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Seismic stratigraphy of Late Quaternary deposits on the continental shelf of Antalya Bay, Northeastern Mediterranean

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Abstract

The Late Quaternary sedimentation and structural features of the continental shelf of Antalya Bay (SW Turkey) have been investigated using a single channel high-resolution shallow profiling system. Two seismic units denoted as unit 1 and unit 2 bounded by two major unconformities (R_1 and R_2) have been identified. R_1 and R_2 are type-1 sequence boundaries that formed under sub-aerial conditions during the Late Quaternary sea level lowstands. An acoustic basement (AB) is recognized in the study region; it is the oldest unit in the area and is overlain by seismic units 1 and 2. The seismic unit 2 deposited on R_2 prior to the Last Glacial Maximum lowstand of the sea level and consists of two subunits (2A and 2B). Subunit 2A is interpreted as a lowstand systems tract. The upper sediments of subunit 2B appear to have been truncated by erosion. Seismic unit 1, the uppermost unit formed on R_1 during the Last Glacial Maximum lowstand of the sea level and the following post glacial transgression, is comprised of three subunits 1A, 1B, and 1C. These subunits form the lowstand, transgressive and highstand systems tracts of unit 1, respectively. Off the Aksu River mouth, where the maximum sedimentation occurs, lowstand delta facies (Δ_1 and Δ_2) formed in both unit 1 and unit 2. Sediment supply and tectonic uplift that interact with glacio-eustatism have also controlled temporal and spatial distributions of Late Quaternary deposits in the shelf of Antalya Bay.

Keywords: Bathymetry; Seismic stratigraphy; Sequence stratigraphy; Holocene; Antalya Bay; Mediterranean Sea

1. Introduction

During the Late Quaternary, despite various influences such as climate and river regimes, sediment deposition on continental shelves has been mainly affected by sea level changes. Seafloor bedforms and shallow subsurface deposits can preserve the effects of the late Pleistocene—Holocene sea-level oscillations.

Several investigations have been conducted in the continental shelf regions of the southern coast of Turkey, to improve the knowledge of the distribution pattern of the Quaternary sedimentary sequences and their depositional history during Late Quaternary times (Alavi et al., 1989; Okyar, 1991; Aksu et al., 1992; Ergin et al., 1992; Ediger et al., 1993). However, no regional shallow high-resolution seismic surveys were previously carried out in the shelf region of Antalya Bay.

The purpose of the present study is to interpret single channel high-resolution seismic data with a view to explain the impacts of the sea level changes

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and tectonism on the Late Quaternary sedimentation in the Bay of Antalya.

Basic knowledge about the structural features of the Antalya Basin comes largely from marine geophysical surveys carried out during the 1970s (e.g. Mulder, 1973; Finetti and Morelli, 1973; Mulder et al., 1975; Malovitskiy et al., 1975; Woodside, 1977; Biju-Duval et al., 1979). More detailed information is based on the interpretation of seismic data collected during cruises of R/V Sismik-1 of MTA in 1980 (Özhan, 1983, 1988; Oral et al., 1988; Ergün et al., 1988; Glover and Robertson, 1998a) and R/V Bannock of CNR in 1987 (Rossi et al., 1988; Taviani and Rossi, 1989). All these researchers inferred the strong Messinian reflector ('-M- reflector' of Woodside, 1977) which is overlain by Plio-Quaternary sediments. Özhan (1983) and Taviani and Rossi (1989) also constructed the isochronopach map of the Plio-Quaternary sedimentary thickness in the basin. Glover and Robertson (1998a) interpreted the whole Plio-Quaternary sequence to be Pliocene ''deltaic facies'' that includes three transgressive phases. In spite of these investigations, little is known about the seismic stratigraphy of the Late Quaternary seismic sequences beneath the continental shelf of the basin (Tezcan, 2001; Tezcan and Okyar, 2001, 2003).

2. Regional setting

2.1. Location and physiography

Antalya Bay is located in the northeastern Mediterranean (Fig. 1). The basin, one of the Neogene basins in the northeastern Mediterranean, covers a region of approximately 6500 km^2 with depths between 2400 and 2600 m (Catani et al., 1983). It is delimited to the north by the Turkish mainland, to the east by Cyprus and the Cilicia Basin, to the south by the Florence Rise and to the west by the Anaximander Mountains (Taviani and Rossi, 1989). The most distinct feature of the sea floor topography of the basin is the NW–SE trending canyon, known as the Antalya Canyon (Fig. 1). Due to the proximity of the canyon to the western coast of the bay, the shelf in the west is narrower than in other parts of the bay.

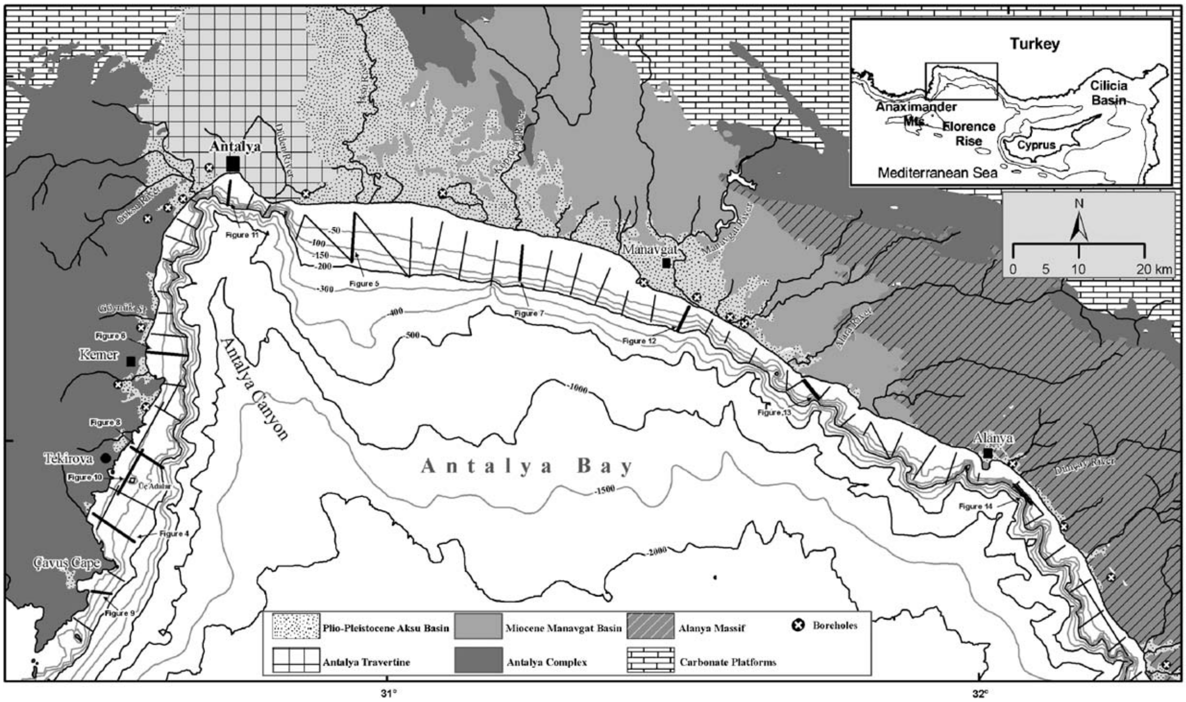


Fig. 1. Location map showing the bathymetry of the study area (compiled from Turkish Navy Charts (1970, 1974, 1975, and 1976) and depth recording data collected along the survey track lines in this study), the onshore geology (modified from Şenel, 2002), and the location of the survey track lines along which echo-sounding and sub-bottom seismic reflection profiles were collected. Bold lines mark the seismic reflection profiles discussed in the text. Inset shows the figure location in the eastern Mediterranean and the main features cited in the text. Isobaths are in meters.

2.2. Geology

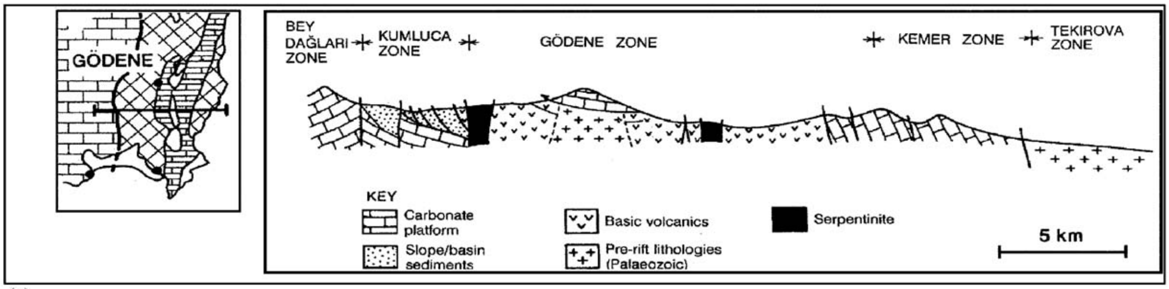
The main tectono-stratigraphic units surrounding the coast of the bay contain, from west to east, the Southwestern Antalya Complex, the Aksu Basin, the Manavgat Basin and the Alanya Massif (Fig. 1).

The SW Antalya Complex consists of five distinct segments, from west to east: the Bey Dağları zone, the Kumluca zone, the Gödene zone, the Kemer zone and the Tekirova zone (Robertson, 1998; Robertson et al., 2003). Of these, the zones nearest to the west coast of the Antalya Bay are the Kemer and Tekirova zones (Fig. 2(a)). The Kemer zone is dominated by Mesozoic platform carbonates, while the Tekirova zone is dominated by Upper Cretaceous ophiolites (Fig. 2(a)).

