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Sedimentological and clay mineralogical investigations in Maliakos Gulf, eastern Greece

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Abstract. The distribution patterns of fine-grained sediments (sand, silt and clay) and the relative abundance of clay minerals (illite, smectite, chlorite and kaolinite) in the clay fraction (< 2 μm) of surficial sediments in Maliakos Gulf is examined. Sedimentation processes within the Gulf are controlled by the presence and evolution of the delta of the River Sperchios, which forms the western and southern coastlines of Maliakos Gulf. Sand is more abundant near the river mouths and along the northern shoreline, with percentages in excess of 80%. The silt content is highest (40-50%) at the delta front area, whilst clay (> 60%) dominates in the central part of the Gulf. The most abundant clay mineral present is illite (60-80%). The smectite content varies between 5% and 20%, whilst the chlorite-kaolinite content lies between 15% and 25%. Clay minerals are of terrigenous origin, with their abundances related to the lithology of the region over which the rivers drain into the Gulf. The clay mineral distributions may be explained in terms of differential settling (size sorting), flocculation and the action of biophysicochemical processes (i.e., pelletization).

1. Introduction

Maliakos Gulf is located on the western coast of the Aegean Sea (central Greece). It is a semi-closed shallow marine embayment with low tidal ranges and restricted wave activity, due to the limited fetches. One of the main geomorphological characteristics is the presence of the prograding delta of the River Sperchios at its western end (Fig. 1). The main source of sediments

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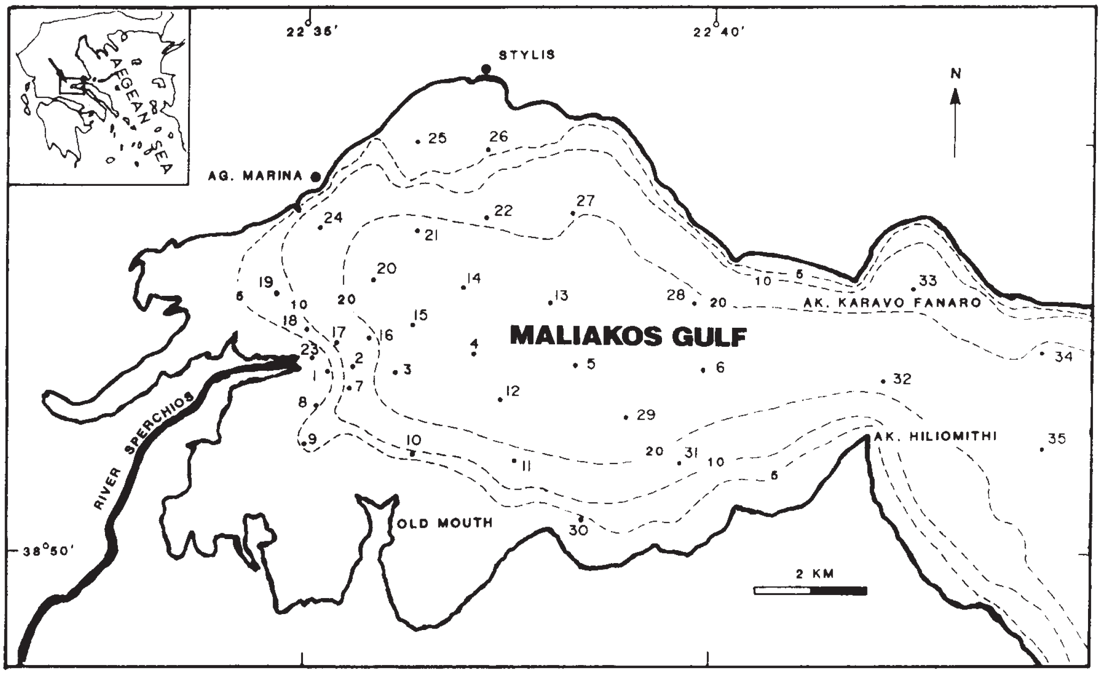

Fig. 1 - Maliakos Gulf: bathymetry, based upon a chart (1:50,000) produced by the Hellenic Army Geographical Service, and the sampling stations (**.**).

in the Gulf is this river, with secondary sources being ephemeral streams, coastal erosion and the advection of suspended material from outside the Gulf.

Previously published investigations on the clay mineralogy of Maliakos Gulf are not known to the authors. On the other hand, the sedimentology and palaeogeography of the Sperchios valley and its littoral zone have been examined by Tziavos (1977). The morphology of the delta and deltaic progradation of the river within historical times has been investigated by Zamani and Maroukian (1979, 1980). Neotectonic movements within the Sperchios valley have been examined by Maroukian and Lagios (1987) and, finally, some morphotectonic observations in the drainage basin of the river were presented by Maroukian and Zamani (1983).

