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Deltaic Sedimentation, Including Clay Mineral Deposition Patterns, Associated with Small Mountainous Rivers and Shallow Marine Embayments of Greece (SE Alpine Europe)

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ABSTRACT

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Dispersion mechanisms and the deposition of fine-grained deltaic sediments are described in three semi-enclosed shallow marine embayments of Greece. Emphasis is placed upon the origin, relative abundance, and lateral distribution of clay minerals; these are the main constituents of the clay-sized fraction. Sandy deposits dominate the areas adjacent to the river mouths (topsets), whilst clays and silts are the main constituents of the delta front (foresets) and prodelta (bottomsets) areas, respectively. The main clay minerals present are illite (the most abundant), smectite, chlorite and kaolinite; all of these are of terrigenous origin. There is a tendency for the illite content to decrease to seawards, whilst the smectite content increases: chlorite and kaolinite are more abundant at the delta front. The observed distributions can be explained in terms of size segregation and bio-physico-chemical processes (*e.g.*, flocculation and pelletization), associated with interaction between the freshwater fluvial outflow and the saline ambient waters (*e.g.*, plume dispersion and upwards entrainment). A generalised depositional model, for fine-grained sediments in such shallow marine environments, is presented.

ADDITIONAL INDEX WORDS: *Fine-grained sediments, clay-minerals, deltas, Greece.*

INTRODUCTION

The distribution patterns of fine-grained sediments within deltaic deposits reflect both the interaction between fluvial and marine processes (WRIGHT, 1985) and the nature of the suspended particles (*e.g.*, particle size, shape, density and composition) which settle either as individual particles and/or as flocs and pellets.

Clay minerals are the main constituent of the finest grain size sediment fraction. Recent studies on the origin of clay minerals in marine sediments associated with river fluxes have shown that, on a world-wide basis, they are predominantly detrital and of terrigenous origin (WEAVER, 1989). The relative abundance of the different clay minerals is dependent mainly upon terrigenous sediment production, with the clay assemblages developed through weathering reflecting the corresponding pedoclimatic conditions (CHAMLEY, 1989). The composition of detrital clay minerals is modified only slightly by depositional and early diagenetic processes (WEAVER, 1958; EDZWALD and O'MELIA, 1975).

The lateral distribution of clay minerals within sea bed surficial sediments has been documented by several authors (NELSON, 1960; PORRENGA, 1967; VENKATARATHNAM and RYAN, 1971; AOKI *et al.*, 1974; HEATH *et al.*, 1974; GIBBS, 1977; SHAW, 1978; CONISPOLIATIS and LYKOUSIS, 1986; KOLLA *et al.*, 1980; LATOUCHE and MAILLET, 1985; ROBERTS, 1985; PARK *et al.*, 1986; STANLEY and LIYANAGE, 1986). On the basis of these investigations, various processes have been proposed to explain lateral trends in the abundance of clay minerals. A distinction can be made between processes relating to the clay mineral particles themselves and those determined by the depositional environment.

Clay mineral particles are affected predominantly by: (a) chemical alteration (GRIFFIN and INGRAM, 1955; POWERS, 1957; JOHNS and GRIM, 1958); (b) differential flocculation (WHITEHOUSE *et al.*, 1960; and EDZWALD and O'MELIA, 1975); (c) size segregation (GIBBS, 1977); and (d) biophysicochemical interactions, such as pelletization of the finer particles (WEAVER, 1989). The latter process is more intensive within areas where high planktonic productivity occurs and causes rapid settling of the land-derived clay particles as fecal pellets and other mucous matter (CHAMLEY, 1989). Clay mineral deposition is influenced also by dynamical processes, which cause circulation and mixing between riverine and seawater (*i.e.*, coastal or oceanic currents, waves, salt-wedge estuarine circulation) and the hydrodynamic characteristics of river plumes.

Many investigations have been published concerning the sedimentation processes associated with the subaqueous del-

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taic deposits of the major river-deltas of the world, formed in open oceanic environments (Amazon (GIBBS, 1977), Mississippi (ROBERTS, 1985), Nile (STANLEY and LIYANAGE, 1986), Ganges (RAO, 1991), and Niger (PORRENGA, 1967)).

The present contribution is concerned particularly with the distribution of fine-grained sediments, together with their clay mineral abundances, which occur seawards of the river-mouth of small mountainous rivers. These rivers drain parts of the southeastern Alpine Europe and discharge into the shallow and semi-enclosed marine embayments of Greece. Within such protected environments of minimal tidal range (<30 cm) and with restricted wave activity, deltaic sedimentation is controlled basically by riverine processes (rather than those associated with tides or waves). Finally, sediment distribution patterns are examined in relation to available information concerning the water column. On the basis of this intercomparison, the dominant depositional mechanisms operating in such protected marine environments are identified.

THE STUDY AREAS

The subaqueous deltaic deposits investigated are located along the Greek shoreline (Eastern Mediterranean Sea), extending between 38° 30′ to 41° 30′ N and 20° 00′ to 27° 30′ E (Figure 1). These systems include: (a) the subaqueous deposits of the rivers Louros and Arachthos which discharge into Amvrakikos Gulf—an essentially enclosed embayment of the Ionian Sea; (b) the subaqueous delta of the River Sperchios, which discharges into the western part of the Maliakos Gulf—a semi-enclosed and rather shallow (<25 m) gulf connecting with the open Aegean Sea through northern Euboekos Gulf; and, (c) the deltas of the Rivers Axios and Aliakmon, along the northwestern coastline of Thermaikos Bay—a semi-enclosed embayment (depths <35 m) within the northwestern Aegean Sea. The general geomorphological, meteorological and oceanographic characteristics of the river-delta systems are presented in Table 1.

The deltaic sediments investigated are being deposited presently in an essentially tideless environment (TSIMPLIS, 1994); furthermore, they are formed in semi-enclosed shallow embayments with limited wave fetches. Hence, the sediments are subjected to only limited wave and wave-induced current activity. Re-working of the material and a limited amount of coastal erosion is taking place only very near the coastline (*i.e.,* in water depths of <2.5 m and only during strong winds) (POULOS *et al.,* 1993). Subaqueous deltaic sedimentation is governed, therefore, by the seaward-spreading of the fresher and sediment-laden river plumes. The seaward dispersion of the plumes of the Rivers Louros (Amvrakikos Gulf), Sperchios (Maliakos Gulf) and Axios and Aliakmon (Thermaikos Gulf) are presented on Figure 2, with respect to an increasing salinity from the river mouth in an offshore direction.

In any shallow river mouth area, under low wave activity and in the absence of any tide, a river plume loses its initial momentum in response to bottom friction. Farther offshore, the riverine input spreads out as a buoyant plume; this then decelerates, due to the upward entrainment of the more saline ambient embayments waters (WRIGHT, 1985). These processes have been described quantitatively elsewhere in the case of the plume of the River Louros (POULOS and COLLINS, 1994); they can be applied, in a similar way, to the currently investigated river-deltas. Profiles representative of the seaward dispersion of the plume of the Louros river are presented, together with the dominant mixing processes considered to operate between the river outflow and the ambient waters, in Figure 3.

