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Distribution of surficial shelf sediments in the northeastern and southwestern parts of the Sea of Marmara: Strait and canyon regimes of the Dardanelles and Bosporus

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ABSTRACT

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Surficial sediment samples collected from the northeastern and southwestern shelf regions of the Sea of Marmara, together with data available from other sources, indicate marked variations in sediment compositions resulting from differences in topographical, hydrological and biological conditions. In the strait channels of the Dardanelles and Bosporus, where strong undercurrents prevail, the floor was covered mostly by coarse-grained sediments (rich in sand and gravel). However, in areas of relatively low energy conditions, sediments contained appreciable amounts of mud, with a tendency towards an increase in the amount of clay towards the open sea. The effects of the strong undercurrents on the bedforms was also apparent in the southern Strait of Bosporus where sidescan sonar surveys revealed the presence of asymmetrical sand ripples. Although terrigenous mud is the principal sediment type in the two canyons (Dardanelles and South Bosporus), the sediments, in particular on the floor of South Bosporus Canyon, show a distinct contrast between the inner N–S and outer E–W trending parts: along its axis, where depths are greatest, the outer part of the canyon appears to contain much more coarse sediment (in part derived from the benthic communities) than the inner canyon. In general, both the topography-related current regimes and the biological activities in the study areas mostly determine the types and modes of sediment distribution.

Among the biogenic components, the calcareous corraline algae Rhodophycae (chiefly *Lithothamnium calcareum* and *L. fruticolusum*) and the mollusc families Galeommatacae and Cerithiospidae are associated with the prevailing Mediterranean undercurrents, especially in the shallower waters of the junction of the Sea of Marmara and Strait of Bosporus. The relatively abundant mollusc species *Mytilus galloprovincialis* and *Modiolus barbatus* and the Trochidae in the Strait of Bosporus are largely affected by Black Sea waters. The wide range of carbonate concentrations in the sediments generally reflects the relative abundances of biogenic admixtures in the samples. High carbonate percentages in the sediments are usually associated with low mud contents, and vice versa. Interestingly, the organic carbon contents of the sediments generally increase with proximity to the Black Sea, suggesting influxes of appreciable amounts of organic matter from the Black Sea.

Introduction

The Sea of Marmara has increasingly received attention not only because it connects the world's largest anoxic basin (the Black Sea) with an evaporitic basin (the Mediterranean Sea) but also because it acts as a trap for sedimentary materials of various types of provenance. Numerous works have reported on the hydrological (e.g., Özsoy et al., 1986; 1988; Ünlüata and Özsoy, 1986), chemical (e.g., Artüz and Baykut, 1986; Baştürk et al., 1988) and biological (e.g., Demir, 1954; Tortonese and Demir, 1960; Caspers, 1968; Ünsal and Uysal, 1988) aspects of the Sea of Marmara. However, there exists very little data on the types and modes of distribution of recent shelf sediments of the Sea of Marmara, especially its northeastern and southwestern areas where strait and canyon regimes are prominent.

Granulometric compositions of some nearshore sediments from the Marmara–Bosporus junction were investigated for the purpose of seafloor

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engineering surveys (DAMOC, 1971) and biological studies (Ünsal and Uysal, 1988). The latter involved visual examination of the sediments. Further shallow-sea sediment studies were concerned with the Late Quaternary seismic stratigraphy at the south entrance of the Strait of Bosporus (Alavi et al., 1989a). Akal (pers. commun., 1987) and DAMOC (1971) investigated the Quaternary marine geology of the northeastern Sea of Marmara using seismic reflection profiling. Studies on deep-sea sediments are rather limited (mainly to the eastern Marmara Basin where geochemical and stratigraphical (Stanley and Blanpied, 1980; Evans et al., 1989) investigations have been carried out). The sediment distribution maps made available by the Turkish Navy Hydrographic Office (obtained from numerous stations) show the dominant grain-size fraction in the sediments from the Strait of Bosporus (in DAMOC, 1971) and the Sea of Marmara (in Adatepe, 1988), but they only reveal very little information on the composition of the sediments there. The geophysics of the Sea of Marmara was reviewed by Adatepe (1988), but with no special reference to the areas of this study.

The main purpose of this paper is to determine the types and modes of distribution of the surficial shelf sediments from the northeastern and southwestern Sea of Marmara, especially in its strait and canyon systems, in order to enhance our limited knowledge of the effects of various hydrological, biological and geological factors controlling the sedimentary processes under the Late Quaternary marine conditions in this marginal and transitional sea. In part, this work has been produced from data by Ergin and Evans (1988).

Geological and hydrographic setting

The strait, canyon and valley-like systems of the Bosporus and Dardanelles of the Sea of Marmara are believed to be remnants of pre-existing faults-associated grabens which formed during the Late Tertiary (mainly Neogene) or Middle–Late Miocene (mainly Sarmatian) (e.g., Brinkman, 1976). During the Late Quaternary, these straits and their approaches to the Sea of Marmara were sites of fluviatile processes of erosional sedimentation and of the formation of terraces, the latter resulting from post-glacial sea-level changes (Caspers, 1957; Ardel and Kurter, 1957; Scholten, 1974; Erinç, 1978; Erol, 1981). Thicknesses of Quaternary sediments of up to 150 m were found in the southern (Alavi et al., 1989a) and northern (K. Timur, pers. commun., 1990) parts of the Strait of Bosporus.

Having a surface area of approximately 11,500 km^2 and a total volume of 3378 km^3, the Sea of Marmara is an almost totally enclosed depression lying between the Black Sea and Aegean Sea. These two seas are connected by two narrow, shallow straits, the Bosporus, trending NNE–SSW, and the Dardanelles, trending NE–SW (Fig.1). The Bosporus is about 31 km long and 0.7–3.5 km wide, with an average depth of 35 m (Gunnerson and Öturgut, 1974). The Dardanelles channel is much longer (62 km), wider (1.2–7 km), and deeper (average 55 m). Both the Dardanelles and the Bosporus cross the shelf diagonally in a NE–SW direction and seem to extend to the deep Marmara Basin through canyon/valley-like features (Figs.2A and B). For convenience, in this work we will refer to the two features as the South Bosporus Canyon and the Dardanelles Canyon. As shown by recent oceanographic investigations (Latif et al., 1989), the Strait of Bosporus also extends into the Black Sea, in form of a channel-like feature which continues down to depths of about 60–80 m, where it makes a bend to the northwest and then joins the shelf topography.

With an axial trend parallel to the coast, the Dardanelles Canyon slopes continuously seaward and down to water depths of 150–200 m southwest of the western Marmara Basin where it terminates (Fig.2A). The Dardanelles Canyon appears to be the eastward extension of the Strait of Dardanelles, and is therefore comparable to many former river valleys on the eastern Mediterranean coasts (Emery et al., 1966; Goedicke, 1972; Gunnerson and Özturgut, 1974; Scholten, 1974; Alavi et al., 1989b). The canyon is flanked on both sides by shallow shelf regions at depths of 60–80 m and its head lies at a depth of approximately 80 m directly north off the Cape of Karaburun. The submarine topography of the shelf east of the canyon is marked by occurrences of several "islands" of

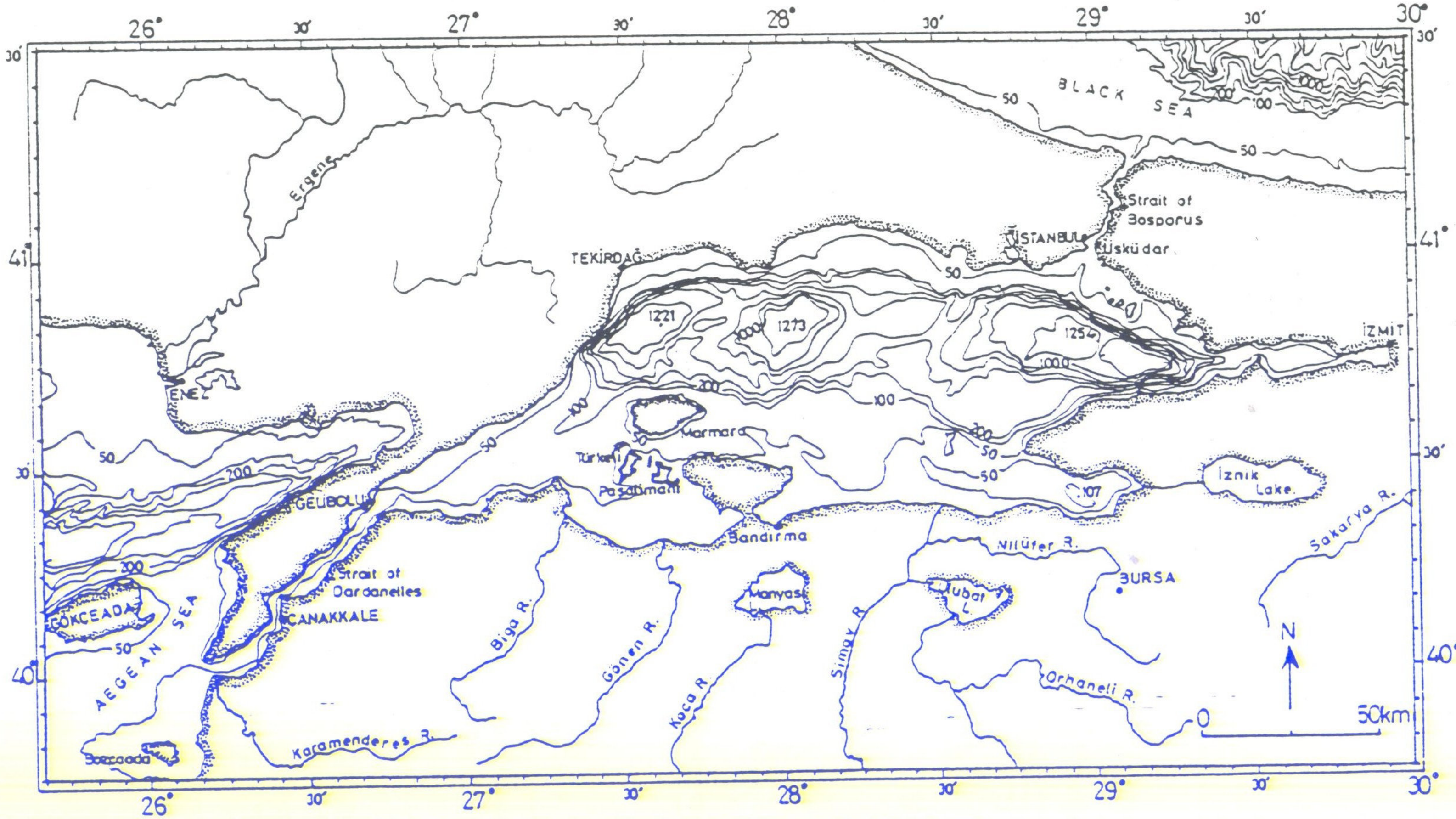
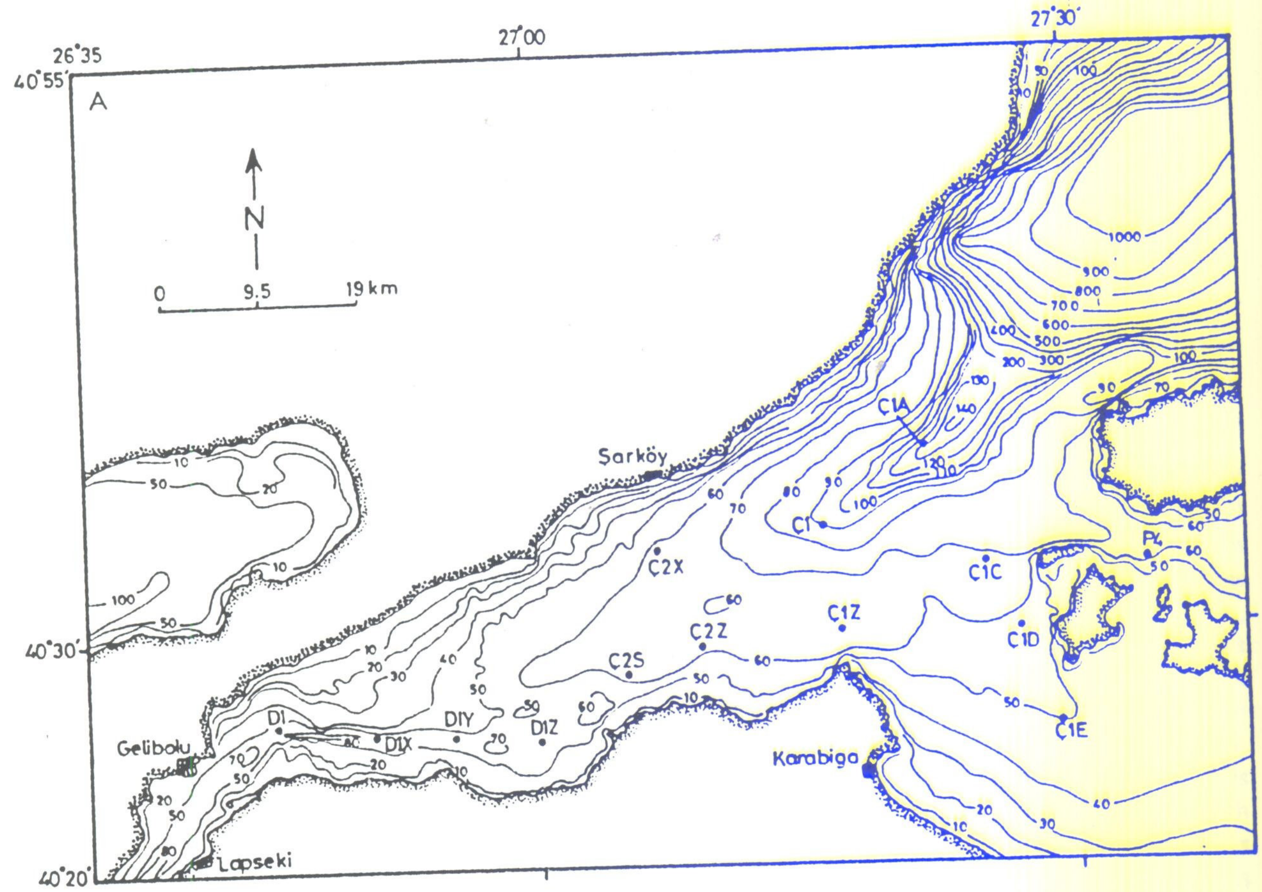


Fig.1. Physiographic map of the Sea of Marmara (reproduced from IOC–UNESCO, 1981).



various sizes. The narrow channel of the inner canyon broadens towards the west-southwest, forming a bowl-shaped floor (except at its head) and a little farther landward it makes a sharp bend to the east at an axial depth of 50–80 m where it joins the E–W trending channel running into the strait (Fig.2A).

