A REVIEW OF MODERN SEDIMENTATION IN THE GOLDEN HORN ESTUARY (SEA OF MARMARA), TURKEY

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Summary Preliminary results from analysis of modern surface sediments and suspended solids collected from the Golden Horn estuary revealed the large influence of the particular hydrographic factors on the types and modes of distribution of suspended solids and bottom sediments in this estuary. Low-carbonate (9-14 % $CaCO_3$), organic-rich (3.17-5.49% Org.C) black mud with dominant silt was widely distributed along the estuary. The importance of the hydrodynamic relations between the prevailing horizontal current velocities in the estuary (5-10 cm/s) and typical settling velocities for silt particles are shown. Favoured accumulation of clays at the head of estuary must result from the flocculation of clays due to their physico-chemical properties, whilst their presence in the outflowing surface layers indicates transportation along with organic substances of much lower density. Three sedimentary facies are recognized in the suspended materials of the estuary: (a) silty and organic-rich clay; (b) fecal-pelletic silt; and (c) pelecypodal-diatomeceous-dinoflagellate silt, suggesting seasonal variations in the species and abundances of both terrigenic and biogenic materials. Anthropogenic substances are present in both suspended materials and bottom sediments and are represented by organic and inorganic materials of varied origin.

Riassunto. I risultati preliminari derivanti dalle analisi dei sedimenti di superficie attuali e del particellato in sospensione raccolti nell'estuario del Corno d'Oro rivelano la grande influenza dei fattori idrografici sui tipi e sulle modalità di distribuzione del particellato sospeso e dei sedimenti di fondo in questo estuario. Fanghi neri caratterizzati da basse percentuali di carbonato (9-14% $CaCO_3$) e ricchi in materia organica (3.17-5.49% Org. C), con silt dominante, sono ampiamente distribuiti lungo l'estuario. Viene illustrata l'importanza delle relazioni idrodinamiche tra la velocità della corrente orizzontale prevalente (5-10 cm/s) e la velocità di sedimentazione tipica delle particelle di silt. Il favorito accumulo di argilla in "testa" all'estuario deriva dalla flocculazione di argilla dovuta alle sue proprietà chimico-fisiche, mentre la sua presenza negli strati superficiali di deflusso indica trasporto con sostanze organiche a densità molto più bassa. Sono state riconosciute tre facies sedimentarie nel materiale in sospensione dell'estuario: a) silt e argilla ricca in materia organica; b) silt con fecal pellets; c) silt con pelecipodi, diatomee e dinoflagellati, che suggeriscono variazioni stagionali nelle specie ed abbondanza sia di materiali terrigeni che biogenici. Le sostanze antropogeniche sono presenti nei materiali sospesi e nei sedimenti di fondo e sono rappresentati da materiali organici ed inorganici di origine varia.

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1. Introduction

Estuaries are transitional zones between fresh and salt water environments where terrigenic, biogenic, and anthropogenic materials of varied origin are known to be trapped in considerable amounts according to the prevailing hydrologic conditions. The Golden Horn Estuary (Haliç) investigated in this work is such a system.

The Golden Horn Estuary, into which the Alibey and Kagithane Creeks discharge (presently at a rate of about $50x10^6$ m^3/y), is a westerly tributary of the Strait of Bosphorus which, in turn, connects the Sea of Marmara in the south with the Black Sea in the north (Fig. 1). The Golden Horn is approximately 7 km long and 150-900 m wide (avg. 370 m) and covers a surface area of about 2.600.000 square meters, having depths of approximately 40 m at the mouth to 1 meter at the upper end. Once a famous promenade of the Ottoman Empire (i.e. Tulip Age: 1718-1730 A.D.), the Golden Horn Estuary has been subjected to an alarming increased of human interference during the last five decades of various types, such as waste disposal, accelerated runoff/erosion, damming, and river control. This has attracted the attention of many researchers in this coastal part of Turkey.

Various meteorological and oceanographic background information was provided in a "Ma-

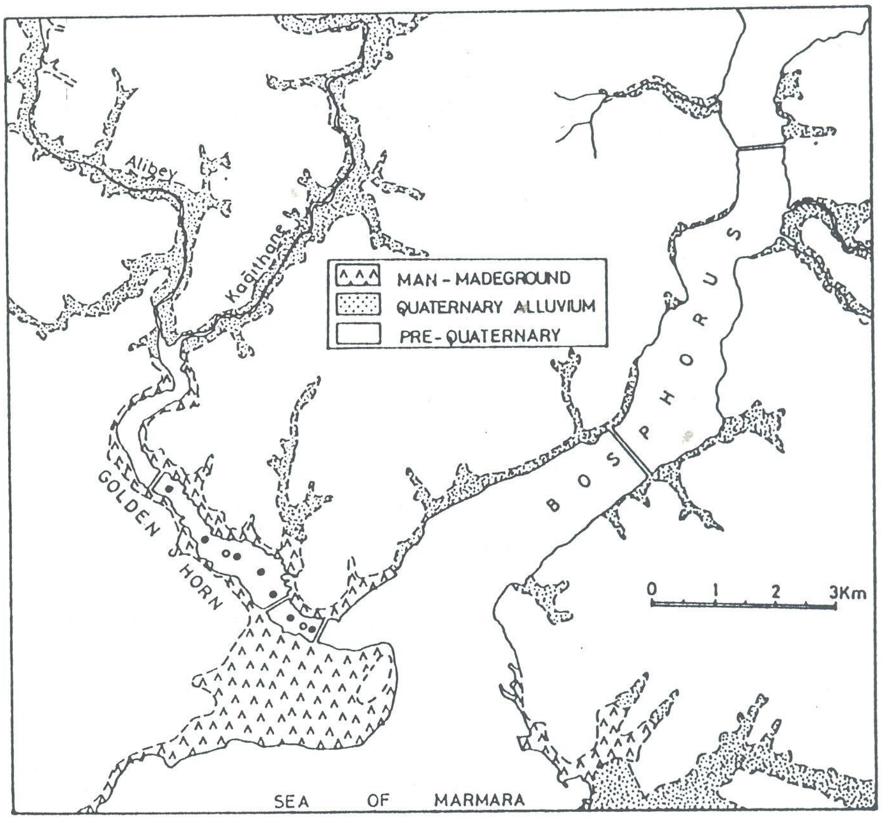

Fig. 1 - Study area, the Golden Horn and its surrounding. The filled circles indicate sampling stations of this study and the open circles are from DAMOC (1971).

ster Plan and Feasibility Report for Water Supply and Sewerage for the greater Istanbul Region (incl. Golden Horn)" (DAMOC, 1971). Later, in 1976 several papers were presented at a national symposium on the Golden Horn held at the Bosphorus University, Istanbul, with emphasis on chemical, physical, environmental and geotechnical aspects of this estuary (Artüz and Korkmaz; Balci; Baykut; Çekirge; Durgunoglu; Güçlüer and Dogusal; Kumbasar et al.; Peynircioglu; Sayar; Utkan; Yalçinlar, 1977a and b). In recent years, a considerable number of multidisciplinary investigations have concentrated upon the health of the Turkish straits, including that of the Golden Horn Estuary (e.g Saydam et al., 1986; Baştürk et al., 1988; Özsoy et al., 1988). Bottom sediments from the Golden Horn were also investigated with emphasis on both organic (Saydam et al., 1986; Ünsal, 1988) and inorganic (Erdem, 1988) pollution in the region.

This paper discusses the results on parameters obtained from sediments and suspended

Table 1 - Results on the physical and chemical analysis of surface bulk sediments in the Golden Horn Estuary. Textural classification according to Shepard (1954).

Sampling stations	Depth (m)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Mud (%)	$CaCO_3$ (%)	Org. C (%)	Texture
H2	41	9	63	20	8	72	9	3.84	gravelly mud
H6	38	21	73	5	1	94	11	4.74	clayey silt
H10	37	19	70	9	2	89	14	5.49	clayey silt
H14	31	12	74	10	4	86	14	5.04	clayey silt
H18	15	10	58	21	11	68	12	5.04	gravelly mud
H22	7	9	64	21	6	73	11	5.42	gravelly mud
H26	3	15	84	1	-	99	14	3.17	silt

