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ORIGINAL ARTICLE

# The influence of the Evros River on the recent sedimentation of the inner shelf of the NE Aegean Sea

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**Abstract** The transboundary Evros River discharges into the Alexandroupolis Gulf, located in the inner shelf of the northeastern Aegean Sea, where it has formed an extended delta. Grain-size and mineralogical analyses of five sediment cores, collected in the subaqueous delta, provide the following information about recent sedimentation processes in the northeastern part of the Aegean shelf: (a) river mouth deposits, consisting of coarse-grained sediments, are mainly deposited in front of the active mouth, whilst some sandy material is expected to be transported alongshore by nearshore currents; (b) delta front deposits are characterised by fine-grained sediments that include evidence of human activities which have taken place, in a more intense way, since the 1950s; and (c) prodelta deposits are represented by almost uniform riverine mud that cover the pre-existed relict sands of the shelf, indicating also the limit (some 15 km to the SW) of the influence of riverine sedimentation on the seabed of the inner shelf of the Alexandroupolis Gulf.

**Keywords** Deltaic sedimentation · Mineralogy · Human impact · Evros River · NE Aegean shelf

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## Introduction

Riverine water and sediment fluxes are decisive factors for the evolution of any deltaic system. Since the beginning of the 20th century, human interferences, expressed mainly by the construction of dams, alignment of river courses and over-pumping of groundwater, have resulted in a significant reduction of freshwater and sediment fluxes carried into the downstream parts of the river basin (i.e. deltaic plain) and/or the sea (Walling 1999; Milliman 2001; Vörösmarty et al. 2003). Such changes of the water flow and sediment budget have led to the degradation of many of the modern deltaic plains. This is expressed by: (i) substantial coastal retreat associated with dam construction, as in the case of the rivers Nile (Fanos 1995), Po (Simeoni and Bondesan 1997) and Ebro (Jimenez et al. 1997); (ii) loss of coastal wetlands, for example in Huanghe (Yellow) River (Yu 2002), Nile, Niger, Mississippi, Po, Danube, Ebro and other major rivers (McManus 2002); (iii) subsidence of the deltaic plain, e.g. in the Nile (Stanley 1996) and the Axios (Stiros 2001) deltas; (iv) salinisation of deltaic aquifers, such as in the rivers of Axios (Zalidis 1998), Ebro (Comin 1999) and Nile (Kotb et al. 2000). Deterioration of the deltaic sedimentological environment includes also incomplete development of the subaqueous delta, erosion of the adjacent seabed and changes in the sedimentary (granulometric) character of the surficial sediments, e.g. in the Yangtze River (Yang et al. 2003) and the Axios River (Kapsimalis et al. 2005).

Furthermore, the management of freshwater and sediment budget of rivers which cross or form the borders of two or more states, confronts many problems due to long-term lack of cooperation and/or unbridgeable gaps of policies, plans and practices, applied by the involved countries, e.g. in the Indus, Euphrates, Nile, Danube and Rhine rivers (Sadoff and Grey 2000) and the Pearl River (Chau and Jiang 2003).

The purpose of this paper is to identify the recent (within the last century) sedimentation processes of the subaqueous delta of the Evros River and to determine changes of the uppermost sedimentary facies related to human activities in its transboundary river basin and deltaic plain.

## The study area

### Physiographic setting

The Evros River, Maritsa in Bulgarian and Meriç in Turkish, is the second largest river of the Eastern Europe after the Danube River. Its total length is 515 km, whilst the drainage basin covers an area of 52,900 km$^2$, divided between Bulgaria (34,900 km$^2$, i.e. 66%), Turkey (14,550 km$^2$, i.e. 27.5%) and Greece (3,450 km$^2$, i.e. 6.5%) (Fig. 1). The lower part of the catchment belongs to the meta-alpine basin of Thrace (Fig. 2), infilled mainly of molassic sediments (~3,000 m thick) (Mountrakis 1985; Magganas 2002). Chalk-alkaline volcanism of the Eocene-Oligocene age produced extensive deposits of volcano-clastic tuffs interbedded by a variety of clastic sediments (Arikas 1979). In some places, Holocene sediments (~10 m thick) of alluvial or coastal origin cover the older formations (Lalechos 1986).

Surface lithology of the catchment area (Fig. 2) consists of volcanic–pyroclastic rocks (5.1%), fluvial depositions (43.3%), conglomerates and sandstones (6.9%), plutonic rocks (1.2%), terrigenous sediments interstratified by volcanic material (2.7%), Triassic schist, calcites, dolomites and marbles (2.1%), Plio-Pleistocene deposits (1.8%), flysch (0.6%), Precambrian crystalline rocks and migmatites (18.6%), granites and diorites (17.4%) and ultramafic rocks (0.3%).

