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Hydrographic, Deltaic and Benthogenic Controls of Sediment Dispersal in the Gulf of İskenderun, SE Turkey (E. Mediterranean)

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Grain size, carbonate and organic carbon data obtained from a total of 73 surficial bottom sediments together with some available hydrographic data were used to investigate the major depositional characteristics and the sediment transport paths on the shelves of the Gulf of İskenderun.

Sediments with more than 30% biogenic carbonate composed of a variety of benthic organisms' remains have formed a belt on the sea-floor of the gulf entrance which extends northwards to the offshore Ceyhan Delta and eastward along the southern coast. North-westerly and easterly flowing open-sea currents, low terrigenous sedimentation, bathymetry and high topographic relief of the coastal hinterland seems to be responsible for the formation of this benthogenic bottom zone. The two other benthogenic bottom zones found in the eastern and north-eastern parts of the gulf are under the influences of increased anthropogenic activities and ephemeral fluviatile input of terrigenous material.

The typical seaward profile of the offshore Ceyhan Delta, near-shore delta-front, pro-delta and offshore facies, was actively modified by current action. The ratio of silt–clay, clay–medium silt, clay–coarse silt, and fine silt–coarse silt fractions of the sediments revealed the occurrences of at least two distinct patterns of concentric zonal depositions, which are in good agreement with the prevailing hydraulic gyre regimes in the gulf. These depositional zonal patterns are characterized by the increased fractionation processes that separate finer-grained and coarser-grained fractions whereby clay contents increase towards the centres of these gyres, predominantly in an offshore direction. Similar zonal deposition was also mirrored by the organic carbon contents of sediments.

We propose patterns of water movement and sediment pathways in the Gulf of İskenderun based upon the interpretation of water-current data and analysis of sedimentological data. Particular conditions for transportation and deposition of terrigenous materials and benthic accumulation are discussed. This model produces a database for understanding dispersal of pollutants in association with water and fine-grained sediment in this gulf.

Keywords: sediments; grain size distribution; organic carbon; carbonates; hydrographic; benthic; deltaic; Gulf of İskenderun; Turkey coast

Introduction

The Gulf of İskenderun is located south-east of Turkey, in the easternmost part of the Mediterranean Sea (Figure 1). Besides its unusual geology (it is situated between the East Anatolian/Kyrenia-Misis Ranges and Dead Sea Fault complexes), the Gulf of İskenderun serves as an ideal natural laboratory to study the combined effects of hydrography, deltaic influences, benthogenic production and, to some extent, anthropogenic activities.

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To the north, the gulf is bordered by a large fluvial and coastal plain where the Ceyhan River (the main supplier of siliciclastic sediments) has built a prominent delta complex (Figure 1) exhibiting several typical lagoons, marshes, abandoned channels, delta mouths, etc. (Russel, 1954; Bal & Demirkol, 1987). In contrast to the south and east, the gulf is bordered by narrow coastal plains usually flanked by high topography where ephemeral rivers and streams enter the gulf (Figure 1).

The general pattern of water movement in the Gulf of İskenderun is governed largely by the action of

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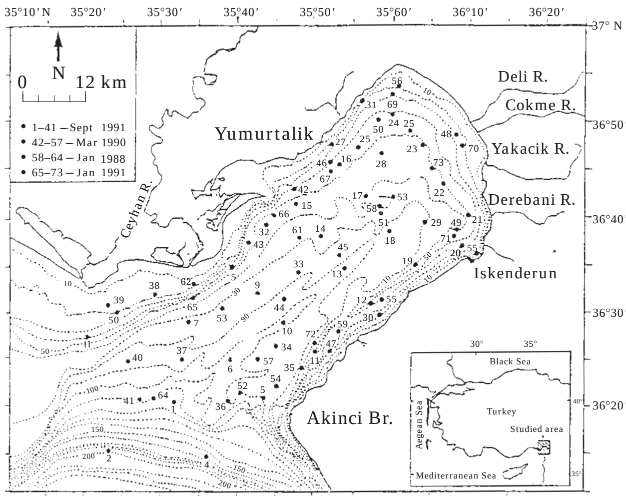

FIGURE 1. Bathymetry of the Gulf of İskenderun showing the bottom-sampling stations of this study.

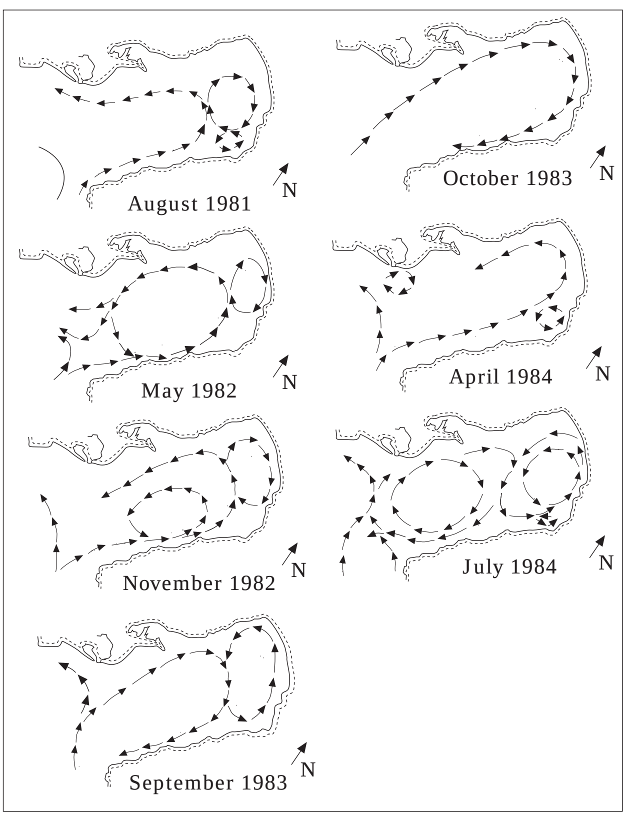

FIGURE 2. Prevailing surface circulation patterns in the Gulf of İskendern (after İyiduvar, 1986). Note the north-westerly flowing open-sea currents and associated gyral currents within the gulf.

north-westerly flowing open-sea currents and the influences of local winds (Figure 2; İyiduvar, 1986). In summer, open-sea waters enter the gulf from the north-west and create clockwise and anticlockwise water transport (Figure 2). In winter, open-sea waters enter the gulf from the south-south-west and move towards the inner gulf along the coast (Figure 2).