The present study investigates the sedimentology of the bottom surficial sediments, of a characteristic microtidal depositional marine environment, with respect to the relative abundance of the sand-silt-clay fraction and the lateral distribution of clay minerals (illite, smectite, chlorite and kaolinite). Particular emphasis is put on the origin, transportation and settling mechanisms of the clay minerals in relation to the prevailing oceanographic regime.

2. The study area

2.1. Geographical setting

Maliakos Gulf lies between 38° 49' and 38° 55' N, and 22° 32' to 22° 42' E; it is connected

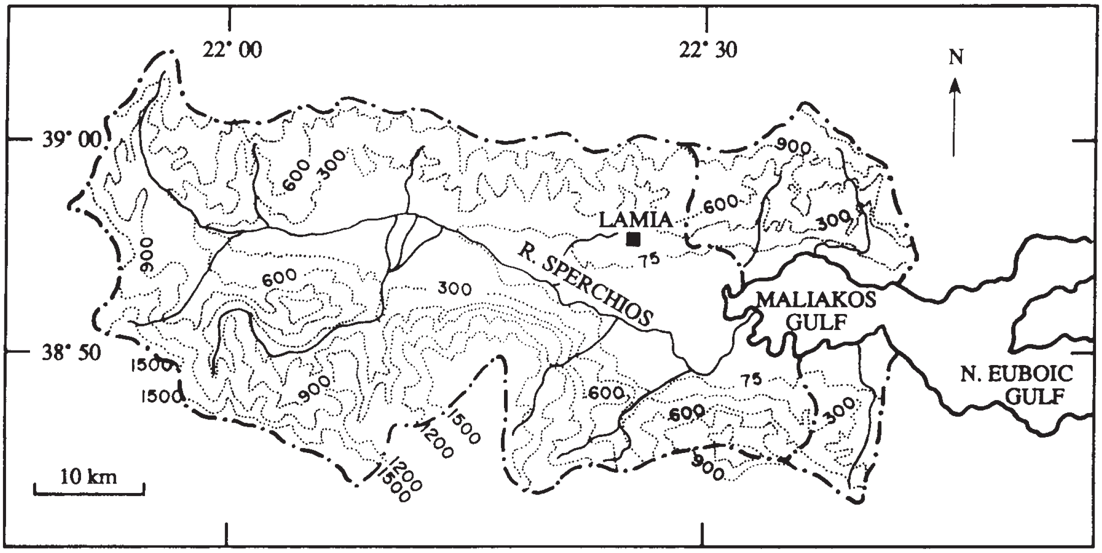

Fig. 2 - Topography and hydrographic network of the area draining into the Maliakos Gulf (altitudes in metres),based upon a topographic chart (1:500,000) produced by the Hellenic Army Geographical Service.

to the Aegean Sea through the North Euboic Gulf (Fig. 1). The average length of the Gulf, in an east-west direction, is about 11 km; its north-south width is 9 km and its maximum depth is about 25 m. The strait between the promontories of Ak. Hiliomidi and Ak. Karavo Fanaro, which connects Maliakos Gulf with the North Euboic Gulf, has a width of 2.5 km and depth of 25 m.

The Gulf receives freshwater inputs mainly from the River Sperchios, on its eastern coastline, together with some other torrents on its northern and southern flanks. The topography of the surrounding area, which drains into the Gulf is shown in Fig. 2; it covers some 2,000 km^2, of which 1,664 km^2 represent the catchment area of the River Sperchios. Elevations are about 800 m in the north and > 1,500 m in the west and south. The maximum elevation, of 2,437 m, is located in the southern part of the catchment.

The River Sperchios, which is the main source of freshwater/sediment supply to the Gulf, has a mean annual water discharge of 62 m^3/s, varying between 110 m^3/s (in January) and 22 m^3/s (in August) (Therianos, 1974). Floods occur commonly, regularly exceeding the channel capacity of 170 m^3/s. For example, on 29th June 1939 a flood discharge estimated at 800 m^3/s occurred, in response primarily to the snowmelt (Zamani and Maroukian, 1980). The mean annual suspended sediment discharge has been estimated to be 1,410 x 10^3 tonnes (Poulos et al., 1996).