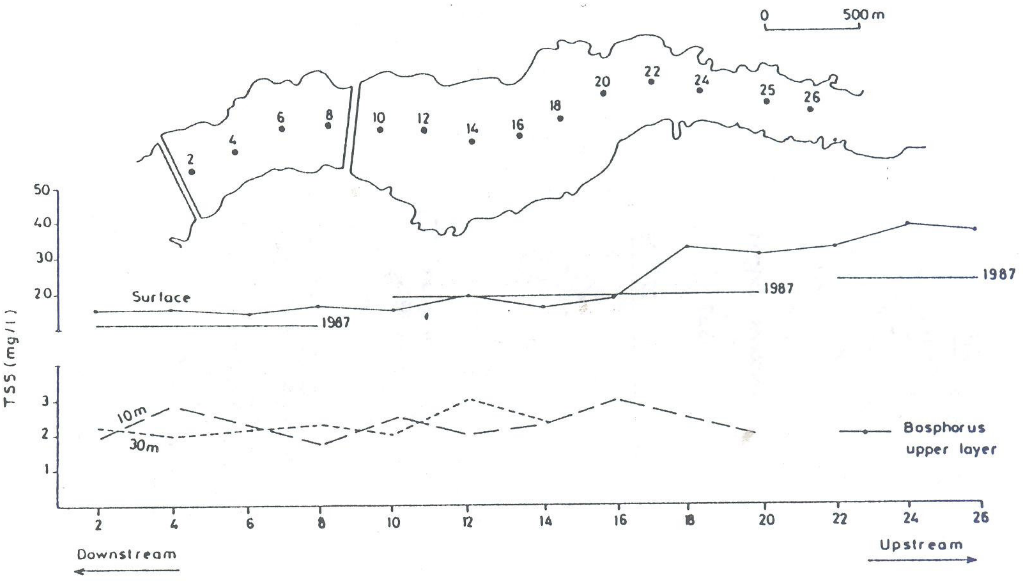

Fig. 2 - Total suspended solid concentrations of the Golden Horn waters, at stations 2 through 26, from O (surface), 10 m and 30 m depths. Note the high TSS values at/near the surface, due to increased influxes from land-based, biogenic, and anthropogenic sources. Data compiled from Saydam et al. (1986) and Baştürk et al. (1988).

matter of the Golden Horn Estuary in the light of several other oceanographic factors, with the aim of determining the mechanisms controlling modern sedimentation processes in this estuary. No other work of this kind was known to the authors.

2. Methods and materials

Surface sediments were collected with a grab at seven stations in the Golden Horn from depths of 2 to 41 m (Fig. 1; Table 1), and were subjected to grain size, organic carbon and carbonate determinations. A total of 138 suspended matter samples collected (Fig. 2) during the R/V Bilim cruises in the Golden Horn in 1987 were examined under the binocular-microscope for their textural and genetic characteristics.

Clay (< 0.002 mm), silt (0.002-0.063 mm), sand (0.063-2 mm) and gravel (> 2 mm) fractions of the sediment samples were separated using standard procedures (sieve plus pipette; Folk, 1974). For sediment classification, both granulometric (Shepard, 1954; Folk, 1974) and genetic (Lisitzin, 1986) compositions were used. Total carbonate contents were determined gasometrically by treating the dried and ground bulk sample with HC1 (after Müller, 1967). Organic carbon determinations (wet-combustion) were made according to the analytical procedures by Gaudette et al. (1974).

3. Hydrographic and geological setting

In the Golden Horn, the particular characteristic of the circulation are governed by the volume and rate of flow of the fresh water (runoff-rainfall), brackish water (from the Black Sea), and saline water (from the Mediterranean Sea) entering the estuary; the size and shape of the basin; and the effects of winds. The region is of low tidal range. Physical and chemical conditions in the Golden Horn Estuary waters have been investigated by several authors (DAMOC, 1971; Artüz and Korkmaz, 1977; Baykut, 1977; Durgunoglu, 1977; Güçlüer and Dogusal, 1977; Utkan, 1977; Saydam et al., 1977; Baştürk et al., 1988; Özsoy et al., 1988) and the major characteristics are summarized below.

Salinity, temperature and dissolved-oxygen distributions in the water column of the Golden Horn (Fig. 3) reveal their sources to be mainly from the Strait of Bosphorus, where a two-layer

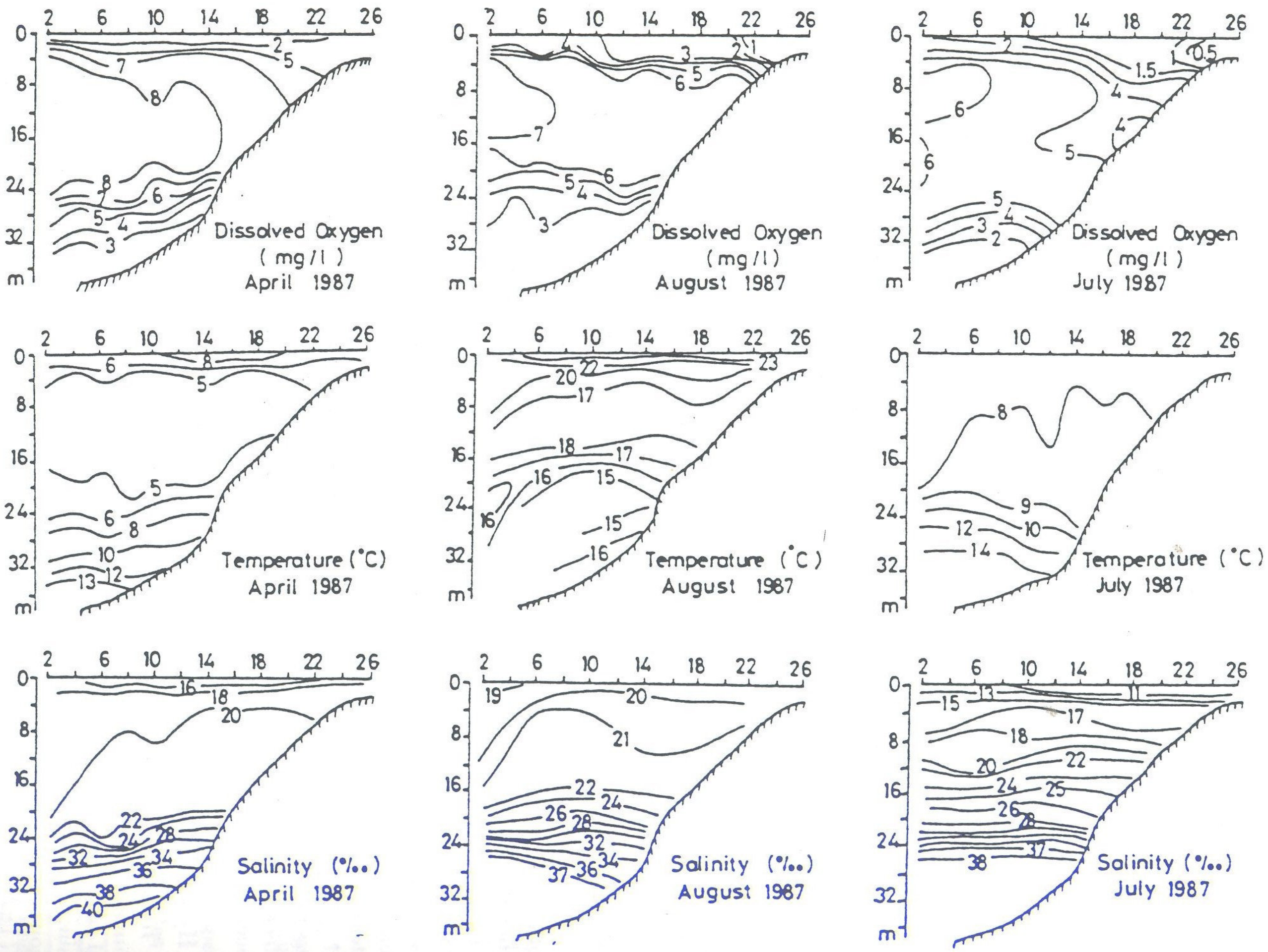

Fig. 3 - Salinity, temperature, and dissolved-oxygen transects along the Golden Horn Estuary (after Özsoy et al., 1988).

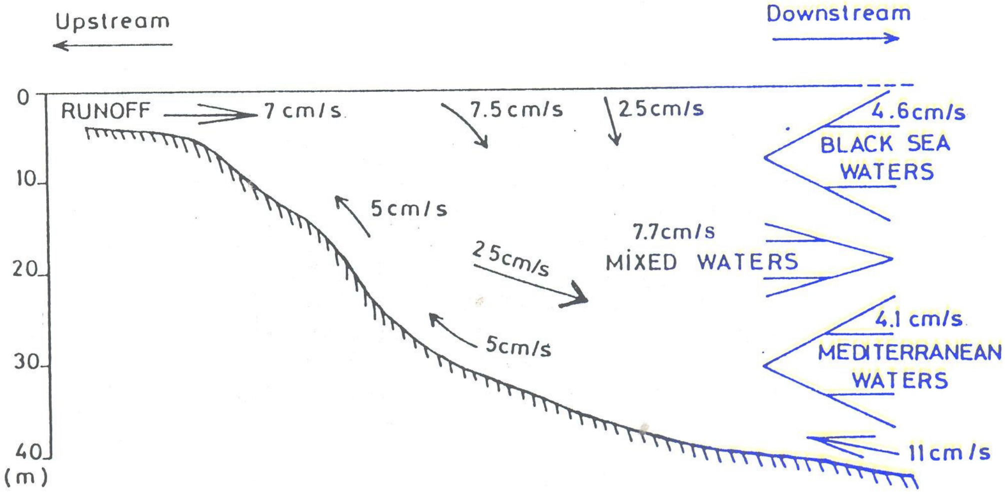

Fig. 4 - Prevailing water movements in the Golden Horn. Note the inflowing Black Sea and the Mediterranean Sea waters and the associated current velocities. Reproduced from data by DAMOC (1971), Artüz and Korkmaz (1977), Güçlüer and Dogusal, 1977), and Saydam et al. (1986).

flow exists; an upper layer outflow of Black Sea origin (Black Sea waters: 18-21 ppt salinity) and a bottom layer inflow of Mediterranean Sea origin (Marmara Sea waters: 36.5-37.5 ppt salinity). The interface between the Marmara inflow and the Black Sea outflow in the Strait of Bosphorus is usually located at 20-25 m depths; however, this level is subject to some changes due to variations in the meteorological conditions. In the Golden Horn, this leads to a three-layer flow system. Either Bosphorus or Black Sea waters flow into the Golden Horn over the surface, from 0-15 m depths; and below the 20-25 m water depths, a bottom inflow carries either Marmara Sea or Mediterranean water, correspondingly, along the Golden Horn (Fig. 4). The upstream movements and circulation of waters in the Golden Horn results in mixing of the inflowing surface and bottom layers so that the mixed waters flow out seaward as the intermediate waters from some 15-25 m depths (Fig. 4). Velocities of the surface and bottom currents are, on the average, 4-5 cm/s, whilst the intermediate outflow reaches higher speeds of up to 7.7 cm/s. although current velocities down to 2 cm/s, or even less than that are measured in the inner estuary (Figs. 4 and 5).