In contrast to the straight channel of the Dardanelles Canyon, the South Bosporus Canyon has a twisting and winding pattern (Fig.2B) (according to the classification by Shepard and Dill (1969)). In addition, the walls of the Dardanelles Canyon are much steeper and narrower than those of the South Bosporus. The axis of the South Bosporus Canyon, which coincides with a flat floor, extends down to the shelf edge at about the 100 m isobath in the south and is continuous with the course of the Strait of Bosporus to the north. In most places seismic profiles show that the shelf break is fault controlled (Akal, 1987, pers. commun.). The head of the canyon is located at approximately 50 m, just off the southern exit of the Bosporus Strait. The shallow shelf regions east of the canyon are marked by distinct topographic differences (islands of various sizes, particularly the Princes Islands). A little farther eastward, a coastal inlet, Pendik Bay, is bordered by the Princes Islands to the west and Tuzla Peninsula to the east.

Another prominent morphological feature of the Sea of Marmara is the Marmara Trough, essentially a submarine morphological extension of the North Anatolian Fault zone (Şengör et al., 1985). This trough consists of three pull-apart sub-basins (1000–1300 m water depth) running in an E–W direction (Fig.1) and separated from each other by relatively low sills of about 700 m (Carter et al., 1972; IOC–UNESCO, 1981). The Marmara Trough is bordered to the south by a 32 km wide

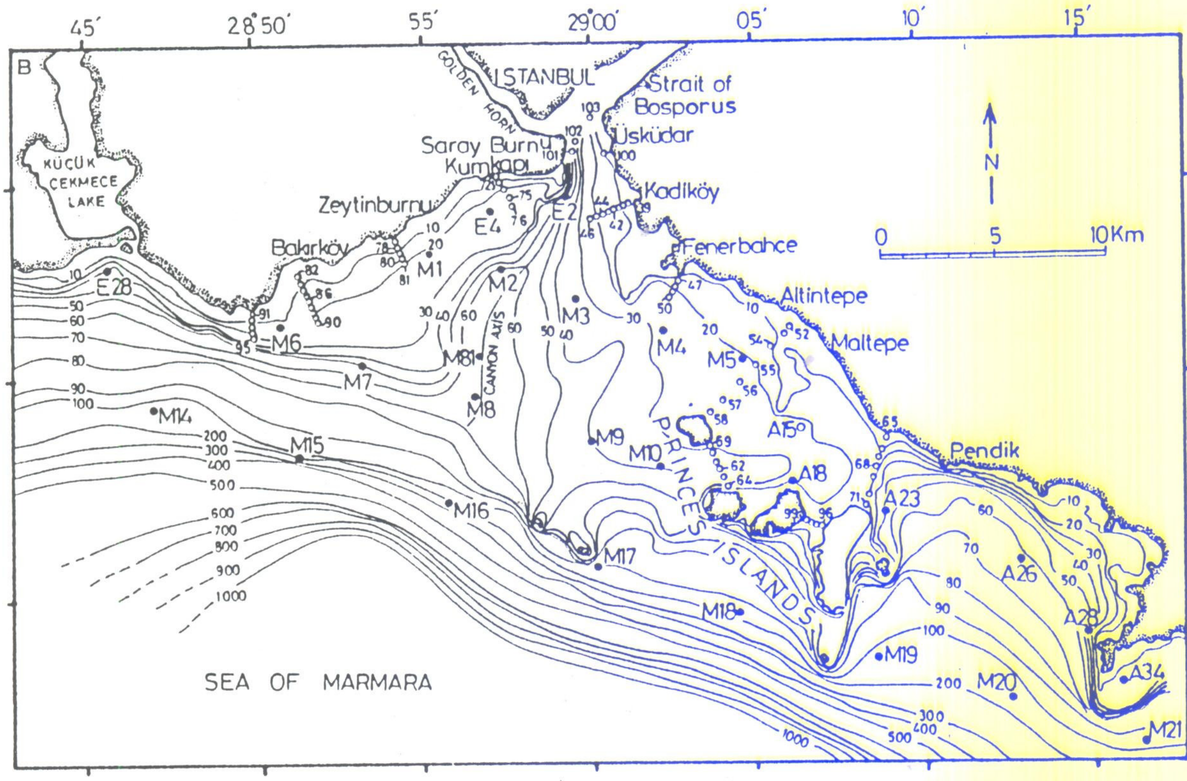


Fig.2. Bathymetry of the study areas. Depth in metres. Reproduced from Turkish Navy Hydrographic Office charts. A. Southwestern Sea of Marmara. Note the Dardanelles Canyon extending into the Strait of Dardanelles in a NE–SW direction. B. Northeastern Sea of Marmara. Note the South Bosporus Canyon with its twisting course to the Strait of Bosporus to the north, and also the Princes Islands in the east. Sampling stations from DAMOC (1971) are indicated with circles.

shelf; this contrasts with the much narrower northern shelf which ranges in width from 2 to 13 km (Carter et al., 1972).

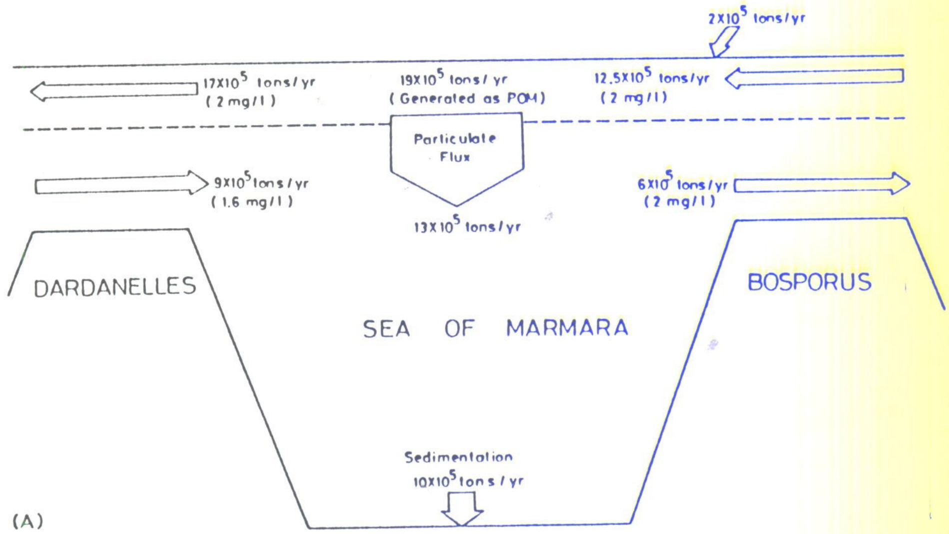
The hydrography of the Sea of Marmara is characterized by a permanent two-layer current flow, a surface outflow from the Black Sea towards the Mediterranean via the Bosporus, the Sea of Marmara, the Dardanelles and the Aegean Sea, and a bottom inflow from the Aegean Sea towards the Black Sea in the reverse direction (e.g., Miller, 1983; Özsoy et al., 1988; Sur, 1988) (Fig.3A). Whilst the upper water layers exhibit a wide range of salinity values, from 17.80‰ in the Bosporus–Black Sea to 29.53‰ at the Aegean Sea–Dardanelles junction, the lower water layers seem to be more uniform, with values from 38.9‰ at the junction of the Aegean Sea and the Strait of Dardanelles to 34.9‰ at the junction of the Strait of Bosporus and the Black Sea (Özsoy et al., 1988; Sur, 1988) (Fig.3B).

In addition to the Straits of Bosporus and Dardanelles, a number of rivers and streams drain into the Marmara sub-basins (Table 1 and Fig.1), supplying considerable amounts of sediment, primarily from the south. Additional material must be derived from coastal erosion and biogenic activity within the Marmara Basin.

The velocity of the currents in the Dardanelles channel ranges from 50 to 200 cm/s in the surface or near-surface (average 80–90 cm/s) and from 20 to 40 cm/s near the bottom (Defant, 1961) (Fig.4). In the Strait of Bosporus surface currents proceed with a speed of between 20 and 500 cm/s and the bottom waters attain velocities of between 5 and 250 cm/s (e.g., Defant, 1961; DAMOC, 1971; Özsoy et al., 1986) (Fig.5).

Materials and methods

A total of 65 surficial sediment samples were recovered during the cruises of R.V. *Bilim* in the



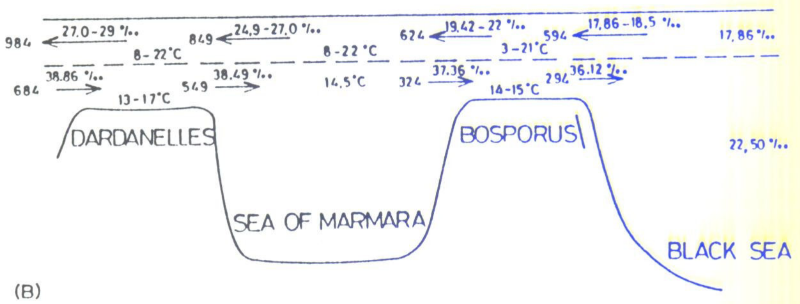


Fig.3. A. Annual average concentrations of total suspended solids (figures in parentheses) and TSS mass fluxes (arrows) in the Sea of Marmara and its straits (after Baştürk et al., 1986). *POM* = Particulate organic matter. B. Salinity and temperature distribution in the two-layer flow system across the Sea of Marmara and its straits. The figures (984, 684, etc.) are flux values (km^3/yr) (based on data by Özsoy et al., 1986).

Sea of Marmara during the years from 1985 to 1989. Sediment samples were taken with a Dietz LaFonde grab sampler in the northeastern and southwestern shelf areas of the Sea of Marmara, (respectively, the Straits of Dardanelles and Bosporus) and from the junctions of these areas with the Sea of Marmara. Locations of sampling stations are indicated in Figs.2, 6 and 7. Samples were kept frozen in plastic bags until they were analyzed for granulometric, chemical and microscopic investigations in the laboratory. Some grain-size data were also available from nearshore sediment samples from the junction of the Sea of Marmara and the Strait of Bosporus (DAMOC, 1971) (Fig.2B). In addition, a sediment distribution map of the Strait of Bosporus based on granulometric measurements from about 150 samples was made available by the Turkish Navy Hydrographic Office (in DAMOC, 1971) (Fig.8); another map, of the Bosporus–Marmara junction (Fig.9), also aided our work.

Sidescan sonar surveys were carried out along twelve shore-parallel lines in the south of the Strait of Bosporus with the intention of determining the main bottom features; some of these results have been reported elsewhere (IMS–METU, 1985; Okyar, 1987).

