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RESEARCH ARTICLE

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Late Holocene sea level change along the coast of Fethiye Gulf in southwestern Turkey

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Abstract

In the Fethiye Gulf on the southwest coast of Turkey, several submerged archaeological sites provide useful data about relative sea level changes since the Byzantine period. The current elevations of contemporary archaeological structures were measured to determine the amount of relative sea level change. The archaeological sea level markers in this seismically active region provide new data about the amount and period of relative sea level rise. Taking into consideration the time of the last use of the structures, instead of their time of construction, three different rates of vertical land movement of 2.18 ± 0.3, 2.96 ± 0.3, and 3.29 ± 0.5 mm/yr were estimated. These data indicate that tectonic activity differs from region to region, most likely related to local normal faults in the gulf. Recent earthquakes have confirmed active seismicity in this area. These results demonstrate that the changing sea levels in the Fethiye Gulf have been strongly influenced by vertical tectonic movement over the last 1,400 years. Results also contribute to studies of future coastal changes in the Fethiye Gulf and its surroundings.

KEYWORDS

Fethiye Gulf, relative sea level changes, submerged archaeological sites, subsidence, tectonic, vertical coastal movement

1 | INTRODUCTION

Submerged archaeological coastal structures are commonly used as indicators of relative sea level changes (Anzidei et al., 2011; Flemming, Czartoryska, & Hunter, 1973; Kolaiti & Mourtzas, 2016; Lambeck, Anzidei, Antonioli, Benini, & Esposito, 2004; Morhange et al., 2013; Pirazzoli, 1991). Recent studies have confirmed that ancient harbor and coastal structures (e.g., quays and fish tanks) are reliable sea level indicators, as they are directly related to sea level at the time of their construction (Auriemma & Solinas, 2009; Benjamin et al., 2017; Evelpidou et al., 2012; Morhange & Marriner, 2015; Vacchi et al., 2016). Rates of local vertical crustal movement can be inferred from the comparison of the current position of the sea level marker, the last usage period or construction time, and the eustatic–isostatic sea level change.

The coast of southwestern Turkey in the southeastern Aegean Sea has a large number of submerged archaeological structures. Historically, the Fethiye Gulf was one of the most important regions of southwestern Turkey, as it was located on ancient sea trade routes (Harrison, 1963). Due to the high volume of maritime activity in the Mediterranean, this region was home to a large number of ancient coastal settlements that contained quays, public buildings, and so forth that are currently submerged. These settlements reached their most prosperous period during the 6th century C.E., and construction activities continued into the 7th century C.E. (Foss, 1996). Destructive earthquakes, Arab invasions, and plague affected the settlements during the 6–7th centuries C.E. and led to their abandonment (Atik, Bell, & Erdogan, 2012; Erel & Adatepe, 2007; Harrison, 1963; Zampaki, 2012). Ceramic evidence dating to the 5–7th century C.E. indicates that coastal constructions were in use until that time (Bass, 1982; Foss, 1996). Both the ceramic finds and the evidence of abandonment demonstrate that the operation of the coastal constructions lasted until the early Byzantine period and that submergence must have occurred after that time. These provide data about the earliest period of vertical land movement.

Geoarchaeological studies that use submerged archaeological remains as sea level indicators consider the construction time of coastal installations to calculate the time of their submersion (Antonioli et al., 2007; Anzidei et al., 2011; Mastronuzzi et al., 2017). In this study, instead of using the construction time to determine the submersion time, which reduces the period of relative sea level rise, the focus here is on the time of the last use of the construction based on the dating of ceramics and abandonment history.

Relative sea level changes result from eustasy, glacio-hydro-isostasy, and vertical tectonic movements (Lambeck, Rouby, Purcell, Sun, & Sambridge, 2014). While eustasy is global and independent from local factors (such as vertical tectonic movement), relative sea level changes are regional or local (Rovere, Stocchi, & Vacchi, 2016). The eustatic–isostatic sea level has risen by ~134 m since the last glacial maximum in response to melting glaciers (Lambeck et al., 2014). Geoarchaeological studies have indicated that eustatic–isostatic sea level change did not exceed 0.5 m during the last 2,000 years on the Mediterranean coasts (Evelpidou et al., 2012; Flemming & Webb, 1986; Lambeck & Purcell, 2005). Flemming (1978), Pirazzoli (1987), and Kızıldağ, Özdas, and Uluğ (2012) have reported that tectonic movement had a greater effect than eustatic factors on the late Holocene relative sea level rise in southwestern Turkey.

The Fethiye region is under the influence of active tectonism, as it is located between the Pliny and Strabo subduction trenches, and its terrestrial extent continues into the Fethiye-Burdur Fault Zone (Hall, Aksu, Yaltırak, & Winsor, 2009; Figure 1). This tectonic framework has produced a large number of earthquakes, which likely had an impact on the submergence of coastal settlements in the region (Figure 1c). In addition to successive strong earthquakes documented in the 20th century, recent earthquake activity that occurred in the Fethiye Gulf in 2012 confirms ongoing active tectonics and the potential for future earthquakes in this region.

In this study, I investigated submerged ancient coastal sites along the coast of the Fethiye Gulf to obtain data about relative sea level changes. These results provide new insights into the amount of vertical coastal displacement that occurred during the late Holocene.

2 | STUDY AREA

2.1 | Tectonic setting

The Fethiye Gulf is located at the border of the ancient regions of Caria and Lycia in the southeastern Aegean Sea (Figure 1). This region is controlled by a tectonic framework dominated by the westward escape of the Anatolian plate as a result of collision between the Arab-African and Eurasian plates (Barka & Reilinger, 1997; Dewey & Şengör, 1979), which formed the Hellenic and Cyprus arcs (Ten Veen et al., 2004; Figure 1b). Seismicity in the Hellenic arc is generated by the subduction of the eastern Mediterranean

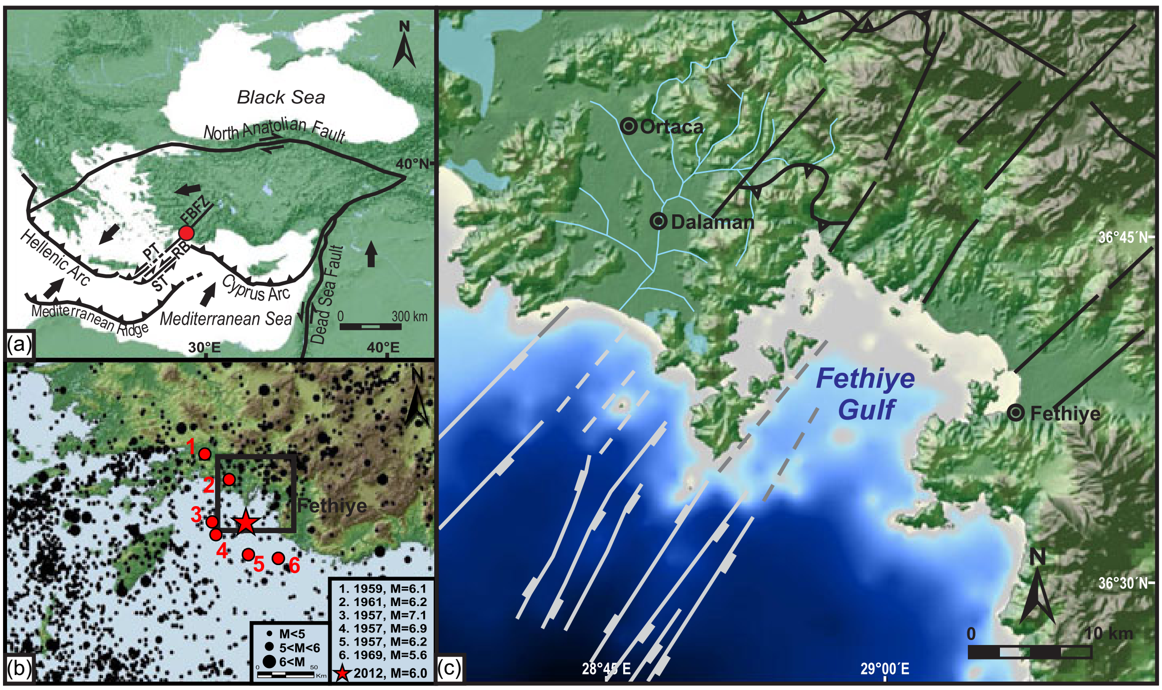

FIGURE 1 Location maps. (a) Main tectonic features of the eastern Mediterranean Sea (modified from Barka & Reilinger, 1997), thick arrows indicate plate motion direction, split arrows indicate strike-slip faults, triangles indicate subduction zones, and the red dot is the study area. (b) Regional seismicity showing epicenters of significant earthquakes in the Fethiye Gulf and vicinity (data from AFAD, USGS, and NCEDC), rectangle indicates area of (c). (c) Major faults in Fethiye Gulf and vicinity (faults are from Bozcu, Yağmurlu, & Şentürk, 2007; Hall et al., 2014; Ocakoğlu, 2012), triangles and rectangles indicate thrust and normal faults, respectively. FBFZ: Fethiye-Burdur Fault Zone, PT: Pliny Trench, ST: Strabo Trench, RB: Rhodes Basin [Color figure can be viewed at wileyonlinelibrary.com]

lithosphere of the African plate under the Aegean lithosphere of the Eurasian plate (Papazachos, Karakostas, Papazachos, & Scordilis, 2000).

