Late Pleistocene and Holocene Sea Level Changes in the Hisarönü Gulf, Southeast Aegean Sea

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Received
22 June 2011
Accepted
22 November 2011

Scientific editing by Christophe Morhange and Jamie Woodward

Published online in Wiley Online Library (wileyonlinelibrary.com).

doi 10.1002/gea.21407

Fluctuations in relative sea level, tectonic movement, and sedimentation during the late Pleistocene to Holocene in the Hisarönü Gulf (SE Aegean Sea) and surrounding area were investigated with a high-resolution geophysical survey and underwater archaeological observations. The Hisarönü Gulf has been affected by vertical tectonic movements and rising sea level following the last glacial period (20,000 yr B.P.). High-resolution seismic data were interpreted to reveal the structure of the late Pleistocene to Holocene deposits and determine the location of the paleoshoreline. In order to describe the relative rise of sea level, principles of sequence stratigraphy were used for the late Pleistocene to Holocene transition, and submerged archaeological remains and bioerosional indicators were used for the late Holocene period. A comparison of archaeological observations in the study area with the known regional sea level curve indicates that the relative rise in sea level for the late Holocene is, for the most part, due to the tectonic subsidence of the coastal plain. © 2012 Wiley Periodicals, Inc.

INTRODUCTION

Global sea level during the late Pleistocene and Holocene rose from −120 m below present sea level (bpsl) to its modern position with a rapid transgression giving rise to landward coastline progression (Shackleton, 1987; Fairbanks, 1989; Bard, Hamelin, & Fairbanks, 1990; Perissoratis & Conispoliatis, 2003). Bard, Hamelin, and Fairbanks (1990) have suggested that the Holocene transgression was in two phases: 21,500–11,500 yr B.P. (late Pleistocene); and 11,500–8000 yr B.P. (early Holocene). Sea level rose rapidly to −60 m bpsl until 11,500 yr B.P. and transgressive deposits began to accumulate. During the last stage of the transgression at c. 8000 yr B.P., with the sea level at −15 m, the sea initially intruded into the lowlands and reached to almost its present position, while highstand deposits accumulated on the shelf as the sea level rose at a rate of 2 mm/yr (Perissoratis & Conispoliatis, 2003).

Owing to the lack of sediment cores, we consider the seismic units observed in our seismic profiles from the Hisarönü Gulf and its surroundings (Figure 1), to have formed during the last transgression and highstand period, based on comparison with similar well-dated studies in the Aegean and Mediterranean seas (Piper & Perissoratis, 2003; Siddall et al., 2003; Kapsimalis et al., 2005; Lykousis, Roussakis, & Sakellariou, 2009). The conceptual model of sequence stratigraphy developed by Mitchum, Vail, and Thompson (1977), Vail, Mitchum, and Thompson (1977), Posamentier and Vail (1988), and Van Wagoner et al. (1988) and other studies (Somoza et al., 1997; Rodero, Pallares, & Maldonado, 1999; Hanebuth, Stattegger, & Saito, 2002; Lobo et al., 2002) has been applied to our high-resolution seismic data. This allows the study of the youngest depositional sequence during the last sea level rise in the late Pleistocene to Holocene. There is remarkably good consistency between all the periods that have been estimated from stacked seismic units on the shelf.

In order to determine sea level rise for the late Holocene, many researchers have shown that submerged archaeological indicators are an important source of evidence (Marriner, Morhange, & Goiran, 2010; Evelpidou et al., 2012; Stanley & Bernasconi, 2012). A large number of ancient settlements and harbors are located along the Turkish coasts, and the present position of most of their remains is consistent with a relative sea level rise which had a negative impact on the ancient coastal settlements.

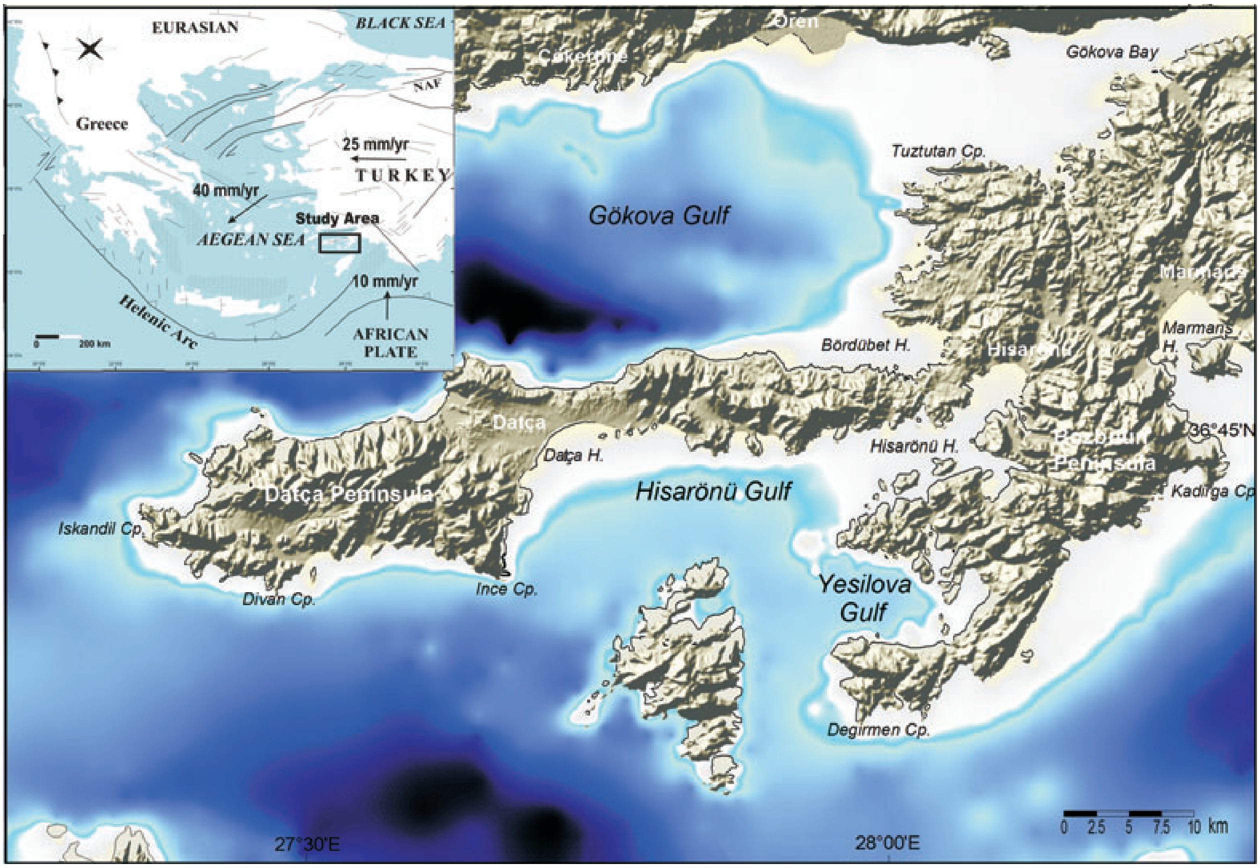

Figure 1 Location of the study area. Seabed morphology was produced from bathymetric data. The inset map shows the tectonic structure around the study area (modified from Barka & Reilinger, 1997).

When some harbors were submerged, they became nonfunctional and were abandoned. Submerged archaeological sites may serve as a laboratory for tracking the relative rise of the sea level. We are able to compare our field data with results of similar studies in the Aegean and Mediterranean (Table I). For instance, a study of the coast of Israel by Sivan et al. (2001) predicted that sea level was at about −13.5 m bpsl 8000 yr ago, whereas archaeological data such as submerged prehistoric settlements and water-wells, placed it at −16.5 m. The estimated sea level rose to about −7 ± 1 m by 7000 yr B.P. and 3 to −4.5 m by 6000 yr B.P., consistent with archaeological evidence, and remained below its present level until about 3000–2000 yr B.P. They concluded that the average rate of vertical tectonic movement for the last 8000 yr along the coast of Israel has been less than 0.2 mm/yr.

Vött et al. (2006) suggested that relative sea level in the Bay of Astakos (Ionian Sea) was at −2.2 m bpsl around 500 cal B.C., based on AMS ^{14}C-dated sedimentological and geoarchaeological data. Müllenhoff (2005) detected a relative sea level maximum at 2500–2000 cal B.C. at approximately −2.5 m for the Büyük Menderes region. Morhange, Laborel, and Hesnard (2001) suggested the relative sea level was at −0.68 ± 0.1 m bpsl at around A.D. 50, taking into account biological indicators (the upper limit of *Balanus*) on the Hellenistic quay in southern France, which was tectonically stable during the late Pleistocene.