Using standard petrographic procedures (Folk, 1974; Lewis, 1984) bulk sediment samples were subjected to wet-sieve and pipette analysis in order

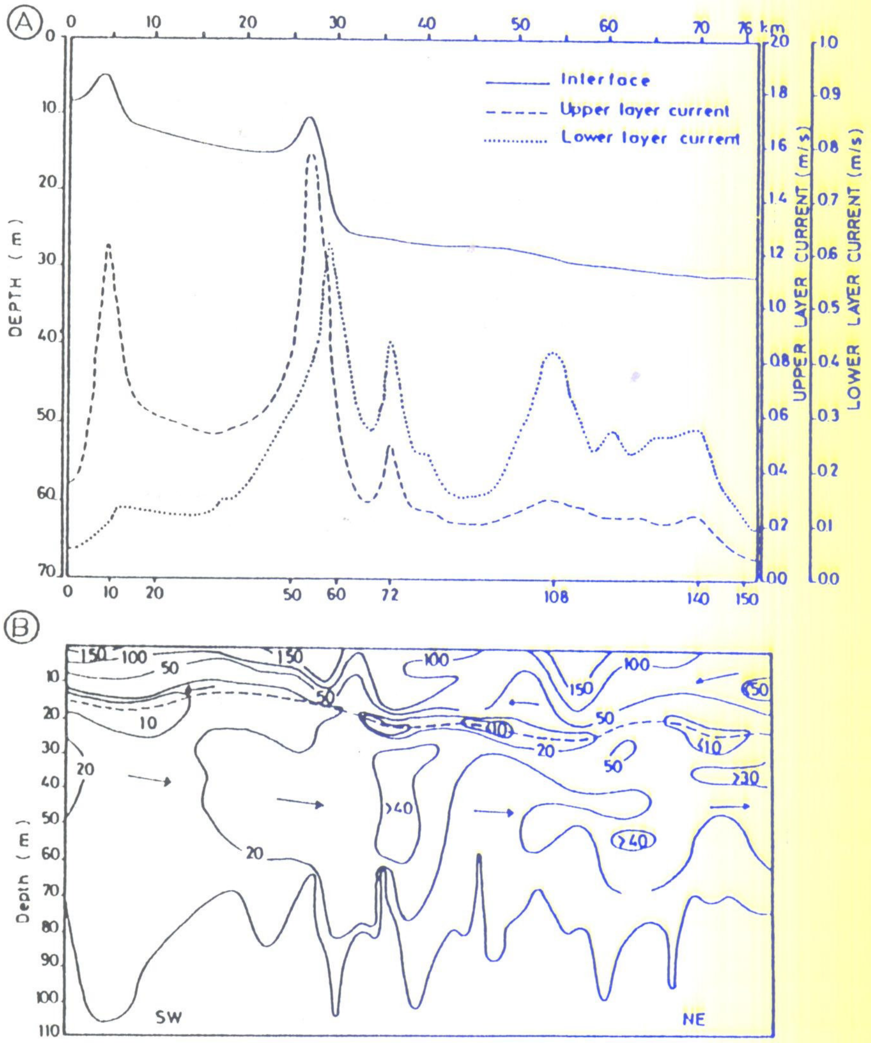


Fig.4. Longitudinal distribution of current velocity (cm/s) (A, after Sur, 1988) and variations in the interface depths in the Strait of Dardanelles (B, after Defant, 1961).

to separate the sand (0.063–2 mm) and gravel (>2 mm) fractions from the mud (<0.063 mm) or silt (0.004–0.063 mm) and clay (<0.004 mm). Bulk sediment samples were classified according to both their granulometric (Shepard, 1954; Folk, 1974) and genetic (Lisitzin, 1986) compositions. Total carbonate concentrations were determined with the gasometric method (after Müller, 1967) after treatment of the ground samples with dilute HCl acid; the results are expressed as $\%CaCO_3$ (absolute error is $\pm 0.5\%$ $CaCO_3$). Organic carbon was determined by wet oxidation of organic matter with chromic acid and back titration with a diphenylamine indicator (Gaudette et al., 1974, accuracy $\pm 0.25\%$). Standard microscopic studies were carried out to identify the nature and the amounts of sedimentary materials in the coarse-grained fractions.

Results and discussion

Distribution patterns of surficial sediments from the northeastern and southwestern shelves of the Sea of Marmara revealed remarkable regional differences in the material composition resulting mostly from differences in the prevailing

TABLE I

Water and suspended solid discharge from the rivers/streams and the Straits of Bosporus and Dardanelles in the Sea of Marmara (compiled from DSI, 1985, 1987; Baştürk et al., 1986; and Özsoy et al., 1986)

Rivers/ streams/ straits	Flow rate (m^3/s)	Total suspended solids (mg/l)	Flux rate of total suspended solids (tons/yr)
Simav[1]	171.0	114	614,000
Kirazdere	7.4	43	10,000
Gönen	5.6	44	7800
Biga	3.4	47	5000
Sellimandra	2.3	59	4300
Sazlıdere	1.1	84	2900
Sarısu	1.0	62	2000
Karasu	0.8	70	1750
Nakkaş	0.7	60	1300
Dereköy	0.5	73	1150
Çakil	0.4	70	883
Total	194.2 (5.39 km^3/yr)		651,100 (6.5×10^5)
Bosporus[2]	624 km^3/yr	2.0	(14.5×10^5)
Dardanelles	549 km^3/yr	1.6	(9.0×10^5)

[1]Included are Nilüfer, Simav, Emet, Orhaneli, M. Kemalpaşa and Manyas.
[2]Fluxes from the Golden Horn included.

topographical, hydrological and biological conditions.

The Strait of Dardanelles

The channel sediments of the Strait of Dardanelles range from clayey silt to muddy sandy gravel depending on the channel geometry (Figs.6 and 10). The coarsest sediments, with the maximum sand and gravel percentages, are found near the meandering Nara Passage (Station D4 and C5) and the junction of the Strait of Dardanelles with the Aegean Sea, where also surface and bottom currents reach their maximum velocities (up to 160 cm/s; Fig.4). This seems to be somewhat similar to many other fluviatile environments having meandering channels, where finer grained bottom materials are usually current swept (Kelling and Stanley, 1972) as a result of the maximum flow velocities in the narrowing and shoaling channels (Leopold et al., 1964).

In contrast, in areas between stations D6 and D4 where relatively low energy conditions prevail, the sediments comprise much finer materials (Fig.10). As shown in Fig.10, the sediments between D6 and D4 generally tend to increase in mean grain size as a result of decreasing clay and silt contents. Similar differences in grain size were also apparent in the upper strait; from the Nara Passage (Station D4) towards the northeast, the clay and silt percentages generally increased (Figs.6 and 10), corresponding to the less severe current regimes (Fig.4).

Of course, such a wide range of grain sizes in the Dardanelles channel sediments can not solely be explained by the differences in current speeds; roughness of the bedforms in the strait must also be taken into account (Fig.11A). As is known, grain size and current velocity and their relationship with various bedforms are prominent factors in many fluviatile environments (Simons et al., 1965). Thus it is obvious that the irregular bottom topography in the Strait of Dardanelles (Fig.11) (elevations and depressions at the sampling stations) seems to be a preferred trap for muddy sediments. On a plane bed the prevailing bottom currents in the channel (10–40 cm/s) (in accordance with the Hjulstrom's diagram) would suggest accumulation of only coarser grained sediments, and erosion and removal of finer grained material.

Microsopic examination of the coarse-grained sediment fractions revealed that pelecypods, gastropods, foraminifera, ostracods, echinoids, bryzoans and coralline algae are the dominant biogenic components (Fig.6); the presence of these organisms indicates marine conditions. Marked occurrences of echinoid fragments in samples from the south (Fig.6) are probably associated with the high sand and gravel percentages of sediments, which provides the best living conditions for the echinoderms in this region (Demir, 1954).

Of importance is the occurrence of coralline algal sand and gravel (Fig.6) on a ridge- or bank-like feature (Fig.11) at the junction between the Strait of Dardanelles and the Aegean Sea (Station C7). Coralline algae are present both as nodules (up to 2 cm in diameter) and as calcified branching fragments mainly of the encrusting (melobesid)

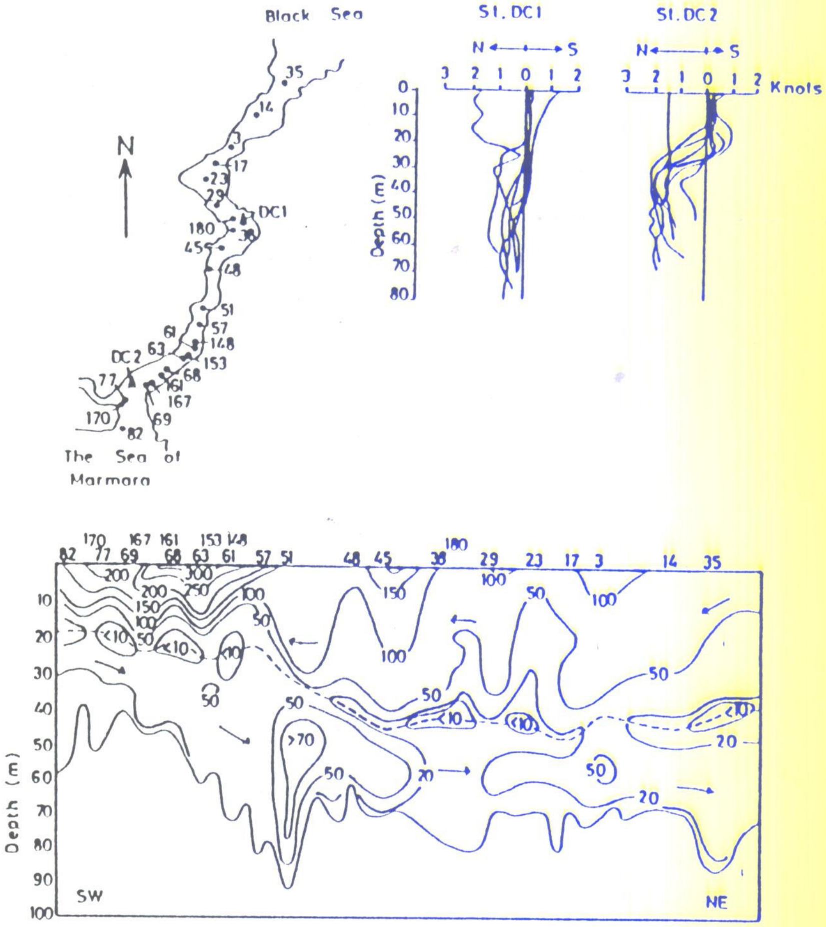


Fig.5. Longitudinal distribution of current velocity (cm/s) in the Strait of Bosporus. After DAMOC (1971) (top right, Stations DC1 and DC2), and Defant (1961) (bottom, Stations 82 to 35, see also top left).

algae (e.g., *Lithothamnium*) with subordinate amounts of molluscan (pelecypods and gastropods) shell remains. Living *Lithothamnium* is also present, but in smaller amounts. Examples of such coralline algal sediments are well known from other regions elsewhere in the Mediterranean (Caulet, 1972; Goedicke, 1972; Milliman et al., 1972; Campbell, 1982; Alavi et al., 1989b) and are usually restricted to shallow-water areas with sandy and rocky bottoms. Although both warm and cold marine conditions may favour the growth of coralline algae (Flügel, 1978), most of these organisms live in waters in tropical and subtropical zones with relatively warm and saline marine water (Brandon, 1973). At Station C7, surface water temperatures reflect great seasonal variations (8–23°C), with salinities of between 27 and 39‰ and oxygen contents of 4.5–7 ml/l. Subsurface temperatures were comparatively uniform in a narrow range from 12 to 17°C and salinities were nearly stable at 38–39‰. Oxygen concentrations differed little (5–7 ml/l) from those at the surface (Özsoy et al., 1986, 1988; and unpublished IMS–METU data files). The bottom currents are usually less than 5 cm/s (Sur, 1988). However, the absence of coralline algae in the bottom sediments within the channel probably indicates high-energy undercurrents, which can restrict algal growth (UNEP/IUCN, 1988).

The sediment samples also contain diverse assemblages of benthic foraminifera which are characteristic of carbonate shelf environments

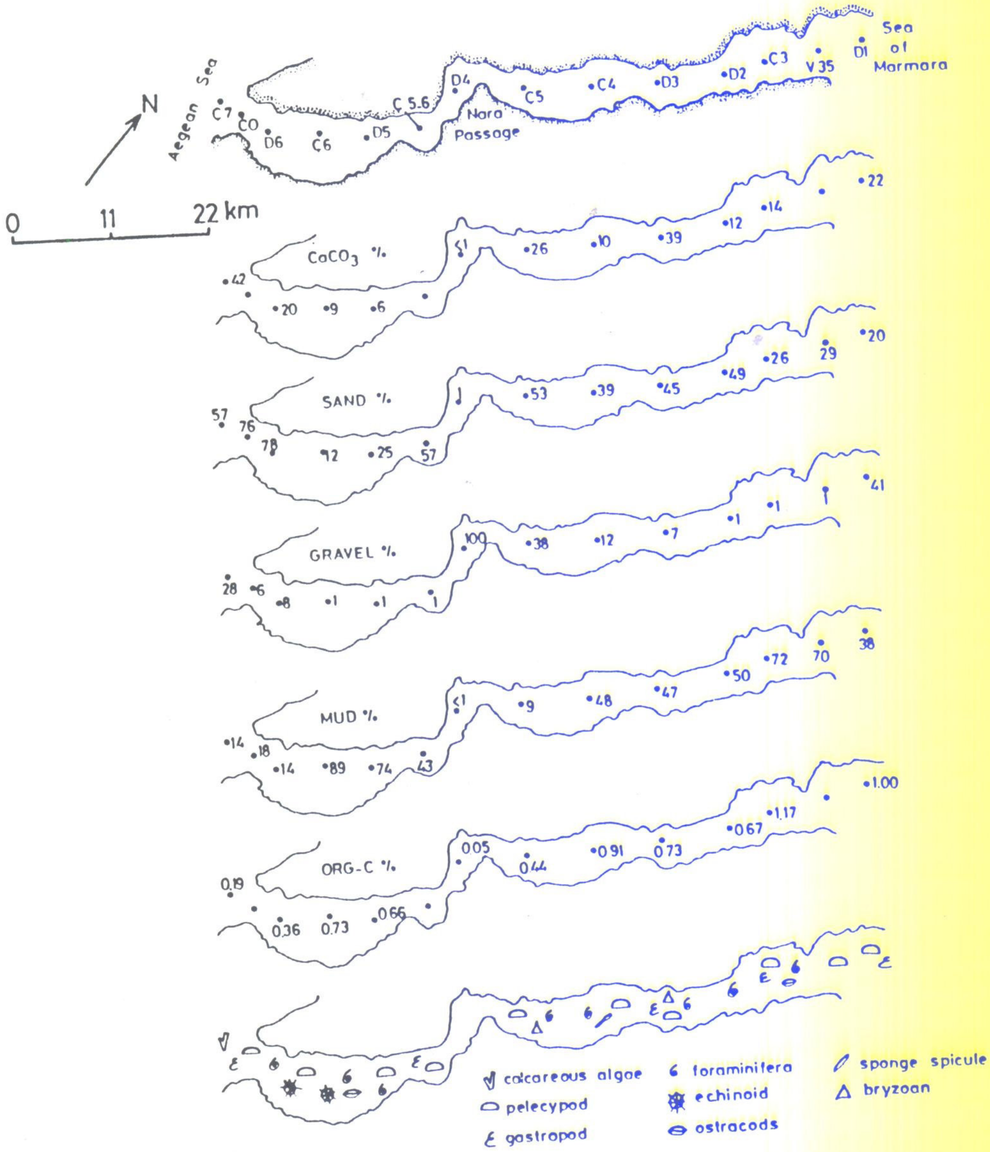


Fig.6. Grain size, total carbonate, organic carbon and biofacies distribution in surface sediments of the inner channel of the Strait of Dardanelles. For details, see text.

around the Mediterranean Sea. These assemblages are often rich in a variety of rotaliids and miliolids (Alavi, pers. commun., 1989). Biological studies on sediment samples revealed that the pelecypods Galeommatacea and *Nucula sulcate* and the gastropods Cerithiospidae and Pyramidellidae are entirely restricted to the Dardanelles, although the Galeommatacae do tend to increase towards the Sea of Marmara, while *Nucula* is homogeneously distributed along the strait.