The subaerial deltaic plain of the Evros River presents a lobate shape, covering an area of approximately 188 km$^2$, from which ~90% belongs to Greece and ~10% to Turkey; this shape indicates the dominance of the marine (wave) processes over the fluvial ones (Galloway 1975). In the western part of the delta plain, the uppermost sediments are mainly silts and clays with low sand content; in the northern part, the soil is rather fertile, consisting of silty clays, whilst in the southern part sands prevail (Ministry of Environment, Greece 1986).

In mid 1970s, the mean annual water discharge of the Evros River was 103 m$^3$/s; the period of high water discharge was between December and April, while monthly values ranged between 135 and 239 m$^3$/s (Therianos 1974).


**Fig. 1** Topographic map of the Evros River basin. *Dark-shaded* areas show high altitudes and *light-shaded* areas indicate low altitudes. The *solid line* designates the catchment; *dotted lines* represent the borders between countries; the *dashed line* denotes the Limnos Trough; and the *curved arrow* shows the Samothraki Anticyclon. A detailed map of the study area is shown in Fig. 3

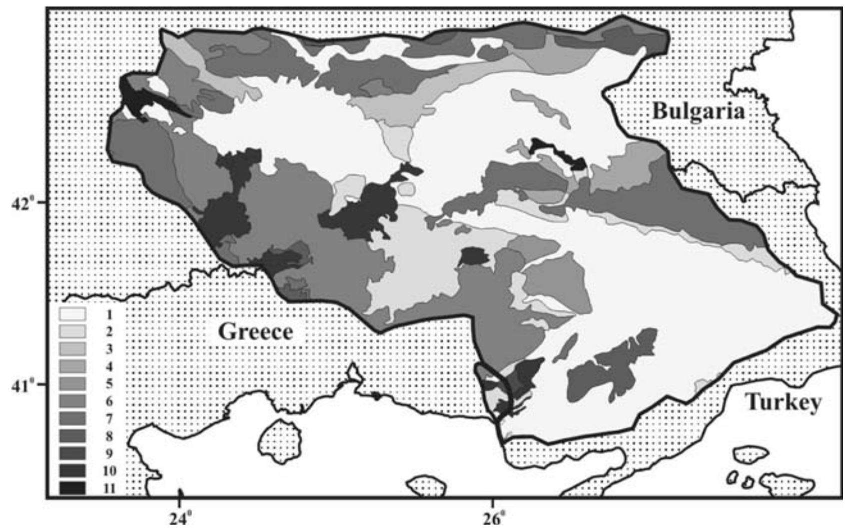


**Fig. 2** Simplified geological map of the Evros River basin (modified by Pehlivanoglou 1995). *1* fluvial deposits, *2* conglomerates and sandstones, *3* terrigenous sediments interstratified by volcanic material, *4* triassic schist, calcites, dolomites and marbles, *5* plio-pleistocene deposits, *6* precambrian crystalline rocks and migmatites, *7* granites and diorites, *8* flysch, *9* ultramafic rocks, *10* volcanic–pyroclastic rocks, and *11* plutonic rocks

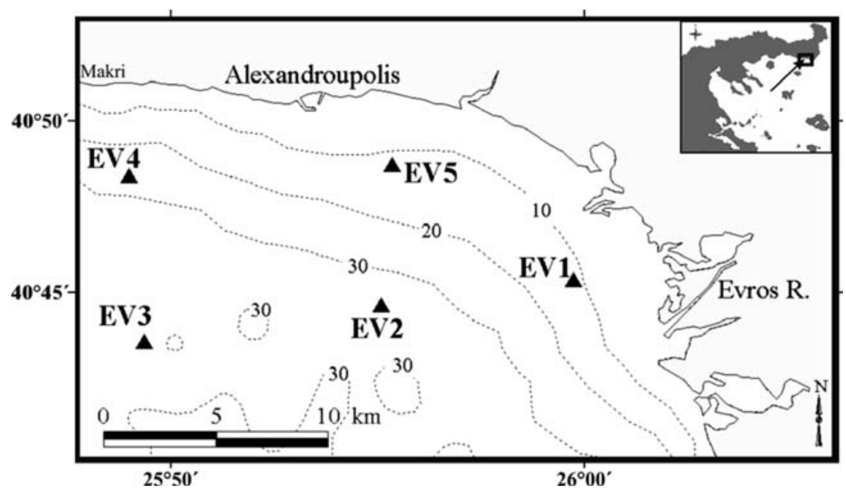


**Fig. 3** Bathymetric map of the northeastern Aegean Sea, showing coring positions in the Alexandroupolis Gulf (contours in metres)

The mean annual suspended sediment load has been in the order of $8.5 \times 10^6$ tons (J.D. Milliman, personal communication), whilst its mean annual dissolved load has referred to reach $2.6 \times 10^6$ tons (Poulos et al. 1996); the latter value is among the highest between all the Balkan rivers discharging into the Aegean Sea. However, the Evros River is expected to have a small riverbed load (<10% of the total sediment load) due to the high weathering resistance of its drainage basin rocks and the relatively low relief of its coastal zone, which is also related to the entrapment of coarser fractions in the deltaic plain.