Hydrographic investigations also showed the presence of a distinct, uppermost water layer of about 2-3 m in thickness extending over the Bosphorus inflow, probably due to the blocking effect of the Galata Bridge pontoons (at the mouth of estuary) and to increasing waste discharges. The sources of fresh water in the Golden Horn include runoff and rainfall which usually outflow at the surface.

The existence of the two principal water bodies flowing into the Golden Horn can best be shown in terms of salinity profiles (Fig. 3): the salinity in the upper layer generally varies from about 18 to 20 ppt, with the exception of values as low as down 10 ppt in the uppermost zone due to increased rainfall and runoff; and the salinity of the bottom layer ranges between 38 and 39 ppt. Thus, the extent of the intermediate water changes between 20 and 38 ppt depending on the meteorological conditions.

The dissolved oxygen distribution in the estuary (Fig. 3) shows differences within the upper layer; the uppermost (top 2-3 m) zone is commonly depleted in dissolved oxygen content (0.5-3 mg/l) as a result of increased pollution; and the layer below has a relatively high content (3-8 mg/l) due to the dominance of the Black Sea waters. The bottom layer originating in the Sea of Marmara shows dissolved oxygen contents in the range between 2 and 6 mg/l. Due to high rates of accumulation of both natural and anthropogenic materials and to the lack of strong currents, dissolved oxygen contents of the Golden Horn waters decreased considerably, and even locally anoxic bottom conditions (H_2S-bearing) may appear.

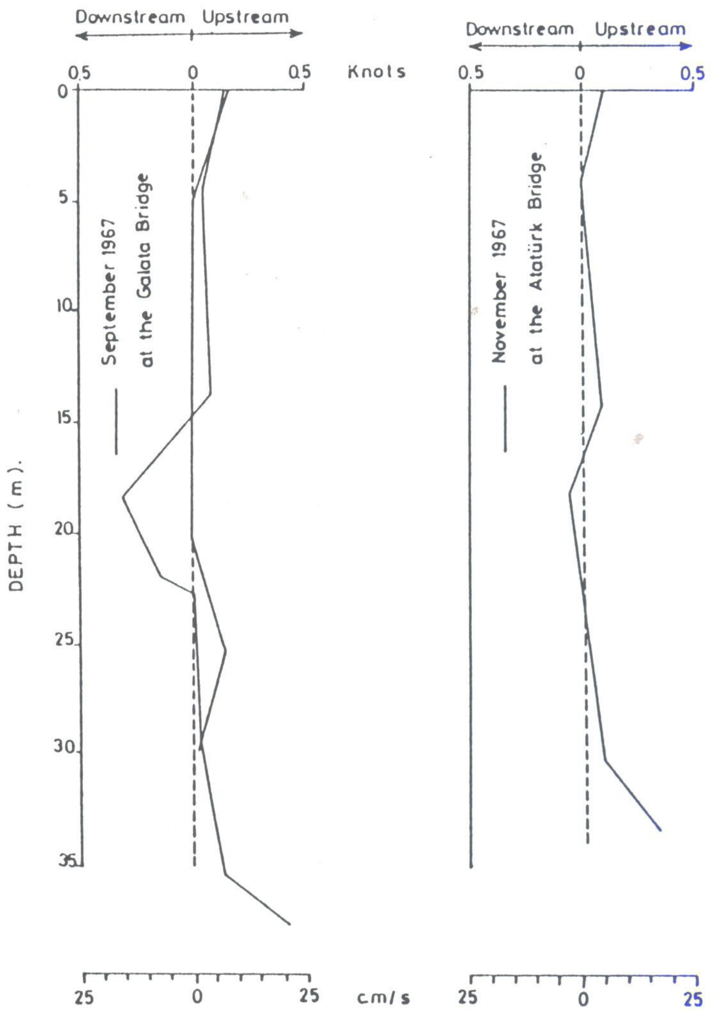

Fig. 5 - Current velocity profiles obtained near the mouth of the Golden Horn Estuary (after DAMOC, 1971).

The geological evolution of the Golden Horn Estuary has been investigated by several workers (Yalçinlar, 1977a; Sayar, 1977; Ercan et al., 1987; Meriç at al., 1988) and there is a general agreement that the geological evolution of the Golden Horn resembles to that of the Strait of Bosphorus. The available data shows that the present shape of the Golden Horn must have originated from a pre-existing, erosional river valley which was repeatedly submerged during the interglacials and exposed during the glacials as the sea level rose. According to definitions by Dyer (1973) and Fairbridge (1980), the Golden Hornd can be classified as a "drowned-river valley" or "coastal plain" type of estuary. Most of the Recent drowned-river valleys in the world were formed during the Flandrian transgression which ended about 3000 B.C. (Aston and Chester, 1976). The Golden Horn seems to be following an old dissected and faulted, graben-like structure which developed during the late Tertiary (probably Pliocene) or much later during the early Pleistocene. The oldest known geological formations in and around the Golden Horn, now partly exposed, include occurrences of graywackes, schists and limestones of upper Paleozoic age (bedrock), which are locally overlain by Neogene (mostly Pliocene or Miocene) sand, gravel, clay and marl beds (Fig. 6). Black and organic-rich, muddy sediments overlying the Recent alluvium deposits cover most of the Golden Horn floor today (Fig. 6). Apart from this, man-made ground materials of wide ranging in origin commonly oc-