Pirazzoli (1986, 2005) and Evelpidou et al. (2011) suggested that submerged tidal notches are an important indicator of former periods of relative sea level stability and can indicate both rapid subsidence or a rapid sea level rise. They surveyed different Mediterranean coasts and observed submerged notches at about 0.5 m bpsl, proposing that relatively recent co-seismic subsidence amounted to about half a meter.

As noted above, relative sea level changes can be the result of both eustatic and crustal components. Pirazzoli (2005) has proposed that data from different

Table I Holocene sea levels inferred from the age of submerged prehistoric architectural remains from different studies in the Aegean, Ionian, and Mediterranean seas.

Location	Years B.P.	Below Present Sea Level (m)	Vertical tectonic movement (mm/yr)	Source
SE Aegean (Turkey Coast)				
Myndus (Gümüşlük)	2000	− 1.2	−0.6	Flemming (1978)
Halicarnassus (Bodrum)	2400	− 1.0	−0.4	Flemming (1978)
Cedreae (Taşbükü)	1500	− 0.3	−0.2	Flemming (1978)
Bozburun	1000	− 1.0	−0.1	Flemming (1978)
Loryma (Bozuk Kale)	1500	− 1.0	−0.7	Flemming (1978)
Saranda	1000	− 0.5	−0.5	Flemming (1978)
Rhodus (N Rhodes)	5000	1.75	0.35	Flemming (1978)
Zimbule (NE Rhodes)	700	− 0.25	−0.36	Flemming (1978)
Aegean/Ionian Sea				
Büyük Menderes	4500–4000	− 2.5	No data	Müllenhoff (2005)
Bay of Astakos	8200	− 12.5	No data, expressed high tectonic subsidence	Vött et al. (2006)
	7100	− 8.3		Vött et al. (2006)
	6000	− 7.6		Vött et al. (2006)
	4000	− 5.4		Vött et al. (2006)
	2500	− 2.2		Vött et al. (2006)
Aegean Sea	6000	− 5.5	No data	Lambeck et al. (2004); Lambeck and Purcell (2005)
	2000	− 1.0		
Mediterranean Sea				
Marseilles	5000	− 1.5	No data	Morhange, Laborel, and Hesnard (2001)
	2000	− 0.6/−0.8		Morhange, Laborel, and Hesnard (2001)
Israel coasts	8000	− 16.5	<0.2	Sivan et al. (2001)
	7000	− 7.0		Sivan et al. (2001)
	6000	− 3.0/−4.5		Sivan et al. (2001)
	3000–2000	Present level		Sivan et al. (2001)

(tectonically active and stable) Mediterranean coasts are consistent with a global eustatic near stability since c. 6000 yr B.P. According to Flemming (1978), the eustatic curve after removal of the tectonic influence suggests a minimum sea level at about −23 cm at 2000 yr B.P. for southwestern Turkey. When their results are corrected for the glacio-hydro isostatic adjustment of the crust subsequent to the last deglaciation—and using geologically constrained model predictions—they suggested that eustatic sea level change since the Roman Period is -0.13 ± 0.09 m.

This study is important for addressing the lack of data in the available literature for geological, geophysical, or underwater archaeological research performed in the Hisarönü Gulf, and it provides the first extensive picture of the structure of the study area and a complementary data set for adjacent gulfs. The objectives of this paper are: (i) to describe the seismic units that formed the Hisarönü shelf during the late Pleistocene to Holocene using high-resolution seismic data in order to determine sea level changes during the last glacial maximum (LGM); (ii) to apply the model of sequence stratigraphic analysis to seismic profiles in order to interpret the relative sea level change controlled by eustatic rise and local tectonic movements in comparison with similar stratigraphic patterns found on other shelves to better reconstruct the their sedimentary conditions, and (iii) to reveal the primary cause for relative sea level change effects on such submerged archaeological remains.

REGIONAL SETTING

The study area includes the entire southern shelf of the Datça Peninsula and the western shelf of the Bozburun Peninsula, comprising the Hisarönü Gulf to the east and the Yeşilova Gulf to the south (Figure 1). The region is the southern part of the E–W trending Aegean grabens, such as Gediz, Büyük Menderes, and Gökova Gulf, which are under a N–S extensional tectonic framework dominated by the westward escape of the Anatolian plate as a result of orogenic collision and back arc extension (McKenzie, 1978; Dewey & Şengör, 1979; Jackson, Haines, & Holt, 1992; McClusky, Balassanian, & Barka, 2000; Bozkurt & Sözbilir, 2004). The westward motion of the Anatolian plate relative to the Eurasian plate and the continental

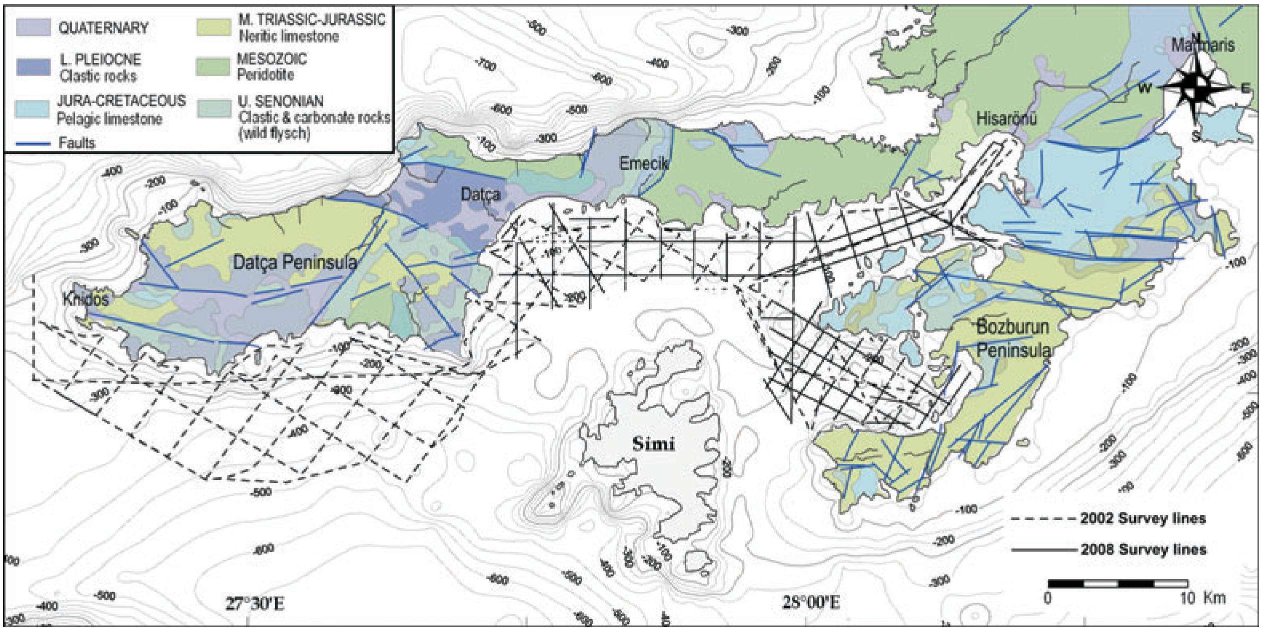

Figure 2 Location of the 3.5 kHz high-resolution seismic profiles from the 2002 survey (dashed lines) and Chirp high-resolution seismic profiles from the 2008 survey (solid lines). Terrestrial geology modified from Ercan and Günay (1981–1982 and Ersoy (1993).

collision between NW Greece–Albania gave rise to E–W shortening in the northern Aegean and to the N–S extension of the southern part (Taymaz, Jackson, & McKenzie, 1991). GPS measurements indicate that the western Anatolian plate is undergoing counterclockwise rotation in a southwest direction (Barka & Reilinger, 1997). Along the southeastern Aegean coast, the average rate of vertical tectonic movement related to the development of the grabens has been 0.5–1.0 mm/yr for the last 120,000 yr according to a range of geological data (Aksu, Piper, & Konuk, 1987a, 1987b; Lykousis et al., 1995; Kaşer, 2004; Uluğ et al., 2005).

This tectonic movement gave rise to several fault systems (Figure 2) that have produced violent earthquakes in the historical past. For example, the Rhodes earthquake of 225 B.C. caused the collapse of the Colossus of Rhodes (Guidoboni et al., 1994). An earthquake in 1609 affected half of the town of Rhodes and over 10,000 people were reported drowned by a tsunami (Ambraseys & Finkel, 1995). It is known that other great earthquakes happened in 1685, 1741, and 1776, and these also damaged the town.

