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# Morphology of coast and textural characteristics of coastal sediments (NE Gökova Graben, SW Turkey)

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**Abstract**
This study examines the morphology, lithological characteristic and controlling factors of coastal sediments in the northeast Gökova Graben (southwest Turkey). The northeast Gökova Graben is located in a region with several human settlements and tourism activities, in the summer. The analysis used in the study is field observation, Digital Elevation Model (DEM) analysis, 18 sieve (including statistical evaluations) and 18 X-ray Fluorescence (XRF) analyses. Due to the boundary of normal faults, predominantly faulted-rocky coasts are expected. However, four different coast types were determined in the northeast Gökova Graben. Evolution of these coast types is dependent on orientation of the normal faults and also distribution of different coastal rocks and rivers. The predominant coast type, rocky coasts are formed by faulted, high-resistant Jurassic-limestone. Owing to reworking and short transportation via brooks and the force of gravity, narrow gravely shingle beaches are only observable in front of the Quaternary-conglomerate cliff. Perennial streams form two different coasts. Long stream formed the wide sandy beach in the eastern end of Gulf. While short streams, which obliquely cut the graben, formed the sandy-gravely beach at the western end of the study area. Recent beachrock, coastal rock staining and wave notches are indicators for a stable sea level in the study area. Past sea level indicators are the hanging beachrocks and wave notches located in the western part of the study area. Past activities of the interior faults within the graben are responsible for ancient sea level fluctuations. Moreover, global warming increases the risk of sea level rise. A possible rise in the future sea-level may destroy narrow-gravely beaches. This risk may also threaten the wide sandy beach as well as the settlement in the area.

**Keywords** Gökova Graben (Southwest Turkey) · Sea level changes · Sandy coast · Rocky coast

## Introduction

Approximately 1.2 billion people in the world prefer to live in coastal regions (Adger et al. 2005). Estimates suggest the number to double in the next 15 years (Adger et al. 2005). Coastal and related marine ecosystems (as in the Mediterranean) supply valuable commodities such as fisheries and summer tourism for its inhabitants (United Nations Environment Program / Mediterranean Action Plan-UNEP/MAP 2012; Intergovernmental Panel on Climate Change - IPCC 2014). These inhabitants are under the threat of coastal erosion, coastal flooding related sea level rise, tsunami, pollution, mismanagement, marine litter, etc. (Adger et al. 2005; Galili et al. 2007; UNEP/MAP 2012; IPCC 2014). According to the map presented by UNEP/MAP (2012), nearly all European countries with coasts neighboring the Mediterranean Sea, are under the threat of coastal erosion. However, because of insufficient studies in Turkey, only few studies were present on the map. In order to prevent such threats, several researchers (Billé 2008; IPCC 2014) presented several adaptation measures including disaster risk management, ecosystem management and structural-physical structures.

Beaches are delicate environments under the equilibrium of coastal accretion and erosion (Pirazzoli and Pluet 1991; Frihy 2001; Mörner 2005; Galili et al. 2007; Cronin 2012; Engelhart

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and Horton 2012; Gül et al. 2017). This dynamic zone is under pressure from atmosphere-land-marine environment and more recently anthropogenic pressure (Frihy 2001; Prospathopoulos et al. 2004; Kilibarda et al. 2014). An irregular sea floor, strength of coastal rocks, sea waves, tides, freshwater and sediment input are all controlling the coastal morphology and coastal sedimentation (Leeder 1982; Reinson 1992; Spezzaferri et al. 2000; Gül et al. 2008a, 2008b, 2009, 2011). Good management of the coastal zones and mitigation practises (including removal of adverse impacts) require description, classification and understanding of coasts (Frihy 2001; Galili et al. 2007; UNEP/MAP 2012).

The coastal rock characteristics (soft or hard, consolidated or unconsolidated, soluble or insoluble), the slope of the coast and structural properties are used in coastal classification (Fairbridge 2004; Finkl 2004). Rocky coast was determined as a dominant coast type for the Mediterranean and Black Sea Coast (Furlani et al. 2004). Some rocky coasts have been formed by fault scarp, while some of them were evolved due to the high resistance of rocks (Furlani et al. 2004). Normal fault may have caused the linear, steep, rocky coasts on the Aegean Sea coast of Greece (Palyvos et al. 2005), and likewise on the Turkish Coast (Uluğ et al. 2005; Uluğ and Kaşer 2007). Fault activities may lead to local sea level variations that maybe spotted by using traces from marine organisms, beachrocks, wave notches and historical marine structures (Switzer et al. 2012; Woodroffe and Murray-Wallace 2012).

The Gökova Graben is one of the seismically active grabens of southwest Turkey (Fig. 1; Görür et al. 1995). A recent major earthquake with magnitude of 6.6 occurred on the 21 July 2017 in the west end of the graben. This earthquake affected Kos Island (Greece) and Bodrum Town (Turkey) (KOERI 2017). In addition, several prominent Turkish settlements, which are leading places of Turkey in terms of summer tourism such as Bodrum, Akyaka and Ören are located on the margin of the Gökova Graben, (Fig. 1). The Gökova Graben, especially the northeastern part, has a variable coastal morphology containing rocky cliff, gravely sandy narrow-shingle beaches, and wide plain deltas (Figs. 1b, 2a). Uluğ et al. (2005) and Uluğ and Kaşer (2007) have suggested tectonic activity and sea level fluctuation as the main controlling agents on interior sedimentation of the Gökova Graben. Similarly, local beachrocks and wave notches at different levels in the northeast Gökova Graben already indicate earlier sea level variations. In addition to tectonic activity, global warming is also increasing the threat of rise in sea level in this region. The main goals of this study are; to assess the risk and effects of a future rise in the sea level on the northeast Gökova Graben; to discuss the normal fault orientation and coastal rock type effects on coastal morphology; to determine coastal sediments characteristics, and to show, depending on local factors, how much variable coastal structures can develop in short distances.

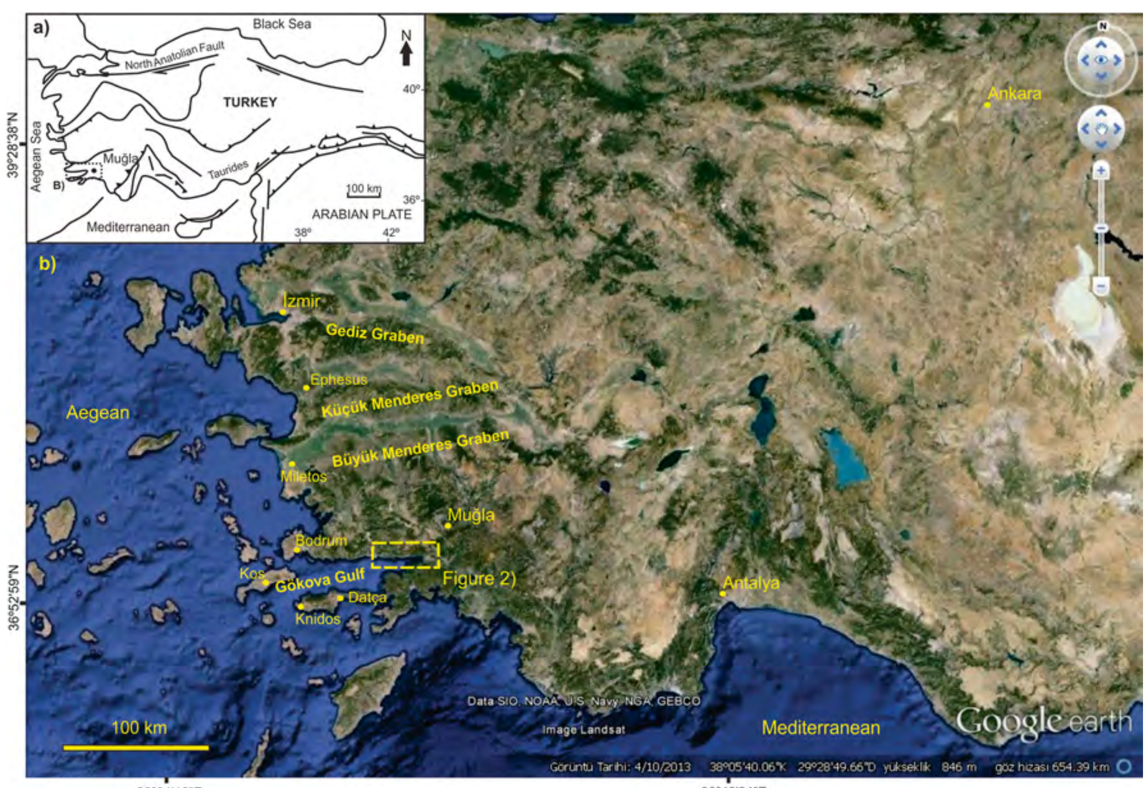



**Fig. 1** **a** The study area is located in the southwest part of Turkey. **b** Grabens of the southwest Anatolia (obtained from www.googleearth.com)

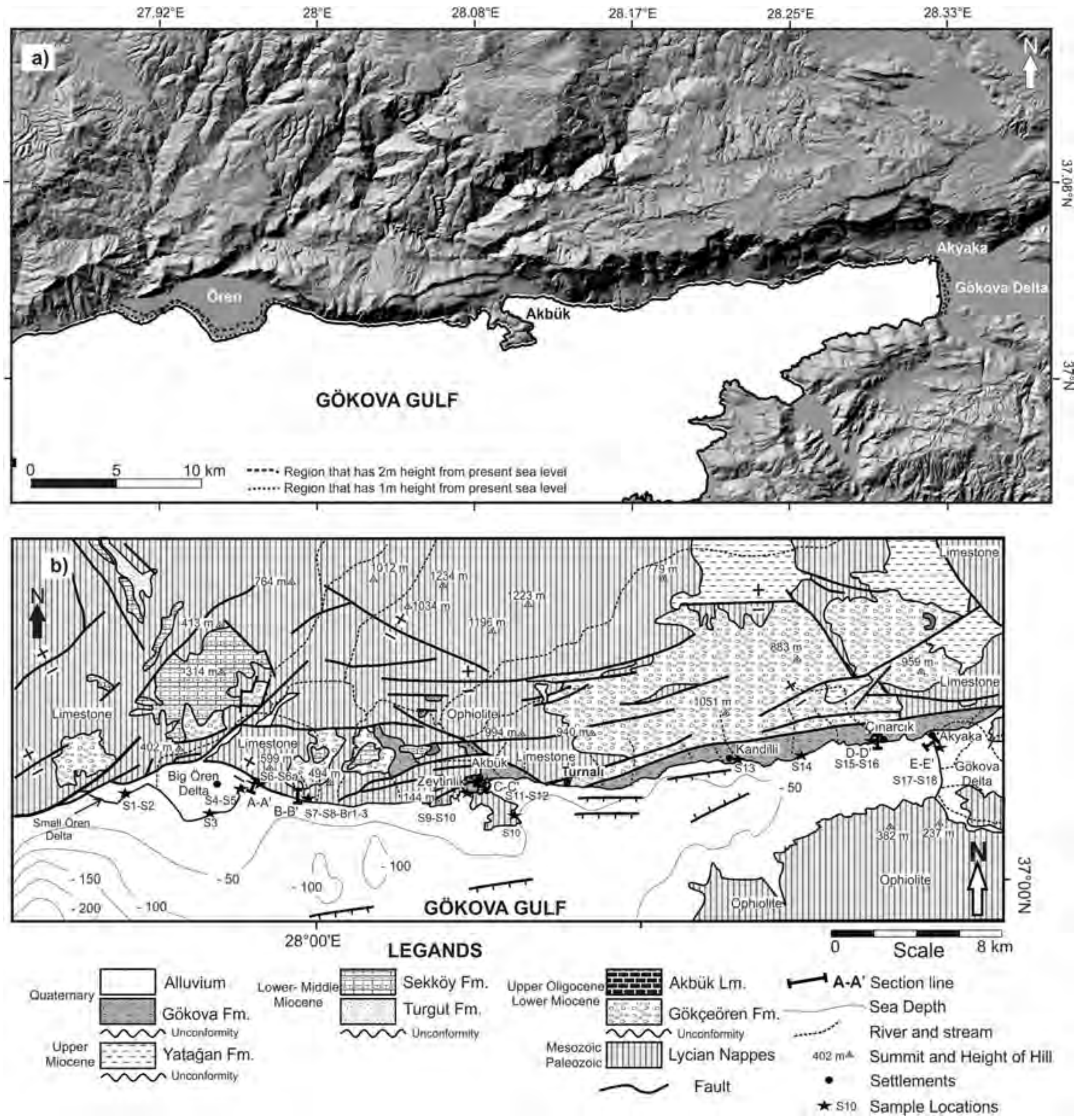



**Fig. 2** **a** Digital Elevation Model (DEM) of the study area. The rocky coast (dark grey to black color) can be delineated from low-inclined or flat sandy beach-gravely beach areas (light grey color). **b** General geological map of the study area (Gürer and Yılmaz 2002). Sea level contours and faults inside the graben were obtained from the Uluğ et al. (2005)

## Materials and methods

The Gökova Gulf is 100 km in length, 30 km in width to the west and 3 km in width to the east, and structurally extends 10 km farther to the east of Akyaka Town (Fig. 1; Görür et al. 1995). This study focuses on northeast of the Gökova Gulf (40 km in length). Sea level in this part is decreasing to the east (Fig.2b). Sediment properties, factors controlling sedimentation, coastal morphology, and threat emanating from possible sea level rise in the coastal region were determined using field observations and the results of laboratory experiments.