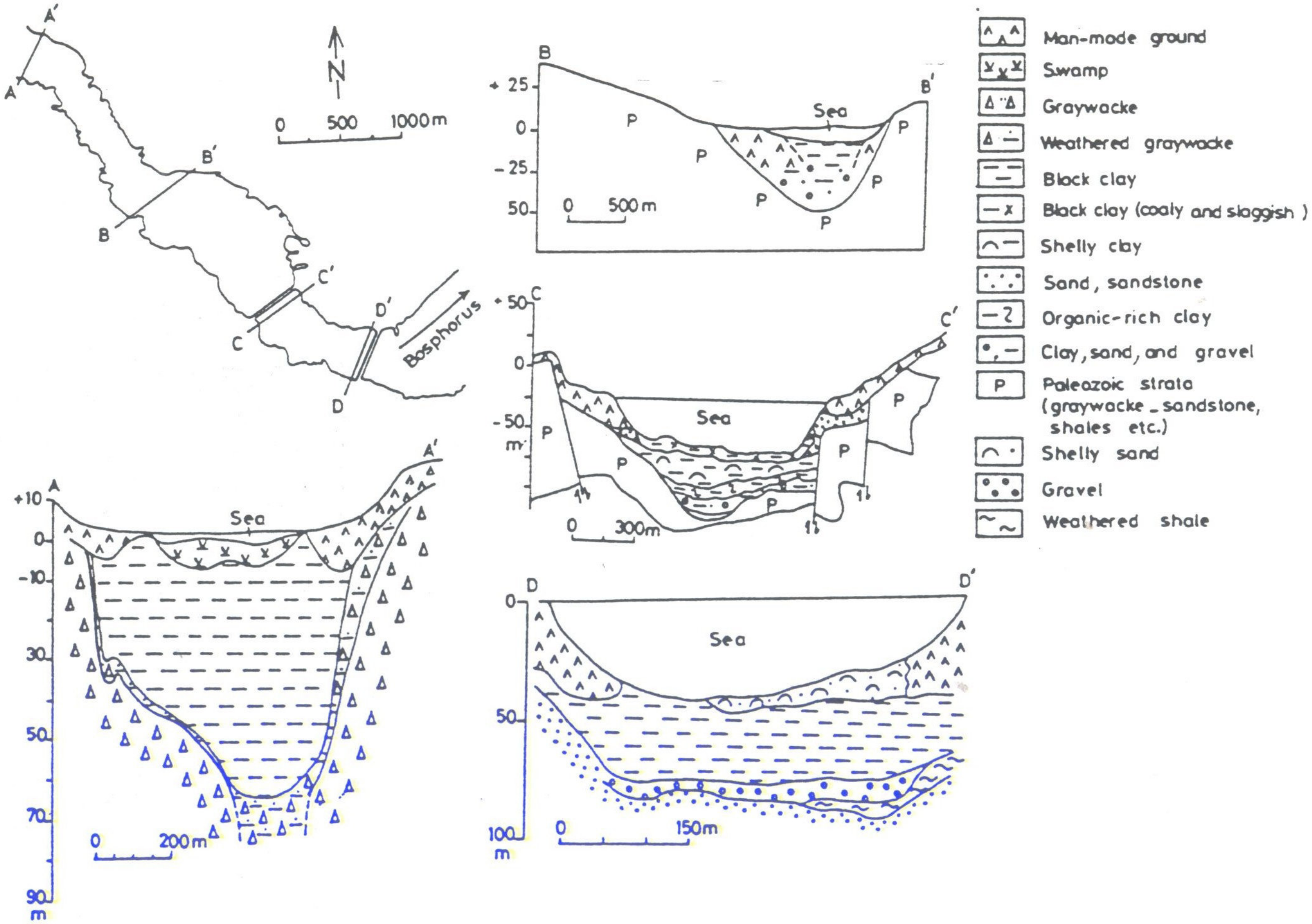

Fig. 6 - Typical geologic cross-sections of the Golden Horn. Note: the Paleozoic bedrock mostly represented by graywacke: the swamp conditions in the upper end; the anthropogenic influenced layers; and the more sandy and shelly materials near the Strait of Bosphorus. Man-madeground is present on the slopesides. Reconstructed from data by DAMOC (1971; A-A'), Sayar (1977; B-B'), Meriç et al. (1988; C-C'), and Özbek (pers. commun. 1989).

cur along both of the estuary.

The majority of the sedimentary materials to be deposited on the floor of Golden Horn comes from land erosion (Durgunoglu, 1977) through the rivers "Alibey" (54.000 m ^{3}/y) and "Kagithane" (5100 m ^{3}/y) (after Çekirge, 1977), but additional material is being deposited to a lesser degree from local domestic and industrial sources. From this, a sediment accumulation rate of up to 6-10 cm per year was estimated for the Golden Horn (Kor; in Balci, 1977).

4. Results and discussion

Various sedimentary and suspended-load parameters obtained in this study are discussed in the light of their geological, biological, hydrological, and anthropogenic aspects and the relationships found are described below.

4.1 Suspended matter distribution

The total suspended solid (TSS) contents of the Golden Horn waters have already been reported in Saydam et al. (1986) and Baştürk et al. (1988) (Fig. 2). The maximum concentrations of TSS (10 to 40 mg/l) were found in the surface waters of less than 1 m depth, around late winter and early spring, and associated with the heavy rainfall in this region. In contrast, the amount of suspended material in the underlying 10 and 30 m water layers was remarkably low (1 to 3 mg/l), as observed during late summer and early autumn. Low suspended matter concentrations, as compared with those from the adjoining open seas (0.1 to 3 mg/l in the Black, Marmara, Aegean and Mediterranean seas; after Emelyanov and Shimkus, 1972; Shimkus and Trimonis, 1974; Baştürk et al., 1988; Salihoglu et al., 1988), reflect more or less open-marine conditions in the lower water layers (around below 10 m) of the Golden Horn Estuary. On the other hand, the highest concentrations of suspended solids in the surface layer, especially in the upper estuary, and the generally decreasing suspended solid concentrations towards the mouth, all indicate the intensity of suspended-load delivery to the Golden Horn from land-based sources - a common feature of many estuaries (e.g., Duinker, 1980). In the underlying water layers of 10 and 30 m depths, the TSS levels were rather low and almost constant throughout the estuary, as a result of the active role of currents.

Results of microscopic studies of suspended matter samples in this work showed great variations in the nature of suspension loads (Fig. 7). In the surface layers of the Golden Horn (0-1 m), silty and organic-rich clay was the most abundant type of suspension, usually yellowish-brown to dark-brown in colour.

The suspended organic matter in this uppermost water layer must be largely represented by the terrigenous humic matter carried by land drainage (Saydam et al., 1986), and to a lesser degree by the organic waste substances derived from industrial and municipal sources. A close relationship between the humic and total suspended solid concentrations in the Golden Horn is shown in Figs. 2 and 8, where both parameters attained their maximum levels concentration with decreasing tendency towards the mouth of the estuary.

The most abundant type of suspension was the fecal-pelletic silt commonly occurring in the underlying waters at depths greater than 10 m (Fig. 7), although some occurrences were also observed in the surface layer. Although the ingestion of suspended material by planktonic and benthonic animals leads to particle aggregation in the form of fecal pellets, in general, the fecal pellets are known to be the excretory matter of invertebrates (mainly gastropods and worms) (e.g., Wetzel, 1937, Schäfer, 1953; Reineck, 1972). The fecal pellets of the Golden Horn waters occurred in different shapes (spherical, elongated, and ellipsoidal) and sizes (loosely consolidatet, from medium-silt to fine-sand) and some of them were more or less decomposed so that their clayey and silty components could be recognized.

The recognition of the fecal-pellet producing animals in the Golden Horns seems to be rather difficult at this stage, but several organisms (both suspension - and deposit - feeders) must be involved in the production of such excretory matter. Furthermore, these fecal pellets may possibily have been moved from the place of genesis through bioturbation (Schäfer, 1953), river-borne sediment transportation (Wagner, 1968), up and down biotic movements (Wolf, 1980), or by the active in-and out-flow currents. The latter may deserve attention because of

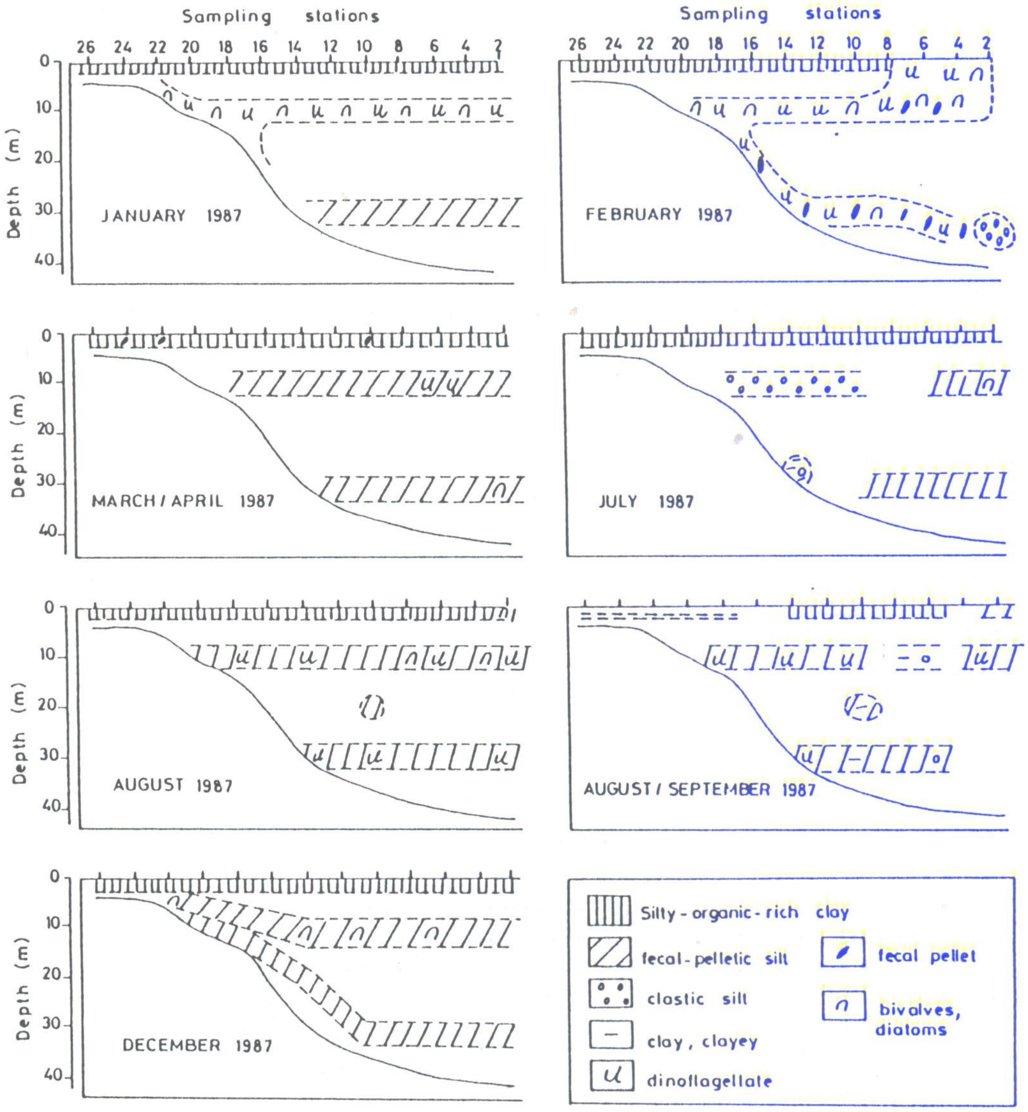

Fig. 7 - Facies distributions and seasonal variations in suspended loads of the Golden Horn waters (for details see text).

the prevailing currents in the Golden Horn (2 to 7 cm/s; s. Figs 4 and 5) which can transport silt-to fine-sand materials long distances, according to the well-known Hjulstrom's diagram (Fig. 9).