2.2. Geological setting

Maliakos Gulf, together with the valley of the River Sperchios, form part of a tectonic trough which is controlled by major east-west trending faults (see Fig. 3). The fault tectonism took place at the end of the Pliocene and beginning of the Pleistocene periods. The Pliocene deposits, located to the south of the Maliakos Gulf, have been uplifted by more than 500 m. Furthermore, the mountainous region at the southern boundary of the River Sperchios catchment area was

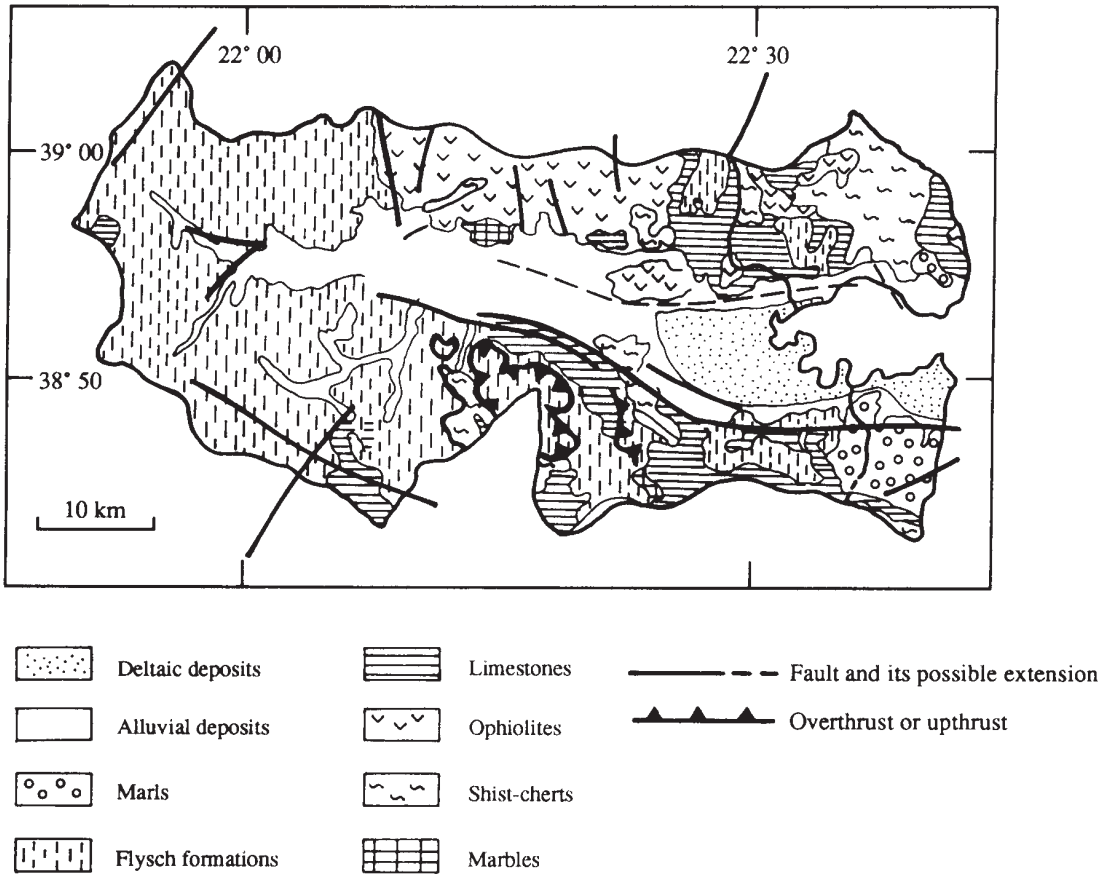

Fig. 3 - General geology of the area draining into Maliakos Gulf, based upon the seismotectonic map of Greece (1:500,000) produced by the Institute of Geological and Mineral Exploration, Athens, 1989.

subjected to tectonic activity for a much longer period during the Quaternary; this has resulted in a vertical displacement of about 1,800 m (Maroukian and Lagios, 1987).

The general geology of the area draining into Maliakos Gulf (with 90% within the River Sperchios drainage basin) is shown in Fig. 3. Four distinct lithological regions can be distinguished: (i) the western half which consists mainly of flysch, Paleocene-Eocene in age; (ii) the north and north-eastern part, covered mainly by an ophiolitic complex in a shale-chert formation; (iii) the southeastern part of the area composed of Middle Triassic-Jurassic massive dolomites and limestones, Upper Cretaceous flysch and limestones, Eocene flysch, and Neogene deposits; and (iv) the central part (which coincides with the River Sperchios valley) covered by Quaternary unconsolidated fluvial deposits (including Holocenic deltaic sequences).

One of the main geological features of Maliakos Gulf is the formation of the River Sperchios delta, along its western and south-western coastline. This deltaic plain, from 480 B.C. to 1970 A.D., extended by 100 km^2, and prograded eastwards by approximately 11 km; this corresponds to a mean annual growth rate of 0.041 km^2/yr (Zamani and Maroukian, 1980).

