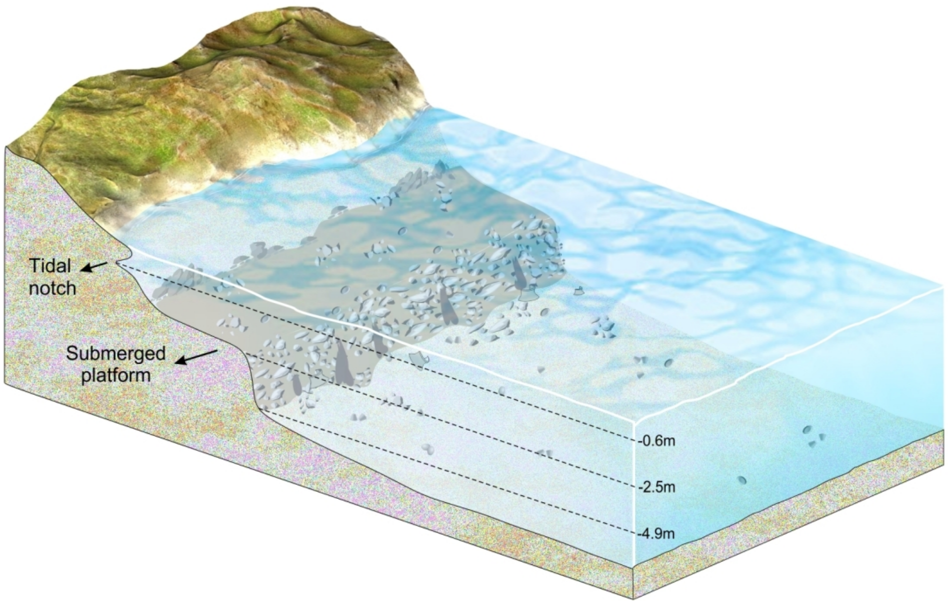
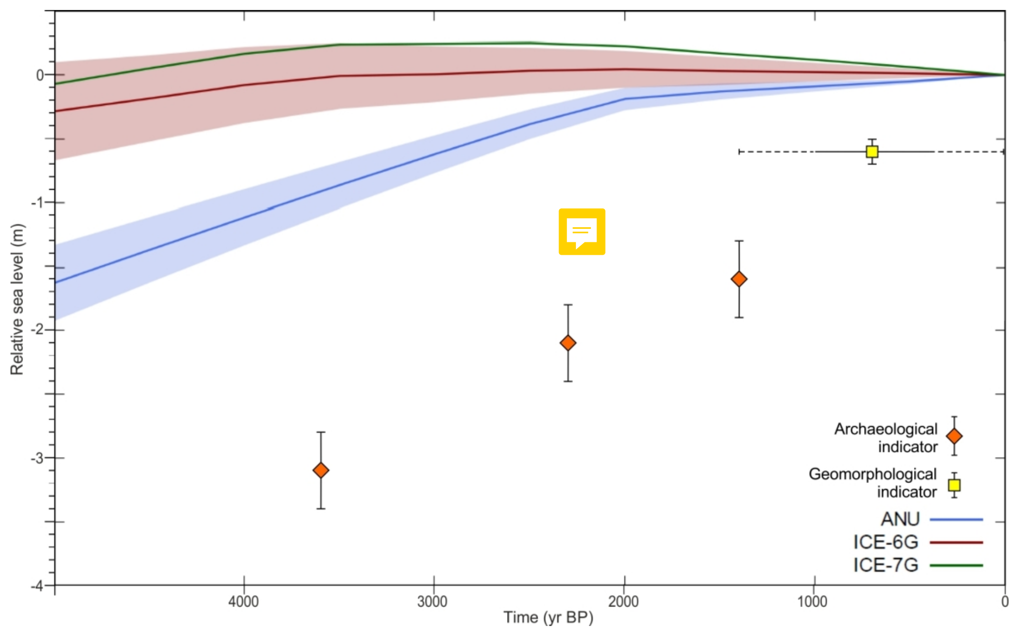



Figure 7. Representative section of the Çamçalık quay platform

144x92mm (300 x 300 DPI)

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180x110mm (300 x 300 DPI)

| Site | AI | C | MD (m) | ME (m) | TL (m) | CD (m) |
|---|---|---|---|---|---|---|
| Çamçalık | Quay | MM III/LM IA | -2.6 | ±0.1 | -0.07 | -2.5±0.1 |
| Hıdırlık | Breakwater | 4th-3rd c. BC | -1.6 | ±0.1 | -0.09 | -1.5±0.1 |
| Kiseli | Breakwater | Early 7th c. AD | -1.1 | ±0.1 | -0.07 | -1.0±0.1 |
| | Quay | Early 7th c. AD | -1.1 | ±0.1 | -0.07 | -1.0±0.1 |