Next in importance was the occurrence of pelecypodal-dinoflagellate silt with some diatom species, mostly at 10 and 30 m water depths during January and February, but also to a lesser extent in August and September (Fig. 7). The appearances of the biogenic layers are in agreement with data from Uysal (1987) who found maximum diatom and dinoflagellate blooms in the Golden Horn and its adjoining waters for the period of January. Although considerable variations both in species compositions and abundances of diatoms and dinoflagellates were observed throughout the year, dinoflagellates were represented by Ceratium and Nuctila, and the diatoms by their centric forms (Uysal, 1987). Other dinoflagellate species are used for lithostratigraphic correlations in the Black Sea (Wall and Dale, 1974).

Fig. 7 also shows a clay dominance in the surface layer suspension, whereas silt dominates

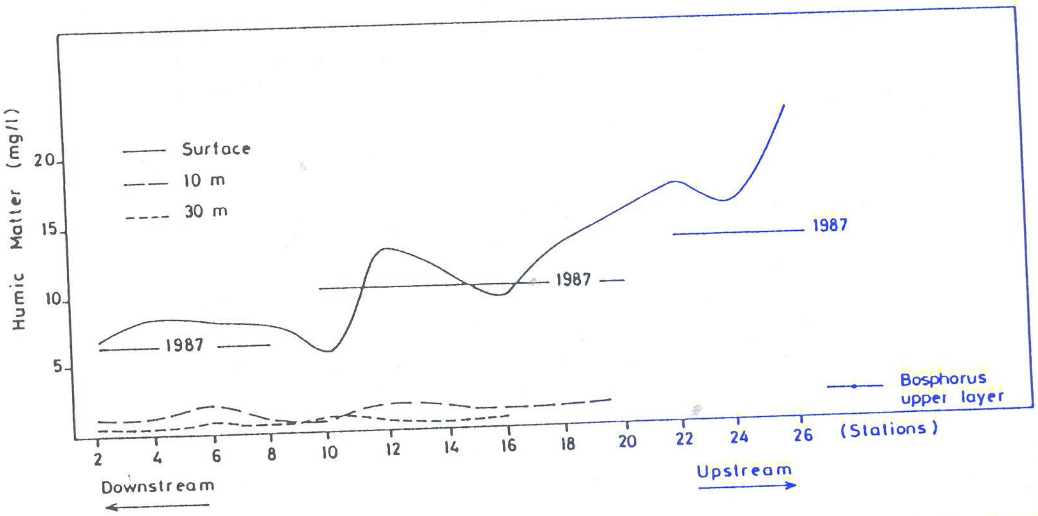

Fig. 8 - Humic matter concentrations in the Golden Horn waters at 0 (surface), 10m, and 30m depths. Note the high HM levels at the surface with an increasing tendency towards the upper end of the estuary where maximum land-based materials are expected. Data compiled from Saydam et al. (1986) and Baştürk et al. (1988).

in the underlying waters of the Golden Horn. It is obvious that the different behaviour of clayey and silty suspensions in an estuary is essentially related to their different physico-chemical properties. For example, clay minerals (Carroll and Starkey, 1960), humic substances (Hair and Basett, 1973), and hydrous iron oxides (Swanson et al., 1972; Burton, 1976) are subject to flocculation in the early stages of estuarine mixing of fresh and saline water, usually below a salinity of about 4ppt (Dyer, 1979). Thus, accumulation and probably sedimentation of large quantities of clay minerals and humic substances is expected in the upper estuary. Otherwise, they can be transported away over the surface waters until they are sufficient in size and shape to settle out of suspension; or are taken up by the fecal-pellet-producing organisms (Dyer, 1979); and/or are transported back towards the upper estuary by inflowing undercurrents. Data so far obtained in this study suggests all the above processes are taking place in the Golden Horn to varying intensities.

The contribution of silt to the suspended loads of the Golden Horn is more likely determined to a great extent by the particular circulation and biological conditions prevailing there. The latter involves uptake of silt by the fecal-pellet-producing organisms, as is the case for the clay-sized materials. The suspended matter samples of this study also contained soft tissues of various marine organisms, and both organic and inorganic waste products of varied origin, but in lesser amounts.

4.2 Textural character and transport modes of the sediments

Terrigenous mud with a dominance of silt is the major sediment type covering the floor of the Golden Horn today (Fig. 10), except for its sideslopes where coarser materials (collapse products from the nearby madeground) are deposited.

Clay percentages varied between 9 and 21; silt from 58 to 84; sand from 1 to 21; and gravel from less than 1 to 11% of the bulk sample (Fig. 10; Table 1). Clay-sized materials, although not determined here, are probably composed of clays, hydroxides and organic matter, as in many estuaries elsewhere (Postma, 1980). Of course, in the Golden Horn, it seems that part of the finer-grained material is supplied by human interference (pollution, deforestation etc.). In the silt, lithic grains (quartz, feldspars, chert etc.) were the most abundant type of material, but anthropogenic substances such as coal and slag particles also occurred in significant amounts. Sand - and gravel - sized fractions were generally made up of lithic grains, organic detritus (wood and plant remains in the form of fibres, flakes, branches and aggre-

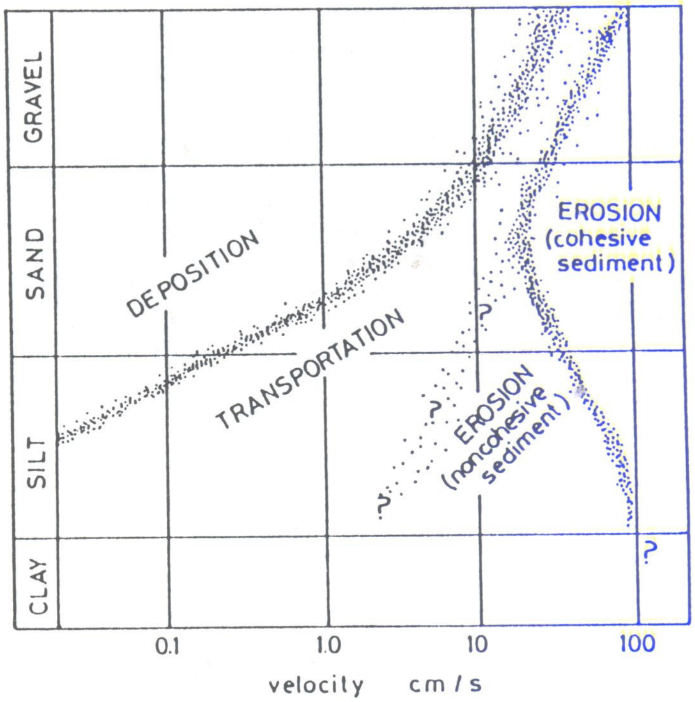

Fig. 9 - Schematic Hjulstrom diagram showing approximate relationships between current velocities and behaviour of stream-bed sediments (from Lewis, 1984).

gates), coal and slag particles, and madeground infill (bricket, earth debris, beton etc.).

Such a varied origin of the admixtures in the grain-size fractions also resulted in the absence of a relationship between grain-size distribution of samples and the topography (Fig. 10), although a tendecy to a decrease in the mean grain size with distance from the upper end of the estuary was excepted. It therefore appears that the circulation pattern is an important factor in determining the sediment dispersal within the estuary, as was also discussed for the modes of distribution of suspended materials in the foregoing section. The importance of density stratification for the favoured accumulation of fine-sediments within the estuaries has been reported by Barner (1965), Werner (1968), Artüz and Korkmaz (1977), and Postma (1980).

One would expect that sediment mixtures introduced into the upper Golden Horn Estuary at depths less than 7 m via the two major rivers, would become separated into mainly silt and clay, whilst sand would enter the estuary at times after heavy rainfalls. In accordance with the hydrodynamic relations between settling velocities and grain size of moving particles (Fig. 11), the horizontal current velocities at the surface of the Golden Horn (5-10 cm/s; s. Fig. 4), (under optimum conditions) are able to carry clay-sized materials up to 7 km toward the mouth of the estuary before settling to the bottom. However, the generally decreasing clay to org. C ratios in the sediment samples, from 4.7 at station H26 to 1.6-2.4 at stations H22-H14, presumably indicates the flocculation and deposition of substantial amounts of clay at the head of the estuary, whilst remaining clays together with various kinds of organic substances (which are or a much lesser density) move seaward, unless moving back under the influence of inflowing surface currents from the Strait of Bosphorus. Again, slightly high clay to org. C ratios (2.3-3.5) at the outer estuary seem to be cause by a complex of processes which may include the increased contribution form various natural and anthropogenic sources, entrapment by the Galata and Atatürk Bridges, and the inflowing Black Sea and Marmara currents.