The Pliny and Strabo Trenches, which resulted from the Hellenic zone roll-back and are controlled by left-lateral faults, follow the eastern part of the Hellenic subduction zone (ten Veen et al., 2004). Ten Veen et al. (2004) suggested that the Pliny Trench is connected to the offshore Finike Basin in the east and that it is not connected with the Fethiye–Burdur Fault Zone (FBFZ). However, Taymaz and Price (1992), Barka and Reilinger (1997), Hall et al. (2009), and Hall, Aksu, Elitez, Yaltırak, and Çifçi (2014) documented that the NE–SW-trending faults that control the Pliocene-Quaternary structural framework of the Rhodes Basin run parallel to the 30–50-km-wide Pliny and Strabo trenches, extending to the Fethiye Gulf and connecting with the FBFZ. Based on seismic data, Ocakoğlu (2012) suggested that Fethiye Canyon (located on the edge of the Fethiye Gulf) forms the northeastern extension of the Pliny Trench, linking this basin to the FBFZ. The FBFZ has consisted of normal faults, as well as active left-lateral faults, since it developed in the Lycian nappes. Elitez and Yaltırak (2016) suggested that the structural evolution of the FBFZ is based on progressive deformation that has been active since the late Miocene.

This tectonic regime resulted in many serious earthquakes along the Hellenic arc and Pliny and Strabo trenches (Altınok, Alpar, Özer, & Aykurt, 2011; Ambraseys & Finkel, 1995; Erel & Adatepe, 2007; Yolsal, Taymaz, & Yalçıner, 2007; Table 1). Reports from archaeological sites located on the FBFZ have indicated that numerous destructive earthquakes occurred during historical times (Akyüz & Altunel, 2001; Bean, 1978; Guidoboni, Comastri, & Traina, 1994; Yerli et al., 2010). Strong earthquakes in the beginning of the 6th century and in the middle or the second half of the 7th century C.E. damaged the ancient city of Sagalassos (Similox-Tohon et al., 2005).

TABLE 1 Earthquakes in the historical and instrumental period in southwestern Turkey and surroundings

No.	Date	Location	I/M	References
1	23	Cibyra	-	a,b,d,f
2	68	Patara, Demre	-	f
3	142	Rhodes, Myra	VIII	b,e,f
5	144	Fethiye, Kalkan	VIII	e
5	226	Rhodes	VIII	e
6	344	Rhodes	IX	e
7	365	Crete, E.Mediterranean	X-XI	e,f
8	417	Cibyra	IX	a,b,d
9	528	Fethiye, Meis	IX	e
10	554	SW Anatolia, Kos	X	f
11	1481	SW Anatolia	IX	f
12	1609	Rhodes	IX	c,f
13	1741	Rhodes	VIII	c,f
14	1756	Rhodes, E.Mediterranean		c
15	1851	Fethiye, Muğla	IX	e,f
16	1852	Fethiye, Muğla	VII	e,f
17	1855	Fethiye Gulf	VIII	e,f
18	1863	Fethiye, Rhodes	IX-X	e,f
19	1864	Meis, Fethiye	VIII	e
20	1870	Fethiye, Rhodes	VIII	e
21	1887	Köyceğiz	VII	e
22	1896	Marmaris, Muğla	VII	e
23	1897	Köyceğiz	VII	e
24	1914	Fethiye, Burdur	7.0	d
25	1957	Fethiye Gulf	6.9	g
26	1957	Fethiye Gulf	7.1	g
27	1959	Fethiye Gulf	6.1	g
28	1961	Fethiye, Rhodes	6.2	f,g
29	2012	Fethiye Gulf	6.0	g

Notes. (a) Bean (1978); (b) Guidoboni et al. (1994); (c) Ambraseys and Finkel (1995); (d) Akyüz and Altunel (2001); (e) Erel and Adatepe (2007); (f) Altınok et al. (2011); (g) Görgün et al. (2014).
I: Intensity (I–XII); M: Magnitude (2–8).

FIGURE 2 Location of investigated sites and ancient settlements [Color figure can be viewed at wileyonlinelibrary.com]

Altınok et al. (2011) documented a tsunami event that caused submergence of 0.5 m on the Fethiye coasts in 1851. Twentieth century earthquakes confirm active tectonism in this region (Akyüz & Altunel, 2001; Görgün, Zang, Kalafat, & Kekovalı, 2014; Figure 1c). The most recent earthquake activity was recorded off Fethiye Bay on 10 June 2012, which had a main shock of $M = 6$. Based on the focal mechanisms and distribution of epicenters, Görgün et al. (2014) suggested the activation of a NW–SE-trending left lateral strike-slip fault with a reverse component. On the other hand, Dogan, Irmak, Karakas, and Kalafat (2016) suggested that oblique faulting connected with NW–SE extension is more dominant than the strike-slip component, which forms the area between Fethiye Bay and the Rhodes Basin.

Sedimentary basins formed over Lycian nappes during the Late Paleocene–Early Eocene, producing formations that outcrop along the northern coasts of the Fethiye Gulf (ten Veen, Boulton, & Alçiçek, 2009). The study area is surrounded by Cretaceous limestones in the west, Cretaceous peridotite rocks in the north, and Quaternary alluvium and dolomite containing limestones that date to the middle Triassic-Liassic in the east (Şenel, 2002). Limestone in the region were exploited for masonry and carving construction techniques in Lycia. The gulf has a very narrow shelf area, reaching a depth of 300 m in both the western and eastern indented coasts. The shelf is relatively wide in the northern part, consisting of numerous islands and shallows. The average water depth is 300 m in the center, rapidly deepening to 1,000 m along the outer margin of the gulf, and it reaches 4,500 m in the Rhodes Basin.

2.2 | Archaeological setting

The Fethiye Gulf, known as the Gulf of Makri or the ancient *Glaucus Sinus* (Strabon, XIV:2), was an important part of the ancient Mediterranean trade route. The gulf is located at the border of the historical regions of Caria and Lycia. The *Cavos Souvelah* (or *Artemisium promontory*) borders the gulf to the west and the *Cavos Angistro* to the east. Numerous protected bays and small islands of the gulf provided well-sheltered anchorage for ancient ships. Several settlements were established on these bays and islands, and on the surrounding hills during the Byzantine period (Bean, 1978; Foss, 1996).

Telmessus (modern Fethiye) is one of the most important cities of Lycia and is famous for its rock-cut tombs. The first historical reference to the city dates to the 5th century B.C.E. (Bean, 1978). Smaller settlements are located at the western side of the Fethiye Gulf (Figure 2). These include the city of *Lydae* from the Hellenistic period, which has a strategic position on a hill on the Kapıdağ Peninsula (Foss, 1996), *Lissa* (Kargın Gölü—Kızılağaç), *Scopea* (Kapıkırı), which has a shallow and well-protected harbor, *Arymaxa* (Batık Hamam), a deme of *Lydae* that is known for its visible, partially submerged Byzantine remains (Hicks, 1889; Tietz, 2003), and *Crya*

TABLE 2 Locations and current elevations of contemporary submerged archaeological remains with measurement errors

Area	Site no.	Site name	Type of indicator	Upper level (m)	Bottom level (m)
A	1	Göcek Island	Quay	−2.5 ± 0.1	−4.0 ± 0.2
			Pool?		−2.5 ± 0.2
	2	Zeytinli-Şeytan Islands	Quay	−2.4 ± 0.1	
			Building		−1.7 ± 0.2
	3	Tersane Island	Pavement	−2.4 ± 0.1	
			Building		−2.0 ± 0.2
B	4	North of Domuz Island	Quay	−3.4 ± 0.1	−5.9 ± 0.2
			Building		−2.9 ± 0.2
	5	West of Domuz Island	Quay	−3.6 ± 0.1	−6.6 ± 0.2
			Building		−3.2 ± 0.2
	6	Taşkaya Bay	Quay	−3.7 ± 0.1	−6.1 ± 0.2
			Pavement	−3.3 ± 0.1	−2.7 ± 0.2
			Steps	−3.3 ± 0.1	−1.8 ± 0.1
			Building		
			Tomb		
C	7	Hamam Bay	Building		−3.4 ± 0.2
	8	Binlik Bay	Building		−4.0 ± 0.2
	9	Kapıkırı Bay	Building		−2.6 ± 0.2

(Bedri Rahmi/Taşkaya), mentioned by Pliny (v. 103) as "*Crya* of the fugitives" Bean, 1978).