2.3. Climatic setting

Maliakos Gulf and its drainage basin are located between the 17.5-18 °C and 500-1200 mm isopleaths, in terms of mean annual temperature and precipitation, respectively (Zabakas, 1981). The predominant wind components are mostly from the east and west, following the localized east-west trend of the Sperchios valley. Average speeds are 1-2.5 m/s for the westerly winds and 2.5-4.5 m/s for those from the east. The climate can be characterised, in general, as a "terrestrial Mediterranean" type.

2.4. Oceanographic setting

As an example of the prevailing spring (April) conditions, average temperatures of 17 °C were found within the upper 2 m of the water column; this was followed by a thermocline at depths of down to 8 m below the water surface, with temperatures decreasing from 16.8 to 13.0 °C. Below 8 m, temperatures decrease very slowly to around 12.8 °C. The position of the thermocline is likely to vary according to seasonal climatic conditions.

There is also a variation in salinity over various areas of the embayment, with surface salinities of 32 ppt near the river mouth and up to 37 ppt towards the east. Bottom salinities reach 38 ppt, which are similar to those of the open Aegean Sea; this is indicative of circulation and mixing between the lower water masses of the Gulf and those of the open sea.

Wave energy is low over the region, in response to restricted fetches and (normally) weak to moderate winds. The tidal range, as elsewhere in the Aegean Sea, is low (Tsimplis, 1994), with an average of about 0.5 m. The maximum tidal range, during spring tides, is 0.95 m; it has a minimum of 0.15 m during neaps (Zamani and Maroukian, 1980).

3. Data collection and methodology

Thirty-five sediment samples were collected from the sea-bed at Maliakos Gulf (Fig. 1), using a Van Veen-type grab. Grain size analyses were done on the samples in order to identify the sand (> 63 μm), silt (2-63 μm) and clay (< 2 μm) components. Each sample was split into the sand and mud (silt+clay) fractions using wet sieving through a mesh size of 63 μm. Samples had been treated previously with H_2O_2 (hydrogen peroxide) in order to remove the organic matter. A deflocculating agent was added to prevent flocculation of the mud-sized particles. The finer-grained material (mud), which passed through the sieve, was split further into its silt and clay fractions using the pipette analysis technique proposed by Folk (1974).

The clay fraction (< 2 μm) was analysed by X-ray diffraction, in order to identify the clay minerals present. The smear-on-glass slide technique (Moore and Reynolds, 1989) was used for the preparation of oriented clay samples. X-ray analysis was done using Fe-filtered CoKa radiation (36kV, 24 mA) on: (i) air dried specimens; (ii) following treatment with ethylene glycol for 1 h at 60 °C; and (iii) after heating for 1 h at 400 °C, and 550 °C. Specific samples were analy-

Table 1 - Percentages of sand, silt, clay and the relative abundances of clay minerals for the clay fraction (< 2 μm) within the surficial bottom sediments.

	Fine Grain Sediment (%)			Clay Minerals (%)		
Stat.	Sand	Silt	Clay	Illite	Chl./Kaol.	Smectite
1	19.83	38.37	42.80	75.0	14.9	8.1
2	0.50	52.08	47.42	69.5	18.7	11.8
3	0.41	46.29	53.30	64.1	23.7	12.2
4	0.43	42.20	57.37	64.1	24.6	11.3
5	0.42	33.91	65.57	68.8	21.9	9.3
6	0.52	34.38	65.10	66.2	21.4	12.4
7	0.40	51.04	42.56	68.0	20.2	11.8
8	0.70	53.10	46.20	70.0	12.4	7.6
9	0.49	51.03	48.46	71.9	19.7	8.4
10	0.43	46.37	52.10	72.5	19.8	7.2
11	0.18	43.71	56.11	73.8	20.2	6.0
12	0.40	40.31	59.29	71.8	21.5	6.7
13	0.72	32.20	67.26	72.0	19.7	8.3
14	1.70	35.38	62.92	69.4	20.3	10.3
15	0.40	44.60	55.30	63.7	22.4	13.9
16	0.42	49.36	50.22	64.4	23.0	12.6
17	1.04	52.25	46.71	70.9	19.1	10.0
18	5.22	47.60	47.18	74.5	17.2	8.3
19	0.30	48.80	50.90	78.5	7.2	4.3
20	0.48	38.78	60.72	77.1	17.4	5.5
21	17.93	31.74	50.43	77.4	16.6	6.0
22	49.48	16.02	34.50	76.4	18.3	5.3
23	63.03	27.29	9.68	78.3	13.5	8.2
24	21.60	30.60	47.80	84.3	13.6	2.1
25	75.05	4.70	20.25	80.4	18.5	1.1
26	64.96	6.23	28.81	80.0	18.4	1.6
27	14.27	30.52	55.21	73.5	19.2	7.3
28	1.60	32.20	66.20	73.8	17.7	8.5
29	0.31	38.35	61.34	73.2	20.3	6.5
30	0.42	54.50	45.08	78.0	17.6	4.4
31	0.23	43.80	55.97	74.2	20.8	5.0
32	0.83	36.21	62.96	58.6	26.1	15.3
33	14.57	33.13	55.20	70.3	18.4	11.3
34	55.10	25.33	19.77	73.9	17.8	8.3
35	0.72	35.82	63.46	55.5	25.0	19.5