At the head of the estuary, in areas of shallow water depth (3 m) where the horizontal surface currents have velocities of approx. 7 cm/s, silt-size particles can be carried no more than a few hundred meters (s. Fig. 11). Thus, the maximum silt contents are found in the se-

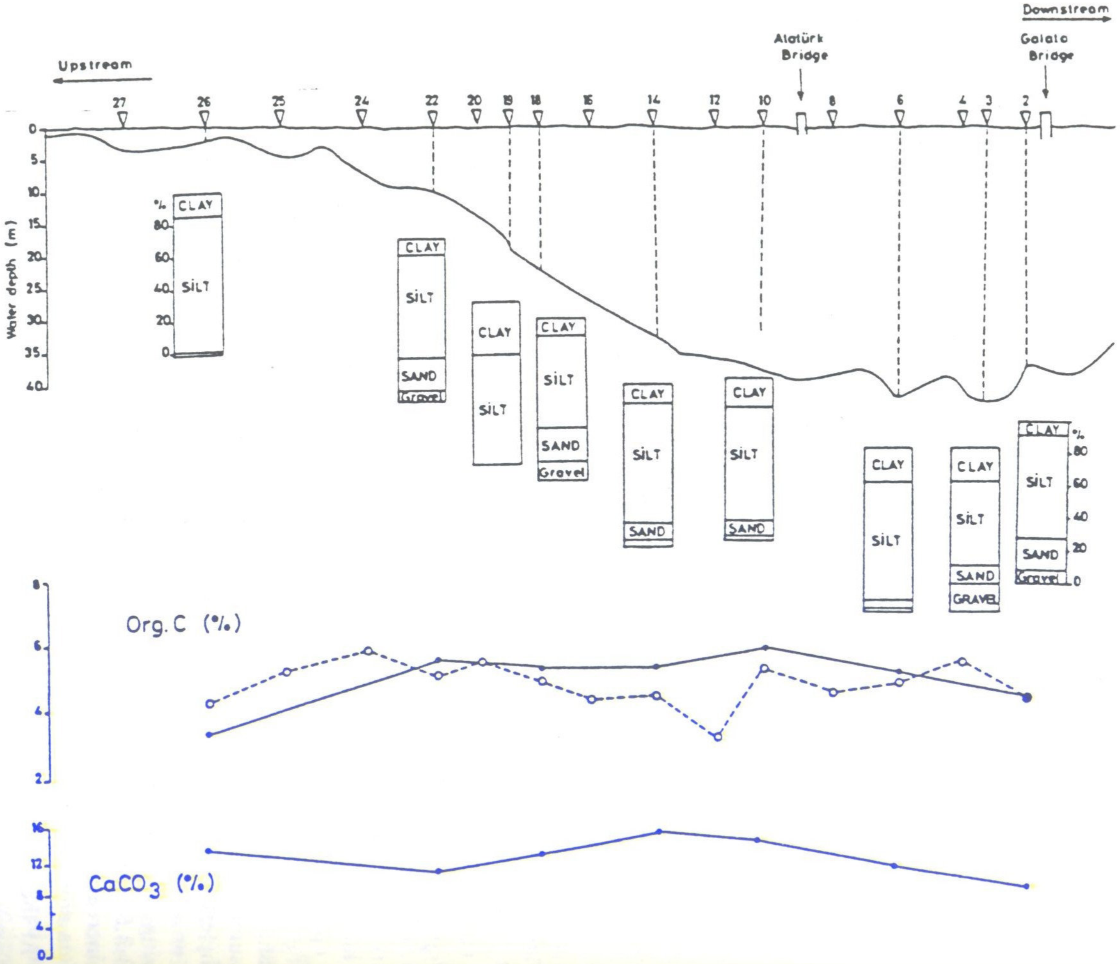

Fig. 10 - Grain size, organic carbon and $CaCO_3$ distributions in surface bottom sediments from the Golden Horn. No relationships between the grain size and bottom topography is apparent; however, mud with a silt dominance is widely distributed. Coarse-grained materials are composed of terrigenic, biogenic and anthropogenic substances (see text for details). Organic carbon data (open circles) by Erdem (1988) is also given for comparison.

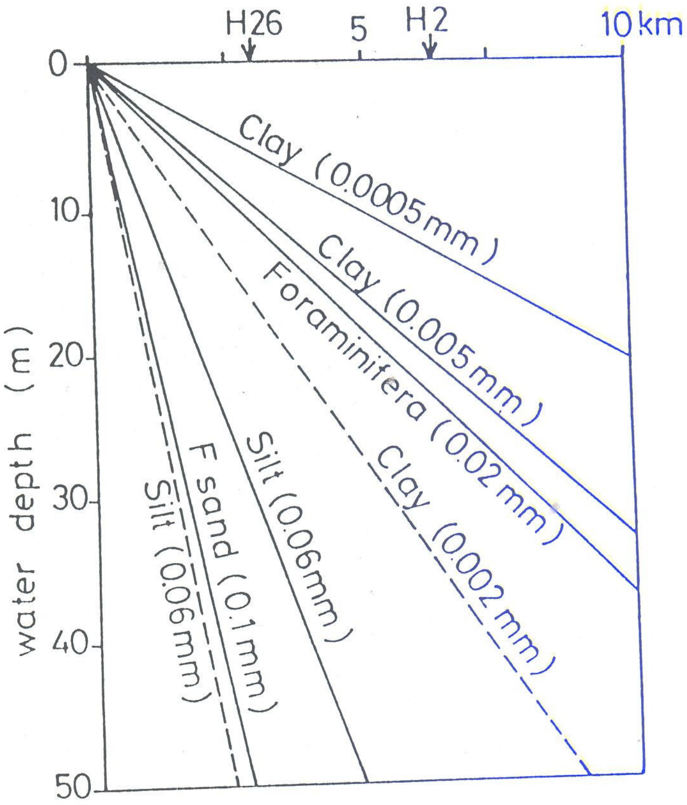

Fig. 11 - Settling velocities of various sized particles in currents flowing horizontally at 5 cm/sec (dashed lines) and 10 cm/sec. Distance travelled by a particle during its settling time is also shown (slightly modified after American Geological Institute, 1967). Notice the preferred sedimentation by silt particles on the floor of the Golden Horn Estuary between the sampling stations H26 (3 m water depth; upstream) and H2 (41 m water depth; downstream).

diment samples from the head of the estuary (84%; St. H 26). However, transportation and deposition of silt particles in the middle and outer estuary apparently follow different patterns, mainly due to their much higher settling velocities. Assuming that optimum conditions occur in the Golden Horn Estuary, with no significant water inflow from the open sea, namely from the Strait of Bosphorus; then, the prevailing currents at velocities of 5-10 cm/s - in accordance with the hydrodynamic relations (Fig. 11) - would cause most of the silt particles to settle out within the estuary. Besides, silt particles - when they reached the outer estuary due to active meteorological influences - would have been markedly trapped and turned back into the estuary by the inflowing Black Sea and Marmara currents. Consequently, silt will be the dominant particle to be deposited in the Golden Horn.

Muddy sediments of the Golden Horn floor had a blackish colour and smelt of H_2S, reflecting anoxic conditions within the sediment at the sampling stations.

4.3 Carbonate and organic carbon distribution in sediments

The total carbonate contents (%$CaCO_3$) were rather low, varying between 9 and 15% by dry weight (Fig. 10; Table 1). Microscopic examination showed calcareous shell fragments from organic remains to be the main fraction of the carbonate contents in the sediments studied, among which the molluscs Ostrea, Cardium, Nassa, and Mytillus should be present (Sayar, 1977).

Only minor amounts of calcareous polychates tubes were found in the samples, although they are the most common benthic organisms in the Golden Horn (Saydam et al., 1986). Unsal (1988) showed that some species of these polychates can be used as indicators of the industrial

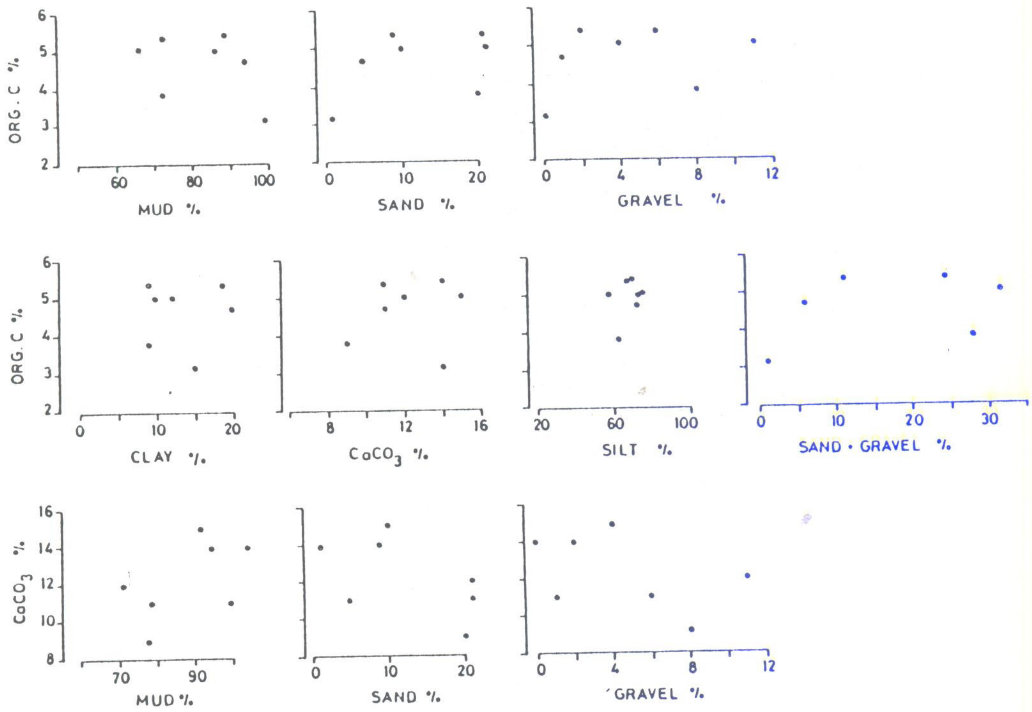

Fig. 12 - Plots of grain size, carbonate and organic carbon percentages. Note the lack of relationships among the parameters due to the wide range of sources of the sediment admixtures.

pollution in this region. A close relationship between grain-size and $CaCO_3$ distributions was not observed (Fig. 12), probably due to the narrow limit of the $CaCO_3$ values.