Several pigeon-hole rock-cut tombs (Bean, 1978) and Hellenic fortress ruins (Hoskyn, 1842) can be seen on the hillside in *Crya*. *Daedala* (İnlice; Pliny v. 103), located on the northern side of the gulf, has tombs carved into rock in the Lycian style (Hoskyn, 1842). Geographer Strabon mentions that this city was the boundary between Caria and Lycia (Bean, 1978). Islands in the *Gulf of Scopea* (Göcek Bay; Oniki islands), such as *Nero Nisi* (Domuz Island), *Telandria* or *Tersanah* (Tersane Island), *Stavro Nisia* (Zeytinli and Şeytan Islands), and *Agio Kisiachi* (Göcek Island; Hoskyn, 1842), also have archaeological sites. *Telandria* has a small harbor surrounded by a Greek village and Hellenic fortress remains (Hoskyn, 1842).

The coastal settlements of Lycia have been inhabited since the Classical period, and construction activities continued well into the 7th century C.E. These settlements reached their most prosperous period during the 6th century C.E., in the era of Justinian, thanks to an abundance of commercial activities (Foss, 1996). Timber, oil, wine, wheat, and other minor commercial goods were shipped from these Lycian ports to Egypt, the eastern Mediterranean, and Greece. Arab invasions that ravaged this region in the 7th century C.E. destroyed this commerce as well as the majority of Lycian cities. In 655 C.E., the Arabs defeated the Byzantine navy at a naval battle off Phoenix that contributed to the vulnerability of these settlements. There is no archaeological evidence of occupation in the cities between the early 7th and 12th centuries C.E. (Foss, 1996). It appears that the coastal and island settlements of Lycia were abandoned in the 7th century C.E. Coins found at the island settlement of *Lebissos* (Gemiler Island, near the town of Fethiye) confirm that continuous occupation ended in the early 7th century C.E. (Foss, 1996).

3 | MATERIALS AND METHODS

Nine submerged archaeological sites along the coast of the Fethiye Gulf were investigated; these sites contain quays, buildings, pavements, rock tombs, and so forth (Figure 2 and Table 2). The following steps were performed:

1. the current elevations of structures were measured with respect to present mean sea level;
2. a minimum original elevation was defined for the structures at the time of their use;
3. an error bar was assigned for both measurements and the uncertainty of the original elevation;
4. eustatic-isostatic sea level rise was evaluated;
5. the time of the last use of construction was determined;
6. the rate of vertical land movement was calculated.

To estimate the amount of relative sea level change, determining the original elevation of archaeological structures is a key factor (Auriemma & Solinas, 2009; Morhange & Marriner, 2015). Antonioli et al. (2007) described functional height as the elevation of the specific architectural parts of an archaeological structure with respect to the mean sea level at the time of construction. However, Auriemma and Solinas (2009) suggest that functional height depends on the typology of the archaeological structure. Harbor structures (e.g., quays, docks, and piers), fish tanks and water wells are more reliable indicators than buildings, pavements, and so forth which are not directly related to former sea level (Morhange & Marriner, 2015; Vacchi et al., 2016; Vunsh et al., 2017).

I focused upon quay remains for the calculation of relative sea level change because they are the most reliable sea level indicators among the submerged remains. A minimum original elevation of 0.6 m was assigned for quays, taking into account their sheltered location close to wave action, the capacity for the landing of small boats and small tidal range (Aucelli, Cinque, Mattei, & Pappone, 2016; Auriemma & Solinas, 2009). Local tides have an average amplitude of ~0.3 m (http://www.psmsl.org/data/obtaining/rlr.monthly.data/1243.rlrdata). An error of ±0.2 m was added for the uncertainty of the original elevation approximation. Due to the lack of harbor structures in some regions (grouped in Area C, Table 1), I considered the foundation level of buildings to estimate relative sea level change. Observations indicate that buildings are always located above the quay platform in Areas A and B; thus, their original elevation would be at least as high as the quay. Nevertheless, a higher error margin of ±0.3 m was assigned for the original elevation of the building due to its low reliability. A vertical error of ±0.1 m was also added to the measurements of preserved and clear surfaces (e.g., the upper limit of the quay) and ±0.2 m for the surfaces covered by rubble stones (e.g., the foundations of the quay and building).

Finally, the rate of vertical land movement was calculated based on the current elevation, the presumed original elevation of constructions, and the time of last usage. I estimated the time of last usage, instead of the construction time, based on historical documents regarding the abandonment date, as well as ceramics recovered at the sites.

Measurements and photographs were obtained through scuba diving. During the dives, ceramic fragments were analyzed in situ, which contributed to the dating of the last usage of coastal constructions. Three-dimensional models were created for some parts of the structures using Agisoft Photoscan (Agisoft LLC., St. Petersburg, Russia). All data were mapped in ArcGIS software (ESRI, US). Aerial photos were taken to establish the distribution of archaeological remains, and bathymetric data were also collected to detect the lateral distribution of the structures. All measurements were taken using Differential Global Positioning Systems (DGPS) during average tide level and favorable weather, when the sea surface was smooth, to ensure maximum possible accuracy.

4 | RESULTS

Coastal archaeological sites along the northwestern coast of the Fethiye Gulf were selected as they have a number of submerged remains that provide remarkable evidence of the relative sea level rise (Table 1). All structures on land date to the early Byzantine period based on both historical documentation and the building techniques (Bean, 1978; Foss, 1996; Hoskyn, 1842; Tietz, 2003). Although the remains of coastal architectural structures are almost entirely covered by vegetation and soil, it is still possible to observe that the walls were built using rough-cut stones and mortar.

Most of the sites contain a submerged quay that has at least two rows of rough ashlar blocks. The foundations of rectangular buildings lie on the quay platforms. The floors of buildings are often covered with rubble stones, archaeological materials, and are partly consolidated in the beach rock. Some sites feature jar sherds, partly buried in quay platforms, which were likely used for salt production

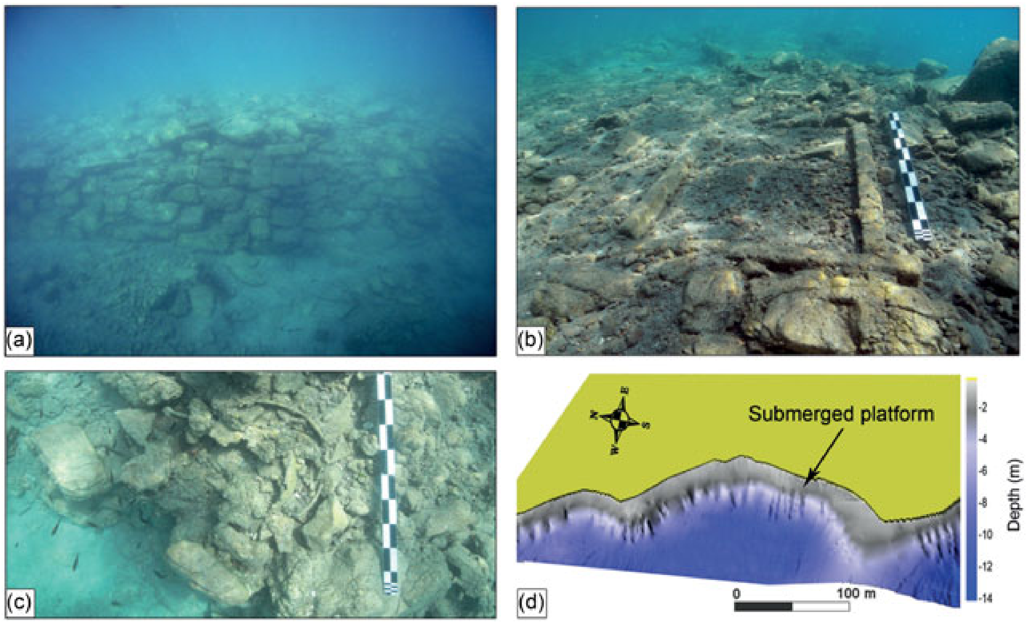

FIGURE 3 The main submerged remains at Göcek Island. (a) Ashlar block of the quay. (b) The foundations of a rectangular structure. (c) A buried jar fragment. (d) Seafloor morphology inferred from echosounder data. Underwater photos by Dr. Özdaş [Color figure can be viewed at wileyonlinelibrary.com]