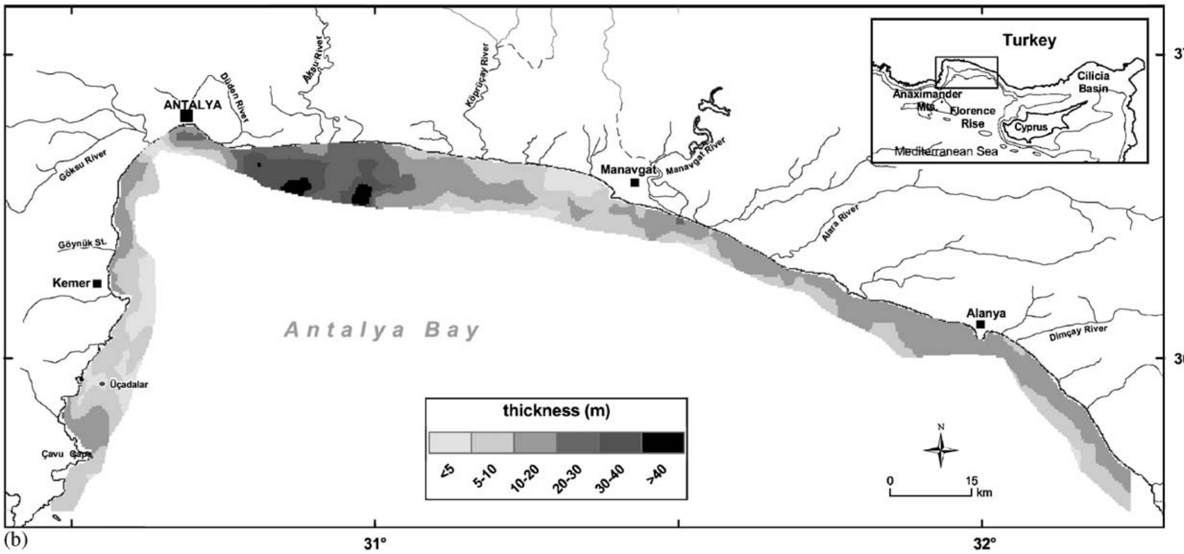
The Aksu basin is dominated by the Middle-Late Miocene mudstones, turbidites, and channelized conglomerates; Messinian to Middle Pliocene shallow marine to deltaic sediments; Late Pliocene to Early Pleistocene alluvial succession; and tufa deposits ('Antalya Travertine' of Burger, 1990) of Pleistocene (Glover and Robertson 1998b; Poisson et al., 2003). The origin of the tufa has been attributed to precipitation from cool-water springs (Burger, 1990; Glover and Robertson, 2003). Fluvial conglomerate terraces associated with the Aksu River are the most recent sediments of the Aksu basin (Glover and Robertson, 1998b).

The Manavgat basin bordering the southern margin of the Alanya Massif (Fig. 1) consists of Miocene—lower Pliocene marine sediments that overlie unconformably the Alanya Massif (Glover and Robertson, 1998a, b; Robertson, 1998).

The Alanya Massif consists of three metamorphic nappes (Okay and Özgül, 1984); Mahmutlar Nappe (lower nappe), Sugözü Nappe (middle nappe) and Yumrudağ Nappe (upper nappe) (Fig. 1).



(a)



(b)

Fig. 2. (a) Cross section taken from east to west along the Antalya Complex. Location is indicated in the inset (from Robertson, 1998). (b) Thickness map of the Unit 1.

2.3. Hydrography

The major rivers flowing into the bay (Fig. 1) and their discharges are: Manavgat (151 $m^3 s^{-1}$), Köprüçay (98 $m^3 s^{-1}$), Aksu (41 $m^3 s^{-1}$), Alara (32 $m^3 s^{-1}$), Düden (21 $m^3 s^{-1}$) and Dimçay (16 $m^3 s^{-1}$) (EİE, 1995). These rivers have played an important role in the formation of coastal plains (Evans, 1970). Glover and Robertson (1998a) hypothesized that the Aksu River was the principal source of sediments to Antalya Bay during the Plio-Quaternary. In addition to these major rivers, there are several smaller streams, such as the Ulupınar, Kocaçay, Kesme, Göynük, Acısu, Karpuz, and Kargı, with an irregular regime (Fig. 1). The discharges of these streams decrease in summer and increase from autumn to spring (Evans, 1970).

3. Materials and methods

Seismic data were collected in the October 1999 cruise of R/V BİLİM. A Trimble NT200 Global Positioning System (in differential mode) was used to obtain position fixes. Depths were recorded by a JMC F-830 echo sounder system. The depth measurements were supplemented by Turkish Navy Charts (1970, 1974, 1975, 1976) in the preparation of the bathymetric map (Fig. 1). The sub-bottom geology of the study area was surveyed utilizing an EG&G Uniboom high-resolution reflection-profiling system along a total of approximately 265 km of track lines (Fig. 1).

Seismic data were interpreted using the principles of seismic stratigraphy method (Mitchum et al., 1977a, b; Sangree and Widmier, 1977, 1979; Vail et al., 1977; Brown and Fisher, 1977, 1980; Posamentier et al., 1988; Posamentier and Vail, 1988; Van Wagoner et al., 1988). Depth conversions from time sections on seismic data were made using a sound velocity of 1500 m/s for water and 1700 m/s for sediments (cf. Malovitskiy et al., 1975; Ergin et al., 1992; Ediger et al., 1993; Tezcan and Okyar, 2001).

Sediment gravity cores, with a recovery of 20–184 cm thicknesses in water depths ranging between 18 and 880 m, were obtained from the shelf and slope areas of the bay (Fig. 3(c)). Lithological logs from 35 onshore boreholes (Fig. 3(b)), which were drilled by DSİ (1985, 2002), were also utilized.

4. Results

4.1. Coastal-plain lithofacies and shelf sediments

Lithological data from boreholes in the coastal zone, which includes the major tectono-sedimentary units of the Antalya Complex, the Plio-Pleistocene Aksu Basin and the Alanya Massif are presented in Figs. 3(a and b).

In the Antalya Complex, the lithological logs of boreholes show that the Quaternary deposits (Şenel, 1995; Glover and Robertson, 1998b) consist of alluvium, and alternations of gravel and clay layers (Fig. 3(b)), with a maximum thickness of 43 m (Borehole 1; Fig. 3(b)). In boreholes 1, 2 and 5 Quaternary deposits are underlain by ophiolite ('Tekirova ophiolite' of Yılmaz, 1984), and Mesozoic-aged limestone and dolomite sequences, respectively (Fig. 3(b)). In the other boreholes (e.g. Boreholes 3 and 4) from the Antalya Complex area Quaternary deposits are missing and the Mesozoic limestone sequences crop out at the surface (Fig. 3(b)).

In the coastal zone of the Aksu basin, boreholes 6–14 (Fig. 3(b)), reveal that Quaternary deposits are mainly gravel, sand, silt and travertine formations (Şenel, 1995; Glover and Robertson, 1998b). The travertine formation has a thickness of more than 80 m in borehole 7 (Fig. 3(b)). Glover and Robertson (2003), indicate that tufa (the term for the travertine) is 250 m thick and is of Pleistocene age. On the other hand, clastic lithofacies in borehole 9 (Fig. 3(b)) are arranged in a fining upward pattern (from gravel to clay), which probably indicates changing depositional conditions from high to low energy settings (Reineck and Singh, 1975). The underlying claystone successions, encountered in boreholes 8–14 belong to Pliocene Yenimahalle Formation (Şenel, 1995; Glover and Robertson, 1998b) (Fig. 3(b)).

In the coastal zone of the Alanya Massif area, Quaternary deposits (boreholes 15–17) consist of clay, sand, gravel and conglomerate layers (Fig. 3(b)). Thicknesses range from 5 m in borehole 16 to 25 m in borehole 17 and up to 50 m in borehole 15. These deposits are underlain by schist and limestone lithologies of the Mahmutlar Nappe (Okay and Özgül, 1984).

Analysis of surficial shelf sediments (grain size and carbonates) of the Gulf of Antalya indicates two distinct regions (Ergin et al., 2004).

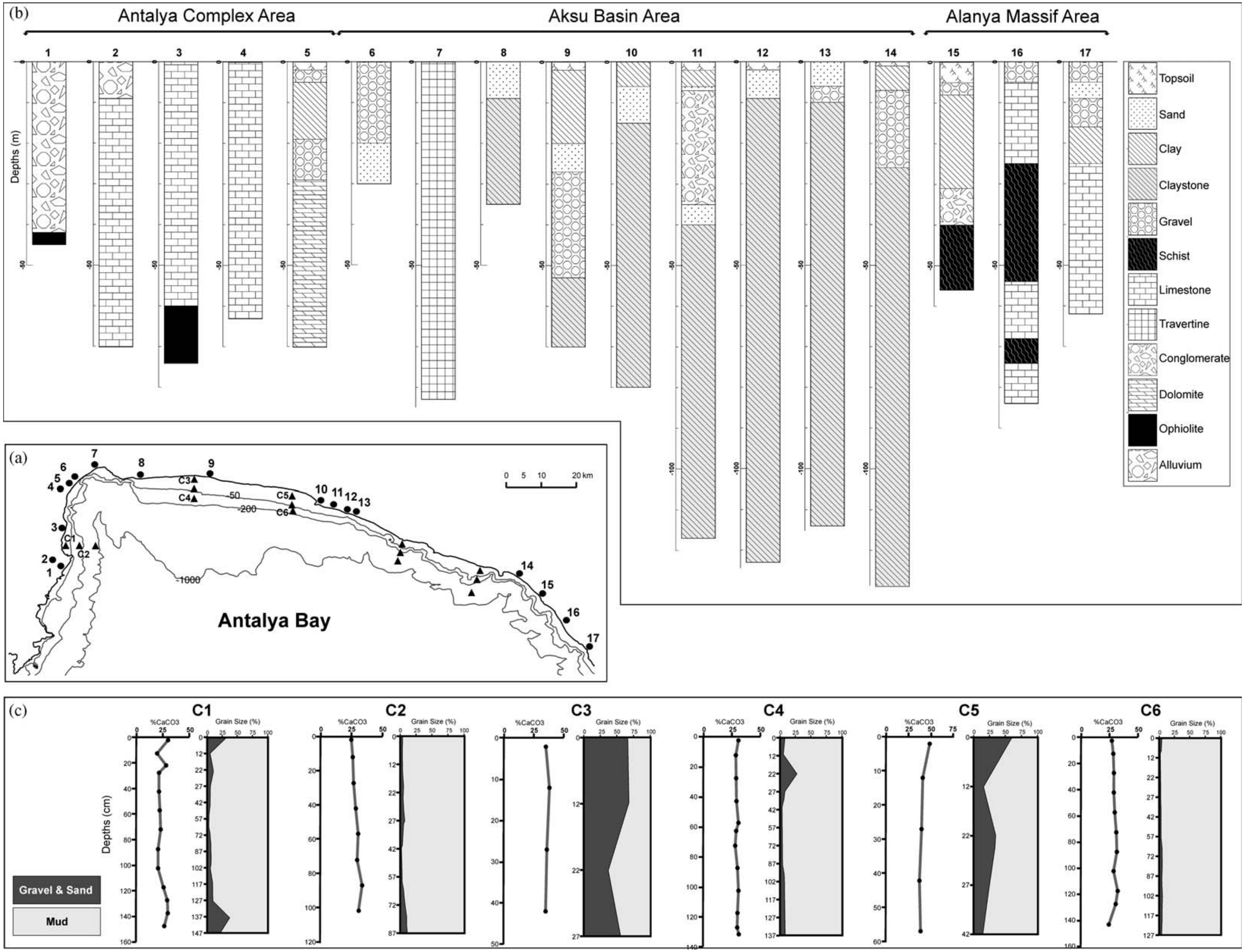


Fig. 3. (a) Location of boreholes (filled circles) and gravity cores (filled triangles). Gravity cores discussed in the text are numbered. Isobaths are in meters. (b) Lithological logs of boreholes. (c) Grain size (sand-gravel/mud) distribution and CaCO3 contents of sediments obtained from gravity corers.