The organic carbon contents of bottom sediments in the Golden Horn ranged between 3.7 and 5.49% by dry weight (Fig. 10; Table 1). These values were somewhat higher than those reported by Erdem (1988; Fig. 10) which is obviously attributable to the use of different sample preparation techniques. However, in general, sedimentary organic carbon percentages found in the Golden Horn Estuary are significantly higher than those reported elsewhere in the adjoining Sea of Marmara (up to 1.80%; Evans et al., 1988; Ergin and Evans, 1988) and the Black Sea (avg. 3.02%; Volkov and Fomina, 1974). Such high C_{org} contents of the Golden Horn sediments are unlikely to be solely due to the high rate of marine-organic production in this region. Obviously, the presence of high rates of sedimentation by both organic and inorganic substances in relatively shallow water of the Golden Horn prevents rapid decomposition and oxidation of the organic matter deposited, as is the case in many estuaries or coastal inlets (Cato, 1977; Patchineelam, 1977; Romankevich, 1984; Prouse and Hargrav, 1987; LeBlanc et al., 1989; Ergin, 1990). Also, of course, particular organic substances from industrial and domestic waste discharges, as well as from the collapse materials of nearby man-made slopesides, would cause an enrichment in the organic matter of Golden Horn sediments.

The varied origin of organic substances and grain-size fractions in the samples also resulted in the absence of significant relationships among these parameters (Fig. 12).

5. Conclusions

Results from suspended matter and sediment analyses obtained in this study indicate that a great part of bottom sediments must be derived from land erosion and carried into the estuary by the two major rivers. This is also inferred from the generally seaward-decreasing concentrations of total suspended solids in water samples.

The elongated shape of the estuary (7 km long); the three prevailing distinct water currents

(5-10 cm/s) moving in opposite directions; the relatively shallow water depths (3-40 m); and the high settling velocities for silt-size particles, all explain the high silt percentages found in the sediment samples.

Favoured accumulation of clays at the head of estaury is marked by the occurrence of: a) high TSS concentrations in water; and b) high clay/org. C-ratios in sediments. Part of the clay minerals is carried out by the surface currents, associated with various organic substances of minimum settling velocities.

Petrographic investigations reveal both natural and anthropogenic sources as the contributors to the bottom sediments, particularly in the coarser-grained fraction.

Low carbonate (9-14% $CaCO_3$) and organic-rich (3.17-5.49% Org. C) terrigenous mud is the most widely distributed sediment type in the Golden Horn Estuary. The blackish colour and strong smell of H_2S reflect post-depositional, anoxic conditions within the sediment.

In the suspensions of the Golden Horn waters, three sedimentary facies are recognized: silty and organic-rich clay; fecal-pelletic silt; and pelecypodal-diatomaceous-dinoflagellate silt. The distributions of these different biofacies are a response to the biogenic productivity in the estuary - both qualitatively and quantitatively - under the partial influence of the inflowing Bosphorus waters which originated in the less saline and organic-rich Black Sea, and saline and relatively organic-poor Mediterranean waters.

The results obtained in this study show that more work has to be done for a better understanding of the mechanisms and factors controlling modern sedimentation in this estuary. Future research needs therefore involve the deployment of several sediment traps, at least three of them, at the head, middle and the mouth of the estuary.

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References

American Geological Institute, 1967: *Investigating the Earth*. Hougthon Mifflin Company, Boston.

Artüz M.I. and Korkmaz K.; 1977: *Haliç' in kirlenmesinde su hareketlerinin rolü (The role of water circulation on pollution of the Golden Horn)*. In: Proc. National Symposium on the Golden Horn, Bosphorus University, Istanbul, February 1976, pp. 75-96 (in Turkish).

Aston S.R. and Chester R.; 1976: *Estuarine Sedimentary Processes*. In: Estuarine Chemistry, Burton J.D. and Liss P.S. (Eds.), Academic Press, London, pp. 37-52.

Balci N.; 1977: *Haliç' in Dolmasi ve Kirlenmesinde Alibey ve Kagithane Derelerinin Rolü (The role of the Alibey and Kagithane creeks in filling and pollution of the Golden Horn.* In: Proc. National Symposium on the Golden Horn, Bosphorus University, Istanbul, February 1976, pp. 279-286 (in Turkish).

Barner U.; 1965: *Untersuchungen an Sedimenten vom Sudausgang des Grossen Belts*. Meyniana, Kiel, 15, 1-28.

Baştürk O., Yilmaz A., Saydam A.C. and Salihoglu I.; 1988: *Oceanography of the Turkish Straits-Second Annual Report-, Vol. II: Health of the Turkish Straits: Chemical and Environmental Aspects of the Sea of Marmara and the Golden Horn*. Institute of Marine Sciences, METU, Erdemli-Içel (Turkey), 130 pp.

Baykut F.; 1977: *Cevre Kirlenmesi ve Haliç (Environmental Pollution and the Golden Horn)*. In: Proc. National Symposium on the Golden Horn, Bosphorus University, Istanbul, February 1976, pp. 75-96 (in Turkish).

Burton J.D.; 1976: *Basic Properties and Processes in Estuarine Chemistry.* In: Estuarine Chemistry, Burton J.D. and Liss P.S. (Eds.), Academic Press, London, pp. 1-36.

Carroll D. and Starkey H.C.; 1960: *Effect of seawater on clay minerals.* In: Clays and Clay Minerals, Ingersen E. (Ed.), Monograph No. 5, Earth Sci. Ser., Pergamon Press, pp. 80-101.

Cato I.; 1977: *Recent sedimentological and geochemical conditions and pollution problems in two marine areas in south-western Sweden.* Striae, 6, 158 pp.

Çekirge A.; 1977: *Istanbul Haliçinin Yagmur Suyu Drenaju Hakkinda Öneriler (Recommendations related to the rainwater discharge in the Golden Horn).* In: Proc. National Symposium on the Golden Horn, Bosphorus University, Istanbul, February 1976, pp. 263-265 (in Turkish).

DAMOC; 1971: *Master Plan and Feasibility Report for Water Supply and Sewage for the Istanbul Region.* Prepared by DAMOC Concertium, LA., California, Volumes I-III.

Duinker J.C.; 1980: *Suspended Matter in Estuaries: Adsorption and Desorption Processes.* In: Chemistry and Biogeochemistry of Estuaries, Olausson E. and Cato I. (Eds.), John Wiley & Sons Publ. pp. 121-151.

Durgunoglu T.; 1977: *Genel Rapor: Geçmişte Haliç ile ilgili Faaliyet (A Review: Previous Works on the Golden Horn).* In: Proc. National Symposium on the Golden Horn, Bosphorus University, Istanbul, February 1976, pp. 11-26 (in Turkish).

Dyer K.R.; 1973: *Estuaries: A Physical Introduction.* John Wiley & Sons Publication, London, 140 pp.

Dyer K.R.; 1979: *Estuarine hydrography and sedimentation.* Cambridge University Press, England.

Emelyanov E.M. and Shimkus K.M.; 1972: *Suspended Matter in the Mediterranean Sea.* In: The Mediterranean Sea: A Natural Sedimentation Laboratory, Stanley D.S. (Ed.), Dowden, Hutchinson & Ross, Inc. Pennsylvania, pp. 417-439.

Ercan A., Utku M. and Yilmaz M.; 1987: *Submarine Structure of Golden Horn by Geophysical Method.* Jeofizik, Ankara, pp. 145-153.

Erdem E.; 1988: *The distribution of trace elements in Golden Horn surface sediments.* Unpubl. M. Sc. Thesis, Institute of Marine Sciences, METU, Erdemli-Içel (Turkey), 89 pp.

Ergin M. and Evans G.; 1988: *Recent Sediments from the Sea of Marmara: Technical Report.* Institute of Marine Sciences, METU, Erdemli Içel (Turkey), 113 pp.

Ergin M.; 1988: *Pre-civilizational and civilizational layers of two sediment cores from the western Baltic Sea.* Boll. Oceanol. Teor. Appl., VIII, 1, 41-50.

Evans G., Erten H., Alavi S.N., Von Gunten H.R. and Ergin M.; 1989: *Superficial deep-water sediments of the Eastern Marmara Basin.* Geo-Mar. Lett., 9, 27-36.