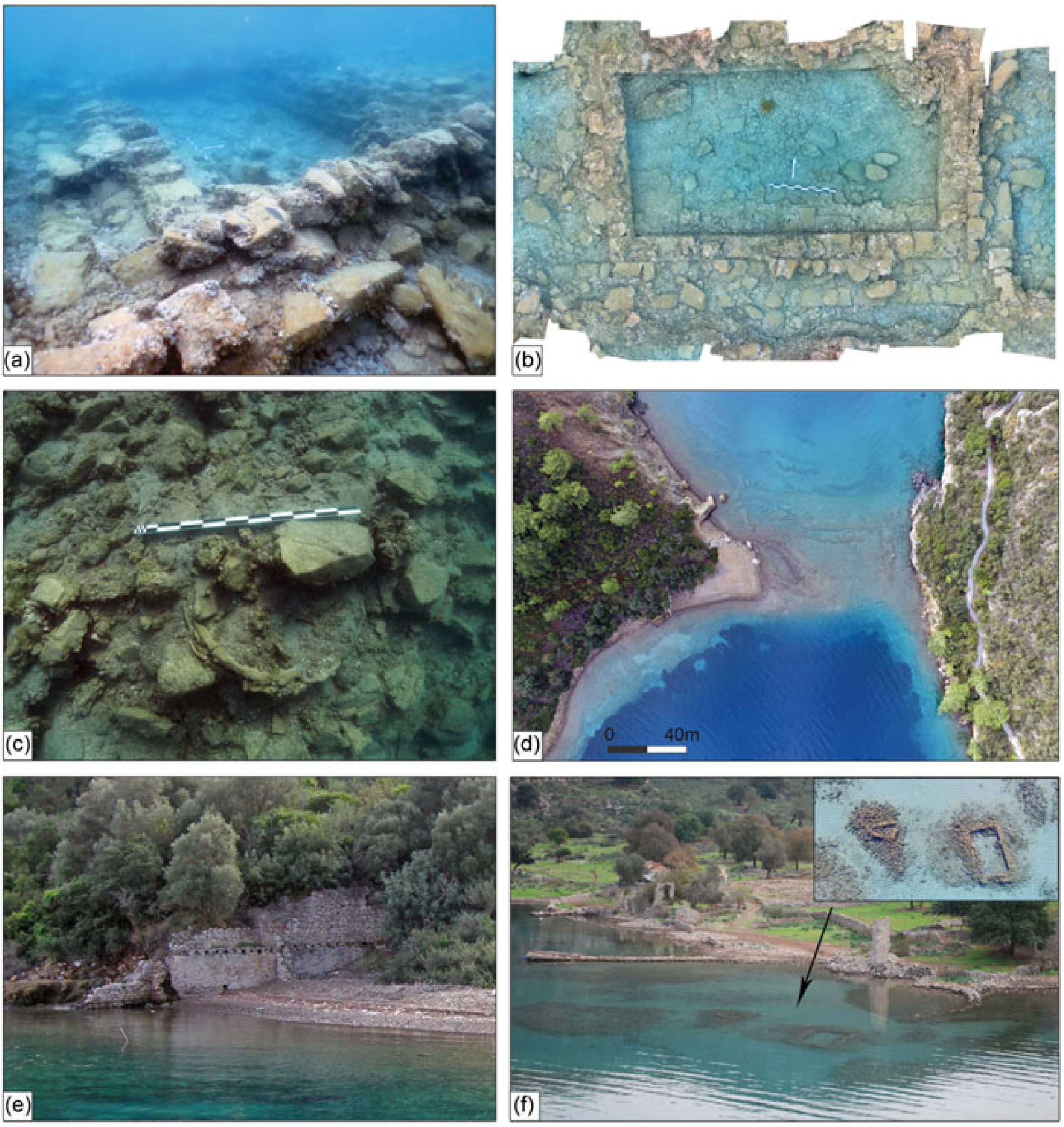

FIGURE 4 Zeytinli-Şeytan and Tersane Islands. (a) The foundations of a rectangular structure. (b) Photomosaic of the submerged structure. (c) A buried jar fragment. (d) Aerial photo of remains between the islands of Zeytinli and Şeytan. (e) Partly submerged Byzantine constructions. (f) Aerial photo of Tersane Island. Underwater photos by Dr. Özdaş [Color figure can be viewed at wileyonlinelibrary.com]

or food storage. The existence of LR1 and LR2 amphora fragments, dated to the 5–7th century C.E. (Bass, 1982; Demesticha, 2005; Karagiorgou, 2001; Opait, 2004) and found scattered among the submerged structures and in front of the submerged quay remains, indicates that the region was occupied until the early Byzantine period.

4.1 | Area A: Göcek, Zeytinli-Şeytan, and Tersane Islands

Göcek Island is located in the most interior and sheltered position in the northern Fethiye Gulf (Figure 2, No. 1). Along ~500 m of a north–south aligned section of the island's western coast, ashlar blocks of quays, foundations of rectangular buildings, and three buried jars are currently located below sea level (Figure 3).

In some parts of the quay, five to six rows of rough-cut ashlar blocks are clearly visible (Figure 3a). The upper surface of the quay lies at an average depth of 2.5 ± 0.1 m below present sea level, while the bottom of the blocks reaches a depth of 4.0 ± 0.2 m (Table 1). The foundations of a rectangular structure (a pool?) constructed with monolithic rectangular stones, 1.2-m long and 1.0-m wide, are almost fully buried among the rubble stones at −2.5 ± 0.2 m (Figure 3b). On the quay platform, three large jar sherds were found buried in the floor, indicating that the measured surface of the quay is preserved (Figure 3c). Additionally, a large number of amphora sherds and roof tiles were observed among the submerged remains. The amphora

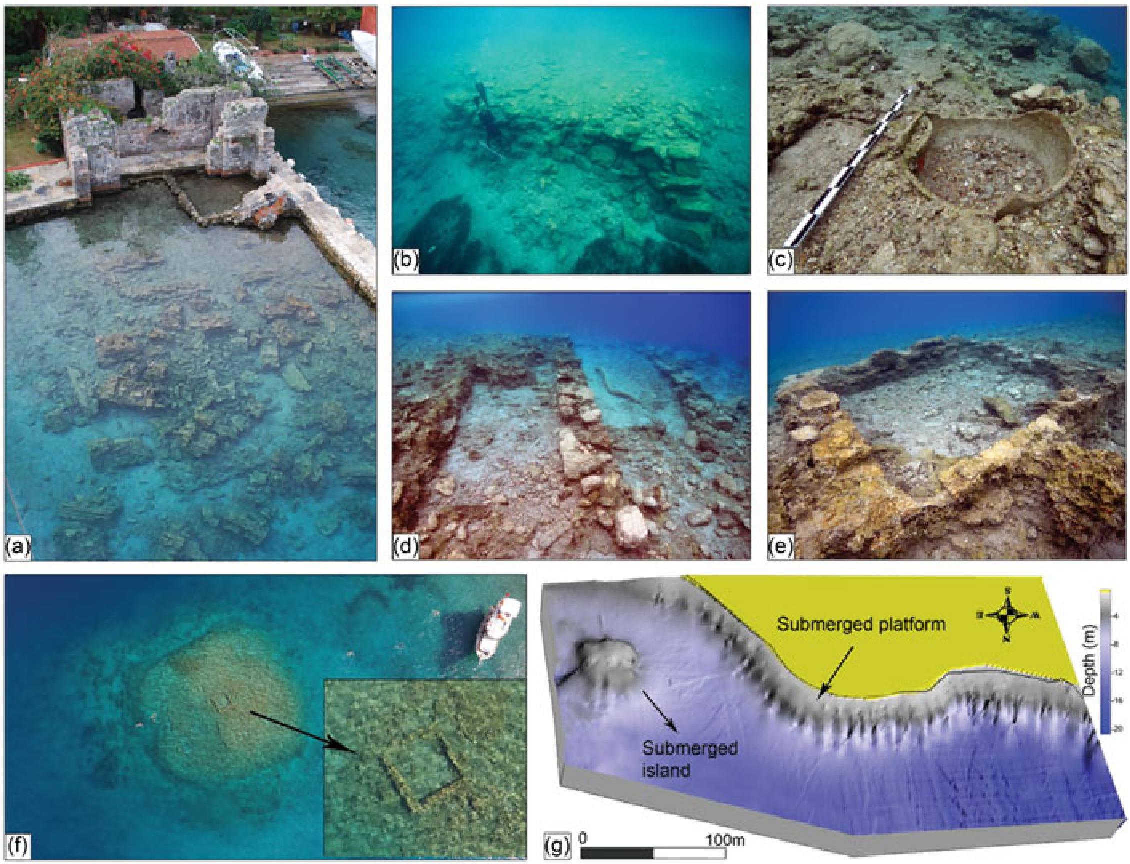

FIGURE 5 The main archaeological sea level markers along the northern coast of Domuz Island. (a) Partly submerged wall remains. (b) Quay remains. (c) A buried jar fragment. (d, e) Foundations of rectangular buildings. (f) Aerial photo of building remains on the sunken island. (g) Seafloor morphology inferred from echosounder data. Underwater photos by Dr. Özdaş [Color figure can be viewed at wileyonlinelibrary.com]

forms (LR1 and LR2) date to 5–7th century C.E. (Bass, 1982; Demesticha, 2005; Karagiorgou, 2001; Opait, 2004) and confirm the use of harbor structures until this time.

