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Holocene Relative Sea-Level Changes Along the Southern Coast of Bodrum Peninsula, SW Anatolia

Bodrum Yarımadası güney kıyılarında Holosen rölatif deniz seviyesi değişimleri, GB Anadolu

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Öz

Anadolu levhasının batısında, genişlemeli tektonik rejimin etkisi altında gelişmiş olan Bodrum Yarımadası, Holosen rölatif deniz seviyesi değişimlerini yansıtan göstergelerin güncel deniz seviyesinin üzerinde görüldüğü alanlardan biridir. Bu göstergeler yarımada boyunca farklı tiplerde karşımıza çıkmaktadır. Bu çalışmada, Bodrum Yarımadası'nın güney kıyısındaki 6 lokasyonda deniz seviyesinden +2,6 m'ye kadar yükselmiş kıyı çizgileri incelenmiştir. Çalışma alanında, iki farklı lokasyonda tarihleme için uygun gösterge bulunmuş ve iki rölatif yükselmiş deniz seviyesi göstrgesi mollusk kavkıları kullanılarak, radyokarbon yöntemiyle tarihlendirilmiştir. Bu göstergelerden biri Gerenkuyu'da saptanmış ve 2678,5±79,5 yıl öncesine tarihlendirilmiş olan +1,3 m yüksekliğindeki plaj deposudur. Diğer gösterge ise Gerindere'de +1,2 m yüksekliğindeki gelgit çentiği ile uyumlu olduğu düşünülen ve 2241±88 yıl öncesine tarihlenen bir plaj deposudur. Gelgit çentiğinin güvenilir bir kıyı çizgisi göstergesi olması nedeniyle Gerindere'deki bu göstergenin yaklaşık son 2241±88 yıl için yükselme hızı 0,53 mm/yıl olarak hesaplanmıştır.

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Abstract

Bodrum Peninsula, which developed under the influence of the extensional tectonic regime in the west of the Anatolian plate, is one of the areas where indicators reflecting relative sea-level changes are seen above the present sea level. These indicators appear in different types throughout the peninsula. This study examined shorelines from sea level to +2.6 m at 6 locations on the southern coast of the Bodrum Peninsula. Suitable indicators for dating were found at two different locations in the study area, and two relative sea-level indicators using mollusk shells were dated by radiocarbon method. One of the indicators is a +1.3 m high beach deposit at Gerenkuyu and was dated to 2678.5±79.5 yr BP. The other indicator is a +1.2 m high beach deposit at Gerindere, which is thought to be compatible with the tidal notch and dated to 2241±88 yr BP. Based on the age data and the reliability of tidal notches as a shoreline indicator, the uplift rate of this indicator in Gerindere for the last 2241±88 years has been calculated to be 0.53 mm/yr.

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1. Introduction

Following the post-glacial warming at the onset of the Holocene, the sea level reached its present position at ca. 6 ka BP (Pirazzoli, 2007). Throughout the Holocene, the sea level was never higher than today (Lambeck and Purcell, 2005); hence, any shoreline above the present sea level indicates coastal uplift. Therefore, uplifted shorelines can be used as good indicators of the relative sea-level rise and the vertical tectonic movements affecting the coast (e.g., Antonioli et al., 2006a-b; Anzidei et al., 2014; Ferranti et al., 2007; Gordillo, 1992; Kolaiti and Mourtzas, 2016; Lambeck et al., 2004; Liberatore et al., 2021; Liew et al., 1993; Morhange et al., 2006; Mourtzas et al., 2016; Pirazzoli et al., 1994; Stiros et al., 2000; Stiros et al., 2022; Surić et al., 2014).

Uplifted or submerged Holocene shorelines along the coasts of the Anatolian Peninsula, located in the north of the subduction zone between the African and Eurasian plates (Anzidei et al., 2011; Desruelles et al., 2009; Doğan et al., 2012; Erol, 1963; Kelletat and Kayan, 1983; Pirazzoli et al., 1991) constitute an important record of active tectonics. According to previous studies on the Mediterranean coast of Anatolia (Figure 1A) (e.g. Anzidei et al., 2011; Çiner et al., 2009; Desruelles et al., 2009; Doğan et al., 2012; Erol, 1963; Kelletat and Kayan, 1983; Kızıldağ, 2019; Pavlopoulos et al., 2012; Pirazzoli et al., 1991), it has been observed that the section between Hatay and the west of Antalya rises (Doğan et al., 2012; Erol, 1963; Pirazzoli et al., 1991). However, some areas of the west of Antalya descend (Anzidei et al., 2011; Pavlopoulos et al., 2012) while others rise (Çiner et al., 2009; Dalongeville-Sanlaville, 1979). Studies have shown that; on the coast of Hatay-Samandağ uplifted shoreline at +2-3 m, reflecting a relative sea level stability during the Late Holocene, was dated to between 5170 ± 190 and 2590 ± 100 yr BP (Erol, 1963; Morhange et al., 2006; Pirazzoli et al., 1991). Platforms rising to +1.3 m were found in Alanya, and it was determined that this uplift was caused by tectonic movements that occurred 1550 yr BP (Kelletat and Kayan, 1983). Platforms in İncekum (Antalya) have been uplifted between +0.5 m and +1.2 m in the period between 1815 BP and 1545 yr BP (Çiner et al., 2009). On the coasts of Finike, Andriake, and Kekova, some sites descended to -4 m below the present sea level (Anzidei et al., 2011; Özdaş and Kızıldağ, 2013). A subsidence at an average rate of 1.48 mm/yr took place during the last 2.3 ka between Kekova and Knidos (the west of Datça Peninsula) (Anzidei et al., 2011). In addition, beachrocks were found -2.2 m below the sea level between Finike-Antalya-Çimtur (Çiner et al., 2009).

In this study, we present uplifted Holocene shorelines on the Bodrum Peninsula, which is located on the western coast of Anatolia (Figure 1B). The Bodrum Peninsula is bounded by Güllük Bay on the north, Aegean Sea on the west and Gökova Bay on the south. The Gökova Bay is an approximately E-W trending marine depression located south of the Bodrum Peninsula (Alcik and Tanırcan, 2018; Tur et al., 2015; Yıldırım et al., 2022). The extensional tectonics around Bodrum Peninsula are controlled by normal faults seismically active (Koçyiğit and Doğan, 2017; Yıldırım et al., 2022) and can produce large magnitude earthquakes.