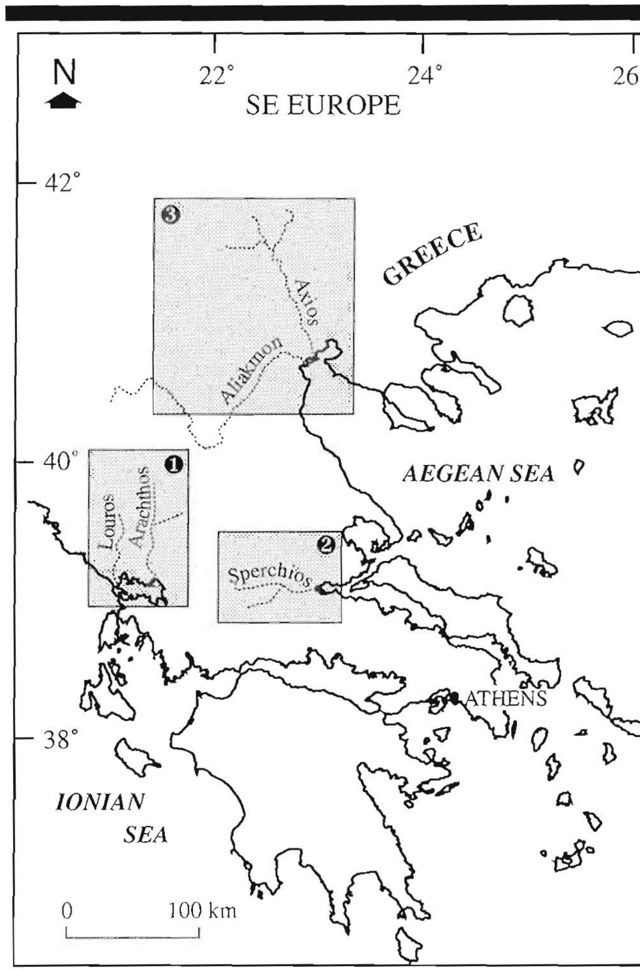

Figure 1. Location of the river-delta systems under investigation: (1) Amvrakikos Gulf; (2) Maliakos Gulf; and (3) Thermaikos Gulf.

Previous sedimentological investigations carried out within the areas under investigation include: Amvrakikos Gulf, by PIPER *et al.* (1982) and POULOS (1989); Maliakos Gulf by TSIAVOS (1977) and POULOS (1989); and the studies of CONISPOLIATIS (1979), CHRONIS (1986) and LYKOUSIS and CHRONIS (1989) within Thermaikos Bay. In these studies, fine-grained riverine sediments were found to be dispersed seaward by the plumes. Suspended sediment concentrations along the main dispersal axis of the plumes of the rivers Louros and Sperchios are shown in Figure 4, together with vertical (turbidity) profiles obtained throughout the water column to seawards of the mouth of the Rivers Axios and Aliakmon. These profiles also indicate the presence of high suspended sediment concentrations near the sea bed, as bottom

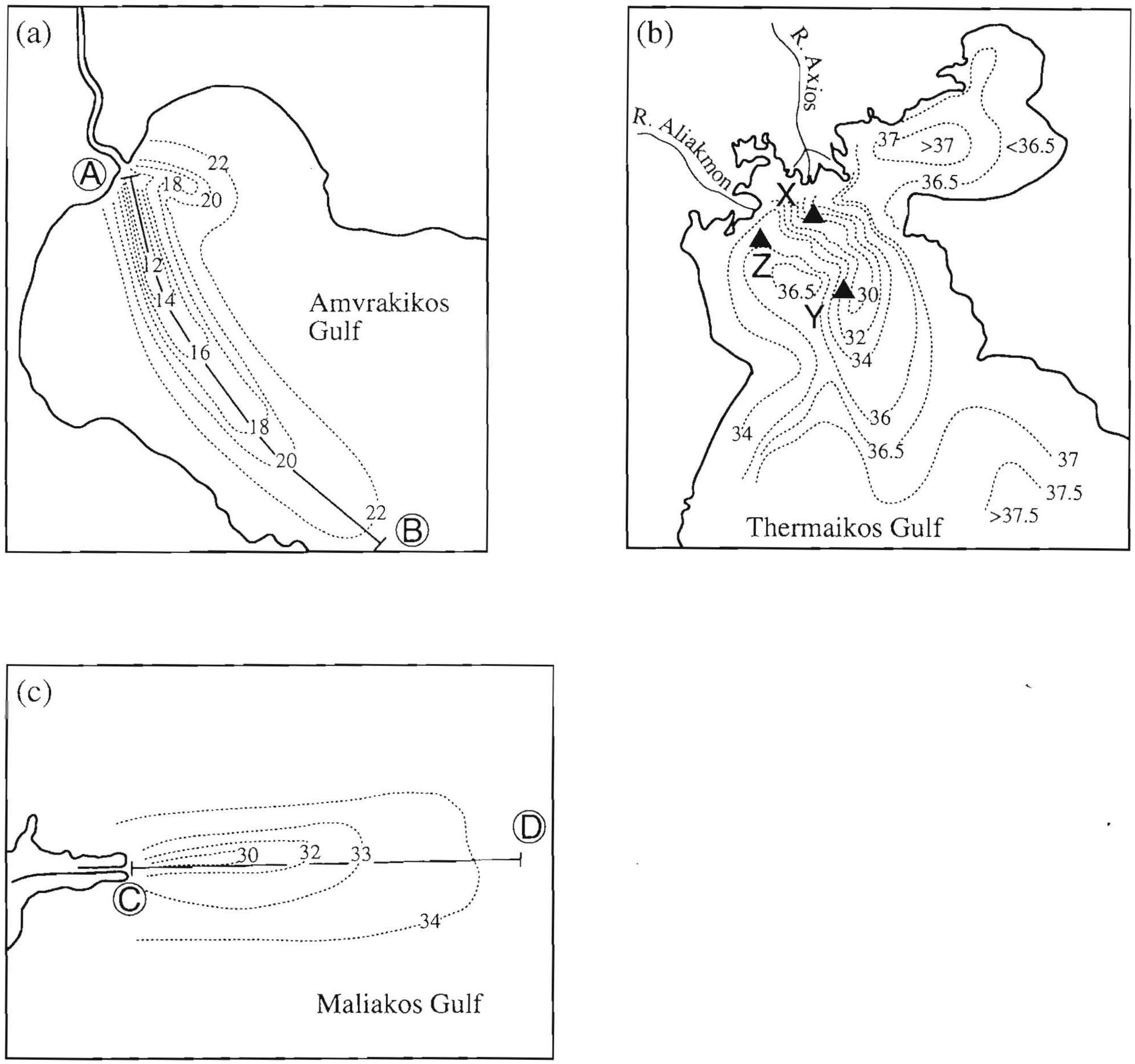

Figure 2. Seaward dispersion of the low salinity plumes of the rivers Louros (a), Sperchios (b) and Axios and Aliakmon (c), as indicated by the surficial salinity distributions (ppt) (from POULOS, 1989). Verticle structure at stations x, y and z is shown in Figure 4.

nepheloid layers. Analogous nepheloid layers within embayments of the Mediterranean Sea have been reported in the Thermaikos Gulf (DURRIE DE MADRON *et al.*, 1992; CHRONIS *et al.*, 1987), the Rhone River (NAUDIN *et al.*, 1992) and the Ebro River (PALANQUES and DRAKE, 1990).

MATERIALS AND METHODS

Field data were collected from the mouths and adjacent seaward areas of the rivers Louros and Arachthos during the spring of 1986. The subaqueous deltaic deposits of the river Sperchios were sampled during the spring of the following year. Information on the surficial deposits to seaward of the mouth of the rivers Axios and Aliakmon, presented here, have been abstracted from CONISPOLIATIS (1979). During the fieldwork programme, local (wooden) fishing boats were used for sampling. The positions of all the sample stations were fixed by reference to established locations on the adjacent shoreline. The accuracy of the position fixing can be assumed to be to within ±20 m, due to the proximity of the shoreline and the prevailing "fair" weather conditions during sampling. Eighty-nine surficial sediment samples were collected using a small (1 litre capacity) Van Veen Grab. The sampling locations for all the areas are presented in Figure 5.

