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RECENT SEDIMENTATION ON THE SHELF AND UPPER SLOPE IN THE BAY OF ANAMUR, SOUTHERN COAST OF TURKEY

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Abstract

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Sedimentological studies, supported by Uniboom profiles and sonographs, of surface sediments from a part of the narrow southern shelf of Anatolia, indented by the head of a submarine canyon and partly covered by meadows of macrophytobenthos, revealed abrupt lateral and vertical variations in the Holocene sedimentary facies. These variations have essentially been controlled by the migration of depocentres, (palaeo-) topography of the shelf and an overall decrease in the rate of fluviatile sediment supply in the late Holocene. As sea level reached approximately its present position nearly 5 ka B.P., the bulk of the siliciclastic input began to be trapped in the inner shelf zone (< 30 m deep) and the course of the Sultançay river, the major source of sediment supply, migrated away from the head of the canyon towards the west. The deeper parts of the shelf began to be influenced by the open-sea water masses and currents, becoming a site with favourable ecological conditions for the colonization of the sea floor by macrophytobenthos, coralline algae and epibenthic macro and microbenthos. Semi-indurated relict sandy sediments composed of quartz and detrital metamorphic and carbonate grains are exposed at some localities on the deeper part of the shelf. At most places in the outer shelf zone, they are covered by a relatively thin veneer of surficial carbonate-rich sediments having a total carbonate content of 30–80%.

Most of the terrigenous mud bypasses the shelf to be trapped in the canyon head, but transport of modern detrital sand and gravel does not take place across the shelf. This is because of the relative weakness of the onshore–offshore currents, the prevailing microtidal conditions and a belt of phytobenthos between 10 and 30 m which traps the sediments. The plants also create the ecological conditions favourable for biological carbonate production. However, some gravel- and sand-size relict sediments have been transported from the outer shelf into the canyon head by gravity-induced or cross-canyon currents. The "mudline" occurs at about the 100 m isobath, marking the deepest limit of effective bottom turbulence for the resuspension of silt and clay on the shelf.

Introduction

This study was undertaken with the aim of contributing to the understanding of Recent processes of sedimentation on the margin of an intermountain marine basin within an active orogenic belt (a favourable setting for the development of shelf siliciclastic facies (Evans, 1971)). Two major modern sedimentary provinces have been recognized along the northern margin of the Cilician Basin (Fig.1). To the east of the Göksu delta, the sediments are richer in siliciclastics supplied from the hinterland by several rivers flowing into the Bay of Mersin (Mange-Rajetzky, 1983). To the west of this delta, the sediments are composed predominantly of biogenic carbonate, the proportion of which rises to as much as about 60% on the shelf of Anamur (fig.5 in Shaw and Bush, 1978; Alavi, 1980). These provinces also have distinct clay mineral assemblages (Shaw, 1978).

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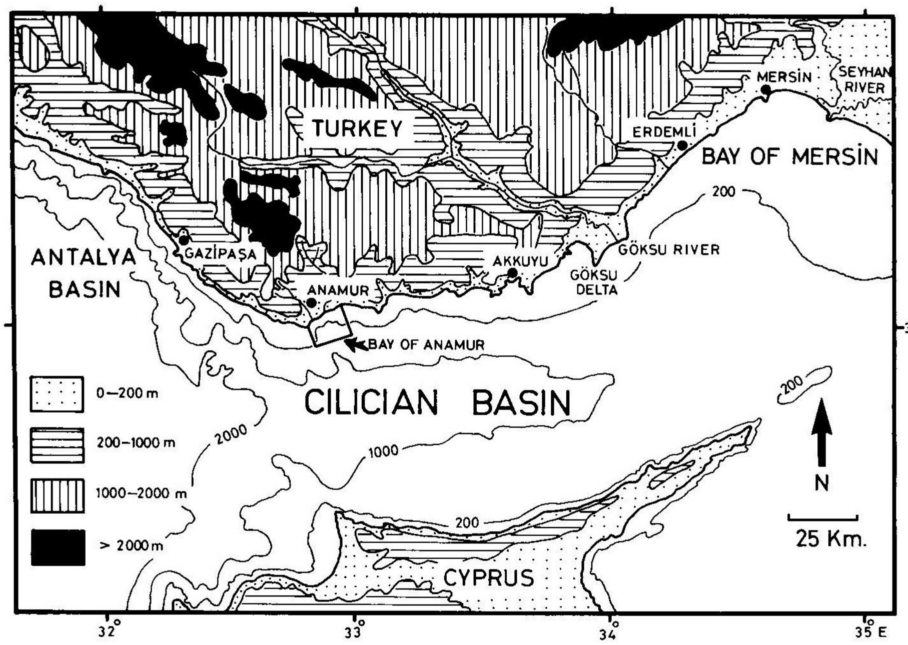


Fig.1. General bathymetry of the Cilician Basin and the topography of the surrounding area. The location of the Bay of Anamur and other localities referred to in the text are shown. Isobaths and elevations (m) from IOC, 1981.

Whereas the Bay of Mersin is surrounded by an extensive deltaic and alluvial plain with two major rivers (Evans, 1971), to the west of the Göksu delta the Taurus Mountains stretch along the coast and the flow of runoff into the sea is reduced. There is little coastal plain and the shelf is very narrow, except for those places where the mountains recede from the coast and embayments are developed (Emery et al., 1966). One of these embayments is the Bay of Anamur (Figs.1 and 2). The studied area is centred over the apical part of the canyon head which indents the shelf in the western part of the bay (Figs.3 and 4).

Methods

Offshore samples were taken by grab and a Phleger-corer (internal diameter of 3.5 cm) at 82 locations. Twelve beach samples were also collected manually and their locations were marked on a 1/5000 topographic map of the coast. Grain-size analyses were carried out by the sieve and pipette technique (Folk, 1974). Total carbonate contents of 54 selected samples were determined using the volumetric technique of Müller (1967), with an accuracy of about 0.5% (Table 1). Gravel and sand fractions (> 125 μm) were examined under a binocular

TABLE 1

Total carbonate contents of the sediments from the Bay of Anamur (% dry weight basis, see Fig.18B)

Sample	$CaCO_3$	Sample	$CaCO_3$	Sample	$CaCO_3$
A3	44.66	F3	24.25	K2	39.94
A4	25.63	F4	34.77	K5	36.26
B2	38.32	F6	34.85	L2	33.94
B3	53.20	G1	28.68	L3	34.84
B4	32.93	H2	37.41	L4	30.59
B5	35.32	H4	9.51	L5	64.93
B6	28.57	H7	35.42	L6	68.13
C6	39.84	I3	25.89	L7	75.64
D2	34.76	I4	42.16	L8	67.49
D4	60.43	I5	45.34	M3	32.89
D5	47.00	I6	36.88	M5	62.65
D6	40.12	J2	41.12	M6	77.72
E2	35.94	J3	50.76	M7	66.32
E6	28.77	J4	45.92	N4	58.41
E7	34.82	J6	31.65	N5	73.58
F2	38.07	K1	61.28	N7	83.53
				N9	35.05

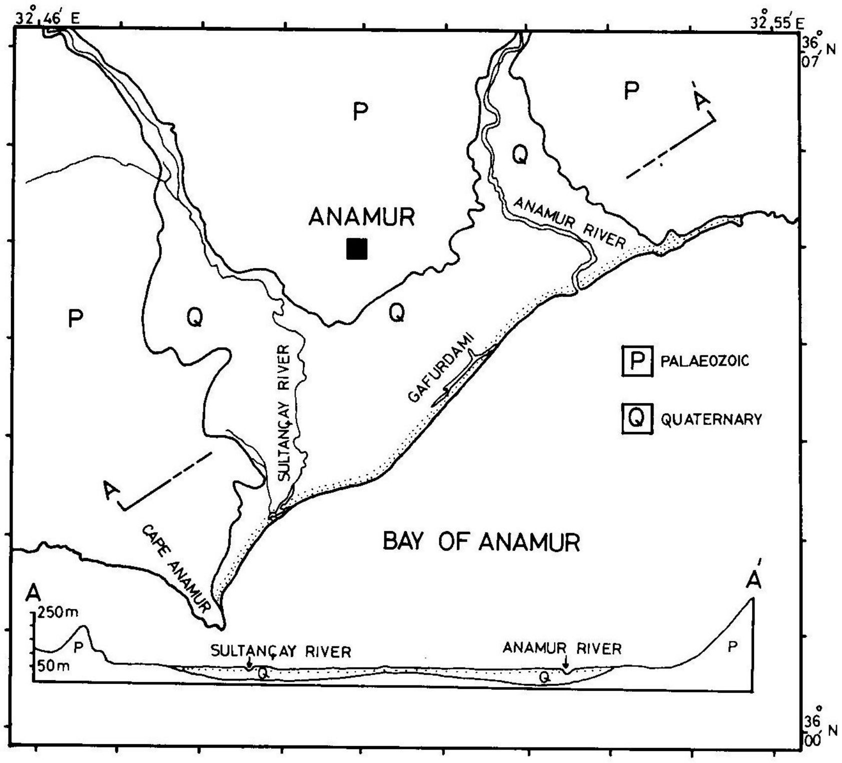


Fig.2. Drainage system and simplified geology of the Anamur coastal plain area (adapted from Ilbal, 1978). Note that the studied area extends from the mouth of the Sultançay River eastward to Gafurdami.

microscope and between 200 and 1100 grains were identified and counted in each sample (Ediger, 1987).

Nine bulk samples were selected and analyzed for their mineralogical compositions by a Philips X-ray diffractometer using CuKα radiation with a nickel filter at 36 kV/24 mA and a 1° detection slit. The goniometer speed was 0.5–2 θ/min and the paper speed, scale and time factor were chosen to produce optimum results. The amount of each mineral in a powdered bulk sample was estimated with a computer program. Factors multiplied by the peak intensities for minerals are taken from Cook et al. (1975). The results are summarized in Table 2.

Bathymetric data were collected by a precision depth recorder (210 kHz) and a portable echosounder (208 kHz) operated along most of the sidescan sonar (signal frequency of 105 kHz) and uniboom lines (Fig.3). Bathymetric data from waters deeper than 100 m were corrected for variations in the speed of sound using the available hydrographic data from the area (IMS, 1985; Ediger, 1987). Position finding was with a trisponder system. The specifications of the sidescan sonar and the seismic profiler are given by Stefanon (1985a, b). The seismic profiler was operated in its 300J mode throughout the survey.

Setting

Geological background

The southern continental margin of Anatolia is undergoing a complex pattern of deformation along a broad zone of collision between the African and the Anatolian plates (Rotstein and Kafka, 1982; Jackson and MacKenzie, 1984). Neogene regional vertical differential movements (Woodside, 1977; Stanley, 1977;

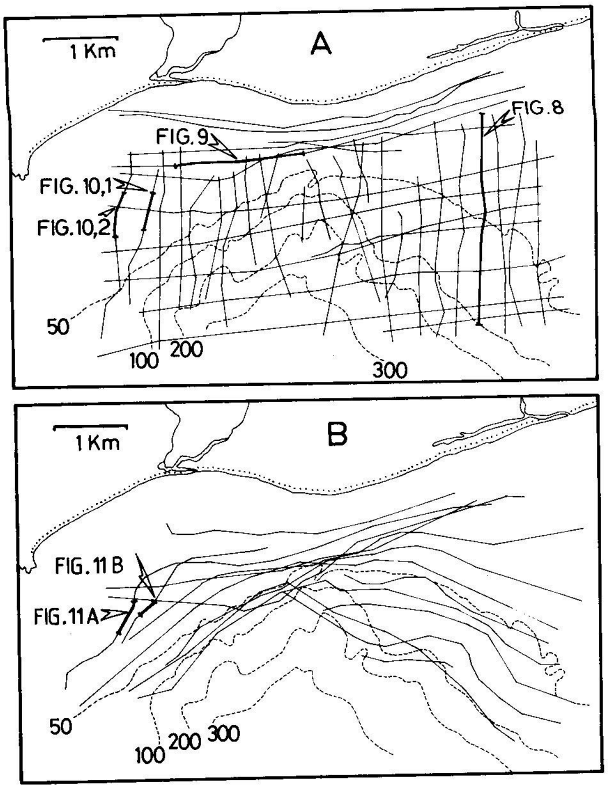


Fig.3. Uniboom (A) and sidescan sonar (B) survey lines. Records from the thickened sections of the lines are illustrated in Figs.8–11. Isobaths (broken lines) in metres.