sed, following treatment with HCl 20% and heating for an hour at 550 °C.

X-ray identification of the minerals is based upon their characteristic basal- reflection maxima (peaks) at certain angles (2θ) of the diffractogram, which reflect their different molecular plane distances (d). Hence, from the diffractogram and using prepared Tables of (2θ) plotted against the (d) spacings (for the X-ray wavelength used), the type of clay mineral can be identified (Brindley and Brown, 1980). In this way, the clay minerals illite, smectite, chlorite and kaolinite were identified, together with other minerals such as quartz, feldspars and some mixed-layer clay minerals (with chlorite-smectite being the most abundant). The results of the applied

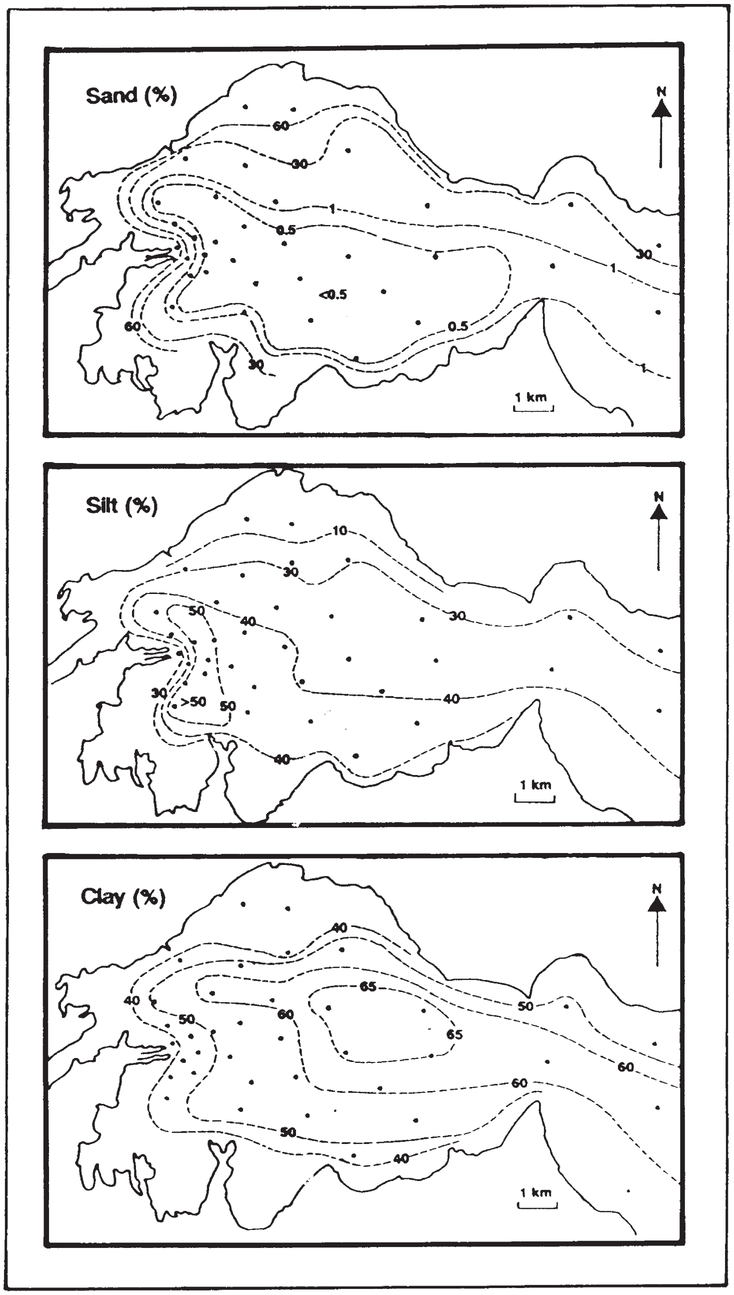

Fig. 4 - Maliakos Gulf: surface distribution of sand, silt and clay fraction, as a percentage of the total weight.

