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Distribution of surficial sediments in the Southern Evoikos and Petalioi Gulfs, Greece

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Abstract

A series of 123 surficial sediment samples from the Southern Evoikos and Petalioi Gulfs was studied for grain-size properties, carbonate content and mineralogical composition. Distribution of the sediments revealed two sedimentary provinces. The first concerns the Southern Evoikos Gulf, characterised by silty sediments with relatively low carbonate content. Quartz, feldspars, micas, clay and carbonate minerals are the major mineralogical components of the sediments. These sediments are the result of the Asopos River supply during Holocene and they contribute to the formation of smooth bottom morphology. The second province concerns the Petalioi Gulf (Northern and Southern), where the surficial sediments are mainly sandy and characterised by very high carbonate content. Their mineralogical composition reflects the lithology of the drainage basin. Since the modern terrigenous solid supply is limited, these sediments are not considered as products of recent sedimentation, but older deposits (relict sands). Their presence at such depths is justified by sea-level fluctuations and their preservation is due to the low sedimentation rate in the Petalioi Gulf, in combination with the strong hydrodynamic status of the area.

Keywords: Grain-size, Relict sands, Carbonates, Heavy minerals, Southern Evoikos Gulf, Petalioi Gulf.

Introduction

Holocene sedimentation in the eastern Mediterranean Sea is strongly influenced by sea-level changes that are related with global paleoclimatic changes of the late Quaternary (POMEROL, 1979). The period between 18 ka to about 5 ka B.P. is generally characterised by increased evaporation rate (initially at the tropic seas), retreat of glaciers, increased rainfalls and subsequent sea-level rise (FAIRBANKS, 1989). The latest sea-level rise evolved rapidly (up to 10 m 1 ka^{-1}; DONOVAN & JONES, 1979) and affected significantly the sedimentation patterns over the continental margins. During the last 5 ka B.P. the sea reached its present level; this relative stability resulted in the deposition

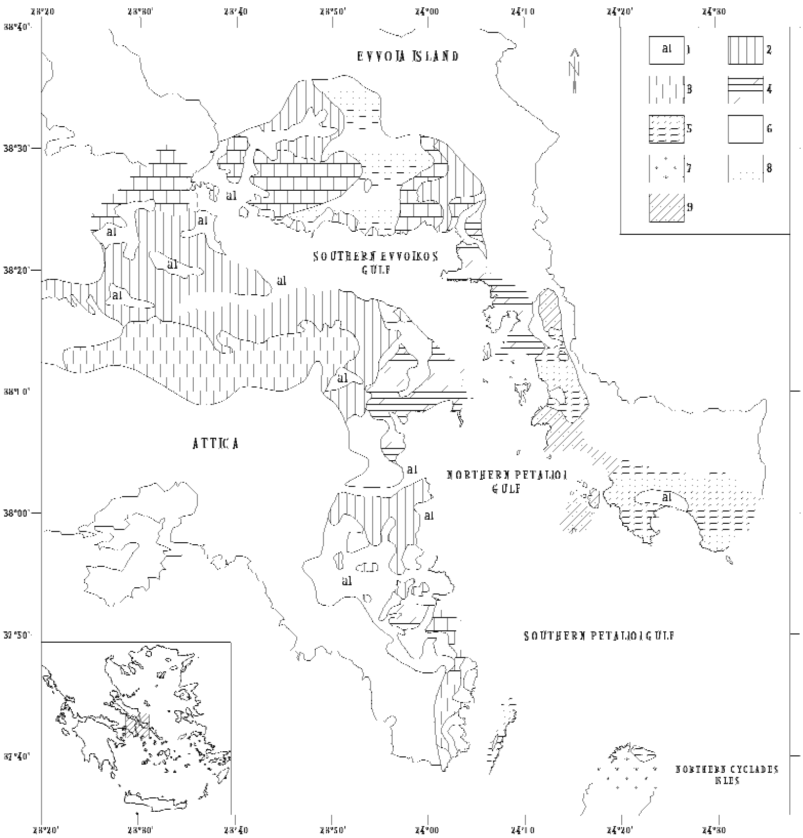

Fig. 1: Petrographic sketch. 1: modern deposits, 2: Miocene-Pliopleistocene lakustrine and terrestrial deposits, conglomerate, marls, sands, red soils, marly limestones, clays, lignites, 3: M.U. Triassic-Eocene, marbles and dolomites, crystal limestones, 4: Mesozoic-Paleocene, marbles and dolomites, crystal limestones, 5: Mesozoic, schists with interstratified marbles, green schists, 6: Jurassic, flint formation, 7: Paleozoic-Triassic, gneiss, schists, amphibolites, 8: Carboniferous-Triassic, schists, phyllites, graywacke, marbles, conglomerates, 9: Cipollines with schists. Modified from BORNOVAS & RONTOYIANNI-TSIAMBAOU (1983).