The Evros River discharges into the relatively shallow (water depths <35 m) Alexandroupolis Gulf, which is located in the inner part of the Samothraki continental shelf; the latter is extended to the north of the Northern Aegean Trough (Fig. 1), where depths exceed 1,200 m. The morphology of the gulf is smooth with very low gradients (<1%), except at its SE and NW edges, where the relief gradients vary between 1 and 2% (Fig. 3).

The surficial sediments of the Alexandroupolis Gulf are mostly fine-grained and distributed mainly in zones with a SE–NW orientation, almost parallel to the nearshore bathymetric contours (Fig. 4). This zonal distribution reflects the subaqueous coastal topography, the influx of riverine sediments (Pehlivanoglou 1989), the near-shore wave and current regime, and the offshore sea-surface circulation pattern; the latter is related to the Samothraki Anticyclon, which disperses the riverine fine-grained sediment load to the south (Georgopoulos 2002). As shown on Fig. 4, there is a central zone consisting of clayey silts, whilst towards the north, the sediment becomes coarser with increasing sand content towards the coastline. Towards the south, there is a transition province which contains a mixture of clays and sands (sandy clay and clayey sand) up to the outer shelf area that is dominated by ‘relict’ sands, which most likely have been deposited during the last transgression, when palaeocoasts had being shifted landwards from a depth of 120–130 m to their present-day

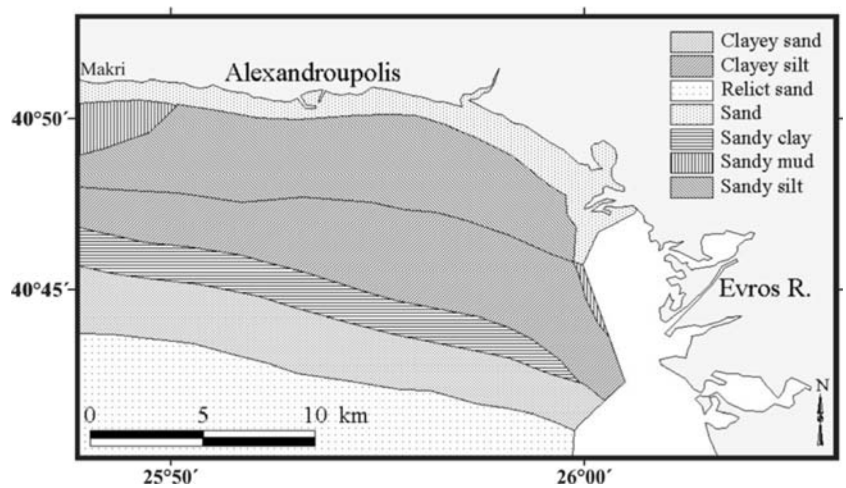


**Fig. 4** Surficial sediment distribution patterns of the Alexandroupolis Gulf (after Pehlivanoglou 1989)

position (Perissoratis and Mitropoulos 1989; Pehlivanoglou 1989 and 1995; Pehlivanoglou et al. 2000).

## Socio-economic setting: environmental management

The river basin of the Evros River hosts a total population of some 2.9 million people, from which the 61% (1.76 million) lives in Bulgaria, the 34% (0.99 million) in Turkey, and 5% (0.13 million) in Greece. The principal main cities and/or towns per country are: in Bulgaria: Stara Zagora (156,000 people), Haskovo (87,610), Pazardjik (86,100) and Dimitrovgrad (49,745); in Turkey: Edirne (134,400 people), Lalapaşa (10,800), Süloğlu (11,300), Uzunköprü (76,100), Lüleburgaz (111,400), Çorlu (154,600), Hyarabolu (40,600), Malkara (61,000) and Muratli (24,300); and in Greece: Orestiada (14,700 people), Didymoteicho (8,600) and Soufli (5,600).

The main land uses in the Bulgarian part of the Evros River basin include farming of cereals, tobacco, fresh vegetables, grass, forests, mines (gold, uranium) and pastures used in animal-culture. In the Turkish part, about half of the area is used for farming mainly of wheat, sunflower and rice, as well as sugar, cane, sesame, corn, onion, garlic, bean, watermelon and melon. In addition, industrial and commercial units have been established along the main motorways (Turkey–Europe Motorway and Bulgaria–Europe E5 Highway). Of particular significance are the wetlands present in the Turkish part of the Evros River delta. In Greece, and in particular in the deltaic plain, agricultural activities (farming of cotton, beet, wheat and corn), grazing of cattle and sheep, and hunting are the most significant activities, whilst aquaculture and commercial fisheries have been developed in the nearby coastal waters (Angelidis and Albanis 1996).