Distinct morphological structures have been observed in the study area and these are related to these tectonic movements. The wide Hisarönü shelf and narrow Datça Peninsula shelf to the west, and the quite steep Yeşilova shelf to the south are good examples (Figure 2). The northwest shelf of Hisarönü has a slope of 1.5° and a width of about 4 km, measured from our data. The narrow western shelf has very high gradients, varying between 4° and 28°, and the narrowest part of the shelf is 0.2 km, with the widest section at 1.7 km. The Yeşilova shelf also has higher seafloor gradients ranging from 6° to 30°, with a mean shelf width less than 1 km. In the eastern Hisarönü shelf, where the morphological structural plane extends from east to center of the gulf, seafloor gradients are lower than 0.4° and the shelf width is about 17 km. The shelf break is located at variable depths of 140–150 milliseconds (ms).

A terrestrial geological map (Ercan & Günay, 1981–1982; Ersoy, 1993) shows that the Datça Peninsula consists of peridotite, with Mesozoic and neritic limestones dated to the Middle Triassic to Jurassic (Figure 2). Around the bay of Hisarönü, conglomerates formed entirely of pebbles of peridotite and deposited in an alluvial fan are found, along with ultramafic rocks. They are at most 100 m thick and devoid of fossils. Underlying these rocks are sedimentary rocks consisting of reef limestone and sandstone, probably of Upper Oligocene or lower Miocene age. The later deposits are Pliocene continental and marine sediments, characterized by conglomerate, sandstone, claystone, and marl, on top of which lie the Quaternary river terrace sediments and are represented on land by alluvium, scree, beach sands, and aerially transported volcanic products present in outcrops (Ercan & Günay, 1981–1982).

MATERIALS AND METHODS

This study is mainly based on 450 km of high-resolution seismic reflection profiles collected during a cruise of R/V K. Piri Reis of The Institute of Marine Sciences and Technology in 2002 (Figure 2, dashed lines). Analog data were acquired using an ORE Sub-bottom Profiler System with 3.5 kHz frequency and recorded on EPC 3200 and 9800 graphic recorders. Another high-resolution seismic survey was performed with R/V K. Piri Reis using a Bathy 2010 Chirp System in 2008 and about 350 km of digital data were collected with lines spaced at 2.5 km (Figure 2, heavy lines) at an average speed of 4 knots. The frequency band of the Chirp system was 2.75–6.75 kHz centered at 3.5 kHz. The data were processed to achieve the envelope traces. A shipboard = Differential GPS system provided navigation. A typical interval velocity of 1500 m/s was used to convert two-way travel time (twt) to depths below sea level.

In addition to the recording of bathymetric and seismic data, submerged archaeological remains (breakwaters and docks) in the study area (Figure 3) were investigated by scuba diving, echo sounding, and side scan sonar. The height between the upper surface of remains and mean sea level was measured in springtime without tidal correction. We used archaeological remains to estimate relative sea level changes by making comparisons with isostatic models and similar studies. As a result of these measurements and comparisons, we are able to suggest an average rate of vertical tectonic movement for the coast of the Hisarönü Gulf for the late Holocene.

Preliminary observations on the remains were carried out in April 2009. In August 2011, ancient harbor sites were surveyed in detail and the sea level was measured in summertime. Submerged tidal notch traces were also measured on the limestone coasts of the study area by snorkeling. All measurements were taken at times of no wave action and the lowest tidal range. It was observed that the trace of present day tidal effect and seasonal changes along the coast of the Yeşilova Gulf does not exceed 20 cm.

RESULTS

Postglacial Deposition

Relative sea level change is viewed as the result of several interacting factors of which the most important are eustatic sea level fluctuations, crustal movements, and sediment accumulation (Allison & Niemi, 2010; Bernasconi & Stanley, 2011; Soter & Katsonopoulou, 2011). It is important to know the global sea level rise and sediment thickness from the last glacial period to estimate the amount of local tectonic subsidence.

In this study, we describe depositional units in our high-resolution seismic data using sequence stratigraphy principles. Late Quaternary postglacial sediments

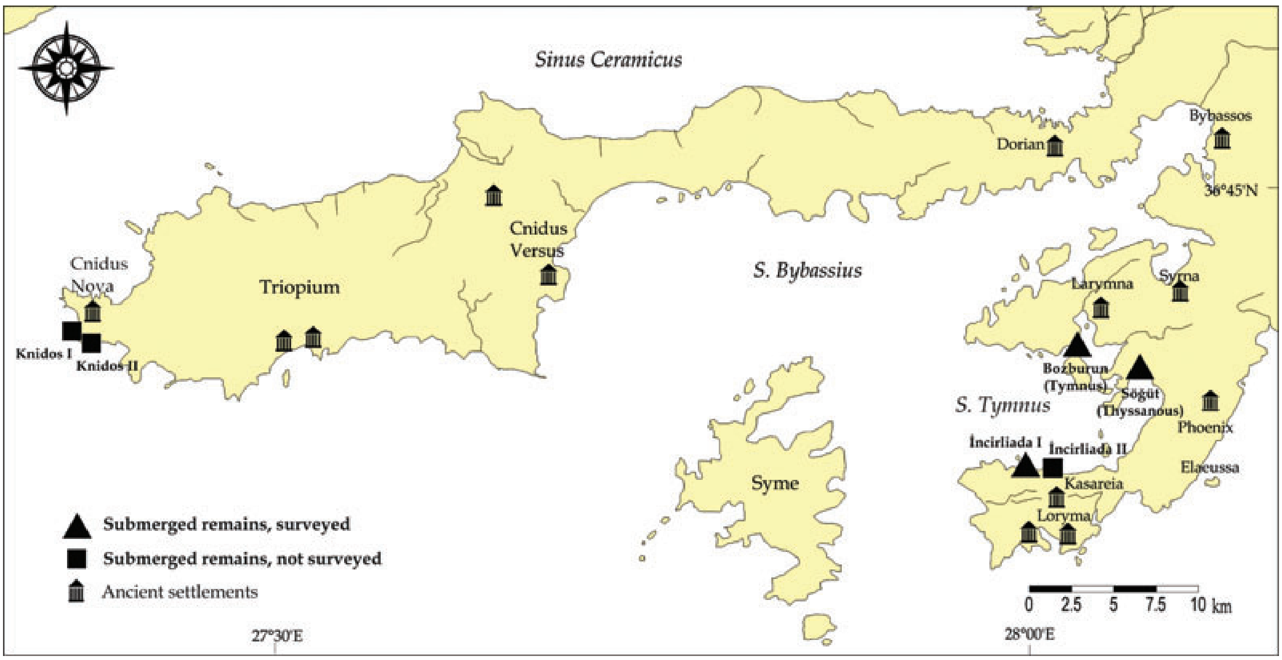

Figure 3 Location of submerged archaeological features in the study area.