of homogeneous fine-grained sediments. The upper Holocene sediments as a thick and silty suite, known by the term "Holocene cover", are found in angular unconformity with the older deposits (CHRONIS, 1986).

This paper studies the horizontal development of the Holocene cover in the Southern Evoikos and Petalioi Gulfs (Central Greece). The Holocene cover is the result of the modern dynamic processes, mainly hydrodynamic, geochemical and biological. These processes are studied in relation to the surficial sediments properties: (i) grain-size; (b) carbonate content; and (c) mineralogical composition. In addition, the geological and physico-geographic regime of the adjacent land, which constitutes the supplier of the marine area with terrigenous material, is examined.

Geological and physicogeographic data

Limestones of Triassic to Eocene age and Neogene and Quaternary conglomerates, sands and marls predominate in the northern section of the adjacent land. In the cen-

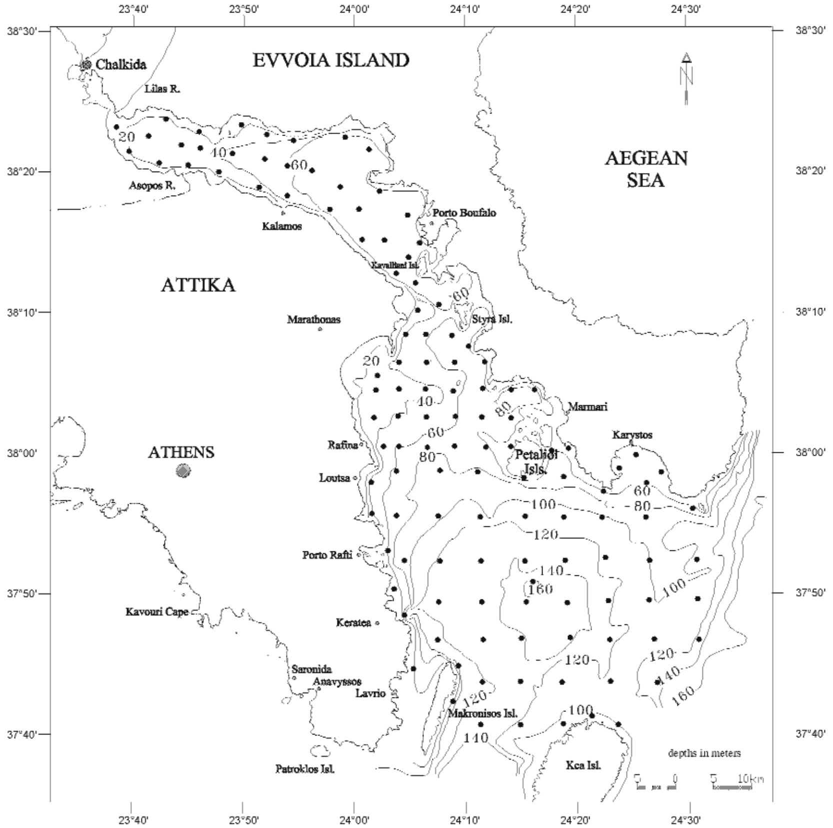

Fig. 2: Bathymetric map and surficial sediments sampling stations (black dots).

tral and southern section of the adjacent land metamorphic rocks dominate, mainly schists, phyllites and marbles, with ages ranging from Carboniferous to Upper Triassic (Fig. 1). The hydrographic network of the area is generally not well developed. The only significant river is the Asopos, flowing in the Southern Evoikos Gulf, with an annual water discharge of 23 x 10^6 m^3 (THERIANOS, 1974). In addition, the small Lilas River and other ephemeral streams discharge in the latter area during the winter and spring seasons.