Grain size analyses were carried out on bed sediment sam-

Table 1. *General characteristics of the river/delta systems under investigation.*

	River/Delta System				
	Axios	Aliakmon	Sperchios	Arachthos	Louros
Geomorphology					
Catchment area (km²)	23,747	9,455	1,664	1,894	785
Subaerial delta[a] (km²)	1,500		155	350	
Name of receiving basin	Thermaikos Bay		Maliakos Gulf	Amvrakikos Gulf	
Type of receiving basin	semi-enclosed		semi-enclosed	enclosed	
Max. depth of rec. basin (m)	35		25	62	
Climate					
Mean annual temperature (°C)	14.5	16.5	17.7	17.7	17.9
Mean annual precipitat. (mm)	650	750	785	1,085	925
Climatic variation	"terrestrial Mediterranean to humid Continental"				
Hydrology					
Mean annual discharge (m^3 sec^{-1})	58	73	62	70	19
Max. monthly discharge (m^3 sec^{-1})	279	137	110	167	31
Min. monthly discharge (m^3 sec^{-1})	49	21	12	4	10
Lithology of Catchment					
Unconsolidated sediments (%)	5.8	8.3	31.9	6.7	24.7
Sedimentary rocks (%)	36.6	72.8	57.1	90.8	73.8
Metamorphic rocks (%)	51.0	6.4	1.2	0.7	1.5
Igneous rocks (%)	6.5	12.5	9.8	1.8	0.0

[a] The delta areas of the rivers Axios and Aliakmon and that of Arachthos and Louros cannot be identified individually from the available topographic and geological charts; hence, the areas (km) presented in the table refer to the deltaic "complex" of these river systems

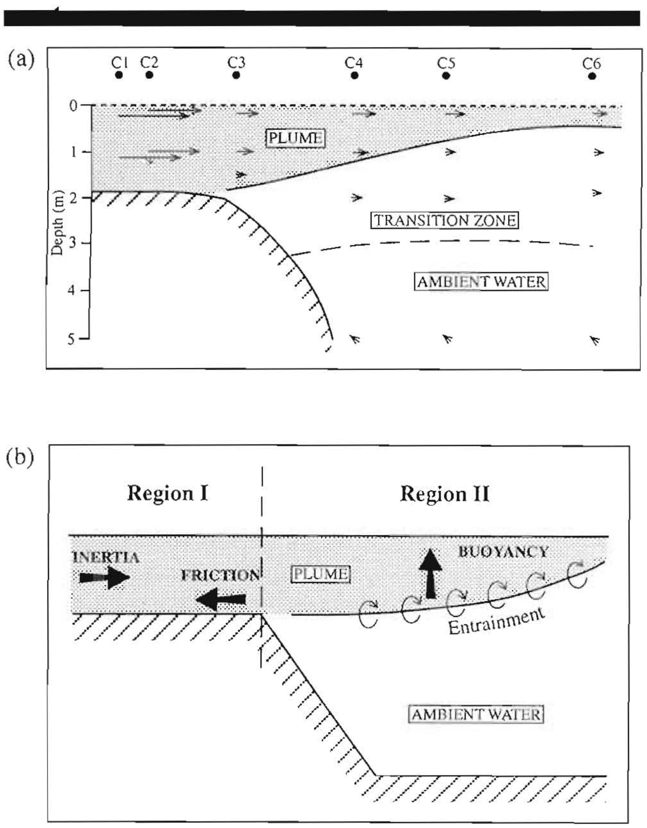

Figure 3. Vertical current profile along the main longitudinal axis of the plume of the R. Louros (a) and synthesis of the associated dispersal processes (b) (from Poulos, 1989). Measurement locations C1 to C6.

ples in order to differentiate the sand (>63 μm), silt (2–63 μm) and clay (<2 μm) components. A sub-sample of each sample weighing 15–25 g was treated with 6% hydrogen peroxide (H_2O_2), in order to remove the organic matter. A deflocculating agent (distilled water, containing 10% Calgon) was added to inhibit flocculation. Each sample was then split into sand and mud (*i.e.*, silt and clay) fractions, by wet sieving through a 63 μm mesh. The mud fraction was split further into its silt and clay fractions using the pipette analysis technique (FOLK, 1974). X-ray diffraction analysis was performed on the clay fraction (<2 μm) of all the samples. The pipette-on-glass slide and air-dry technique (BISCAYE, 1965) was used for the preparation of oriented clay samples. For each sample, natural, glycolated and preheated (at 550 °C) specimens were examined to identify the major clay mineral groups. Selected samples were heated at 300 °C and 400 °C in an effort to differentiate chlorite from kaolinite. Unfortunately, the attempt was unsuccessful due to the collapse of chlorites at a temperature of 400 °C.

"Semi-quantitative" estimates of clay mineral abundances have been derived, based upon the intensities of their characteristic basal X-ray reflections. The relative clay mineral (illite, smectite, chlorite + kaolinite) proportions were determined by comparing the weighted intensities (peak areas) of the basal reflections of the different clay minerals after glycolation of each specimen (BISCAYE, 1965). The reflections and weighting factors were those proposed by BISCAYE (1965) and used by CONISPOLIATIS (1979): 10 Å for illite (×4); 17 Å for smectite (×1); and 7 Å reflection for chlorite + kaolinite (×2). This procedure, established by BISCAYE (1965), is still in use for clay-mineral identification (MOORE and REYNOLDS, 1989). However, there has been some recent skepticism expressed concerning its application to fully quantitative anal-