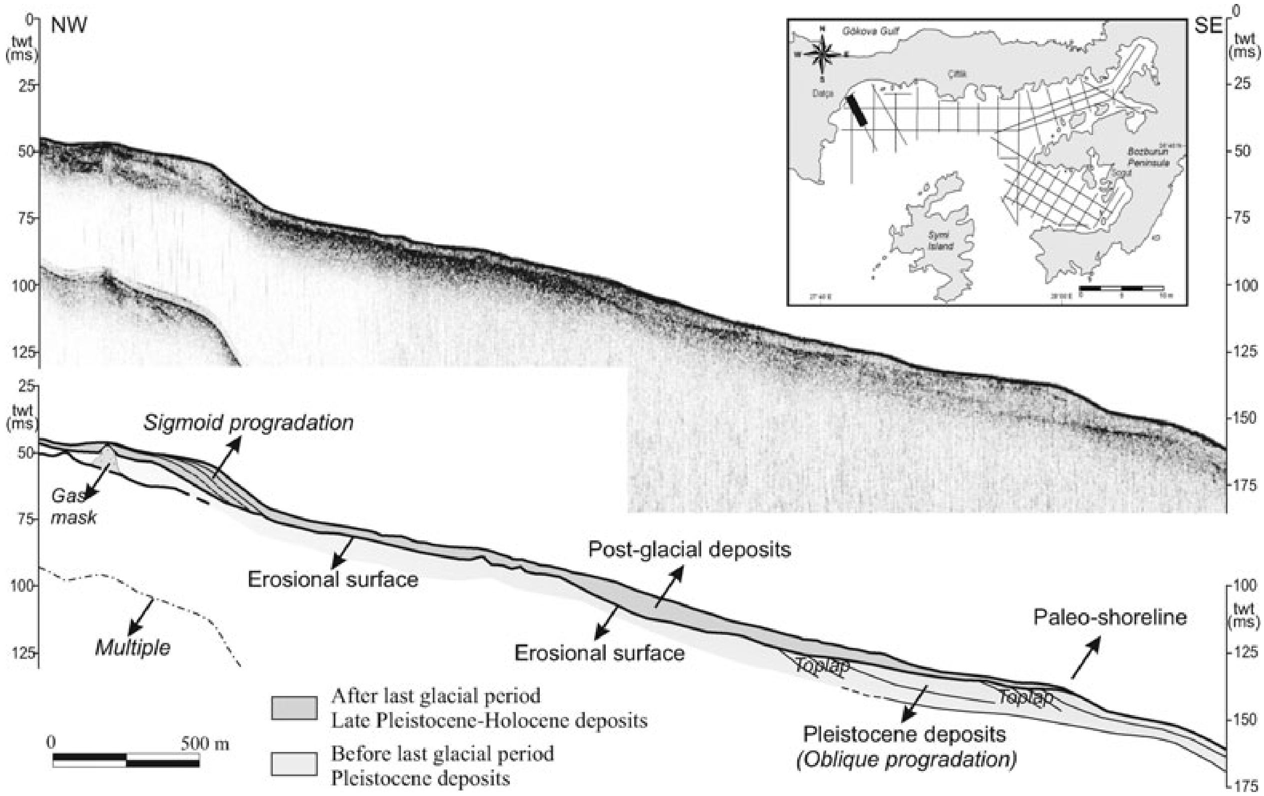

Figure 4 NW-SE directed Chirp seismic reflection profile from the Datça Shelf and seismic stratigraphic interpretation. The inset shows the location of the profile. (twt = two way travel time).

accumulated on an erosional surface, which was defined over the continental shelf from seismic profiles. The erosional surface in the outer shelves represents a toplap surface for the underlying Pleistocene deposits. This is defined as an unconformity in seismic profiles, which represents a stratigraphic discontinuity and is identified as a strong reflector, indicating the level of the paleoseabed during the global LGM (Posamentier & Allen, 1999). This is observed at depths of maximum 150 ms bpsl at the present day shelf break (Figure 4).

Postglacial sediments that accumulated on erosional surfaces consist of transgressive and highstand units. Transgressive seismic units are associated with rapid postglacial sea level rise above the shelf margin and are observed as a thin layer because the accommodation area is large and the amount of sediment accumulation is small when sea level begins to rise rapidly. Holocene highstand seismic units are formed during the highstand of the sea level downlapping transgressive units. These deposits onlap the basement in a landward direction and generally downlap the top of the transgressive unit seawards. These units are commonly widespread on the shelf and may be characterized by one or more aggradation to progradational parasequence sets with prograding clinoform geometry (Figure 4).

Oblique progradation generally indicates high sediment input, low basin subsidence, or stable sea level (Emery & Myers, 1996). Therefore, the location of this pattern can be interpreted as the paleoshoreline position, placed 150 ms bpsl, verifying sea level rise of about 110 m since the LGM (20,000 yr B.P.) to present (Kaşer, 2010) (Figure 4).

Although seismic units are locally masked by gas in a landward direction, the maximum identified thickness is 25 m in the eastern Hisarönü Gulf and at the center, decreasing basinward, and less than 10 m on the entire shelf. Sediment accumulation rates can be estimated roughly from the thickness of transgressive and highstand deposits over the erosional surface. Total sediment thickness is estimated at a maximum of 18 m on the Hisarönü shelf with an average of 7.5 m (Kaşer, 2010). In the Yeşilova Gulf, this rate does not exceed 4 m. The results are compatible with other studies performed in the İzmir and Kuşadası gulfs, where an average

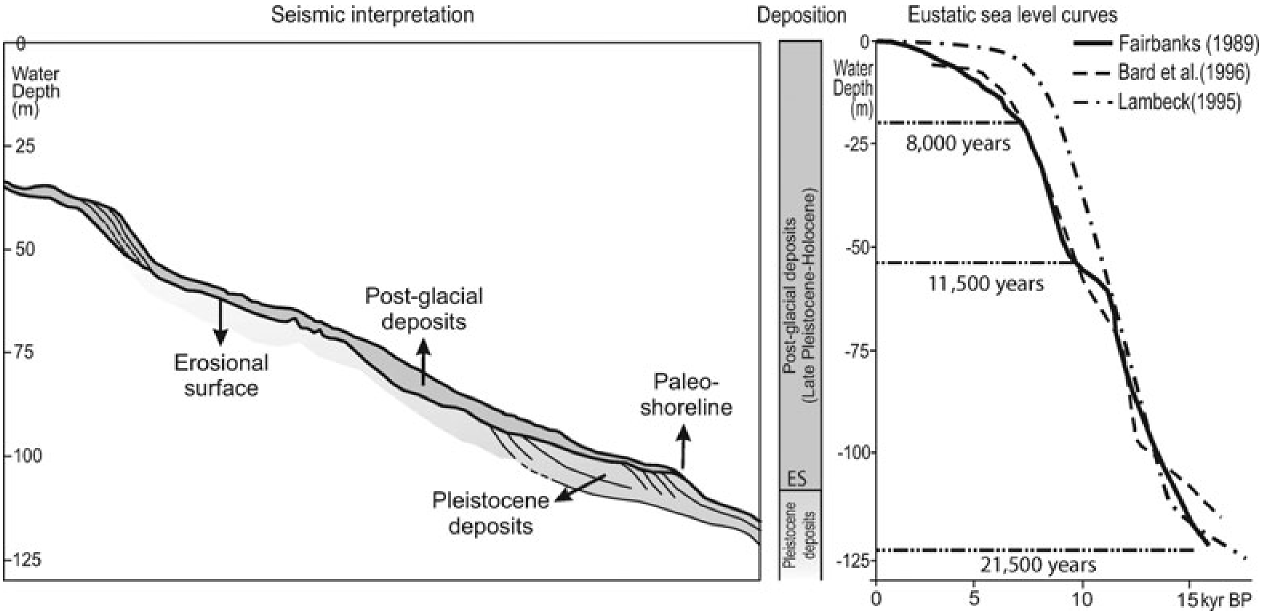

Figure 5 Schematic model of postglacial deposits in the study area and representative curves for late Pleistocene and Holocene sea level change. Depths in meters. ES = erosional surface; kyr B.P. = 1000 years before present.

figure of 6 m has been recorded (Aksu, Piper, & Konuk, 1987a, 1987b). Therefore, sediment accumulation rates deposited on the shelf in Holocene times reached a maximum of 1.0 mm/yr and averaged 0.4 mm/yr.

Relative Sea Level Changes

Late Pleistocene to Holocene sea level changes

The main source of data for sea level changes in the southeastern Aegean Sea is geological evidence and the global curve of Fairbanks (1989), Bard et al. (1996), and Lambeck (1995) defining former sea level positions (Figure 5). According to Fairbanks (1989) and Bard, Hamelin, and Fairbanks (1990), sea level was 120 m lower at about 21,500 yr B.P., and it started rising at a rate of 5 mm/yr at about 18,000 yr B.P.; −60 m at 11,500 yr B.P. and −15 m at 8000 yr B.P. (Perissoratis & Conispoliatis, 2003). Lambeck (1995,) suggested that the sea level at 18,000 yr B.P. was between −115 and −135 m, while at 10,000 yr B.P., the values ranged from −43 to −45 m for the Aegean, considering the glacio-isostatic effect. For the same stages, the values from the Barbados curve are about −120 and −43 m, respectively.

In the Hisarönü Gulf, the results indicate that the internal structure of the shallow marine sediments is composed of transgressive and highstand deposits characterized by rapid sea level rise during the last transgression and a stabilization of sea level, respectively (Figure 5). The lowest sea level position was determined at about −110 m which corresponds to the present shelf break and, which is recognized from seismic reflection data (Kaşer, 2010) compatible with the values presented in Lambeck (1995,). As the sea level rises, the migration of shorelines landward reaches a maximum of 17 km in the study area.