Rocky coast, narrow gravely shingle beach, wide sandy beach and deltas were classes of the coastal morphology of the study area. Various formation, mainly limestone and conglomerate, formed coastal rocks (Fig. 2b). The gravely and sandy beaches were described based on surface sediments. During the field study, eighteen loose sediments from surface and four-beachrock samples were collected (Table 1). Sometimes two loose sediment samples (representing coarse-grained and fine-grained sediments) were collected base on surficial sediment distribution in a beach. Sieve analyses of loose sediments (1165–2895 g in weight) with nine sieves (screen sizes ranging from 64.0–32.0-16.0-8.0-4.0-2.0-1.0-0.5-0.25-0.125-0.0625 mm), which were determined on the basis of dominant grain size. Statistical parameters (including median, sorting, skewness and kurtosis), for comparing the loose sediments, were

**Table 1** Eighteen loose beach sediments and four hard beachrock samples were collected during the field study

| Region | Sample No | Latitude | Longitude | Location |
|---|---|---|---|---|
| Ören Deltas | S1 | 37.02840 | 27.88333 | Small Delta - W |
| | S2 | 37.03057 | 27.91667 | Small Delta - E |
| | S3 | 37.01960 | 27.95000 | Big Delta - Centre |
| | S4 | 37.02513 | 27.96667 | Big Delta - E |
| | S5 | 37.02922 | 27.96667 | Big Delta Coast - E |
| | S6a (Beachrock)<br>S6 (Sandstone) | 37.03188 | 27.96667 | Big Delta - Port |
| Ören Deltas – Akbük Region | Br1, Br2, Br3, S7, S8 | 37.03033 | 27.98333 | Ören Deltas – Akbük Region |
| Akbük Region | S9 (fine sand-clay)<br>S10 (gravely) | 37.02643 | 28.06667 | Akbük Bay W - Zeytinlik Bay |
| | S11 | 37.01732 | 28.10000 | Akbük Bay W |
| | S 12 | 37.03305 | 28.08333 | Akbük Bay |
| Akbük Region – Akyaka Town | S 13 | 37.03838 | 28.18333 | Turnalı District |
| | S 14 | 37.05127 | 28.26667 | Kandilli District |
| | S 15 (sandy)<br>S 16 (gravely) | 37.04833<br>37.04890 | 28.30000<br>28.28333 | Çınar Beach |
| Akyaka Town | S 17 | 37.05073 | 28.31667 | Akyaka Town Beach |
| | S 18 | 37.05010 | 28.31667 | Gökova Delta |

calculated based on suggestions of Folk (1974) from (Ø) values that were obtained from the cumulative sieve retaining versus grain size (Ø) graph. Mud, sand and gravel size sediment percentages (obtained from the cumulative sieve passing versus grain size (mm) graph), which show the main grain size differentiation, were determined based on Wentworth (1922) classification. In order to display dominant grain sizes, we draw the frequency of histograms versus grain size graphs. Mode values (Ø) were fixed from this graph. General variation trends of sediments were shown by correlating the graphs of different statistical values, including sorting versus average grain size and sorting versus skewness. The dominant components (limestone, ophiolite fragments, and fossil shell fragments) were noted macroscopically, and even during the sieve analysis in different mesh. The major element analysis of twenty-two ground samples was using the Rigaku ZSX Primus II XRF equipment located at the Mersin University (Turkey) Research Laboratory. The main compositions of sediments and beachrock were described using the analysis. For provenance correlation, CaO versus $SiO_2$, $TiO_2$ versus $Fe_2O_3$ + MgO, and $Al_2O_3$ / (CaO + NaO) versus $Fe_2O_3$ + MgO graphs were prepared. During the field study, wave notches, the gray staining of coastal rock and beachrock formations were noted as a previous sea level indicator (Desruelles et al. 2009).

## Geological settings of the study area

The study area is surrounded by the Lycian Nappes. They include Triassic clastic, Jurassic carbonates (denoted as an Lmst in Fig. 2b), Upper Cretaceous clastic; Campanian-Maastrichtian ophiolite containing dunite, harzburgite, peridodite and dolerite dikes (denoted as an Oph in Fig. 2b), and Upper Cretaceous-Paleocene flysch and ophiolite mélange (Fig. 2; Ersoy 1990; Görür et al. 1995; Şenel 1997; Collins and Robertson 1997, 1998, 1999). The Lycian Nappes tectonically overlie the Menderes Metamorphic Massif (including Precambrian augen gneiss and metagranites in core; schist, marbles, and limestone in the cover) in the north (Okay 1989; Bozkurt and Satır 2000; Bozkurt 2001; Özer et al. 2001).

The Gökçeören Formation (Upper Oligocene-Lower Miocene) unconformably overlies the Lycian Nappes, and consists of shallow marine conglomerates (including mainly ophiolite pebbles and limestone pebbles) and sandstone (Fig.2b; Gürer and Yılmaz 2002). The Akbük limestone (Upper Oligocene-Lower Miocene) conformably overlies the Gökçeören Formation (Görür et al. 1995; Gürer and Yılmaz 2002; Gürer et al. 2013). The Turgut Formation consists of sandstone, siltstone, claystone, lignite, clayey limestone and marl, while the Sekköy Formation contains limestone and marl (Atalay 1980; Görür et al. 1995; Gürer and Yılmaz 2002). The Upper Miocene Yatağan Formation consists of conglomerate (including gneiss, quartz phyllite, and chert pebbles bearing), sandstone, siltstone, claystone, clayey limestone, limestone and tuff (Atalay 1980; Görür et al. 1995; Gürer and Yılmaz 2002). The Gökova Formation comprises of Quaternary lithified conglomerates (including ophiolite and limestone pebbles with varying ratio) and sandstones cropping out between the Akbük bay and the Akyaka Town (Ersoy

1991; Görür et al. 1995). The youngest unit of the study area is alluvial deposits including slope debris, alluvium, delta sediments and beach sand. Slope debris or colluvium contains poorly sorted, angular-sub angular rock fragments derived from the slope rocks, while alluviums contain well-rounded sediments (Görür et al. 1995). Recent beachrocks are present in different parts of the Gökova Gulf (Görür et al. 1995; Dirik et al. 2003), whereas, in the context of this study; they are existent only in the Ören Delta.

## Coastal properties between the Ören and Akyaka towns

The area between the Ören and Akyaka towns contains mainly rocky coasts, many narrow, sandy gravely shingle beaches, and wide, plain sedimentation areas (Ören delta, Akbük bay delta, Gökova delta-Akyaka sandy beach). The morphological properties, sieve analysis results of the coastal sediments, their chemical analysis results, and sea level changes are given below.

### Morphological properties

The study area morphologically includes four different coast types.

#### Rocky coast

The rocky coast is the main coast type of the study area (Figs. 1, 2). Dark gray and black parts in the DEM model refer to rocky coasts (Fig. 2a). The maximum height of the hill is around 600 m between Ören Town and Akbük bay (the summits and height of some hills are presented in Fig. 2b). The coastal rock of this area is the Jurassic limestone of the Lycian Nappes (Fig. 1b, 2; Görür et al. 1995; Şenel 1997). These limestones include calcite filled, fractured, fine-to-medium crystalline or micritic, and crystallized limestone–dolomitic limestone. They are classified as medium to high strength rock based on Schmidt Hammer Rebound Values (Şenel 1997; Gül et al. 2013; Gül 2015). The region in between the Akbük bay and Akyaka Town (20 km long) has the steep, rocky, active normal faulted coast. The maximum height of this section reaches up to 1000 m (Fig. 2). The host rock of this area comprises the lithified conglomerates of Gökova Formation with patchy outcrops of the Jurassic limestone of the Lycian Nappes (Fig. 1b, 2; Görür et al. 1995; Gürer and Yılmaz 2002). In some places, those rocky coasts are separated from the sea by the narrow, short gravely sandy and shingle beaches. They were classified as a fault controlled cliff coast type by Gül et al. (2017) based on the Fairbridge (2004) coastal classification system. Finkl (2004) compiled separate coastal classification systems that were prepared by different researchers (Johnson 1919; Shepard 1948; Owens 1994) based on different properties of the coast. The rocky coast of the study area can also be classified as a Fault Coast - Neutral Coast (Johnson 1919); or Fault coast - Shaped by diastrophism of the Coast by non-marine agencies (Shepard 1948).

#### Delta

Deltas make up the largest recent sedimentation in the study area. Gray colors, and plain coastal areas in DEM view were evaluated as delta (Fig. 2a). They are located at the mouth of perennial streams. Two fan-shaped deltas are in the Ören region (Figs. 1, 2). The small Ören delta is located in the west and covers about 2 $km^2$. However, the big Ören delta is situated in the east and covers about 10 $km^2$ (Figs. 1b, 2). This big delta serves as a residential area, containing many hotels, hostels and agriculture field. The gravel beach of the big Ören delta is a home for summer holidays. The port there is used for military purposes and for fish boats. The A-A’ cross section was taken from the big Ören delta coast (Figs. 2b, 3). Fig. 4 shows the coastline of the Ören delta that has gravely and sandy beaches, and patchily distributed beachrock occurrences. An apparent thickness of the Ören delta sediment increases towards the north (max. 10 m). According to marine geophysical measurements, the thickness of the deltaic sediments increases up to 50 m into sea (Uluğ and Kaşer 2007).

Another small delta is in the Akbük bay (Figs. 1, 2, 3c, 5). This delta has a narrow gravely beach, 5–6 m in width and 1 km in length (Figs. 3c, 5). The northern side of the beach contains swamp with reeds. The biggest delta of the study area is the Gökova delta, where a widespread sandy beach is present (Figs. 1, 2). The Akyaka Town is on the northeastern side of this delta.

This type of coast was classified as a ‘soft, weakly consolidated and erodible coast’ type by Gül et al. (2017) based on the Fairbridge 2004 classification system. It can also be denominated as a Delta Coast - Neutral Coast type (Johnson 1919); Delta coast - river deposition - terrestrial (subaerial) deposition of the coast shaped by non-marine agencies (Shepard 1948); pebble-cobble beaches - unconsolidated materials (Owens 1994).