The total carbonate content of the sediments (from less than 1 to 42% $CaCO_3$; Fig.6) is mainly represented by the concentrations of shell fragments of various calcareous organisms. On the basis of their biogenic carbonate contents, the sediments of the Dardanelles channel are mostly of terrigenous origin (< 30% $CaCO_3$). Exceptionally, at two stations, one in the northeast (Station D3) and the other in the southwest (Station C7), the sediments are considered to be of biogenic origin (> 30% $CaCO_3$).

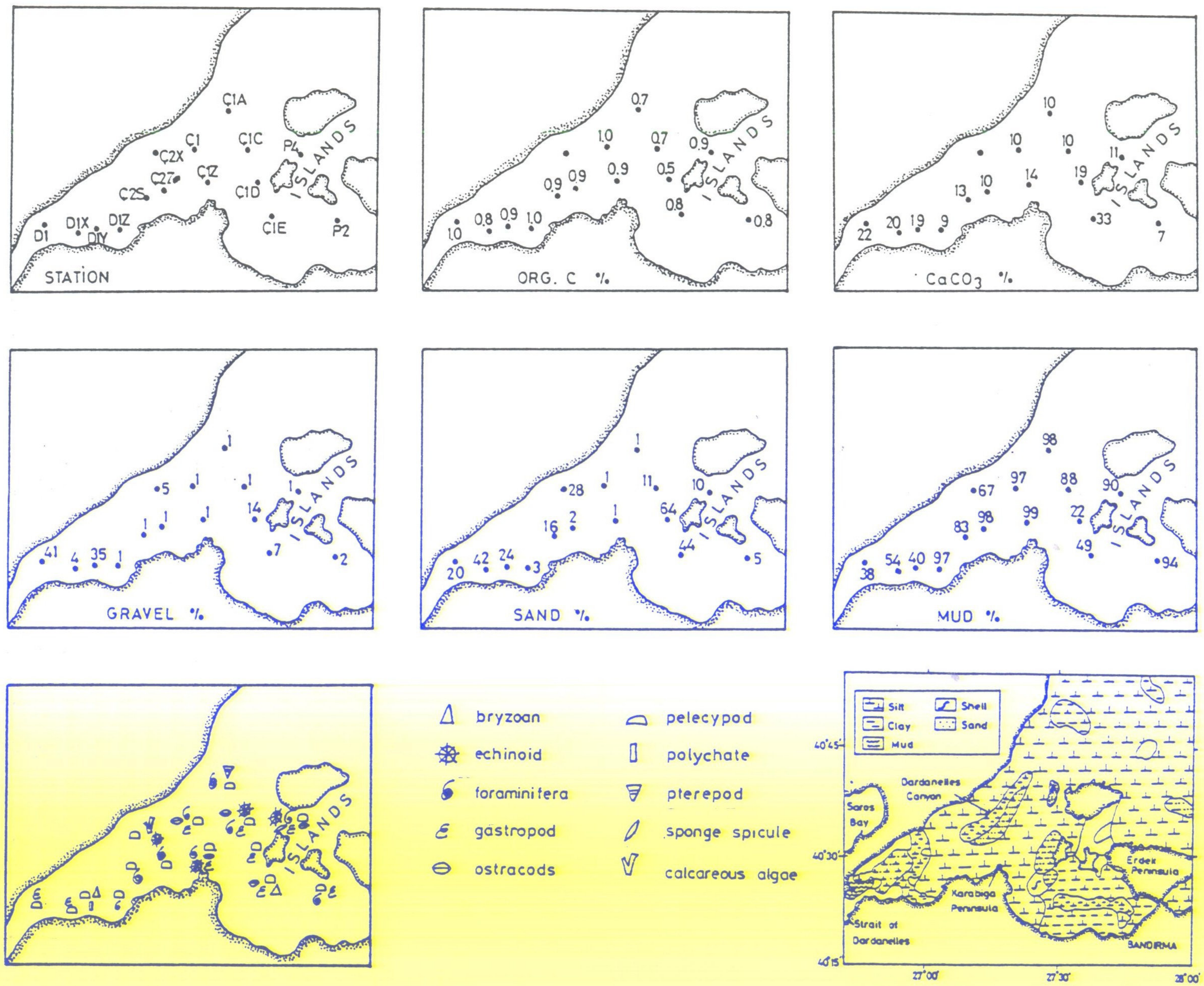
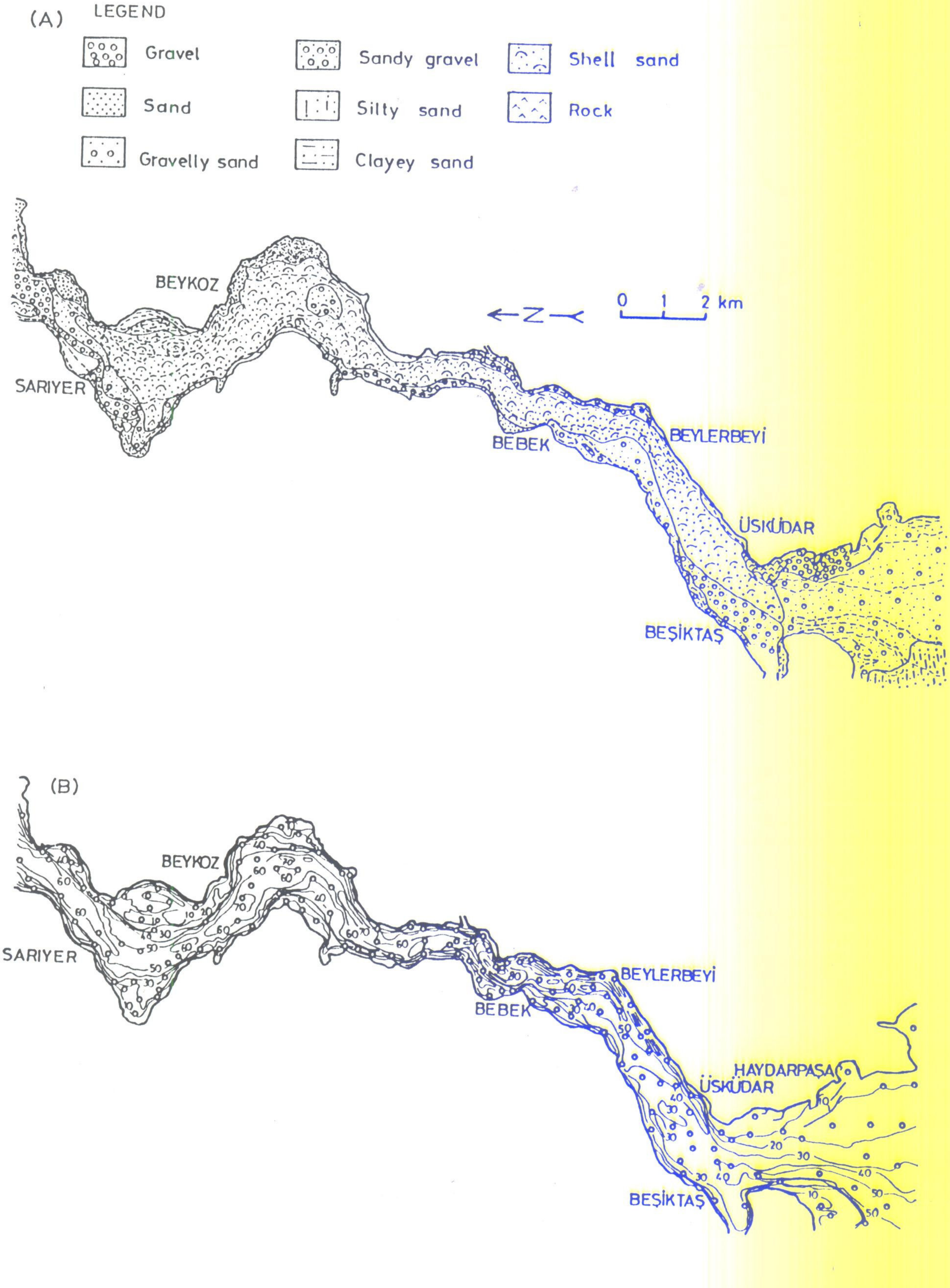


Fig.7. Grain size, total carbonate, organic carbon and biofacies distribution in surface sediments of the southwestern Sea of Marmara. For details, see text. Note the sediment distribution map of the Turkish Navy Hydrographic Office (bottom right) for comparison.


(A)
LEGEND
Gravel
Sandy gravel
Shell sand
Sand
Silty sand
Rock
Gravelly sand
Clayey sand
BEYKOZ
SARIYER
0 1 2 km
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BEŞİKTAŞ
(B)
BEYKOZ
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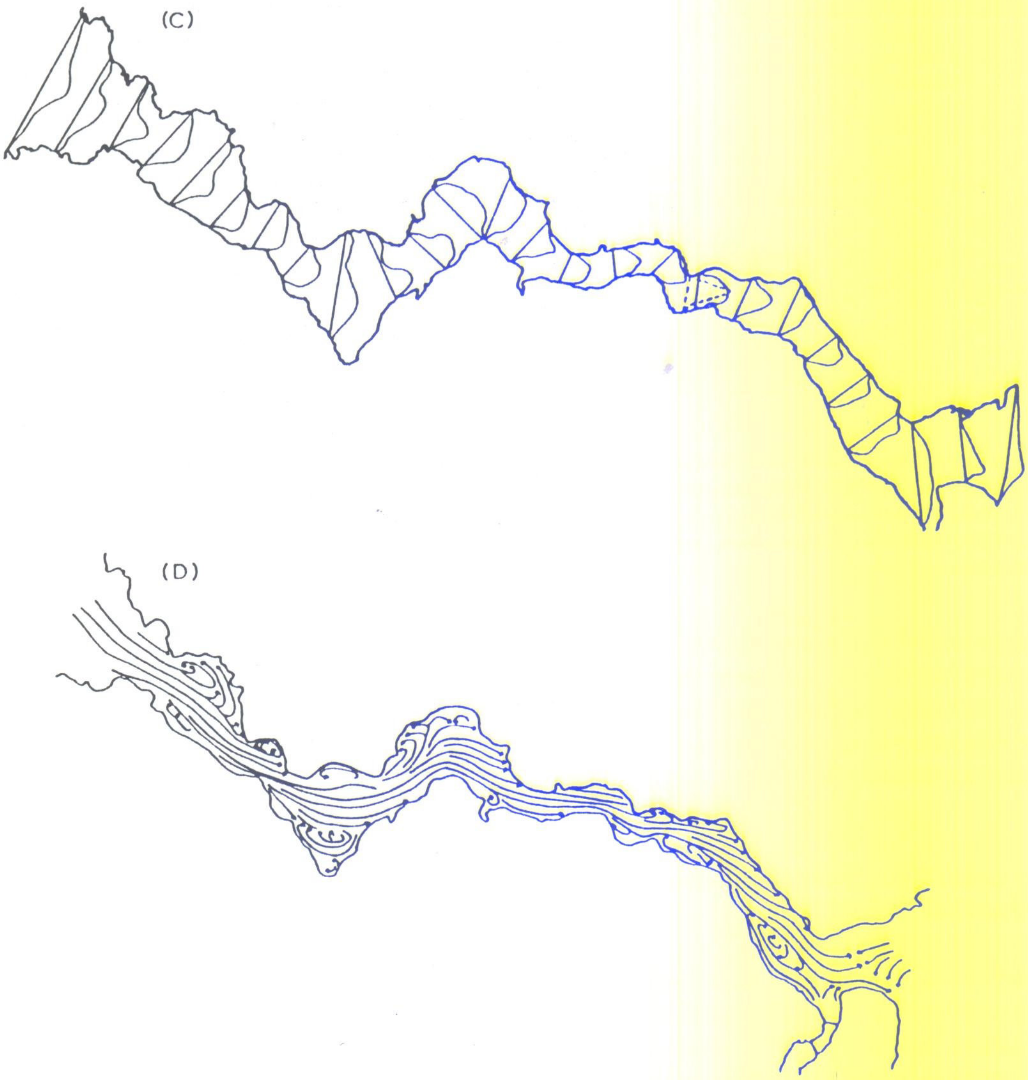

Fig.8. Sedimentation and hydrography (bathymetry in metres) in the Strait of Bosporus. A. Sediment distribution map obtained from about 150 stations (B) (reproduced from DAMOC (1971)). C. Morphometric cross sections along the strait (after Gunnerson and Özturgut, 1974). D. Current distribution patterns showing the eddies at 10 m water depths (after Möller, 1928). In (A), note the relatively finer clastic deposits along the point bars.