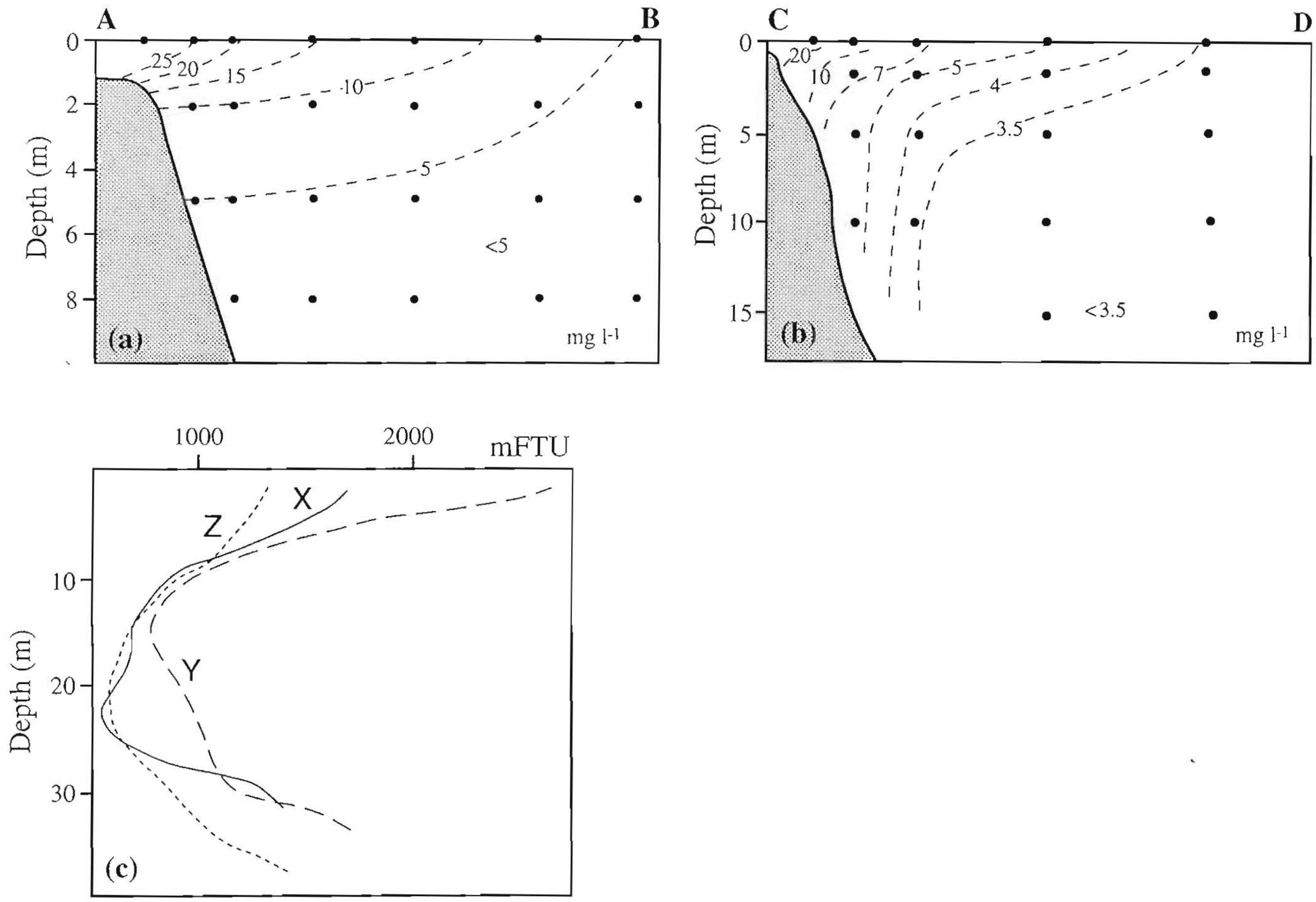

Figure 4. Suspended sediment concentrations throughout the vertical and along the main longitudinal dispersal axis of the plume of R. Louros (a), R. Sperchios (b) (measurements points shown), and within the water column (in turbidity units) at stations offshore the mouth of the Rivers Axios and Aliakmon (for station locations, see Figure 2) (from POULOS, 1989).

yses (McMANUS, 1991). Use of this technique in the present investigation is considered useful since: (a.) no superior technique is available to produce more reliable quantitative results, with all such methods being "semi-quantitative" in character; and (b.) the application of this procedure, used in previous studies in the eastern Mediterranean Sea (*e.g.*, VENKATARATHNAM and RYAN, 1971; SHAW, 1978; CONISPOLIATIS, 1979; CONISPOLIATIS and LYKOUSIS, 1986; and, STANLEY and LIYANAGE, 1986), ensures that the same systematic errors are involved and that results can be directly compared.

RESULTS AND DISCUSSION

Sand, Silt and Clay Content

The grain-size distribution patterns (expressed as percentages of sand, silt and clay) of the surficial bottom sediments, adjacent to and offshore from the mouths of the Rivers Louros, Arachthos and Sperchios, are shown in Figures 6, 7, and 8. The sand, silt and clay distributions within the deltaic deposits of the Rivers Axios and Aliakmon (abstracted from CONISPOLIATIS, 1979) are shown in Figure 9.

The surficial sea-bed sediments of the deltas can be divided into three regions according to their grain size, the subaqueous delta morphology, and associated depositional mechanisms. These regions are: (a.) the area around the rivermouth, including the distributary mouth bar and the nearby shoreline and extending into water depths of about 5 m; here, sand is dominant (>60%), supplied mainly by the river outflow and to a lesser extent modified by coastal erosion and; occasionally some offshore and longshore transport of sand is expected to take place due to wave activity. (b.) The delta front region extending between 5 m and 20 ± 5 m, where the sand content decreases rapidly with depth to <5% at water depths of >15 m and; silt and clay predominate, with the silt content exceeding the clay by approximately 20%. (c.) The prodelta area, incorporating water depths >20 m; here, silt content decreases gradually to seawards to <40% whilst the corresponding clay content exceeds 60% and; the (fine) sand content is very low, *i.e.*, <0.5%.

The distribution patterns described above, resulting from interaction between the fluvial and marine processes, are consistent with those associated with most subaqueous del-

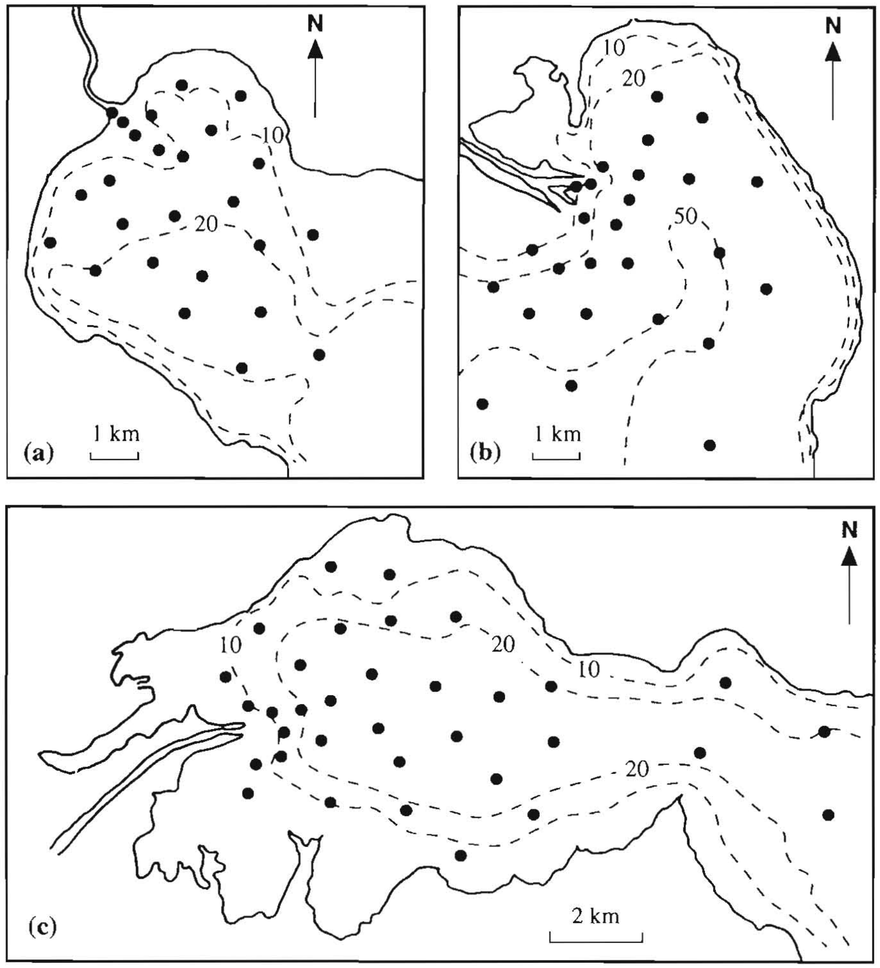

Figure 5. Sea bed sampling positions over the various delta areas: (a) R. Louros; (b) R. Arachthos; (c) R. Sperchios. Bathymetric depths in metres.

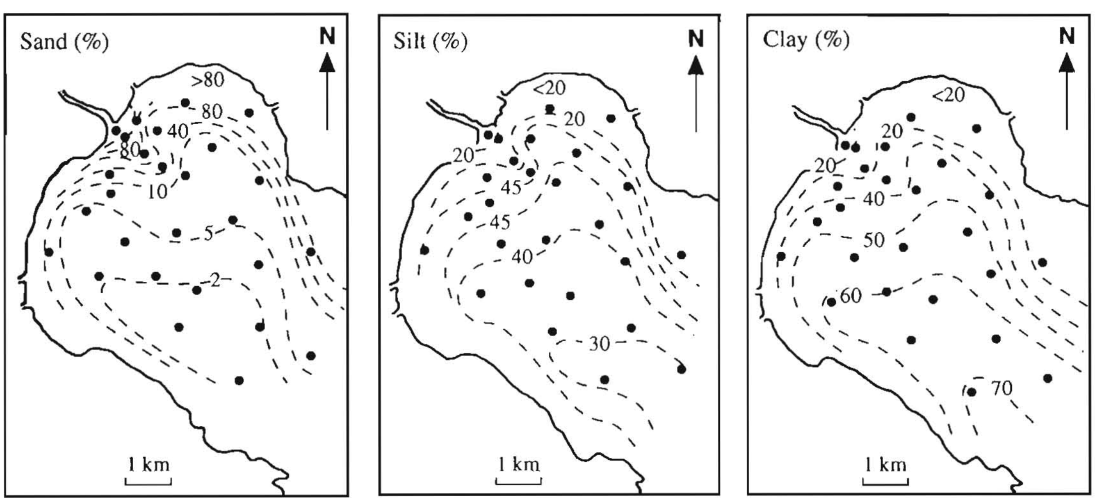

Figure 6. R. Louros: sand, silt and clay content (%) of the surficial sea bed sediments.