The seafloor morphology inferred from echosounder data (Figure 3d) indicates that a noticeable submerged platform lies parallel to the coast with a mean width of ~20 m. This horizontal surface between the present coastline and the seaward quay-remains lies beneath the submerged or partly submerged archaeological remains. The platform indicates that ~20 m of shoreline transgression has occurred in the region since Byzantine times.

Archaeological sea level indicators are also observed between two small islands (Zeytinli and Şeytan Islands) in the northwest gulf (south of Göcek Island; Figure 2, No. 2). The tiled floors of rectangular buildings built of ashlar blocks are visible at −1.7 ± 0.2 m and covered with architectural fragments mixed with rubble stones (Figure 4a,b; Table 1). Amphora fragments that date to 5–7th century C.E., which were cemented in the beach rocks, indicate early Byzantine activity at the site (Bass, 1982; Demesticha, 2005; Karagiorgou, 2001; Opait, 2004). A quay remain was located on the northern coast of Şeytan Island, with an upper surface at −2.4 ± 0.1 m. A large jar fragment, with a diameter of 0.8 m, was found buried in the quay platform (Figure 4c). The current position of submerged remains indicates that the two islands were connected before the rise of relative sea level in Byzantine times (Figure 4d). The parts of coastal structures that date to the Byzantine period are now partly submerged (Hoskyn, 1842; Tietz, 2003; Figure 4e).

Another location in Area A, Tersane Island, lies to the south of the Zeytinli Island (Figure 2, No. 3). Submerged remains in the island's northern bay can be clearly distinguished in aerial photos. The coastal area surrounding the bay is notable due to the presence of a large quantity of partially destroyed architectural remains dating to the Byzantine period (Hicks, 1889; Hoskyn, 1842; Tietz, 2003; Figure 4f). Stones from architectural remains and fine-grained sand cover the seafloor. Walls of a rectangular building are clearly visible in the southeastern part of the bay, at a distance of ~30 m from the shore (Figure 4f). The remains, currently located below sea level, show that ~170 m of coastline transgression has occurred since Byzantine times at this location. Partly buried rectangular construction remains were also observed in the bay. The foundations of the ashlar walls are located at −2.0 ± 0.2 m, which coincides with the depth of the remains at Zeytinli and Şeytan Islands and partly coincides with those at Göcek Island (Table 1). The most submerged section of ashlar blocks of the pavement is located at −2.4 ± 0.1 m.

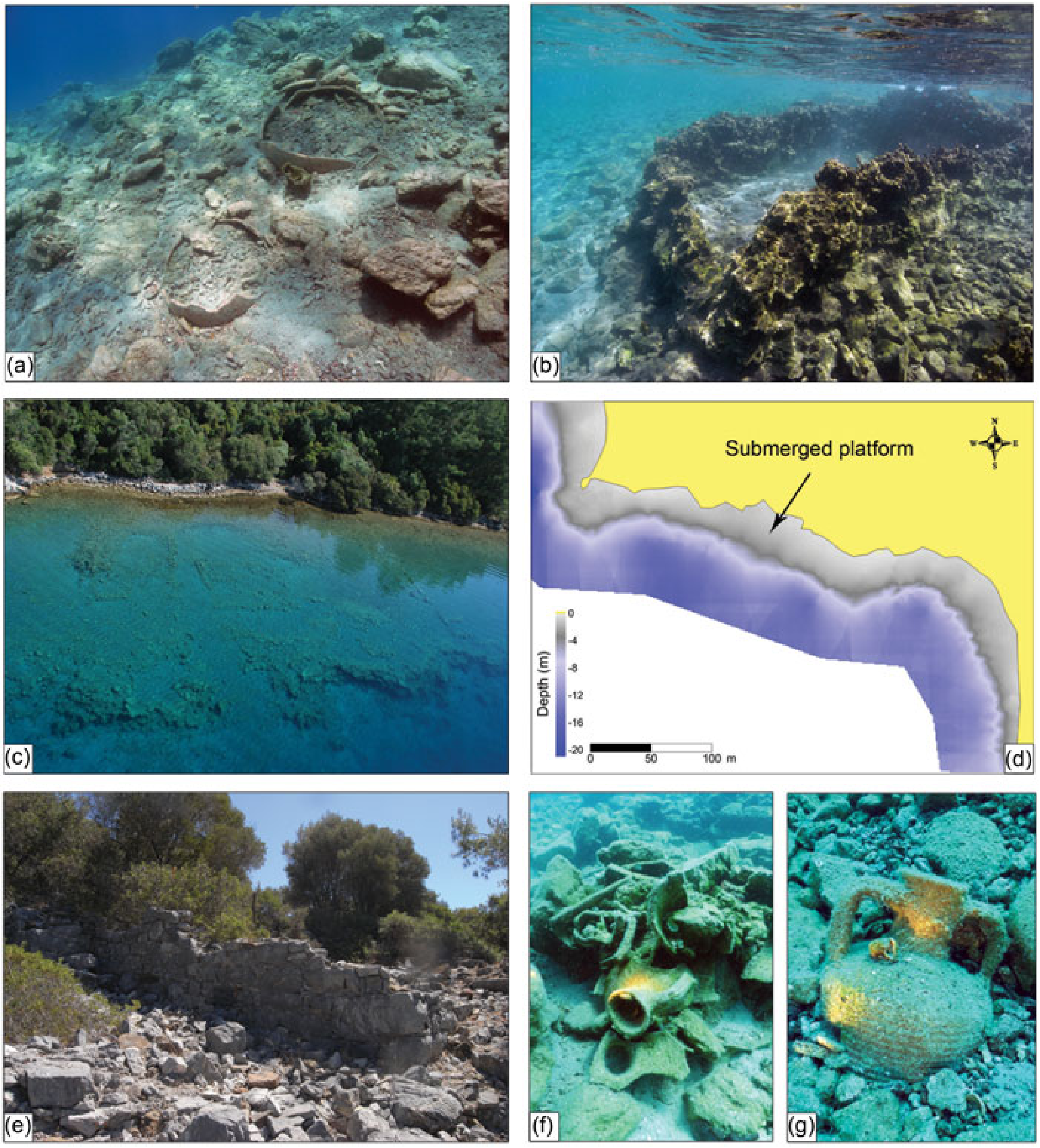

FIGURE 6 The main submerged remains along the western coast of Domuz Island. (a) Buried jar fragments. (b) Rectangular construction. (c) Aerial photo showing foundations of buildings and paleoplatform. (d) Seafloor morphology inferred from echosounder data. (e) Land extensions of the submerged remains. (f, g) LR1 and LR2 pottery remains. Underwater photos by Dr. Özdaş [Color figure can be viewed at wileyonlinelibrary.com]

Taking into consideration the fact that the minimum original elevation at the time of use for the quay would have been 0.6 ± 0.2 m above mean sea level, I suggest an average relative sea level rise of 3.05 ± 0.3 m for Area A (Figure 9 and Table 1).

4.2 | Area B: Northern and western coasts of Domuz Island and Taşkaya Bay

Domuz Island, located ~300 m west of Tersane Island (Figure 2, No. 4), is a significant site that provides precise sea level indicators. The remains of ashlar quays, foundations of rectangular buildings, and buried jars are currently located below sea level along the northern coast of the island. On the nearby shore, partly submerged buildings in a poor state of preservation date to the Byzantine period (Hicks, 1889; Hoskyn, 1842; Figure 5a). At a distance of ~20 m from the shore, five to six rows of rough-cut ashlar blocks of quays are located (Figure 5b). The average depth of the upper surface of blocks is 3.4 ± 0.1 m below the present sea level (Table 1). The seafloor at the base of the quay blocks is located at a depth of 5.9 ± 0.2 m, with two embedded jars found on the quay platform (Figure 5c). The foundations of rectangular buildings lie on the platform at a depth of 2.9 ± 0.2 m (Figure 5d). A large quantity of LR1 and LR2 amphora