X-ray procedures show that kaolinite is present in small amounts relative to chlorite, which is not well crystalised. Hence, these clay minerals could not be separated accurately. Consequently, the reflection of 7.15Å (d) at 14.2° (2θ) was used for the quantitative estimation of both chlorite and kaolinite.

Evaluations of clay minerals present was based upon the "semi-quantitative" procedure proposed by Biscaye (1965). The relative proportions of illite, smectite, chlorite and kaolinite were determined by comparing the weighted intensities (peak areas) of the basal reflections of the different clay minerals, after glycolation of the specimens. The reflectors and the factors used (Biscaye, 1965; Shaw, 1978) are: the 10Å reflection for illite (x4), the 17Å reflection for smectite (x1), and the 7Å reflection for chlorite and kaolinite (x2). The percentages of the sand, silt, and vand clay fraction of the surficial sediments of the Gulf, together with the relative abundances of the clay minerals, are presented in Table 1.

4. Results and discussion

4.1. Fine-grained sediments

The distribution of sand, silt and clay within the bottom sediments of Maliakos Gulf are shown in Fig. 4. The sand percentages are very high near the river mouth (> 60%); they decrease rapidly to 5% some 500 m off the mouth, and to less than 0.5% within the central part of the Gulf. The sand content increases slightly towards the strait connecting Maliakos Gulf with the northern part of Euboic Gulf (Fig. 1). High sand percentages (> 60%) are present over the northern part of the Gulf, especially adjacent to the port of Stylis and along the northern coastline.

The silt content ranges between 30% and 40% over the central part of the Gulf; it exceeds 50% over the delta front area, and remains low (< 30%) along the northern shoreline, and very low (< 10%) near Stylis Port.

The highest clay contents (> 60%) occur within the sediments of the central part of the Gulf. There is a low clay content (approx. 20%) associated with sediments outside Stylis and, generally, along the northern shoreline of the Gulf. Over the delta area, the clay content is about 10%; it increases seaward, reaching levels of 50% and 60% .

The distribution patterns of sand, silt, and clay within the surficial deposits of Maliakos Gulf indicate that the area may be divided into two regions: (i) that influenced by progradation of the River Sperchios delta; and (ii) an area not dominated by the deltaic evolution. The first area incorporates the eastern, southern and central parts of the Gulf, where mud (silt and clay) is abundant. The delta front area and the zone along the southern coastline are associated with high silty contents. Clay dominates the central part of the Gulf. The second area consists of the northern part of the Gulf; it includes the Port of Stylis and the northern shoreline, where sand is the dominant material within the bottom sediments of the embayment.

The presence of fine-grained material (clay and silt) only within the surficial deposits of the central area of Maliakos Gulf is indicative of the dominance of river-borne sediments, which are spread by dispersion of the plume and superimposed wave and current activity induced mainly by westerly winds. Moreover, the banded structure of the bottom deposits along the shoreline of the Gulf (described previously), together with the easterly-orientated configuration of its southern coastline, provides evidence for the presence of an easterly longshore current carrying fine-grained sediments towards the eastern entrance to the Gulf.