#### Narrow gravely and sandy beaches

These are 2–250 m in width and 50 m-2 km in length (Figs. 2a, 3b, d, 4c, 6). They have a patchy distribution in front of the cliff. They start with colluvial deposits in front of the Jurassic limestone and Quaternary conglomerate cliffs (generally faulted). The structural (fracture) and lithological properties of the coast rocks and brooks may lead to the formation of such beaches and fix their place. The western narrow beach in front of the Ören-Akbük rocky coast, which has links with the

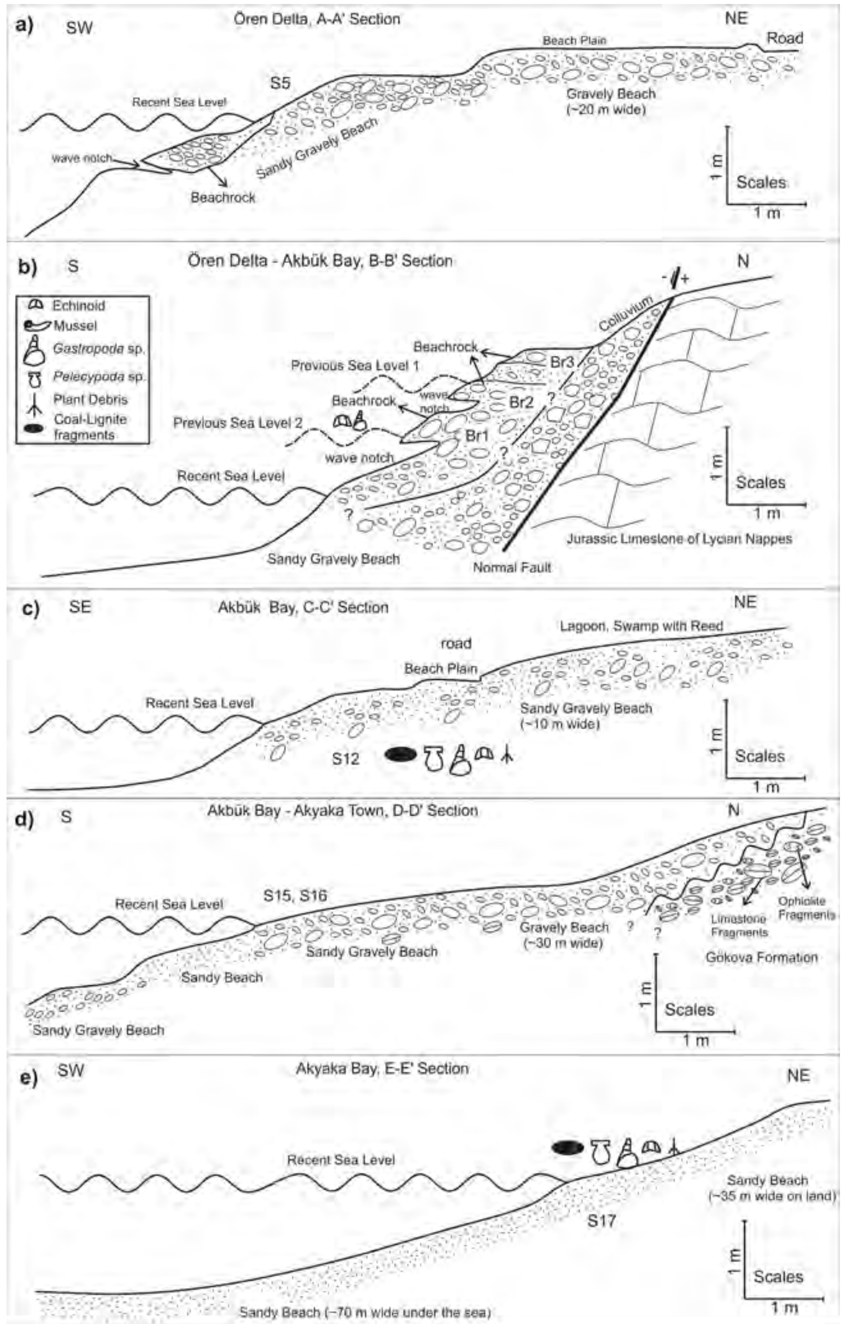



**Fig. 3** Schematic coastal profiles of the study area were prepared based on field observations. Their locations are shown in Fig. 2b

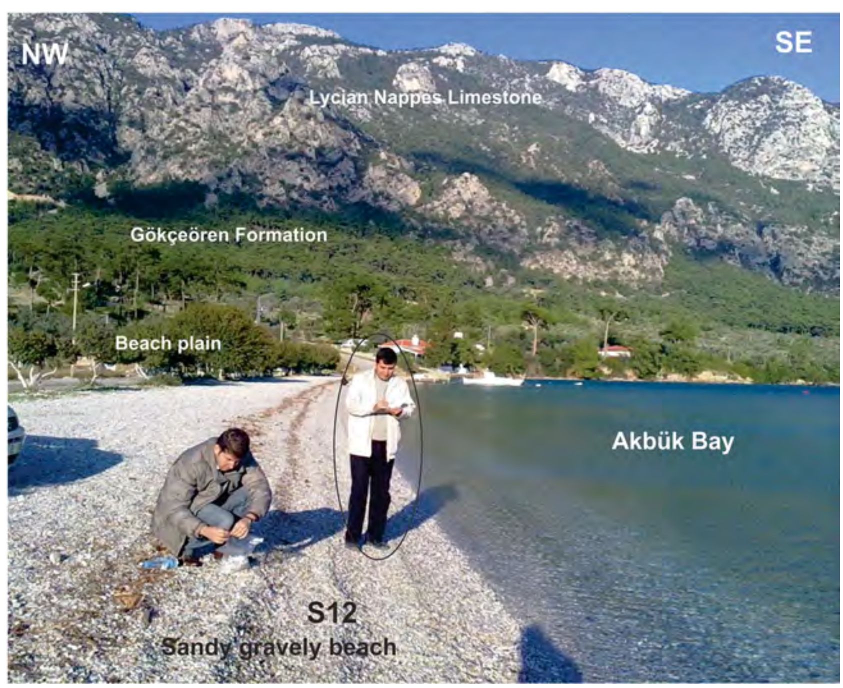
Ören delta, includes well-rounded limestone-ophiolite-marl gravels. However, the coastal rocks of the Ören delta contain Jurassic limestone (Görür et al. 1995; Gürer and Yılmaz 2002). The source of the sediments of the recent beach may well be the reworking of the big Ören delta by the longshore current.

The narrow beaches between Akbük bay and Akyaka Town contain similar sediments with the Gökova Formation (Fig. 6c). After disintegration, the Gökova Formation sediments have been transported to the coasts by gravity or temporary-seasonal brooks. They form rounded reworked conglomerate pieces and limestone-ophiolite gravels (the release of gravel depending on the weathering of the matrix). Winnowing of the finer-grained sediments among gravels by sea wave promotes gravely (shingle) beach formation.

Gül et al. (2017) (based on the Fairbridge (2004) coastal classification system), classified those small and narrow coasts under the 'soft, weakly consolidated and erodible coast' type. They can be classified as sand-pebble beach's-unconsolidated materials (Owens 1994). However, their textural characteristics are different from the delta and the wide-sandy beach.


**Fig. 4** **a** Field view of the gravely beach of the small Ören delta. **b** Field view of the western side of the big Ören delta (man in the circle for scale: 1.75 m). **c** Field view of the beachrock development in eastern side of the Ören port. The B-B′ cross section belongs to this region (hammer in circle for scale: 33 cm). **d** Close view of the gravely shingle beach sediments in front of the beach rock (L: limestone fragments; Op: ophiolite rock fragments; Q: Quartz fragments; S5: loose sediment sample; Br1: Beachrock level)

**Fig. 5** Field view of sandy gravely beach of the Akbük bay (man in circle for scale: 1.75 m). The C-C′ cross section belongs to this region. (S12: loose, beach sediment sample)



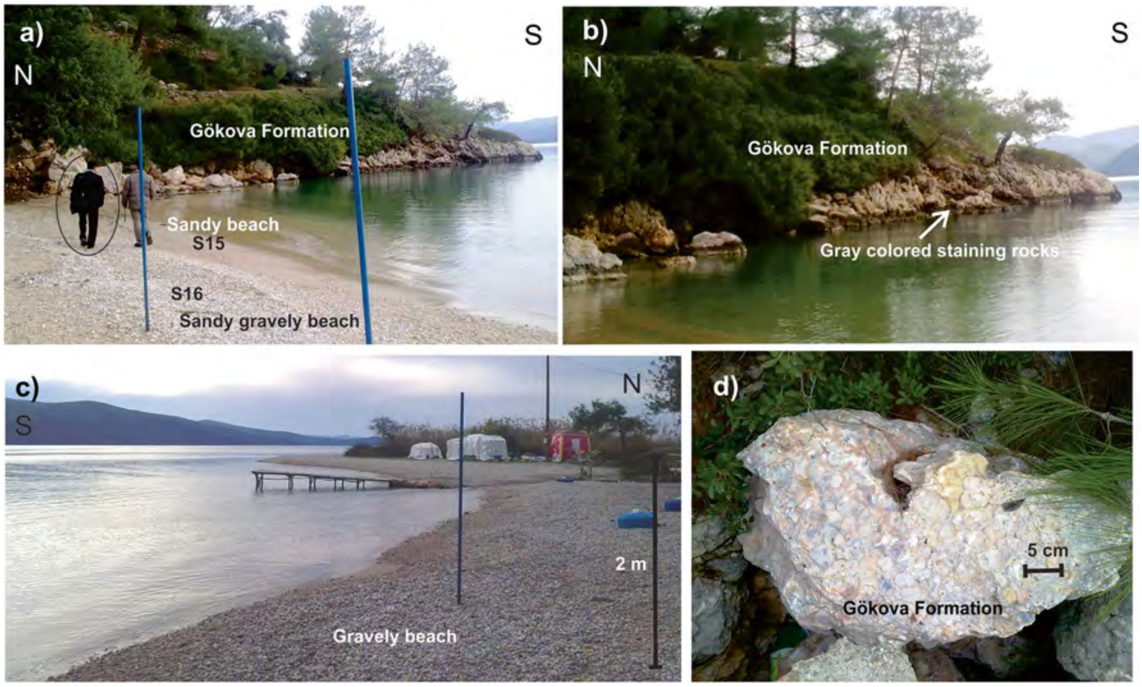



**Fig. 6** **a** Field view of the sandy gravely beach of the Çınar beach (man in circle for scale: 1.75 m). The D-D' cross section belongs to this region. **b** The conglomerates of the Gökova Formation limited the beach. Grey color staining is the results of recent sea level fluctuation. **c** Western side of the Çınar beach contains gravely beach. **d** Close view of the Gökova Formation contains well-rounded rock fragments, which are similar to recent beach gravel

### Wide sandy beach

This beach is 35 m in width, and 300 m in length and located in Akyaka Town (E-E' section in Fig. 3e). It extends to the south (25–50 m in width and 1.7 km in length). This delta is the widest flat region (20 km$^2$) of the study area and contains sand size sediments (Figs. 1, 2, 3e, 7). It offers its visitors a places for swimming and, the wind and kite surfing during summer time. This wide sandy beach is located where the Gökova delta and the Gökova gulf meet. The hinterland of the Gökova delta contains the Jurassic limestone of the Lycian Nappes, the Gökova Formation clastic in the north (steep rocky areas), and ophiolite in the southern part (small hill; Fig. 2).

Gül et al. (2017) also classified this coast as a 'soft, weakly consolidated and erodible coast' type (based on the Fairbridge (2004) system). This type can also be classified as a Delta Coast - Neutral Coast type (Johnson 1919); Delta coast - river deposition - terrestrial (subaerial) deposition of Coast shaped by non-marine agencies (Shepard 1948). However, if the material/sample properties are considered, they can be classified as sand beach-unconsolidated materials (Owens 1994).