(i) On the inner middle shelf (water depths less than 100 m), the sediments consist predominantly of sand/gravel sized lithogenic and biogenic materials. Carbonate content ranges from 20% to 80%. For example Core C1 from south off Kemer contains 1–36% sand and gravel and 20–30% $CaCO_3$ (Fig. 3(c)). Here coarse-grained sediments are mostly derived from biogenic remains. Core C3 taken east off Antalya City constituted 35–67% sand and gravel with 35–38% $CaCO_3$ (Fig. 3(c)), suggesting that both lithogenic and biogenic admixtures are important. Core C5 taken west off Manavgat, contained 11–60% sand and gravel with 38–49% $CaCO_3$ (Fig. 3(c)). The relatively high percentage of carbonate content in the sediment is related to the presence of coarse-grained (sand + gravel) materials.

(ii) On the outer shelf and slope (depths between 160 and 880 m) sediments are siliciclastic and calcareous mud. Carbonate content varies from 15% to 61% (Ergin et al., 2004). Core C2 taken from south off Kemer contained 1–9% sand and gravel with 25–34% $CaCO_3$ (Fig. 3(c)). Sediments of Core C4 from east of Antalya City contained 1–27% sand and gravel with carbonate amounts from 28% to 31% (Fig. 3(c)). Core C6 taken from west off Manavgat contained 1–3% sand and gravel but 25–33% carbonate materials (Fig. 3(c)).

4.2. Seismic stratigraphic analysis

From the seismic data, two prominent reflectors R_1 and R_2 that mark the base of the seismic units 1 and 2, respectively, and an acoustic basement (AB) have been identified in the study area (Figs. 4–14).

The acoustic basement (AB) underlies the units 1 and 2 (Figs. 4–14). Where unit 2 is absent, its upper boundary is in direct contact with unit 1. The

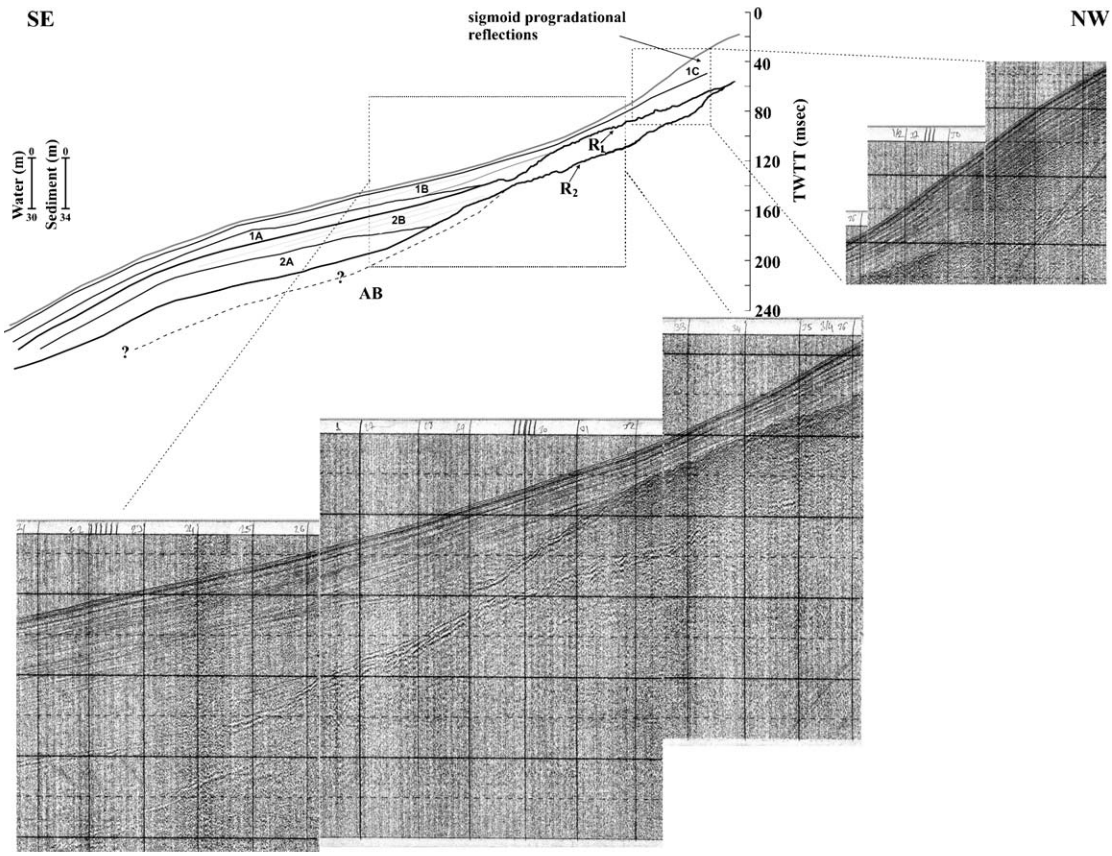


Fig. 4. Interpreted line drawing of the seismic profile and enlarged seismic record sections on the same profile. Subunits 1A–1C of Unit 1, and 2A, 2B of Unit 2, acoustic basement (AB), and unconformities (R_1, R_2) were delineated on the line drawing. Note the Unit 2 pinches out landward over the acoustic basement. For location, see Fig. 1.

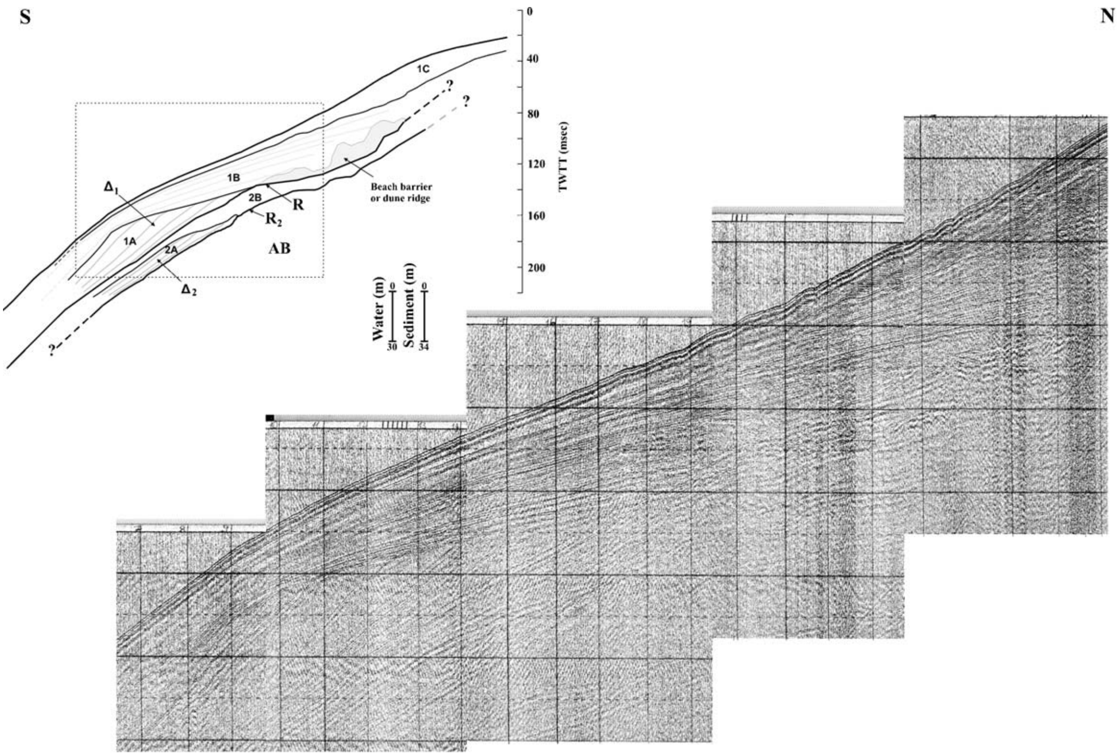


Fig. 5. Interpreted line drawing of the seismic profile and an enlarged seismic record section on the same profile. Subunits 1A–1C of Unit 1, and 2A, 2B of Unit 2 were delineated on the line drawing. Δ_1 and Δ_2 denote the paleo-delta facies within the Unit 1 and Unit 2, respectively. Note the beach barrier or dune ridge structure buried under the Holocene sediments (Unit 1). For location, see Fig. 1.

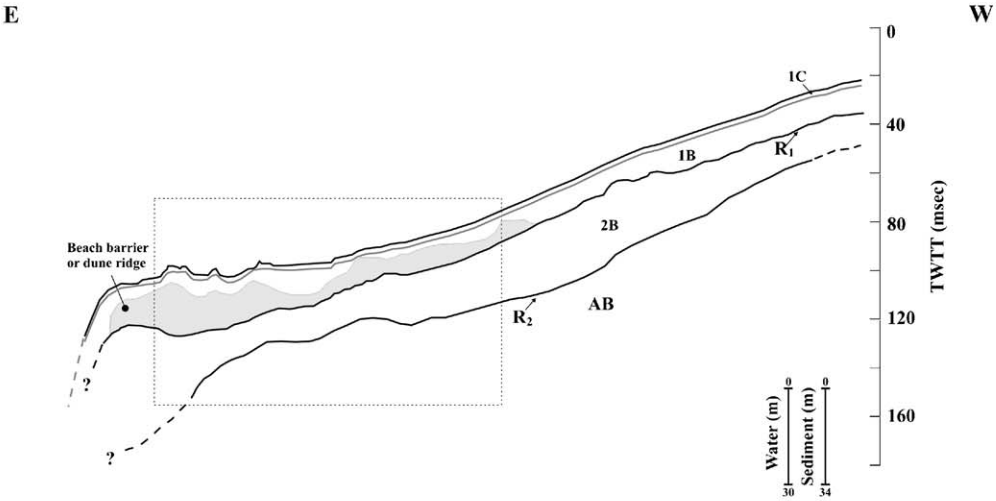
acoustic basement, consisting of the seaward extension of onshore sequences, is characterized by chaotic reflection configurations. The acoustic basement crops out in the vicinity of islands (Üçadalar, Sıçan Adası) (Fig. 10), off the rocky shorelines and along the crests of mounds where the sediment cover is absent (Tezcan, 2001).