Fairbridge R.W.; 1980: *The Estuary: Its Definition and Geodynamic Cycle.* In: Chemistry and Biogeochemistry of Estuaries. Olausson E. and Cato I. (Eds.), John Wiley & Sons Publ. pp. 1-35.

Folk L.R.; 1974: *Petrology of Sedimentary Rocks.* Hemphil Publications, Tulsa, Oklahoma, 182 pp.

Gaudette H., Flight W., Tones L. and Folger D.; 1974: *An inexpensive titration method for the determination of organic carbon in recent sediments.* J. Sed. Petrology, 44 (1), pp. 249-253.

Güçlüer S. and Dogusal M.; 1977: *Haliçte Fiziksel Oşinografik Durumun Incelenmesi (Physical Oceanographic Investigations in the Golden Horn).* In: Proc. National Symposium on the Golden Horn, Bosphorus University, Istanbul, February 1976, pp. 61-74 (in Turkish).

Hair M.E. and Bassett C.R.; 1973: *Dissolved and particulate humic acids in an east coast estuary.* Est. Mar. Coast. Sci., 1, 107-111.

Kumbasar V., Ülker R. and Kip F.; 1977: *Haliçte inşa olunmuş bazi yapilarin temel sistemleri (Foundation systems of some structures in the Golden Horn region).* In: proc. National Symposium on the Golden Horn, Bosphorus University, Istanbul, February 1976, pp. 375-390 (in Turkish).

LeBlanc C.G., Bourbonniere R.A., Schwarz H.P. and Risk M.J.; 1989: *Carbon isotopes and fatty acids analysis of the sediments of Negro Harbour, Nova Scotia, Canada.* Est. Coastal and Shelf Sci. 28, 261-276.

Lewis D.W.; 1984: *Practical Sedimentology.* Hutchinson Ross Publ. Stroudsburg, Pennsylvania, 229 pp.

Lisitzin A.P.; 1986: *Principles of geological mapping of marine sediments (with special reference to the African continental margin).* Unesco Reports in Marine Sciences, Paris, 37, 101 pp.

Meriç E., Sakinç M. and Eroskay O.; 1988: *Istanbul Bogazi ve Haliç Çökellerinin Evrim Modeli (Evolution Model of Bosphorus and Golden Horn Deposits, Istanbul.* Engineering Geology Bulletin, 10, 10-14 (in Turkish).

Müller G.; 1967: *Methods in Sedimentary Petrology.* Schweizerbart, Stuttgart, 263 pp.

Özsoy E., Oguz T., Latif M.A., Ünlüata U., Sur H.I. and Beşiktepe S.; 1988: *Oceanography of the Turkish Straits-Second Annual Report: Vol. I: Physical Oceanography of the Turkish Straits.* Institute of Marine Sciences, METU, Erdemli, Içel (Turkey), 109 pp.

Patchineelam S.R. and Forstner U.; 1977: *Bindungsformen von Schwermetallen in Marinen Sedimenten: Untersuchungen an einem Sedimentkern aus der Deutschen Bucht.* Senkenbergiana marrit., 9 (1/2), 75-104.

Peynircioglu H.; 1977: *Haliç Sahillerinde Temel ve Stabilite Sorunlari (Problems relating to foundation and stability of structures around the Golden Horn coasts).* In: Proc. National Symposium on the Golden Horn, Bosphorus University, Istanbul, February 1976, pp. 391-401 (in Turkish).

Postma H.; 1980: *Sediment transport and sedimentation.* In: Chemistry and Biogeochemistry of Estuaries, Olausson E. and Cato I. (Eds.), John Wiley & Sons Publ., pp. 153-186.

Prouse N.J. and Hargrave B.T.; 1987: *Organic enrichment of sediments in Bedford Basin and Halifax Harbour.*

Can. Tech. Rep. Fish. Aquat. Sci. No 1571: v+36 pp.

Reinech H.-E.; 1972: *Tidal flats.* In: Recognition of ancient sedimentary environments, Rigby J.K. and Hamblin W.K. (Eds.), Soc. Econ. Paleontologists Mineralogiste Spec. Publ. 17. pp: 146-159.

Romankevich E.A.; 1984: *Geochemistry of Organic Matter in the Ocean.* Springer, Berlin-Heidelberg, 334 pp.

Salihoglu I., Yilmaz A., Baştürk Ö., Saydam C. and Yilmaz K.; 1987: *Akdeniz Eylem Plani II. Aşama Uzun Sürcli Izleme Programi (Med-Pol II) 1987 Yili Final Raporu (Long Term Pollution Monitoring and Research Programme/MED-POL, Second Phase, Final Report for the year 1987).* Institute of Marine Sciences, METU, Erdemli, Icel (Turkey), 196 pp., (in Turkish).

Sayar C.; 1977: *Haliç ve civarinin jeolojisi (The Geology of the Golden Horn/Haliç and its surroundings).* In: Proc. National Symposium on the Golden Horn, Bosphorus University, Istanbul, February 1976, pp. 355-374 (in Turkish).

Saydam C., Latif M.A., Salihoglu I., Özsoy E., Oguz T. and Ünsal M.; 1986: *Golden Horn Oceanographic Investigations-First Annual Report.* Institute of Marine Sciences, METU, Erdemli-Içel (Turkey), 92 pp.

Schäfer W.; 1953: *Zur Unterscheidung gleichformiger Kotpillen meerischer Evertebraten.* Senckenbergiana, 34, 81-93.

Shepard P.R.; 1954: *Nomenclature based on Sand-silt-clay ratios.* Journ. Sed. Petrol., 24, pp. 51-68.

Shimkus K.M. and Trimonis E.S.; 1974: *Modern Sedimentation in Black Sea.* In: The Black Sea-Geology, Chemistry, and Biology, Degens E.T. and Ross D.A. (Eds.), Am. Assoc. Petroleum Geologists Memoir 20, Tulsa, Oklahoma, pp. 249-278.

Swanson V.E., Love A.H. and Frost I.C.; 1972: *Geochemistry and diagenesis of tidal-marsh sediment, northeastern Gulf of Mexico.* Bull. U.S. Geol. Surv. 1360, 83 pp.

Ünsal M.; 1988: *Effects on Sewerage on the Distribution of Benthic Fauna in Golden Horn.* Rev. Int. Oceanogr. Med. Thomes, Vol. 91-92, 105-124.

Utkan M.N.; 1977: *Haliçin Dolmasi ve Temizlenmesinin Oseanografik Açidan Incelenmesi (Oceanographic investigations on the fill and dredging of the Golden Horn).* In: Proc. National Symposium on the Golden Horn, Bosphorus University, Istanbul, February 1976, pp. 303-312 (in Turkish).

Uysal Z.; 1987: *Fate and distribution of plankton around the Bosphorus, southwestern Black Sea, Bosphorus, Golden Horn, Northeastern Marmara and the Bay of Izmit.* M. Sc. thesis, Institute of Marine Sciences, METU, Erdemli, Içel (Turkey), 151 pp.

Volkov I.I. and Fomina L.S.; 1974: *Influence of Organic Material and Processes of Sulfide Formation on Distribution of Some Trace Elements in Deep-Water Sediments of Black Sea.* In: The Black Sea-Geology, Chemistry, and Biology, Degens E.T. and Ross D.A. (Eds.), Am. Assoc. Petroleum Geologists, Memoir 20, Tulsa, Oklahoma, pp. 456-476.

Wagner G.; 1968: *Zur Beziehung zwischen der Besiedlunghsdichte von Tubificiden und dem Nahrungsangebot im Sediment.* Int. Rev. Ges. Hydrobiol., 53, 715-721.

Wall D. and Dale B.; 1974: *Dinoflagellates in Late Quaternary Deep-Water Sediments of Black Sea.* In: The Black Sea-Geology, Chemistry, and Biology, Degens E.T. and Ross D.A. (Eds.), Am. Assoc. Petroleum Geologists Memoir 20, Tulsa, Oklahoma, pp. 364-380.

Werner F.; 1968: *Gefügeanalyse feingeschichteter Schlicksedimente der Eckernförder Bucht (westliche Ostsee).* Meyniana, Kiel, 18, 70-105.

Wetzel W.; 1937: *Die koprogenen Beimengungen mariner Sedimente und ihre diagnostische und lithogenetische Bedeutung.* Neues Jahrb. Mineral. Beil.-Bd 78 B, 109-122.

Wolf W.J.; 1980: *Biotic Aspects of the Chemistry of Estuaries.* In: Chemistry and Biogeochemistry of Estuaries, Olausson E. and Cato I. (Eds.), John Wiley & Sons Publ. pp. 264-295.

Yalçinlar I.; 1977a: *Istanbul Haliçindeki Dolmanin Bir deniz Kanaliyla Önlenmesi (Prevention of the fill of the Golden Horn estuary by constructing of a submarine channel).* In: Proc. National Symposium on the Golden Horn, Bosphorus University, Istanbul, February 1976, pp. 287-298 (in Turkish).

Yalçinlar I.; 1977b: *Istanbul' un Planlanmasi ve Haliç' in Temizlenmesi Üzerine (On the city planning of Istanbul and dredging of the Golden Horn).* In: Proc. National Symposium on the Golden Horn, Boshporus University, Istanbul, February 1976, pp. 409-420 (in Turkish).

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