Foose, 1985) have formed a basinal complex to the north of the Cyprus Arc (Misis–Kyrenia Range) (Biju-Duval et al., 1978). This consists of the Adana and Mut Basins on land (Bizon et al., 1974; Mulder et al., 1975; Yalçin and Görür, 1984) and the Cilician and Antalya Basins offshore (Evans et al., 1978; Şengör et al., 1985; Evans et al., 1988). As the margins of the latter basins have remained narrow, much of the sediment derived from the north seems to have accumulated in their rapidly subsiding deeper parts (Lort and Gray, 1974; Baroz et al., 1978). Thus, away from areas of deltaic sedimentation, neotectonic activities have maintained fairly narrow coastal plains and margins surrounding the basins, with a relatively thin sequence of Plio-Quaternary sediments blanketing a heterogeneous and highly tectonized pre-Neogene basement (Evans, 1971; Woodside, 1977; Evans et al., 1978).

Geology of the Bay of Anamur

The coastal plain of Anamur (ancient Anemurium) is associated with a structural offset in the central Taurus Mountains. Two major NW–SE-trending Alpine thrust faults extend

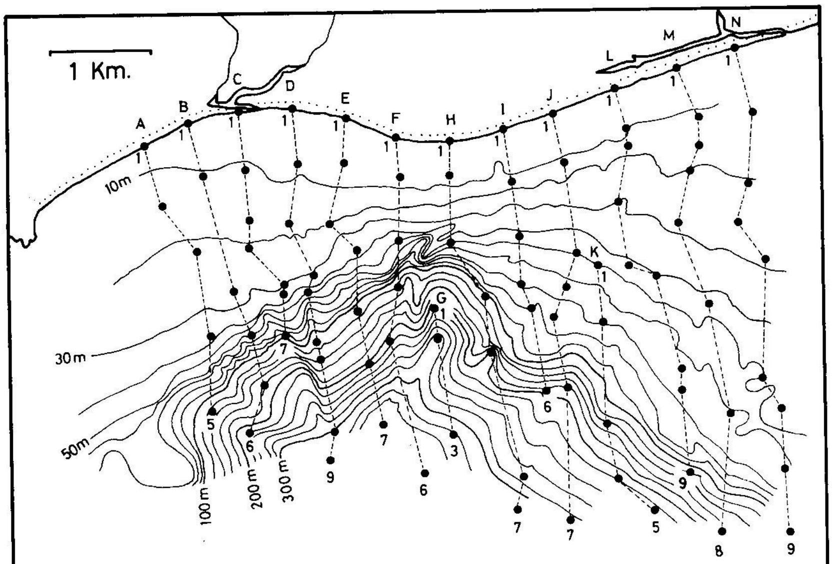


Fig.4. Detailed bathymetry of the shelf and upper slope and locations of sediment samples.

TABLE 2

Results of X-ray mineralogical analyses on nine selected bulk sediment samples from the shelf in the Bay of Anamur (see Fig.19)

	D2	D5	I3	I5	I6	J2	J3	K2	M3
Percentage abundance									
Calcite	10	10	13	21	26	10	17	21	18
Mg-Calcite	–	6	3	8	–	–	9	6	5
Aragonite	–	2	–	6	–	–	6	4	–
Dolomite	39	11	7	8	9	48	8	8	9
Quartz	21	18	23	26	24	15	21	23	25
Alkali Feldspar	2	–	–	–	17	3	–	–	–
Plagioclase	9	27	10	12	–	8	11	9	9
10Å Micas	15	20	35	13	19	12	22	24	26
Chlorite	3	4	6	5	5	3	5	5	6
Peak intensity ratios									
Qtz./Calc.	3.3	3.1	2.8	2.0	1.5	2.5	2.0	1.8	2.3
Qtz./Dol.	0.8	2.4	4.8	5.0	4.2	0.5	3.8	4.5	4.3
Calc./Dol.	0.2	0.8	1.7	2.4	2.8	0.2	1.9	2.6	1.9
Qtz./Plag.	6.6	1.8	6.3	5.9	–	5.4	5.4	6.8	8.0
Qtz./Chl.	29.5	23.4	19	27.4	23.5	25	20.6	24.7	19.7
Qtz./Micas	8.2	5.3	3.9	11.8	7.3	8	5.6	5.7	5.8

towards this plain (Özgül, 1984). The western fault appears to control the course of the Sultançay valley which is located on the southeastern flank of a Palaeozoic metamorphic complex known as the Alanya Massif (unit) (Brunn et al., 1971). The trend of this fault is also in approximate alignment with the axis of the Anamur submarine canyon (Hall, 1981; Ediger et al., 1988), suggesting that the large-scale morphology of the area is controlled by basement structural lineations and their possible reactivation in recent geological times. The alluvial deposits in the plain are directly underlain by the Palaeozoic metamorphics which form a prominent headland just to the west of the Bay of Anamur (Cape Anamur) (Ilbal, 1978) (Fig.2). Seismic (sparker) reflection profiles from the continental slope (Evans et al., 1978; Hooker, 1981) show that a well-stratified to moderately transparent Plio-Quaternary sequence, locally disturbed by slides and slumps, is underlain by a strongly reflective and step-faulted basement. This sequence thins out rapidly towards the coast. Faulting has also exerted some control on the pattern of Recent sedimentation and the morphology of the shelf. These characteristics typify the margin as an immature, unstable and rifted feature with a dissected type of shelf break (Vanney and Stanley, 1983; Vanney and Gennesseaux, 1985).

Drainage system

The drainage system of the Bay of Anamur erodes extensive exposures of the low-grade (mainly chlorite schist and mica schist) metamorphic facies of the Alanya unit and, to a lesser extent, a variety of Palaeozoic and Mesozoic carbonate and clastic rocks (shale, quartzite, arkosic sandstone and dolomitic limestone) before reaching the coastal plain. The metamorphics are also undergoing marine erosion in the region (Shaw, 1978; Mange-Rajetzky, 1981) and the beach is rich in metamorphic and carbonate lithic grains (Evans, 1971). The Sultançay and Anamur Rivers each have an average annual discharge rate of 0.34 m^3/s (Ilbal, 1978). This is much lower than in the Deliçay River (about 3 m^3/s), one of the small rivers flowing into the Bay of Mersin (IMS, 1986).

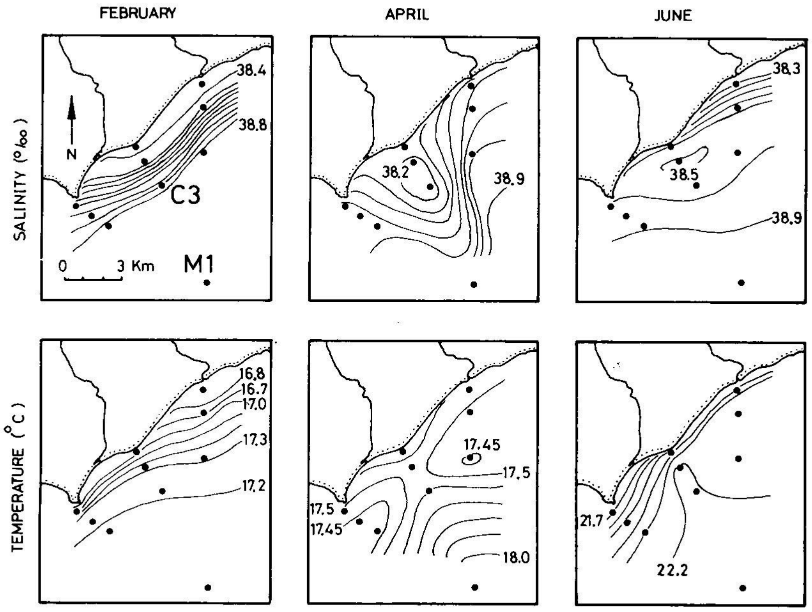


Fig.5. Seasonal surface salinity and temperature variations in the Bay of Anamur. Note the strong landward deflection of the isotherms in April accompanied by a reduction in the surface salinity. Locations of the hydrographic stations are indicated (from IMS, 1985).

Climate

The southern coast of Turkey has long, warm and dry summers with mild rainy winters and springs (Van Zeist et al., 1975; Mediterranean Pilot, 1976). The annual mean wind direction in the Anamur area is from the southwest (Ataktürk, 1980). However, between November and April, northerly winds may frequently blow between Akkuyu and Anamur. The wind stress tends to reach its maximum in December when the speed of the northerlies (Poyraz) can increase to as much as 24 m/s.

The average annual rate of precipitation ranges between 400 and 1000 mm. The higher values are recorded in the elevated parts of the coast (Van Zeist et al., 1975; Özsoy et al., 1981). Most of the precipitation takes place in winter and spring (November–April) and the rate of river discharge usually peaks in spring as the snow begins to melt (Evans, 1971).

Oceanography

Oceanographic data from the area include the results of seasonal hydrographic casts, dissolved oxygen and Secchi-disc measurements in 1984 and 1985 (IMS, 1985) (Figs.5–7). The neritic water masses between Anamur and Akkuyu undergo the same cycle of seasonal changes as the offshore waters of the northeastern Levantine Sea (Ünlüata, 1986). Salinity ranges between 38.20 and 39.20‰ and temperature between 16.5 to 25°C down to

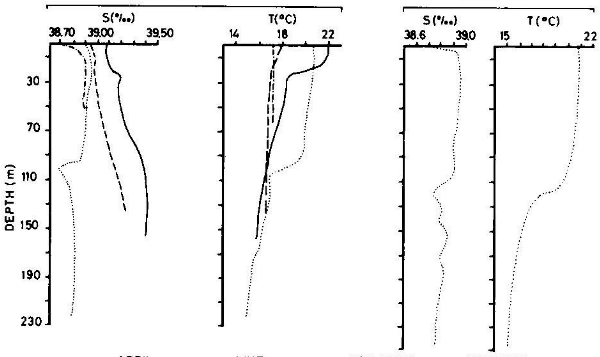


Fig.6. Temperature and salinity profiles at stations M1 and C3. Note a distinct salinity minimum at about the 100 m depth in November (from IMS, 1985). Locations of the stations are shown in Fig.5.