The marine area under investigation comprises two sub-basins formed during the post-alpine evolution of the Cyclades plateau. The first basin extends from Chalkida to Porto-Boufalo and the second one from Porto-Boufalo and Kavalliani Isl. to the Makronisos and Kea Isles, and the southern tip of Evoia Isl. (Hydrographic Service, 1982; LYKOUSIS & SOURI - KOUROUMBALI, 1984; LYKOUSIS *et al.,* 1989; PAPANIKOLAOU *et al.,* 1989; KARAGEORGIS, 1992).

Over the Southern Evoikos Gulf water depths range from 20 to 68 m (Fig. 2) and the seafloor relief is characterised by low gradients (1:1000). Higher gradients and depths are observed in the Northern and Southern Petalioi Gulfs. In the latter area, depth contours show a concentric pattern and form a circular basin with a maximum depth of 162 m (KARAGEORGIS, 1992).

Recent current measurements with acoustic devices (ADCP, Acoustic Doppler Current Profiler) showed that the current velocities in the Southern Evoikos Gulf are

Table 1
Grain size classification (wt. %), mean grain size Mz (phi) and total carbonates (wt. %) of the samples analysed.

Sample	Sand %	Silt %	Clay %	Mz phi	Carbo-nates %
Southern Evoikos Gulf					
NE-1	1.24	62.22	36.54		10.70
NE-2	0.89	73.10	26.01		14.00
NE-3	2.79	58.74	38.47		19.30
NE-4	2.44	63.07	34.49		25.80
NE-5	28.97	31.96	39.07		40.60
NE-6	0.18	34.04	65.78		17.30
NE-7	0.72	59.20	40.08		20.40
NE-8	0.75	44.28	54.97		17.30
NE-9	1.49	48.71	49.80		21.70
NE-10	0.94	57.12	41.94		22.40
NE-11	0.38	54.17	45.45		23.60
NE-12	1.72	64.71	33.57		38.40
NE-13	18.13	50.40	31.47		72.20
NE-14	0.43	49.54	50.03		25.80
NE-15	3.13	64.43	32.44		26.90
NE-16	1.12	58.71	40.17		18.70
NE-17	17.77	55.11	27.12		36.00
NE-18	0.87	68.78	30.35		24.10
NE-19	0.95	54.48	44.57		21.60
NE-20	3.34	73.59	23.07		21.90
NE-21	1.41	47.33	51.26		20.00
NE-22	0.55	59.67	39.78		20.70
NE-23	1.08	42.54	56.38		25.50
NE-24	0.38	43.83	55.79		24.10
NE-25	0.54	37.79	61.67		22.10
NE-26	16.60	50.04	33.36		14.50
NE-27	0.76	50.61	48.63		22.80
NE-28	12.10	45.25	42.65		29.60
NE-29	0.92	38.65	60.43		26.90
NE-30	2.11	49.92	47.97		25.70
NE-31	69.29	16.89	13.82		22.70
NE-32	1.17	42.50	56.33		31.40
NE-33	1.42	49.29	49.29		31.70
NE-34	10.97	41.84	47.19		76.30
Northern Petalioi Gulf					
NE-35	7.42	64.80	27.78		80.40
NE-36	18.22	55.61	26.17		66.10
NE-37	25.88	35.58	38.54		68.80
NE-38	26.32	36.84	36.84		46.30
NE-39	6.19	65.76	28.05		49.50
NE-40	62.07	25.79	12.14	2.80	55.60
NE-41	54.67	30.37	14.96	2.50	54.60
NE-42	9.12	80.88	10.00		37.70
NE-43	69.69	21.82	8.49	2.70	46.40
NE-44	55.97	26.86	17.17	2.23	59.00
NE-45	26.42	41.20	32.38		76.90
NE-46	44.80	35.84	19.36	1.13	79.50
NE-47	48.34	23.22	28.44	2.22	82.20
NE-48	40.53	33.30	26.17	3.10	65.30
NE-49	5.55	50.06	44.39		42.20
NE-50	2.42	69.28	28.30		40.30