Anthropogenic activities are important, particularly along the east-north-eastern coasts, where waste discharges of domestic and industrial origin are discharged into the gulf (Yılmaz *et al.*, 1992).

The Gulf of İskenderun has been insufficiently studied with respect to its recent sediments and the only available data is of the distributions of sedimentary heavy metals (Ergin *et al.*, 1996), some near-shore clay minerals (Kapur *et al.*, 1989) and Quaternary seismic stratigraphy (Aksu *et al.*, 1992). Thus, the very limited knowledge on the recent marine sedimentology of the Gulf of İskenderun prompted the present investigation of bottom sediments' texture with special reference to the peculiarities in the hydrography, offshore delta growth, benthogenic production and possible anthropogenic impact. Particular emphasis here is placed on the carbonate and grain size distribution in the sediments.

Materials and methods

A total of 73 surface (top 5 cm of the sea-floor) sediment samples were taken during the 1988–1991 cruises of RV *Bilim* and RV *Çubuklu* in the Gulf of İskenderun (Figure 1). Sediment samples were collected using a Dietz Lafonde grab in water depths ranging from 15 to 190 m.

Standard sieve and pipette analysis techniques (slightly modified from Folk, 1974) were used to determine the clay (<0·002 mm), silt (0·002—0·063 mm), sand (0·063–2 mm) and gravel (>2 mm diameter) fractions of the sediments. Silt fractions were further divided into fine silt (0·002–0·016 mm), medium silt (0·016–0·031 mm) and coarse silt (0·031–0·063 mm) fractions. The term ' mud ' used in this study defines a sediment mixture composed of the varying proportions of silt plus clay with no sand and gravel. Folk's (1974) textural classification was used to determine the main sediment types in the gulf. The principal lithogenic and biogenic components of the sediment samples were identified by standard microscopic examination techniques.

A representative split of each bulk sediment sample was ground to a fine powder using an agate mortar for carbonate and organic carbon analysis. Total carbonate contents were determined volumetrically in a modified Scheibler apparatus through the release of CO_2 (Müller, 1967) and the results are expressed as $\%CaCO_3$. Organic carbon was determined by wet oxidation of organic matter with chromic acid and

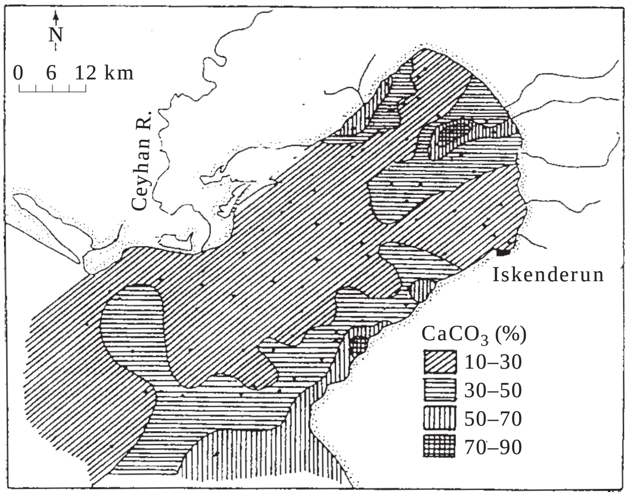

FIGURE 3. Total carbonate in surface sediments of the Gulf of İskenderun. Note the biogenic sediments with more than 30% $CaCO_3$ content forming benthogenic bottom zones in the southern, eastern and north-eastern parts of the gulf. Diagonal lines, 10–30%; horizontal lines, 30–50%; vertical lines, 50–70%; crossed lines, 70–90% $CaCO_3$.

back titration with diphenylamine indicator (after Gaudette *et al.*, 1974; accuracy: ± 0·25%).

A high-resolution seismic reflection profile was obtained across the gulf, to compare the external configurations of depositional units between the large deltaic coasts in the north-west and mountainous high-relief topography in the south-east. An EG&G Uniboom system was used (100–300 J) with a resolution of about 30 cm.

Results and discussion

Biogenic carbonate belts in the southern, eastern and north-eastern parts of the gulf

A common nomenclature was used to distinguish the major sediment types in which sediments containing more than 30% biogenic $CaCO_3$ (Figure 3) are classified as biogenic, whereas those with less than 30% $CaCO_3$ (Figure 3) are classified as terrigenous.