4.2. Clay mineralogy

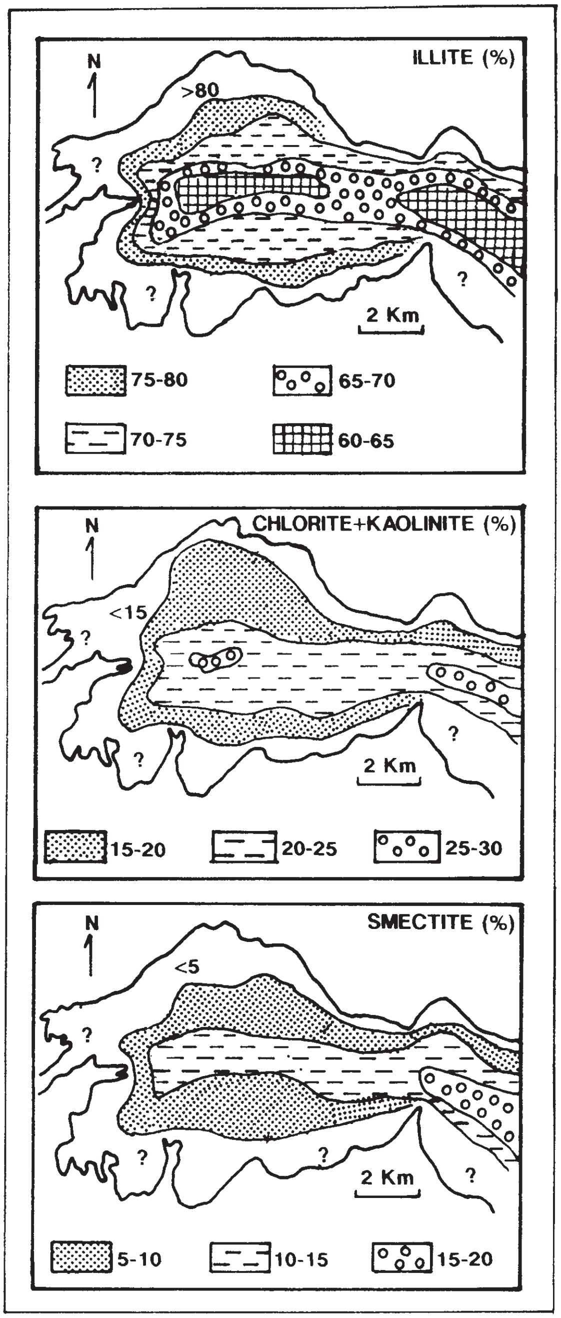

Fig. 5 - Maliakos Gulf: surface distribution of relative percentages of illite, chlorite-kaolinite and smectite.

The distribution of illite, chlorite-kaolinite and smectite within the surficial bottom sediments of Maliakos Gulf is shown in Fig. 5. Illite is the dominant clay mineral present, with percentages between 60% and 85%. The chlorite-kaolinite percentage lies between 10% and 25%, whilst smectite varies from 5% up to 20%.

The illite content is at its maximum (80%) near the river mouth and adjacent to the coastlines; it decreases to 60% towards the central part of the Gulf. Chlorite-kaolinite contents are generally about 10-15%, increasing rapidly to 20-25% over the delta-front area; this indicates the riverine origin of these clay minerals. Along the coastlines and away from the river mouths, the chlorite-kaolinite content is less than 15%. At the entrance to Maliakos Gulf and to the east, the content reaches levels in excess of 25%. The smectite contents are 5-10% near to the river mouths, and increase gradually to > 15% towards the centre of the Gulf. This latter observation, together with the low smectite levels near the northern and the southeastern coastlines (< 5%), indicates that the main source of this mineral is the River Sperchios. Consequently, the smectite content increases to > 15% towards the east, between the promontories of Ak. Hiliomidi and Ak. Karavo Fanaro in the northwestern part of Euboic Gulf.

The relative abundance of clay minerals within the subaqueous deposits of Maliakos Gulf is analogous to that of Thermaikos Bay (Conispoliatis, 1983) and the Bay of Kavala (Conispoliatis and Lykousis, 1986), located within the northwestern and northeastern parts of the Aegean Sea, respectively. Thermaikos Bay receives discharges from the Axios, Aliakmon and Gallikos rivers, whilst the eastern shoreline of Kavala Bay consists of the deltaic deposits of the River Nestos. In general, illite is the most abundant clay mineral present, varying from > 70% nearshore to 50% offshore. Smectite ranges from < 10% to 20% in these areas, reaching 35% in the case of Thermaikos Bay. At the same time, the chlorite-kaolinite content lies between 10% and 30% .

Illite, a member of the mica group of minerals, is abundant within most rocks and their corresponding soils (Kostov, 1967). Hence, large quantities of illite may be expected from the rather easily-weathered alluvial and clastic rocks (about 70% of the drainage area is covered by Quaternary deposits and flysch).

Chlorite and kaolinite contents lie between 10% and 30%. Kaolinite is mainly the product of chemical weathering, at low latitudes (Kostov, 1967); its presence at higher latitudes is associated usually with the lateritic weathering processes (Biscaye, 1965). This mineral is not expected, therefore, to be present in high quantities in the study area, which does not satisfy the above criteria. Minerals from the chlorite group are the products of mechanical, rather than chemical weathering of argillaceous sediments, low grade metamorphic and igneous rocks (Biscaye, 1965). These rock types are not dominant within the catchment area, where, in addition, the low chlorite content (20%) is attributed probably to the presence of ophiolites and some metamorphic rocks (i.e., schists). Furthermore, any chlorite found is related also to soils which are rich in Mg, Ca, K, originating from the weathering of limestones and dolomites (Nakos, 1979); these underlie some areas of the drainage basin.

The low percentages (10-20%) of smectite could have been predicted, as ultrabasic and pyroclastic rocks do not occur extensively within the catchment area. Thus, smectite is the product of weathering of ophiolitic-type rocks. The relatively higher levels of smectite (approx. 35%) within Thermaikos Bay (Conispoliatis, 1983) are related to the presence of basic and volcanic rocks within the drainage basin of the River Axios and, to a lesser extent, the River Aliakmon.