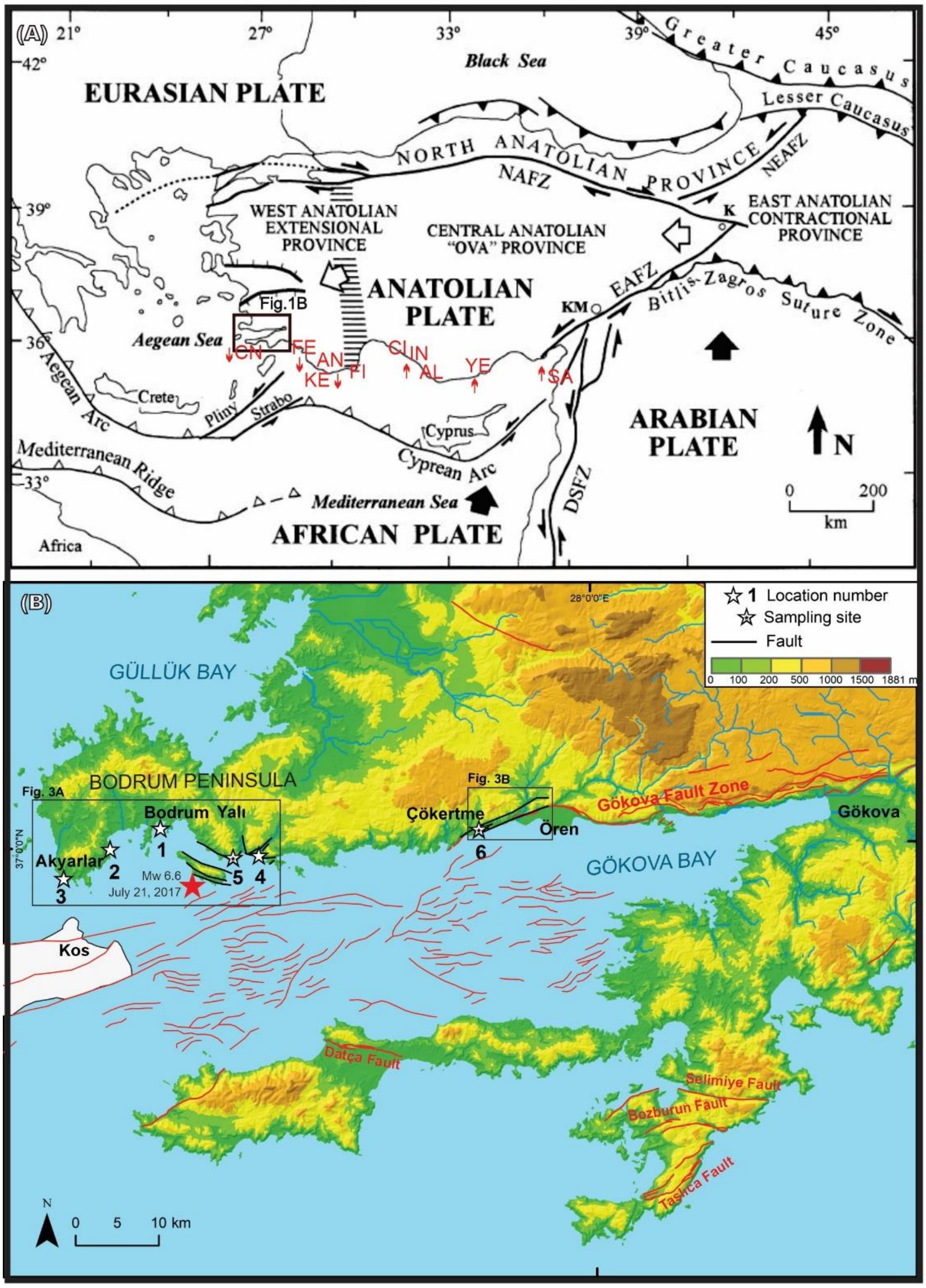

Figure 1. A) Tectonic outline of the eastern Mediterranean area (from Bozkurt, 2001; K–Karlıova, KM–Kahramanmaras¸ DSFZ–Dead Sea Fault Zone, EAFZ–East Anatolian Fault Zone, NAFZ–North Anatolian Fault Zone, NEAFZ–Northeast Anatolian Fault Zone) and previous studies on the Mediterranean coast of Anatolia (CN-Cnidos, FE-Fethiye, KE-Kekova, AN-Andriake, FI-Finike, CI-Çimtur, IN-İncekum, AL-Alanya, YE- Yeşilovacık, SA-Samandağ; Up red arrows show uplift, and down show subside), **B)** Location map of the study area (Offshore faults The faults located in the sea were taken from Tiryakioğlu et al. (2018). The Gökova fault zone and other active faults (shown in red) were taken from Emre et al. (2018). The other faults in the study area are based on Emre et al. (2013) and Koçyiğit (2017). The red star indicates the epicentre of the 21 July 2017 Bodrum/Kos earthquake (Tiryakioğlu et al., 2018).

The 6.6 Mw earthquake that hit south of Bodrum at a focal depth of 5 km on July 21, 2017, also caused a small tsunami (Yalçıner et al., 2017). The extensional tectonics around Bodrum Peninsula are controlled by normal faults seismically active (Koçyiğit and Doğan, 2017; Yıldırım et al., 2022) and can produce large magnitude earthquakes. The last destructive earthquake in Gökova Bay occured on July 21, 2017, at 01:31 local time, at a depth of 5 km, with a moment magnitude of Mw=6.6, at a depth of 6-10 km (Sözbilir et al., 2017). The earthquake's epicentre was 12 km E-NE of the Greek island of Kos and 8 km S-SW of Bodrum town (Yalçıner et al., 2017). The fault systems closest to the earthquake epicenter are known by their south-dipping normal fault character; the Gökova Fault Zone (GFZ) and the north-dipping Datça Fault (Figure 1B) (Kadirioğlu et al., 2017). It is estimated that a rupture zone that developed almost parallel to the Aegean coast may be active again to eliminate the tension difference in the region, which was shaken by the earthquakes caused by the normal faults in an approximately E-W direction (Sözbilir et al., 2017). This earthquake caused heavy damage along Kos Island (Greece), with tsunami waves reaching 1.9 m and liquefaction along the Bodrum coast (Yalciner et al., 2017).

After the July 21, 2017 earthquake, numerous researchers conducted field observations determining the faults that triggered the earthquake and assessing its effects on the coast and settlements (Kadirioğlu et al., 2017; Kalafat, 2017; Koçyiğit and Doğan, 2017; Sözbilir et al., 2017; Utku, 2017; Yalçıner et al., 2017; Yıldırım et al., 2017). Some of these studies concluded that the new active faults triggered by earthquake (Koçyiğit and Doğan, 2017) and vertical movement on the Bodrum Peninsula (Ocakoğlu et al., 2018; Yıldırım et al., 2017, 2022). Other researchers carried out studies presenting findings or models related to the tsunami (Dimova and Raykova, 2018) and the aftershocks (Alcık, 2018; Öztürk and Şahin, 2019). Only Yıldırım et al. (2022) mentioned the coseismically uplifted shorelines on the coasts of Gökova Bay related to the July 21, 2017, Bodrum/Kos earthquake. The authors focused on the geomorphological markers of modern and paleoseismic deformations. The current tidal notches rose to +0.3 m and mentioned at least five large-magnitude (M>6) offshore earthquakes that uplifted the shoreline to +1.5 m in the town of Ören, east of Bodrum.

In this study, relative sea-level indicators in the Bodrum peninsula were investigated and evidences of the Holocene coastal uplift of the area were sought. This study investigated elevated tidal notches, abrasion platforms, litophaga holes and beach deposits on the coast of the Bodrum Peninsula. The study compared the results with a similar previous study and compiled the uplifted shorelines of the region. To conclude, the study aims to showcase the significance of the Bodrum peninsula in regard to coastal tectonics. It presents concrete evidence of sea-level changes and sets a foundation for future studies in the area.