## Sieve analysis of coastal sediments

Sediment composition and grain size supply information about the transportation process, and about source rocks (Carranza-Edwards et al. 1998). The sieve analysis of loose beach sediments provides more information about energy and environmental condition of the beach (Sahu 1983; Ramamohanarao et al. 2003). Table 2 shows the sieve analysis results. Fig. 8 presents the frequency curves, cumulative sieve retaining (%) versus grain size (Ø), and cumulative sieve passing (%) versus grain size (mm) graphs. Fig. 9 exhibits Mean (Ø), Sorting (Ø), skewness (Ø) and Kurtosis (Ø) versus sample number graphs. Fig. 10 shows sorting (Ø) versus average grain size (Ø), and skewness (Ø) versus sorting (Ø) correlation graphs.

Figures 8 and 9 indicate that the examined coastal sediments of the study area mainly include poorly sorted, fine-skewed, leptokurtic, pebble and to a lesser extent, fine-grained sand sediments. However, some strong deviations from the general trend were determined. The average grain size of the study area sediments has an inversely proportional relation with sorting. An increasing of the finer-grained sediments ratio (+Ø values) promotes the well sorting (close to zero, Fig. 10a). Most of the sediment then drops into the river sediment section (Fig. 10b).

The S1 sandy gravel sample (small Ören delta) contains well-rounded mainly limestone (gray-dark gray-white) fragments, and to a lesser extent ophiolite rock pieces (dark green-black-red) and quartz grains (glassy). The S2 sample consists of mainly ophiolite gravels. The S3, S4 and S5 samples (eastern side of the Ören delta) include well-rounded, limestone and ophiolite fragments with variable ratio. The beachrocks (Figs. 3b, 4c) have composition similar to the loose beach

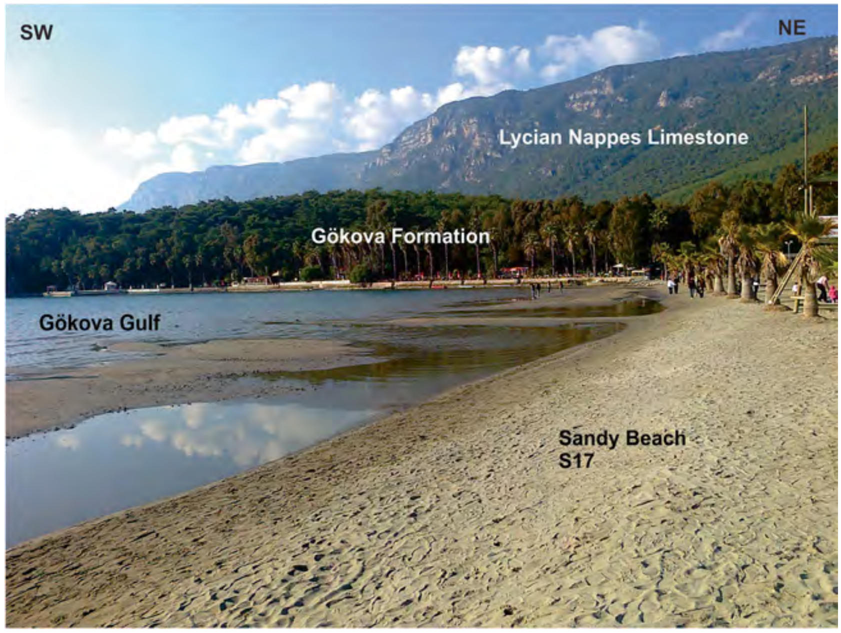



**Fig. 7** Field view of the sandy beach of Akyaka Town (man for scale: 1.75 m). The E-E' cross section belongs to this region (S17: beach sediment sample)

sediments. The Br1 and Br3 beachrock levels abundantly include limestone gravels, while Br2 has an equal ratio of the ophiolite and limestone fragments (Fig. 4c).

The S9 and S10 samples (Zeytinlik bay to the west of Akbük bay), contain well-rounded limestone gravels, and to a lesser extent the ophiolite rock and shell fragments. The S11 sample (from the pocket beach to the south of Akbük bay), has a similar composition to the S9 and S10 samples. The S12 sample (Akbük bay beach; Figs. 3c, 5) is made up of well-rounded, very fine-to-fine gravel size limestone and ophiolite fragments, and to a lesser extent shell fragments, plant fragments and coal-lignite pieces.

The S13 sample (Turnalı District) contains reworked conglomerate fragments in addition to the other mentioned contents. The S14 sample (Kandilli District) has similar properties to the S13 sample without shell fragments. The Çınar beach mainly includes gravels (S16) and to a lesser extent sands (S15).

Macroscopically, the S17 sample (Akyaka Town, E-E' section in Figs. 3e, 7) consists of ophiolite rock fragments, shell fragments and coal-lignite pieces with the size of fine-very fine gravel and very coarse sand. Macroscopically, the S18 sample (300 m to the southeast of the S17 sample location) contains ophiolite and to a lesser extent limestone fragments of granule-pebble size; shell fragments of granule size; and coal-lignite pieces of the size of coarse-grained sand.

## Chemical analysis of the coastal sediments

In order to determine the source rock characteristics and variations of the source depending on drainage system of the area, we apply XRF analysis on the coastal sediments. Applying the XRF analysis was especially to understand the source type of fine-grained sediments because we did not macroscopically define the fine-grained sediments. In order to clarify the similarities of components in Table 3, the higher values were marked as a bold compared to the average values.

The main chemical components of the examined coastal sediments of the study area are CaO, $SiO_2$ and to a lesser extent $Fe_2O_3$, $Al_2O_3$ and MgO (Table 3). There is an inverse relationship between CaO and $SiO_2$ (Fig. 11a). CaO was component of the limestone, while $SiO_2$ was from the ophiolite and quartz bearing sedimentary rock. $TiO_2$ has a linearly proportional relationship with $Fe_2O_3 + MgO$ (Fig. 11b). Similarly, ($Al_2O_3$/NaO + CaO) has linearly proportional relation with $Fe_2O_3 + MgO$ (Fig. 11c).

The highest $SiO_2$ values were determined from sediments collected in the western (the Ören deltas) and eastern (the Akyaka Town) sides of the study area (Table 3). However, the highest CaO were found in sediments obtained in the middle part of the study area (rocky coast with narrow shingle beaches, the Akbük, Akbük-Akyaka; Table 3). The sediments of the Ören delta and Akyaka Town beach were transported by perennial river further away from the depositional site (Figs. 1, 2). Sometimes, variable source results in an equal amount of CaO and $SiO_2$ ratio. The recent beachrock in Ören delta (S6a-Br) has higher $SiO_2$ than the older beachrocks (Br1, Br2, and Br3). Depending on a local source change, some deviations from the main trend as in the S1, S5, and S7 samples have occurred.

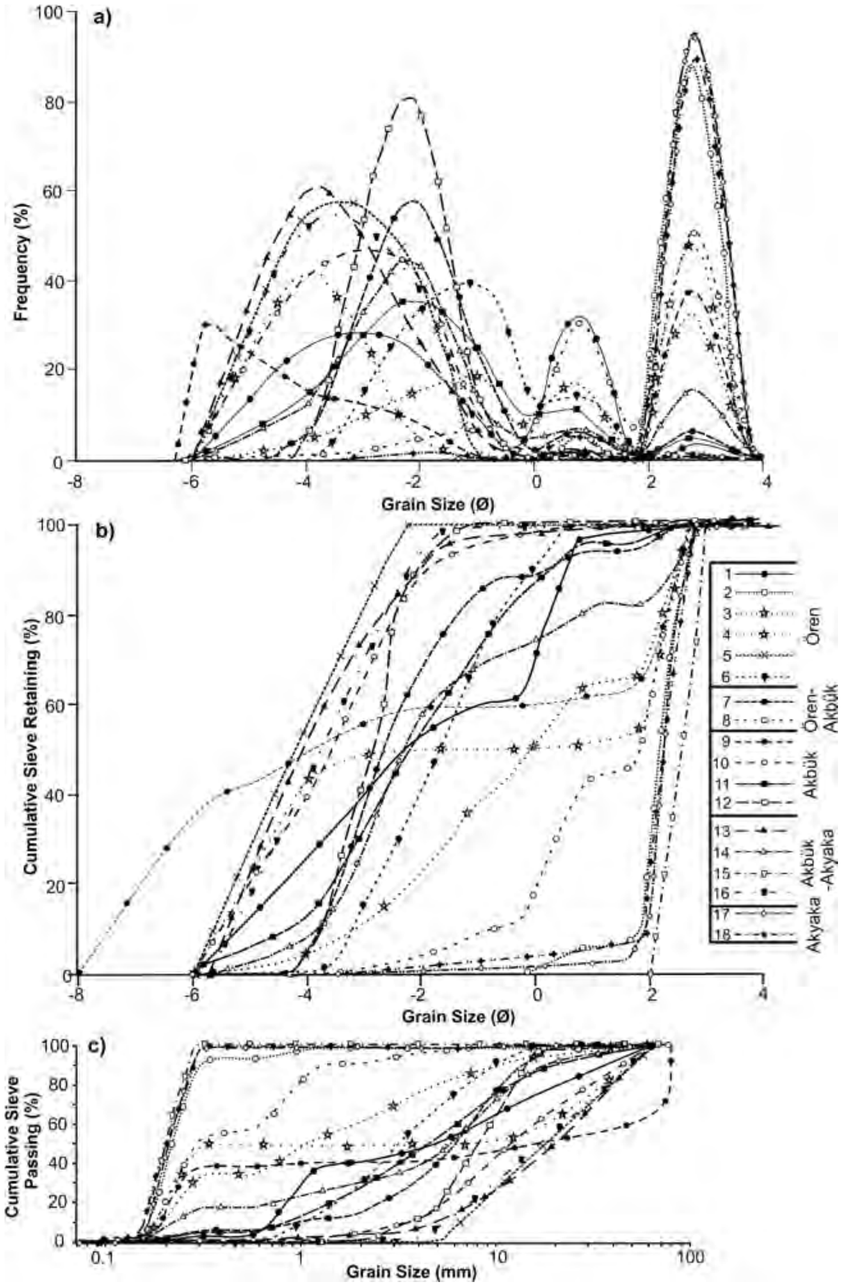
The Jurassic limestone of the Lycian Nappes and the Quaternary Gökova Formation form the primary coastal rocks of the study area. Therefore, the main source of the CaO components of the study area were limestones The higher amount of MgO and CaO values comparative to the average values

**Table 2** Detailed grain size distribution of loose samples, and statistical parameters of sieve analysis were determined based on the suggestions of Folk (1974)