The organic carbon content of the sediment is between 0.19 and 1.17% by dry weight (Fig.6). These values seem to be higher than those from the junction between the Strait of Dardanelles and the Aegean Sea (0.20–0.30% C_{org} (work in progress), but much lower than those from the junction between the Strait of Bosporus and the Black Sea (1–2% C_{org}; Rozanov et al., 1974; Yücesoy, pers. commun., 1989). It has been shown that the SW-flowing Black Sea waters at the surface, which are rich in organic matter because of the relatively high primary productivity and terrigenous influxes, are subject to exchange with the subsurface northeasterly flow of Mediterranean waters (poor in organic matter) in the Strait of Dardanelles; this increases the total organic carbon concentration of the bottom water layers (Baştürk et al., 1986, 1988; Polat, 1989) (Fig.12). From this it appears that such a water-mass exchange between the Black Sea and Mediterranean Sea waters in the Strait of

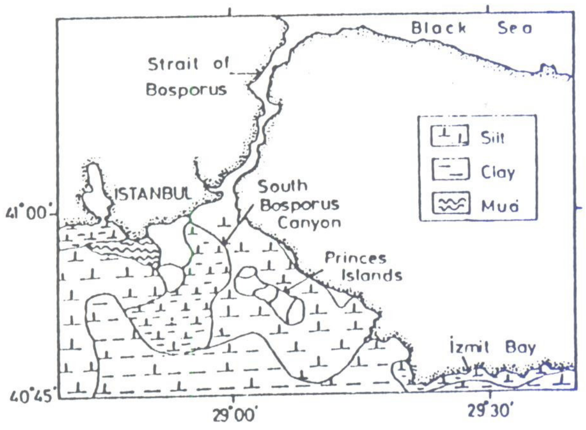

Fig.9. Sediment distribution map from the northeastern Sea of Marmara (after Turkish Navy Hydrographic Office, in Adatepe, 1988). Note the surface sediments from South Bosporus Canyon with relatively high mud contents (see also Fig.13 and 14 for comparison).

Dardanelles would also contribute to the increased organic influxes to the sediments here. Because such an exchange is less significant from the Strait of Dardanelles to the Aegean Sea, both the waters and sediments are low in organic carbon content.

Junction between the Strait of Dardanelles and the Sea of Marmara

The sediments here show a wide range of grain sizes, from silty clay to muddy gravel (Fig.7). In general, there seems to be a tendency for an increase in the proportion of clay in the downcanyon direction, from 18% at the narrow entrance of the Strait of Dardanelles (Station D1) to 64% at the downcanyon end (Station C1A) (Fig.10). Furthermore, the N–S trending outer parts of the canyon appear to have much more coarse sediment than the inner canyon (Fig.10). In addition, the sediments from the axial depths (Stations C1 and C1A) consist almost entirely of mud (Fig.10). This suggests that the clay represents the tail of a current of decreasing velocity which in turn must have resulted from changes in intensity of the downcanyon flow of undercurrents, from the shallow waters of the strait (high-energy conditions) to the deeper waters of the canyon (low-energy conditions). High sand and gravel percentages remain near the entrance to the strait (Stations D1, D1A and D1Y) and also shoreward around the islands (Stations C1D and C1E) (Fig.7). Marked changes in the dominant grain-size fractions of sediments in and around the Dardanelles Canyon can also be seen on the Turkish Navy Hydrographic Office sediment distribution map (Fig.7): north of the Karabiga Peninsula and east of the Marmara Islands, sediments contain appreciable amounts of clay with some sand content, whereas the floor of the outer canyon largely comprises silt.

Pelecypods, foraminifera, gastropods, ostracods, pterepods, echinoids and bryzoans are important biogenic components in the coarse sediment fractions of the Strait of Dardanelles (Fig.7). Distinctive occurrences of echinoids are to be found around the Marmara islands (Fig.7), although some concentrations may be small. In general, the echinoderm population originated recently after migration from the Aegean or Mediterranean Sea; echinoderms are thus scarce in the Sea of Marmara (Tortonese and Demir, 1960). Here, coralline algal sediments are found at station C2X (Fig.7) a little to the west of the canyon head, with a relatively coarser grained substratum.

The $CaCO_3$ percentage of the sediments ranges from 7 to 33% by dry weight (Fig.7). The microscopic studies revealed that shell fragments of the calcareous organisms are the major source. High carbonate contents tend to be concentrated in coarse-grained fractions. Except for one sample south of the Marmara Islands (Station C1E) which is of biogenic origin (> 30% $CaCO_3$), sediments at the junction between the Strait of Dardanelles and the Sea of Marmara can generally be considered as largely terrigenous (< 30% $CaCO_3$).

The organic carbon content of the sediments varied in a narrow range between 0.8 and 1.00% by dry weight (Fig.7), values not much different from those found in the Strait of Dardanelles. This is in good agreement with the total organic carbon concentrations of the bottom waters, which reflects uniform conditions both at the Aegean and Marmara exits of the strait (Fig.12). However, the upper water layers show significant influxes of organic matter from the Black Sea (Fig.12).

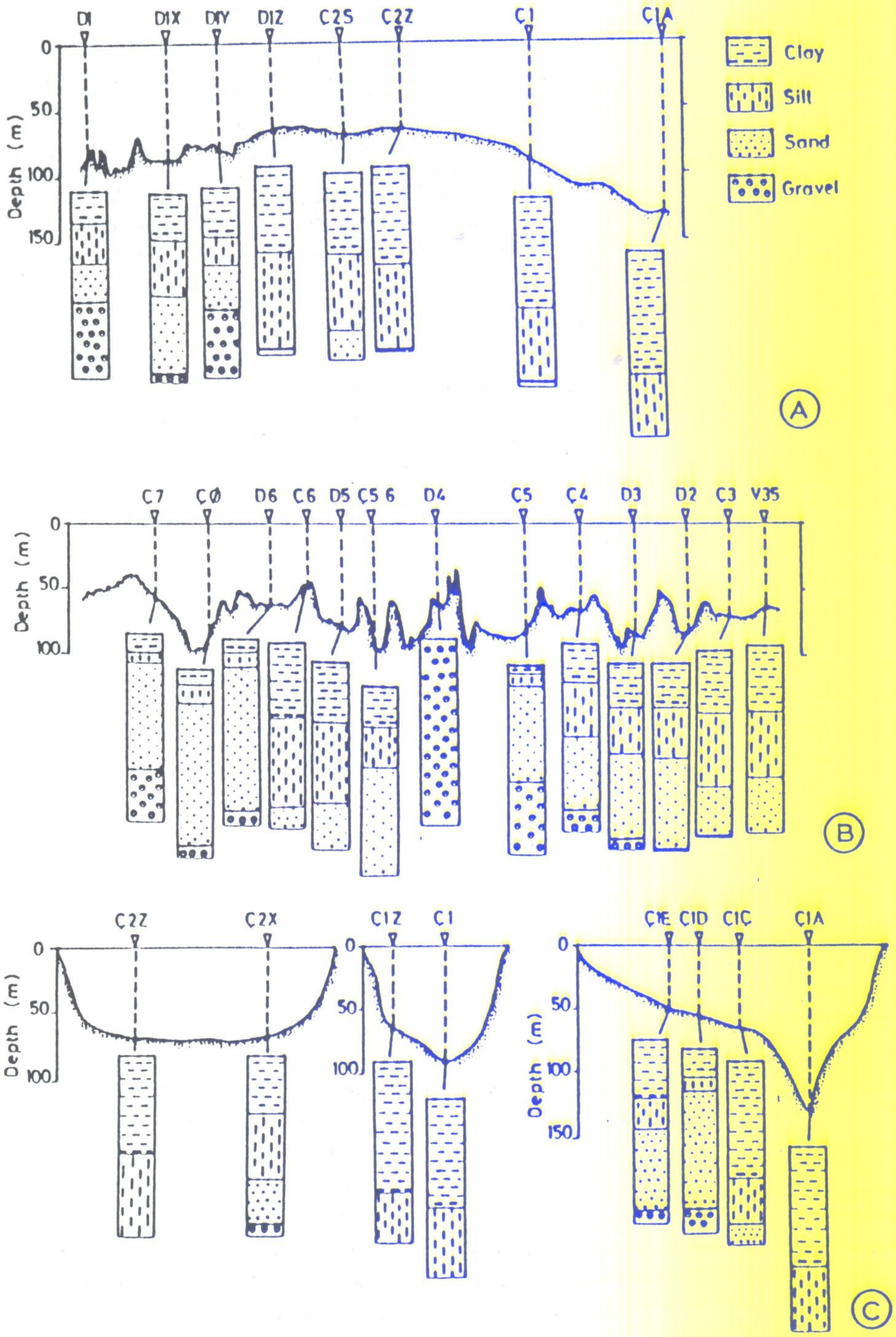

Fig.10. Grain-size distribution of surface sediments from the southwestern Sea of Marmara. Clay + silt + sand + gravel = 100%. A. Along the inner course between the exit of the Strait of Dardanelles and the Dardanelles Canyon (see Fig.2A for location of samples). Note the generally increasing tendency towards sediment of clay grade down the canyon. B. Along the inner channel of the Strait of Dardanelles. Note the area of coarse sediments due to the high-energy conditions (St.D4 Nara Passage) and fine sediment related to the low-energy conditions (see Fig.3, and for location of samples, see Fig.6). C. Transverse profiles of the Dardanelles Canyon and its upper reaches off the Strait of Dardanelles. Note the deposition of fine sediments (increasing clay content) down the canyon as a result of decreasing curent energy with distance from the strait (see Fig.2A for location of samples).

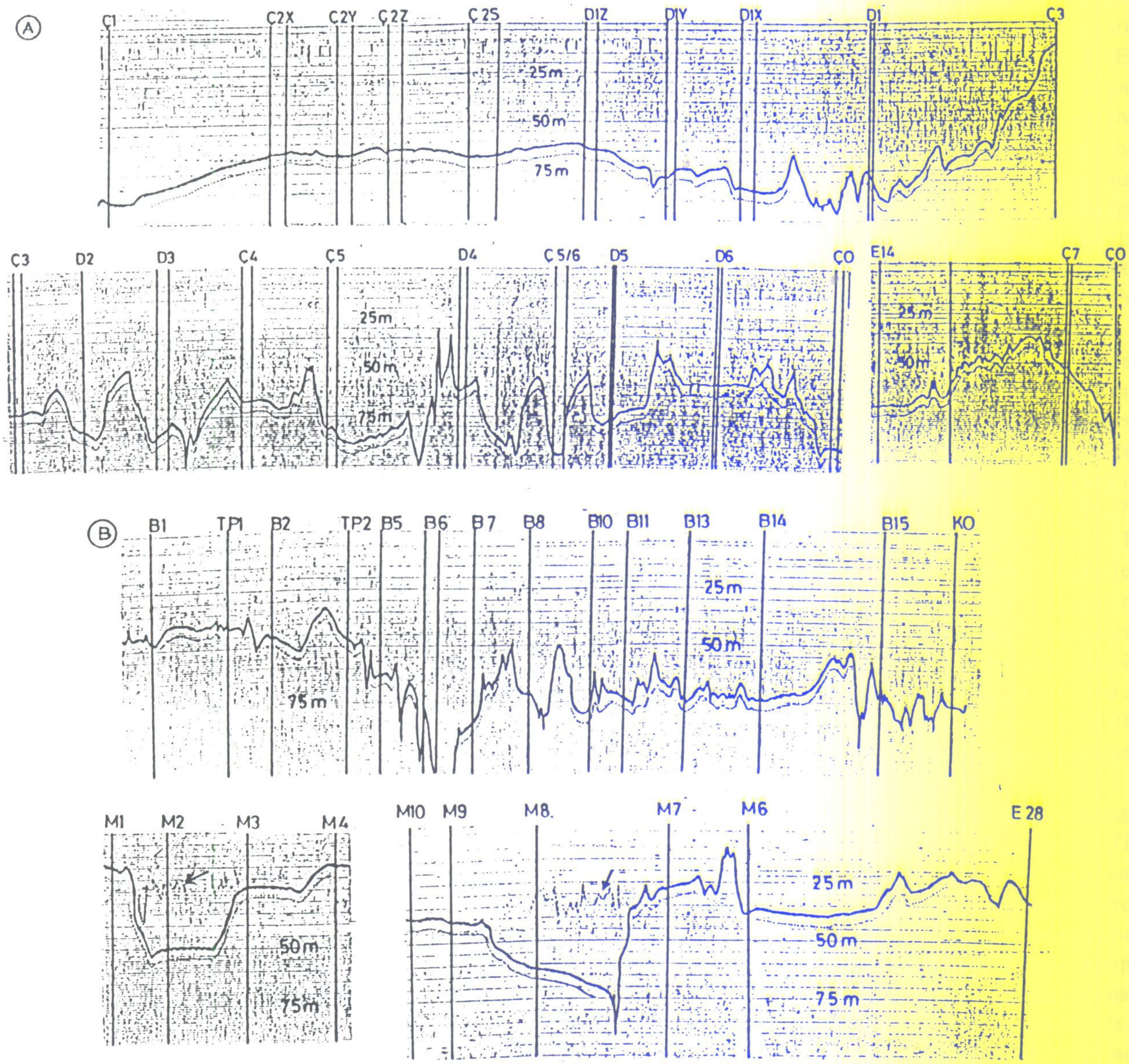

Fig.11. Typical echosounder profiles of the study areas. A. *Top*: Between Gelibolu Harbour (St.C3) and the head of the Dardanelles Canyon (St.C1). *Bottom left*: Along the inner channel course of the Strait of Dardanelles, from St.C3 (Gelibolu Harbour) to C0 (southwest exit of the Strait of Dardanelles to the Aegean Sea). Note the narrowing Nara Passage (St.D4). *Bottom right*: A bank- or reef-like bottom feature at the southwest exit of Strait of Dardanelles (St.C7) with a high biogenic component (e.g., the coralline algae *Lithothamnium*). B. *Top*: The Strait of Bosporus from south (St.B1) to the north (St.K0 approach to the Black Sea). *Bottom*: East–west trending cross section from the South Bosporus Canyon. Arrows indicate possible suspended load in the inner canyon.