2. Regional Geology

The study area is located in the Aegean extensional tectonic regime region in the west of the Anatolian plate (Şengör and Yazıcı, 2020). In the study area (Figure 2), mainly Jurassic-Cretaceous-aged and Triassic-aged limestones are evident throughout the area, especially from the coastal zone where the city of Bodrum is spread to Ören (Figure 2). The western part of the peninsula is characterized by Middle-Upper Miocene volcanic rocks. The Quaternary alluvial deposits constitute the youngest cover deposited under the control of the current extensional neotectonic regime (Ercan et al., 1982). The faults formed as a result of the extensional tectonics are important in terms of the seismicity of the region, and the GFZ (Gökova Fault Zone) is the most critical factor controlling the active tectonics (Gürer and Yılmaz, 2002; Hançer and Tekin, 2017; Tur et al., 2015; Yıldırım et al., 2022). The fault zone is 120 km long (Sözbilir et al., 2017) and is characterized by numerous normal fault segments. The Ören Basin is the area with the most apparent onshore evidence of the GFZ, (Gürer and Yılmaz, 2002; Sözbilir et al., 2018), and the Ören fault in this region plays an active role in the forming of the coast (Yıldırım et al., 2022).

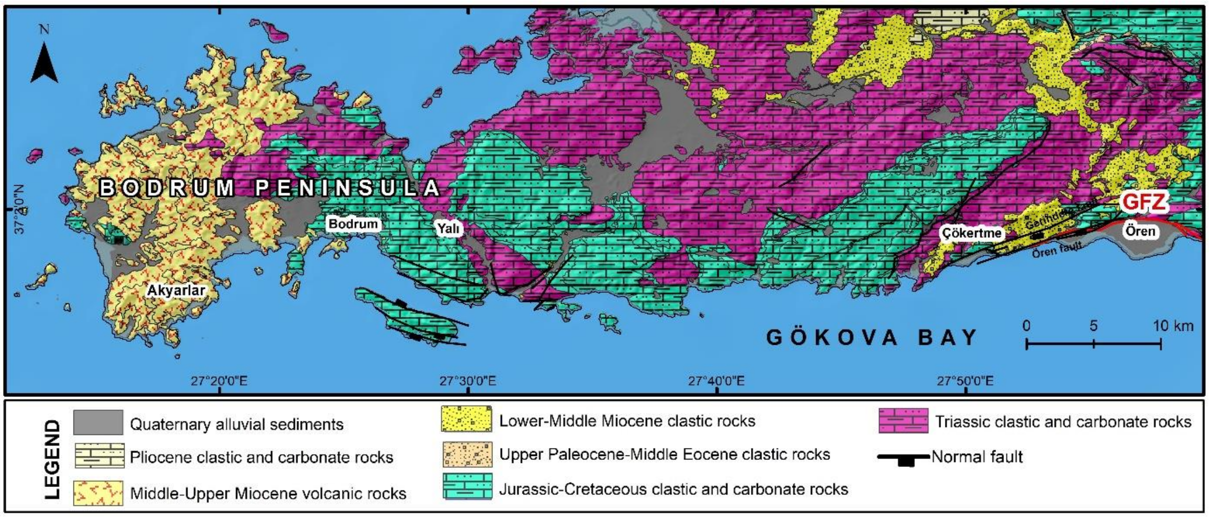

Figure 2. Geological map of Bodrum Peninsula and adjacent areas (Adapted to 1:500.000 scale geological map (Şenel, 2002) and the faults based on Emre et al., 2013; 2018 and Koçyiğit, 2017).

3. Materials and Methods

The depositional, erosional/chemical and biological sea-level markers were considered when determining the shoreline position (Doğan et al., 2012; Ferranti et al., 2006). Tidal notches are among the most essential bioerosional markers that usually cut limestone cliffs in the mid-littoral zone and accurately indicate sea level (Evelpidou and Pirazzoli, 2015). In general, tidal notches are indirectly dated by being associated with nearby deposits of known age (Cerrone et al., 2021). Accordingly, if the time dimension is to be considered in studies, it is also necessary to correlate sedimentological data with notches (Doğan and Özer, 2011). Another indicator considered after the tidal notches in the study area was the lithophaga hole bands. The Pelecypod lithophaga lithophaga colonizes the calcareous rocky coasts in the first 20 m below sea level, but statistically, it is common in the first 2 m below mean sea level. As a reliable indicator of past mean sea level position, a semi-horizontal line is defined at the upper border of the lithophaga holes, and the margin of error on this mark is +2 m (Ferranti et al., 2006).

Mollusk shells that we collected from the uplifted coastal deposits were sent to TÜBİTAK MAM 14 Carbon Analysis laboratories. The local reservoir correction (DeltaR) was applied to the radiocarbon results of mollusk shells using OxCal online calibration software (https://c14.arch.ox.ac.uk/oxcal.html), and calibrations were made according to the Marine 13 curve (Reimer et al., 2013). In a previous study, calibration was made according to the Marine 13 database using the DeltaR 151 ± 40 yr value applied to a sample dated by the 14 C method (Siani et al., 2000) on the Çanakkale Strait (Dardanelles).

4. Results

4.1. Holocene Relative Sea-Level Indicators on the Bodrum Peninsula Coast

We detected various Holocene sea-level indicators at +2.60 m asl (above sea-level) at six locations on the coast of the Bodrum Peninsula (Figure 1). These indicators consist of uplifted beach deposits, notches, platforms, and lithophaga holes (Table 1). While no material could be found to determine the age of the platforms and notches developed on the Miocene volcanic rocks on the west and south coast of Bodrum city, ages were obtained from the elevated beach deposits in the east of the town. The first location is in the south of Bodrum, on the İnce Promontory east of Gümbet Bay (Figure 3). Notches and abrasion platforms developed on the Middle-Upper Miocene-Pliocene volcanic rocks were identified here. We observed wave abrasion notches on the bedrock at +1.8 and +2.6 m asl and wave abrasion platforms at +0.6 and +1.6 m asl (Figure 5).