Biogenic calcareous sediments are found extensively along the southern part and in some patchy areas in the eastern and north-eastern parts of the gulf (Figure 3). Microscopic examination revealed that the biogenic carbonates are composed primarily of the remains of gastropods, pelecypods, benthic foraminifers, ostracods, calcareous red algae and bryzoans which are often found in the coarse-grained sand and gravel fractions of sediments. In particular, calcareous red algae and bryzoans are important biogenic constituents in sediments found in the south; they are very rare in other parts of the gulf. The occurrence of the benthogenic carbonate zone along the southern areas is probably related to the peculiar hydrography of this region. Also, the southern part of the Gulf of

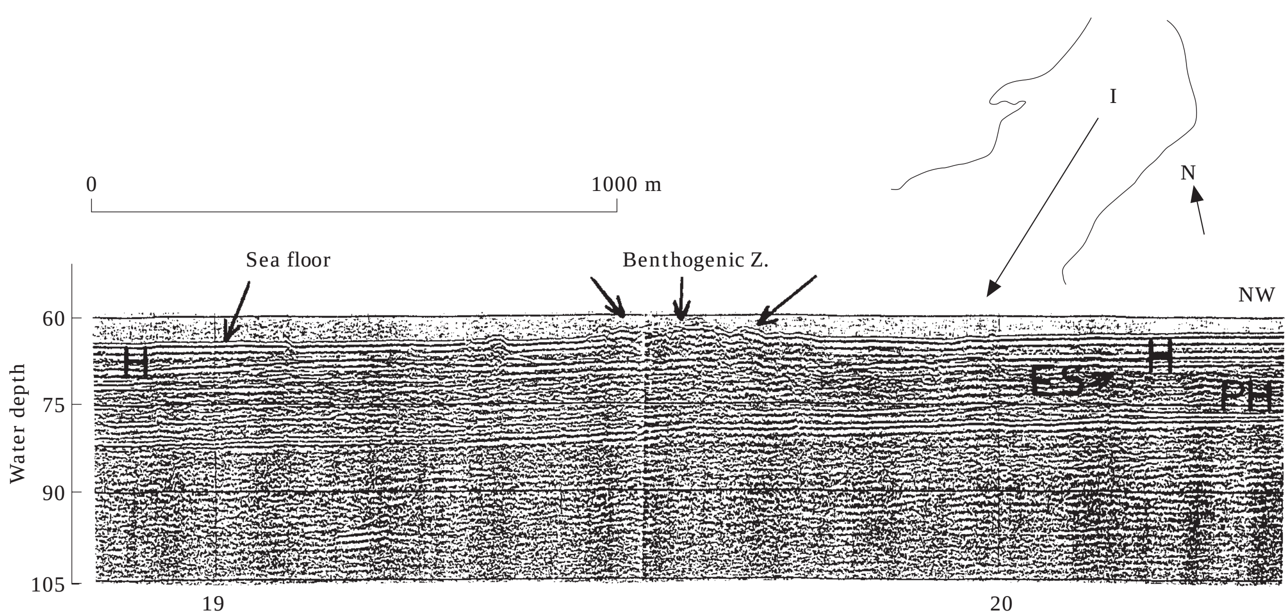

FIGURE 4. High-resolution shallow-seismic profile taken in the eastern part of the gulf, on the western part of the eastern benthogenic bottom zone. Note that the hummocky and chaotic seismic reflections rising on the terrigenous sea-floor suggest areas of increased benthic accumulations. Parallel seismic reflection configurations (H) indicate the mainly Holocene deposits overlying the Late Pleistocene erosional surface (ES) at low stands of sea level; PH, pre-Holocene deposits.

İskenderun is flanked by a hinterland of high topographic relief with no important terrigenous supply. Furthermore, the north-westerly flowing open-sea currents which enter the gulf from the south and move along the coast apparently favour benthic carbonate production.

The biogenic sediments of the benthic carbonate zone in the eastern and north-eastern part of the gulf are under the influences of anthropogenic activities and terrigenous input from ephemeral rivers. In contrast to the benthogenic carbonate zone in the southern part, the benthogenic zones from the eastern and north-eastern parts of the gulf contain no significant occurrences of calcareous red algae and bryzoans. This presumably indicates the combined effects of pollution and ephemeral river input in these two areas. As it is beyond the scope of this work, at this stage, it is difficult to provide a better explanation for the favoured growth of benthic carbonate production under the pollution and ephemeral terrigenous input. Based on the interpretation of seismic profiles (Figure 4), particularly, in the eastern part of the gulf, a benthogenic bottom has been shown to rise about 2–3 m above its surrounding sea-floor and this seems to be a very recent phenomena. Observations made during sampling onboard suggested that the benthic organisms found in the sediments are, at least in part, of modern species (bioherms, algal reefs!). However, it is quite possible that part of the biogenic calcareous sediments is also relict or residual derived from organic remains accumulated sometime during the late Pleistocene or early Holocene periods. This will be a topic for further investigation in the future. Similar biogenic calcareous sediments of various origins are known from the Algerian continental shelf where biogenic sediments can be divided into modern, relict and residual groups (Caulet, 1972).