Late Holocene sea level changes: underwater archaeological and bioerosional indicators

The Turkish coasts have a number of ancient settlements with harbor constructions. Many of the ancient harbors located in the Aegean and western Mediterranean are now submerged at least 1 m bpsl, indicating the relative sea level rise. Flemming (1978) surveyed coastal tectonism around the archaeological sites in the SE Aegean and eastern Mediterranean coasts (Table I) to explain their present day situation. It is known that the eustatic sea level rise did not exceed 1 m in the Aegean and Mediterranean seas over the past 3000–2000 yr (Pirazzoli, 1976) (Figure 6).

Submerged archaeological remains (breakwaters and docks in the ancient harbors) and tidal notches were investigated in order to estimate relative sea level changes and suggest an average rate of vertical tectonic movement for the coast of the Hisarönü Gulf and surroundings for the late Holocene. The remains of the three ancient

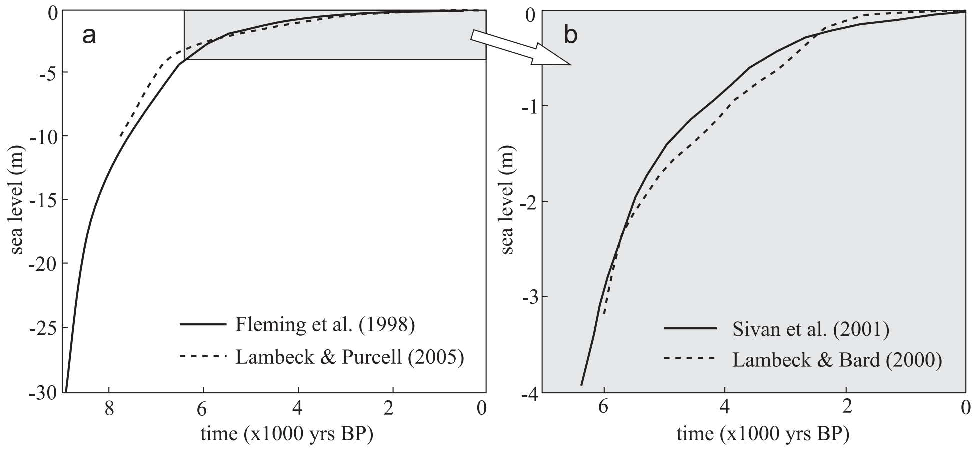

Figure 6 Eustatic sea level curves for the late Holocene. (a) Predicted sea level (solid line) and relative sea level corrected for the global ice volume equivalent sea level function. (b) Predicted sea levels along the coast of Israel (solid line) and eustatic sea level from locations far from the major ice sheets (dashed line).

harbors surveyed are dated to the Hellenistic and Roman period (about 2400–2000 yr B.P.) based on historical documentation and archaeological data (Carter, 1991, 2004; Özdaş, 2008) (Figure 3).

The İncirliada (Miniko) remains are located on the southern coast of the Yeşilova Gulf on the northern Loryma Peninsula (Figure 7). There is a small ancient harbor and a building of Hellenistic construction onshore (Carter, 2004) with a submerged breakwater about 30 m in length. The upper surface of the remains lies −1.5 m bpsl in the middle part (Kaşer, 2010). There are also two submerged harbor remains in the northeastern Yeşilova Gulf. The ancient harbor of Söğüt (Thyssanous) in Söğüt Bay (Saranta Bay) also has a submerged central breakwater at −0.7 m (Figure 8). The Bozburun (Tymnus) ancient settlement has both submerged breakwaters and dock remains (Figure 9). The upper surface of the breakwater lies −1 m bpsl. The construction of both the Thyssanous and Tymnus cities are dated to the Hellenistic period (Carter, 1982). Three submerged breakwaters (upper limits place them lower than −2 m seaward) have also been found in the Tekir Cape (Knidos), western Datça Peninsula, and close to İncirliada, but these remains have not been examined in this study.

However, the upper limits of these structures must have been at least 0.5 m above mean sea level at the time of their construction in order to provide adequate protection in the harbor for the maximum local high tide and wave effect (Antonioli et al., 2007) (Figure 10). Thus, the above archaeological observations indicate that the relative sea level rose c. 1.2–2.0 m since the time of construction (at least 2000 yr B.P.).

In the Yesilova Gulf, the midpoints of submerged tidal notches on limestone coasts were observed between −44 and −52 cm bpsl (Figure 11, Table II). The upper level of these notches is at −10 cm, while the lower level is at −78 cm with a total vertical height of 68 cm along the İncirliada harbor coasts. The maximum inward depth (lateral penetration into the bedrock) was measured to be 63 cm. On the Söğüt coastline, the submerged tidal notch level lies at a depth of −12 to −92 cm with an inward depth of 78 cm. The notch trace on the base rock of Bozburun is between −30 and −60 cm bpsl with a relatively narrow inward depth of 17 cm (Table II).

Pirazzoli (1986, 2005) and Evelpidou et al. (2011) reported that the rate of intertidal bioerosion ranges between 0.2 and 1 mm/yr in the Mediterranean. They use these limits to estimate the duration of the periods of relative sea level stability. Therefore, a value of 78 cm inward depth shows that the relative stability of sea level was long enough to form the notch. It has been observed that the trace of the present day tidal effect and seasonal changes is at about 20 cm along the coast of the Yeşilova Gulf. Evelpidou et al. (2011) have proposed that if the height of the notch exceeded the local tidal range, relative sea level rise during the period of notch development occurred gradually, and this is in accord with our observations.

DISCUSSION AND CONCLUSIONS

The changes of relative sea level in the Hisarönü Gulf and surrounding area (SE Aegean Sea) are presented in this study in order to increase understanding of the

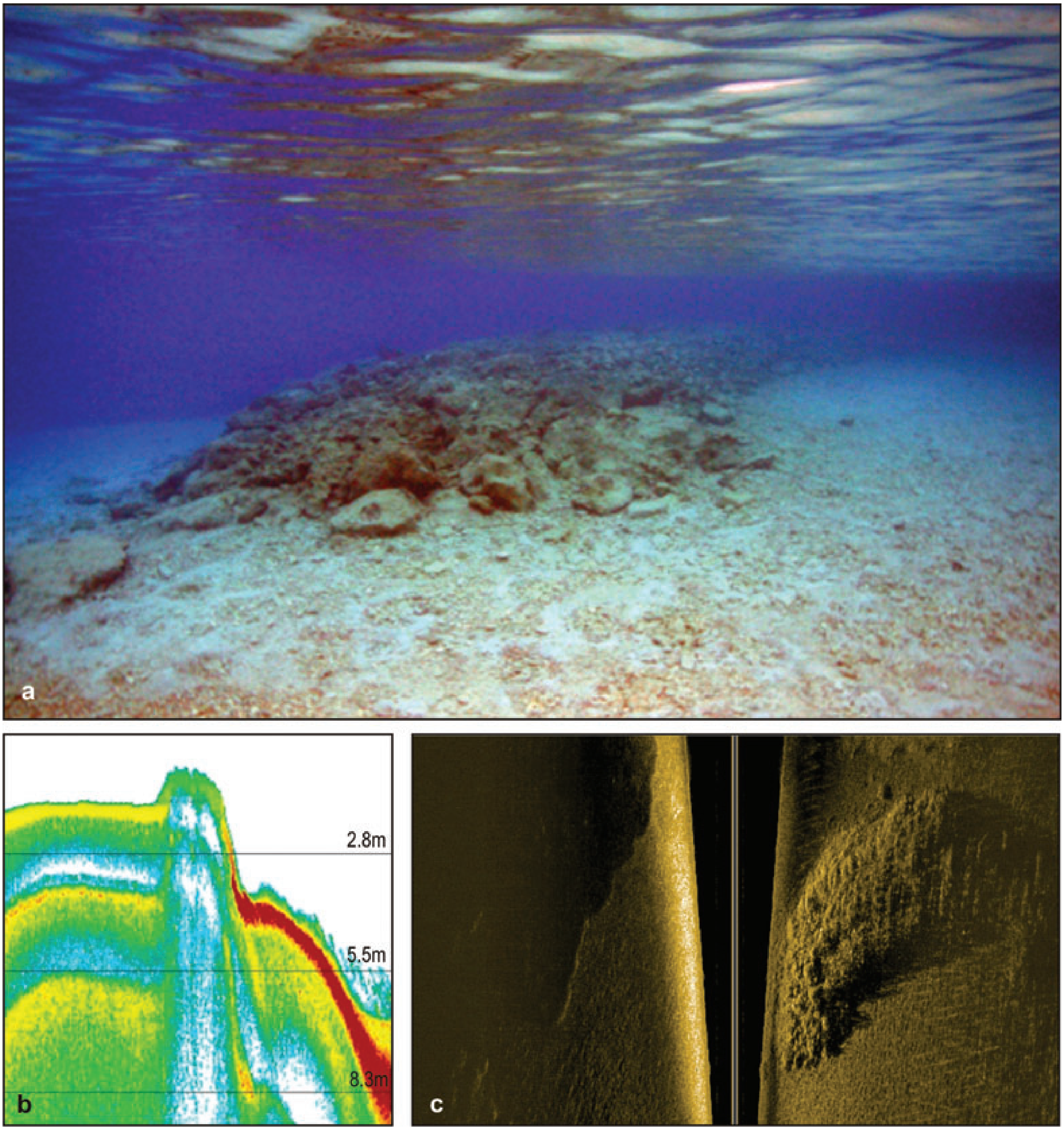

Figure 7 Submerged breakwater remains belonging to an ancient harbor in İncirliada in the southern Yeşilova Gulf. (a) Underwater photograph by H. Özdaş. (b) Ecosounder and (c) side scan sonar images of archaeological features.

patterns of global fluctuations of sea level and tectonic movement during the last transgression and the following highstand period (20,000 yr B.P.). During the late Pleistocene to Holocene transition, glacio-eustatic sea level changes formed postglacial depositional units, as determined from our high-resolution seismic profiles in the Hisarönü Gulf.