| Region | Sample No | Class percentage (%) | | | | | | | | | | | | | | | | Statistical Parameters (ϕ) | | | | | Mode (ϕ) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | C (o) | VCG (*) | CG (*) | MG (*) | FG (*) | VFG (*) | VCS (+) | CS (+) | MS (+) | FS (+) | VFS (+) | Mud (−) | Gravel (*) | Sand (+) | Total (o,*,+,-) | Folk (1974) | Median (Ø) | Average Grain Size (Ø) | Sorting (Ø) | Skewness (Ø) | Kurtosis (Ø) | Mode 1 | Mode 2 | Mode 3 |
| Ören Deltas | 1 | – | 14.0 | 12.0 | 14.0 | 13.0 | 6.6 | 11.4 | 25.0 | 2.0 | 1.8 | 0.2 | – | 59.6 | 40.4 | 100 | sG | −2.3 | −2.2 | 2.3-VPS | 0.0-S | 0.6-VPK | 0.8 | −2.3 | – |
| | 2 | – | – | – | 0.4 | 0.1 | – | 1.5 | 3.6 | 28.4 | 65.8 | 0.1 | 0.1 | 0.5 | 99.4 | 100 | (g)S | 2.2 | 2.2 | 0.5-WS | −0.3-CS | 1.4-LK | 2.7 | – | – |
| | 3 | – | 2.0 | 2.9 | 8.6 | 10.5 | 14.4 | 12.1 | 14.5 | 11.0 | 23.7 | 0.3 | – | 38.4 | 61.6 | 100 | sG | −0.1 | −0.1 | 2.2-VPS | −0.1-S | 0.7-PK | 2.7 | −1.0 | 0.8 |
| | 4 | – | 20.0 | 21.8 | 4.2 | 4.0 | 0.6 | 0.1 | 1.3 | 14.0 | 33.6 | 0.4 | – | 50.6 | 49.4 | 100 | sG | −2.4 | −1.7 | 3.2-VPS | 0.2-FS | 0.5-VPK | 2.7 | −4.0 | – |
| | 5 | – | 28.0 | 26.3 | 26.7 | 18.2 | 0.3 | 0.1 | 0.1 | 0.3 | – | – | – | 99.5 | 0.5 | 100 | G | −4.2 | −4.1 | 1.2-PS | 0.1-S | 0.7-PK | −3.7 | – | – |
| | 6 | – | 0.5 | 0.4 | 19.1 | 20.0 | 31.7 | 18.3 | 9.9 | 0.1 | – | – | – | 71.7 | 28.3 | 100 | sG | −1.7 | −1.8 | 1.3-PS | 0.0-S | 0.9-PK | −1.0 | – | – |
| Ören Deltas – Akbük Region | 7 | – | 3.0 | 2.5 | 32.5 | 29.0 | 17.8 | 4.2 | 5.0 | 2.0 | 3.7 | 0.3 | – | 84.8 | 15.2 | 100 | G | −2.6 | −2.4 | 1.6-PS | 0.4-VFS | 1.3-LK | −2.3 | – | – |
| | 8 | – | – | 1.0 | 1.0 | 2.0 | 5.4 | 8.6 | 26.0 | 22.0 | 33.6 | 0.4 | – | 9.4 | 90.6 | 100 | gS | 1.8 | 1.4 | 1.3-PS | −0.6-VCS | 0.9-PK | 2.7 | 0.8 | – |
| Akbük Region | 9 | 33.5 | 7.5 | 8.0 | 5.0 | 5.0 | 0.1 | 0.9 | 2.0 | 16.0 | 21.8 | 0.2 | – | 25.6 | 40.9 | 100 | sG | −4.0 | −0.6 | 1.0-PS | 4.3-VFS | 0.5-VPK | −6.0 | 2.7 | – |
| | 10 | – | 20.0 | 20.3 | 25.7 | 21.0 | 8.2 | 2.8 | 1.5 | 0.1 | 0.3 | 0.1 | – | 95.2 | 4.8 | 100 | G | −3.6 | −3.7 | 2.0-PS | 0.2-FS | 1.6-VLK | −3.2 | – | – |
| | 11 | – | 6.0 | 7.8 | 18.2 | 22.0 | 19.4 | 13.6 | 8.0 | 3.0 | 1.9 | 0.1 | – | 73.4 | 26.6 | 100 | sG | −2.2 | −2.1 | 1.8-PS | 0.0-S | 0.9-PK | −2.3 | – | – |
| | 12 | – | 2.0 | 1.7 | 46.3 | 37.0 | 12.7 | 0.2 | 0.1 | – | – | – | – | 99.7 | 0.3 | 100 | G | −3.0 | −3.0 | 0.8-MS | 0.1-S | 1.0-MK | −2.3 | – | – |
| Akbük Region – Akyaka Town | 13 | – | 28.0 | 32.0 | 18.0 | 13.0 | 5.3 | 1.7 | 1.4 | 0.1 | 0.4 | 0.1 | – | 96.3 | 3.7 | 100 | G | −4.4 | −4.2 | 1.4-PS | 0.3-FS | 0.9-PK | −4.0 | – | – |
| | 14 | – | 6.0 | 7.0 | 26.0 | 21.0 | 10.5 | 6.5 | 6.0 | 6.0 | 10.9 | 0.1 | – | 70.5 | 29.5 | 100 | sG | −2.6 | −1.6 | 2.6-VPS | 0.4-FS | 1.0-MK | −2.3 | 2.7 | – |
| | 15 | – | – | – | – | – | 0.4 | – | 0.1 | 0.2 | 97.3 | 2.0 | – | 0.4 | 99.6 | 100 | (g)S | 2.3 | 2.3 | 0.3-VWS | −0.1-S | 0.7-PK | 2.7 | – | – |
| | 16 | – | 28.0 | 28.0 | 22.0 | 20.0 | 1.8 | 0.2 | – | – | – | – | – | 99.8 | 0.2 | 100 | G | −4.1 | −4.1 | 1.2-PS | 0.0-S | 0.7-PK | −3.8 | – | – |
| Akyaka Town | 17 | – | – | – | – | 0.3 | 1.4 | 0.3 | 1.0 | – | 97.0 | – | – | 1.7 | 98.3 | 100 | (g)S | 2.2 | 2.2 | 0.3-VWS | 0.1-S | 0.7-PK | 2.7 | – | – |
| | 18 | – | – | – | – | 0.3 | 0.3 | 0.4 | – | – | 97.0 | 2.0 | – | 0.6 | 99.4 | 100 | (g)S | 2.2 | 2.2 | 0.5- WS | −0.3-CS | 1.9-VLK | 2.7 | – | – |

**Notes: Class Percentage:** C:Cobble, VCG: Very Coarse Gravel, CG: Coarse Gravel, MG: Medium Gravel, FG: Fine Gravel, VFG: Very Fine Gravel, VCS: Very Coarse Sand, CS: Coarse Sand, MS: Medium Sand, FS: Fine Sand, VFS: Very Fine Sand; **Sorting:** VPS: Very poorly-sorted, PS: Poorly-sorted, MS: Moderately-sorted, WS: Well-sorted, VWS: Very well-sorted. **Skewness:** SFS: Strongly fine skewed, FS: Fine skewed, S: Symmetric, CS: Coarse skewed, VCS: Very coarse skewed. **Kurtosis:** VPK: Very platykurtic, PK: Platykurtic, MK: Mesokurtic, LK: Leptokurtic, VLK: Very leptokurtic. **Sediment Class (Folk 1974):** G: Gravel, sG: Sandy gravel, (s)G: Slightly sandy gravel, gS: Gravely sand, (g)S: Slightly gravely sand

**Fig. 8** **a** Frequency curves, **b** Cumulative sieve retaining (%) versus grain size (Ø) and **c** Cumulative sieve passing (%) versus grain size (mm) graphs of the eighteen loose samples of beach sediment of the study area




indicate that they are from the dolomitic rocks of the Lycian Nappes. The samples with higher values in comparative to the average values of $Fe_2O_3$, $Al_2O_3$, $TiO_2$ and $SiO_2$ show the same source rock (sourced from ophiolite rocks and/or the Gökova Formation; Fig. 2b). The northern and eastern sides of the study area include sedimentary rock with various lithology and small ophiolite and limestone nappes; they may result from the local source variation (Fig. 2b).

## Sea level changes in the study area

The understanding the coastal morphology, the coastal sedimentation characteristics, the controlling factors on sedimentation and the investigation of the effects of sea level changes on the coast require the determination of recent and ancient sea level variations (Switzer et al. 2012; Woodroffe and Murray-Wallace 2012).

The Ören delta includes a 30 cm thick gravely beach plain, which is 70 cm above the present sea level (A-A' section; Figs. 1, 2,3a, 4a, b). The recent beachrocks and wave notch at the east edge of big Ören delta show stable recent sea level (Fig. 3a). The B-B′ section contains two wave notches and two beachrock levels, which are located 2 km east of edge of the Big Ören delta (Figs. 1, 2, 3b). Both beachrock levels consist of small organisms' cavity (Fig. 4c). Those beachrocks were classified as a 'soluble: beachrock and eolinite' type by Gül

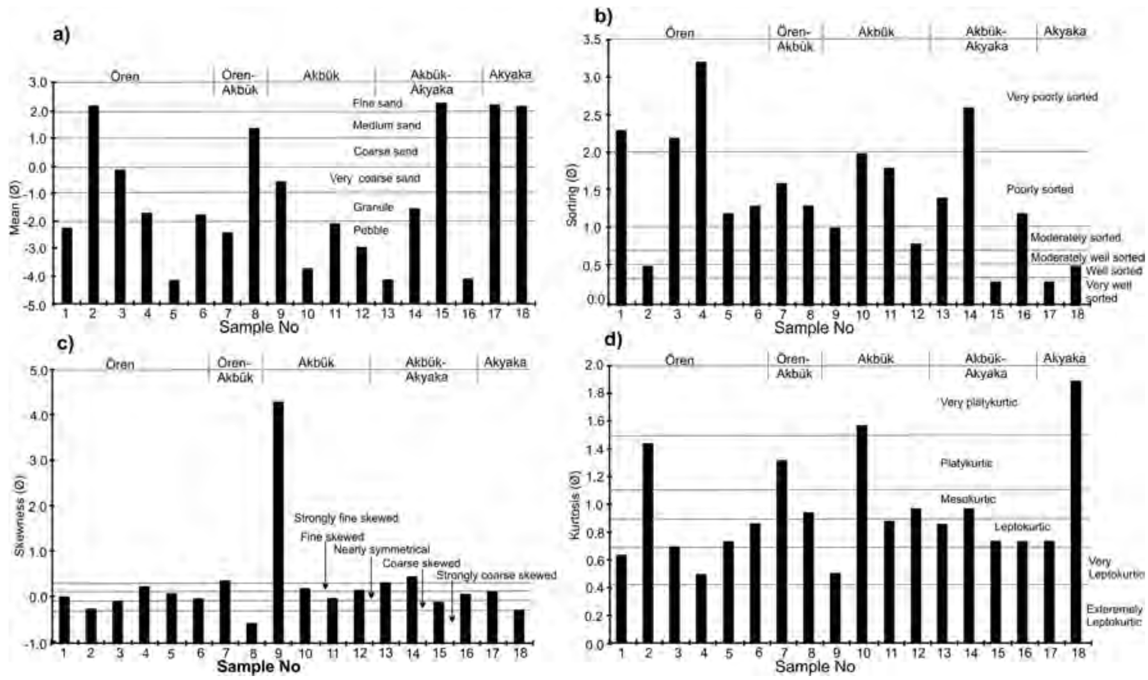



**Fig. 9** Frequency histograms and statistical evaluations of the eighteen loose samples of beach sediment of the study area

et al. (2017) based on the Fairbridge (2004) system. The colluvium and beachrocks are tightly attached to fault mirror-footwall. After cementation of the beachrocks and colluvium, they may be moving upward with the periodic movement of the footwall. Thus, the uppermost beachrock levels indicate previous sea levels. At least, such beachrock levels point to the local tectonic effects on local sea level changes in the study area.

The beachrocks were not present at the east of the Ören Deltas; only wave notch and gray color staining were fixed at the bottom of the rocky coast in the limestone of the Lycian Nappes. They show stable recent sea level similar to other eastern regions (D-D' section; Figs. 3d, 5). There is one beach plain, 50 cm above the recent sea level in the Akbük bay beach (C-C′ section; Figs. 3c, 5). The beachrock and beach plain did not develop in the east of Akbük bay even in the submarine side (based on observation sea depth of 2–3 m) and in the Akyaka Town beach (E-E' section; Figs. 3e, 7).

Previous sea level indicators were present only in the western and middle part of the study area, but they were not present on the eastern side. The evolvement of the older beachrocks was local with very limited exposures in the Ören. Similarly, the wave notches also have limited exposures. Wave erosion or weathering in other parts may have destroyed them. The beachrock, beach plain and wave notch represent the recent stable sea level. The stable sea level should develop during tectonically inactive period.

## Results

The Quaternary activity of boundary faults of the Jurassic limestone of the Lycian Nappes and Quaternary Gökova Formation conglomerate formed the northern horst of the Gökova Graben (Figs. 1, 2; Görür et al. 1995; Barka et al. 1996; Eyidoğan et al. 1996; Brückner 1997; Gürer and Yılmaz 2002; Aktar et al. 2006).