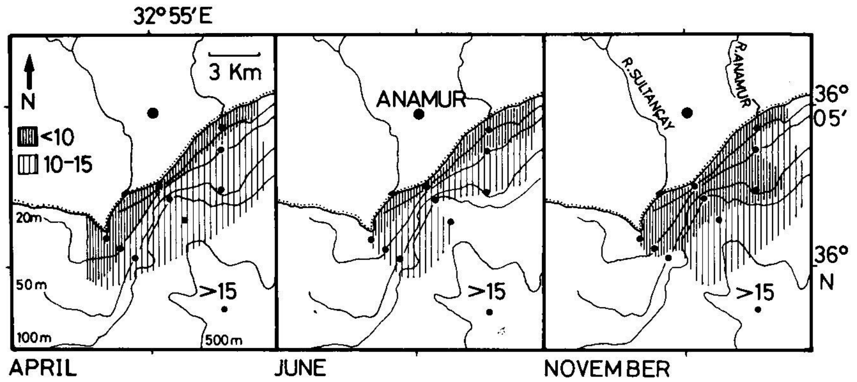


Fig.7. Secchi-disc depths (m) for three seasons in the Bay of Anamur (1984). (Data from M.A. Latif, pers. commun., 1987).

about 100 m, this being the deepest limit of the surface mixed layer (Fig.7). This is mainly due to the narrow width of the shelf facilitating water exchange between the coastal and offshore waters, as well as the low rate of fluviatile discharge. A weak reduction in the surface salinity occurs in April (Fig.6), when a minimum value of 38.20‰ was recorded in the centre of the bay. This event probably reflects downwelling over the head of the canyon. Similar hydrographic situations above the heads of some canyons off the coast of California have been attributed to downwelling (Felix and Gorsline, 1971; Inman et al., 1976), the cause of which may be the interaction of internal waves with the topography of the canyon head (cf. Hotchkiss and Wunsch, 1982).

Currents

Although current measurement data are not available for the area, measurements near Erdemli, the Göksu delta and Akkuyu together with analyses of hydrographic data (Ünlüata et al., 1983) have shown that surface currents on the shelf flow most strongly and frequently parallel to the coast with an average velocity of about 10 cm/s. The interaction of offshore currents with the steep and dissected slope of the shelf and the rugged topography of the coast can generate local gyres with counter currents over the shallower parts of the shelf between the Göksu delta and Cape Anamur (Fig.1) (Ünlüata et al., 1983). This effect can significantly reduce the coupling of inshore and offshore currents in shallow embayments, resulting in temporary isolation of coastal waters. There are no significant tidal currents and the maximum range of the tidal fluctuations of sea level under normal weather conditions is about 50 cm. The results of shelf current measurements off Erdemli and Akkuyu have also shown that the average velocity of the onshore–offshore component of the currents is consistently less than that of their longshore component.

In the open sea, a branch of the surface cyclonic gyre in the Levantine Sea (Lacombe and Tchernia, 1972; Malanotte-Rizzoli and Robinson, 1988) brings some Atlantic surface waters into the Cilician Basin from the east. This current (the Asia Minor Current) has a mean direction of flow towards the west with a measured surface velocity of 4–30 cm/s (Guibout, 1972; Ünlüata et al., 1980). As it meanders along its course, at some places it impinges on the shelf edge (Ünlüata et al., 1983; 1985).

Water transparency

As expected, the results of Secchi-disc depth measurements (Fig.7) show that the lowest values of water transparency (< 10 m readings) occur in the inner shelf zone (depths < 30 m). However, surprisingly low values (2.5 m) were registered locally further offshore in November. There is no evidence to suggest that this is caused by an input of terrigenous suspensate. It is probably due to high productivity. Seasonal determinations of chlorophyl-α (Yilmaz, 1986) in the northeastern Levantine Sea have shown that primary productivity peaks at this time of the year. This is largely controlled by the decay of the seasonal thermocline and increased wind-induced turbulence (Fig.7). Productivity may also be enhanced by upwelling in the head of the canyon.

The Secchi-disc data suggest that the coastal waters in the Bay of Anamur can be as turbid as the nearshore waters in the Bay of Mersin, which receives a much larger quantity of natural and anthropogenic solid matter. Readings at 25 locations in waters less than 40 m deep off Mersin in October 1985 did not exceed 9 m (average value 4.2 m) (IMS, 1986). The total suspensate content ranged between 2.2 and 8.8 mg/l at the same time and locations. Hence, the total suspensate content of the inshore waters off Anamur may be assumed to be nearly the same as that of the Bay of Mersin, at least at certain times of the year. Collins and Banner (1979) also estimated a maximum concentration of 7.0 mg/l of silt- and clay-size suspensate for Secchi-disc depths of less than 10 m. The offshore waters are highly transparent and the concentration of total suspensate is usually much lower than 2 mg/l (Salihoğlu et al., 1988).

In summary, in their conservative properties the neritic waters show the same cycle of seasonal fluctuations as the offshore waters. They remain well oxygenated (>6.0 mg/l dissolved O_2). Only the inshore waters may come under some influence of runoff in the rainy season. Offshore currents flow mainly parallel to the coast and may affect most of the shelf. The near-shore waters remain turbid most of the times. The absence of significant tidal currents and the dominance of southwesterly and westerly winds may explain the weakness of currents across the shelf.

Morphology of the shelf and upper slope

The maximum width of the shelf is about 4 km in the surveyed area and its gradient varies between 1° and 3°. It is wider on the eastern side of the canyon where the shelf break occurs at about the 100 m isobath. The shelf break is generally defined by the upper rim of the canyon head (Fig.4). The apex of the canyon head is located about 1 km from the coast and the shelf break shoals to about the 50 m isobath towards the west. The gradient of the shelf increases in the same direction, reaching a maximum (approximately 3°) at the apex of the canyon head. These morphological changes around the canyon head have been controlled by neotectonic movements and regional differences in the rate of sedimentation on the shelf during the late Quaternary.

Seismic records from the shallower (<20 m) parts of the shelf revealed that the modern coastal sedimentary wedge attains a thickness of about 20 m opposite the apex of the canyon head where the beach may have been recently prograding. This wedge thins out away from this area along and across the shelf (Figs.8 and 9). Sedimentary starvation of the deeper parts of the shelf is reflected by the submarine exposures of (aeolian?) sand ridges close to the shelf break at some places (Fig.10). In general, shallow-buried relict features and neotectonic movements exert more control on the microtopography of the sea floor with increasing depth. This is mainly a result of the rise of sea level over a steep Pleistocene coastal plain, rapidly shifting depocentres, and greater slope instability close to the shelf edge as the gradient of the slope in the canyon head increases to as much as 13°. The scalloped rim of the canyon (Fig.4) may have also been formed in part as a consequence of slides and slope failure at the shelf edge.

The dendritic pattern of the V-shaped tributaries of the canyon head is comparable with that of some canyons off the coast of Levant (Beydoun, 1977; Almagor and Hall, 1980). These tributaries are considered to be the drowned parts of their related coastal valleys. However, submarine erosion in the shallower parts of these canyons by mass wasting or channelized and gravity-induced currents may

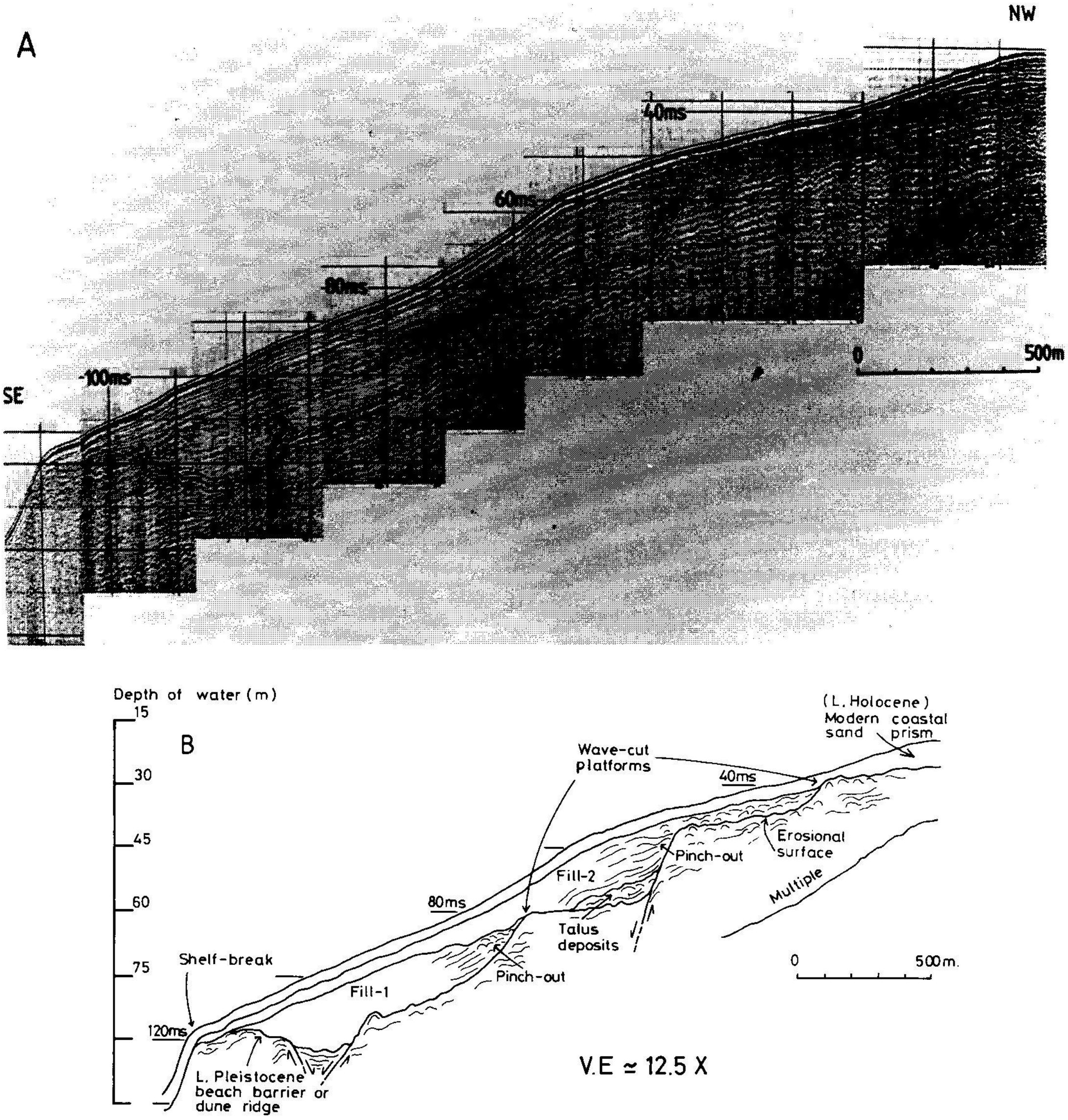


Fig.8. A. Uniboom record taken across the shelf to the east of the canyon. B. Interpretation. (See Fig.3 for the locations of the records shown in Figs.8–11.)

also have contributed to the incision of the tributaries. The dendritic drainage pattern of canyons whose heads reach close to the mouths of active rivers can be produced through rapid erosion of the seabed by sediment-laden river plumes flowing into the canyons (Reimnitz and Gutierrez-Estrada, 1970). Subsequent lateral shifts in river courses would also change the course of their corresponding channelized flows. Buried river channels and accretionary (oblique-bedded) interchannel bank sediments (Fig.9) close to the apical part of the head of the Anamur canyon indicate that the drainage system of the Sultançay River extended into the head of the canyon in the late Pleistocene. Some of the minor valleys may also be abandoned "sand chutes" (Shepard, 1963) carved out by mass movement of sand prompted by wind-driven circulation cells when the coastline was close