The junction between the Sea of Marmara and the Strait of Bosporus

Although in terms of topography this region may show some similarities to the junction between the Strait of Dardanelles and the Sea of Marmara, its sediments are more varied because of its proximity to the Strait of Bosporus and, thus, the Black Sea. In addition, at this junction there exists an upcanyon flow of bottom currents which is the reverse of that seen in the Dardanelles system where bottom currents move in the downcanyon direction.

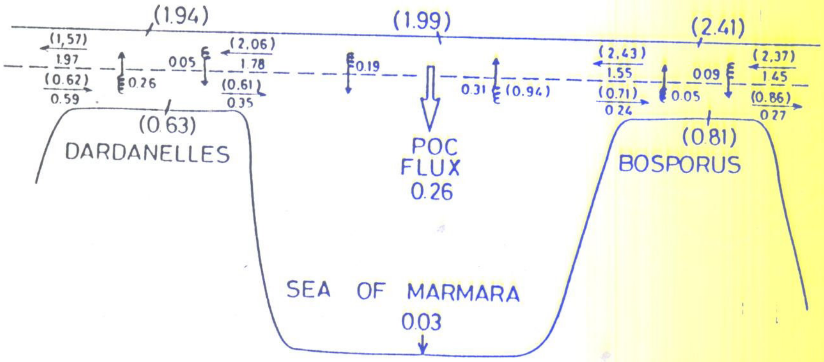

Fig.12. Horizontal and vertical organic carbon concentrations and fluxes ($\times 10^6$ tons C/y) for budget calculation. Values in parentheses indicate total organic carbon concentration (TOC, POC) in mg C/l (after Polat, 1989). Note the generally decreasing organic carbon content with increasing distance from the Black Sea.

The grain size ranges from silty clay to gravelly mud, with an increasing tendency toward fine material in the downcanyon direction, both along the N–S trending axis and along the E–W trending sidewalls (Figs.13, 14 and 15). For example, the mud percentages show an increase from 17% at the head of the canyon (Station E2) to 88% at the downcanyon end (Station M16), and from 15% and 38% in the outer canyon at nearshore stations (M10 and M6 respectively) to 67–80% in the inner canyon along the axis (Stations M2 and M8) (Fig.14). This downcanyon fining (or upcanyon coarsening) of sediments (Fig.15) can best be explained as being related with changes in submarine topography and corresponding undercurrent regimes. As noted previously, the bottom currents of the Sea of Marmara flow continuously toward the Black Sea and attain their high velocities as they approach the Strait of Bosporus, where the maximum current speeds are measured. Consequently, the changes in the energy conditions, from low energy in deeper waters to high energy in shallower waters, will result in coarsening of sediments on approaching the strait and the shore; this coincides with fining with increasing distance from the strait or head of the canyon. A comparable contrast between the inner and outer parts of a canyon has also been reported from other canyons (e.g., Tokyo Canyon, Shepard and Dill, 1969).

Occasional nearshore increases in mud are characteristic of the eastern shelf regions, especially north of Princes Islands where the eastern flank of the canyon widens and broadens shoreward (Fig.14). The presence of these islands and their associated irregularities together with the active wind regimes are known to be responsible for occurrences of various small-scale cyclonic and anticyclonic flow regimes around the islands (Özsoy et al., 1988), which in turn may account for the favourable conditions for accumulation by fine sediments. Here, stations M4, M5 and A15 (Fig.2B)seem to be sites of such cyclonic and anticyclonic fine sedimentation (Fig.14).

High percentages of mud are also common in the Bay of Pendik, which is bordered to the east by the Tuzla Peninsula and to the west by the Princes Islands. Here, at stations A23, M19, A26 and M20 (Fig.2B), the sediment contains an exceptionally high proportion of mud (72–99%) (Fig.14). Comparison of grain size results in the present paper with those of the Turkish Navy Hydrographic Office showed some differences, although there seems to be a general agreement that the sediments of the canyon floor contained much more clay than those of the adjoining eastern and western shelf regions (Fig.9).

The $CaCO_3$ contents of the sediments are between 12 and 90% by dry weight (Fig.16A). Minimum carbonate concentrations are found in the inner canyon, with a tendency to increase towards the shore around the western edge of the outer canyon; indeed, it is here where the highest carbonate percentages occur (Fig.16A). In general,

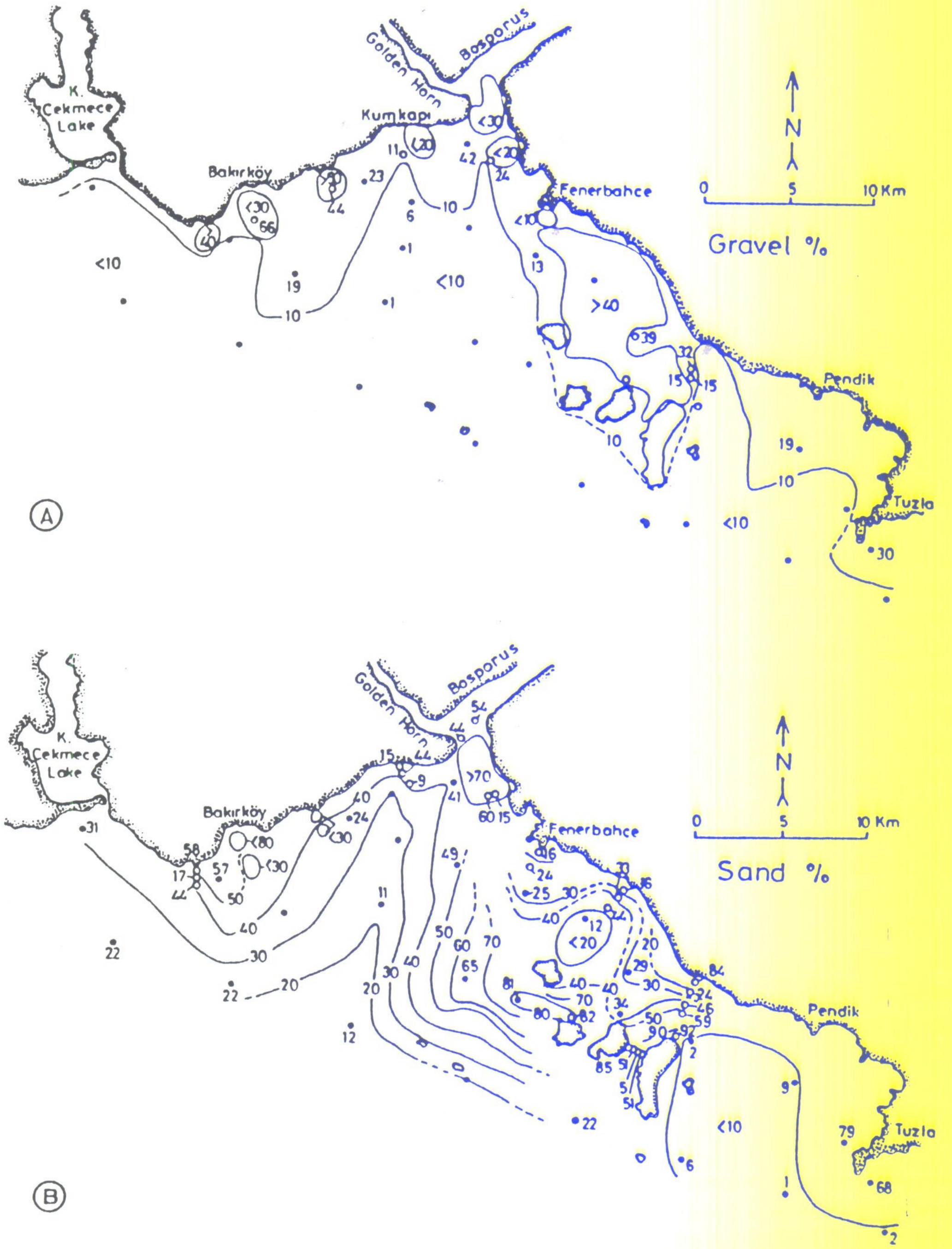

Fig.13. Gravel (A) and sand (B) distribution in surface sediments of the northeastern Sea of Marmara. Note the general tendency towards coarsening of sediment from the inner canyon toward the coastal and island shores due to the increasing current energy and biological activity.

the carbonate content is inversely related with the mud content (Figs.14 and 16A). As inferred from the microscopic observations, the carbonate fractions of the sediments must be supplied largely by the calcareous remains of organisms, such as coralline algae (e.g., *Lithothamnium calcareum* and *L. corallinoides*), gastropods, pelecypods, echinoids and foramifera, all of which are abundant in

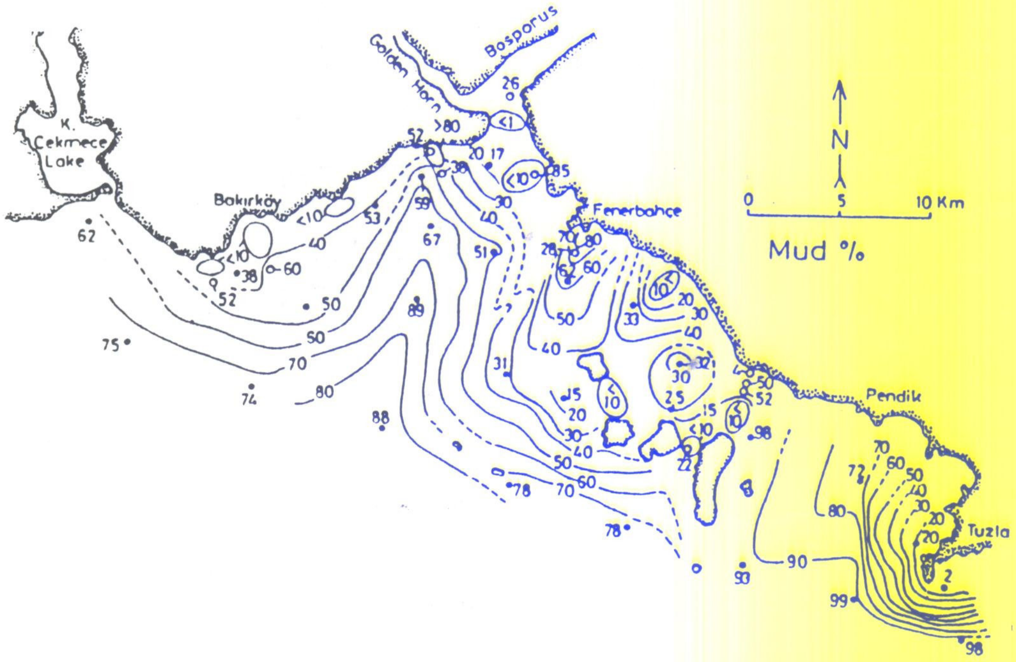

Fig.14. Mud distribution in surface sediments of the northwestern Sea of Marmara. Note the general fining of sediment toward the inner canyon as a result of decreasing current energies. Also, note the nearshore cyclonic accumulation of mud due to the specific hydrographic conditions in the regions (see text for explanation, and see Fig.9 for comparison).

the sand and gravel fractions. On the basis of the characteristic appearance of these biogenic components, the shelf sediments of the Bosporus–Sea of Marmara junction may be separated into various biotazones (Fig.17). These include a pelecypodal–foraminiferal–gastropodal assemblage in the inner canyon, usually at depths greater than 40 m, a pelecypodal–foraminiferal–sponge assemblage on the eastern flank (walls and upper rim) of the canyon, commonly at depths from 25 to 40 m, a pelecypodal–gastropodal–foraminiferal–coralline algal assemblage in areas between the 20 and 50 m water depths, and an assemblage of miscellaneous molluscs, especially bivalves, along the nearshore areas in depths of less than 20 m. The deeper waters of this northeastern shelf region (> 70 m), farther south of the canyon, are marked by the occurrence of a pelecypodal–foraminiferal assemblage (Fig.17). The pelecypodal–foraminiferal–gastropodal–coralline algal assemblage is also characteristic of the area off the Cape of Tuzla (Fig.17).

Tortonese and Demir (1960) showed that in general the echinoderm faunas of the Sea of Marmara are indicative of environmental conditions which are under the influence of Mediterranean waters. According to their investigations, there existed a remarkable decrease in the number of echinoderm species with distance from the Mediterranean Sea.