Human intervention to the nature of the Evros River system was not significant until the World War II, a fact that is proved from minimal morphological changes in the delta plain. During this period, the alluvial plain and the delta area have been used by the local communities mainly for stock-raising and agricultural activities. Since 1950, the situation has changed dramatically, primarily due to the construction and operation of 27 major dams and tens of minor reservoirs along the main route of the Evros River and its main distributaries, namely the Ergene River in Turkey, and the Ardas River in Greece. Nowadays, there are 18 major and tens of smaller dams in operation in Bulgaria; 8 dams and 59 reservoirs, for irrigation purposes, in Turkey; and 1 irrigation dam in Greece (Kyprinos), irrigating 25,000 ha of arable land. Moreover, the Turkish government will construct another three dams and four reservoirs within 2008 (GDSHW 2006).

Furthermore, in 1950s a major draining project carried out in the deltaic plain of the Evros River both in Greece and Turkey, including alignment of the lower course of the river accompanied by re-location of its mouth (some 7 km to the south of its natural mouth), construction of an extended irrigation network in order to gain some 6,000 and 3,400 ha of cultivated area in the Greek and Turkish part of the deltaic plain, respectively (Angelidis and Athanasiadis 1995; BirdLife International 2006).

The operation of the dams together with the increasing consumption of freshwater for irrigation and watering purposes have led to a reduction of riverine water and sediment fluxes towards the deltaic plain and its associated coastal area. Angelidis and Athanasiadis (1995) have reported changes in the hydrologic balance of the plain, reduction of the fresh groundwater level and increase of salinisation of the deltaic aquifers.

Although the UNESCO Chair/INWEB (International Network of Water Environment Centres for the Balkans) has declared the Evros River basin as one of the most significant transboundary catchments in Balkans, there is not yet any effective integrated management of its water resources. Huge problems in the decision-making processes arise due to lack of coordination and communication between authorities in a national, regional and even in a local level. Recently, two international programs have been contracted, entitled: (a) ''Assessment and Management of Transboundary Water Related Risks in the Balkans'' (TRANSRISKBA) funded by UNESCO/ROSTE Work plan for 2004–2005 and (b) ''Regional initiative for Internationally Shared Aquifer Resources Management in the Balkans'' (ISARM-Balkans) funded by UNESCO/IHP. The former deals with the assessment and resolution of potential conflicts related to transboundary water related risks in South Eastern Europe, whilst the latter aims to identify key issues and priorities for action in the catchment. In addition, the adoption of the EU Water Framework Directive (WFD) 2000/60 in the Greek legislation (L3199/03) provides also a significant tool for the sustainable management of the Evros River water fluxes.

Finally, the Evros River deltaic ecosystem has been recognized since 1986 as an important bird area, protected by the Ramsar Convention and the Bern Convention on special species of flora and fauna (Ministry of Environment, Greece 1986). It is also cited in the list of regions of special protection according to the EU Directive 79/409/EEC and the national Greek legislation 66/81.

## Materials and methods

Five sediment cores of 2.5 m maximum length were recovered from the Alexandroupolis Gulf during a cruise of the ''R.V. Aegaeo'', in February 1998 (Fig. 3). Grain size and mineralogical analyses were carried out in the laboratories of Hellenic Centre for Marine Research (HCMR), in order to reveal the sedimentary processes that have taken place in the study area.

All subsamples were split into sand and mud (silt + clay) fractions by wet sieving through a 63 μm mesh. The mud fraction was determined by a grain-size analyser (Sedigraph Micromeritics 5000 ET). Textural characterization of subsamples was based on the Folk's nomenclature (Folk 1974).

The mineralogical composition was determined by X-Ray Diffraction and performed on the bulk and the clay fraction (<2 μm) of all the samples. The XRD system was a Rigaku D/MAX B, using nickel-filtered Cu-$K_\alpha$ radiation and graphite monochromator. Scanning speed was normally $1^o$ $2\theta$ per minute. The diffractogram was obtained in the range of $2^o$–$50^o$ $2\theta$ for bulk mineralogy and $2^o$–$40^o$ $2\theta$ for clay mineralogy. The other diffractometer settings were: voltage, 40 kV; current, 20 mA; Divergence Slit (DS), $1^o$; Receiving Slit (RS), 0.3 mm; and Scatter Slit (SS), $1^o$. Each clay mineral was identified by its enhanced basal X-ray reflection: (a) chlorite was identified at the series of peaks of 14.2 Å (001), 7.1 Å (002), 4.73 Å (003), 3.55 Å (004); (b) illite at 10.1 Å (001), 5.04 Å (002), 3.36 Å (003); (c) kaolinite at 7.15 Å (001), 3.57 Å (002); (d) smectite at the board peak of 14–14.7 Å (001), which shifts to the 17–17.6 Å after glycolation. Following the method of Biscaye (1964), semi-quantitative determinations of the relative abundance of major clay minerals were obtained on glycolated diffractograms by the intergraded peak areas. Cores EV3 and EV5 were not subjected to semi-quantitative analysis, as their clay content was very low (<10%).