Seismic unit 2 is bounded at its top and base by unconformities R_1 and R_2, respectively. In general, unit 2 pinches out over the acoustic basement at the depth of ~50 m below the present sea level. On the basis of their reflection configurations and terminations, two distinctive ‘s were identified.

Subunit 2A pinches out landward on the reflector R_2 at about 150 ms bsl (below sea level) (Figs. 4 and 5). North of the Çavuş Cape (Fig. 4), subunit 2A exhibits parallel–subparallel reflection configuration, baselap on the lower boundary and concordance to toplap in the upper boundary. In front of the Aksu river mouth subunit 2A (Fig. 5) shows oblique prograded reflection configuration (paleo-delta facies Δ_2, Fig. 5). The topset to foreset transition of Δ_2 occurs at about 180 ms bsl.

Subunit 2B is observed on seismic profiles located off the west coast between Çavuş Cape and Göksu River mouth (Figs. 4, 6, 8) and off the north coast between Aksu and Manavgat River mouths (Figs. 5, 7, 12). This subunit rests on subunit 2A or the acoustic basement, and is overlain by subunits 1A and 1B. It has a wedge like external form. It is characterised by parallel–subparallel to chaotic reflection configurations. Reflection terminations are onlap (lower boundary) and erosional truncation that evolves seaward to toplap (upper boundary).

Seismic unit 1 could be followed in the entire study area. It is a wedge shaped unit thickening seaward, and overlying the seismic unit 2 or the acoustic basement. It is the youngest unit that has been deposited on the shelf of the bay. The lower boundary of unit 1 corresponds to the unconformity R_1. The top of this unit represents the present sea floor. In general, unit 1 has a maximum thickness value of 25 m in the eastern part of the continental shelf and 20 m in western part. It thickens (Fig. 2(b)) in the near shore region off the river mouths due to greater sediment supply. The maximum thickness



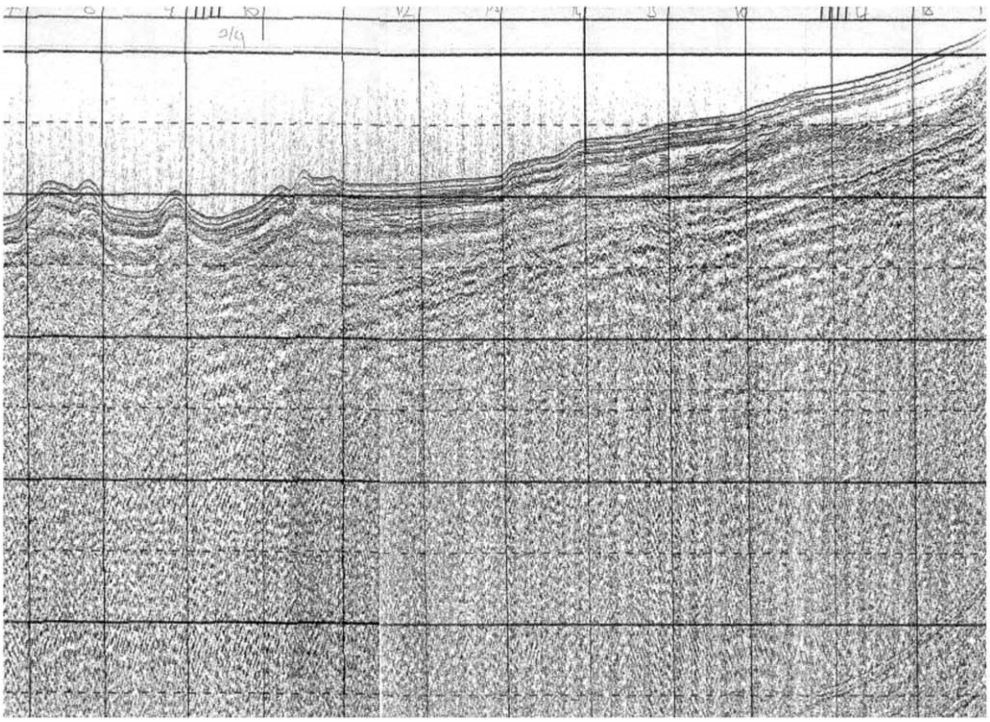
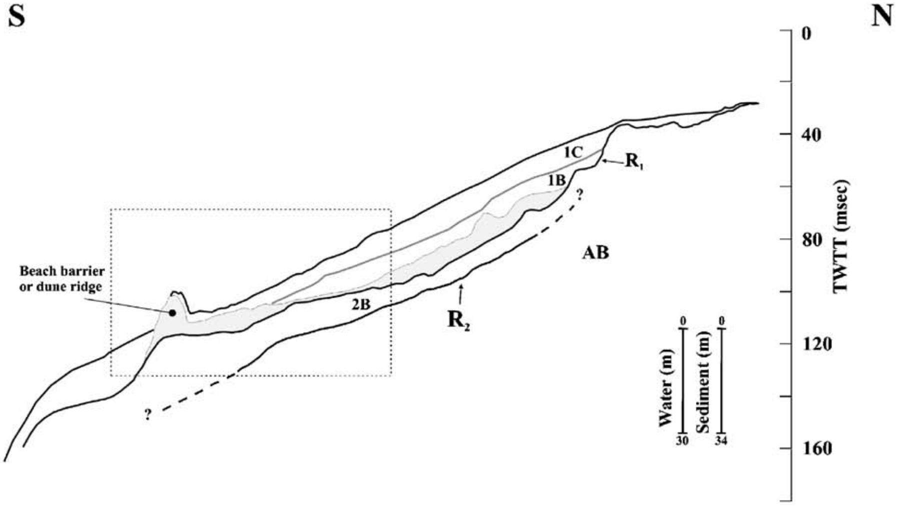


Fig. 6. Interpreted line drawing of the seismic profile and an enlarged seismic record section on the same profile. Note the buried beach barrier or dune ridge structure extending from the shelf break to landward. For location, see Fig. 1.

($>$40 m) occurs off the Aksu river mouth. The absence of unit 1 in the deeper regions of the shelf is probably due to steep gradient of the slope.

Based on seismic reflection geometry and types of reflection termination, unit 1 was divided into three subunits.

Subunit 1A is observed on seismic profiles located to the north of the Çavuş Cape (Fig. 4) and in front of the Aksu River mouth (Fig. 5). It is wedge-shaped and pinches out landward at about 130 ms bsl. It exhibits parallel–subparallel reflection configurations, baselap on the lower boundary and concordance to toplap in the upper boundary. In front of the Aksu River mouth, this unit exhibits oblique prograded reflection configuration where clinoforms terminate by toplap at



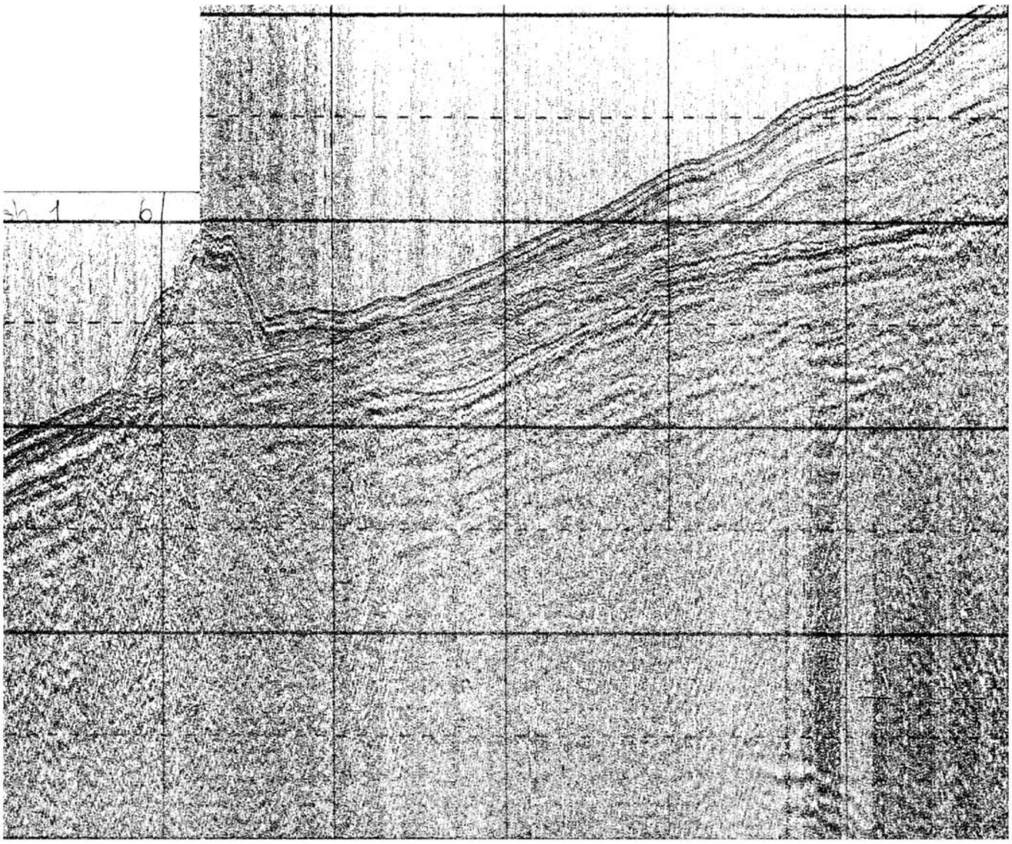


Fig. 7. Interpreted line drawing of the seismic profile and an enlarged seismic record section on the same profile. Note the outcropping part of the beach barrier or dune ridge caused an irregularity on the sea floor. For location, see Fig. 1.

the upper boundary and by downlap in the lower boundary (paleo-delta facies Δ_1, Fig. 5). The transition from topset to foreset beds occurs at about 170 ms bsl.