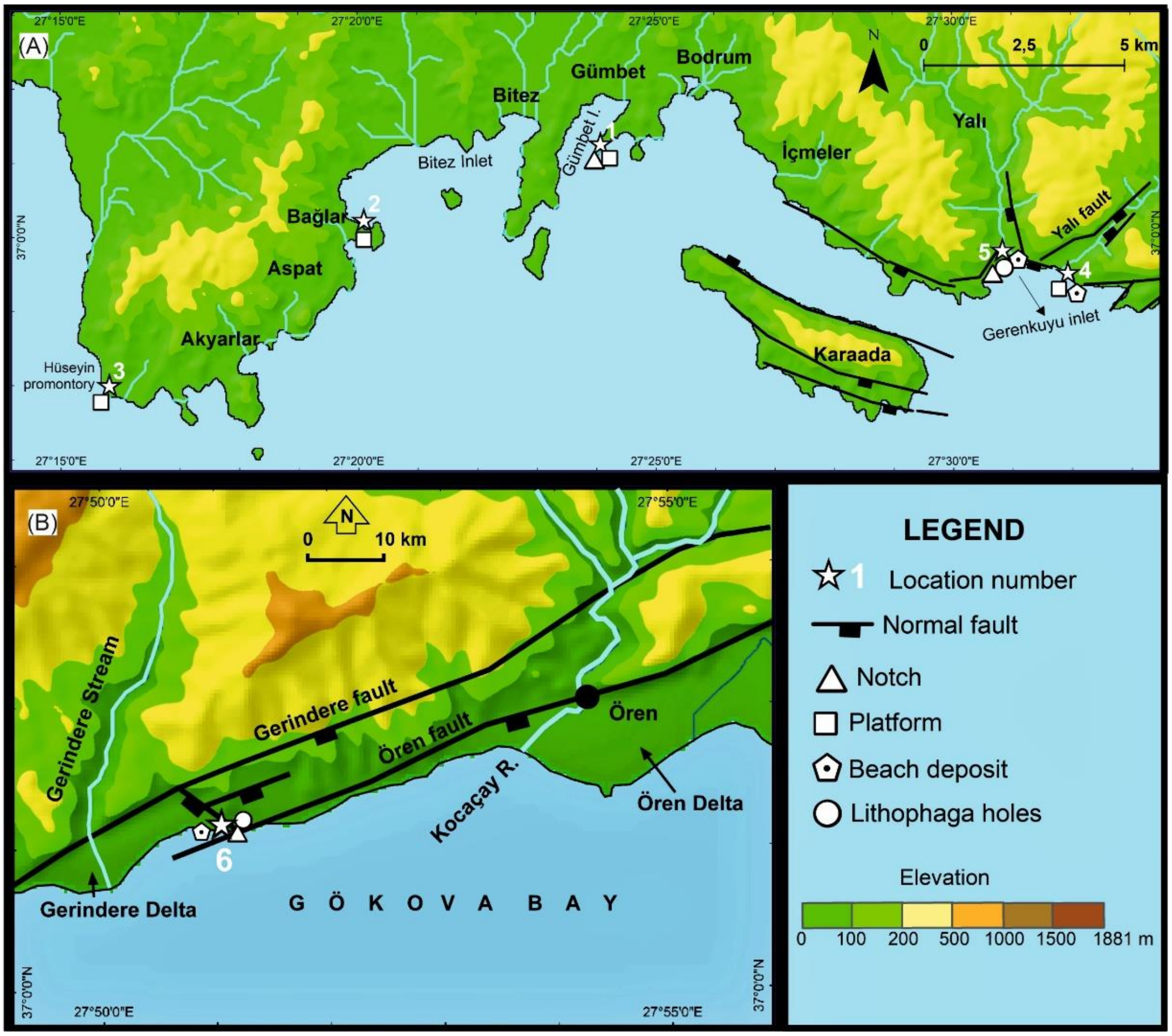

Figure 3. Raised Holocene shoreline markers and normal faults in the study area. (The important faults in the study area are based on Emre et al., 2013; 2018 and Koçyiğit, 2017).

Table 1. Raised Holocene shoreline markers on the Bodrum coast.

Loc. number	Coordinates	Study area	Indicator	Elevation (m)
1	37°1'7.14"N-27°24'0.83"E	İnce Promontory	Notch	1.8, 2.6
			Platform	0.6, 1.6
2	37°0'6.68"N-27°20'5.05"E	Bağlar Promontory	Notch	0.9
			Platform	0.5, 1.6
3	36°57'53.41"N-27°15'50.50"E	Hüseyin Promontory Lighthouse	Platform	0.5
			Sand dune	7
4	36°59'29"N-27°31'55"E	Shipyard	Platform	0.5
5	36°59'37.52"N-27°30'48.04"E	Gerenkuyu Beach	Notch	0.5
			Lithophaga hole band	0.5
			Beach deposit	2
6	37°1'8.67"N-27°50'57.24"E	Gerindere Beach	Notch	0.5, 1.2
			Lithophaga hole band	2.2
			Beach deposit	0.5, 1.2

A notch +0.9 m asl was detected on a volcanic block on an uplifted wave-cut platform at Location 2, 6 km west of Location 1 (Figure 3A, Figure 4). In this location, another platform with an inner edge with a height of +1.6 m asl is present (Figure 3A, Figure 5). These relative sea-level markers also developed on the Miocene volcanic rocks.

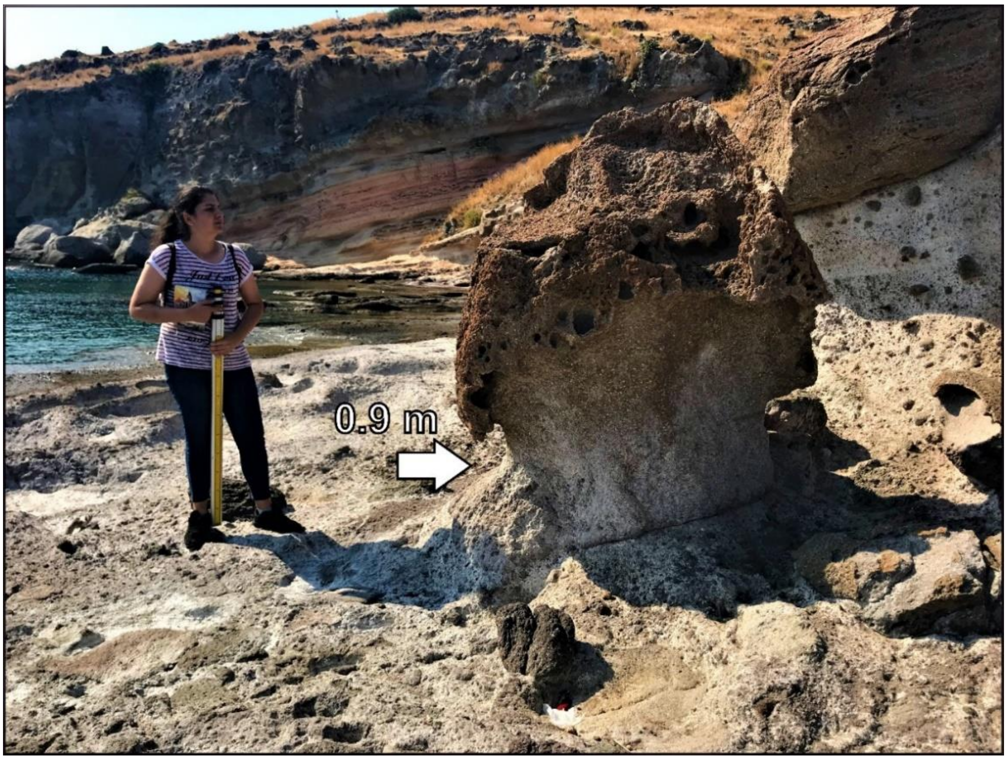

Figure 4. +0.9 m asl high notch preserved on the volcanic block on the wave-cut platform in Location 2.

Figure 5. The wave-cut platforms were observed in A, B, C) Location 1, and D) Location 2.

Location 3 is situated around Hüseyin Promontory Lighthouse in the southwest of the Bodrum Peninsula. As in Location 2, this location is mainly composed of Middle-Upper Miocene volcanic rocks and has a gently sloping coast forming the westernmost part of the study area. Although a climbing backshore dune was identified at ~7 m asl on the cliff, the dune could not be dated due to human interference. In the same location, there is an abrasion platform at +0.5 m asl on the Miocene agglomerates.

Location 4 is in the east of Bodrum city, ~1.7 km southeast of İçmeler, in a place where it is difficult to reach the coast from land (Figure 3A). In this location, a beachrock formation and a raised beach deposit were observed (Figure 6). No material suitable for dating could be found in the beach deposit, which upper level is at +1.8 m asl and consists of gravels. This beach deposit is incised by a stream, providing evidence of coastal uplift. The upper level of the beachrocks located at the intersection of the beach deposit with the sea is at the present sea level. (Figure 3A, Figure 6).