Similar illite (40-50%), smectite (30-40%) and chlorite-kaolinite (10-30%) contents have been described for the open Aegean Sea (Venkatarathnam and Ryan, 1971); these are the result of similar climatic latitudes and, therefore, weathering processes within the surrounding mainland.

Within Maliakos Gulf, the illite content tends to decrease seawards; smectite increases, whilst the chlorite-kaolinite content present is higher over the lower part of the delta front. The depositional tendency of the clay minerals (described above) could result either from differential settling, flocculation, or biophysicochemical interactions, such as pelletization (Weaver, 1989). Likewise, deposition could be caused by a combination of these mechanisms (the extent to which each of the mechanisms contributes to clay mineral deposition should be the subject of further, detailed investigations). The mechanism of floc formation is related to an increasing offshore chlorinity (salinity) of the river plume, as discussed previously. Hence, illite is deposited initially near the river mouth, then chlorite-kaolinite; here, the salinity is low relative to the waters further offshore where smectite is deposited (Whitehouse et al., 1960). When floc formation is inhibited by the presence of organic matter, metallic coatings on the suspended particles, or strong currents and minimal salinity differences, clay minerals are deposited according to their physical size (Gibbs, 1977). In this case, the same distribution pattern as described previously would result, since the individual illite particles are larger than those of chlorite-kaolinite; smectite particles are the smallest (Gibbs, 1977). Biophysicochemical interactions (i.e., pelletization) of fine-grained particles are present only over areas (i.e., the prodelta) where there is thinning of the freshwater plume and it is diluted within the ambient salt waters (Weaver, 1989).

Similar settling tendencies of illite, smectite and chlorite have been found by Shaw (1978) within the surficial bottom sediments of the Cilician Basin, on the southern Turkish coastline (eastern Mediterranean).

The increase of chlorite-kaolinite and smectite percentages near the active mouth of the R. Sperchios (i.e., the delta front and the commencement of the prodelta) is associated with the fact that this area of the sea bed is overlain by sediment-laden river plumes, even during moderate-to-low river discharge levels. Further offshore, the prodelta is covered only during high river discharges, which occur during winter and early spring (Therianos, 1974).

At the same time, when the river is at moderate to high discharge levels, the comparatively higher velocities within the plume (than during periods of low discharge) are capable of removing the finest clay minerals (smectite), leaving behind the coarser grains (chlorite-kaolinite, illite) which will eventually deposit nearshore. This process is enhanced by the lower salinities inshore, which favour the formation of chlorite and kaolinite flocs rather than those of smectite (Whitehouse et al., 1960).

The relative increase of smectite and chlorite-kaolinite at the entrance to the eastern Maliakos Gulf and further to the east indicates some transport of these clay minerals from the northern Euboic Gulf towards Maliakos Gulf. Such transport is most probably induced by the tidal advection and wave activity, with tides in the N. Euboic Gulf reaching around 1 m at springs (Tsimplis, 1994).

5. Conclusions

Sedimentation processes within Maliakos Gulf are dominated by the presence of the River Sperchios, whose deltaic deposits form the southern and eastern coastlines. This river is, therefore, the main source of sediments. Some sedimentary input is provided, however, by a few ephemeral streams discharging along the northern part of the Gulf, and coastal erosion. Likewise, some fine suspensates (clays) are advected into Maliakos Gulf from the Euboic Gulf by tidal and wave activity.

Sand is abundant over the northern part of the Gulf, which is not affected by the deltaic progradation, and around the river mouths. The remainder of the Gulf is covered by mud, with silt more abundant over the delta-front region, and clay covering the whole of the central part of the Gulf. The former indicates that the suspensates supplied by the river plume are eventually dispersed throughout the Gulf by currents caused by local winds and the tidal regime. Clay minerals are of terrigenous origin, being the main constituent of the clay-size river suspensates. Illite is the most abundant of the clay minerals, ranging from 50% to 80%; smectite lies between 5% and 20%, with chlorite-kaolinite contents ranging from 10% to 25%. The relative abundance of minerals is similar to that found in the other gulfs/embayments of the Aegean Sea, as they are the products of analogous weathering processes controlled by the same climatic and lithological conditions. The seaward-decrease in illite percentages, associated with an increase of smectite content and the relatively higher percentages of chlorite-kaolinite over the delta-front area, may be explained by the mechanisms of size-segregation, differential flocculation and biophysicochemical proce ses (i.e., pelletization).

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