The rate of sediment accumulation since the last glacial period is estimated at 0.4 mm/yr from high-resolution seismic data in the Hisarönü Gulf (Kaşer, 2010). We

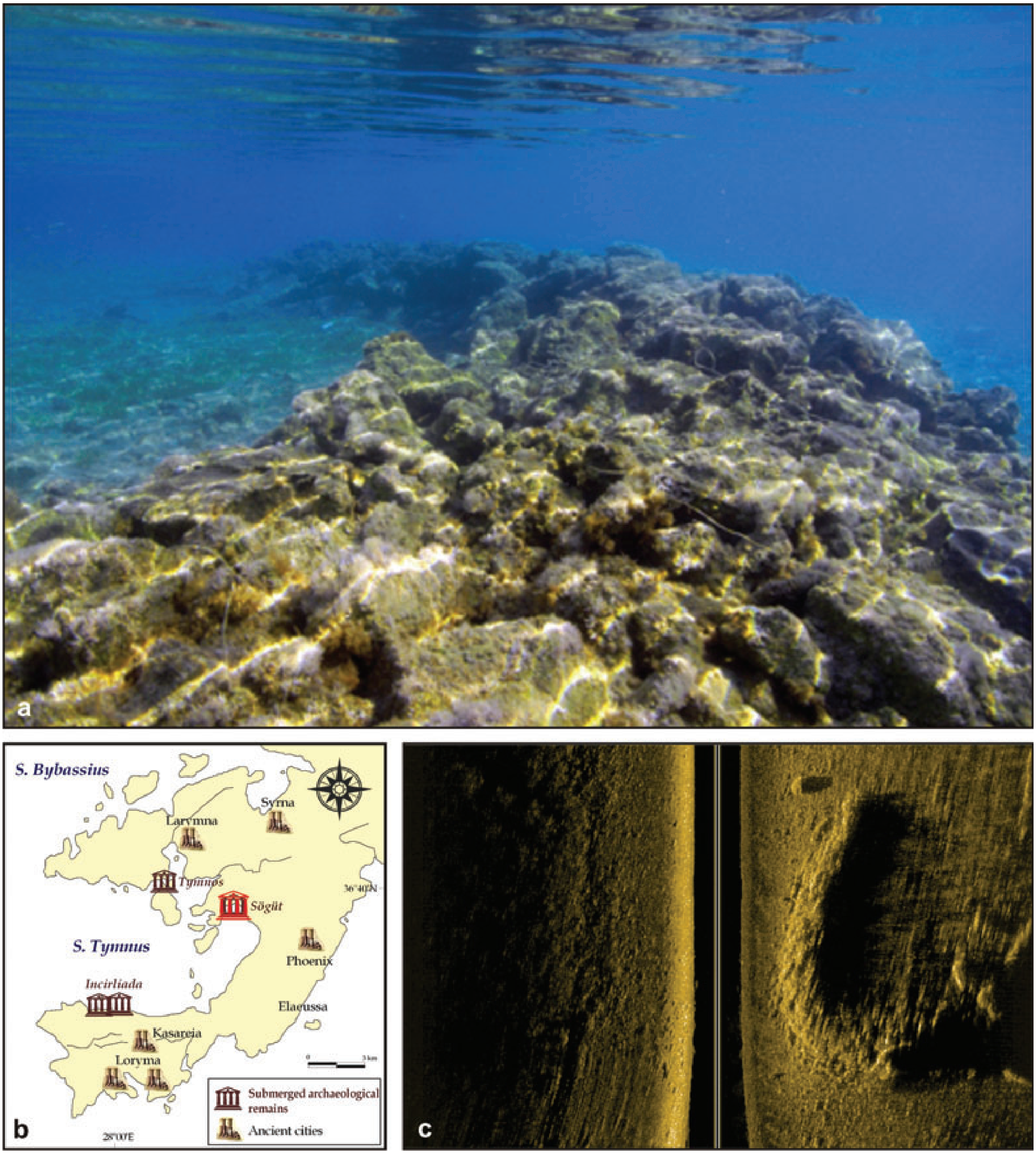

Figure 8 Submerged breakwater remains belonging to Söğüt in the northern Yeşilova Gulf. (a) Underwater photograph by H. Özdaş. (b) Location of features and (c) side scan sonar images of the remains.

have also established the location of the paleoshoreline at the LGM from a eustatic sea level curve combined with our regional stratigraphic results, and estimated that the coastline prograded landward to a maximum of 17 km from its former glacial positions (Figure 12). It is difficult to propose a more precise estimate for changes in sea level and sedimentation rates without geochronological control. However, the location, termination, and