The colluviums in front of the limestone cliff include angular-sub angular limestone fragments. Longshore current is transporting and redistributing them. They have formed the

**Fig. 10** Graphs of correlation of the different statistical values. **a** Sorting (Ø) versus Average grain size (Ø). **b** Skewness (Ø) versus Sorting (Ø) show the differentiation river and beach sands (Friedman 1967)

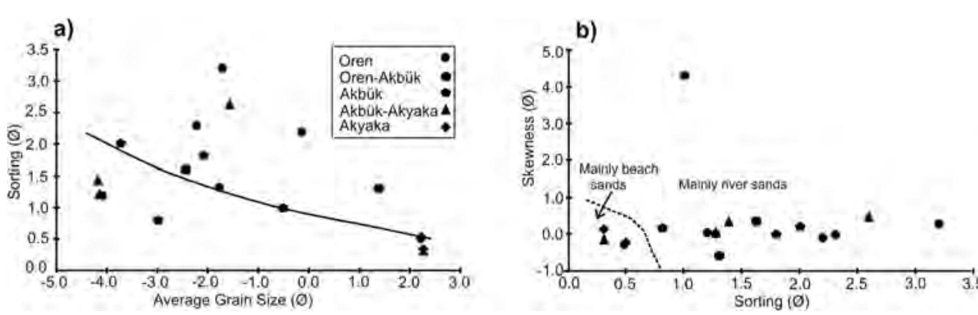


**Table 3** The major element analysis results of the 22 samples were determined by the XRF method

| Regions | Sample No | Main Element (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $SiO_2$ | CaO | NaO | MgO | $Fe_2O_3$ | $Al_2O_3$ | $K_2O$ | $TiO_2$ | $P_2O_5$ | $SO_3$ | Cl | Total |
| Ören Deltas | 1 | **42.40** | 48.65 | 0.63 | 1.45 | 2.67 | 2.70 | 0.46 | 0.17 | **0.07** | 0.12 | 0.26 | 99.58 |
| | 2 | **55.52** | 21.02 | **1.63** | 2.69 | **6.41** | **8.94** | **1.56** | **0.73** | **0.12** | **0.27** | **0.61** | 99.5 |
| | 3 | **62.06** | 25.17 | **1.10** | 1.40 | **3.89** | **3.85** | **0.70** | **0.32** | 0.06 | **0.24** | **0.82** | 99.61 |
| | 4 | **55.15** | 32.46 | **1.02** | 1.58 | **3.51** | **3.83** | **0.72** | **0.35** | 0.06 | **0.20** | **0.56** | 99.44 |
| | 5 | 23.00 | **69.50** | 0.30 | **3.08** | 1.68 | 1.76 | 0.29 | 0.15 | 0.03 | 0.06 | 0.05 | 99.9 |
| | 6a Br | **59.27** | 27.80 | **0.98** | 1.64 | **3.80** | **4.72** | **0.75** | **0.28** | **0.08** | 0.09 | 0.16 | 99.57 |
| | 6 | **50.03** | 35.84 | **1.48** | 2.70 | **3.46** | **3.78** | **0.64** | **0.25** | **0.09** | **0.47** | **0.77** | 99.51 |
| Ören Deltas – Akbük Region | Br1 | 34.62 | **51.01** | **1.67** | **3.30** | **3.82** | 2.78 | 0.46 | **0.26** | **0.07** | **0.44** | **1.14** | 99.57 |
| | Br2 | **42.36** | 41.82 | **1.31** | **3.17** | **4.88** | **4.04** | **0.61** | **0.32** | **0.09** | **0.30** | **0.64** | 99.54 |
| | Br3 | 37.82 | 49.41 | **1.10** | 1.60 | **3.60** | **3.90** | **0.62** | **0.26** | **0.08** | 0.17 | **0.46** | 99.02 |
| | 7 | **60.40** | 31.71 | 0.51 | 1.19 | 2.52 | 2.47 | 0.42 | 0.17 | 0.06 | 0.07 | 0.09 | 99.61 |
| | 8 | **45.09** | 49.45 | 0.34 | 1.17 | 1.54 | 1.48 | 0.28 | 0.11 | 0.04 | 0.07 | 0.06 | 99.63 |
| Akbük Region | 9 | 15.62 | **76.51** | **0.92** | 1.67 | 1.55 | 1.65 | 0.20 | 0.16 | 0.03 | **0.53** | **0.75** | 99.59 |
| | 10 | 3.78 | **93.35** | 0.21 | 0.92 | 0.58 | 0.57 | 0.09 | 0.05 | 0. 01 | 0.08 | 0.07 | 99.7 |
| | 11 | 16.79 | **77.45** | 0.51 | 1.11 | 1.64 | 1.39 | 0.24 | 0.11 | 0.02 | 0.14 | 0.20 | 99.6 |
| | 12 | 5.99 | **88.70** | 0.20 | **3.56** | 0.49 | 0.51 | 0.10 | 0.04 | 0.02 | 0.05 | 0.07 | 99.73 |
| Akbük Region – Akyaka Town | 13 | 10.10 | **76.90** | **2.36** | **6.56** | 1.67 | 1.81 | 0.28 | 0.12 | 0.03 | 0.07 | 0.08 | 99.98 |
| | 14 | 4.99 | **85.40** | 0.25 | 0.99 | **3.51** | **3.81** | 0.09 | **0.46** | 0.02 | 0.07 | 0.08 | 99.67 |
| | 15 | 24.17 | **64.10** | 0.21 | 1.95 | 2.34 | 1.24 | 0.16 | 0.19 | 0.03 | 0.08 | 0.04 | 94.51 |
| | 16 | **63.38** | 24.10 | **1.17** | 1.50 | **3.59** | **3.88** | **0.65** | **0.30** | 0.06 | **0.25** | **0.67** | 99.55 |
| Akyaka Town | 17 | **57.32** | 20.56 | **1.19** | **9.16** | **6.03** | **3.46** | **0.61** | 0.18 | 0.05 | 0.03 | **0.65** | 99.24 |
| | 18 | **51.61** | 25.05 | 0.62 | **8.89** | **7.08** | **4.71** | **0.72** | **0.34** | 0.06 | 0.13 | 0.07 | 99.28 |
| Average | | 37.34 | 50.73 | 0.90 | 2.79 | 3.19 | 3.06 | 0.48 | 0.24 | 0.06 | 0.18 | 0.38 | 99.34 |

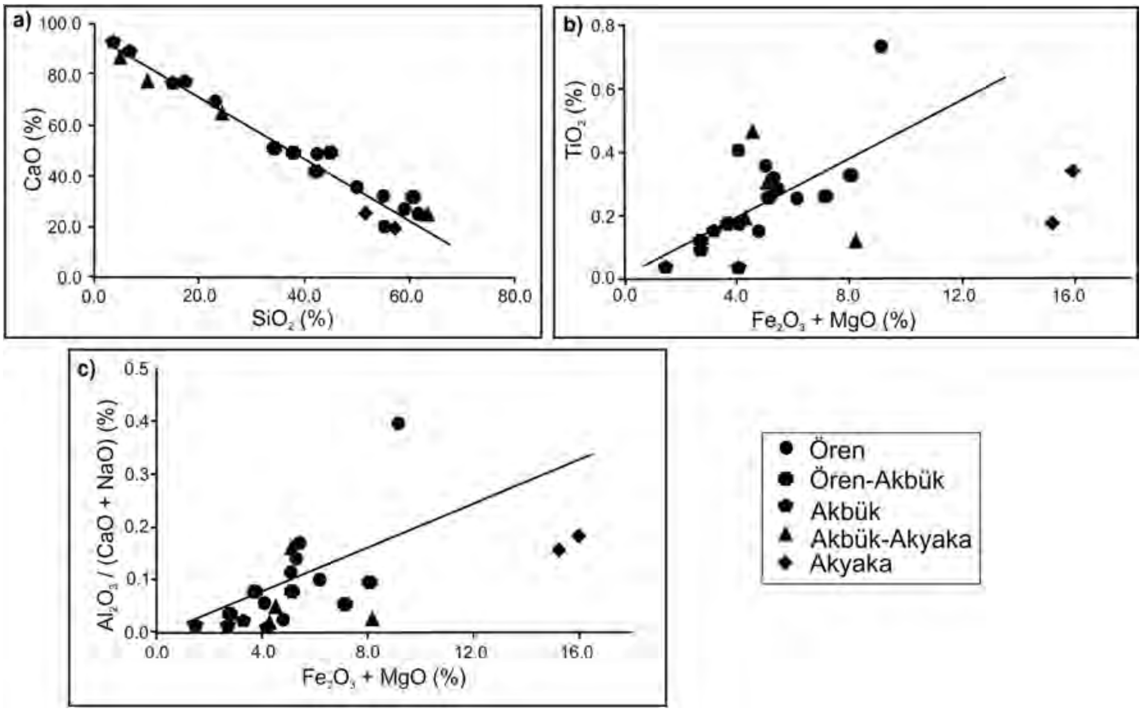



**Fig. 11** XRF analysis results were evaluated based on graphs proposed by Bhatia (1983). **a** $SiO_2$ (%) - CaO (%) diagram. **b** $TiO_2$ (%) - $Fe_2O_3$ + MgO (%) diagram. **c** $Al_2O_3$/(CaO + NaO) - $Fe_2O_3$ + MgO (%) diagram

narrow gravely beach with restricted distributions (Fig. 3b). Similarly, the narrow-strip shaped gravely shingle beaches in between the Akbük bay and the Akyaka Town (Figs. 2b, 3d) were evolving in front of the Gökova Formation cliff. Gravity and seasonal brooks as a result of down dip direction in this part transported conglomerate fragments (reworked), limestone and ophiolite gravels. The longshore current has distributed them in front of the hill. Moreover, sea wave may winnow the fine-grain size sediments and promote the development of gravely shingle beach.

The deltaic sediments of Ören Town, Akbük bay and Akyaka Town were observed in front of the perennial stream mouth (Figs. 1, 2, 3). The wide sandy beach has evolved in shore of the Akyaka Town, while the rest of the Gökova delta beach contains a bimodal sandy gravel beach. The longest stream of the study area, located in the Akyaka region may form the finest and the widest sediment accumulation (Table 2; Figs. 1, 2, 3). Short streams feed the Ören deltas, the Akbük and Zeytinlik bay beaches (Fig. 2b). The hinterland of these streams contains durable-resistant limestone and less durable ophiolite. Under similar weathering and transportation condition, limestones form coarser sediments. The main chemical components of the examined sediments from the Gökova Gulf coast are CaO because of feeding from limestone. The $SiO_2$ and to a lesser extent $Fe_2O_3$, $Al_2O_3$ and MgO are other components and sourced from ophiolitic rocks, or from reworking of old conglomerate, which have the same source (Table 3).

The recent and old beach rock formations and beach plain development were only observed in the western part of the study area. They are not present in the eastern part.

## Discussions

In this section, we discussed the environmental implication of future sea level rise on the NE Gökova Graben. Followed by a clarification of the reasons of variable coastal structures formation at short distances such as normal fault orientation, coastal rock type differences, and fresh-water entrance.

### Sea level variations around the study area and environmental implications of Future Sea level changes

The southwest Anatolia and Gökova Graben have suffered from coastal line changes, sea level variations and seismic activities since ancient times (Brückner 1997; Bekaroğlu 2008; Desruelles et al. 2009; Brückner et al. 2010). For example, the Ephesus and Miletus ancient port cities were landlocked areas as a result of the high sediment input from the Büyük Menderes River (Fig.1; Brückner 1997; Brückner et al. 2010). A sea level fall of 2 m hit the ancient city of Knidos (southwest of the Gökova Gulf) during the fourth century AD (Fig. 1; Kayan 1988). Uluğ et al. (2005) determined that the sea level was (−110 m) lower than present in 18 millennia BC in the Gökova Gulf. They determined a 0.3 to 0.4 mm/year basin collapse from sedimentary records. An 8 cm rise in sea level occurred in Bodrum Town between 1985 and 2005 (Demir et al. 2011). Yıldız et al. (2003) emphasized that there were no sea level changes depending on the tectonic activities in Bodrum between 1992 and 2002. Therefore, a rise of 8 cm sea level between 1985 and 2005 (Demir et al. 2011) might have been from climatic effect. Based on Bodrum observatory station measurements, Alpar et al. (2000) reported annual seasonal wave variation between −12.6 cm (on May) and 6.2 cm (December) after 1985.