Coralline algae (the calcareous Rhodophyceae (mainly *Lithothamnium calcareum*, *L. fruticolusum* and *Lithophyllum racemus*)) are prominent at shallow water depths (usually between 20 and 40 m) (Stations E4, M4, M5, M6, M7, A14, A15, and A18; Figs.2B and 17) where relatively saltier Mediterranean waters are flowing near the bottom. Here, particularly in the shallower parts of the shelf around the Princes Islands, occurrences of calcareous algal meadows are reported, reflecting typical Mediterranean characteristics (Tortonese and Demir, 1960). Figure 17 also shows characteristic patterns of distribution of the calcareous algal assemblages: almost no species are found in the N–S trending inner canyon, while the E–W trending parts of the outer canyon towards the shores seem to be providing favourable conditions for algal growth. Obviously, the presence of a high

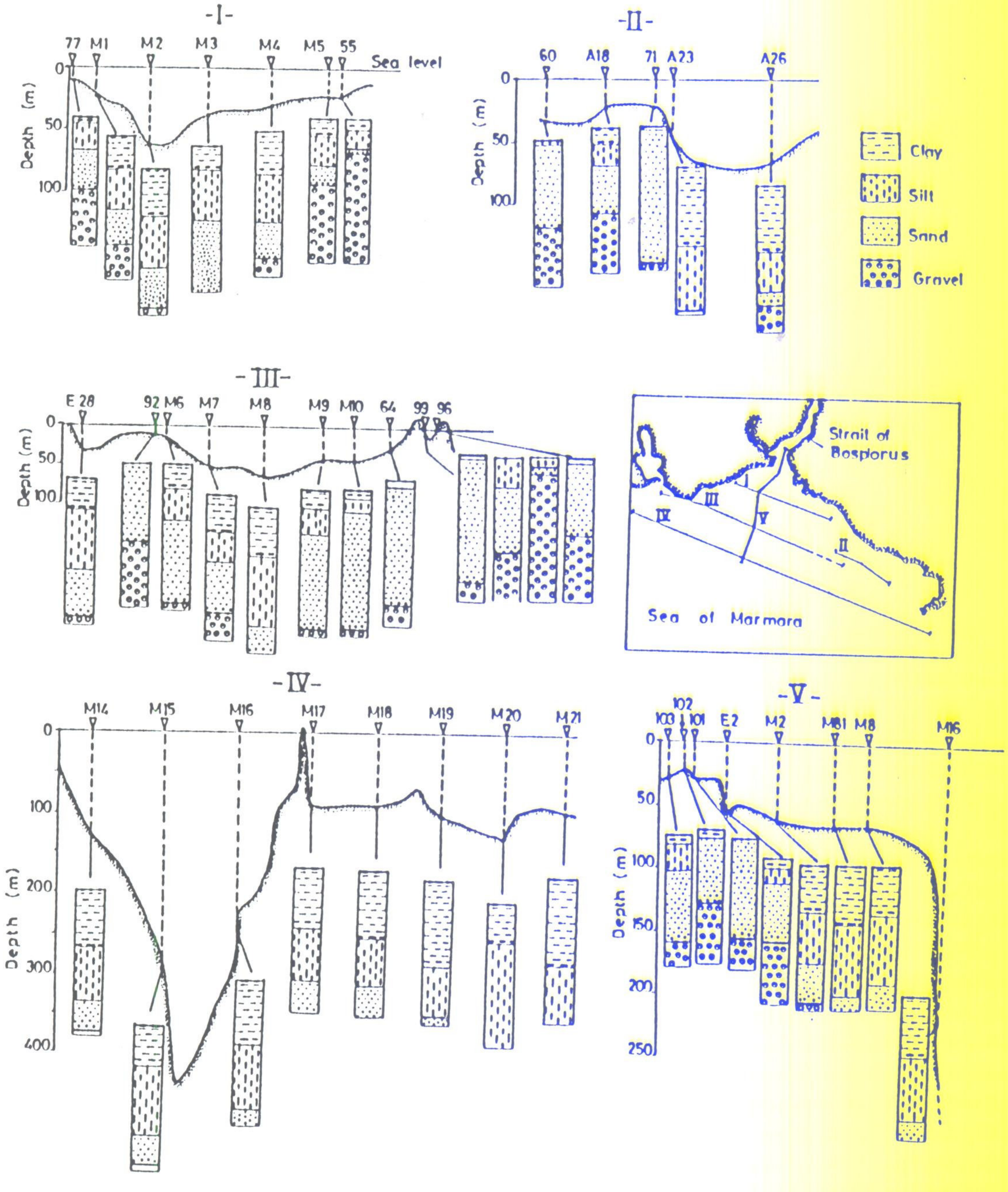

Fig.15. Grain-size distribution in surface sediments of the northeastern Sea of Marmara. Sections I, III and IV are transverse profiles and section V is a longitudinal profile of the South Bosporus Canyon. Note the general decrease in grain size in the downcanyon direction due to lowering of energy levels of the undercurrents. Clay + silt + sand + gravel = 100%. For sample locations, see Fig.2B.

rate of mud deposition and the greater water depths restrict coralline algal growth in the inner canyon. According to the observations of Güre (1990), species diversity and biomass content in the bottom sediments generally increase with decreasing mud content. Large concentrations of these organisms were also found in sediments in the junction between the Strait of Dardanelles and the

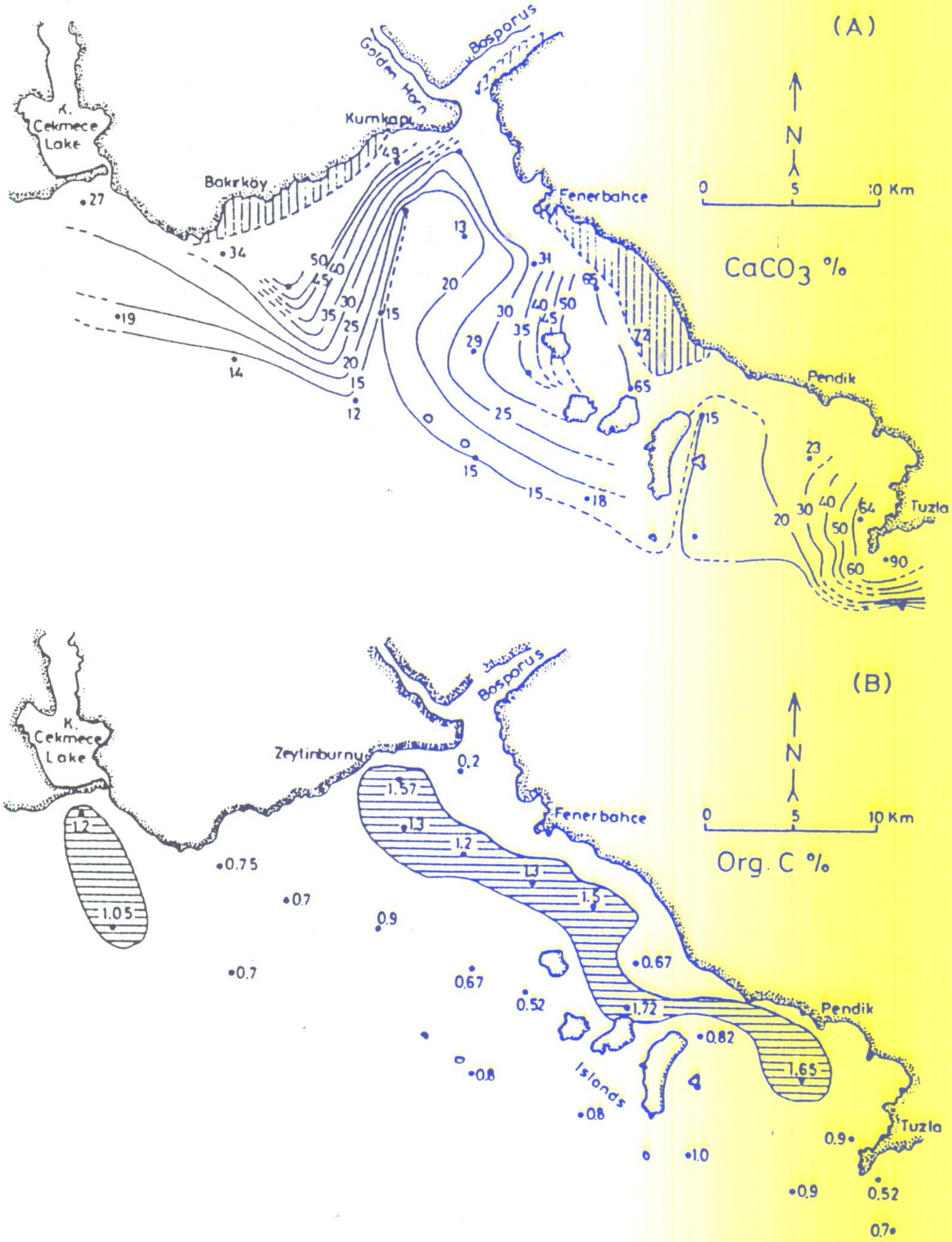

Fig.16. Total carbonate (A) and organic carbon (B) distribution in surface sediments of the northeastern Sea of Marmara. Note the generally shoreward increasing carbonate contents related to the high biogenic activity of benthic organisms. Shaded areas show zones of shell sands and gravels (after DAMOC, 1971) (the regions with highest carbonate contents). The distribution pattern for organic carbon indicates close relationships between high organic carbon concentration and primary productivity rates in the area.

Aegean Sea (Fig.6), a region where Mediterranean waters enter the Sea of Marmara through the strait. According to direct measurements by the IMS-METU (Özsoy et al., 1986, 1988; and unpublished data files), the annual temperatures, salinities and dissolved oxygen contents of the surface waters at the sampling stations in the northeastern Sea of Marmara (at places where

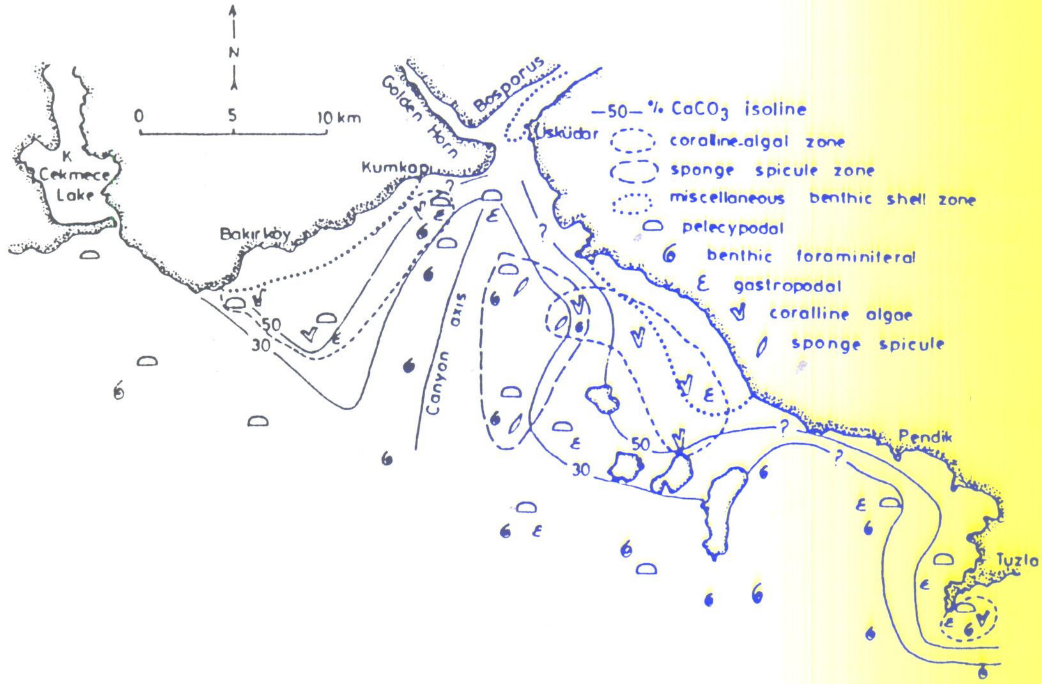

Fig.17. Distribution of the major biotazones on the shelves of the northeastern Sea of Marmara. Note the prominent coralline algal zone on both sides of the South Bosporus Canyon.

coralline algae were prominent) range from 5 to 23°C, 20 to 31‰ and 4 to 12 mg/l respectively. The underlying Mediterranean waters also exhibited a wide range of temperature, salinity and oxygen values (7–18°C, 23–38.5‰ and 1.5–12 mg/l respectively). Such marked variations in these parameters in the waters of the northeastern Sea of Marmara are usually attributed to the responses of the region to local climatic changes, as well as to those occurring in the adjacent Aegean Sea and Black Sea (Özsoy et al., 1988).

Among the benthic organisms, the siliceous sponges display another characteristic distribution, especially on the eastern shelves of the canyon near the Princes Islands; it appears that the shelf regions surrounding the Princes Islands are suitable for a rich development of these benthic organisms (Demir, 1954). The northeastern region of the Sea of Marmara, especially its approaches to the Strait of Bosporus, is known to be very rich in molluscan species when compared with other regions of the sea (Güre, 1990). In particular, the pelecypods *Mysella bidendata*, *Cingula* sp. and *Myrtea spinifera* are the most frequent species of molluscan fauna characterizing the region.

On the basis of their biogenic carbonate contents, sediments of the junction between the Bosporus and the Sea of Marmara can be both terrigenous (< 30% $CaCO_3$) and biogenic (> 30% $CaCO_3$) in nature. For example, sediments of the inner canyon are usually terrigenous, while those from the shoreward part of the outer canyon are biogenic in origin. Apparently, the specific distribution of the biogenic and terrigenous fractions of the sediments are somewhat interrelated. As shown in Figs.14 and 16, the sediments generally tend to be composed of finer material and of lesser carbonate with increasing distance from the shore. Thus, the shoreward coarsening of sediments with increasing distance from the canyon axis cannot be solely explained with a depositional model for clastic sedimentation (i.e. shoreward coarsening due to increasing water energy). The effects of benthic production seem to be very important here in controlling the types and modes of sediment distribution.