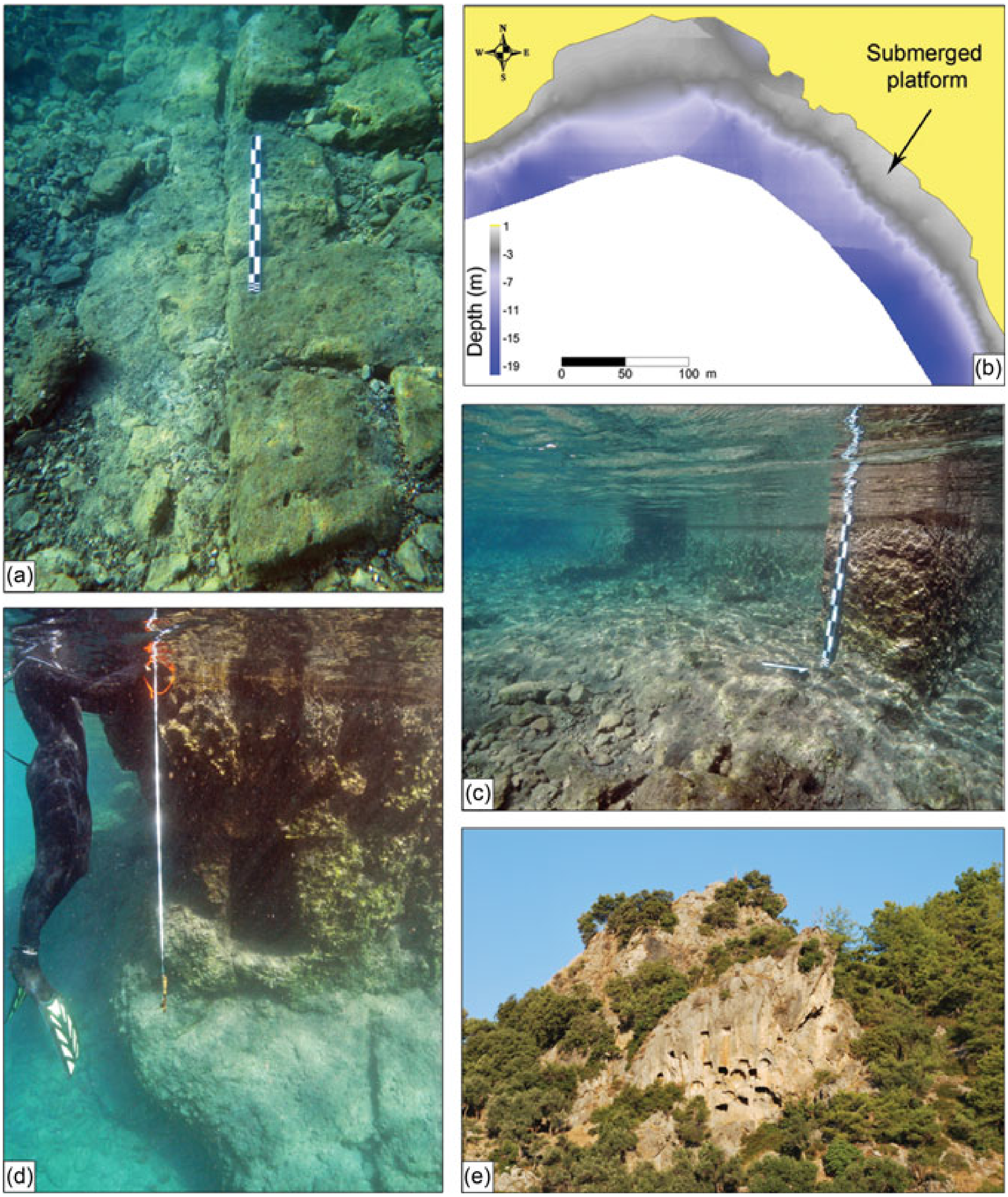

FIGURE 7 The main archaeological remains in Taşkaya Bay. (a) Foundations of constructions. (b) Seafloor morphology inferred from echosounder data. (c) Partly submerged rock-cut building. (d) Submerged rock-cut tomb. (e) Pigeon-hole rock-cut tombs located on hill. Underwater photos by Dr. Özdaş [Color figure can be viewed at wileyonlinelibrary.com]

sherds were found at Domuz Island among the remains dating to the 5–7th centuries C.E. (Bass, 1982; Demesticha, 2005; Karagiorgou, 2001; Opait, 2004). No later ceramics were observed in the area.

Another remarkable indicator is a small, submerged island located at a distance of ~80 m from the shore, which contains the foundations of a rectangular structure (3.6 m × 4.2 m), currently located below sea level (Figure 5e,f). The rough stones of the walls, along with ceramic bricks and tiles with mortar, now lie at −1.6 ± 0.2 m. The remains are likely to be the foundations of a lighthouse.

The echosounder data show that a smooth plain, that is a submerged platform, 15–20-m wide, lies on the coast, followed by a slope (Figure 5g). The seafloor at the base of the slope occurs at depths of 15–20 m. The bathymetric data indicate that marine transgression has increased up to ~20 m in the area since Byzantine times.

The coastal installations of the western coast of Domuz Island consist of the remains of quays, buried jars, buildings, and a pool (?; Figure 2, No. 5). These remains extend ~1 km along the shore in a NW–SE direction. At present, the mean upper level of the quays is

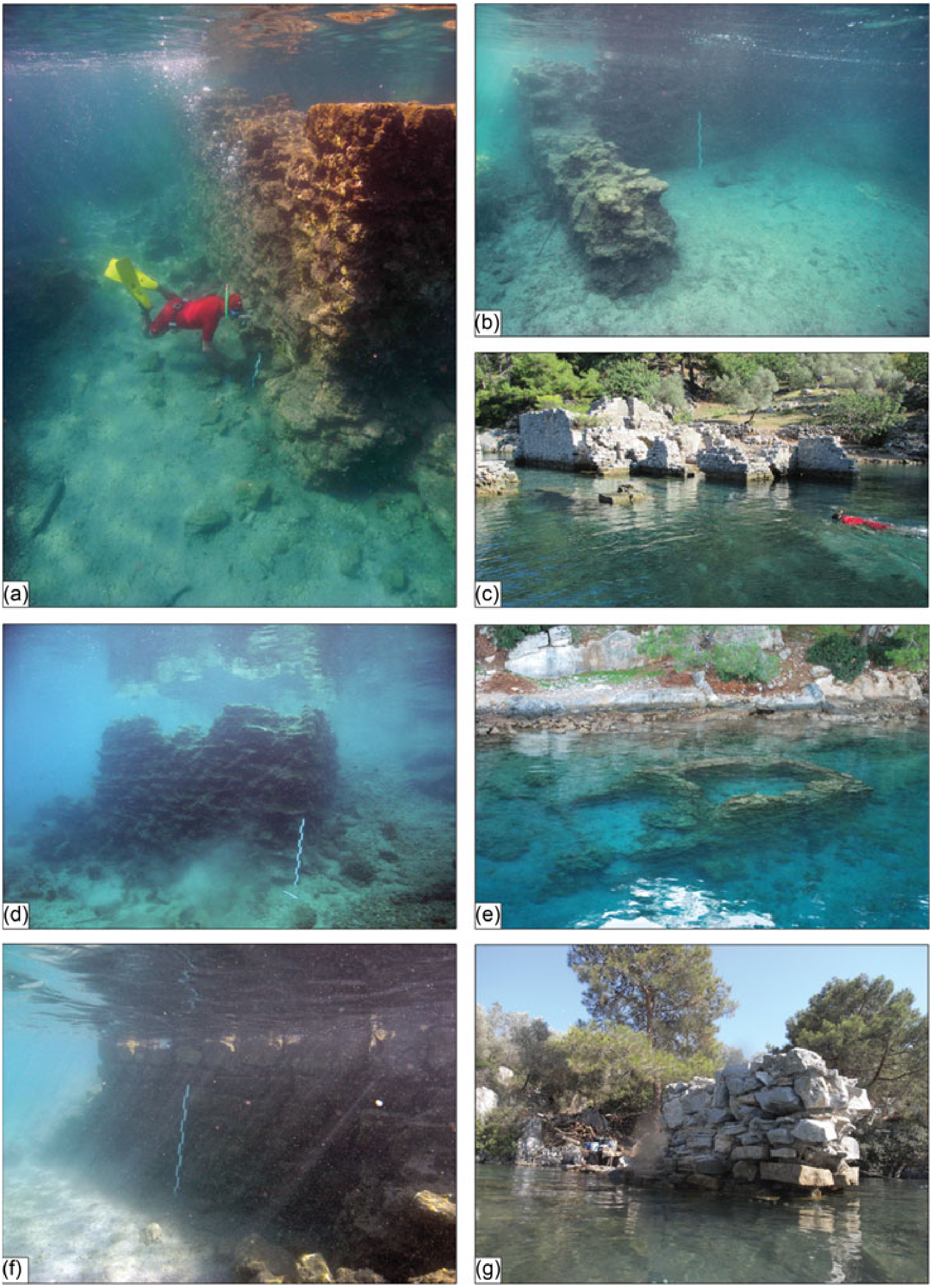

FIGURE 8 Site C at Hamam, Binlik, and Kapıkırı Bays. (a–c) remains of a partially submerged building complex in Hamam Bay. (d,e) Submerged remains of a rectangular construction in Binlik Bay. (f,g) Wall remains of partially submerged buildings in Kapıkırı Bay. Underwater photos by Dr. Özdaş [Color figure can be viewed at wileyonlinelibrary.com]