Figure 6. A) Beachrocks at present sea level, and B) raised pebbly beach deposit incised by a stream in Location 4.

Location 5 is found on the shore of the fan-delta deposit in Gerenkuyu Inlet at the western end of Gökova Bay (Figure 3A, Figure 7A). The fan-delta formed by the Gerenkuyu stream and the inlet is located in a sub-graben bounded by normal faults from the east and west. The sub-graben orientated obliquely to the general E-W trend of the major Gökova Bay graben, developed under the control of NW trending normal faults. An uplifted beach deposit and an uplifted tidal notch on the western edge of the inlet were identified at this location. The upper level of the beach deposit consists of gravel. It is +2 m above the present sea level, located on the fan-delta front.

We collected mollusk shell samples from medium-sized and coarse gravels of the beach deposits at +1.3 m asl and +1.8 m asl (Figure 7). We also found a tidal notch at +0.5 m asl on the western edge of the same beach deposit. The tidal notch was well preserved on the limestone with several lithophaga holes (Figure 7). No material for dating could be found on the tidal notch, and the berm deposit consisted of beach gravels and extended in association with this tidal notch.

Figure 7. A) Raised fan-delta beach deposit and sampling sites in Location 5. B) Close-up view of +0.5 m asl tidal notch and lithophaga holes.

Location 6 is ~40 km east of Bodrum town and on the northern coast of Gökova Bay. This location is to the east of the uplifted fan-delta that has back tilted towards the Gerindere Fault in its north (Figure 3B). At the eastern border of the Gerindere fan-delta, there are uplifted tidal notches, lithophaga hole band, and beach deposits on the Jurassic-Cretaceous limestones. There are two tidal notches here at +0.5 and +1.2 m asl (Figure 8). Another indicator is the lithophaga hole band that reaches up to +2.2 m above the upper tidal notch.

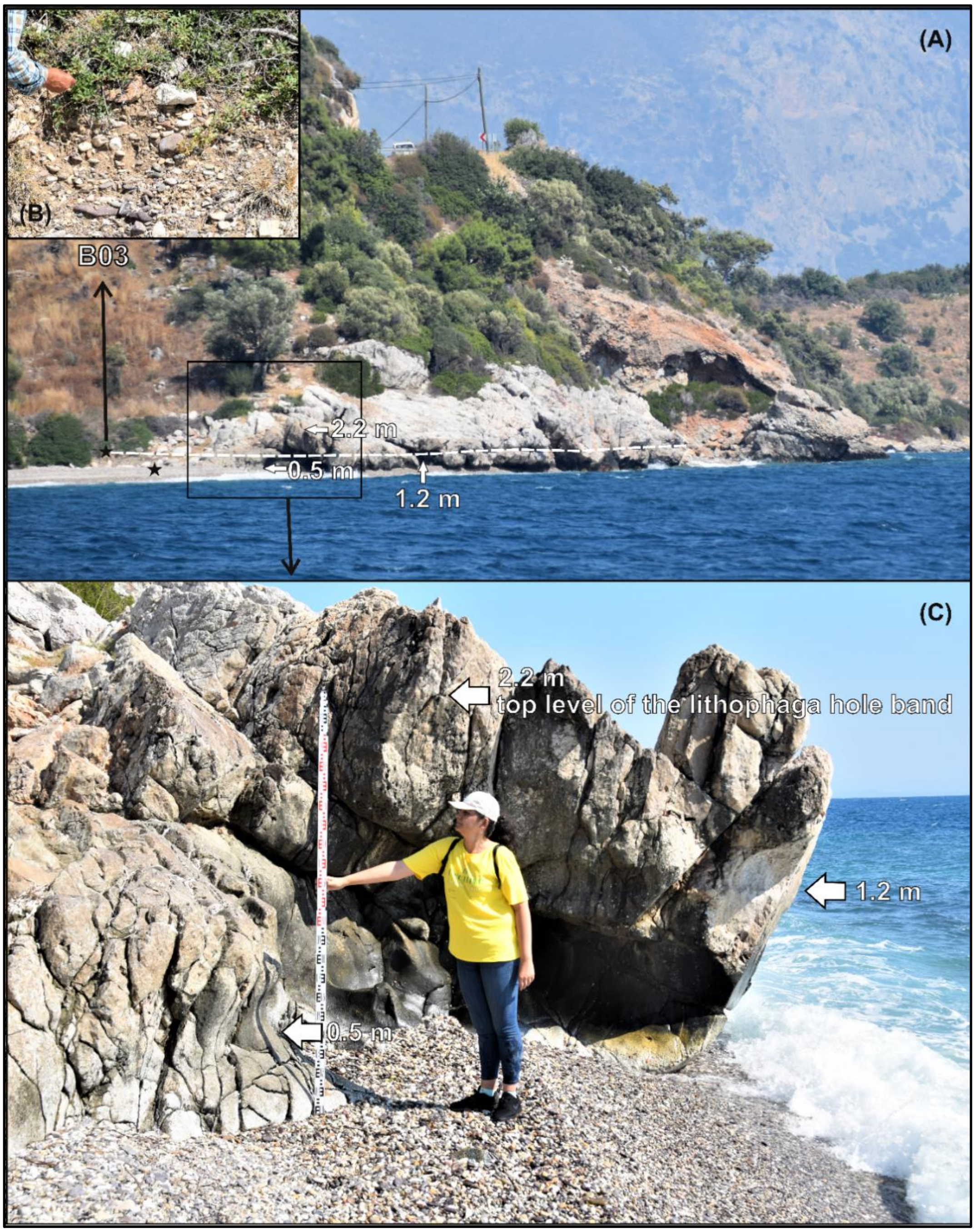

Figure 8. A) General view of Location 6. B) Beach deposit associated with 1.2 m notch. C) Uplifted lithophaga hole band.

4.2. Dating Results

Four shell samples were collected between +0.5 and +2 m asl from two locations in the coastal zone of Bodrum Peninsula for radiocarbon dating (Table 2). The Marine 13 calibrated ages of samples B01 (+1.3 m asl) and B02 (+1.8 m asl) were determined as 2678.5 ± 79.5 yr BP and 836 ± 74 yr BP, respectively. As sample B02 is much younger than B01, we consider it an outlier and exclude it from further consideration. The age of the sample B03 (+1.2 m asl) taken from Gerindere Beach was 2241 ± 88 yr BP. Sample B04, taken from a current winter berm deposit of +0.5 m asl on Gerindere Beach, yielded a Marine 13 calibrated age of 36.5 yr, indicating another outlier.

Table 2. Radiocarbon results for fossil mollusk shells.