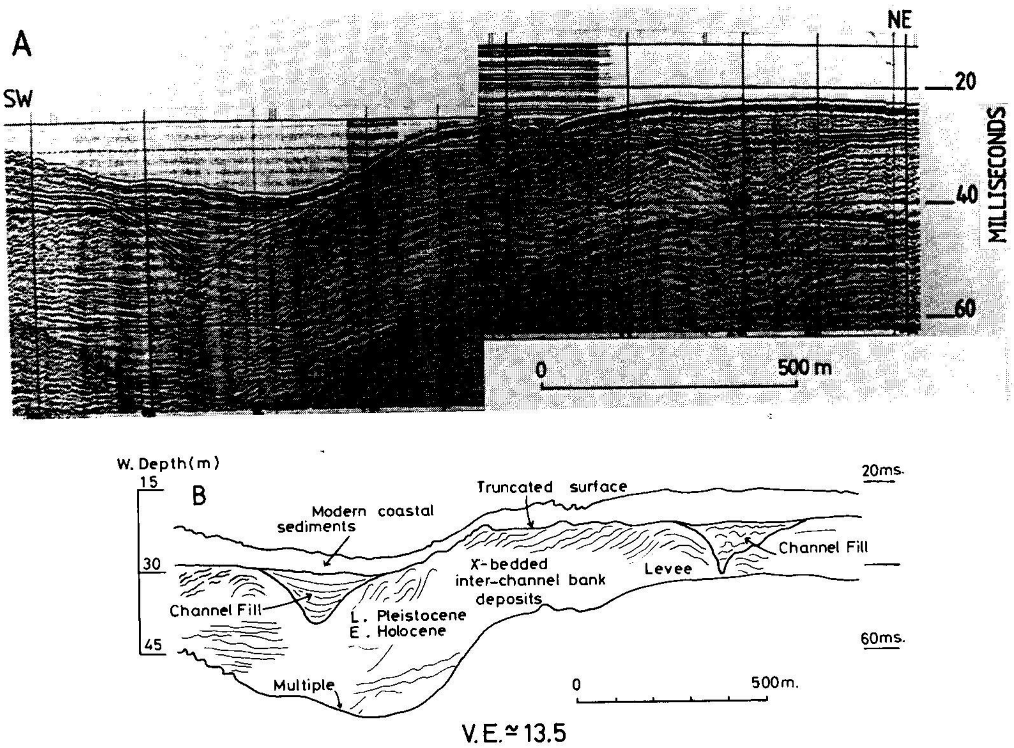


Fig.9. A. Uniboom record from the shelf parallel to the coast. B. Interpretation. Note the subsurface infilled river channels.

to the shelf edge (Felix and Gorsline, 1971; Inman et al., 1976). Although this mode of sand transport is unlikely to be operative today because of the great depth of water (>40 m) and the predominance of mud in the canyon head (see below), occurrences of admixtures of relict (or palimpsest) sand and gravel with tests of shallow-water benthic foraminifers in some parts of the canyon head support this view. Boulder-sized marble fragments from the Anamur coastal mountains have been recovered by a core from a valley cut in the ridge between the Cilician and Antalya Basins (G. Evans, pers. commun., 1988). In addition, Holocene and late Pleistocene sediment cores from the floor of the Antalya Basin contain several turbiditic sand layers (Catani et al., 1983). It is also worth noting that the sector of the Anatolian margin between Anamur and Alanya is dissected by several canyons whose heads reach close to the coast. In short, the interaction of the neotectonics of the margin with the dynamics of shelf and upper slope processes of sedimentation, modulated by Quaternary sea-level fluctuations, may have shaped much of the detail of the canyon head.

Late Quaternary sedimentary evolution of the shelf

The seismic survey (Fig.3) revealed that the rate of Recent sedimentation has varied considerably over the shelf in space and time (Ediger, 1987). The most important factors affecting these variations are proximity to sources of fluviatile discharge and the (palaeo-) relief of the shelf. Other influential factors include syn-depositional subsidence, temporary halts in the post-glacial sea-level rise, and an overall decrease in the rate of terrigenous deposition on the deeper parts of the shelf.

On the eastern (broader) sector of the shelf, three phases of sedimentation can be distinguished. At the shelf edge (100–110 m), a

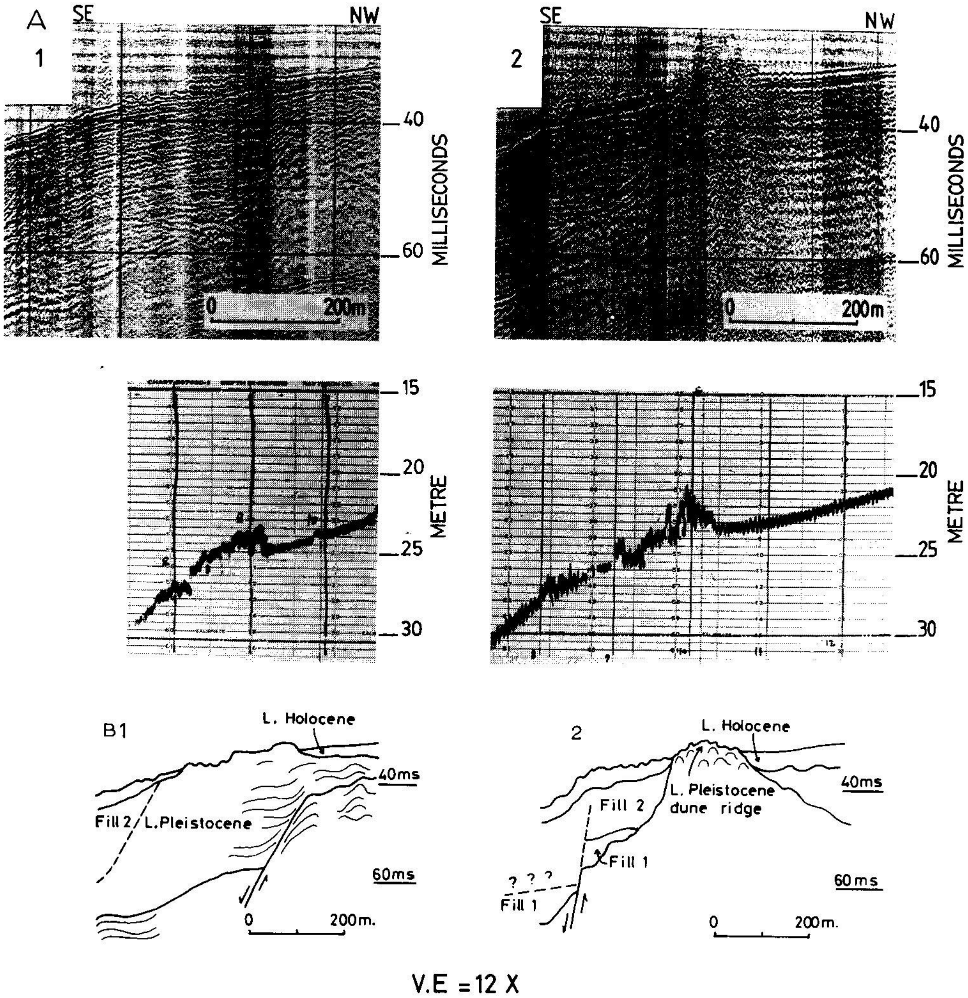


Fig.10. A. Uniboom and echosounder (210 kHz) records taken across the western part of the shelf. B. Interpretations of the seismic profiles.

shallow-buried ridge occurs on most profiles (Fig.8). It shows a distinct chaotic to hummocky seismic facies (Got et al., 1987; Canals et al., 1988). This feature may be a part of a late Pleistocene beach–barrier system which was probably backed by a lagoonal depression at the time of the maximum decrease in sea level by nearly 110 m below its present level (Van Andel and Lianos, 1984). This system continues to the west across the canyon head, maintaining its relationship with the shelf break (Fig.10). However, its eastern part has subsided and is located at a level deeper than that of the western part.

On the landward side of this ridge, a relatively thick (about 15 m) and well-stratified sedimentary sequence (probably of lagoonal origin in its lower part) was recognized on most of the seismic profiles to the east of the canyon (fill 1 in Fig.8). This sequence lies in a palaeodepression between the present shelf edge and the 60 m isobath. The floor of the depression shows some relief and has subsided as a small graben. The sequence thins out rapidly towards the buried barrier ridge and the landward edge of the depression, where a clear wave-cut platform can be observed on some records. A temporary halt in the post-glacial sea-level rise may have terminated an early Holocene cycle of sedimentation (fill 1) when sea level stood approximately 50 m lower than at present.

The second sedimentary unit is represented by a wedge-shaped body which thins to a few metres close to the shelf edge as it mounts the late Pleistocene barrier (fill 2 in Fig.8). Towards the coastline, this unit onlaps over a terrace-like feature cut into the acoustic basement (late Pleistocene) about 1 km landward of the edge of the depression containing the first fill. This terrace may be a fault scarp, the profile of which has been subsequently modified by coastal erosion as may be seen by a small wedge of talus deposits found at the base. The scarp probably formed as an approximately 4 m high coastal cliff at the time of the temporary break in the post-glacial sea-level rise. The terrace can be followed further to the east on some seismic profiles.

The second unit (fill 2) continues as a series of uneven, discontinuous, closely spaced and wavy reflectors over the upper surface of the terrace as far as another shallow buried wave-cut platform near the 30 m isobath (Fig.8). The same seismic facies continues beneath the youngest (late Holocene) sedimentary unit towards land, indicating that after the deposition of the second unit the sea-level rise began to slow down, permitting the development of a basal transgressive sandy layer over a large area before the deposition of the youngest sedimentary unit (cf. Swift, 1970). These seismic facies characteristics are identical with those of the most landward parts of the first fill (Fig.8). However, in the latter case the sediments abruptly terminate against the talus deposits at the foot of the fault scarp. These deposits were probably extensively reworked in a narrow, high-energy shoreface zone as the Pleistocene step-like coastal plain became gradually submerged.

Between the location of the younger wave-cut platform and the coast, only the uppermost (late Holocene) sedimentary unit (modern coastal sand prism) can be clearly resolved on the seismic records. This unit records the youngest cycle of sedimentation, and in areas shallower than 25 m its thickness increases rapidly towards the coast. It overlies the transgressive sandy deposits underlain by the late Pleistocene–early Holocene alluvial facies.

Over the western and central parts of the shelf, close to the apex of the canyon head, the rate of deposition has been lower than in the east. This is mainly due to the narrower width of the shelf and channeling of fluvial sediments into the canyon in the late Pleistocene–middle Holocene. In this area, only the younger Holocene sedimentary units can be resolved on seismic records, and the subsurface sediments outcrop at some localities (Fig.10). The seismic facies characteristic of these outcrops and their very rough surface microtopography (Fig.11A) are indications of deposition in a coastal beach and dune complex. In some places the sediments are cross stratified and their contact with the surficial sedimentary unit is usually erosional (Fig.9). These sedimentary structures also indicate high-energy coastal and/or aeolian conditions of deposition. A similar sub-bottom facies outcrops in some parts of the nearshore (< 20 m) zone in the Bay of Mersin (Bodur, 1987). Furthermore, the profiles of these ridges and their seismic facies are similar to those of the late Pleistocene dune ridges from the Israel shelf (Almagor, 1979).