Subunit 1B is observed on all seismic profiles (Figs. 4–14). This unit overlies subunit 1A and unit 2 and is topped by subunit 1C. Subunit 1B is wedge-shaped and characterized by parallel–subparallel

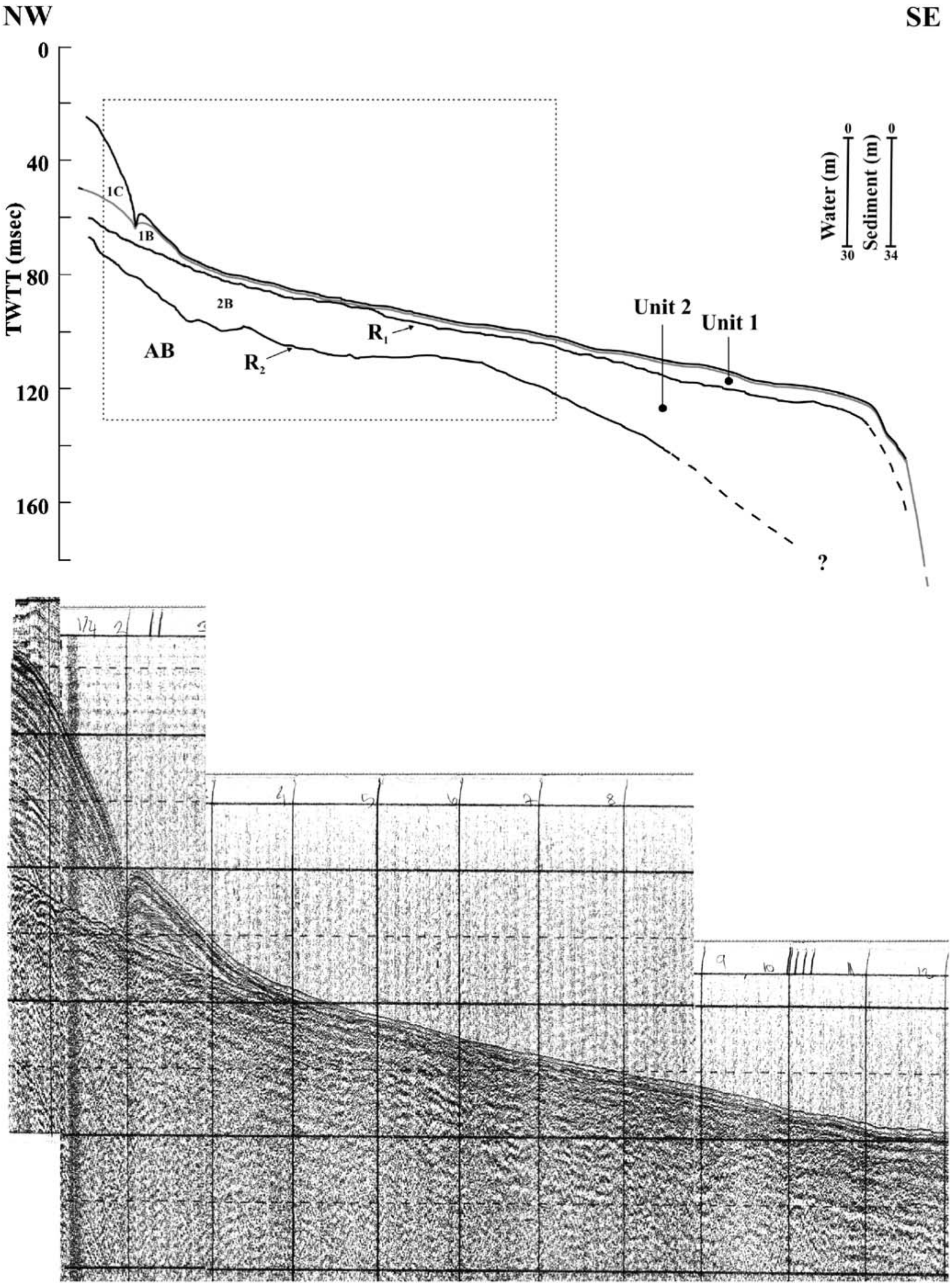


Fig. 8. Interpreted line drawing of the seismic profile and an enlarged seismic record section on the same profile. For location see Fig. 1.

internal reflection configurations. The reflection terminations are onlap on the lower boundary and concordance in the upper boundary. At the base, the parallel–subparallel reflection patterns of sub-unit 1B, give way in places to chaotic to hummocky reflections which may possibly represent beach barrier or dune ridge features extending from the shelf edge towards the coast (Figs. 5–7). They caused the bottom irregularities where they were exposed on the sea floor (Fig. 7).

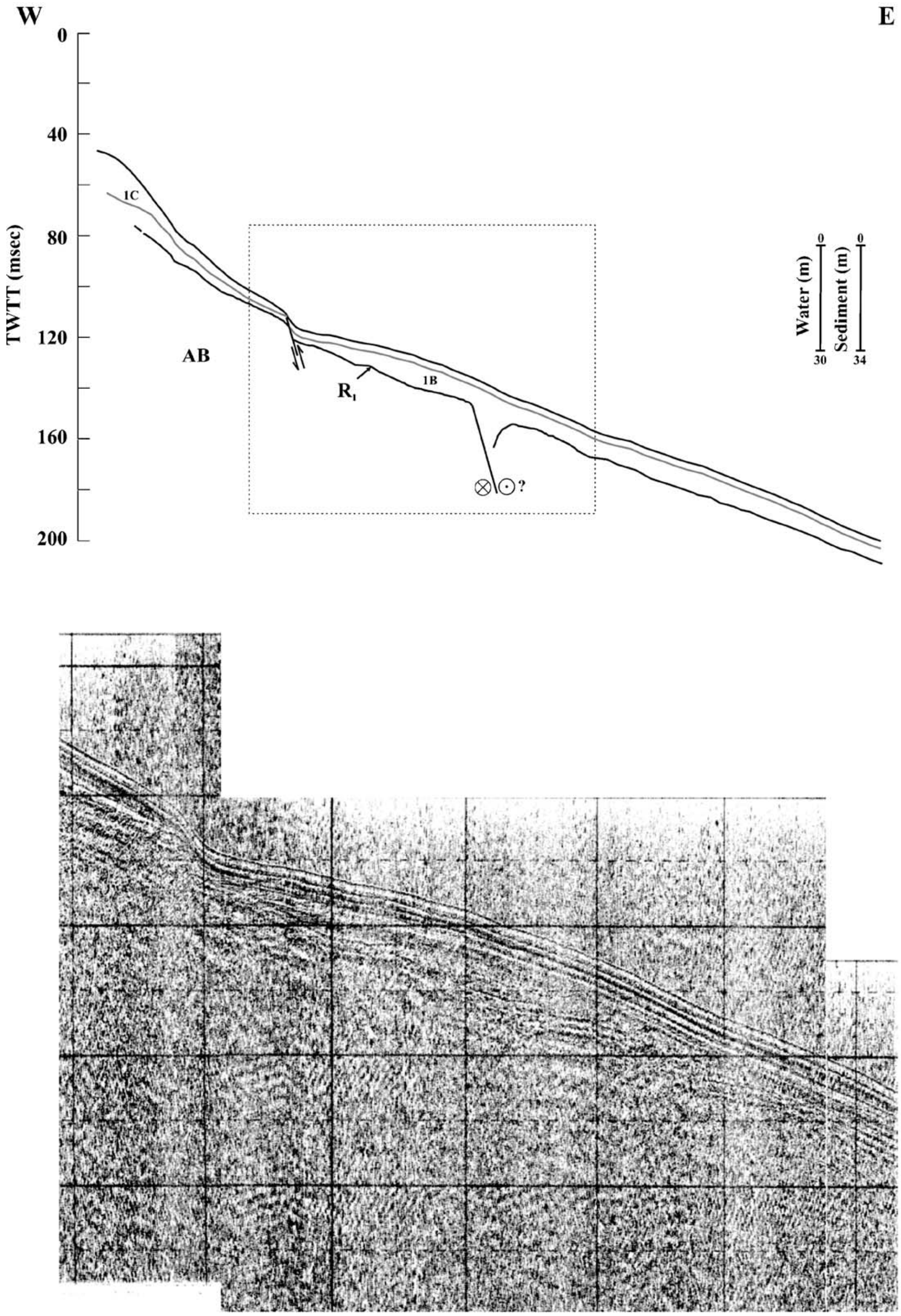


Fig. 9. Interpreted line drawing of the seismic profile and an enlarged seismic record section on the same profile. The faults are interpreted as the offshore extensions of the Olympos Faults (Glover and Robertson, 1998a, b). For location see Fig. 1.

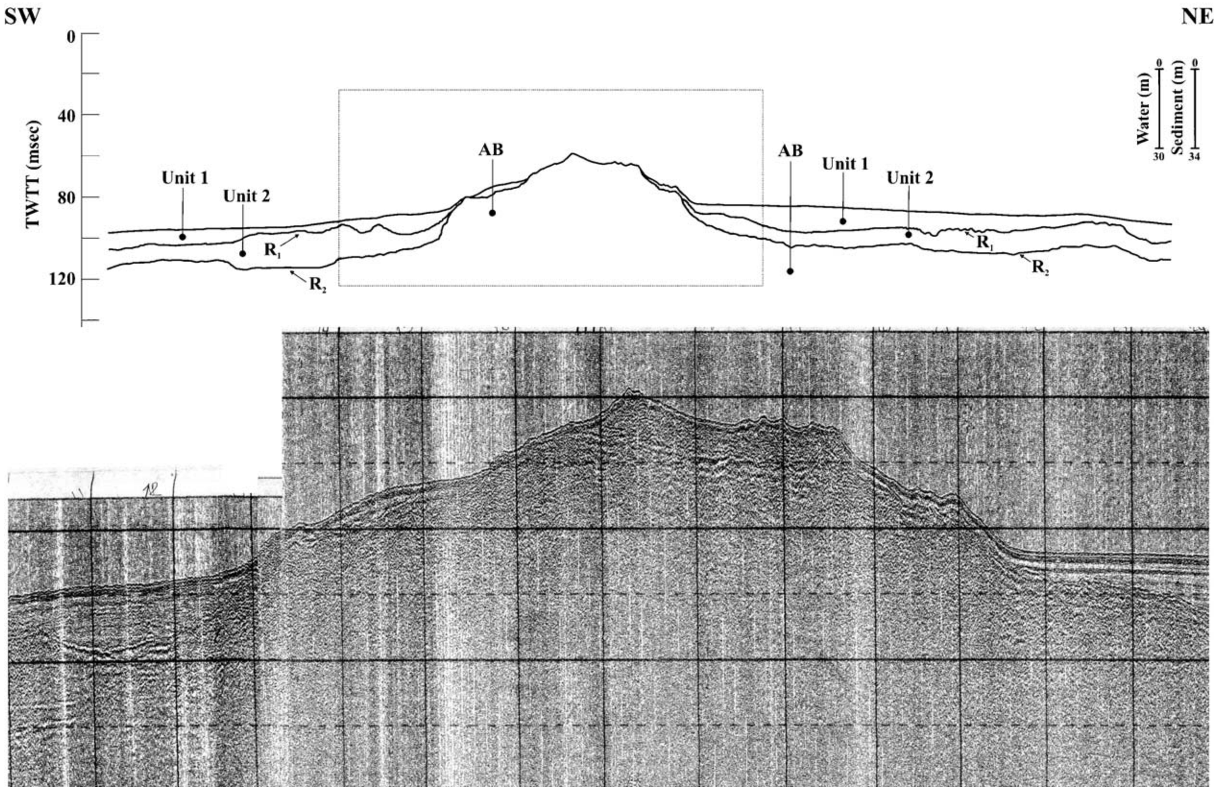


Fig. 10. Interpreted line drawing of the seismic profile and an enlarged seismic record section on the same profile. Note the acoustic basement (AB) exposed on the sea floor near the island of Üçadalar. For location see Fig. 1.