Location number	Lab. Code	14C (BP)	Delta R (cal BP)	Marine 13 (cal BP)
5	B01 TÜBİTAK-0877	2908 ± 30	2501 ± 161	2678.5 ± 79.5
5	B02 TÜBİTAK-0878	1292 ± 25	703.5 ± 88.5	836 ± 74
6	B03 TÜBİTAK-0879	2580 ± 29	2083.5 ± 156.5	2241 ± 88
6	B04 TÜBİTAK-0880	1.0746 ± 0.0031	151	36.5

5. Discussion

Bodrum Peninsula, located in an extensional tectonic realm, contains normal faults on both land and seabed. These active and prominent fault segments shape the steeply sloped northern margin of Gökova Bay. Due to vertical movement along these faults, the Holocene sea-level indicators have risen to their present positions along the coast. Our study on the Bodrum coast determined geomorphological and biological relative Holocene sea-level markers as high as +2.6 m in six locations. Wave-cut platforms at various elevations were detected in the study area, and the platform's height was observed to reach +1.6 m asl in Locations 1 and 2. Uplifted tidal notches were encountered at +1.8 m and +2.6 m asl in Location 1, +0.9 m asl in Location 2, +0.5 m asl in Location 5, and +0.5 m and +2.2 m asl in Location 6. A lithophaga hole band was identified in Location 6, reaching +2.2 m asl. Our observations have some implications for the uplift rates of the Bodrum Peninsula coast and the location of the faults in the region.

5.1. Previous studies along the Aegean coasts

The seismically active Aegean Sea is in an extensional tectonic regime controlled by offshore normal faults. Therefore, displaced shorelines along the shores have always been used as indicators of tectonic movements and relative sea-level changes (Desrulles et al., 2009; Evelpidou et al., 2014; Evelpidou et al., 2019, 2021; Karkani et al., 2019; Karymbalis et al., 2022; Lambeck, 1995; Ott et al. 2021; Sakellariou and Tsampouraki-Kraounaki, 2019; Shaw et al., 2008; Stiros et al., 2000, 2011; Triantafyllou et al., 2022; Yıldırım et al., 2022).

According to previous studies on the islands in the Aegean Sea (Figure 9), most of the Cycladic islands are generally considered to be affected by subsidence (Desrulles et al., 2009; Lykousis, 2009; Evelpidou et al., 2021; Karkani et al., 2019) attributed to the crustal thinning in an extensional tectonic regime (Karkani et al., 2019; Sakellariou and Tsampouraki-Kraounaki, 2019). A study conducted on Mykonos, Delos, and Rhenia islands (Cyclades, Greece) identified three stands below sea level: (1) -3.6 ± 0.5 m (2000 BC), (2) -2.5 ± 0.5 m (4000 BC) and, and (3) -1 ± 0.5 m (1000 AD) (Desruelles et al., 2009). The average tectonic subsidence rate has been reported as 1.0± 0.4 mm/yr since 5500 yr BP in the Central Cyclades (Karkani et al., 2019). At Naxos, the subsidence rate has been 0.8–0.9 mm/yr for about the last 3000 yr (Evelpidou et al., 2014).

Samos Island, located northeast of the Cyclades, is rising (Evelpidou et al., 2019, 2021; Stiros et al., 2000, 2011). On the northwest coast of Samos Island, a notch at +2.3 m asl was dated to 3600-3900 yr BP (Stiros et al.,2000). In addition, a raised dendropoma reef was dated to 950-1150 AD on the Ikaria Island coast ~1 m asl (Stiros et al., 2011). An uplift trend of ~0.8 ± 0.2 mm/yr since 5700 yr BP was reported in the southeast of Samos (Evelpidou et al., 2019). In addition, Evelpido et al. (2021) reported an uplift ranging from 8 ± 5 cm to 23 ± 5 cm due to the Mw=7 earthquake that occurred on October 30, 2020 in their study on Samos Island. Although observed under the current sea level in 2015, some notches and benches on the island were now visible above the present sea level due to this uplift.

Rhodes, Crete and Antikythera, located south of the Cyclades, are other islands rising in the Aegean Sea (Lambeck, 1995). In Rhodes, uplift rates were found to vary between 0.7 and 1.9 mm/yr, resulting from the regional tectonic regime (Lambeck, 1995). Triantafyllou et al. (2022) reported this rate as ~1 mm/yr for the last 6 ka. In Crete, on the other hand, the uplift rate decreases towards the east of the island but increases up to ~5 mm/yr in the southwest (Lambeck, 1995). Previous studies report that the shorelines in Crete, up to +9 m, synchronously with a devastating earthquake in AD365 (e.g., Pirazzoli et al., 1996; Shaw, 2008; Stiros, 2011). On the contrary, Ott et al. (2021) attributed this increase to more than one event. Shaw et al. (2008) suggest a long-term average uplift rate of 2 mm/yr, consistent with uplift occurring in AD 365-type events that repeat every 4500 yr in western Crete (Shaw et al., 2008). Antikythera Island, located northwest of Crete, revealed an uplift rate of 1.9 mm/yr (Lambeck, 1995).

Previous studies on the Aegean Sea coast revealed different uplift and subsidence speeds depending on Holocene tectonic activity. While Samos, Rhodes, Crete, and Antikythera tend to uplift, the Cyclades islands coasts subside. The uplifted areas on the Aegean coast of Turkey are Miletus (Muğla) (Pavlopoulos et al., 2012), Ilıca (İzmir), Kazıkbağlar (İzmir), Ephesus (İzmir), and Mavişehir (Aydın) (Lambeck, 1995) to the north of the Bodrum Peninsula. While this rate is 0.5-0.6 mm/yr at Miletus, Ilıca, Kazıkbağlar and Mavişehir, in Ephesus, it increases up to 2.7 mm/yr (Pavlopoulos et al., 2012). The subsided areas on the Aegean coast of Turkey are Datça Peninsula (Anzidei et al., 2011; Özsayın et al., 2021) and Gemile Island in Fethiye. In the coastal part where the ancient city of Knidos is situated to the west of Datça Peninsula, immediately south of the Bodrum Peninsula, a subsidence rate of 0.73 mm/yr is reported (Anzidei et al., 2011), the eastern part, including the town of Datça, these rates were found to vary between 0.36 and 1.15 mm/yr (Özsayın, 2021). Furthermore, the coast of

Gemile Island in Fethiye (Muğla), located southeast of the Bodrum Peninsula, is among the areas subsiding at a rate of ~1.5 mm/yr (Anzidei et al., 2011; Lambeck, 1995).

It is difficult to make a general assessment with limited data. More studies are needed on the Aegean costs of Anatolia, where tectonic movements are intense, to understand the extent and impact of past tectonic movements and to interpret their relationship with the surrounding areas.