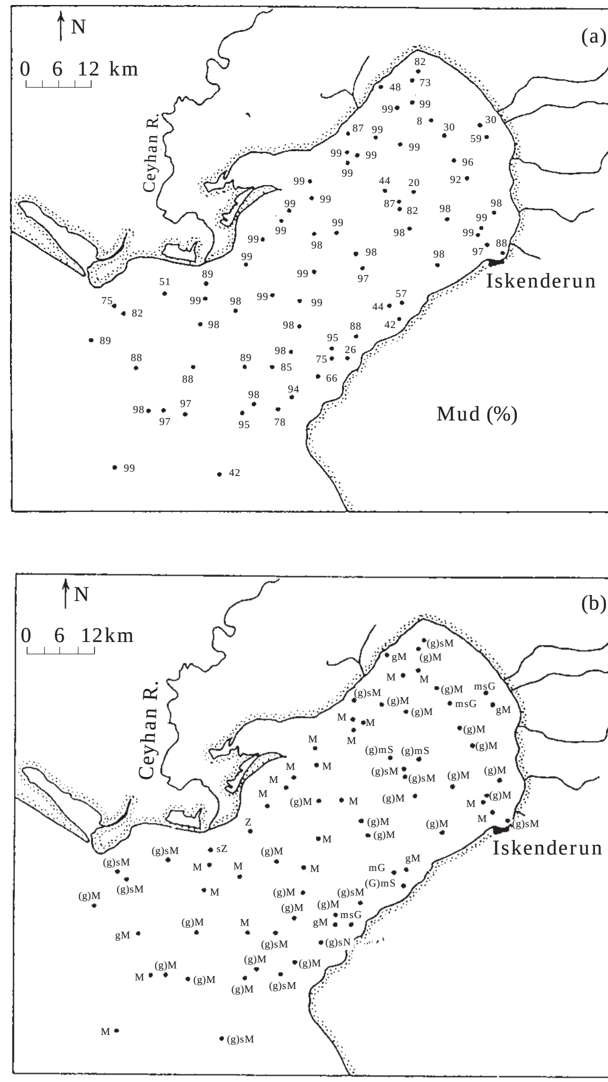

FIGURE 5. Mud contents (a) and related textural classification (b) (after Folk, 1974) of surface sediments in the Gulf of İskenderun. M, mud; (g)M, slightly gravelly mud; (g)sM, slightly gravelly sandy mud; (g)mS, slightly gravelly muddy sand; msG, muddy sandy gravel; Z, silt; sZ, sandy silt; etc.

Fractionation of terrigenic clay and silts in the northern and central parts of the gulf

Fine grained sediments, referred to as muds, dominate in most of the parts of the gulf (Figure 5). Gravelly mud, muddy sand, muddy sandy gravel, sandy mud, silt and muddy gravel are further sediment types often found in the gulf (Figure 5). The surficial sediments consist of large volumes of silt and clay and lesser amounts of sand and gravel, predominantly of late Quaternary age.

Clay contents range from 4 to 57%, being relatively high in offshore and low in near-shore parts of the gulf (Figure 6). The coast parallel currents and wave actions (Figure 2) in the gulf probably do not allow the deposition of clay-rich sediments in near-shore areas. On the sloping face of the offshore Ceyhan Delta, the bottom sediments become progressively finer with increasing distance from the river mouth. Here, clay contents increase from 10% near-shore to 40% offshore, with extension in predominantly southern and western directions. Near the outer limit of deltaic-clay deposition, seaward, to the south, the sediments coarsen again and, thus, the clay contents gradually decrease shoreward to the south. This is due to the accumulation of coarse skeletal debris of benthic organisms. A similar dilution of clay content (down to 10%) due to the presence of coarse-grained biogenic components occurs in sediments in the eastern parts of the gulf (Figure 6).

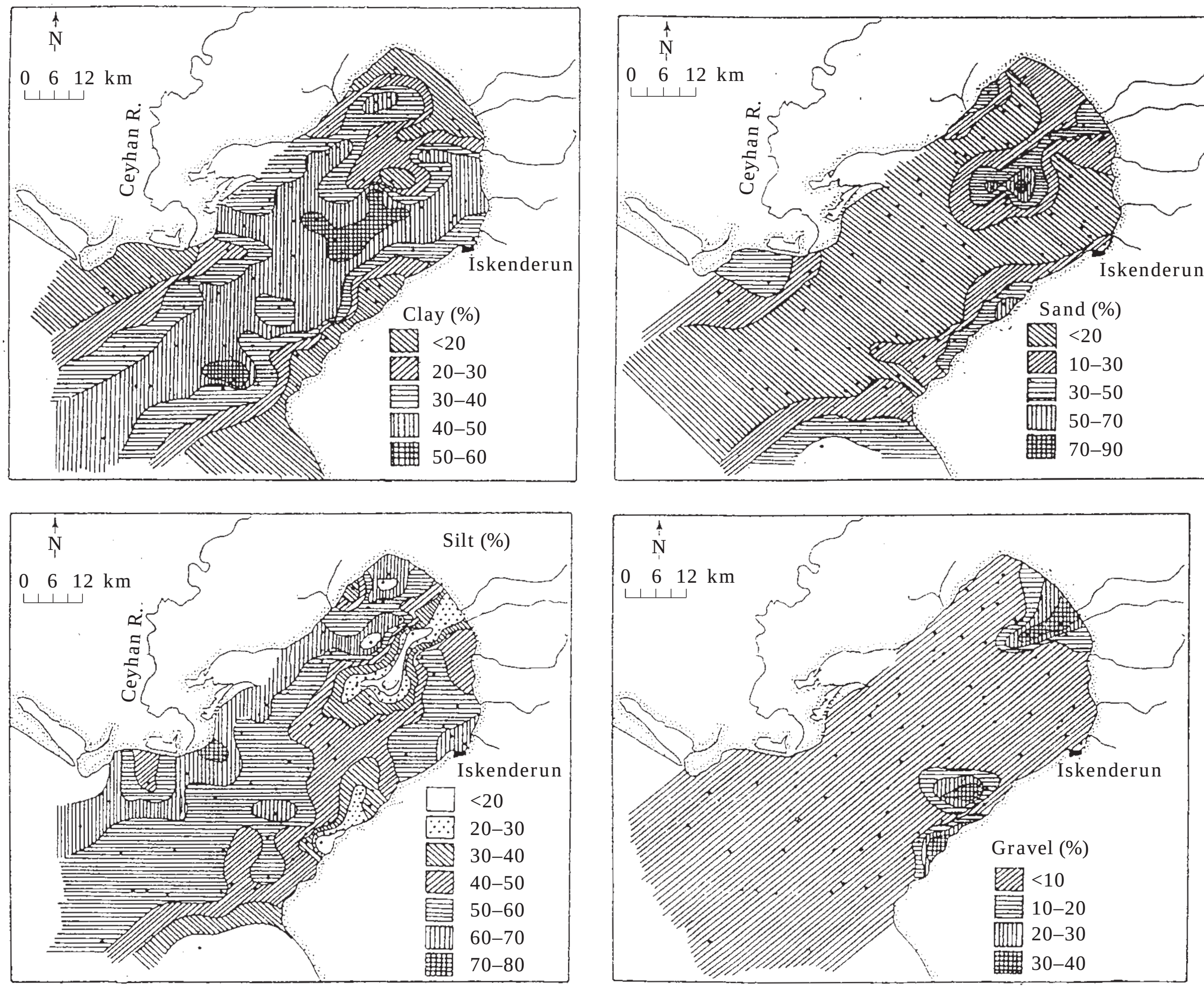

FIGURE 6. Clay, silt, sand and gravel distributions in surface sediments of the Gulf of İskenderun. See text for details.