Uluğ et al. (2005) and Uluğ and Kaşer (2007) worked on the subaerial and subaqueous parts of the Ören delta. They reported the tectonic activities of local structures affecting sedimentation and sea level fluctuation during Late Quaternary. Balas and İnan (2011) and Balas et al. (2011) emphasized that the coastal erosion and shore line changes in the easternmost part of the Gökova Graben were due to man-made structure. Büyüksaraç et al. (2010) used geophysical techniques to point out the site of the ancient harbor city called Idyma to the east of the Akyaka Town. Sediments of the Gökova delta have covered this city (Büyüksaraç et al. 2010; Fig. 2b). High sediment input and coastal erosion control the coastal line change and local sea level variation in the eastern end of the Gökova Gulf.

Desruelles et al. (2009) emphasized that during the stable (probably for several centuries) shoreline, evolution of beachrocks occurred. Moreover, they emphasized that the beachrock is a less reliable sea level indicator than the bioerosion and wave notches. Galili et al. (2007) reported that cementation of beachrock may occur within a few centuries or decades or a thousand years like the beachrock in the Carmel coastal plain (Israel). Therefore, there is no consensus on the duration of a stable sea level for beachrock formation. Climatic condition, $Ca^{+2}$ and $CO_3^{-2}$ concentrations, organic activity, cold-fresh water entrance and the clarity the of sea may control the beachrock formation (Turner 2005). A warm sea, high $Ca^{+2}$ and $CO_3^{-2}$concentrations, high organic activity and limited fresh water entrance promotes the beachrock formation in a short time. The Ören delta is under subtropical climatic condition, with fresh-cold water input and a lack of high organic activity. Thus, the recent beachrock formation may need longer time, more than a decade or even centuries. Their presence in the restricted region is due to local fault. On the other hand, subsequent wave actions, residential areas, road constructions or agricultural activity may destroy the local fault extension. The recurrence time of the boundary of normal fault in a graben and its correlation with the age of beachrock are required in determination of tectonically induced sea level changes.

Threat to coastal regions may emanate from global warming (extreme temperature rise, rainfall reduction, drought, coastal erosion, and flooding of shores and low-altitude areas) and pollution of ground water due to seawater intrusions (Mörner 2005; Bindoff et al. 2007; Christensen et al. 2007; IPCC 2007; Cronin 2012; Engelhart and Horton 2012; Switzer et al. 2012; Woodroffe and Murray-Wallace 2012; IPCC 2014). According to IPCC (2014), the last thirty years are the warmest period of the last 1400 years due to anthropogenic factors. The sea level will continue to rise for centuries and will continue to pose a threat to coasts and low-lying areas, even if global mean temperature is stabilized (IPCC 2014). In addition to the natural process (such as storms and tsunami), the agricultural process, urbanization and mismanagement of the coastal region, rapid and uncontrolled coastal structures and buildings have affected the coastal region in the last millennium (Frihy 2001; Switzer et al. 2012). Mediterranean societies must develop adaptation strategies to avoid the negative effects of climate changes (Billé 2008). Possible sea level rise will affect the Turkish coasts, which may result in loss of Turkish gross national income (Demirkesen et al. 2008; Simav et al. 2008). The possible sea level rise will affect Muğla, the city with the longest coast in Turkey.

Karymbalis and Seni (2005) proposed that the low-lying region including agricultural and settlement area in the Argos Gulf (Greece) is the area most sensitive to future sea level rise; land below 1.0 m was considered to be a high-risk area, 1.0–2.0 m was considered to be medium-risk, and the region between 2.0 and 4.0 m was considered a low risk area. They also concluded that the possible sea level rise would not significantly affect the rocky coast; however, erosion due to sea level rise would destroy the narrow shingle beaches. Moreover, the 6.6 magnitude earthquake on 21 July 2017 caused a 13 cm height tsunami wave and a sea wave 30–40 cm in height. The tsunami waves climbed to a height of 1.9 m in some regions of Bodrum Town and dragged the cars into the sea (KOERI 2017). Fig. 2a shows the high risk and medium risk area of study region. Those regions contain settlements and are very important for summer tourism (beaches of the Ören deltas, Akbük bay and Akyaka Town). They are under a great risk of wave erosion and invasion of seawater.

In order to avoid these adverse effects, such coastal areas should be closed to urbanization, ground water extraction should be limited and the additional gauge station should be established in different part of the Gökova Gulf in order to monitor the sea level fluctuations. Relocation of some residential buildings close to the shoreline may be considered.

## Coastal morphology under the effects structural properties, coastal rock, and sediment input

According to geophysical studies, steep normal faults form the northern edge of the Gökova Graben, while the southern edge contains low inclined normal faults (Kurt et al. 1999; Uluğ et al. 2005). In addition to master faults, the NW-SE oriented small faults are located inside this graben (forming submarine rifts and trenches) and obliquely cut the basin margin (Gürer and Yılmaz 2002; Uluğ et al. 2005).

The normal fault scarps formed the rocky coasts of the eastern and western side of the Ören Town (Fig. 2). The rocky coasts to the west of Zeytinlik bay are formed by high resistant limestone. The durable Quaternary conglomerates form the rocky coast between Akbük bay and Akyaka Town (Fig. 2). Margin faults (normal fault) in this region have led to the formation of the steepness of the cemented conglomerate. The subsequent wave erosion promotes this steepness.

Relatively big and longer rivers pour into the Gökova Gulf in the Ören and Akyaka Town area. Their hinterland properties (source rock type, climate and structural properties) control the type and amount of sediment input, leading to sandy beach development in the Akyaka Town area and gravely sandy beaches in Ören Town. Despite the short transportation distance, the narrow-gravely shingle beach in the study area contain well to moderately rounded sediments. These narrow-gravely shingle beaches sediments were mainly reworked from the Quaternary fluvial Gökova Formation (Görür et al. 1995).

The present study pointed out that different controlling factor (river, hinterland of river, fault orientation, coastal rock type), which may significantly affect the coast type and coastal sedimentation even in a short distance. A more detailed study dealing with tectonic induced sea level variation in the graben is recommended, since subsequent tectonic activities may cause rapid and inevitable sea level rise. Continuous, but small-scale sea level rise due to global warming increases the risk of coastal invasion. Recently, these coastal regions are under the threat of high urbanization, the construction of man-made structures, global warming and the rise of sea level due to tectonic activities. Therefore, the nature and morphology of the coast must be explored in detail before any constructive, restorative and preventive measure.

## Conclusion

The coastal rock type (limestone and conglomerate), the structural features of the study area (normal faults, fractures) and rivers have led to the formation four different coasts: the rocky coast, delta, narrow gravely shingle beach and wide sandy beach. The narrow gravely shingle beaches of the study area contain poorly to very poorly sorted, well-rounded gravel and sandy gravels. The longer transportation of sediments by river results in well to moderately sorted, fine-grained sediment bearing sandy beach. The recent beachrocks, wave notch and beach plain development indicate the long-term static-stable sea level in the study area. However, emerged beachrocks and wave notch levels indicate previous sea levels, which evolved, as a result of the normal fault activities. The coastal rock type and tectonic activities are primary controlling factors on the coastal type and on sedimentation in the Gökova Gulf. Local sea level changes, longshore current, drainage path, and weathering are the other factors controlling beach sedimentation.

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## References

Adger WN, Hughes TP, Folke C, Carpenter SR, Rockström J (2005) Social-Ecological Resilience to Coastal Disasters. Science309: 1036–1039

Aktar M, Karabulut H, Childs D, Mutlu A, Ergin M, Yörük A, Geçgel V, Bulut F, Kaya T (2006) Determination current seismic activity of active faults in the Gulf of Gokova (Mugla). The Scientific and Technological Research Council of Turkey (TÜBİTAK), report no: 104Y336, 31 p (unpublished, in Turkish)

Alpar B, Dogan E, Yüce H, Altıok H (2000) Sea level changes along the Turkish coasts of the Black Sea, the Aegean Sea and the eastern Mediterranean. Mediterranean Marine Science 1(1):141–156. https://doi.org/10.12681/mms.285

Atalay Z (1980) Stratigraphy of continental Neogene in the region of Muğla-Yatağan, Turkey. Geological Bulletin of Turkey 23:93–99 (in Turkish with English Abstract)

Balas L, İnan A (2011) Determination of sediment transport in coast and coastline changes in Akyaka.The Scientific and Technological Research Council of Turkey (TÜBİTAK), report no: 109Y180, 53 p (unpublished, in Turkish)

Balas L, Inan A, Yılmaz E (2011) Modelling of sediment transport of Akyaka Beach. J Coast Res 64:460–463

Barka A, Altunel E, Akyüz S, Şaroğlu F, Emre Ö, Kuşçu İ (1996) Determination of earthquake activity active faults near Gulf of Gokova and Saros with geological, geomorphological palaeoseismic methods and 1995 Dinar earthquake. The Scientific and Technological Research Council of Turkey (TÜBİTAK), report no: YDABÇAG 237-G, 102 p (unpublished, in Turkish)

Bekaroğlu E (2008) A review on the elevated shorelines in the eastern Mediterranean during the Late Holocene. Coğrafi Bilimler Dergisi (Journal of Geographical Sciences) 6(1):1–21 (in Turkish with English Abstract)

Bhatia MR (1983) Plate tectonics and geochemical composition of sandstones. J Geol 91:611–627

Billé R (2008) Adapting to climate change in the Mediterranean: Some Questions & Answers. Synthèses No: 1/2008 Climate Change

Bindoff NL, Willebrand J, Artale V, Cazenave A, Gregory J, Gulev S, Hanawa K, Le Quéré C, Levitus S, Nojiri Y, Shum CK, Talley LD, Unnikrishnan A (2007) Observations: oceanic climate change and sea level. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, (Eds.) Climate change 2007: The physical science basis. Contribution of working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Bozkurt E (2001) Late alpine evolution of the Central Menderes massif, Western Anatolia, Turkey. Int J Earth Sci 89:728–744

Bozkurt E, Satır M (2000) The southern Menderes massif (western Turkey): geochronology and exhumation history. Geol J 35:285–296

Brückner H (1997) Coastal changes in western Turkey; rapid delta progradation in historical times. In: Briand F, Maldonado a (Eds.) transformations and evolution of the Mediterranean coastline. In: CIESM science Series3:63–74

Brückner H, Kelterbaum D, Marunchak O, Porotov A, Vött A (2010) The Holocene Sea level story since 7500 BP – lessons from the eastern Mediterranean, the black and the Azov seas. Quat Int 225:160–179

Büyüksaraç A, İren K, Kaya C (2010) An Investigation Archaeological Area of Idyma (Mugla) Ancient City with using and Integrated Geophysical Method. The Scientific and Technological Research Council of Turkey (TÜBİTAK) Report No: 108Y235, 46 p (unpublished, in Turkish with English Abstract)

Carranza-Edwards A, Bocanegra-Garcia G, Rosales-Hoz L, Galan LP (1998) Beach sands from Baja California peninsula, Mexico. Sedimentary Geology119:263–274

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Koll RK, Kwon WT, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P (2007) Regional climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (Eds.) Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University press, Cambridge, United Kingdom and New York, NY, USA

Collins AS, Robertson AHF (1997) Lycian mélange, southwestern Turkey: an emplaced late cretaceous accretionary complex. Geology 25:255–258

Collins AS, Robertson AHF (1998) Processes of late cretaceous to Late Miocene episodic thrust sheet translation in the Lycian Taurides, SW Turkey. J Geol Soc Lond 155:759–772

Collins AS, Robertson AHF (1999) Evolution of the Lycian allochthon, western Turkey, as a north-facing late Palaeozoic to Mesozoic rift and passive continental margin. Geol J 34:107–138