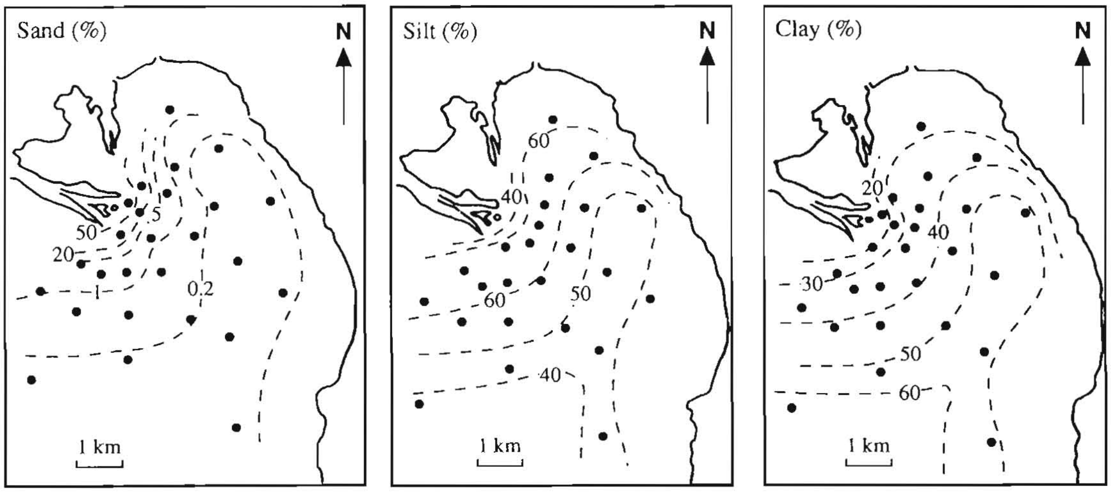

Figure 7. R. Arachthos: sand, silt and clay content (%) of the surficial sea bed sediments.

taic deposits described elsewhere by SCRUTON (1960), COLEMAN (1981) and WRIGHT (1985).

The near-mouth area is dominated by the sand fraction which is supplied by the river outflow as bed load (*e.g.*, pebbles, coarse sand) and in suspension (*e.g.*, medium sand) when, during high river discharges, the velocity of the freshwater outflow exceeds 1 m/sec; this is the case of Louros River (Figure 3). In this region, some re-working of the deposited material takes place only very near the coastline (*i.e.*, in water depths of <2.5 m) during short periods of high wave activity (POULOS *et al.*, 1993).

The sediments deposited over the delta front and prodelta areas are supplied, mainly, by the sediment-laden river plumes. These plumes consisting of fresher water move seawards, gradually losing their initial momentum (*e.g.*, plume of R. Louros (Figure 3)) and transporting ability. Thus, deposition of suspended sediment takes place initially over the delta front area. Besides, spatial and vertical salinity differences between the fresher plume waters and the ambient seawater (see also Figures 2 and 3) is expected to induce flocculation processes, leading to the further deposition of suspended particles (WHITEHOUSE *et al.*, 1960). Salinity differences >5 ppt have been measured at the mouths of the rivers Louros, Arachthos, Sperchios (POULOS, 1989) and Axios and Aliakmon (ROBLES *et al.*, 1983) during moderate to high river discharges (see also Figure 2).

Farther offshore, over the prodelta area, the plume is characterized by low velocities and only small salinity differences compared with those of the ambient seawaters. Under such conditions, the very fine-grained sediments (*i.e.*, fine silts and clays) are expected to be deposited primarily as individual particles; and secondarily, they may be deposited as flocs and/or pellets.

Clay Minerals

The relative percentages of illite, chlorite + kaolinite and smectite contents in the <2 μm fractions of the surficial subaqueous deposits in the areas of the deltas of the Rivers Louros, Arachthos and Sperchios are shown in Figures 10, 11 and 12. The clay mineral distributions within Thermaikos Bay (*i.e.*, the deltas of Rivers Axios and Aliakmon) have been abstracted from CONISPOLIATIS (1979) and presented in Figure 13.

Illite is the most abundant clay mineral present within each of the areas, varying from about 80% near the river mouth to 50% over the prodelta. The chlorite + kaolinite contents lie between 10% and 30%; smectite ranges from <10% near the river mouth, to 30% over the prodelta area. Similar concentrations of illite (40%–50%), smectite (30%–40%) and chlorite + kaolinite (10%–30%) have been reported for the open water areas of the Aegean Sea, by VENKATARATHNAM and RYAN (1971).

As a micaceous clay mineral, illite is abundant within most types of rocks and their corresponding soils (KOSTOV, 1967; WEAVER, 1989). Moreover, large quantities of illite can be expected to be supplied from the alluvium and easily-weathered clastic rocks (flysch and molasse) in the catchment areas of the rivers under investigation (Table 1). The abundance of illite in the associated soils of the very young epeirogenic mountain regions of southeastern Europe reflects the strong erosion of the tectonically-rejuvenated relief, rather than the slightly hydraulytic climate (CHAMLEY, 1989). High percentages of illite have been reported for the open Aegean Sea (VENKATARATHNAM and RYAN, 1971) and for Kavala Bay, in the northeastern Aegean Sea (CONISPOLIATIS and LYKOUSIS, 1986).

The chlorite + kaolinite contents over each of the areas lie between 10% and 30%. Pedogenic kaolinite predominates usually in areas of high-grade tropical weathering (KOSTOV, 1967; WEAVER, 1989); its presence in higher latitude sediments usually is associated with lateritic weathering processes (BISCAYE, 1965). In contrast, pedogenic chlorite is usually the product of mechanical rather than chemical weathering of argillaceous sediments and low-grade metamorphic

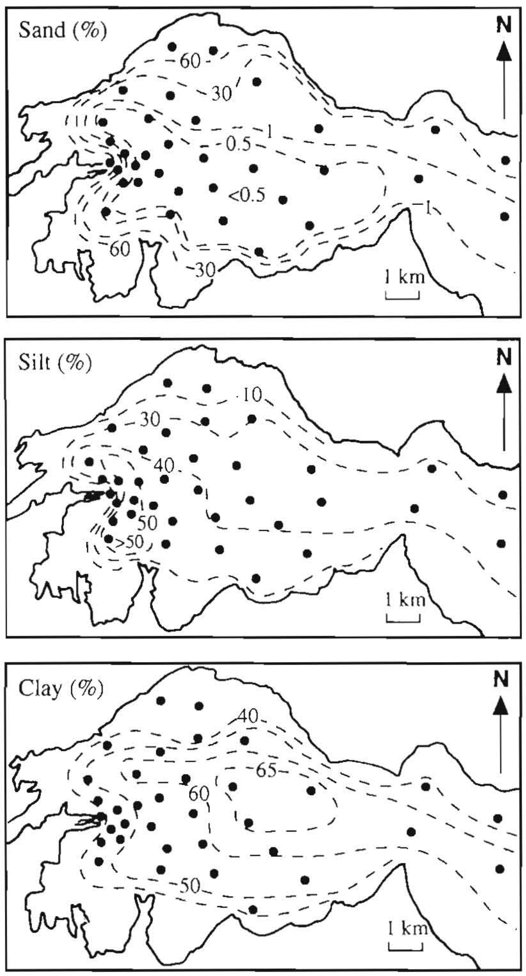

Figure 8. R. Sperchios: sand, silt and clay content (%) of the surficial sea bed sediments.