The rapid seaward pinch-out of the youngest sedimentary unit at about the 25 m isobath suggests that a large part of the terrigeneous sediment delivered to the shelf has been trapped in the inner shelf zone and the modern beach–dune system. The sea probably encroached inland over the distal parts of the present fluvial plain in the late Holocene before the final progradation of the beach to its present position (cf. Evans, 1971). The situation may have been similar to that of the deltaic plains of some rivers on the Aegean coast of Turkey (Eisma, 1978; Erol, 1983; Aksu et al., 1987) where rapid deposition has led to alluviation and infilling of marginal water bodies over the past few millennia. These

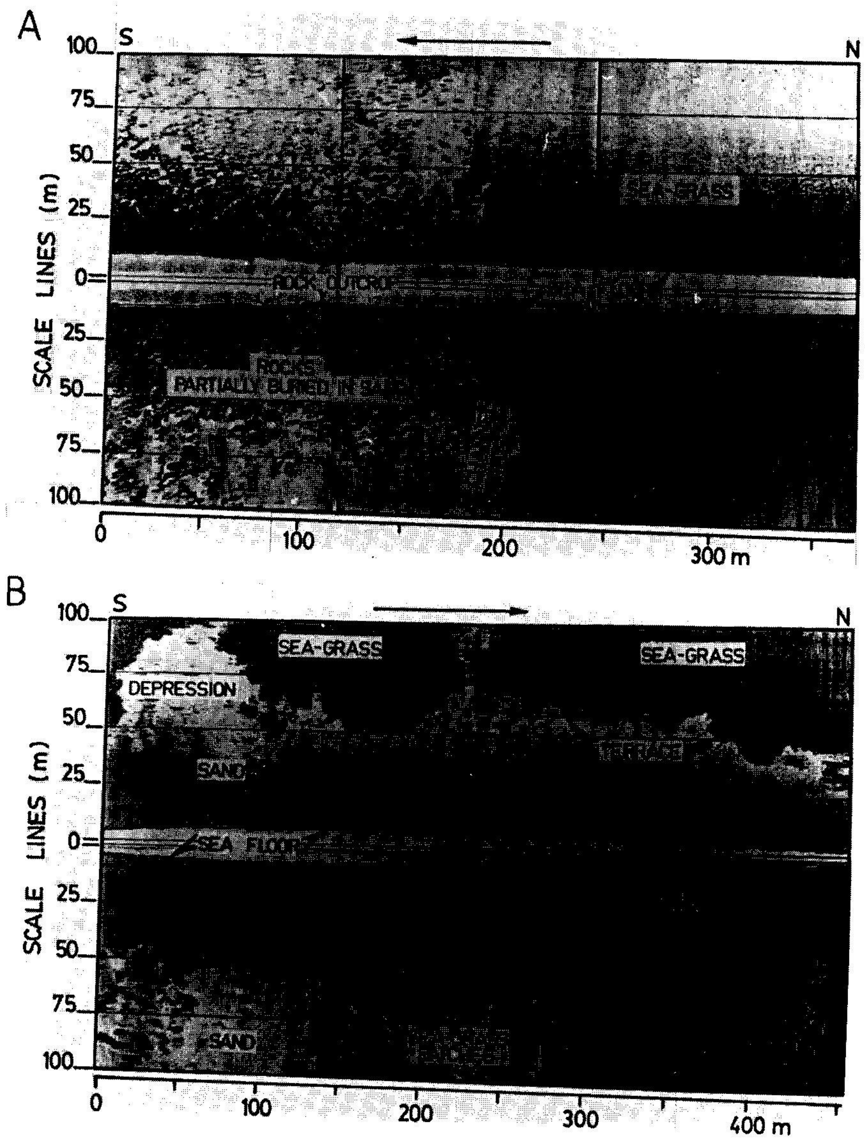


Fig.11. A. Sonograph from the same area as the records in Fig.10. The rocky area is located seaward of the zone of macrophytobenthos. B. Sonograph from the zone of phytobenthos. Note the strong reflectivity of the patches of seagrass.

deposits mark the most landward limit of the last phase of the Flandrian transgression and the beginning of a modern phase of regression close to active sources of terrigenous input and major deltas.

The sidescan sonar survey showed that large parts of the shelf between the depths of 10 and 35 m are covered by patches of sea grass (Fig.11). Most of the surface sediment samples from this zone contain fresh thalli of *Posidonia* and *Zostera* (Ediger, 1987) (Fig.12). The meadows are variable in shape and size but all produce strong reflections (Fig.11). The pattern of reflections and shadows closely resembles the sonographs from areas of phytobenthos growth in the northern Adriatic Sea (Newton and Stefanon, 1975, 1982). The images are very similar to those of rocky areas. As explained by Newton and Stefanon, this is because of the formation of a semi-indurated layer of sedi-

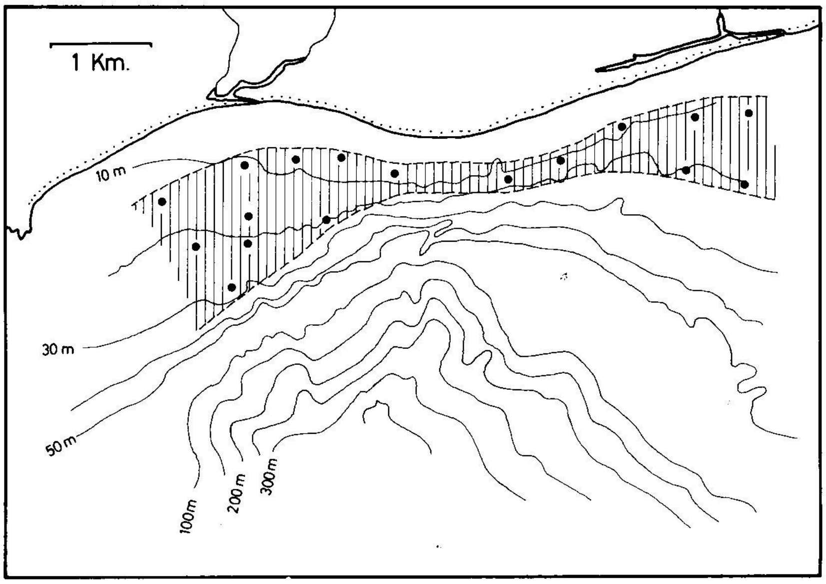
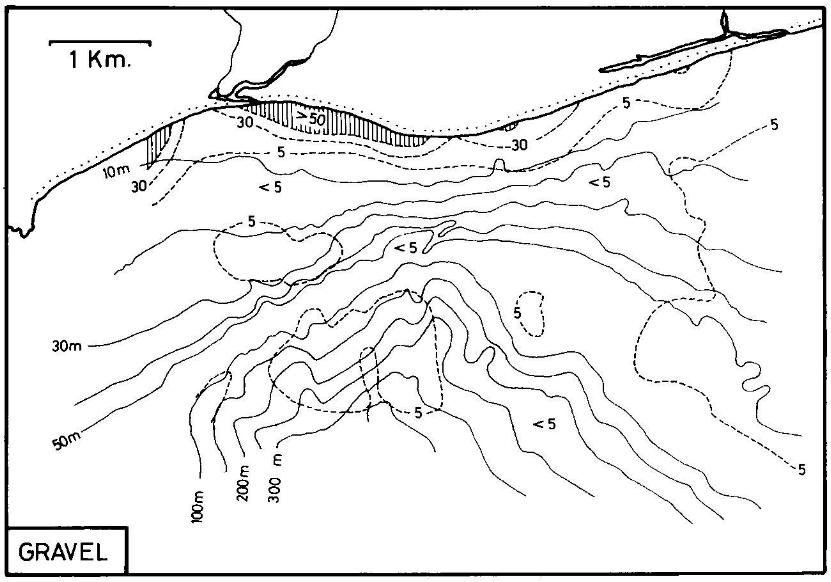


Fig.12. The area of phytobenthos growth on the shelf. Dots indicate the locations of samples containing fresh thalli of *Posidonia* and/or *Zostera*.

ment (matte) by the binding action of the foliage of the dead plants and their holdfasts. After the death of the plants, this layer is eroded into low platforms separated by shallow channels producing echo patterns very similar to those of a rocky seafloor.

These plants often grow over sandy bottoms in clear waters away from sources of fresh-water input and provide favourable ecological conditions for a variety of macro- and micro-benthic organisms whose skeletal remains eventually enrich the bottom sediments (e.g., Blanc, 1969; Caulet, 1972; references in Boudouresque, 1977). Plant remains have been found on beaches at many localities to the west of Akkuyu as far as the extreme western parts



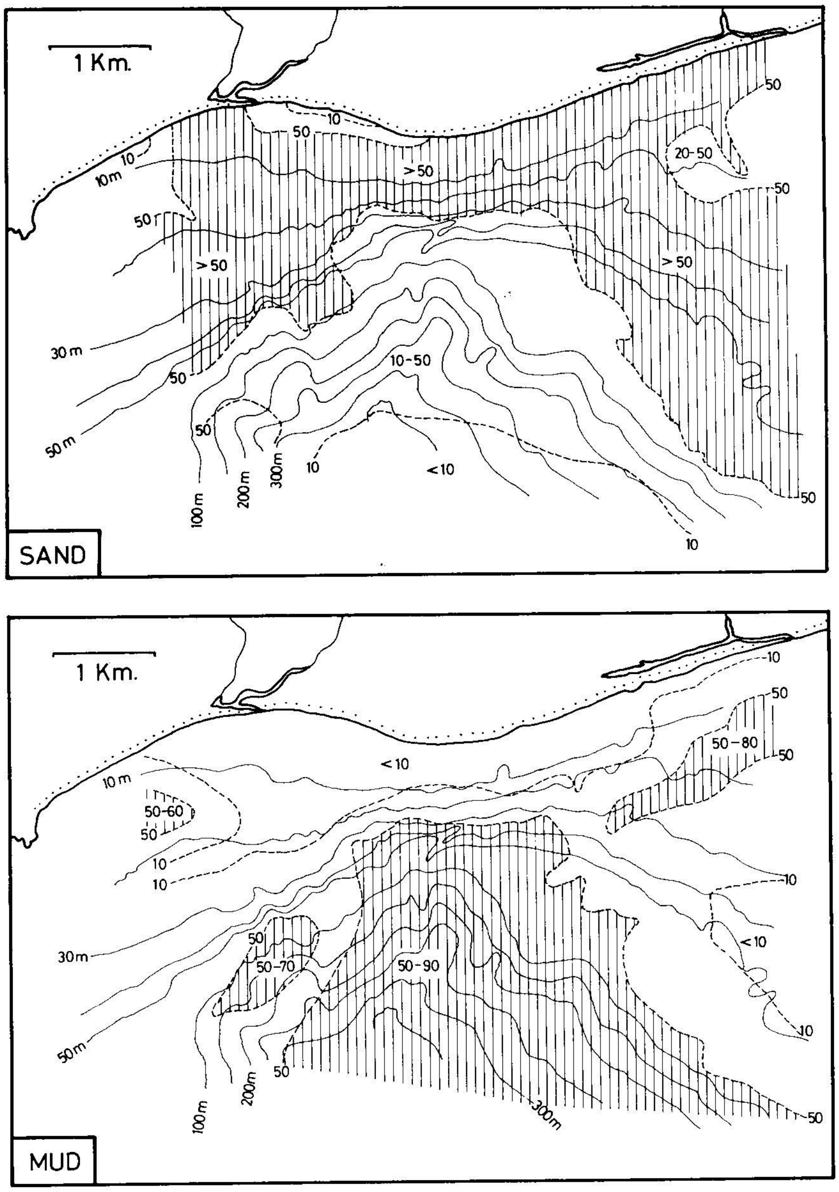


Fig.13. Abundance distributions of gravel, sand and mud (%) in the surface sediments. Shaded areas have values greater than 50%.

of the southern coast of Turkey. However, we have not observed any remains along the coast in the Bay of Mersin. Extensive seafloor sampling in the latter area has never yielded remains of these plants. The prevalence of rocky shores and a limited rate of runoff to the west of the Göksu delta, as well as a greater impact of offshore waters on the shelf may provide suitable bottom conditions for the plants. The absence of plants can also be one reason for the relatively low carbonate content of the sediments to the east of the Göksu delta.