Cronin TM (2012) Rapid sea-level rise. Quat Sci Rev 56:11–30

Demir C, Yıldız H, Simav M, Cingöz A (2011) Long-Term Sea Level Changes on Turkey Coast,ftp://144.122.146.136/pub/uik_sunum/Hasan_Yildiz.ppt. (Access date: 25 September 2011), (in Turkish)

Demirkesen A, Evrendilek F, Berberoğlu S (2008) Quantifying coastal inundation vulnerability of Turkey to sea-level rise. Environment Monitory Assessment 138:101–106

Desruelles S, Fouache E, Çiner A, Dalongeville R, Pavlopoulos K, Kosun E, Coquinot Y, Potdevin JL (2009) Beachrocks and sea level changes since middle Holocene: comparison between the insular group of Mykonos–Delos–Rhenia (Cyclades, Greece) and the southern coast of Turkey. Glob Planet Chang 66:19–33

Dirik K, Türkmenoğlu A, Tuna N, Dirican M (2003) Neotectonics, Geomorphology of the Datça Peninsula, and Their Impact on Ancient Civilizations Placement and Development Middle East Technical University Project No: AFP-00-07-03-13, 66 p (in Turkish)

Engelhart SE, Horton BP (2012) Holocene Sea level database for the Atlantic coast of the United States. Quat Sci Rev 54:12–25

Ersoy Ş (1990) The analysis of evolution and structural items of the Western Taurus - Lycian–nappes. Journal of Geological Engineering 37:5–16 (in Turkish with English Abstract)

Ersoy Ş (1991) Stratigraphy and tectonics of the Datça (Muğla) peninsula. Geological Bulletin of Turkey34 1-14(in Turkish with English Abstract)

Eyidoğan H, Akıncı A, Gündoğdu O, Polat O, Kaypak B (1996) Analysis of current seismicity of the Gökova Basin. The Scientific and Technological Research Council of Turkey (TÜBİTAK) Report No: YDABÇAG 238-G: 36 p (unpublished, in Turkish)

Fairbridge RW (2004) Classification of coasts. J Coast Res 20(1):155–165

Finkl CW (2004) Coastal classification: systematic approaches to consider in the development of a comprehensive system. J Coast Res 20(1):166–213

Folk RL (1974) Petrology of sedimentary rocks: Hemphill publishing co. TX, Austin 182 p

Friedman GM (1967) Dynamic process and statistical parameters for size frequency distributions of beach and river sands. Journal Sedimentary Petrology 37:327–254

Frihy OE (2001) The necessity of environmental impact assessment (EIA) in implementing coastal projects: lessons learned from the Egyptian Mediterranean coast. Ocean & Coastal Management 44: 489–516

Furlani S, Pappalardo M, Gómez-Pujol L, Chelli A (2004) Chapter 7 the rock coast of the Mediterranean and black seas. Geological Society, London, Memoirs 40:89–123

Galili E, Zviely D, Ronen A, Mienis HK (2007) Beach deposits of MIS 5e high sea stand as indicators for tectonic stability of the Carmel coastal plain, Israel. Quat Sci Rev 26:2544–2557

Görür N, Şengör AMC, Sakınç M, Tüysüz O, Akkök R, Yiğitbaş E, Oktay FY, Barka A, Sarıca N, EcevitoğluB DE, Ersoy Ş, Algan O, Güneysu C, Aykol A (1995) Rift formation in the Gökova region, Southwest Anatolia: implications for the opening of the Aegean Sea. Geol Mag 132(6):637–650

Gül M (2015) Lithological properties and environmental importance of the quaternary colluviums (Mugla, SW Turkey). Environmental Earth Sciences 74:4089–4108

Gül M, Kurt MA, Zorlu K (2008a). The effects of global warming and sea level rise in and around the center of Mersin Province monitored until the end of the 21$^{st}$century. Mersin symposium, 19–22 November 2008, Proceedings, Mersin (in Turkish)

Gül M, Özbek A, Karayakar F, Kurt MA (2008b) Biodegradation effects over different types of coastal rocks. Environ Geol International Journal of Geosciences 55:1601–1611

Gül M, Özbek A, Kurt MA, Zorlu K (2009) Controlling factors of the recent clastic coastal sediments Viranşehir, Mersin Bay-S Turkey. Environmental Geology International Journal of Geosciences 57(4): 809–822

Gül M, Altun NE, Zeybek Ö, Yılmaz Ö (2011) Morphological characteristics of the coastal zone, coastal sediments classification, to investigate the possible effects of sea level rise in between the Akyaka and Ören (Mugla). Muğla Sıtkı Koçman University, Research Fund Project, Project No: BAP 10-20:54p (unpublished in Turkish)

Gül M, Karacan E, Aksoy ME (2013) An investigation of general geologic and engineering geological properties of Mugla city Centre and surrounding. Mugla Sıtkı Koçman University Research Fund: BAP Project No: 12/54. 25 p (in Turkish)

Gül M, Danladi IB, Kore BM (2017) Coastal types of graben: the Gulf of Gökova, Mugla-SW Turkey. J Coast Conserv 21:127–138. https://doi.org/10.1007/s11852-016-0481-5

Gürer ÖF, Yılmaz Y (2002) Geology of the Ören and surrounding regions, SW Turkey. Turkish Journal Earth Science 11:2–18

Gürer ÖF, Sanğu E, Özburan M, Gürbüz A, Sarica-Filoreau N (2013) Complex basin evolution in the Gökova gulf region: implications on the late Cenozoic tectonics of Southwest Turkey. Int J Earth Sci (Geol Rundsch) 102:2199–2221

IPCC-Intergovernmental Panel on Climate Change (2007) Climate change 2008: The physical science basis. Contribution of the working group I to the fourth assessment report of the intergovernmental panel on climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) . Cambridge University Press, Cambridge, p 996

IPCC-Intergovernmental Panel on Climate Change (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team: Pachauri RK and Meyer LA (eds.)]. IPCC, Geneva, Switzerland, 151 p

Johnson DW (1919) Shore processes and shoreline development. Wiley, New York 584p

Karymbalis E, Seni A (2005) Coastal geomorphology and future sea-level rise impacts at the Eastern Gulf of Argos In: (Ozhan E, (Ed)) Proceedings of the Seventh International Conference on the Mediterranean Coastal Environment, M*EDCOAST* 05, 25–29 October 2005, Kuşadası-Turkey, 1287–1298

Kayan İ (1988) Late Holocene Sea-level changes on the Western Anatolian coast. Paleogeography, Paleoclimatology, Paleoecology 68:205–218

Kilibarda Z, Graves N, Dorton M, Dorton R (2014) Changes in beach gravel lithology caused by anthropogenic activities along the southern coast of Lake Michigan, USA. Environmental Earth Science 71: 1249–1266

KOERI (2017) http://www.koeri.boun.edu.tr/sismo/2/wp-content/uploads/2017/07/Gokova.Korfezi.v4.pdf (access date: 08.09.2017)

Kurt H, Demirbağ E, Kuşçu İ (1999) Investigation of the submarine active tectonism in the Gulf of Gökova, Southwest Anatolia–Southeast Aegean Sea, by multi-channel seismic reflection data. Tectonophysics 305:477–496

Leeder MR (1982) Sedimentology, process and product. Chapman and Hall, USA 344 p

Mörner NA (2005) Sea level changes and crustal movements with special aspects on the eastern Mediterranean. In: Fouache E, Paulopoulos K (Eds.) Sea Level Change in Eastern Mediterranean during Holocene – Indicators and Human Impacts, Annals of Geomorphologie Supplemented Volume: 137. Gebrüder Borntraeger, Berlin, Stuttgart, 91–102

Okay Aİ (1989) Geology of the Menderes massif and the Lycian nappes in the south of Denizli. Bulletin of General Directorate of Mineral Research and Exploration Institute (MTA)109:45–58 (in Turkish)

Owens, EH (1994) Canadian Coastal Environments, Shoreline Processes, and Oil Spill Cleanup. Ottawa, Ontario: Environment Canada, Environmental Emergency Branch, Report EPS 3/SP/5, 328p

Özer S, Sözbilir H, Özkar I, Toker V, Sarı B (2001) Stratigraphy of upper cretaceous–Palaeogene sequences in the southern and eastern Menderes massif (western Turkey). International Journal Earth Science 89:852–866

Palyvos N, Pantosti D, De Martini PM, Lemeille F, Sorel D, Pavlopoulos K (2005) The Aigion–Neos Erineos coastal normal fault system (western Corinth gulf rift, Greece): geomorphological signature, recent earthquake history, and evolution. J Geophys Res 110: B09302, 15p

Pirazzoli, PA, Pluet J (1991) World Atlas of Holocene Sea-Level ChangesElsevier Oceanography Series 58,311 p

Prospathopoulos A, Sotiropoulos A, Chatziopoulos E, Anagnostou C (2004) Cross-shore profile and coastline changes of a sandy beach in Pieria, Greece, based on measurements and numerical simulation. Mediterr Mar Sci 5(1):91–108. https://doi.org/10.12681/mms.214

Ramamohanarao T, Sairam K, Venkateswararao Y, Nagamalleswararao B, Viswanath K (2003) Sedimentological characteristics and depositional environment of upper Gondwana rocks in the Chintalapudi sub-basin of the Godavari valley, Andhra Pradesh, India. Journal of Asian Earth Science 21:691–703

Reinson GE (1992) Transgressive Barrier Island and estuarine systems. In: Walker RG, James NP (eds) Facies models; response to sea level change. Geological Association of Canada, pp 179–194

Sahu BK (1983) Multigroup discrimination of depositional environments using size distribution statistics. Indian Journal Earth Science 10:20–29

Şenel M (1997) Fethiye–L7 Quadrangle, 1: 100 000 Scale Geological Map and Explanatory Text Mineral Res Explor Institute of Turkey (MTA) Publications, 17 p (unpublished, in Turkish)

Shepard FP (1948) Submarine geology. Harper, New York 348p

Simav M, Yıldız H, Arslan E (2008) Investigation of sea level variations in the eastern Mediterranean Sea by using satellite altimetry data. Journal of Map (Harita Dergisi) 139:1–31 (in Turkish with English Abstract)

Spezzaferri S, Basso D, Koral H (2000) Holocene palaeoceanographic evolution of the Iskenderun bay, south-eastern Turkey, as a response to river mouth diversions and human impact. Mediterr Mar Sci 1(1): 19–44. https://doi.org/10.12681/mms.3

Switzer AD, Sloss CR, Horton BP, Zong Y (2012) Introduction: preparing for coastal change. Quat Sci Rev 54:1–3

Turner RJ, (2005) Beachrock.In: Schwartz, M.L., (Ed), Encyclopedia of Coastal Science. Kluwer Academic Publishers, the Netherlands 183–186

Uluğ A, Kaşer N (2007) Structure and seismicity of the Ören Delta in the Gulf of Gökova, southeastern Aegean Sea. 6th National Coastal Engineering Symposium (Ulusal Kıyı Mühendisliği Sempozyumu). Proceedings İzmir, pp 453-458(in Turkish, with English Abstract)

Uluğ A, Duman TM, Ersoy Ş, Özel E, Avcı M (2005) Late Quaternary Sea-level change, sedimentation and neotectonics of the Gulf of Gökova: southeastern Aegean Sea. Mar Geol 221:381–395

UNEP/MAP United Nations Environment Program / Mediterranean Action Plan (2012) State of the Mediterranean marine and coastal environment. UNEP/MAP – Barcelona convention. Athens 2012:96

Wentworth CK (1922) A scale of grade and class terms for clastic sediments. J Geol 30:377–392

Woodroffe CD, Murray-Wallace CV (2012) Sea-level rise and coastal change: the past as a guide to the future. Quat Sci Rev 54:4–11

Yıldız H, Demir C, Gürdal MA, Akabalı OA, Demirkol EÖ, Ayhan ME, TürkoğluY (2003) Analysis of sea level and geodetic measurements of Antalya-II, Bodrum-II, Erdek and Menteş tide gauges in the period of 1984-2002. Journal of map (Harita Dergisi), Special Issue, 17, 75p (in Turkish with English Abstract)