## Results and discussion

### Grain size profiles

Core EV1, recovered from 13 m of water depth (at the seaward edge of the delta front) consists of fine-grained material (silt + clay > 90%) with the clay (C) fraction ranging from 46 to 80% (Fig. 5). The fact that the sand percentage is very small implies that almost all of the coarse-grained material is trapped within the subaerial deltaic plain and at the river mouth area. Sharp fluctuations of the silt and clay percentages at the core depths between 40 and 74 cm are likely to be associated with the deltaic-plain reclamation works, started in the 1950s which caused a major change in the river's hydrologic balance, including the shift of its mouth. This is confirmed by the estimated age of these sediment layers by $^{210}Pb$ determinations (Kanellopoulos et al. 2006). According to Kanellopoulos (2003), the mean carbonate content is ~2%. Such a very low value has also been observed in front of other Greek rivers, e.g. Axios River (Chronis 1986), Alfhios River (Poulos et al. 2002), and is attributed to the high accumulation rate of terrigenous material.

The dominant types of sediment grain sizes along Core EV2 (Fig. 5), collected from the prodelta area (sampling depth: 38 m), are sandy mud (sM), mud (M) and clay (C), according to Folk's (1974) classification. The upper 41 cm consist of brown mud, with some biogenic remains and indications of bioturbation. At depths between 42 and 194 cm, the sand content is high (12–25%), with the exception of two layers at 50–56 cm and 130–155 cm, where the sand fraction reaches values of 60 and 35%, respectively. Below the depth of 194 cm, the sand decreases from 22 to 3%. The high silt + clay content in the upper layers of the core (0–42 cm) indicates that recent sedimentation is taking place under low hydrodynamic conditions, i.e. beyond the reach of intensive wave activity, and is associated with riverine fine-grained sediment fluxes