Subunit 1C is observed in the near-shore part of all seismic profiles (Figs. 4–14). Its upper boundary represents the present day sea floor. Subunit 1C has a wedge-shaped external form gradually thinning seaward. It displays sigmoid in near-shore waters less than 10 m (see Figs. 4 and 8) and parallel–subparallel reflection configurations in depths greater than 10 m. The reflection terminations are baselap on the lower boundary and concordance in the upper boundary. Gravity cores penetrated the uppermost sediments of Subunit 1C and showed that this subunit consists of sand and gravel in the shallow depths (<100 m), and siliciclastic mud mixed with appreciable amounts of calcareous mud in deeper areas (>160 m).

4.3. Structural and morphological features

From the seismic data several active faults are interpreted in the surveyed area (Figs. 9, 12, and 13). South of the Çavuş cape (Fig. 9), the faults are considered to be the offshore extensions of the Olympos fault lineaments (NE–SW and NW–SE right-lateral faults and NNE–SSW striking normal faults) reported by Glover and Robertson (1998a, b). These authors suggested that these faults were recently active. Other active faults affecting the sea floor are also interpreted in the seismic data off Manavgat (Fig. 12) and Alanya (Fig. 13).

In the northern part of the bay the shelf is relatively wide (about 10 km) and gently slopes seawards until the shelf break at about 150 m water depth (Fig. 1). The reason for the relatively wide shelf is probably the high sediment supply from the Aksu and Köprüçay rivers.

In the western part of the bay, the shelf is narrow and structurally limited by the western wall of the Antalya Canyon. This canyon, which was inferred to be tectonic in origin, created by the interactions of the NW–SE major tectonic alignments with the N–S trending fault system (Taviani and Rossi, 1989). Glover and Robertson (1998a), who regarded this feature as the offshore extensional graben, also reported some NW–SE structural trends in the

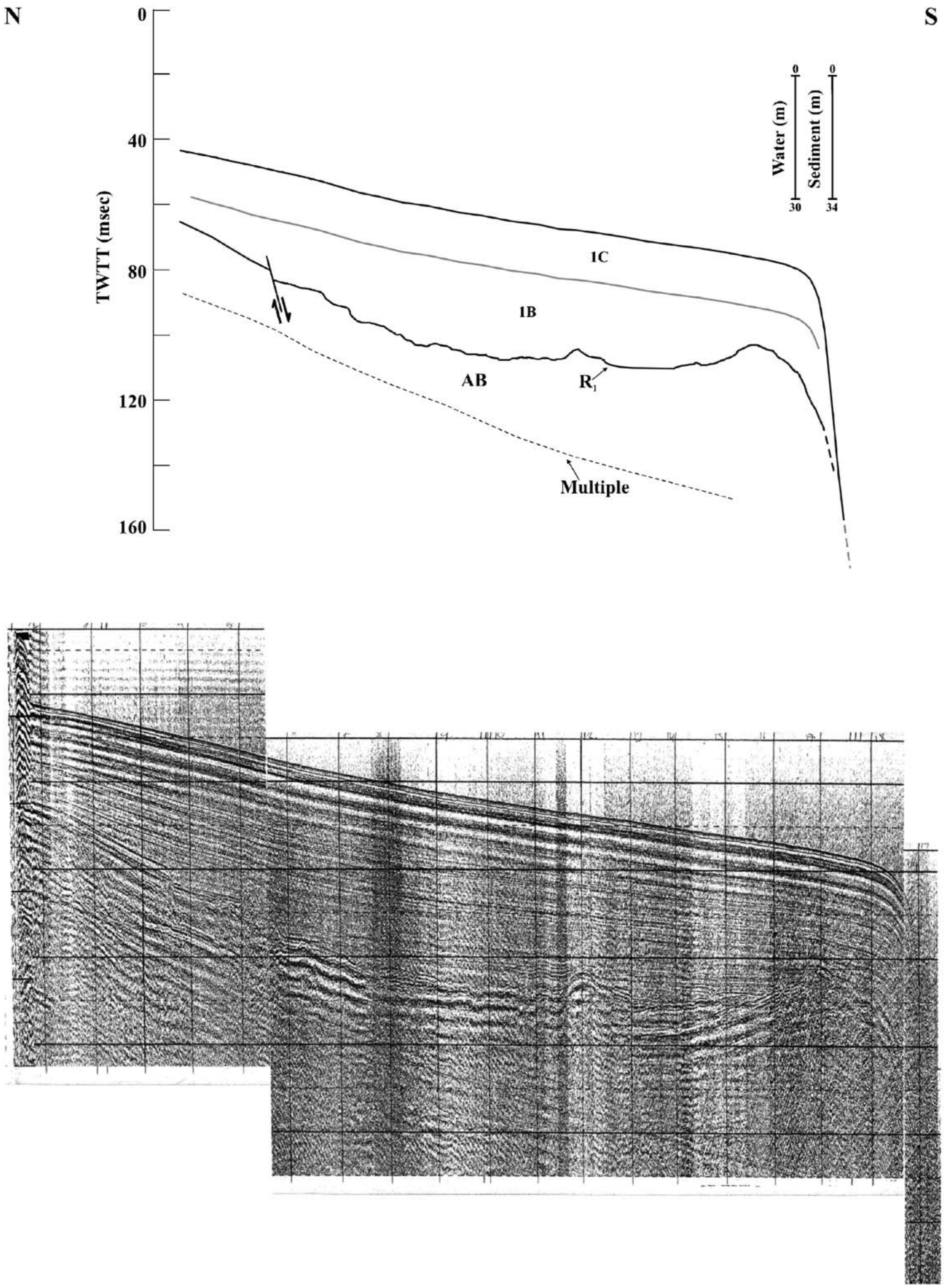


Fig. 11. Interpreted line drawing of the seismic profile and an enlarged seismic record section on the same profile. Note the reflector R_1 is the upper boundary of a submerged tufa terrace (Burger 1990; Glover and Robertson, 2003). The tufa terrace is covered by modern sediment deposits. For location see Fig. 1.

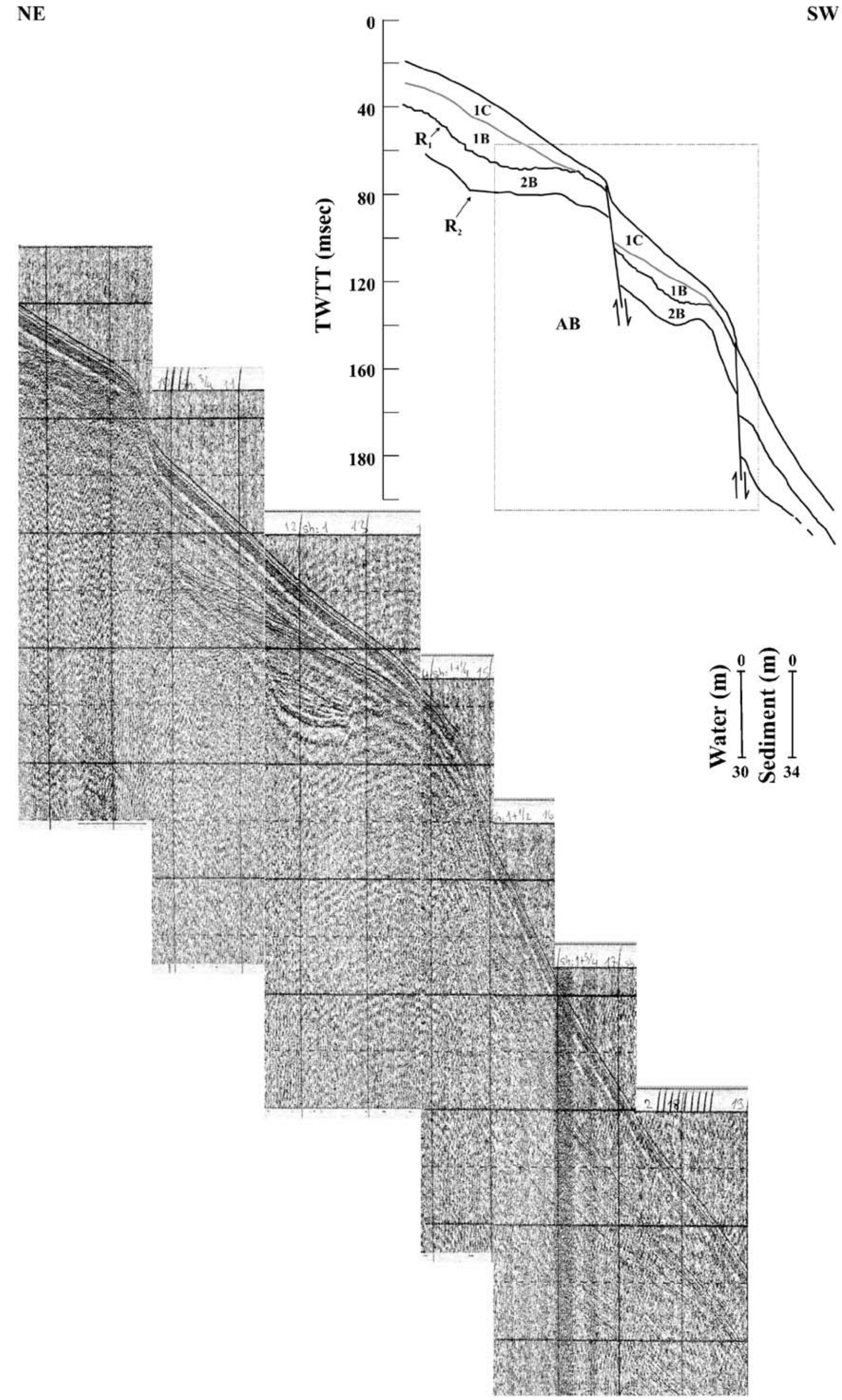


Fig. 12. Interpreted line drawing of the seismic profile and an enlarged seismic record section on the same profile. Note the normal faults that have large vertical displacement. For location see Fig. 1.