Surface sediment characteristics

Texture

The distribution patterns of gravel, sand and mud (silt and clay) (Fig.13), based on the granulometric analyses of all samples (Fig.4), show that most of the shelf is covered with muddy sand, while sandy mud predominates in the canyon head. The beach samples are rich in gravel and sandy gravel but free of mud. The gravel content of sediments decreases to about 5% at a depth of 10–15 m and does not exceed this value over most of the deeper parts of the shelf. Sediments containing between 5 and 10% gravel in the canyon head are relict (or palimpsest). This is also partly the case to the west of the canyon head on the shelf, but to the east of it similar proportions of gravel are encountered in areas of high abundance of calcareous shell fragments.

The mud content of the sediments on the shelf steadily increases with depth, reaching 50% at a depth of about 100 m (group B in Fig.14A). In the canyon head, this rate of increase with depth is sharply reduced. The sand/mud ratio also approaches unity close to the shelf break (Fig.15A). This depth may be regarded as the "mud-line" (Stanley et al., 1983).

Only five (14%) of the total of 27 samples from the slope (> 100 m) contain less than 50% mud. These samples are concentrated in the apical and western parts of the canyon head where the sediments are richer in gravel (5–10%) (Fig.13). Nine (15%) of all the shelf (< 100 m) samples (58) contain more than 60% mud (group A in Fig.14A). Four of these are located in the shallowest parts of the canyon head in a depth interval of 35–50 m, another four in an area shallower than 30 m to the east and the last one at a depth of nearly 15 m close to the mouth of the Sultançay River (Fig.14B). The highest percentage of mud on the shelf (80%) is recorded on the eastern part of the shelf off Gafurdami (Fig.13). This area probably receives mud from the Anamur River further to the east. The mud-laden river plumes in the region are usually deflected by longshore or offshore currents parallel to the coast. Except for the plumes of large rivers, they loose their identity behind the inner or the middle parts of the shelf (Collins and Banner, 1979, Fig.2). Patches of mud-rich surface sediments are also often located in protected embayments or close to rivers in other parts of the Mediterranean Sea (Got et al., 1985). Further evidence in support of the local deposition of fluviatile mud on the shelf comes from the pattern of distribution of mica on the shelf (see below).

We suggest that the bulk of the riverine mud in this area bypasses the shelf into the canyon head. This is based on the pattern of distribution of the shelf samples containing more than 50% mud (Fig.14B). These samples define a narrow zone that passes through the apex of the canyon head. The pattern is attributed to the very narrow width of the shelf and its exposure to open-sea currents capable of resuspending and transporting mud off the shelf. Surficial slope (200–1000 m) sediments to the west of the Göksu shelf are richer in mud when compared with the sediments from the same depth interval to the east of the Göksu delta (Alavi, 1980). Analyses of the absolute abundance of the tests of benthic foraminifers per unit gramme of sediments (foraminiferal number of Cita and Zocchi, 1978) revealed that a higher rate of supply of mud to this slope can explain a sharp reduction in the absolute abundance of benthic foraminifers in samples from the depth range of 200–800 m between Akkuyu and Anamur. The only other area in the whole of the Cilician Basin which shows the dilution of the tests to a comparable degree is the prodeltaic area of the Seyhan River. Shaw (1978) also interpreted the distribution of different clay minerals along this part of the margin in terms of differential settling and resuspension of clay particles. In addition, studies of sediment dispersal in areas close to canyon heads have shown that the main route of transport of fluviatile mud across the shelf is through a near-bottom nepheloid layer (Drake, 1976; Aloisi et al., 1982; Carson et al., 1986). The latter authors, and Monaco et al. (1987), concluded that on narrow shelves influenced by a boundary current, most of the fluviatile mud is transferred to the slope or is trapped in the heads of submarine canyons.

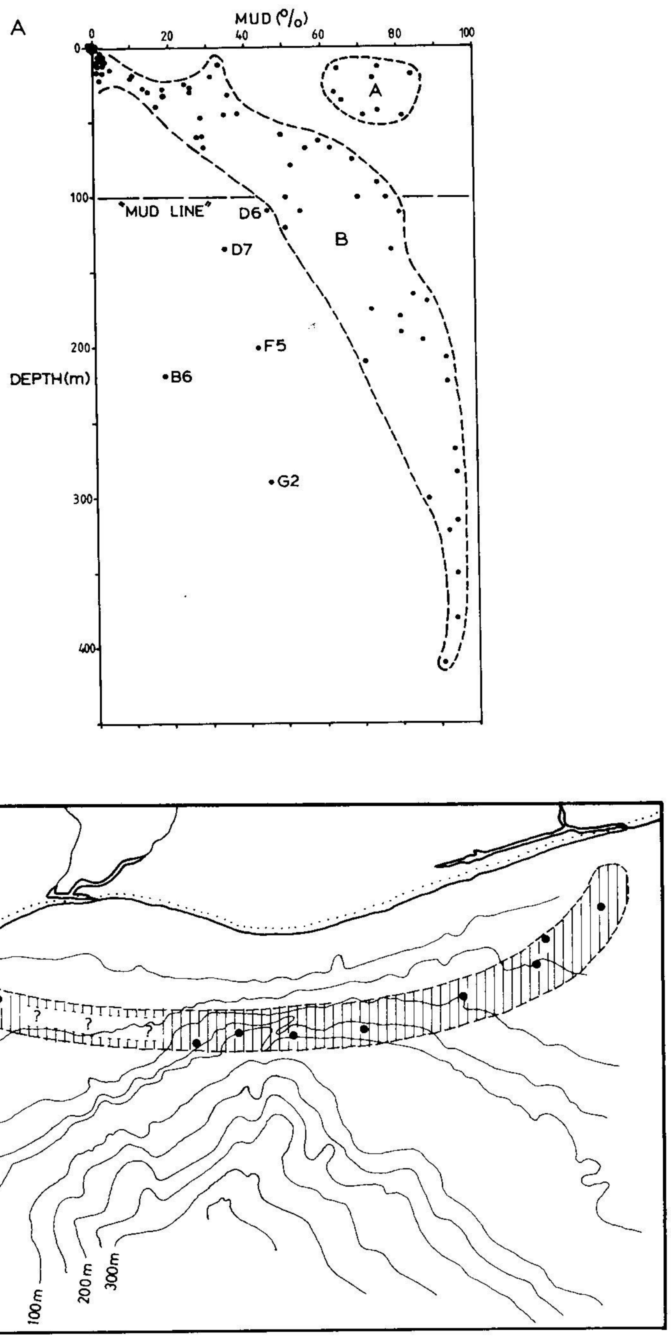
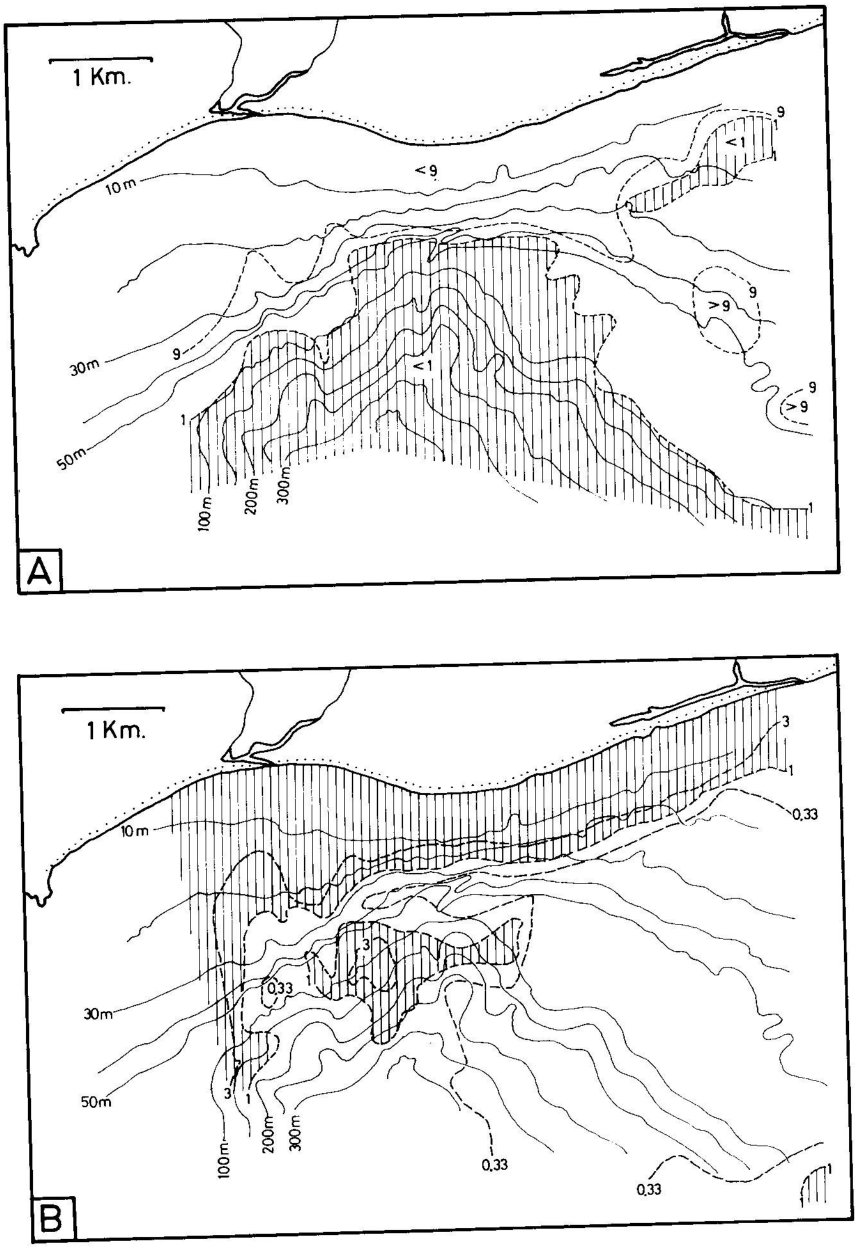


Fig.14. A. The relationship between the mud content of the sediments versus depth (beach samples are not plotted). Note the "mud line". B. Locations of the shelf samples containing more than 60% mud (group A samples in Fig.14A). For explanation of group B, see text.

Grain composition

The results of the microscopic identification and counts of gravel and coarse to medium sand (> 125 μm) grains showed that on the shelf these grains are either of terrigenous origin (derital component) or originate from the calcareous skeletal remains of various groups of benthic invertebrates, foraminifers and coralline algae (biogenic component). The ratio of the terrigenous to biogenic components consistently increases towards the coast, and in areas shallower than 25 m the former usually accounts for more than 30% of the grains in the gravel and sand fractions (Figs.15B and C). On the westernmost part of the shelf, detrital gravel occurs abundantly (>50%) down to about the 50 m isobath. This gravel is partly reworked from the exposed subsurface sediments in this area, as the proportion of quartz also does not decrease to less than 30% of the counted sand grains (Fig.16). This is also believed to be the case in an area to the east of the canyon head close to the shelf edge, where the proportion of quartz reaches as high as 30% of the coarse and medium sand fractions



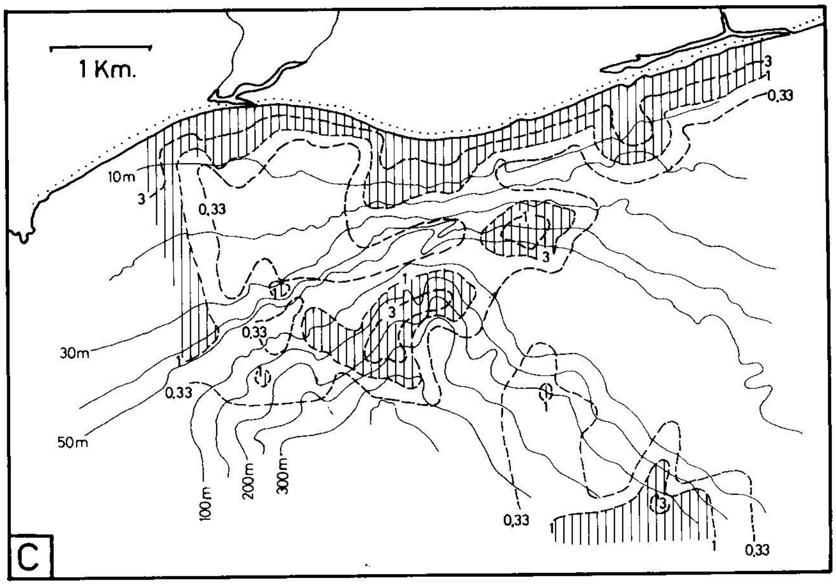


Fig.15. Distribution patterns of the sand/mud ratio (A) (shaded areas have values less than one), and the ratio of terrigenous to biogenic components in the gravel (B) and sand (C) fractions (shaded areas have values greater than one).

and the terrigenous/biogenic ratio increases to the same level as in the nearshore zone. However, in the latter zone sediments containing over 50% of detrital grains in their sand fraction represent the modern coastal sand prism (Caulet, 1972; Swift et al., 1972). These grains are essentially the product of coastal erosion and fluviatile admixtures. Mineralogical evidence in support of this is given below.