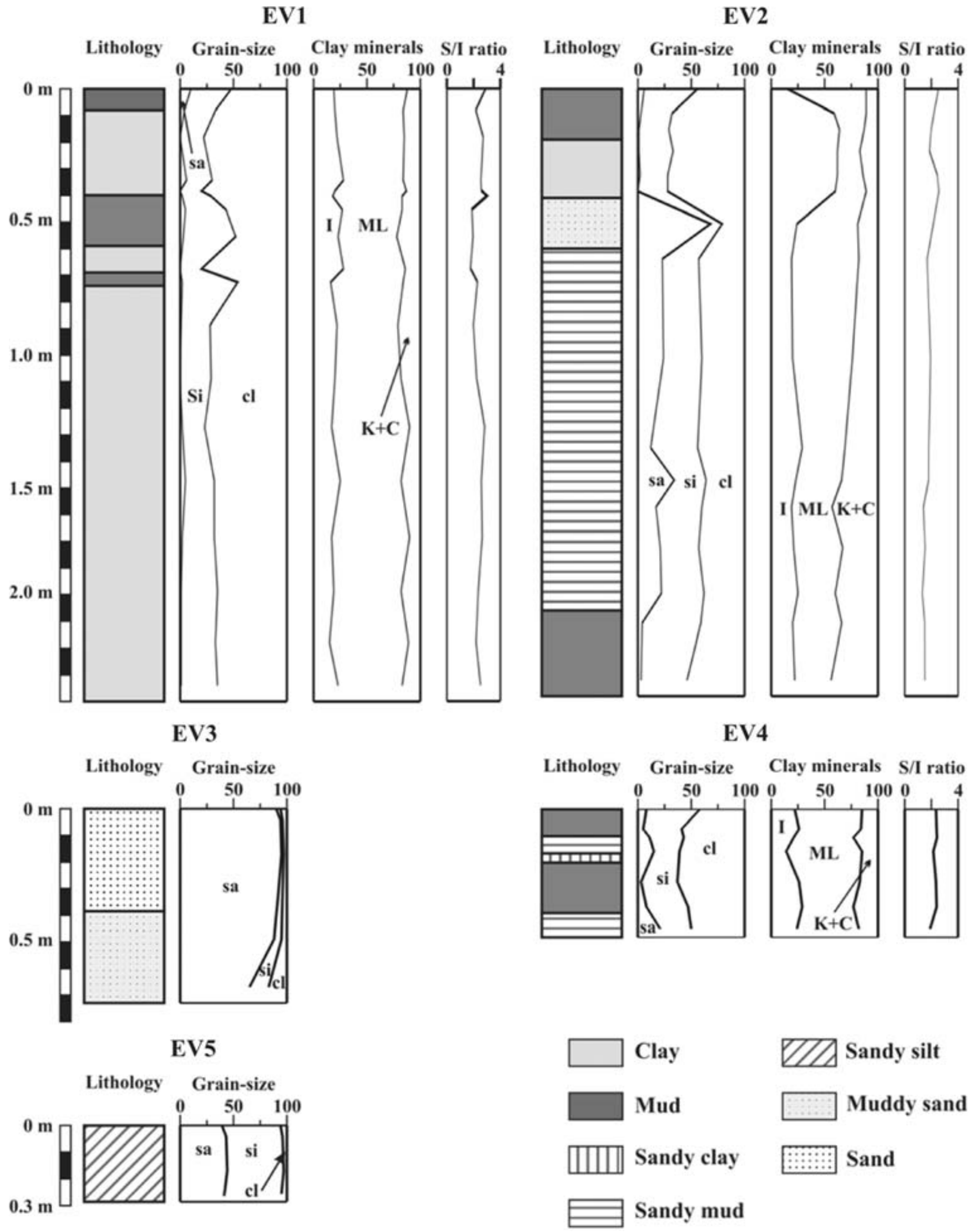


**Fig. 5** Variations of grain-size fractions, clay minerals and Smectite/Illite (S/I) ratio along the short cores. *sa* sand (>63 μm), *si* silt (63–2 μm), *cl* (<2 μm), *I* Illite, *K* Kaolinite, *S* Smectite, *C* Chlorite and *ML* Mixed Layers of Illite/Smectite

and to the offshore circulation pattern. The increased sand percentage (68%) between 50 and 56 cm may be attributed to some extreme events that could resuspend and transport sand-sized sediments from the nearby relict deposits; this extreme event could be, for example, the progradation over the inner shelf of a tsunami, like that took place in 1896 (Papazachos and Papazachou 2003), which was classified III+ on the Ambraseus scale and caused a lot of damage in Samothraki Island and the coastal area of Alexandroupolis.

The sediments of the Core EV3 (sampling depth: 45 m) are mainly sands (S), with a very low percentage of silt and clay (Fig. 5). Since the position of this core is very far from the river mouth (~20 km), only a few fluvial materials can reach this area, transported by the offshore water circulation. Furthermore, the sand fraction of these deposits is relict in origin, deposited during low stand periods of the sea level. Similar, relict sand deposits have also been found in many places of the North Aegean Shelf, e.g. the Thermaikos Gulf (Lykousis and Chronis 1989), the Agion Oros Gulf (Perissoratis and Panagos 1982), and the Thassos–Chalkidiki Shelf (Pehlivanoglou and Souri–Kouroubali 1984).

The Core EV4, collected from the coastal area to the west of the city of Alexandroupolis and to the east of the old mouth of the Evros River (sampling depth: 30 m), consists mainly of mud (M) interbedded by layers of sandy mud (sM) and sandy clay (sC) (Fig. 5). The sand fraction is less than 3% presenting higher values (up to 20.8%) at depths of 26–30 cm and 43–47 cm, respectively. The main source of the fine-grained material is believed to be the Evros River. This riverine material is transported westward by the littoral currents, whilst some of the terrigenous sand portion is associated with erosion processes of the adjacent coast.

Core EV5 abstracted from the upper part of the delta front area (sampling depth: 12 m) consists of sandy silt (sZ) (Fig. 5). Deposition in this area is controlled primarily by the sediment influxes of the Evros River and the Loutros River (a torrential river located to the west of the Evros River mouth) (Kanellopoulos 2003) and secondarily by entrapment of fine-grained material by the existed anticyclonic seawater circulation (Georgopoulos 2002).

## Mineralogical composition

Qualitative mineralogical analysis of the bulk sediments shows that the study area consists mainly of quartz, feldspars, micas, amphiboles, pyroxenes, carbonates and clay minerals. Feldspars are present as plagioclase and K-feldspars. Micas originate mainly from the igneous rocks of the drainage basin; they are represented by muscovite, while biotite seems to be absent in the Alexandroupolis Gulf sediments. The amphiboles, mainly actinolite, come from the Palaeozoic amphibolites found in the Bulgarian part of the catchment basin. Pyroxenes come from greenschists and metavolcanic series of the Rhodope Massif (Magganas 2002). Carbonates are mainly present as calcite and Mg-calcite; the latter is presumably of biogenic origin.

The main clay minerals found in the area are illite, kaolinite, smectite and chlorite, while mixed layers of illite/smectite are also abundant. Illite is derived from the weathering of the metamorphic rocks (schists) and unconsolidated Neogene and Quaternary coastal sediments (Pehlinanoglou et al. 2000). The possible origin of kaolinite is the trachyrhyolites from the eastern Rhodope Mountain, which is part of the Evros River catchment (Popov and Michalev 1990). Chlorite comes from chlorite schists of the Rhodope Massif (Magganas 2002). The mixed layers of illite/smectite originate possibly from the total vitiation of micas or feldspars under land weathering conditions (Tsirabidis and Trontsios 1993).

The vertical distributions of clay minerals and smectite to illite ratio (S/I) along the cores EV1, EV2 and EV4 are also shown in Fig. 5.