Silt contents range between 10 and 74%. In general, silt content decreases in amount and is fractionated by settling with increasing distance from the Ceyhan River mouth (Figure 6). It seems that silt of the suspended load of the offshore Ceyhan Delta has been distributed to the south and farther shoreward to the south by currents. It continues to decrease in amount due to dilution by coarse-grained benthic components. In the eastern part of the gulf, silt contents decrease to 10%, as a result of similar benthogenic effect.

The dominance of mud in the Gulf of İskenderun sediments may be explained not only by the fluviatile terrigenic input, but also by the particular hydrography of this gulf. The shape of the gulf (Figure 1) acts as a trap for fine sediments. As shown, coastal embayments are major sinks for fine sediments (Kirby, 1987). Moreover, the inflowing currents produce gyres (Figure 2) which apparently transport the fine particles back into the gulf and prevent their escape.

There are three major areas of higher sand content (Figure 6). High sand content occurs in the northwest off the Ceyhan River mouth and represents nearshore delta-front deposits due to increased coarse-grained terrigenic input and relatively high energies in these shallower waters. On the other hand, high sand contents in the south and east indicate influences of increasing, coarse-grained, benthic accumulation. The latter is confirmed by microscopic examination of sand fractions.

Gravel contents were mostly less than 1%. Higher gravel contents (>30%) occurred in the southern and eastern parts of the gulf, mainly due to benthogenic contribution.

Since the grain size fractions presented here result from both hydraulic fractionation processes during

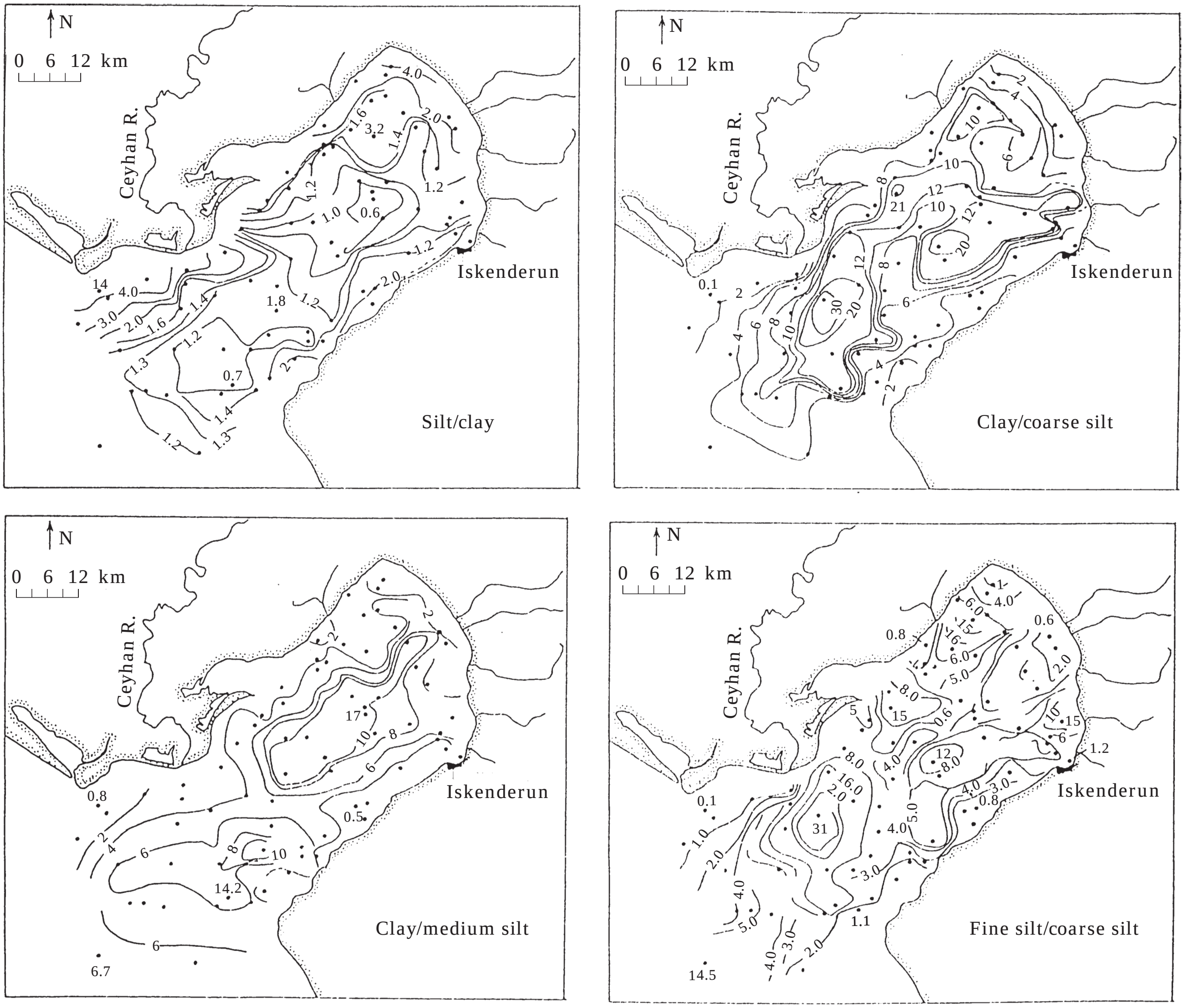

FIGURE 7. Fractionation of silt and clay, clay and medium silt, clay and coarse silt, and fine silt and coarse silt in surface sediments of the Gulf of İskenderun. Note the areas of gyral depositions in the western and eastern parts of the Gulf. See text for details.