With the exception of one value of 0.20% at the canyon head, the organic carbon concentrations of the sediments range from 0.52 to 1.72% by dry weight (Fig.16B). These values are rather higher than those found at the junction between the Strait of Dardanelles and the Sea of Marmara (0.5–1.0%) and at the junction between this same strait and the Aegean Sea (0.20–0.30% C_{org}; work in progress), but they are lower than those at the junction between the Strait of Bosporus and the Black Sea (1–2% C_{org}; Rozanov et al., 1974; Yücesoy, pers. commun., 1990). The general tendency revealed by this study for the C_{org} content to increase from the Aegean Sea towards the Black Sea seems to coincide with a similar distribution pattern for organic carbon in the waters of the Sea of Marmara (see Fig.12). As reported by Baştürk et al. (1988), Göçmen (1988) and Polat (1989), the average annual primary productivity rates and the corresponding total organic carbon contents of the waters generally show a tendency to decrease (Fig.12) from the Strait of Bosporus to the Strait of Dardanelles. For example, the average annual primary productivity rates in the Black Sea, the Sea of Marmara–Bosporus junction, the Marmara Basin proper, and the junction between the Strait of Dardanelles and the Sea of Marmara are 150–250 g C/m²/yr (Sorokin, 1983) (according to Göçmen (1988), 52–98 g C/m²/yr), 94 g C/m²/yr (Baştürk et al., 1988; Göçmen, 1988), 60–103 g C/m²/yr (Ünlüata and Özsoy, 1986; Baştürk et al., 1988; Göçmen, 1988), and 12–24 g C/m²/yr (Baştürk et al., 1988) respectively. Thus, the sediments at the junction between the Sea of Marmara and the Strait of Bosporus reflect influxes of substantial amounts of organic matter from the Black Sea. The generally high organic carbon contents of sediments at the Bosporus–Marmara junction (1.20–1.72%, from Stations E4, M2, M3, M4, M5, A18 and A26) can best be related to the occurrences of high primary productivities, influxes from the adjacent land sources, and influxes from the Black Sea. As shown by Ünlüata and Özsoy (1986), Baştürk et al. (1988) and Göçmen (1988), the Bosporus–Marmara junction is one of the most productive areas of the Sea of Marmara.

Strait of Bosporus

The principal sediment types of the floor of the Strait of Bosporus are illustrated in Figs.8 and 18. A belt of shell sand is indicated along the main channel of the straits where coarse sediments with predominant sand and gravel includes significant amounts of shell fragments (Fig.8A) mostly derived from the pelecypods, bryozoans, gastropods, echinoids and foraminifera. Marked occurrences of these organisms in the Strait of Bosporus have also been reported by Caspers (1968) and Meriç et al. (1988). Of the molluscan fauna, the pelecypods *Mytilus galloprovincialis*, *Modiolus barbatus*, *Mysella bidendata*, *Pitar rudis* and *Corbula gibba* are

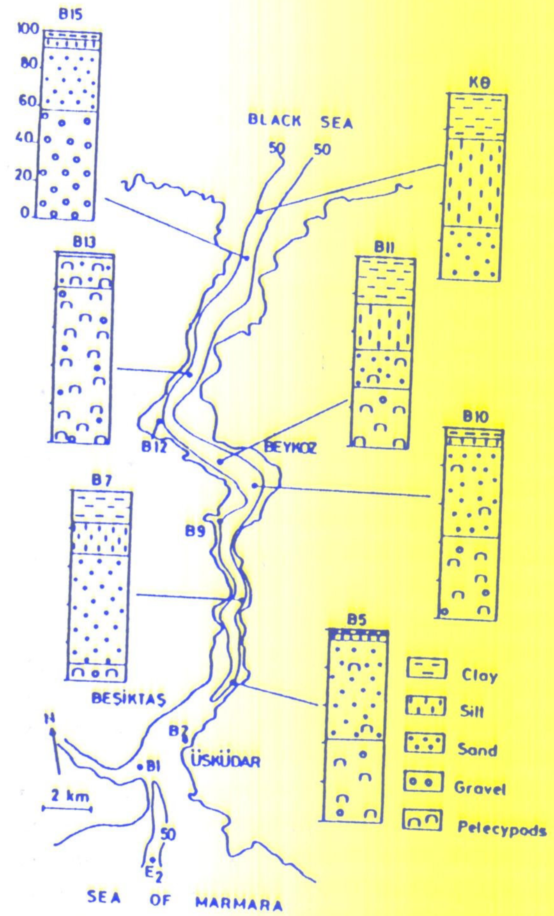

Fig.18. Grain-size distribution of surface sediments of the Strait of Bosporus, indicating deposition of coarse material due to high-energy conditions. Clay + silt + sand + gravel = 100%. For details, see text.

the most frequent species (Güre, 1990). The mussel *Mytilus galloprovincialis* is of economic importance (Artüz and Erdoğan, 1962; Uysal, 1970). The distribution of these species is promoted by the specific conditions of temperature, salinity, a hard, sandy, gravelly bottom, and nutrients which are essential for these benthic organisms in this strait (Demir, 1954; Uysal, 1970; Hasanoğlu, 1975) where less saline, organic-rich and colder Black Sea waters are of importance. Otherwise, the relative abundances of molluscs usually decrease with increasing distance from the Strait of Bosporus towards the Aegean Sea (Uysal, 1970). That is why most of the Mediterranean echinoderms are absent in the bottom sediments of this strait (Tortonese and Demir, 1960). Among the gastropods, the Trochidae reflect the influences of Black Sea waters (Güre, 1990).

Except for biogenic influences on the grain size of sediments, which result in a coarsening, the occurrences of high sand and gravel contents in the clastics in the Strait of Bosporus (Figs.8A and 18) generally reflect high-energy conditions in the strait. The dominant bottom currents, which are usually faster than 10–20 cm/s (Fig.5), are capable of eroding and removing finer material. This, together with the effects of irregular bottom contours (Fig.11B), results in the formation of several sand and gravel patches on the floor, as has been observed south of the Strait of Bosporus between Beşiktaş and Üsküdar just beyond the southern exit to the Sea of Marmara (Fig.19). Here, the sidescan sonar surveys revealed the presence of asymmetrical current ripples of sand ranging in lengths from 2 to 25 m and reaching heights of 90 cm (IMS–METU, 1985; Okyar, 1987) (Fig.19). The trends of these ripples agree with the general direction of the N-flowing bottom currents. According to Belderson et al. (1972), the occurrence of these ripples is indicative of sandy environments with high current speeds (50–100 cm/s). In this area, the bottom currents have been measured to approximately 60 cm/s about 7 m above the seafloor (IMS–METU, 1985), a value which is consistent with those required for the formation of such current ripples.

Sediments on the concave sides of the meandering Strait of Bosporus show a certain relationship to the prevailing water regime here. For example, in the short inlets where eddies and cyclonic water circulations occur (Fig.8D), sediments are rich in finer clastics which were presumably trapped in these areas as a result of decreasing hydraulic energy. This is a feature resembling the situation in the depositional environments of meandering river channels (Reineck and Singh, 1975).

The presence of some coarse sediments (clastic sand and gravel) along the shores of the strait must be reflecting the eroding effect of both the S- and N-flowing currents here.

Organic carbon contents of the sediments range between 0.25 and 1.28% (Fig.18); the high values are found in the finer grained sediments (1.03 and 1.28% at Stations B11 and K0 respectively) and the low values occur in the coarser grained sediments (0.25–0.72% at Stations B5, B7 and B15). This suggests that the local changes in the hydrographic conditions, such as coastal topography, current energy etc., mostly control the rate of deposition of the organic matter into the sediments. However, the extent of total organic carbon concentration in the waters within the strait is controlled by several other factors, such as local and seasonal changes in surface primary productivity, depth of the halocline, meteorological conditions, rate of oxygen utilization, influxes from the Black Sea etc. (Baştürk et al., 1986, 1988; Ünlüata and Özsoy, 1986, Polat, 1989).

The $CaCO_3$ content of the sediments varies between 2 and 28% by dry weight (Fig.18), reflecting the amount of calcareous organism remains in the samples.

Conclusions

The results obtained in this study together with data vailable from other sources demonstrate significant local differences in sediment composition due to variations in topography, hydrology and biology. In places where high-energy conditions prevail, in the Strait of Dardanelles and Strait of Bosporus, coarse-grained sediments rich in sand and gravel are widely distributed, and in some other places, where current energies were low, mud deposition occurred. In the canyons, along the axial depths sediments tended to increase in mean

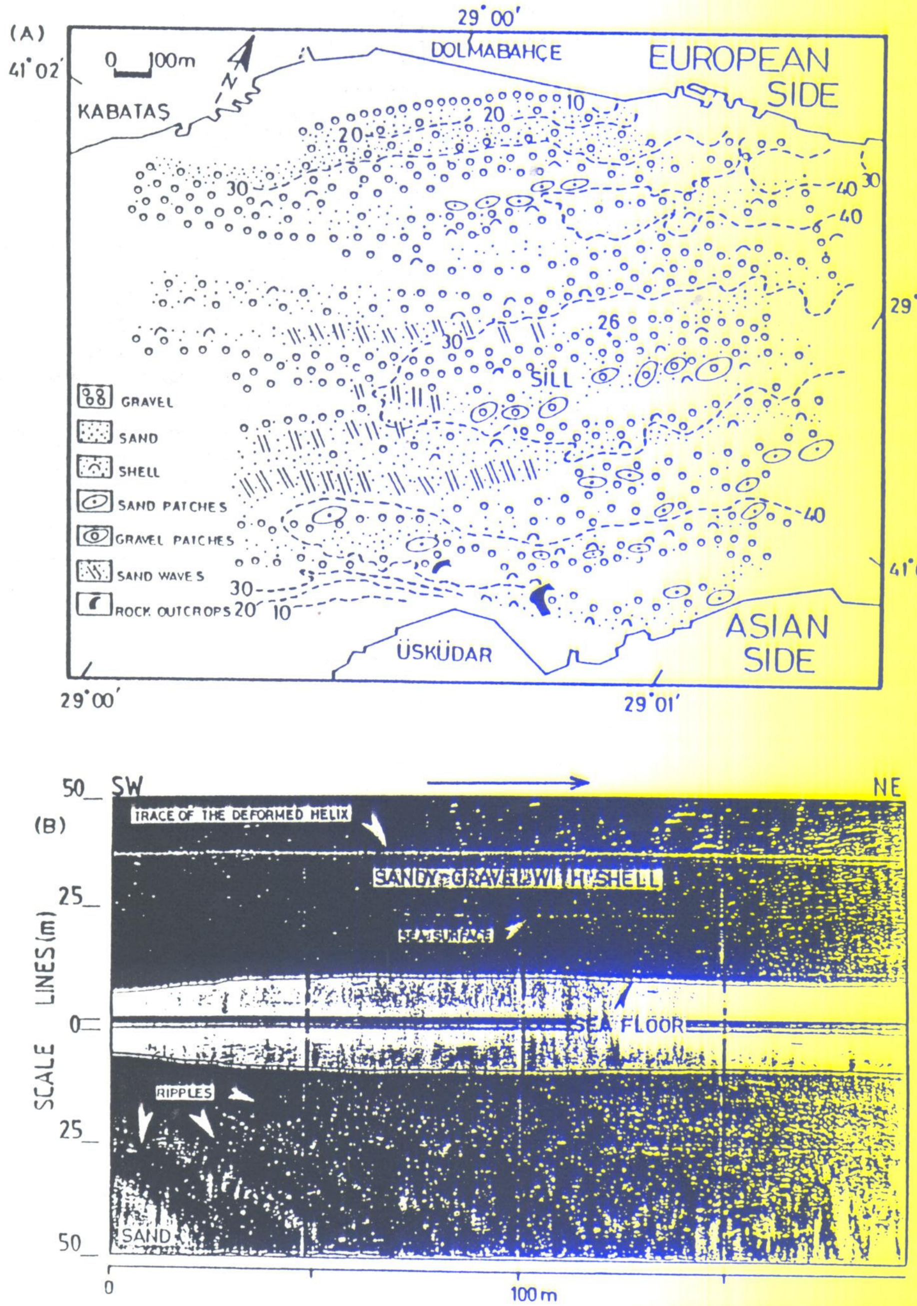

Fig.19. Bottom features of the downstrait part of the Bosporus (IMS–METU, 1985; Okyar, 1987). A. Sediment distribution map based on sonograph interpretations (contours in metres). Note the sand ripples (B) indicative of the strong N-flowing undercurrents.

grain size in the downcanyon direction. The shelves bounding the outer canyon, especially south of the Bosporus, are marked by the occurrence of large amounts of shell fragments resulting in a general coarsening of sediments from the inner canyon towards the shores. Several biogenic assemblages are found, of which the molluscs *Mytilus galloprovincialis*, *Modiolus barbatus* and the Trochidae are indicative of the Black Sea influences in the Strait of Bosporus. In contrast, the presence of calcareous Rhodophyceae (the coralline algae *Lithothamnion*) and some molluscan faunas (Galeommatacae and Cerithiospidae) are characteristic of the Mediterranean undercurrents in the E–W trending outer parts of the South Bosporus Canyon. The generally increasing organic carbon content of the sediments from the Aegean towards the Black Sea suggests significant amounts of organic influx from the Black Sea.

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