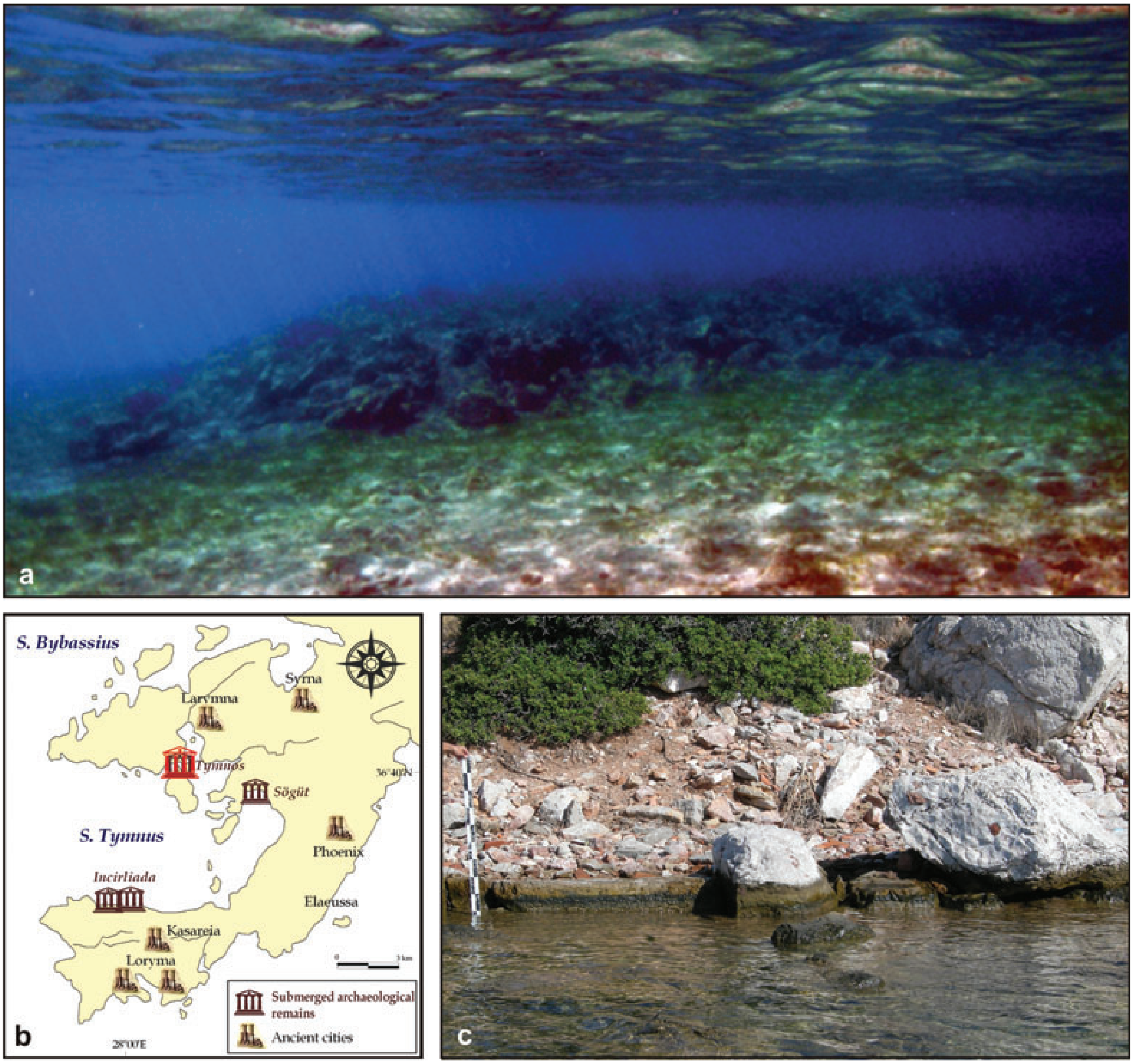

Figure 9 Submerged breakwater remains belonging to the ancient harbor at Tymnos in the northern Yeşilova Gulf. (a) Underwater photograph by H. Özdaş. (b) Location of the features and (c) a shoreline photograph showing the local tidal range.

water depth of postglacial transgressive and Holocene highstand deposits, and the sediment accumulation rate in the study area are compatible with the shelf deposits in the adjacent gulfs. In the Gökova Gulf, located at the north end of the study area, 25–35 m of posttransgressive sediment accumulated in the delta with rates of 1.25–1.75 mm/yr (Kaşer, 2004). The amount of sedimentation near the Turkish coast of the Aegean Sea is about 1.1 mm/yr (Westaway, 1994). The maximum Holocene sediment thickness on the shelves of Aegean coasts estimated from the depth of the pre-Holocene–late Pleistocene surface ranges from 6–35 m (Perissoratis & Conispoliatis, 2003). In the İzmir and Kuşadası bays, sediment thickness is 6 m, while it is 35 m in the delta region of Kuşadası (Aksu, Piper, & Konuk, 1987a, 1987b).

We used submerged archaeological remains and tidal notches to estimate sea level changes and local tectonic movement in the late Holocene by comparing isostatic models and similar studies performed in the Aegean and Mediterranean seas (Flemming, 1978; Fairbanks, 1989;

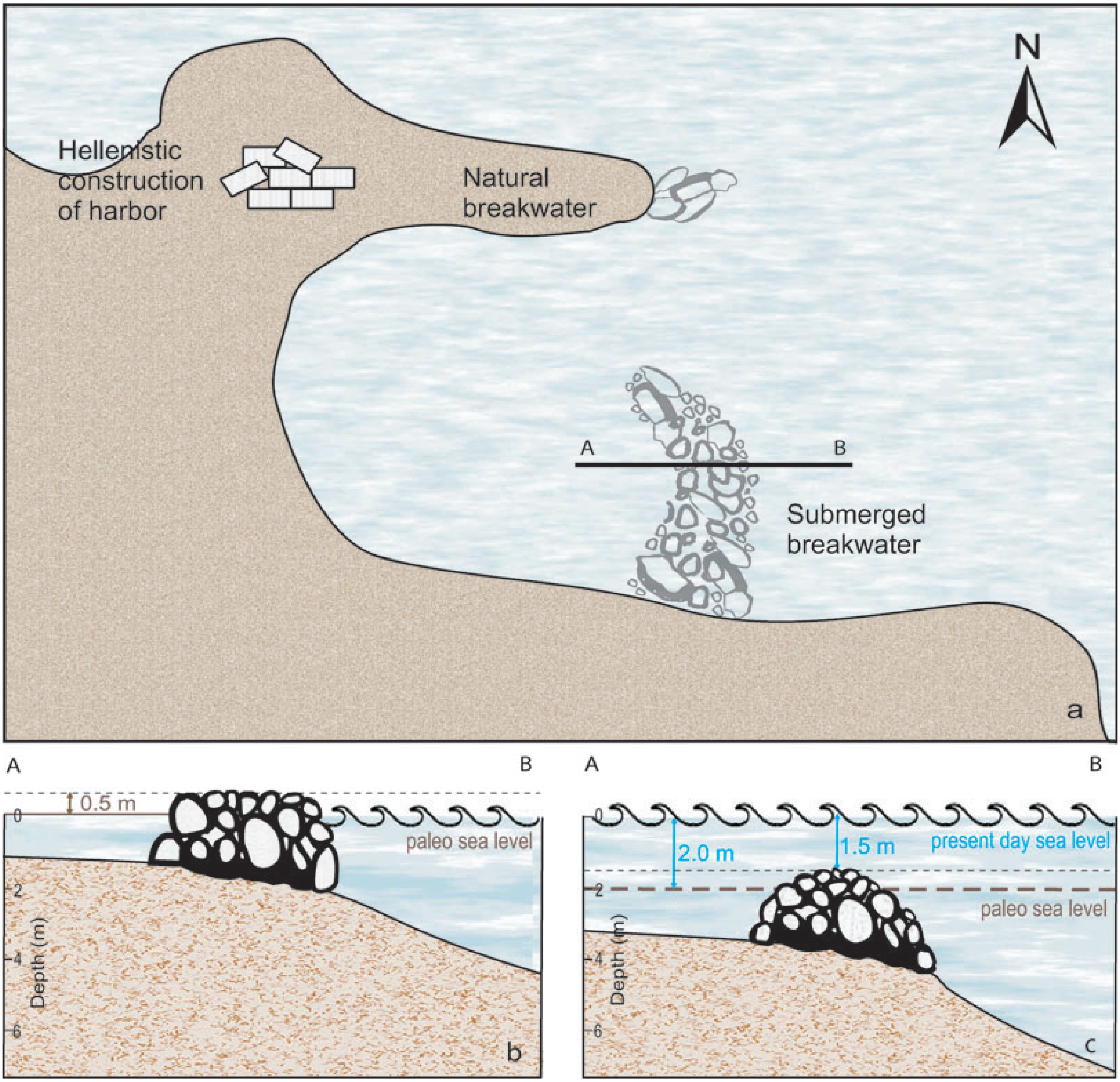

Figure 10 Representative cross-section of a breakwater at İncirliada. (a) Location of the breakwater and (b) the position of the breakwater in Hellenistic time. The upper surface of this construction must have been at least 0.5 m above sea level. (c) Present position of the breakwater. The upper surface of the breakwater lies approximately –2.0 m bpsl.

Fleming et al., 1998; Lambeck & Bard, 2000; Morhange, Laborel, & Hesnard, 2001; Sivan et al., 2001; Lambeck et al., 2004; Lambeck & Purcell, 2005; Vött et al., 2006; Marriner & Morhange, 2007) (Table I). Our archaeological observations indicate that the relative sea level change was at least 1.2 m, whereas previous studies performed in the Aegean and Mediterranean seas have suggested the eustatic sea level rise to be about 0.5 m during the past 2400–2000 years in the tectonically stable region. In the Yeşilova Gulf, the sediment thickness, determined from seismic data, which accumulated since that time is not significant. We know that the eustatic sea level rose about 0.5 m over the past 2000 years and the upper limits of ancient remains must have been at least 0.5 m above mean sea level at the time of their construction. However, these remains are now approximately 0.7–1.5 m