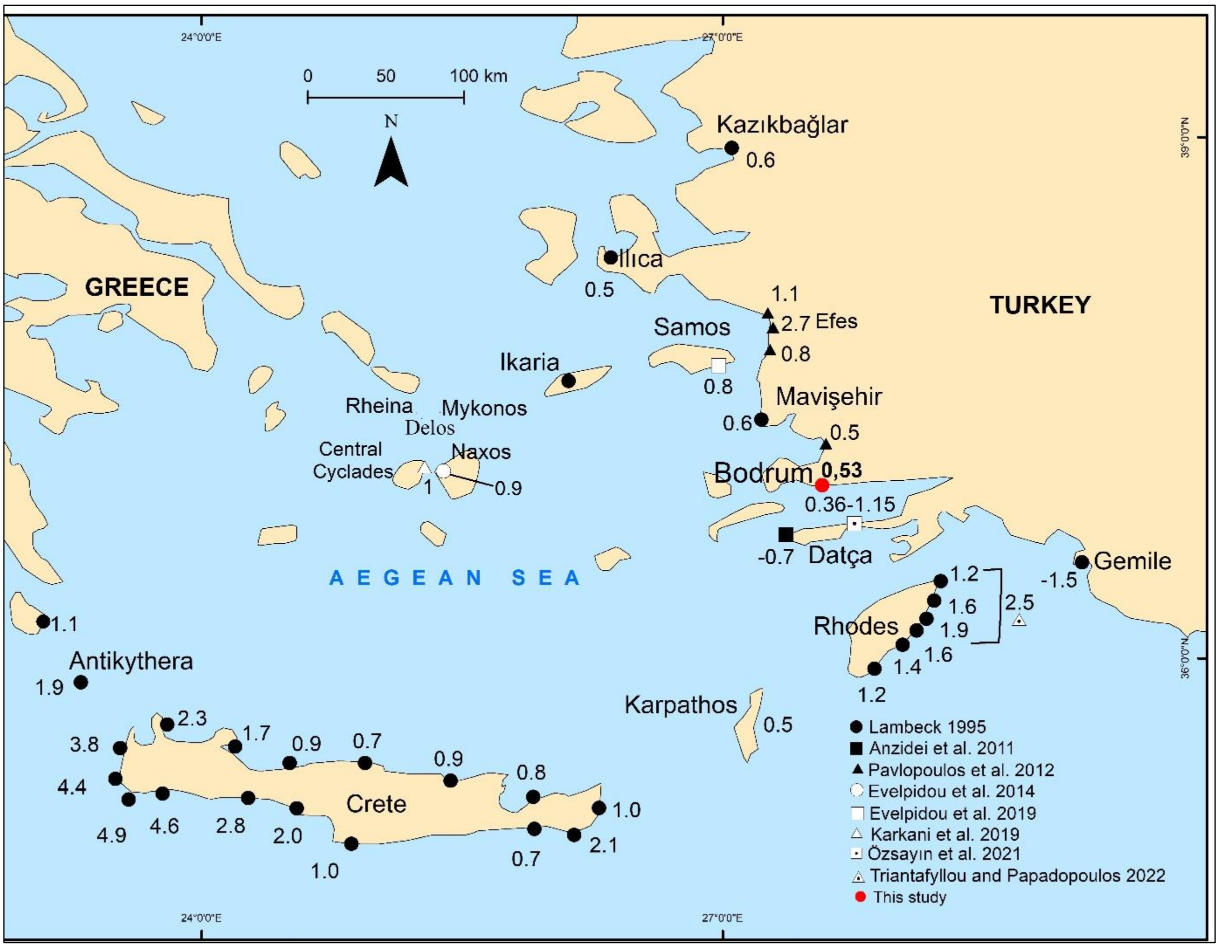

Figure 9. Uplift rates (mm/yr) on the Aegean Sea coasts.

5.2. Interpretation of Field and Age Data

There are two main reasons for the limited number of indicators with low error margins in the study area. Firstly, field observations are restricted due to the occupation and destruction of Bodrum Peninsula's coastal belt or the obstruction of transport facilities by hotels and summer residences. Secondly, the lithological differences between the east and west of the peninsula play an important role. The raised sea-level markers are not preserved on Miocene volcanics and sandstones, the most extensive rocks on the Bodrum Peninsula's coast, particularly in the west. The sea level markers, especially beach deposits, might have been eroded after the coastal uplift. On the other hand, the notches and other indicators formed on the limestone rocks were better preserved.

As a result, only four samples suitable for dating were found in the study area (Locations 5 and 6). Unfortunately, not all age data of these samples could be evaluated in our study. In Location 5, the mollusk sample (B01) taken from the beach deposit at +1.3 m asl was dated to 2678 ± 79.5 yr BP. However, we could not calculate the uplift rate because we could not determine the paleo-sea level forming this beach. The terrestrial mollusk sample (B02) taken from +1.8 m asl was dated to 836 ± 74 yr BP and was considered an outlier and hence was not used. In Location 6, a gastropod sample taken from a gravelly berm deposit, located approximately at the same level as the +0.5 m notch, was dated 36.5 yr ago, indicating that the berm deposit is recent. Fossil mollusks taken from the uplifted beach deposit, assumed to be associated with the tidal notch at +1.2 m asl, were dated to 2241 ± 88 yr BP. Therefore, we report only two reliable 14C results from our study area. However, only one could be associated with an uplifted shoreline indicator.

Abrasion platforms and tidal notches observed above the present sea level result from tectonics (Antonioli et al., 2006a-b; Anzidei et al., 2014; Ferranti et al., 2007; Gordillo, 1992; Lambeck et al., 2004; Liew et al., 1993; Morhange et al., 2006; Pirazzoli et al., 1994; Stiros et al., 2000; Surić et al., 2014). These markers were not observed at the same level everywhere in this study, probably because tectonics do not have the same magnitude and was not simultaneous throughout the Bodrum Peninsula. The current positions of the sea-level markers in these locations on the footwall blocks of the normal faults on the Bodrum coast and Gökova Bay are related to past earthquakes with a magnitude greater than six on these faults (Yıldırım et al., 2022).

In addition, the age and uplift of Location 6 may be associated with the Ören Fault. The fact that this location is on the footwall block of the Ören Fault indicates that these uplifted sea-level markers are coseismic uplifts due to this fault (Figure 3B). Another inference can be drawn from this location based on the presence of lithophaga hole bands. Generally, the upper boundary of the lithophaga hole bands is concentrated 2 m below sea level and has an error margin of +2 m as a sea-level indicator (Ferranti et al. 2006). Therefore, the lithophaga hole band, the upper level observed at +2.2 m asl, may point to a shoreline raised to +4.2 m in this location.

5.3. Uplift Rate and Previous Regional Data

Calculating the uplift rate in the region is challenging due to the majority of relative sea level indicators found in the study area being developed on volcanic rocks and dating those developed on carbonate rocks is difficult. By calculating the uplift rate using the +1.2 m notch at location 6 and the 2241± 88 yr BP aged deposit at that level, the resulting rate is 0.53 mm/yr.

Important conclusions have been reached in a recent study by Yıldırım et al. (2022) that includes the Bodrum Peninsula and the Holocene sea-level markers uplifted by the last earthquake. Yıldırım et al. (2022) conducted field observations at 11 locations on the coasts of Gökova Bay, where detected several sea-level indicators above and below the present sea level (Figure 10). While some of these indicators are related to the July 21, 2017, Bodrum/Kos earthquake (coseismic), this study also reported Holocene tectonic activity in Datça, Karaada, and east of Ören. As geomorphological markers of the relative sea level change, they detected a series of notches at +0.2, +0.5, +0.8, +1.1, and +1.5 m asl east of Ören on the northern coasts of Gökova Bay. And also found paleo sea-level indicators at +0.6 and +1.2 m asl on

Karaada, south of Bodrum. On the southern coast of Gökova Bay, submerged shorelines -1, -3, and -4 m below present sea level and well-preserved tidal notches up to +1.2 m were encountered. This study state that these uplifted sea-level markers to be associated with earthquakes of magnitude greater than six during the last 3-4 ka BP and those below sea level as ancient sea-level markers. And also found a well-preserved wave-cut marine terrace at 238.3±1.9 m asl in Datça and considered Pleistocene in age. Evidence of coseismic uplift varies between +0.1 m and +0.3 m asl in Bodrum town and on the coast of Karaada (Yıldırım et al., 2022).