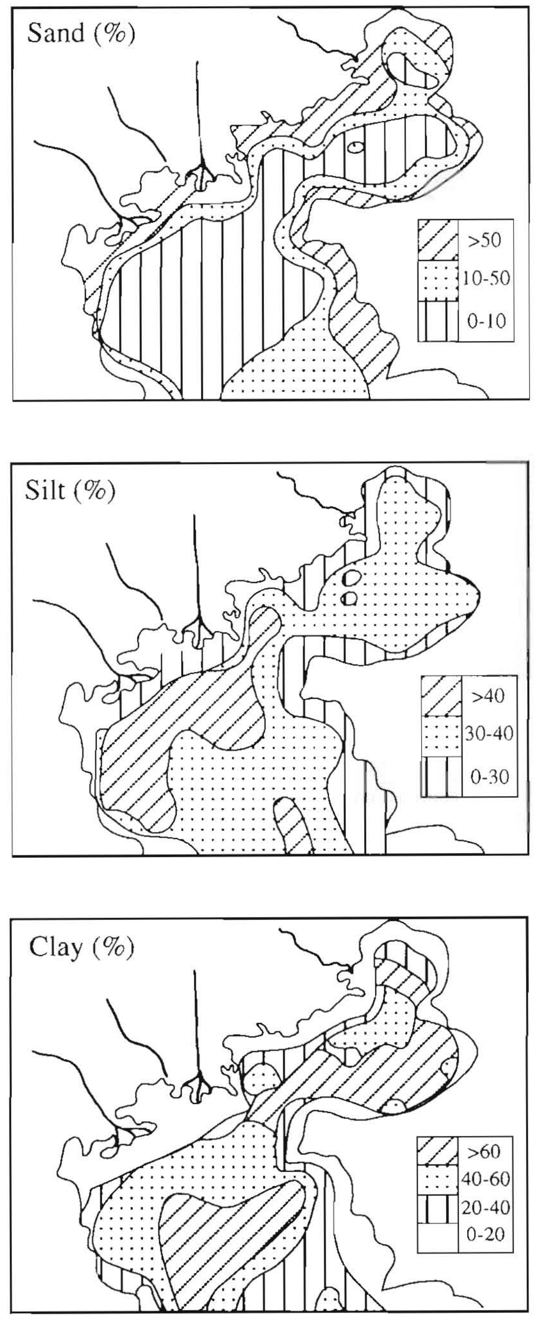

Figure 9. R. Axios and R. Aliakmon: sand, silt and clay content (%) of the surficial sea bed sediments (abstracted from CONISPOLIATIS, 1979).

and igneous rocks (BISCAYE, 1965). Since these rock types are not dominant within the catchment areas, chlorite is not expected to be abundant. Hence, modern formation of chlorite and kaolinite is not expected to take place within the regions studied; their presence might be attributed to the previous pedogenic and weathering history of the rocks within the catchment areas (CHAMLEY, 1989).

The low percentages (10%–20%) of smectite found within the deltaic deposits could be attributed to the limited presence of ultrabasic and pyroclastic rock outcrops within the catchments of the rivers (Table 1). Smectite would be produced by weathering of basic rock types (KOSTOV, 1967; CHAMLEY, 1989). The relatively high levels of smectite (>30%) within Thermaikos Bay may possibly be related to the greater presence of basic and volcanic rocks within the drainage basins of the River Axios and, to a lesser extent, the River Aliakmon.

Seawards of the river mouths, the clay mineral distribution patterns show an offshore decrease in the abundance of illite associated with an increase in the smectite content. The chlorite + kaolinite are generally more abundant over the delta front and at the commencement of the prodelta area. Similar clay mineral distribution patterns have been identified within the offshore surficial sediments of the Seyhan Delta Region in the Cilician Basin of southern Turkey (SHAW, 1978). This latter area of the eastern Mediterranean receives sediment

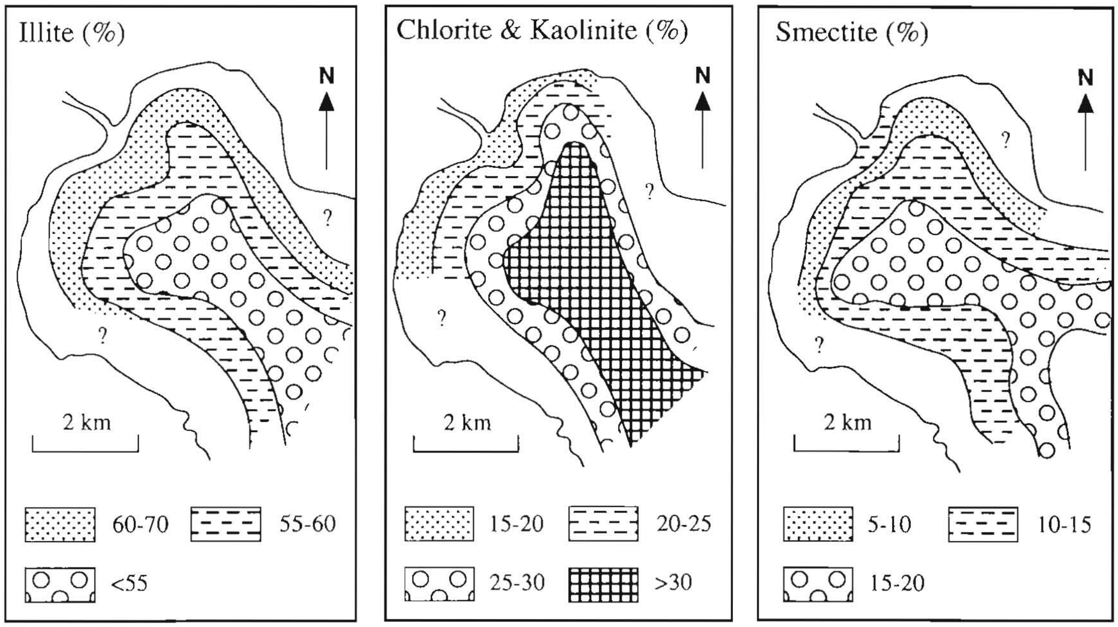

Figure 10. R. Louros: clay mineral distributions (%) within the surficial sea bed sediments.

from the numerous rivers and streams that drain the Taurus Mountains, which are characterised by geological and climatic conditions similar to those of the Greek river systems being investigated.