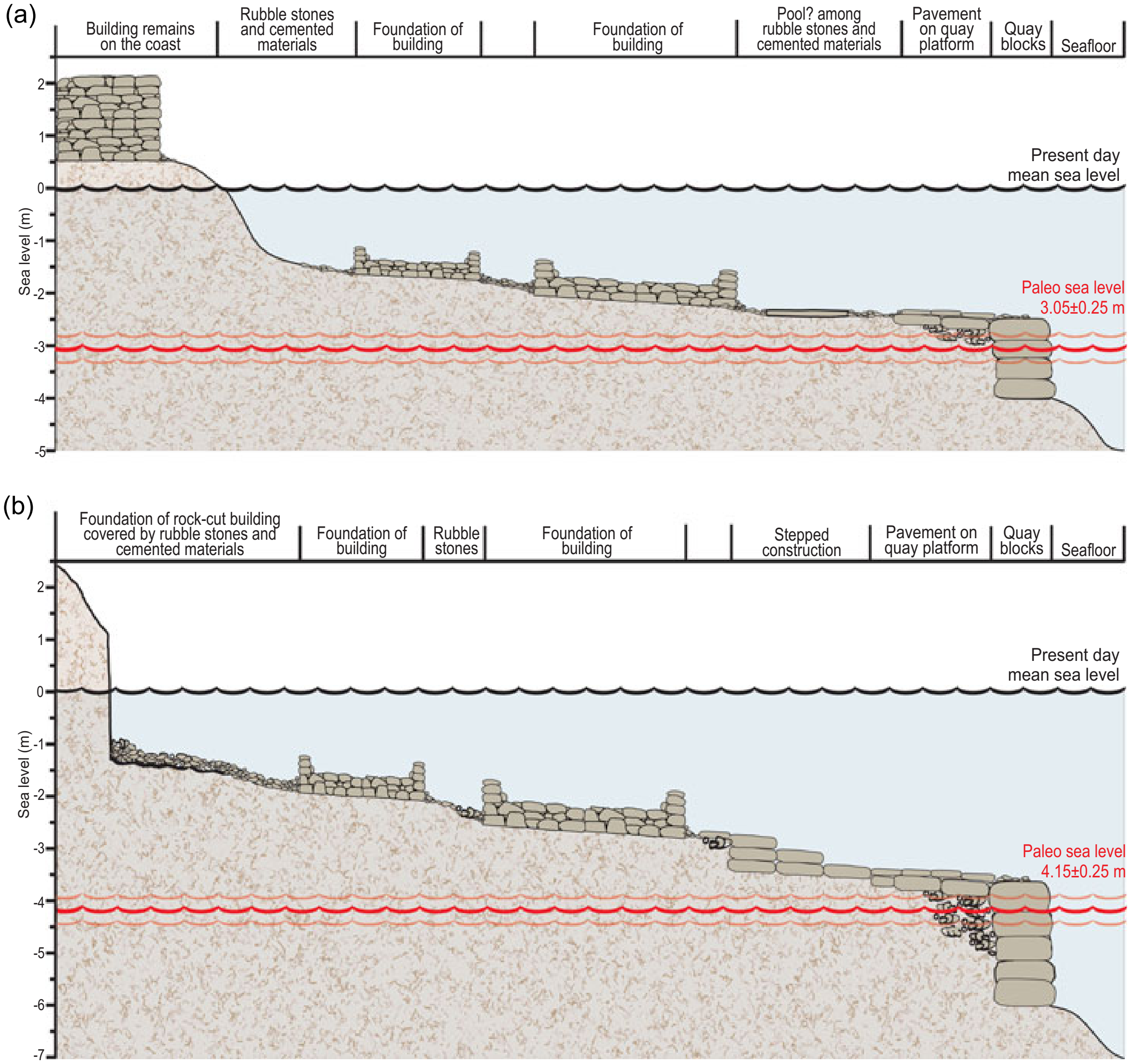

FIGURE 9 Representative cross-sections of submerged remains showing the relative sea-level change, compared with Area A (a) and Area B (b) [Color figure can be viewed at wileyonlinelibrary.com]

located 3.6 ± 0.1 m below sea level, with the remains of seven buried jars on the upper surface (Figure 6a and Table 1). The maximum depth of the seafloor at the base of the quay blocks is 6.6 ± 0.2 m. A rectangular structure located on the small cape might have been used as a storage pool (Figure 6b). Its bottom lies 2.1 ± 0.2 m below the present sea level. Additionally, foundations of 12 rectangular buildings on the platform of the quay are visible, which are covered with archaeological material and rubble stone (Figure 6c). The deepest foundation level was measured at −3.2 ± 0.10 m. The seafloor morphology shows that a submerged platform lies along the coast with a maximum width of ~40 m (Figure 6c,d). The platform is followed by a slope, with a base at a mean depth of 15 m.

The land extensions of submerged remains, dating back to the early Byzantine period, are clearly visible (Hicks, 1889; Hoskyn, 1842; Tietz, 2003; Figure 6e). The seafloor is covered with cemented construction materials, rubble stones, and pottery sherds. A large number of LR1- and LR2-type amphora sherds were observed along the coast, up to −15 m, scattered in front of the submerged quay remains, similar to those observed on the north side of this island (Figure 6f,g). Amphora fragments mixed with roof tiles and ceramic wares verify that the island was occupied until this time.

The other location in Area B is Taşkaya Bay (also known as Bedri Rahmi Bay), which is located on the Kapıdağ Peninsula (Figure 2, No. 6). Submerged remains extend along the shore ~500 m in an E–W direction on the north coast. The remains of quays, rectangular buildings, pavements (?), and stairs are visible, which lie on the submerged platform (Figure 7a,b). A map of seafloor morphology has been obtained by performing an echosounder survey. These data show that the seaward edge of the plain is located at a distance of ~60 m from the present-day shoreline (Figure 7b). In this bay, the upper level of the quay is located at −3.7 ± 0.1 m, and the sea bottom at its base is located at −6.1 ± 0.2 m (Table 1). The ashlar blocks of pavement, partially buried in the sandy bottom, are located 3.3 ± 0.1 m below the present sea level. Partially submerged rock-cut building floors lie at −1.2 ± 0.2 m (Figure 7c), covered by rubble stones, and their foundations reach up to −2.7 ± 0.2 m. A stair structure was observed, with three visible steps at depths of −2.7 ± 0.1, −3.0 ± 0.1, and −3.3 ± 0.1 m, respectively. Additional archaeological evidence was found in the western part of the bay: a sarcophagus, today totally submerged, with a base at 2.1 ± 0.2 m below the present sea level. The most significant feature of the region is a rock-cut tomb that is currently located below present sea level (Figure 7d). At present, its bottom is located at 1.8 ± 0.1 m below sea level. The tomb definitely demonstrates that sea level rise has occurred; however, considering its current situation, precise data about the rate of sea level changes cannot be inferred. The tomb most likely dates to the Hellenistic period (Ross, 1985), based on similar rock-tombs located on the hill (Figure 7e).

Considering the minimum approximate original elevation of the quays, the sea level must have risen by an average of 4.15 ± 0.3 m for Area B, thus demonstrating noticeable differences with Area A (Figure 9 and Table 1).

4.3 | Area C: Hamam, Binlik and Kapıkırı Bays

Area C consists of the Hamam, Binlik, and Kapıkırı Bays, which are located on Kapıdağ Peninsula (Figure 2). The sites were evaluated in the same area, considering both their close proximity and the absence of a precise sea level marker (e.g., a quay). Hamam Bay, also called "Cleopatra's Bath," is a sunken site in the Onikiadalar region well known for its visible, partially submerged building complex (Figure 2, No.7). A walking path, with a length of ~300 m, leads to the western coast of the Peninsula from Hamam Bay. A building complex of rectangular composite structures dating to the Byzantine period is located in the bay (Hoskyn, 1842; Figure 8a–c). The seafloor at the bottom of the walls at the seaward end is located at −3.4 ± 0.2 m (Table 1).

Another relatively well-preserved rectangular structure (3.8 m × 8.0 m) was found underwater in Binlik Bay, located on Kapıdağ Peninsula (Figure 2, No. 8; Figure 8d,e). The seafloor at the base of the structure lies at a depth of 3.4 ± 0.2 m, which coincides with the depth of the remains in Hamam Bay (Table 1). The walls of the structure were built of ashlar stones and mortar. Since the operational function of this structure is not clear, it provides no precise data about the amount of sea level rise. The bottom of the foundations of another rectangular building in this bay lies at a maximum depth of 4.0 ± 0.2 m. Architectural remains on land seem to be contemporary compared to the structures located at the other sites.

Kapıkırı Bay is located on the eastern coast of the Kapıdağ Peninsula, across from Domuz Island (Figure 2, No. 9). The partially submerged remains of a rectangular structure (2.2 m × 2.5 m) built of ashlar blocks and mortar are visible in the bay (Figure 8f, g). The base of the walls is located at −2.6 ± 0.2 m on their seaward end (Table 1).