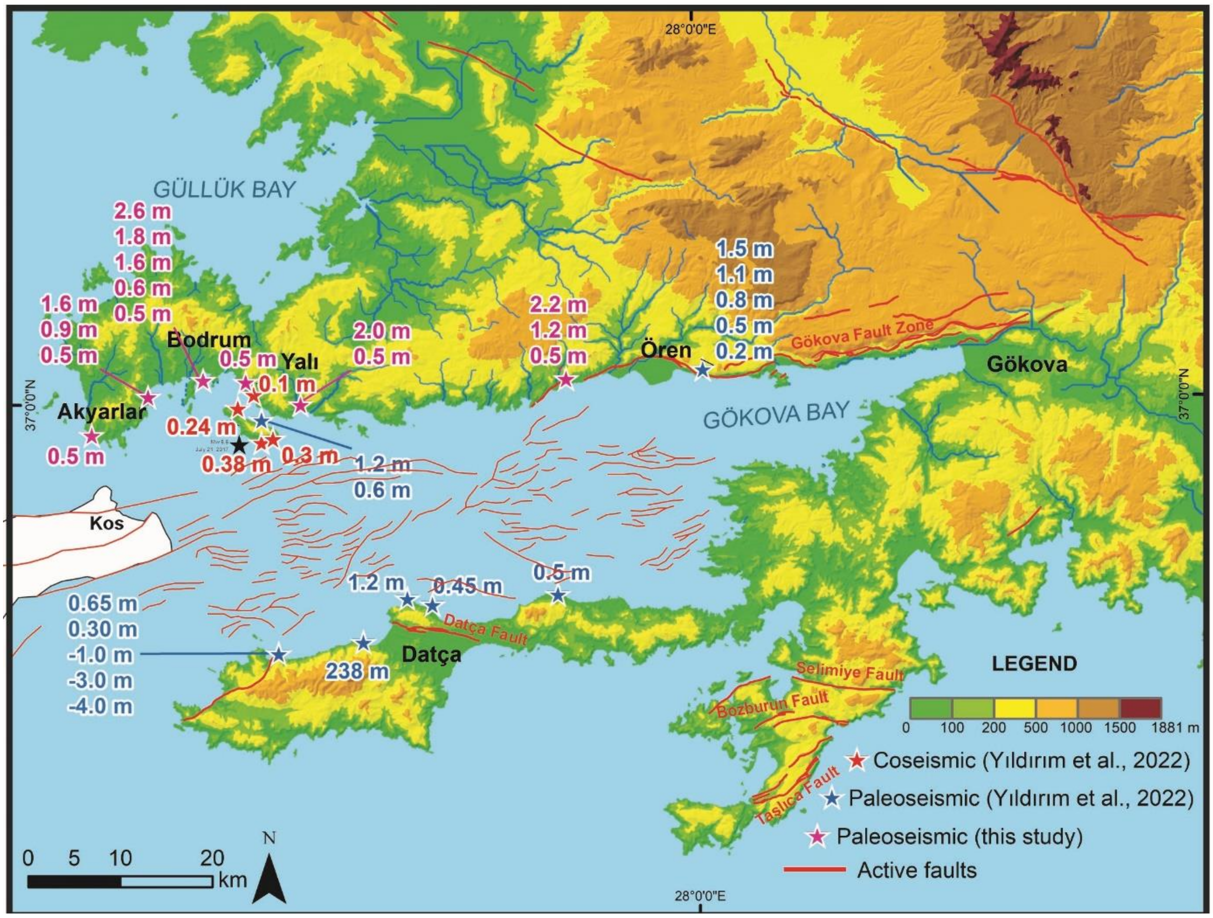

Figure 10. Distribution of the coseismic and paleoseismic events along the coasts of Gökova Bay. Active faults based on Emre et al., (2018). The black star indicates the epicentre of the 21 July, 2017, Bodrum/Kos earthquake (Tiryakioğlu et al., 2018).

Yıldırım et al. (2022) reported that the tectonic uplift rate significantly exceeded the eustatic rise in this region, indicating that Karaada was seismically uplifted due to the July 20, 2017, Bodrum/Kos earthquake. Also dated gastropods collected at +0.6 and +1.2 m asl of the beach deposit, a typical fan-delta on the northern coast of Karaada, to 1038 and 2802 yr BP, respectively. In addition, they dated the lithophaga samples at +0.56 m asl at Ören to 2314 ± 32 BP and calculated the uplift rate in this area as 0.24 mm/yr. This location is only ~14 km west of our Location 6. The uplift rate at Ören (0.24 mm/yr) is lower than what calculated at Gerindere (0.53 mm/yr). This can be explained by the different timing and magnitude of seismic events on the faults bordering the northern part of Gökova

Bay. Therefore, only two uplift rates can be mentioned in the region. These are 0.24 mm/yr east of Ören (Yıldırım et al., 2022) and 0.53 mm/yr at Gerindere beach.

The notch at +1.2 m asl in Location 6, north of Gökova Bay, was dated to 2241± 88 yr BP. We calculated the 0,53 mm/yr uplift rate for the Gerindere. A lithophaga hole band with an upper limit of ~+2.2 m asl above the +1.2 m notch at location 6 indicates that this notch does not represent the oldest sea level in the Holocene. On the other hand, considering the upper limit of the lithophaga hole band here and assuming that the uplift rate in the Gerindere has been the same during the last 6 ka, the probable today's position of the oldest Holocene sea-level can be estimated. The lithophaga hole band at +2.2 m asl, with a +2 m margin of error (Ferranti et al., 2006), should belong to a sea level at ~4.2 m. Moreover, we know that the global sea level was situated at −4 m before 6.7 ka (Lambeck, 1995; Lambeck et al., 2014), and the oldest Holocene notch in the Mediterranean dated to 6 ka BP (Boulton and Steward, 2015). Assuming that the vertical uplift rate on the Gerindere is 0,53 mm/yr during the last 6 ka with the method followed by Yıldırım et al. (2022), it can be concluded that the oldest tidal notch, which was formed between 6.7-6 ka BP, when the sea level was -4 m, should be ~4.5 m above the present sea level.

6. Conclusion

At six locations on the southern coast of Bodrum Peninsula in SW Türkiye, we report uplifted marine beach deposits, notches, and platforms developed during the Holocene. The uplifted sea-level markers are well preserved on the rocky limestone coasts but are scarce in volcano-sedimentary rocks, except for the abrasion platforms. A tidal notch at +0.5 m and an elevated beach deposit at +2 m asl were found in Gerenkuyu Inlet (Location 5). The mollusk samples taken from +1.3 m asl of this beach deposit are dated to 2678.5 ± 79.5 yr BP. On the eastern edge of the Gerindere fan-delta (Location 6), two notches were detected at +0.5 and +1.2 m asl and a lithophaga holes reaching +2.2 m asl. The beach deposit, which we think was formed simultaneously with the +1.2 m notch, was dated to 2241 ± 88 yr BP, and the uplift rate was calculated as 0.53 mm/yr. The limited data on the relative sea-level change and uplift rates in the Bodrum Peninsula and around Gökova Bay reveal that new studies are needed to understand the crustal deformation in the Holocene.

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