In addition to quartz, metamorphic and carbonate litharenite and mica flakes were found to constitute the other important elements of the terrigenous component (Figs.16 and 17). The metamorphic and detrital carbonate grains are often well rounded. The metamorphic litharenites have mostly roller or blade shapes and show polished surfaces. These are concentrated at two localities, off the mouth of the Sultançay River in the nearshore zone and at a depth of about 150 m in the canyon head. In the latter area, they are also accompanied by high proportions of quartz as well as lithic carbonate grains in the sand fraction. In the same part of the canyon head, the sediments are richer in gravel and the terrigenous/biogenic ratio increases to the same levels as in the nearshore zone (Fig.15C).

The detrital sand grains are mostly well rounded and show highly polished surfaces and some are coated with authigenic minerals of iron and manganese. Stained and well-abraded tests of typical shallow-water benthic foraminifers such as *Peneroplis* and *Amphistegina* also occur, in low numbers. Species of the former genus occur most abundantly in areas shallower than 20 m around the Mediterranean Sea and the Cilician Basin, but *Amphistegina* can be found in association with coralline algae down to about 80 m (Alavi, 1980). *Amphistegina* also occurs in association with the phytobenthos in the littoral zone along rocky shores to the west of the Göksu delta. The state of preservation of the tests and their faunal association leave no doubt that they come from an earlier cycle of deposition. *Peneroplis* and other typical shelf-dwelling benthic foraminifers (e.g., *Elphidium* and *Ammonia*) and highly polished gravel and coarse sand-size grains were also found in some samples from the deeper parts of the canyon. Similar assemblages of shallow-water foraminifers occur in surficial sediments from the floor of the Antalya Basin (Cita and Zocchi, 1978).

This is evidence of syn/post-depositional

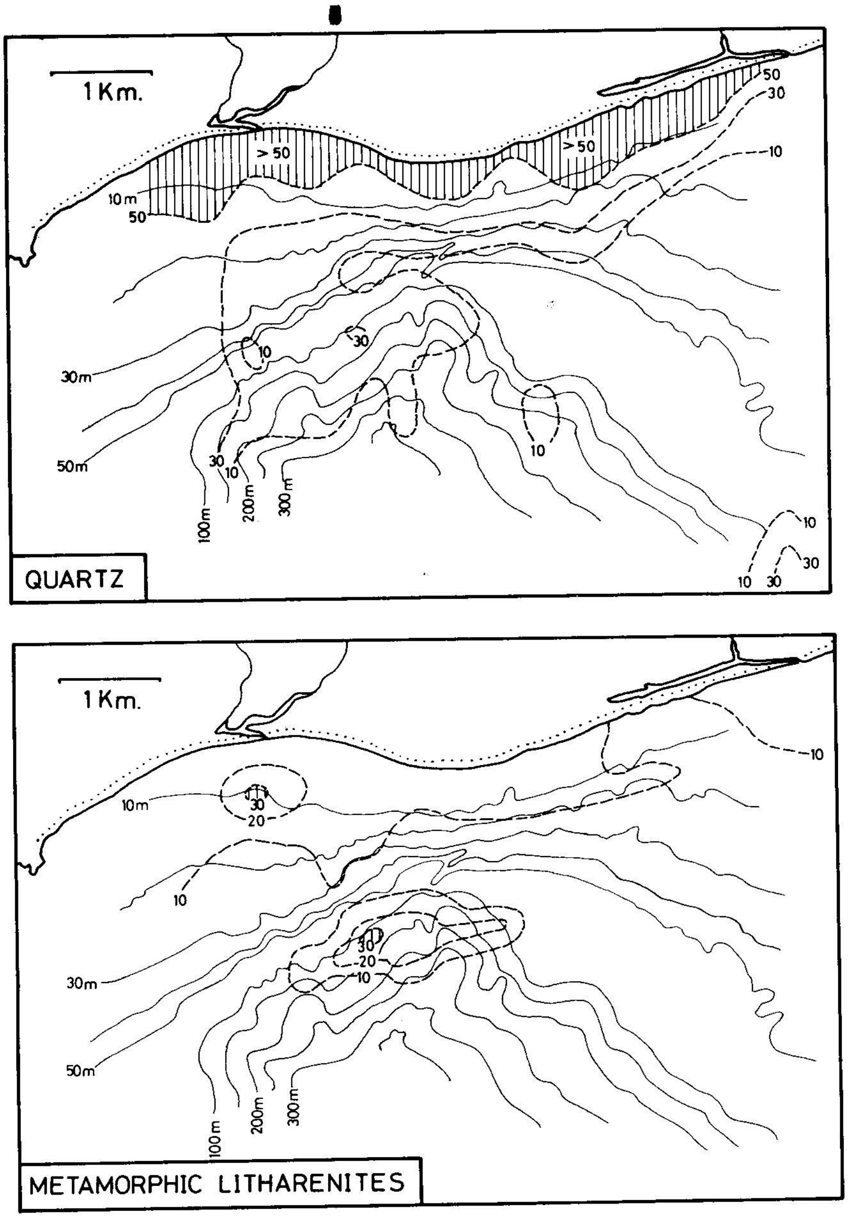


Fig.16. Distribution patterns (%) of quartz and metamorphic litharenites in the sand fraction. Shaded areas have values greater than 50% and 30%, respectively.

transport of shallow-water sand from the outer parts of the shelf by channelized or gravity-induced currents into the canyon at times of lower sea-level (May et al., 1983). However, no clear evidence of active transport of substantial quantities of modern sand or gravel from the inner shelf zone into the canyon could be found. The principal reason for this is the landward displacement of depocentres during the Holocene. The present microtidal conditions and weak advection across the shelf may also contribute to this effect.

Most of the sand-size mica flakes appear to deposit on the inner to middle shelf zone (Fig.18). This component is concentrated off the mouth of the Sultançay River and in the extreme east of the area between the 10 and 20 m isobaths. These are the locations of active

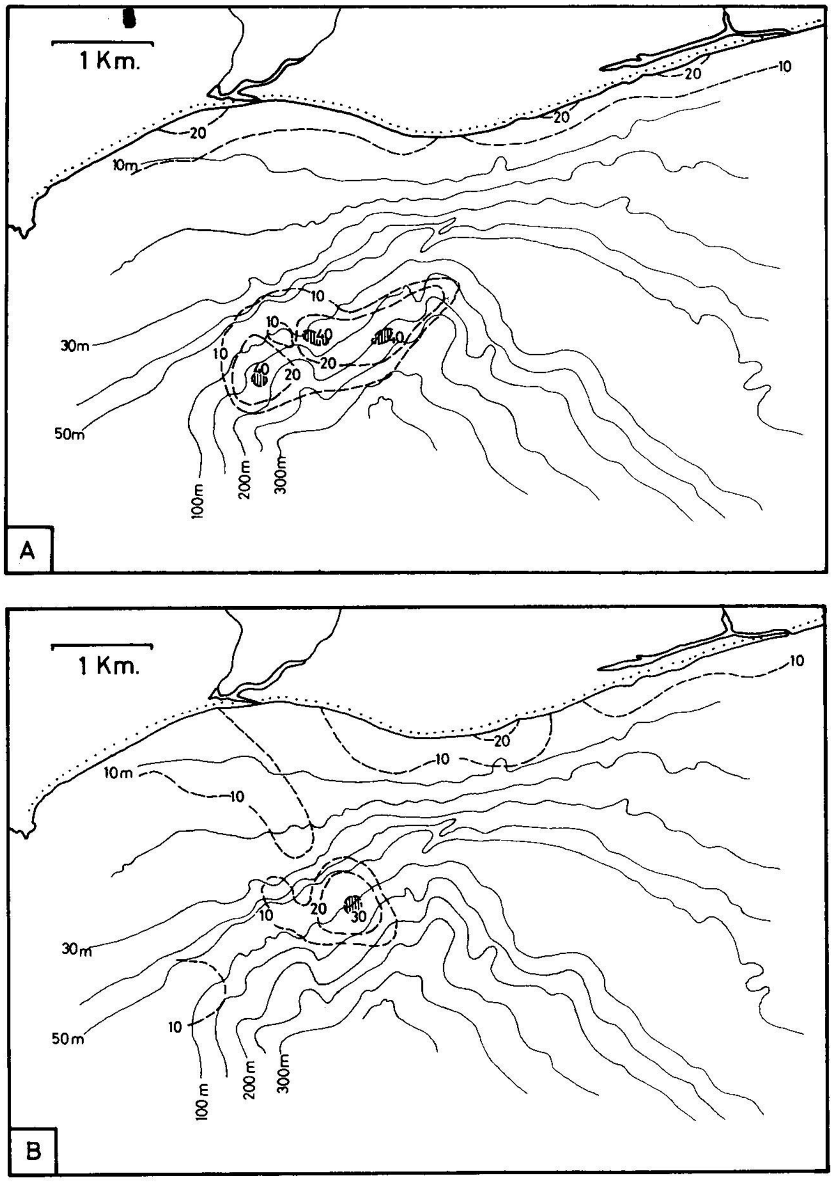


Fig.17. Distribution patterns (%) of lithic carbonate grains in the gravel (A) and sand (B) fractions. Shaded areas have values greater than 40 and 30%, respectively.

mud deposition on the shelf. In addition, the >10% mica contour defines a belt which closely corresponds to the zone of dense growth of phythobenthos (Fig.12). This zone extends on the offshore side of the modern coastal sand prism. Sand-size mica grains behave as the hydraulic equivalent of silt and clay particles and their pattern of distribution is a reliable indicator for the determination of areas of active deposition on the shelf (Doyle et al., 1968; Adegoke and Stanley, 1972). The lower settling velocity of the flakes results in their more efficient transport away from the high-energy nearshore environments (Nelson, 1972). This pattern of distribution of mica on the shelf also agrees with the previously mentioned fluviatile source of mud and its route of transport via the near-bottom nephe-