Since building structures are not reliable indicators, submerged remains can only provide a rough estimation about the relative sea level rise in Area C. However, based on the fact that we did not observe any building foundation deeper than the top of a quay, we can assume that a building would have an original elevation at least as high as the quay. Considering the deepest submersion measurement of 4.0 ± 0.2 m in Binlik Bay, and assuming that the bottom of the building would have been at least 0.6 m above the mean sea level with an error of ± 0.3 m, one may deduce that the relative sea level has risen by at least 4.6 ± 0.5 m in Area C.

5 | DISCUSSION

5.1 | Original elevation and dating approximation

Historical documents indicate that construction activities on the coastal and island settlements of the Fethiye Gulf continued into the 7th century C.E. (Foss, 1996). The region was abandoned after this period, an event probably related to Arab invasions (beginning in 655 C.E.) and/or destructive seismic events (documented between the 4th and 7th centuries C.E.). In addition, archaeological finds suggest that the coastal maritime constructions were in use until the 7th century C.E., maintaining their function. A large quantity of LR1- and LR2-type amphora sherds, dated to the 5–7th century C.E. (Bass, 1982; Demesticha, 2005; Karagiorgou, 2001; Opait, 2004), were observed among the submerged archaeological remains mixed with roof tiles and ceramic wares. The absence of later ceramics suggest that the island was not inhabited after the 7th century C.E. Both the archaeological finds and historical documents regarding abandonment verify that the sites were in use until the early Byzantine period and that submersion occurred in the last 1,400 years.

Since the precise estimation of relative sea-level change is based on the accuracy of both the original elevation and the approximation of dating, a minimum rate of vertical land movement was proposed for the late Holocene based on the minimum original elevation and earliest date of the last operation. Although Area C contains valuable evidence of rising sea levels, there is no reliable archaeological marker to define an accurate original elevation. Nevertheless, noting that the buildings in Area C have more submergence than the quays located at the other sites, and assuming that the buildings are always located above the quay platforms, we used the buildings to obtain estimates by assigning a minimum original elevation and a higher error margin than that used for quays.

Contemporary submerged ancient coastal structures indicate three different paleo-sea levels in the Fethiye Gulf (Figure 10). Taking into account the original elevation and the last time of use for the constructions, the average relative sea level changes were determined to be 3.05 ± 0.3 m for Area A, 4.15 ± 0.3 m for Area B, and 4.60 ± 0.5 m for Area C. Based on the structures' approximate last usage time of 1,400 years ago, we suggest rates of vertical land movement of 2.18 ± 0.3 mm/yr for Area A, 2.96 ± 0.3 mm/yr for Area B, and 3.29 ± 0.5 mm/yr for Area C.

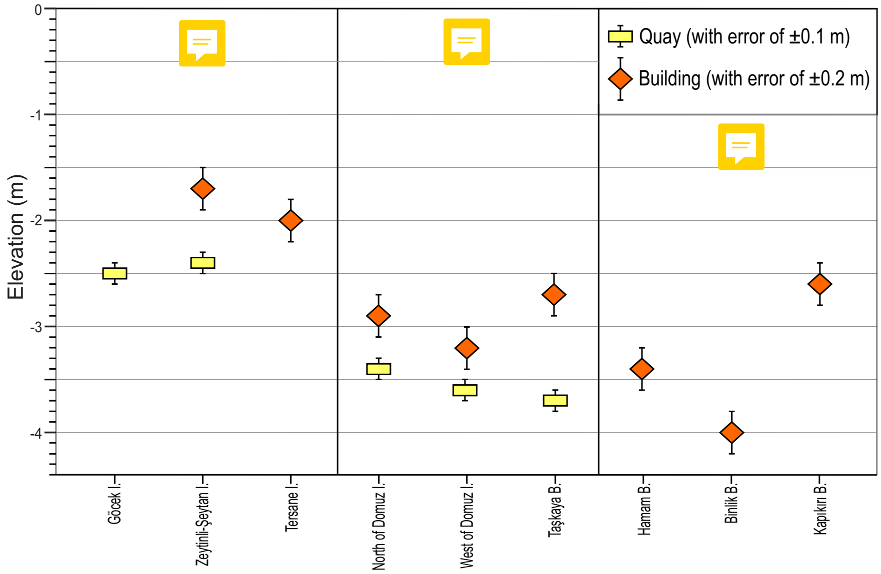

FIGURE 10 Elevations of contemporary archaeological indicators with respect to present mean sea level. Symbols include vertical error for measurement [Color figure can be viewed at wileyonlinelibrary.com]

5.2 | Late Holocene eustatic-isostatic sea level changes and vertical coastal movements

According to the geologically constrained model predictions of Lambeck et al. (2004), the eustatic sea level change that has occurred since the Roman Period is 0.13 ± 0.09 m. Therefore, relative sea level variations are mostly associated with vertical land movements resulting from tectonic movement and glacial isostatic adjustment; thus, the eustatic component has been negligible since the Roman Period (Stocchi & Spada, 2009). Geoarchaeological studies have proposed an eustatic-isostatic sea level change of ~0.5 m during the last 2,000 years along the Mediterranean coast (Evelpidou et al., 2012; Flemming & Webb, 1986). According to the glacio-hydro-isostatic model for Greece developed by Lambeck and Purcell (2005), the predicted sea level was at approximately −0.5 m ~1,400 years ago. Studies performed in tectonically stable regions in the Mediterranean indicate relative sea level rises of 0.4 ± 0.1 m at Frécus and ~0.7 m at Corsica since Roman times (Morhange et al., 2013; Vacchi, Ghilardi, Spada, Currás, & Robresco, 2017). The very recent glacio-isostatic adjustment model of Roy and Peltier (2018) indicated that relative sea level change has been less than 0.5 m for the last 2,000 years along the Italian coasts.

Even though local eustatic-isostatic changes are not clear for the southwestern Turkish coastline, sea level studies carried out in the Mediterranean indicate a relative sea level rise of ~0.5 m since Roman times, mostly due to glacio-isostatic adjustment. The rise of relative sea level was likely less over the last 1,400 years. Assuming a maximum sum of the eustatic–isostatic factor of 0.5 m and reducing this component from vertical land movement, average rates of tectonic subsidence of 1.82 ± 0.3 mm/yr for Area A, 2.61 ± 0.3 mm/yr for Area B, and 2.93 ± 0.5 mm/yr for Area C were calculated. This calculation was inferred based on the time of the structures' last use (Özdaş & Kızıldağ, 2013), instead of the construction time that was taken into account in previous studies (Antonioli et al., 2007; Anzidei et al., 2011; Mastronuzzi et al., 2017). Anzidei et al. (2011) suggested a rate of tectonic subsidence of 1.48 ± 0.3 mm/yr for the entire Fethiye coastline, assuming that the ages of its constructions correspond to 1.95 ± 0.18 ka and 1.6 ± 0.10 ka. In this paper, a more precise period for submersion is proposed, as the approximate time of the structures' last use reduces the period while increasing the amount of tectonic subsidence. Thus, the results presented here noticeably differ from the results suggested by earlier authors.

Results from the current investigation demonstrate that vertical displacement is mostly due to local and regional active tectonics, which control the coastal evolution of Fethiye. The variation in the rates of vertical movement at the sites is most likely associated with local normal faults in the gulf. However, taking the entire gulf into consideration, such large-scale tectonic subsidence rates must indicate regional tectonism, rather than local seismic events. Although such great vertical land movements are also seen in the Kekova region, on the southern coast of Turkey (Özdaş & Kızıldağ, 2013), the Fethiye coastline is the most submerged region in Turkey. At least one tectonic event, related to the Hellenic Arc, must have occurred and been responsible for the submergence of the coastal sites in the study area.

6 | CONCLUSIONS

Submerged archaeological remains in Fethiye Gulf in southwest Turkey were investigated to estimate the relative sea level changes during the late Holocene. This study considered current elevations and assumed the original elevations of archaeological remains, as well as the eustatic–isostatic sea level change and the last episodes of human occupation. In contrast to previous studies, new data are provided for the rates of vertical land movement of 2.18 ± 0.3 mm/yr for Area A, 2.96 ± 0.3 mm/yr for Area B, and 3.29 ± 0.5 mm/yr for Area C since the early Byzantine period. This demonstrates that vertical coastal movement increases from north to south, in other words, from the coast to the deeper part of the Mediterranean, most likely related to local normal faults.

Numerous active faults located in the gulf have the potential to produce serious earthquakes that could cause further significant subsidence. Recent earthquake activity in 2012 is evidence of the area's ongoing tectonism. Relative sea level rise along the coast of the Fethiye Gulf is consistent with a large-scale vertical tectonic movement associated with the eastern part of the Hellenic Arc and the Pliny and Strabo Trenches. These results can shed light on future studies about coastal evolution in the Fethiye Gulf and surroundings.

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