Kemer lineaments dominated by the Late Pliocene–Early Quaternary extensional faultings. In the present study it is found that the head of the Antalya Canyon is comprised of three branches, probably formed during the Late Quaternary sea-level lowstands. At that time the rivers Göksu

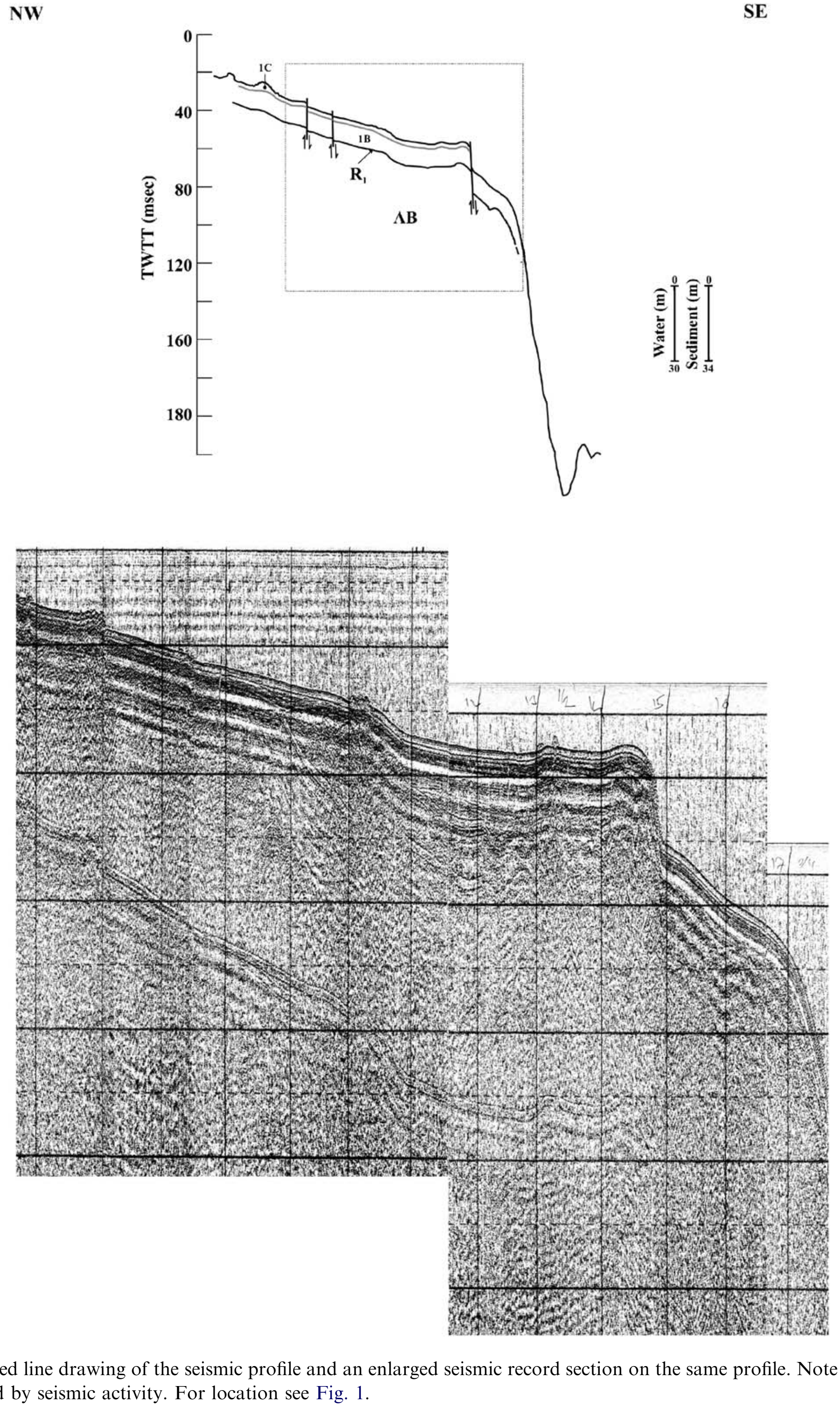


Fig. 13. Interpreted line drawing of the seismic profile and an enlarged seismic record section on the same profile. Note the normal faults possibly produced by seismic activity. For location see Fig. 1.

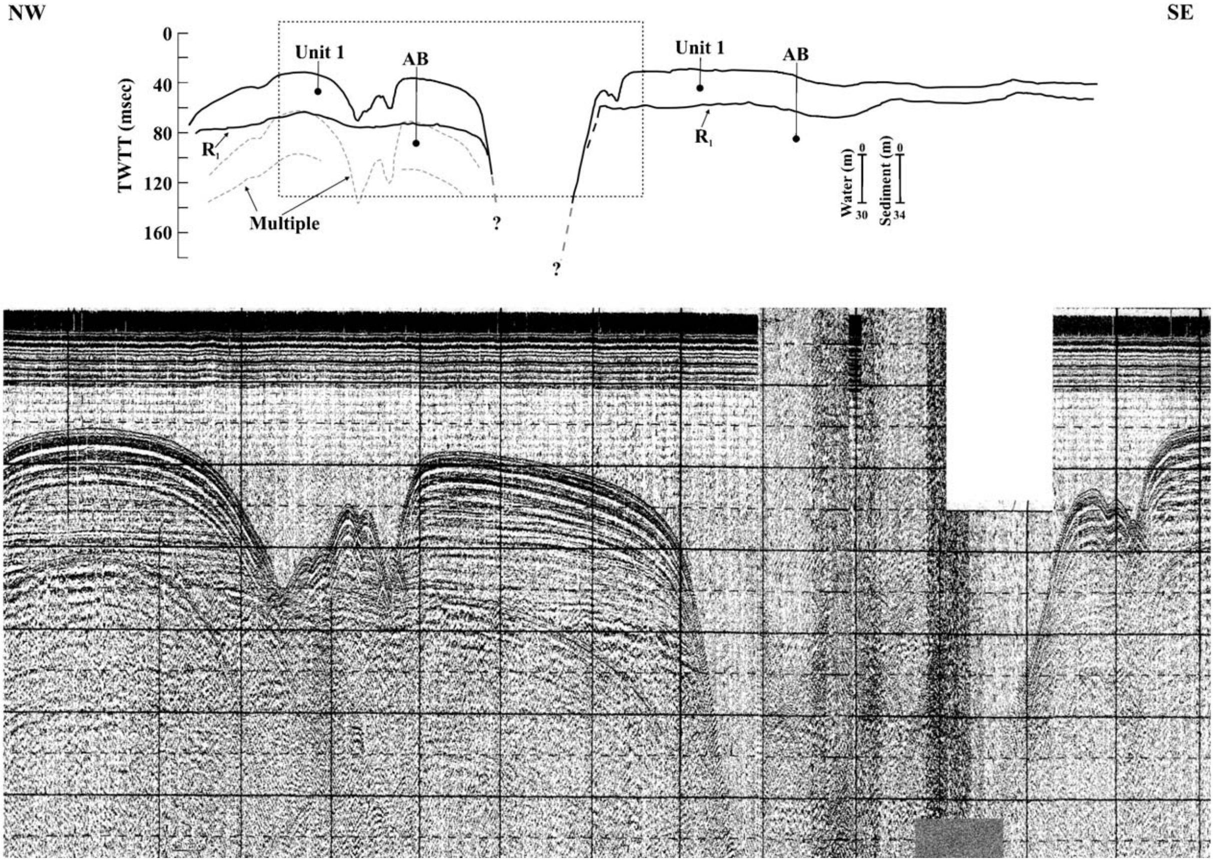


Fig. 14. Interpreted line drawing of the seismic profile and an enlarged seismic record section on the same profile. Note the submarine canyons that incised the shelf. For location see Fig. 1.

(Karaman River in Glover and Robertson, 1998a, b) and Düden, must have been very active, cutting their beds and discharging their sediment loads away from the shelf region. According to Glover and Robertson (1998a), the Karaman (Göksu) river was more active in carrying sediments into the bay area than the other major sediment source, the Aksu river, during the Late Quaternary-Recent. The seismic profiles obtained from the northwestern shelf region are usually limited by steep slopes on their seaward sides (Figs. 6, 8, and 11). These slopes are probably due to the normal faults developed along the graben structure (e.g. Taviani and Rossi, 1989; Glover and Robertson, 1998b). However, these faults could not be deduced from the present study because of operational limits on the seismic instrument.

The eastern part of the shelf is also restricted by the existence of the gully like features. These features are mostly concentrated in front of the present day rivers and streams (e.g. Dimçay, Fig. 1). An example of this feature is seen clearly in the seismic profile parallel to the coast near Alanya (Fig. 14).

5. Discussion

The chaotic reflection configurations in the acoustic basement are interpreted either as strata deposited in a variable, relatively high-energy setting, or as initially continuous strata which have been deformed so as to disrupt continuity (Mitchum et al., 1977b). Based on the surficial sediment lithology and age of onshore formations (Şenel, 1997; Glover and Robertson, 1998a), it can be tentatively concluded that the acoustic basement is composed of Mesozoic aged limestone series of Antalya Complex in the west (e.g. Boreholes 3–4 in Figs. 3(a and b)), and Pleistocene aged travertine deposits of the Aksu Basin in the north (e.g. Borehole 7 in Figs. 3(a and b)). On the other hand, off the city of Antalya, the acoustic basement has a

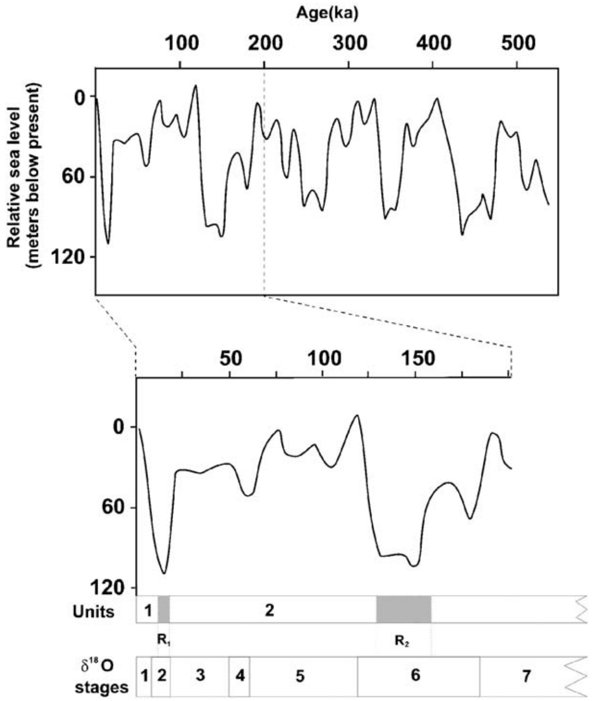


Fig. 15. Sea level curve and corresponding isotopic stages (modified from Skene et al., 1998). Note interpreted seismic units 1 and 2, and unconformities R_1 and R_2 are tentatively marked on the curve.

terrace-like form that lies horizontally below recent sediments at a depth of about 110 ms (~80 m) (Fig. 11). This terrace, reported earlier by Burger (1990) and Glover and Robertson (2003), can be interpreted as a part of extensive tufa deposits of the Plio-Quaternary Antalya coastal plain. According to Glover and Robertson (2003), this submarine terrace possibly formed in response to Late Quaternary sea-level fall, followed by post-glacial submergence and sculpting of coastal cliffs.