In embayments protected from intense wave action, the deposition of terrigenous clay minerals seaward of a river mouth is mainly related to river discharge levels, the relative abundance of the clay minerals within the source areas, and their rate of settling as either flocs and/or pellets. One of the factors inducing floc formation is related to an offshore increase in chlorinity (salinity) within the river plume, due to the upward entrainment of more saline ambient waters (see

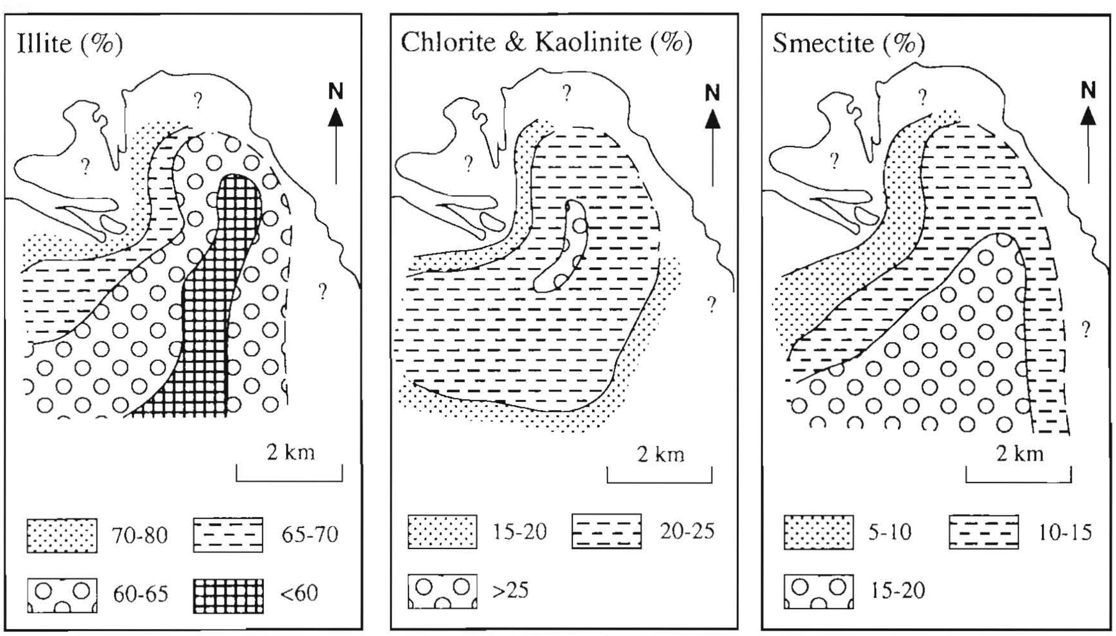

Figure 11. R. Arachthos: clay mineral distributions (%) within the surficial sea bed sediments.

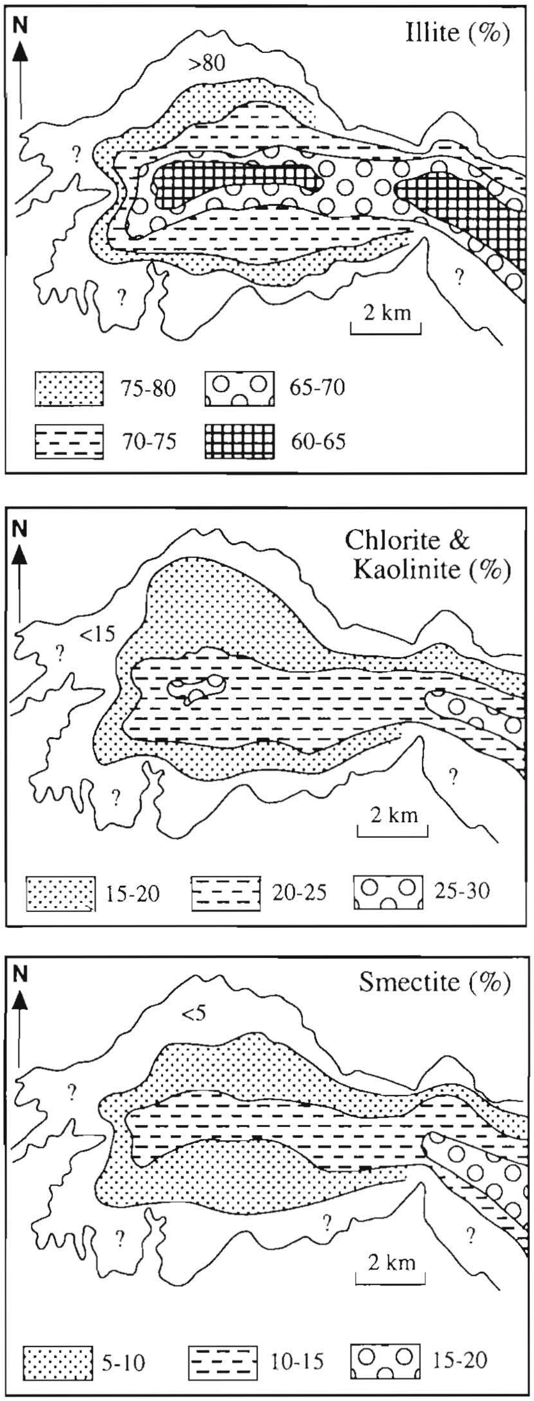

Figure 12. R. Sperchios: clay mineral distributions (%) within the surficial sea bed sediments.

Figure 3). In response to such a mechanism, illite, chlorite, and kaolinite are expected to be deposited closer to the river mouth, where the salinity differences between the river plume and the surrounding sea water are higher. Smectite settles farther offshore where the increasing salinity of the plume reaches eventually that of the seawater (WHITEHOUSE *et al.*, 1960). Unfortunately, no data are available to be able to investigate role of several biological processes.

In the case that floc formation is inhibited either by the presence of organic matter, coatings on the suspended particles or intensive turbulence, the clay minerals are deposited differentially according to their physical size (GIBBS, 1977). Investigation of the size distribution of various suspended minerals transported by the Amazon (GIBBS, 1977) and Mississippi (JONHSON and KELLER, 1984) showed that proportionally illite provides the largest particles, smectite the smallest, kaolinite is intermediate sized while chlorite particle sizes vary but are never larger than illite or smaller than smectite. As a consequence, CHAMLEY (1989) has indicated that clay mineral segregation by differential settling usually causes smectite to be transported farther offshore. The bottom sediments adjacent to each of the river mouths of the deltas, covered continuously by the river outflow even during very low discharge levels, are most abundant in illite. The relatively higher percentages of chlorite + kaolinite over the delta front and at the initial part of the prodelta are likely to be related to the presence of sediment-laden river plumes, even during moderate to low river discharges. Thus, the comparatively higher velocities (during floods) are capable of keeping in suspension and removing further offshore the finest of the clay minerals (*i.e.,* smectite), leaving behind the relatively coarser clay mineral grains (illite, chlorite, kaolinite). Over the prodelta area, the remaining very fine suspensates are deposited. Here, the very low velocities within the river plume, and the high salinities favour the settling of smectite either slowly, as individual particles, or relatively rapidly as flocs and/or pellets.

Similar distributional trends of clay minerals (illite and smectite) have been identified within the near-bottom nepheloid layer (up to 2 m above sea-bed) in the Thermaikos Gulf (CHRONIS *et al.*, 1989). Thus, on the inner shelf (extending down to 45 m) and under the influence of the plumes of the Axios and Aliakmon Rivers, the smectite/illite (S/I) ratio in the homogeneous bottom sediments increased by three times from nearby the river mouths (water depths <10 m) to offshore (in water depths of 30 to 40 m). Similarly, the S/I ratio within the observed bottom nepheloid layer increased by 4.5 times to seaward; this may incorporate some contribution from bottom resuspension. It appears, therefore, that there is a general correspondence between the observed clay mineral distribution pattern within the surficial deltaic sediments and the associated near-bed nepheloid layers.