In Core EV1, the percentage of illite (I) varies between 15 and 28%. The minimum value is recorded at a depth of 206–210 cm, and the maximum value at depths of 34–36 cm and 67–69 cm. The interstratified illite/smectite content (ML) ranges from 55% (at 55–59 cm) to 74% (at 206–210 cm). The total percentage of kaolinite + chlorite (K + C) shows the minimum (11%) at depths of 167–170 cm and 206–210 cm, whilst the maximum (22%) is recorded at 55–59 cm depth. The S/I ratio fluctuates from 1.8 to 3.0 and shows a complicated pattern, corresponding to rapid changes of local hydrodynamic conditions and/or river discharges.

In Core EV2, the illite content ranges from 15 to 64% at depths of 1–3 cm and 15–19 cm, respectively. A significant decrease of illite occurs at the uppermost part of the core; this variation took place during the last 50 years, as it has been determined by $^{210}Pb$ analysis (Kanellopoulos et al. 2006). The mixed layers of illite/smectite show the minimum percentage (21%) at a depth of 23–27 cm and the maximum (74%) in the surface sediment. The kaolinite + chlorite content varies between 11%, at depths of 1–3 cm and 9–13 cm, and 45% at a depth of 219–224 cm. In general, there is a clear increasing trend of kaolinite + chlorite percentage in the deeper layers. The S/I ratio shows high and rapid fluctuations in the upper 60 cm of the core and an increasing trend in the lower parts. This pattern indicates that the modern sedimentary processes became more changeable and intensive than those, which correspond to lower and older sediments of the core, settled under more calm hydrodynamic conditions. Perhaps this is explained by the artificial displacement of the river mouth southward (in the 1950s) and, therefore, closer to the position of Core EV2. High S/I values indicate either low river discharge periods or ‘early settlement’ of smectite near the river mouth (Aloisi et al. 1977). Physicochemical properties of seawater, i.e. salinity, temperature, pH and Eh, together with high concentrations of Fe ions and organic carbon favour the flocculation and the subsequent settlement of smectite in front of the river mouth (Pehlivanoglou et al. 2000).

In Core EV4, the minimum percentage of illite (14%) is recorded at a depth of 15–18 cm, while the maximum (29%) occurs at a depth of 35–39 cm. The interstratified illite/smectite ranges from 48 to 71% at depths of 35–39 cm and 15–18 cm, respectively. The kaolinite + chlorite content presents its lowest value (14%) at a depth of 15–18 cm and its highest value (24%) at a depth of 35–39 cm. The S/I ratio remains almost constant, indicating stable sedimentation conditions.

## Recent sedimentation and future evolution

Sedimentological data, derived by the study of our short cores, complies with the results of the analysis of surficial sediments published earlier by Pechlivanoglou (1989), showing the zonal distribution pattern of the subaqueous deltaic facies of the Evros River in the Alexandroupolis Gulf (Fig. 6). The main axis of deltaic growth is directed towards E-W, with riverine mouth deposits to cover the

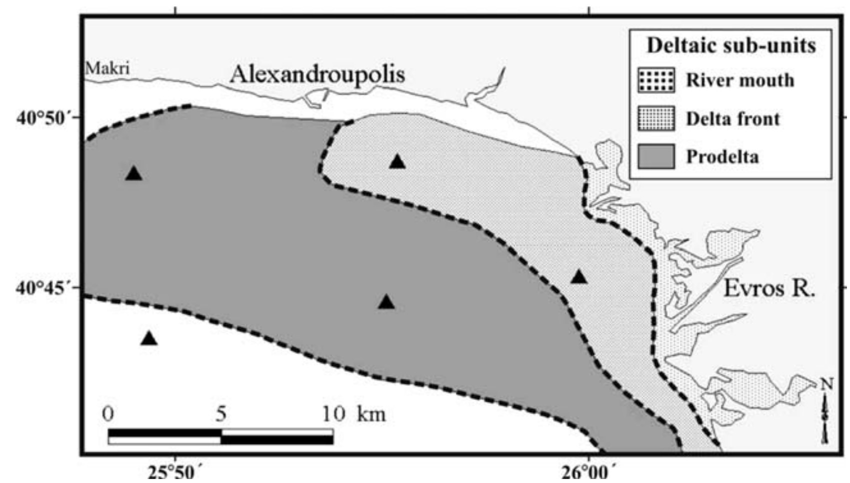


**Fig. 6** Depositional units of the Evros River delta in the Alexandroupolis Gulf. The *dashed lines* represent the tentative boundaries between the deltaic sub-units of the river mouth, delta front and prodelta

nearshore zone (water depths < 5 m). The delta front sediments cover a large part of the Gulf, whilst the prodelta deposits are extended to the central and western part of the Gulf; the outer southern and southwestern part of the Gulf remains unaffected by the modern riverine processes. It is covered by sands deposited during lower sea level stages; moreover, their 'relict' character was revealed by granulometric examination under the microscope.