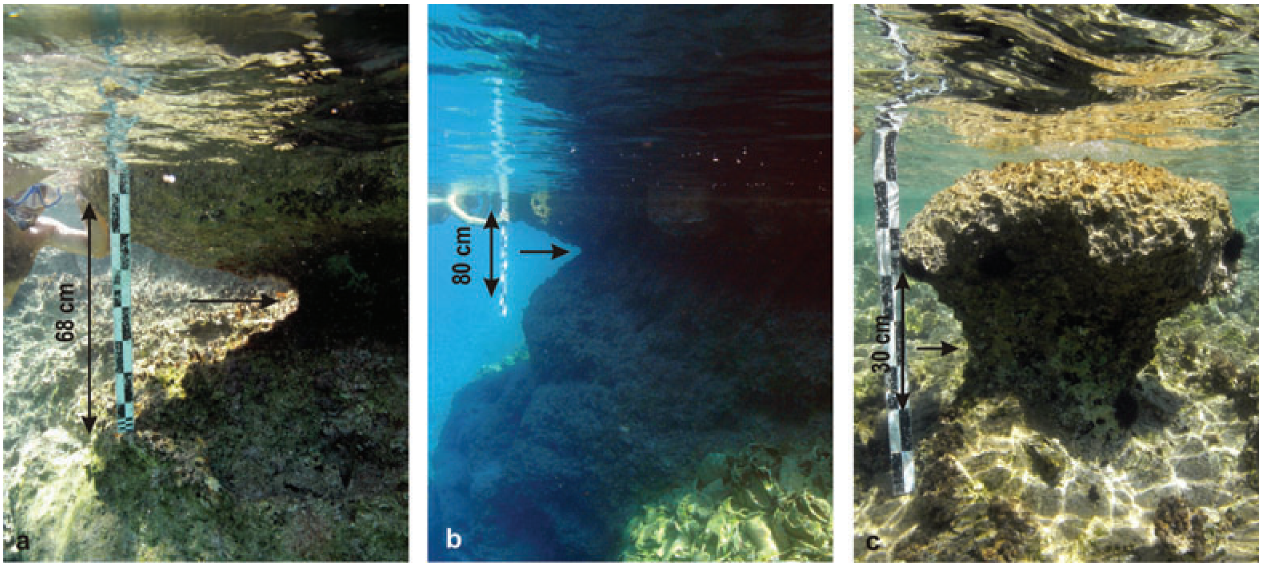

Figure 11 Underwater photographs of submerged tidal notches along the coast of the Yeşilova Gulf. Horizontal arrows indicate former mean sea level positions. Vertical arrows show the heights of notches in the following areas: (a) İncirliada, (b) Söğüt, and (c) Bozburun.

Table II Measurements of submerged tidal notches along the coast of the Yeşilova Gulf. *Top level depth* is the depth of the upper limit of the notch below sea level. *Height* is the full vertical extent of the notch. *Inward depth* is the lateral penetration of notch into the bedrock. *Mean level depth* is the midpoint of the notch below sea level.

Site Name	Location	Top Level Depth (cm)	Height (cm)	Inward Depth (cm)	Mean Level Depth (cm)
İncirliada	Southern Yeşilova Gulf	10	68	63	44
Söğüt	Northern Yeşilova Gulf	12	80	78	52
Bozburun	Northern Yeşilova Gulf	30	30	17	45

bpsl. If there was no tectonic subsidence during this period, then the upper limits of remains would have been at the same level as the present day sea level. Therefore, we suggest that the coast of the Bozburun Peninsula has subsided by 0.7–1.5 m due to tectonic activity since Hellenistic times, corresponding to a rate of 0.35–0.75 mm/yr, which is compatible with Flemming's (1978) rate of 0.7 mm/yr for Loryma, on the southern Bozburun Peninsula.

Depths of submerged tidal notches along the Yeşilova coasts are at between −44 and −52 cm bpsl, indicating subsidence of about 0.5 m and in agreement with estimates presented in Pirazzoli (1980) and Evelpidou et al. (2011) (Table II). A present day tidal notch trace has not been observed along the limestone coasts of the Yeşilova Gulf. The absence of a modern notch indicates that the former notch was formed recently (Evelpidou et al., 2011). According to Evelpidou et al. (2011), this formation became submerged not more than one or two centuries ago. On the Bozburun Peninsula, a number of faults observed on land have potential for producing important earthquakes that could cause significant subsidence.

The upper level of the middle part of the submerged breakwaters is at 0.7–1.5 m bpsl, while all tidal notches are located at 0.5 m bpsl along entire coast of the Yeşilova Gulf. We conclude that the archaeological remains became submerged due to a vertical tectonic movement that took place before the subsidence of the tidal notches. Tectonic movement which occurred during at least two different periods gave rise to a change in the form of the coastline. Archaeological and bioerosional observations reveal clear evidence of tectonic activity in the study area.

Thus, archaeological, morphological, and geological data indicate that local tectonic movement had the more important effect on the late Pleistocene and Holocene relative sea level rise in the Hisarönü Gulf and surroundings, while eustatic factors acted at much lower rates. We believe that further multidisciplinary studies are needed in order to test these results. While aspects of this work are preliminary, our results provide new insights into the late Pleistocene and Holocene stratigraphy and sea level

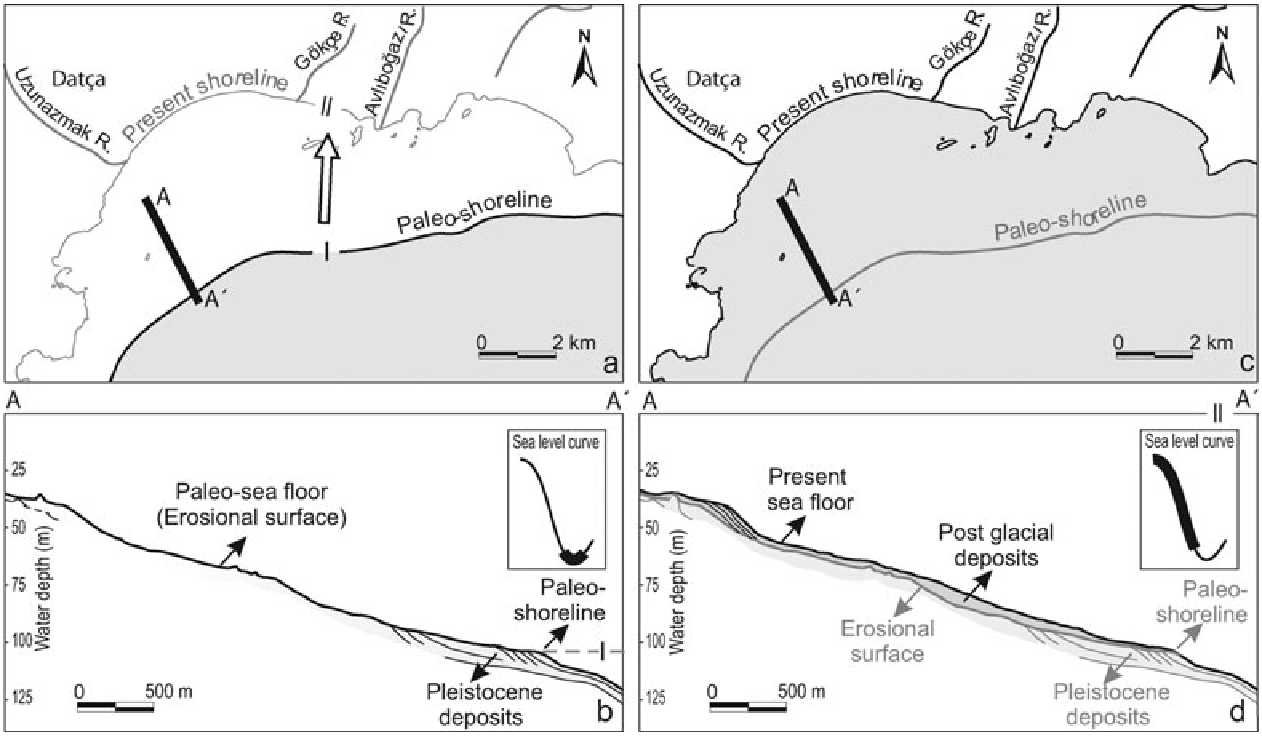

Figure 12 Sediment accumulation on the Datça Shelf and the shoreline position since the last glacial period. (a) The lowstand state at the last glacial maximum. (b) An accumulation model for Pleistocene sediments on the A-A´ section during the lowstand. (c) The highstand state and present day location of the shoreline. (d) An accumulation model for late Pleistocene to Holocene sediments on the A-A´ section during the highstand. The gray lines and gray shaded areas show the former positions while sea level rises from I (paleoposition) to II (present day position).

changes in the Hisarönü Gulf that have significance over a much wider area.

This study is a part of a PhD research project carried out by Nilhan Kızıldağ (Kaşer) at Dokuz Eylül University, Institute of Marine Sciences and Technology. The data are from research projects funded by the Scientific and Technical Research Council of Turkey (TUBITAK, Project Nrs. YDABCAG-75 and SOBAG 106K054). Permission is given by the Republic of Turkey Ministry of Culture and Tourism. Thanks to crew members of the R/V K. Piri Reis for acquiring digital seismic data; our team members for underwater measurements; and to Hasan Sözbilir and Kurultay Öztürk for their contributions. We would also like to thank the external reviewers, especially P.A. Pirazzoli, for their valuable suggestions and Lawford Anderson (Boston University) for the English revision. We also thank Jamie Woodward for copy editing our text.

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