CONCLUSIONS

The sedimentological characteristics of the various subaqueous deltaic deposits investigated are somewhat similar. Such similarity reflects their geological, climatological and oceanographic setting. All the deltas are formed by rivers draining southeastern Alpine Europe; they are climatically uniform in their setting, prograding into shallow and semienclosed embayments of the eastern Mediterranean Sea. Tidal activity is negligible and the waves play a secondary role, compared with riverine processes and their high sediment

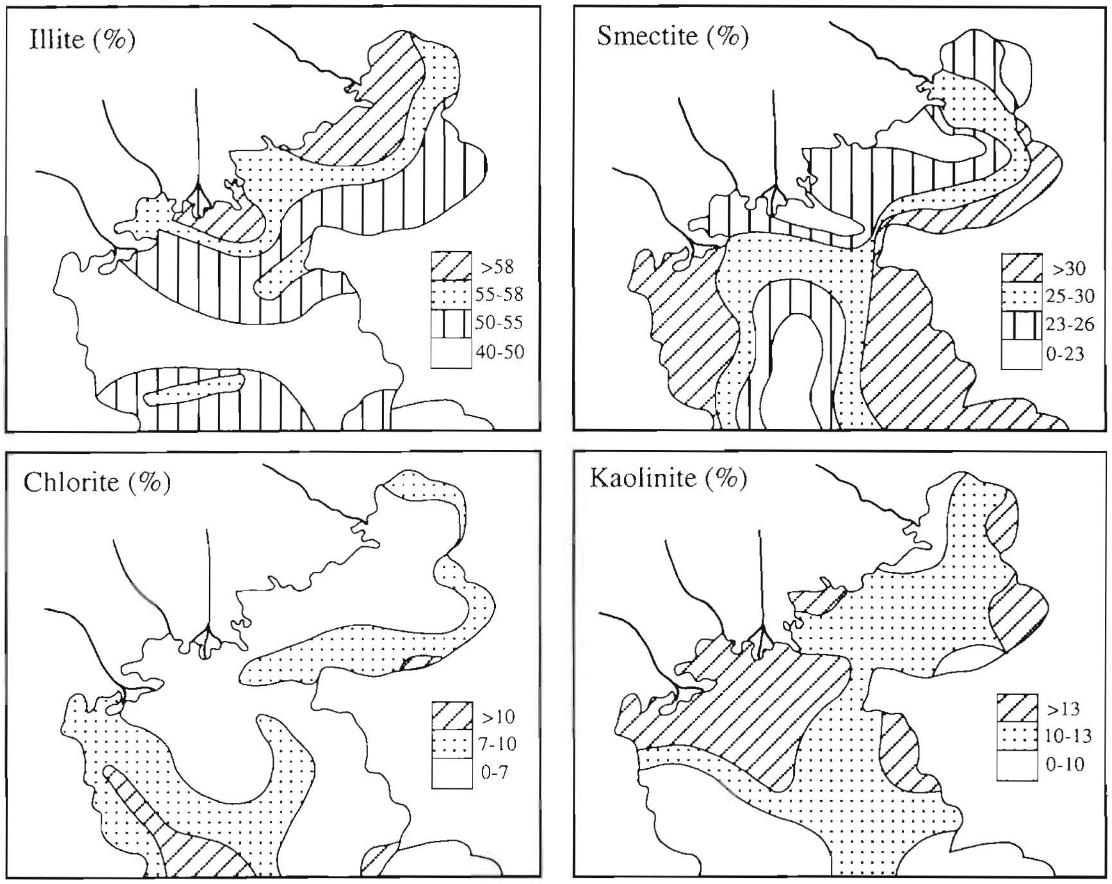

Figure 13. R. Axios and R. Aliakmon: clay mineral distributions (%) within the surficial sea bed sediments (abstracted from CONISPOLIATIS, 1979).

fluxes (MILLIMAN and SYVITSKI, 1992; and POULOS *et al.*, 1995).

The seabed profiles of the subaqueous deltas consist typically of three regions: the river mouth area (0–5 m), where the distributary mouth bar is formed; the delta front (from 5 to 20 ± 5 m), with a steeply-sloping sea bed; and the gentler sloping prodelta area. Deposition of sediments over these regions leads to the formation of topset, foreset and bottomset deltaic facies, respectively. Sand is the predominant (>60%) constituent material of the river mouths (topsets); its contribution decreases rapidly at the delta front (<10%), where silt and then clay become abundant (foresets). The prodelta area consists mainly of clay-sized (>70%) particles and some silt; sand is present only in minimal quantities (bottomsets). The absence of any relict sediments on the seabed in the areas covered by the sampling programme is indicative of the dominance of fluvial inputs and modern deltaic depositional processes.

The clay mineral distribution patterns, contained within the clay fraction (<2 μm) of the surficial bottom sediments of the subaqueous delta profile, show that illite is the dominant (50–80%) clay mineral present. It is more abundant at the river mouth, decreasing gradually seawards. Chlorite and kaolinite (10–30%) are more abundant than smectite near the river mouth and within the transition zone, between the delta front and the prodelta. Smectite increases with increasing distance from the river mouth and is relatively more abundant (about 30%) over the prodelta area. Similar distributional tendencies have been observed within bottom nepheloid layers in Thermaikos Gulf by CHRONIS *et al.* (1989).

For such depositional environments, subjected to minimal tidal and limited wave activity, subaqueous deltaic sedimentation (during moderate to high river discharges) is associated with: (a) seaward dispersion of the river outflow; and (b) processes related to the settling of the suspended material, such as flocculation and differential settling (*i.e.*, size sorting) and pelletization. Near the mouth of the river, freshwater outflow undergoes rapid deceleration and the coarser fraction of the suspended sediment (*i.e.*, sand and coarse silt) settles and contributes to the formation of the river mouth bar. Because of the dominance of the freshwater input over this region, differential settling is expected to be the dominant process.

Prograding from the delta front in an offshore direction, the river outflow spreads as a buoyant plume and continues to decelerate due to upward entrainment of the ambient sea water. Finer-grained material (*i.e.*, fine silt and clay) settles either through the formation of flocs or as individual parti-

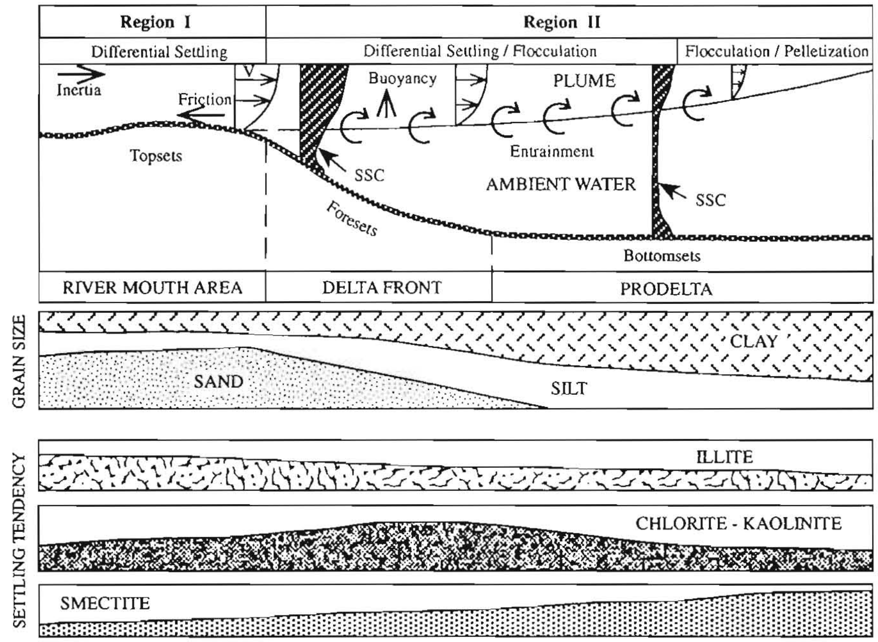

Figure 14. Generalised conceptual model of deltaic sedimentation processes, showing the dominant mechanisms controlling the deposition of fine-grained sediments. Currents are shown with arrows and the suspended sediment concentration profiles are shaded.

cles. The flocculation mechanism is regarded as being the dominant process here because of significant differences in salinity between the river plume and the ambient waters of the receiving basin.

Farther offshore and above the prodelta area where salinity differences between the slowly spreading plume and surrounding seawaters are very small, the very fine particles which remain in suspension are deposited as individual particles, flocs or pellets. Further, the depositional tendency of the clay minerals (described above) could result either from differential settling, flocculation, pelletization or a combination of these mechanisms.

On Figure 14, the processes summarised above have been integrated with the observed grain size distributions of (sand, silt and clay) and that of the clay minerals to provide a preliminary generalised model.

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