The growth axis of the modern delta does not coincide with the southward direction of the main river channel at the commencement of the deltaic plain, but it is turned to the W; this is the case for both the old and modern river mouth resulting from the coastline configuration of the gulf, the incoming high waves from the S and SW and associated longshore currents. Such a shift has also been observed by Chronis et al. (1991) in the case of the deltas of the Ebro River (Spain) and the Po River (Italy).

The majority of riverine coarse-grained sediments are likely to be entrapped in the deltaic plain and only a small amount of them are to be deposited in front of the river mouth, forming topset facies. Sometimes, fine sand can escape towards the open sea when special conditions are present, i.e. river floods and extreme meteorological phenomena (storms). Pehlivanoglou (1995) points out that on the northern coast of the Alexandroupolis Gulf, complicated pattern of long shore drift exists. From the river mouth up to the city of Alexandroupolis the riverine sand moves to the west, whilst from Makri to the city of Alexandroulopis coarse-grained sediment derived by coastal erosion moves to the east (for locations, see Fig. 3).

Fine-grained sediments of riverine origin predominate in the delta front and prodelta facies of the Evros River delta. The main factors that control the distribution of these sediments are the grain size, mineralogy, flocculation and the hydrodynamic regime in the Gulf; the latter incorporates: (a) an offshore anticyclonic circulation pattern (Georgopoulos 2002); (b) offshore waves, approaching from S, SE and E directions (Kanellopoulos 2003); and (c) waves, induced cross and long-shore currents (Pehlivanoglou 1995). The effect of 'early settlement' of smectite (Aloisi et al. 1977) has been identified also in the delta front facies near the river mouth, whilst changes in the vertical distribution of clay minerals, e.g. increase of more than 35% of the illite content at the depth of 40–50 cm in the Core EV2, could be related to the diversion of the river mouth to the south during reclamation projects that took place in the 1950s; these have included river course rearrangement and other reclamation works on the deltaic plain for exploitation of new land for agricultural purposes. However, these works in association with the agricultural practice have changed the hydrologic regime of the river. This has resulted not only in salinisation of the surficial and underground waters of the southern delta plain (Angelidis and Athanasiadis 1995), but also, in changes in riverine sediment transfer and deposition. Nowadays, the river load is forced through two artificial channels, when in the past it discharged naturally through one main and many other secondary channels, possibly operating during flood events. This kind of reclamation does not allow sediments to settle on the delta plain, and therefore, enhances sediment transportation to the coastal waters. On the other hand, the construction of dams since the 1950s (most of them located in Bulgaria) has resulted in the upstream entrapment of a significant amount of sediment load. Kanellopoulos et al. (2006) found, based on $^{210}Pb$ inventories, that a reduction of the sedimentation rate has been recorded since the 1950s. Therefore, over the last decades, the decreased supply of most of the riverine coarse-grained and the reduced amounts of the fine-grained sediments has inhibited deltaic evolution and in anticipation to near future sea level rise could lead to the erosion and destruction of the deltaic coasts and ecosystem. Besides, apart from the quantitative modification of the sediment supply, the quality of the Evros River prodelta sediments has reduced in the last

50 years, since a considerable increase of heavy metals, such as Cu, Zn, Cd and Pb, has been reported (Kanellopoulos et al. 2006).

## Conclusions

The Evros River drains three countries (Bulgaria, Turkey and Greece) and flows into the Alexandroupolis Gulf, located in the northeastern shelf of the Aegean Sea. The submarine part of the delta is developed along a E-W direction, being the result of the interaction of the offshore plume dispersion, wave and nearshore currents induced predominately by the S, SW and W winds and the existed offsore anticyclonic sea-surface circulation pattern. The uppermost part of the subaqueous delta is characterized by three distinct depositional facies: (a) the river mouth sediments which are characterized by increased amounts of sand of river origin; (b) muddy delta front sediments that cover an extended subaqueous area to the water depths up to 18 m; and (c) prodelta sediments, consisting of distal fine-grained riverine deposits that rest on the pre-existed relict sands. The remaining seabed of the Gulf, which is not affected by the deltaic sedimentation, consists of relict sands deposited during lower sea level stands.

Human intervention in the river basin with the construction of more than 20 major hydroelectric and irrigation dams, together with the reclamation projects, which took place in the terrestrial part of the delta, since the 1950s, has caused changes in the sedimentary character of the subaqueous deltaic sedimentation patterns, shown by sharp changes of the grain size and clay mineral percentages. This is accompanied by the quality reduction, i.e. remarkable increase of heavy metals, of the prodelta sediments. Finally, the overall reduction of terrestrial sediment fluxes is expected not only to reduce further deltaic growth, but also to enhance its vulnerability to any future climatic change, i.e. sea level rise and increasing storminess.

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