transport of terrigenic input and additional debris of *in situ* benthic organisms, the relationships of the distribution of clay and silt fractions are considered (Figures 7 and 8) in an attempt to define transport and depositional conditions in the gulf to understand the existing patterns of water and sediment movement.

In general, silt/clay ratios are higher in near-shore and lower in offshore sediments; a typical grain size fractionation due to high-energy coast parallel currents and waves (Figure 2) and a low energy offshore circulation. Such dispersal patterns have also been reported from the Gulf of Mexico where silt deposition was displaced by the current action (Mazzullo & Petersen, 1989). Silt–clay ratios decrease from 14 off the Ceyhan River mouth to 0·7 in the western central part and again increase to 2 in the southern benthogenic zone [Figure 8(a)]; from delta-front sand and silt in the north to pro-delta silt and clay and to offshore-clay facies in the centre of the western gulf [Figure 8(a)]. Further southward, these deltaic progradational sediments are flanked by benthogenic bottom deposits with slightly higher silt–clay ratios [1·3–2·0; Figure 8(a)]. Besides the effect of offshore-fining of the deltaic deposits of terrigenous origin, two major depositional zonal patterns [Figure 8(b)] are found which are consistent with the general pattern of water movement and

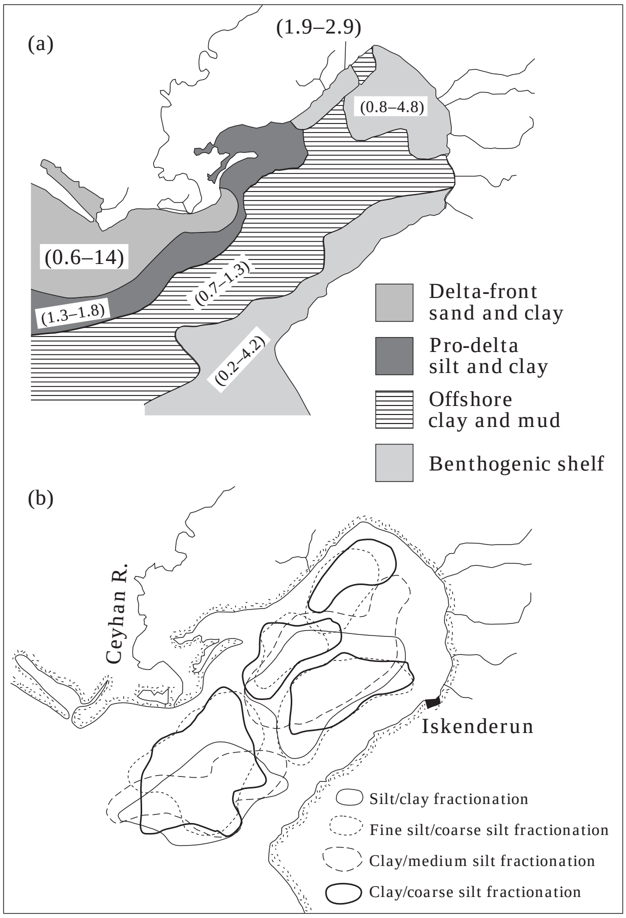

FIGURE 8. Major depositional facies in the Gulf of İskenderun based on grain size and other petrographic data. Values within parenthesis indicate silt/clay ratios. Note the north-westerly offshore Ceyhan Delta province and southerly–easterly benthogenic zones (a). Note the boundaries of most important depositional zones marked by gradually increased fractionation of clay from silt (b). See text for details.

hydrographic gyral circulation in the gulf (Figure 2). These zones [Figure 8(b)] are characterized by gradually decreasing silt–clay ratios (down to 0·6–0·7; Figure 7) towards their centres. High silt–clay ratios found in the north-eastern part of the gulf (Figure 7), similar to those off the Ceyhan River mouth, possibly indicate both increased terrigenic input and local pattern of gyral circulation currents.

Gyral circulation by currents (Figure 2) is also evident from the clay–medium silt fractionation which shows enrichment of clay relative to medium silt in the western and eastern parts of the gulf [Figures 7 and 8(b)] where clay to medium silt ratios increase from approximately less than 1 in outer parts to about 14 or 17 in inner parts of the gyres (Figure 7). These E–W trending and elongated depositional zonal patterns almost coincide with the gyres of hydrographic circulation patterns (Figure 2). In particular, off the Ceyhan River mouth, clay–medium silt ratios increase in southward and then eastward directions (Figure 7). This suggests both source and current controls on the clay over medium silt contents in gulf sediments. Similarly, clay enrichment relative to medium silt (17) is observed on the eastern part of the gulf, beyond the influences of Ceyhan Delta.

Fractionation of clay relative to coarse silt is prominent in offshore (higher ratios) than in near-shore (lower ratios) sediments (Figure 7). In the western part of the gulf, clay/coarse silt ratios increase from less than 1 in near-shore to more than 30 in offshore areas. This fractionation is best developed off the Ceyhan River mouth (Figure 7). Similar high clay/coarse silt ratios are also obtained in the eastern part of the gulf due to the prevailing gyral circulation patterns here.