According to seismic stratigraphic concepts (Posamentier and Vail, 1988; Haq, 1991), R_1 and R_2 are interpreted as two major unconformities, formed under subaerial conditions during the last two major Quaternary sea level lowstands (Fig. 15). Reflector (R_2) is interpreted to have been formed during the next to last major late Quaternary sea level lowstands (Fig. 15). This reflector can also be correlated with the shelf crossing unconformity Q1 observed in the Sea of Marmara (Hiscott et al., 2002).

Reflector R_1, which is widespread in the region, representing the uppermost shelf crossing unconformity, is interpreted as late Pleistocene and early Holocene erosional land surface at lowered sea level, now buried under the sediments of the subsequent post-glacial (Flandrian) transgression. This unconformity can be time equivalent to the lowstand unconformities interpreted on nearby continental shelves. In the Sea of Marmara, a lowstand unconformity β_3 which lies below the first deposits of the Holocene transgression was identified (Hiscott et al., 2002). In the southwestern shelf of the Black Sea, an unconformity denoted as α, encompassing the entire width of shelf and extending to the shelf break at 100–120 m has been reported (Aksu et al., 2002). Erosional surfaces similar to reflector R_1, which represent the Pleistocene–Holocene transition, are also reported by several investigators (e.g. Tesson et al., 1990; Ergin et al., 1992; Ryan et al., 1997; Park and Yoo, 1988; Okyar and Ediger, 1999).

Unit 2 developed above the R_2 type 1 sequence boundary (Van Wagoner et al, 1988). The lower subunit 2A was deposited in the form of prograding shelf edge delta (Δ_2 in Fig. 5) and is interpreted as a lowstand systems tract. The overlying subunit (2B) may present transgressive deposits but the assignment to a transgressive system tracts is difficult due to the upper parts being truncated by erosion during the subsequent sea level fall.

Unit 1 is considered to have been deposited during the Last Glacial Maximum lowstand of the sea level and the following post glacial transgression. The lower boundary of unit 1, R1, is a type 1 sequence boundary (Van Wagoner et al., 1988).

In front of the Aksu River mouth, oblique progaded reflection configurations of the subunit 1A represent a seaward prograding shelf-edge delta (Δ_1 in Fig. 5). Subunit 1A is interpreted as the lowstand systems tract that deposited during the lowstands of the sea level and early stages of the subsequent transgression. During the deposition of Δ_1, the sediments carried by the Aksu River bypassed the inner-middle shelf areas and were deposited on the shelf edge leading to the development of oblique prograding depositional packages. Similar lowstand shelf-edge delta facies developed in many parts of the world's oceans during glacial periods, as the rivers extended to the shelf edge (e.g. Sutter and Beryhill, 1985; Anderson et al., 1996; Chiocci et al., 1997; Aksu et al., 1999; Hiscott, 2001; Aksu et al., 2002). The lowstand systems tract is topped by a marine-flooding surface (transgressive surface) that shows minor submarine erosion (Van Wagoner et al., 1988).

At the base of the subunit 1B, the chaotic to hummocky reflections may possibly represent beach barrier or dune ridge features extending from shelf edge towards the coast (Figs. 5–7). These features were possibly formed during the period of lowering sea level and were subsequently partly removed during the post glacial sea level rise (Gensous, Pers. Commun., 2005). Similar beach barriers or dune ridges were also observed in the bay of Anamur on the southern coast of Turkey (Alavi et al., 1989). Subunit 1B is interpreted to be a transgressive systems tract. It possibly began to accumulate in the late lowstand and became well developed during the post glacial sea-level rise (landward migration of the onlap terminations) The top of the subunit 1B is a marine-flooding surface onto which the toes of prograding clinoforms in the overlying subunit 1C (Van Wagoner et al., 1988).

Subunit 1C is interpreted as a highstand systems tract. It is separated from the underlying subunit 1B by a minor unconformity, a downlap surface (Van Wagoner et al., 1988). It is characterised by prograding sigmoidal reflection pattern in shallow areas grading into parallel–subparallel reflection configurations at depths >10 m.

Seismic units equivalent to unit 1 and unit 2 have been interpreted by Yaltırak et al. (2000) and Hiscott et al. (2002) in the Sea of Marmara, and by Aksu et al. (2002) in the Black Sea. Yaltırak et al. (2000) denoted the upper seismic unit as unit 3 which was deposited after the last major sea level lowstand (17–18 ka BP) until the present; and the lower sediment unit as unit 2b that corresponds to the second important sea level lowstand (135–150 ka BP). Hiscott et al. (2002) divide the upper seismic unit into 3 subunits (unit 1–3). The oldest, unit 3, includes the first deposits of the Holocene transgression above lowstand unconformity β_3 (reflector R_1 in the present study). They also describe unit 4 and unit 5 which correspond to unit 2 in the present investigation. In the Black Sea, Aksu et al. (2002) also separate the upper unit in 4 subunits: 1A–1D. They interpreted 1A as a lowstand systems tract that was deposited during the last sea level lowstand, 1B and 1C as transgressive systems tracts associated with the last glacial–Holocene sea level rise, and 1D as a high systems tract.

According to correlation with previous works and the sea level curve (Skene et al., 1998), it can be tentatively concluded that the R_1 and R_2 were truncated during the maximum fall in sea level in isotopic stages 2 and 6, respectively (Fig. 15). Unit 1 has been deposited during the isotopic stage 1, and unit 2 was deposited during isotopic stages 3–5. These dates are time equivalent to those of the DS1 and DS2 in the İskenderun and Cilician basins in the NE Mediterranean Sea (Aksu et al., 1992). The topset to foreset transitions of the Δ_1 and Δ_2 correspond probably to the maximum sea level falls in isotopic stages 2 and 6, respectively. We presume that the Aksu River, believed to be the principal source of sediment to Antalya Bay during the Plio-Quaternary (Glover and Robertson, 1998b), reached the shelf edge at 6–7 km offshore from the present shoreline.

Glover and Robertson (1998b) explained that in this area there is considerable geological and geomorphological evidence that strong regional surface uplift has occurred throughout the Pleistocene. The Isparta Angle that includes the study area is a major re-entrant that separates the western and central Tauride Mountains and extends offshore in the Antalya Bay (Glover and Robertson, 1998b). During Late Pliocene–Early Pleistocene, a N–S half graben extending into Antalya Bay formed due to the extensional faulting while the adjacent Tauride Mountains were progressively uplifted (Glover and Robertson, 1998a, b). There was no fault activity at the eastern margin of the basin at that time. The rifting was contemporaneous with regional uplift of the Tauride Mountains, as part of central Anatolia that underwent westward "tectonic escape" towards to Aegean (Glover and Robertson, 1998a, b).

This was followed by a major tufa deposition in Aksu Basin. The tufa deposition that is thickest near the axis of the half graben was tectonically controlled (Glover and Robertson, 2003). The origin of the tufa terraces relates to the combination of regional uplifting and eustatic sea-level changes (Glover and Robertson, 1998b, 2003). Notches in the tufa indicate that the sea cliffs along the shoreline are the result of the uplifting (Glover and Robertson, 1998b).

At present, there is no significant tectonic and sedimentary activity in the basin, but erosional processes occur. The depositional processes include continued formation of fluvial terraces that is related to the Aksu River sediment supply and coastal marine erosion (Glover and Robertson, 1998b).

During the investigation of seismic data, several faults have been observed. However it is impossible to tie these faults to each other due to several reasons. Firstly, there are not sufficient fault data on the landside to correlate them and secondly, the submarine canyons incised the shelf prevent from tracing the extensions of the faults (Fig. 14). These faults can be related to the regional uplifting as explained by Glover and Robertson (1998a). However, seismic activity with several intermediate earthquakes has been also reported in Antalya Bay (Papazachos and Papaioannou, 1999). We believe that some of these faults, cutting entirely the Holocene sediments (Fig. 13), are directly related to seismic activity rather than regional uplifting.

The canyon-likes features on the shelf are especially common in the northwest and the eastern parts of the bay. In the northwest, these submarine canyons are linked to the Antalya canyon. In the eastern part of the bay, submarine canyons generally occur close to the rivers mouths. We consider that during the sea-level falls these rivers incised the shelf, and as the onshore lithology comprised of the Alanya Massif's metamorphic rocks, prevented the development of a wide shelf in the eastern bay region.

6. Conclusions

A high-resolution seismic investigation had been done on the continental shelf of Antalya Bay, SW Turkey. In this study, two seismic units and an acoustic basement have been interpreted on the shallow seismic profiles.

The differences in the lithological composition of the acoustic basement are related to the tectonic evolution of the basin. The lower unit, Unit 2, is bounded by type-I boundaries; R_2 at its base and R_1 at its top. It was deposited during isotopic stages 3–5. The upper part of this unit was truncated during the development of R_1 in isotopic stage 2. Unit 1 has been deposited since the last glacial maximum (isotopic stage 1) above R_1.

It is believed that the development of these units is intimately linked with the glacio-eustatic sea level changes associated with the regional uplifting and sediment supply.

Based on the surficial shelf sediment analysis, the inner middle shelf sediments consist of sand/gravel-sized lithogenic and biogenic materials, in the outer shelf and slope sediments comprise of siliciclastic and calcareous mud.

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