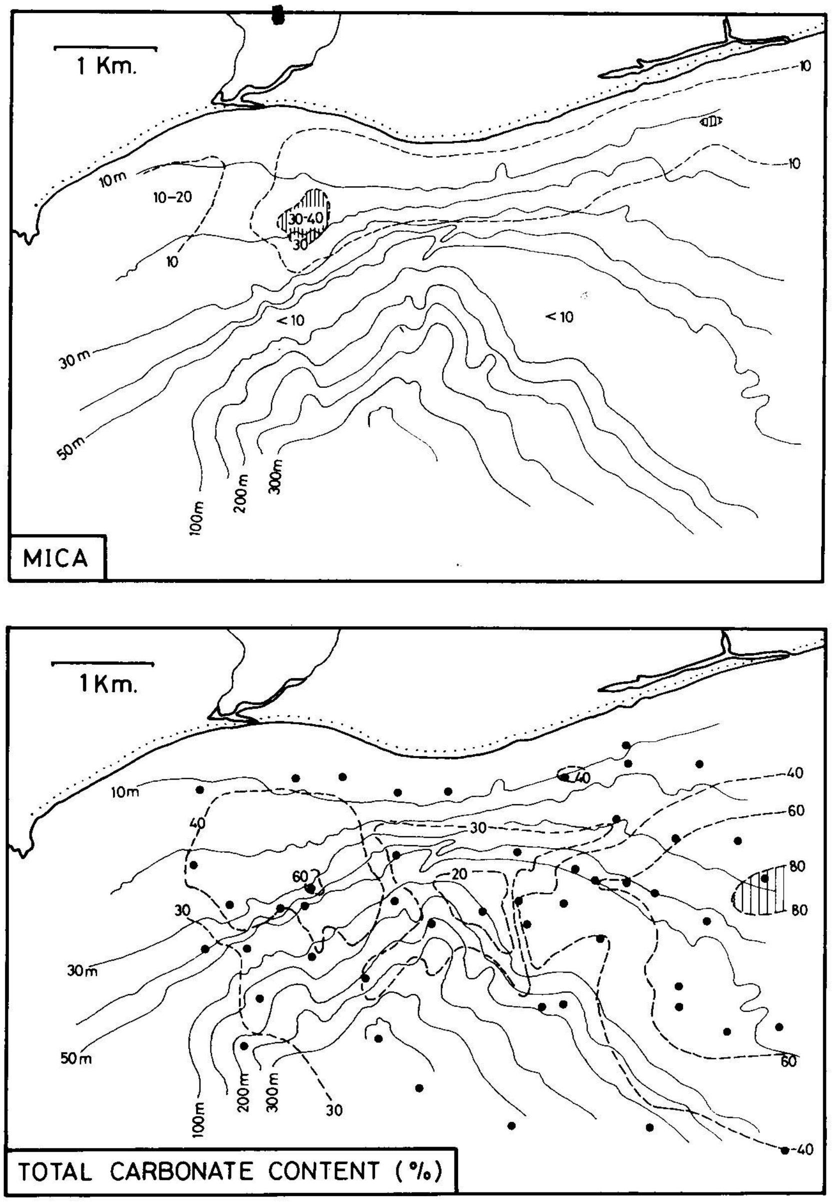


Fig.18. Distribution of mica in the coarse- and medium-sand fractions (shaded areas have values between 30 and 40%) and distribution of the total carbonate content (%) of the sediments (dots indicate the locations of the analyzed samples). The shaded area has values greater than 80%.

loid layer into the canyon head (cf. Aloisi et al., 1982).

Over most of the middle and outer parts of the shelf, the proportion of the biogenic component of the sediments remains above 30% (Fig.15). This component mainly comprises the skeletal fragments of invertebrates and can be regarded as "foramol" (Lees, 1975), as benthic foraminiferal and molluscan (gastropods, pelecypods and scaphopods) remains are most abundant in the majority of the samples (Ediger, 1987). Bryozoans, serpulids, ostracods and crustose coralline algae (mainly *Lithothamnium*) represent the less abundant groups. The total carbonate content of the sediments also reaches its highest values

(60–80%) (Table 1) over the same parts of the shelf, increasing towards the east (Fig.18). Off the shelf, apart from areas of occurrences of redeposited relict sediments, remains of planktonic foraminifers and pteropods constitute the bulk of the sand-size skeletal grains and the abundance of invertebrate shell fragments diminishes noticeably below a depth of 200 m.

The skeletal remains of benthic organisms from the carbonate-rich sediments are often intensely corroded, infilled, stained brown or pitted and bored. Many of them are covered or infested by micro-organisms such as the epibenthic foraminifer *Cornuspiramia adherens* (Le Calvez). These are taken as signs of the slow rate of burial due to the restricted supply of terrigenous mud over the deeper parts of the shelf, allowing physiochemical and biological alteration in the bioclasts. An almost identical facies has been studied on the southeastern sector of the shelf in the Bay of Mersin close to the Gulf of Iskenderun (Alavi, 1980; Weedon, 1983). The sediments from both areas show a similar microfaunal (foraminifers and ostracods) content and are rich in the calcareous remains of molluscs and coralline algae. This facies is best developed over those parts of the shelf away from active sources of siliciclastic input, i.e., well exposed to offshore water masses. The coralline algae are also known to grow most prolifically over hard substrates where conditions are favourable for the majority of filter-feeding and grazing organisms which contribute to the production of this lithofacies (Milliman, 1974; Almagor, 1979; Colantoni et al., 1979).

Mineralogy

The results of X-ray mineralogical analyses of nine selected bulk samples from the shelf (Table 2) show that quartz, dolomite, 10Å micas (biotite and muscovite), plagioclase and calcite are the most abundant constituents of the sediments. Mg-calcite, aragonite, chlorite, kaolinite and smectite are the less abundant species.

The most significant trends of variations in the mineralogical composition of the sediments across the shelf are shown in Fig.19. The abundance of calcite steadily increases towards the outer shelf, while that of dolomite sharply decreases to less than 10% outside the inner shelf zone. The abundance of quartz does not show any clear trend with increasing distance from the shore, reflecting its polygenic and more diffuse distribution in the area. This is also supported by the widespread occurrences of chlorite, mica and plagioclase throughout the shelf. However, while the quartz/calcite ratio steadily decreases with distance from the shore, that of calcite/dolomite remains below unity close to land and sharply increases to >2 towards the outer shelf.

These mineralogical trends from only nine samples across the shelf support the results of grain identifications in the sand and gravel fractions. Dolomite and quartz are good repre-

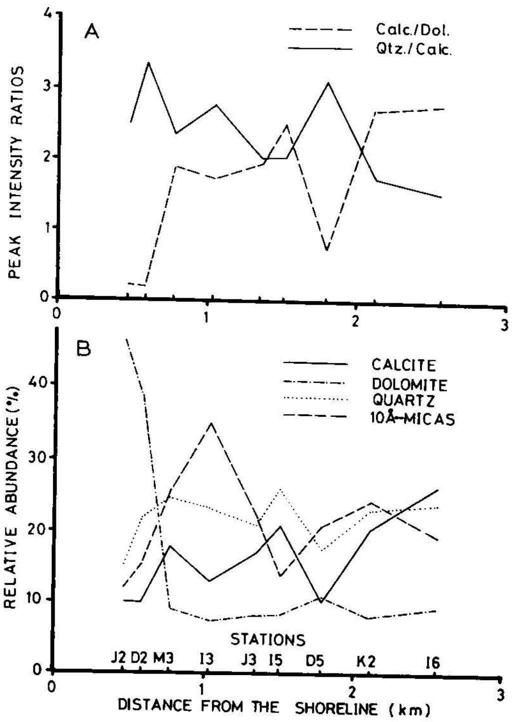


Fig.19. A. Variations in the peak intensity ratios of calcite to dolomite and quartz to calcite. B. Relative abundance of the most common mineral species versus distance from shore.

sentatives of terrigenous supply, and therefore their increasing relative abundance over calcite (which is primarily of biogenic origin) towards the shore is consistent with the predominance of detrital mineral grains and lithic fragments in the nearshore zone. Detrital dolomite has also been recorded in deep-sea sediments from the eastern Mediterranean Sea (Milliman and Muller, 1973). Sample D5, at a depth of 50 m on the western side of the shelf (about 2 km from the shore) (Fig.4), is from the area of exposure of relict sand ridges (Fig.10). This is clearly reflected in its relative enrichment in quartz and dolomite (Table 2). As was noted earlier, sediments from this area are rich in well-rounded sand grains comparable to those of modern beach deposits. The mid-shelf peak in the relative abundance of micas is also reflected by the mineralogical data (Fig.19).

Discussion and conclusions

The unexpected enrichment in biogenic carbonate of the shelf sediments west of the Göksu delta (Shaw and Bush, 1978) was found to be disharmonious with the physiography and active tectonics of the southern Anatolian margin. Modern carbonates on the Göksu shelf are in part supplied from thick sequences of Cretaceous and Neogene carbonates in the drainage basin of the river. This source of input becomes increasingly restricted towards the west. Similar biogenic carbonate facies are known from the shallow banks in the Strait of Sicily (Blanc, 1969, 1972) and on the broad Tunisian–Sicilian platform in the Pelagian Sea (Burrollet et al., 1979). In the absence of stratigraphic and chronological controls, the carbonate component was considered as relict, originating from an earlier cycle of sedimentation (Alavi, 1980).

The present study shows that this is not the case. The main reasons for the formation of carbonates are the low rate of terrigenous mud deposition and the prevalence of open-sea conditions over most of the shelf since the time of the approach of sea level close to (or a few metres above) its present level about 5 ka B.P. (Aloisi et al., 1978). The transparency of the waters and stable hydrographic conditions were recognized by Blanc (1969) as essential for the flourishing of diverse communities of filter-feeding and light-dependent carbonate-producing organisms on the shelf.

It is concluded that these conditions became established when the entrapment of the fluviatile sediments in the nearshore zone and the distal parts of the modern alluvial–fluvial plain accelerated. This has led to a restriction in the supply of sediments to the middle and outer shelf, where late Pleistocene sand ridges are exposed or shallow-buried. The semi-indurated relict deposits provide favourable substrate conditions for the growth of a variety of encrusting epibenthic organisms (Colantoni et al., 1979) and the formation of the so-called "organic rock" on them. This is better known as the coralligenic facies in the literature (cf. Newton and Stefanon, 1982 and references therein).

Some evidence for increased aridity since the early Holocene in the region is presented by Van Zeist et al. (1975) and Erinç (1978). If aridity had increased, there may have been an overall decrease in the rate of fluviatile input on the southern Anatolian shelf in the late Holocene. As most of the shelf is exposed to open-sea currents and high-amplitude waves, the bulk of the mud is eventually resuspended and transported off the shelf or becomes trapped in the canyon head, thus concentrating the sand-size bioclasts in the shelf sediments. The velocity of offshore currents is known to decrease sharply with depth, being generally less than 10 cm/s at depths greater than 100 m (Guibout, 1972). This depth seems to correspond to the "mud-line" in the Bay of Anamur and it probably marks the level of a significant reduction in the erosional capability of the currents. The distribution pattern of muddy sediments and mica flakes indicates that active mud deposition takes place only in areas close to rivers. Meadows of *Posidonia* and *Zostera* provide suitable ecological niches for carbonate-producing organisms and may act as a barrier against the bedload transport across the shelf (cf. Gunatilaka, 1977). The meadows may even trap a part of the suspensate load transported via the bottom nepheloid layer. This effect can partly explain some overlapping of the zone of mica concentration (Fig.18) with the belt of macrophytobenthos growth (Fig.12).

The canyon head has acted as a conduit for the downward transport of some coarse-grained sediment off the shelf at times of lower sea-level when the Sulatançay River flowed directly into it. Spillover of outer shelf sediments, particularly from the west, may have also taken place under the influence of cross-canyon currents (Shepard et al., 1979). However, no convincing evidence for the transportation of modern coastal sand into the canyon was found. Thus, if the canyon is ever to be used as a channel for urban waste disposal, further investigations are required.

Acknowledgements

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