Fractionation of fine silt relative to coarse silt is better developed in the western part than in the eastern part of the gulf (Figure 7) where values increase from about 1 in near-shore sediments up to 31 in offshore sediments; a combined effect by terrigenic input and modification by gyral current regimes in the gulf (Figure 2). This pattern of dispersal is more easily recognized off the Ceyhan River mouth (Figure 7). Here, fine silt/coarse silt ratios increase from near-shore to offshore in southern and south-eastern directions, and their distributions follow the prevailing current regimes in the gulf.

In summary, the existing open-sea and interior gulf current regimes modify most of the terrigenous sediments entering the gulf, whereby major gyral zones are identified within the gulf which are characterized by increased separation of clay from the silt.

Supply of terrigenous sediments into the Gulf of İskenderun

The available data (EİE, 1982, 1984) shows that the Ceyhan River is the only river which supplies appreciable siliciclastic sediments into the Gulf of İskenderun. The Ceyhan River drains a basin of approximately 20 500 km^2 with an average annual discharge of 303 $m^3 s^{-1}$ and annual sediment yield of 5500 × 10^3 tonnes (compiled from EİE, 1982, 1984).

However, a high-resolution shallow-seismic reflection profile obtained along a NW–SE extending trackline (Figure 9) revealed that, as well as the coastal progradation of the Ceyhan Delta in the north-west, at least one important sediment wedge of coastal

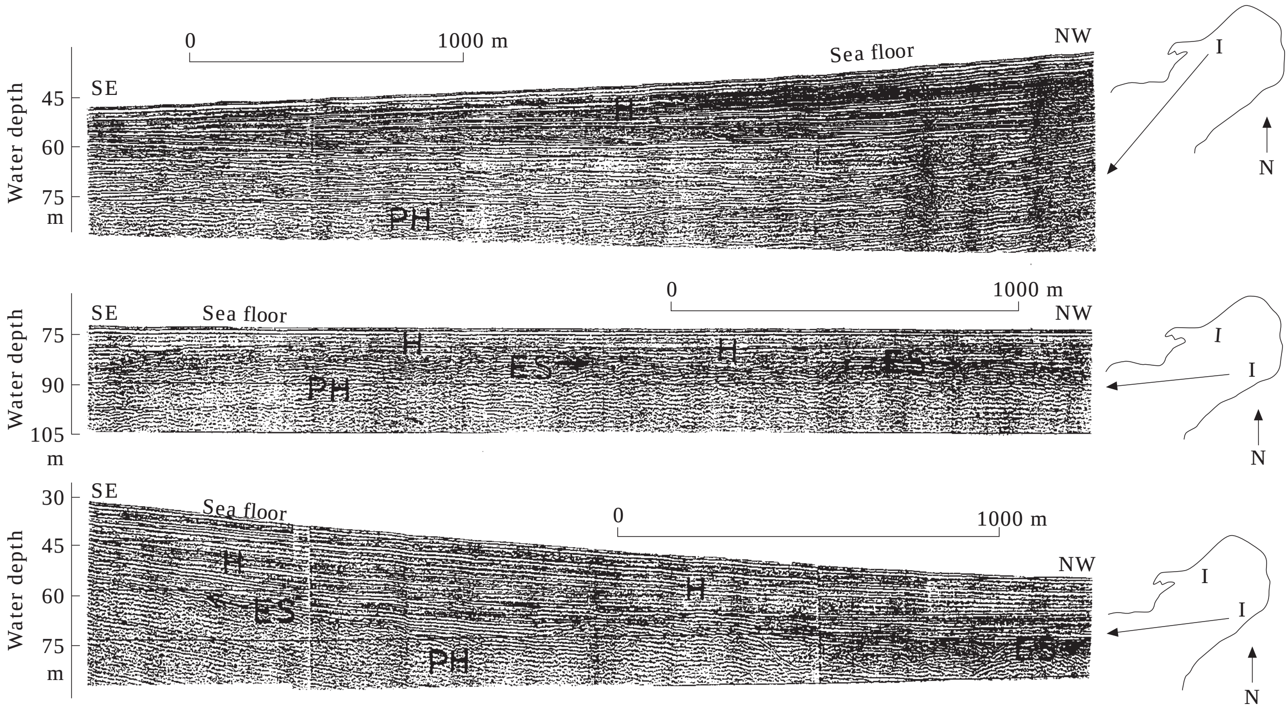

FIGURE 9. High-resolution shallow-seismic profiles obtained in the eastern part of the gulf. Sediment wedges with shoreward-thickening sequences are found both in the north-eastern (top) and south-eastern (middle and bottom) parts of the gulf suggesting significant terrigenous input from the north-west and south-east. Note the parallel/divergent to sigmoidal seismic reflection configurations of mainly Holocene age (H) overly the Late Pleistocene erosional surfaces (ES) produced by subaerial, fluvial erosion of the pre-existing shelf; PH, pre-Holocene sequences.

progradation exists in the south-east, just west of İskenderun. As detailed seismic stratigraphy is beyond the scope of this work, attention is given only to seismic reflection configurations and related depositional sequences lying between a sub-surface erosional unconformity and the present-day sea-floor. Such erosional unconformities or surfaces are usually related to the effects of erosional processes on the subaerially exposed shelf during the low stands of sea level of the last glacial maxima between Late Pleistocene and Early Holocene (i.e. Van Andel & Lianos, 1984; Ergin *et al.*, 1992). On the seismic profile, the supposed Holocene deposits, overlying the erosional (Late Pleistocene) surface, thicken shoreward in both north-western and south-eastern directions to produce thick sediment wedges which become thinner seaward, in the central part of eastern gulf (Figure 9). There is a lack of important rivers and, thus, terrigenous input in the southern and eastern parts, in contrast to the north–north-western parts of the gulf. However, seismic records indicate roughly similar Holocene thicknesses in both north-western and south-eastern areas (Figure 9). As reported (i.e. Milliman & Syvitski, 1992) ephemeral or small mountainous rivers can provide very high sediment loads, a prediction which seems to be further confirmed in this study. Thus, additional sediment sources, as well as the northerly Ceyhan River, must be present in the eastern part of the Gulf which supplied terrigenous material onto the floor of the gulf. It appears that the western depositional zone receives its sediments from the northerly Ceyhan Delta while the easterly zones received their sediments from the easterly or south-easterly ephemeral rivers.

It is assumed that Holocene transgressive deposits overlying the probable erosional surface at last Glacial maxima and the majority of most modern deltas in the eastern Mediterranean have been developed during the last *c.* 10 000 years (Vita-Finzi, 1972), the Holocene sedimentation rates were about 5–15 m 10 000 years^{-1} (average 100 cm 1000 years^{-1}) in the offshore to more than 30 m 10 000 years^{-1} (average 300 cm 1000 years^{-1}) in the near-shore waters. Using average sedimentation rates of about 100–200 cm 1000 years^{-1} suggests the ages of the sediment samples (5 cm) used in this study to be between 25 and 50 years.

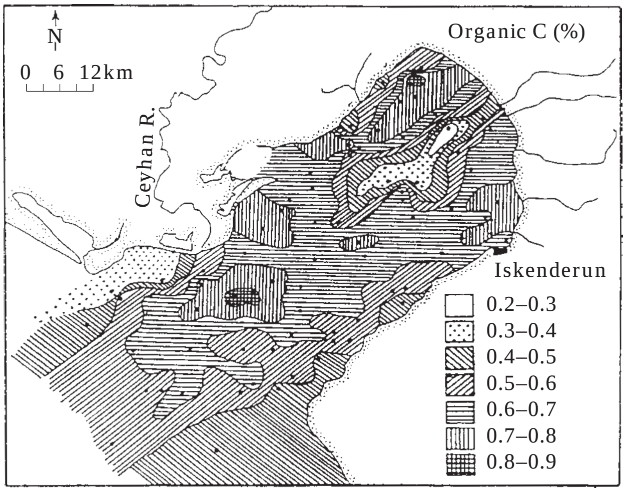

FIGURE 10. Organic carbon distribution in surface sediments of the Gulf of İskenderun suggesting zonal depositional patterns in the western and eastern parts of the gulf due to prevailing gyral water circulations in the gulf (see Figure 2). See text for details.

Depositional behaviour of organic matter in the Gulf of İskenderun

Organic carbon contents of the sediments range from 0·33 to 0·83%. The majority of the organic C contents in the sediments fall in the range between 0·58 and 0·68% and represents primarily-produced organic matter under normal marine conditions. These values are similar to those reported in many marine regions of the Mediterranean Sea (Emelyanov & Shimkus, 1986). The high organic C contents found in near-shore sediments from some coastal areas in the eastern part of the gulf are most likely due to the proximity of the ephemeral rivers and existing sewage outfalls.

It is interesting to note that the organic carbon contents of sediments follow similar zonal distribution patterns (Figure 10) as clay and silt fractionations (Figure 7), presumably due to the grain size which is commonly found in marine sediments. For example, in the western part of the gulf, organic C contents increase with increasing distance from the Ceyhan River mouth (organic C: 0·4%) not only towards the south (organic C: 0·6%), but also towards the east (organic C: 0·8%) to form a zonal distribution pattern (Figure 10). Further south, organic C contents again decrease due to mixture with the benthogenic carbonate contents in the sediments (Figure 10). The benthogenic effect on the organic carbon contents was recognized in the eastern part of the gulf where values decrease down to 0·3% as a result of benthogenic admixtures. The zonal deposition pattern of organic carbon with a tendency to increase from near-shore to offshore seems to be less developed in the eastern part of the gulf (Figure 10). Such increasing offshore organic carbon contents are also found in the Black Sea (Shimkus & Trimonis, 1974) where production of organic matter occurs mainly in the shallower near-shore waters; however, they can be transported to deeper offshore areas (Kıratlı *et al.*, 1995) by the prevailing gyral circulation (Sur *et al.*, 1994).

Conclusions

On the basis of grain size, microscopic and hydrographic data, the following conclusions can be drawn.

On the sloping face of offshore Ceyhan Delta, there is an offshore increase in clay and decrease in sand and silt content deposited as typical delta-front, pro-delta and offshore facies. The west to southward extension of the offshore Ceyhan Delta has been actively modified by the open marine and interior gulf currents. At least two distinct sites of zonal deposition are found in the gulf, which are characterized by the increased clay over silt contents in an offshore direction. These concentric patterns of depositions coincide with the gyral circulation of water movement in this gulf. The western depositional zone receives its terrigenous material predominantly from the northerly Ceyhan Delta, whereas the eastern zone is supplied with terrigenous material from the south-east-easterly ephemeral rivers. The organic carbon contents of sediments also show the presence of this depositional gyral effect, with values tending to increase radially in an offshore direction. Inflowing currents and low terrigenous input are thought to be responsible for the occurrence of a benthogenic belt extending from west to east along the southern gulf. Two other benthogenic zones found in the eastern and north-eastern areas are under the influence of increased anthropogenic activities with some terrigenous input.

This study shows that application of inter-relationships among the fine grain size fractions of sediments seem to be generally a valid technique for determining the sources and dispersal of terrigenous material in areas such as the Gulf of İskenderun.

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