NE-51	12.81	65.39	21.80	3.65	45.20
NE-52	40.09	37.74	22.17	2.62	74.90
NE-53	24.96	43.52	31.52	2.70	87.00
NE-54	35.59	46.28	18.13	2.55	79.50
NE-55	68.96	13.35	17.69	2.70	69.40
NE-56	18.18	42.55	39.27	2.18	76.60
NE-57	66.87	24.18	8.95	2.43	44.40
NE-58	39.98	40.21	19.81	2.15	77.50
NE-59	47.34	29.49	23.17	3.18	67.80
NE-60	75.34	12.33	12.33	3.37	58.80
NE-61	47.25	42.25	10.50	1.32	87.30
NE-62	54.12	25.69	20.19	3.28	83.60
NE-63	56.33	20.09	23.58		66.70
NE-64	60.06	22.76	17.18	1.87	66.80
NE-65	48.14	31.12	20.74	2.67	73.90
NE-66	34.27	34.18	31.55	2.67	88.10
Southern Petalioi Gulf					
NE-67	25.27	51.56	23.17		85.20
NE-68	50.35	44.69	4.96		62.80
NE-69	65.38	31.50	3.12		49.50
NE-70	23.50	35.68	40.82		91.50
NE-71	63.92	25.98	10.10		67.00
NE-72	25.75	65.34	8.91		28.40
NE-73	33.95	56.14	9.91		50.50
NE-74	30.34	48.76	20.90		87.60
NE-75	67.37	27.41	5.22	1.88	62.50
NE-76	43.22	28.96	27.82	1.25	94.80
NE-77	54.78	32.11	13.11	3.25	68.50
NE-78	71.24	26.35	2.41	2.07	82.50
NE-79	49.85	31.59	18.56	2.25	73.20
NE-80	44.13	40.23	15.64	3.52	76.50
NE-81	36.22	45.29	18.49	3.55	53.50
NE-82	37.55	38.09	24.36	1.90	78.10
NE-83	65.31	16.30	18.39	1.33	62.40
NE-84	57.24	24.80	17.96		68.40
NE-85	39.36	36.99	23.65		53.70
NE-86	34.04	44.19	21.77	3.08	63.10
NE-87	14.78	60.50	24.72	3.55	46.30
NE-88	20.95	56.92	22.13	3.52	47.60
NE-89	29.38	49.43	21.19	3.47	43.60
NE-90	55.42	27.64	16.94	3.47	44.90
NE-91	68.02	22.71	9.27	3.50	46.90
NE-92	79.66	14.85	5.49	3.20	68.70
NE-93	67.49	20.16	12.35	1.82	77.70
NE-94	44.04	33.58	22.38	1.35	77.80
NE-95	26.76	51.26	21.98	3.38	70.40
NE-96	79.74	14.59	5.67	3.48	44.20
NE-97	45.94	43.25	10.81	3.50	44.30
NE-98	36.76	45.53	17.71	3.50	42.90
NE-99	33.76	49.68	16.56	3.50	41.60
NE-100	14.68	65.70	19.62	3.48	42.80
NE-101	12.01	67.75	20.24	3.50	44.20
NE-102	44.58	42.12	13.30	2.63	66.30
NE-103	78.54	19.95	1.51		69.80
NE-104	37.83	46.63	15.54		67.10
NE-105	21.03	64.76	14.21	3.43	46.30
NE-106	47.35	36.86	15.79	3.47	48.30
NE-107	51.00	31.36	17.64	3.35	57.20
NE-108	68.76	25.93	5.31	3.02	68.70
NE-109	83.28	8.36	8.36	1.87	80.70
NE-110	86.18	6.50	7.32	0.07	80.80
NE-111	64.57	18.36	17.07	2.30	87.50
NE-112	58.21	30.92	10.87	0.78	84.00
NE-113	60.82	27.81	11.37	1.25	87.20
NE-114	51.25	25.84	22.91	3.27	79.50
NE-115	46.02	38.25	15.73	2.83	70.00
NE-116	29.19	36.11	34.70	2.80	74.00
NE-117	71.76	17.79	10.45		75.40
NE-118	38.58	35.63	25.79	3.25	81.80
NE-119	75.27	23.65	1.08	0.62	89.20
NE-120	51.21	27.32	21.47	0.98	80.50
NE-121	75.48	18.23	6.29		87.10
NE-122	94.43	5.02	0.55		60.20
NE-123	98.41	1.55	0.04		67.85

Mean Size values, Mz (phi) and classification

0 – 1	Coarse sand (Ψ > 0.5 mm)
1 - 2	Medium sand (0.5 < Ψ < 0.250 mm)
2 - 3	Fine sand (0.250 < Ψ < 0.125 mm)
>3	Very fine sand (0.125 < Ψ < 0.063 mm)

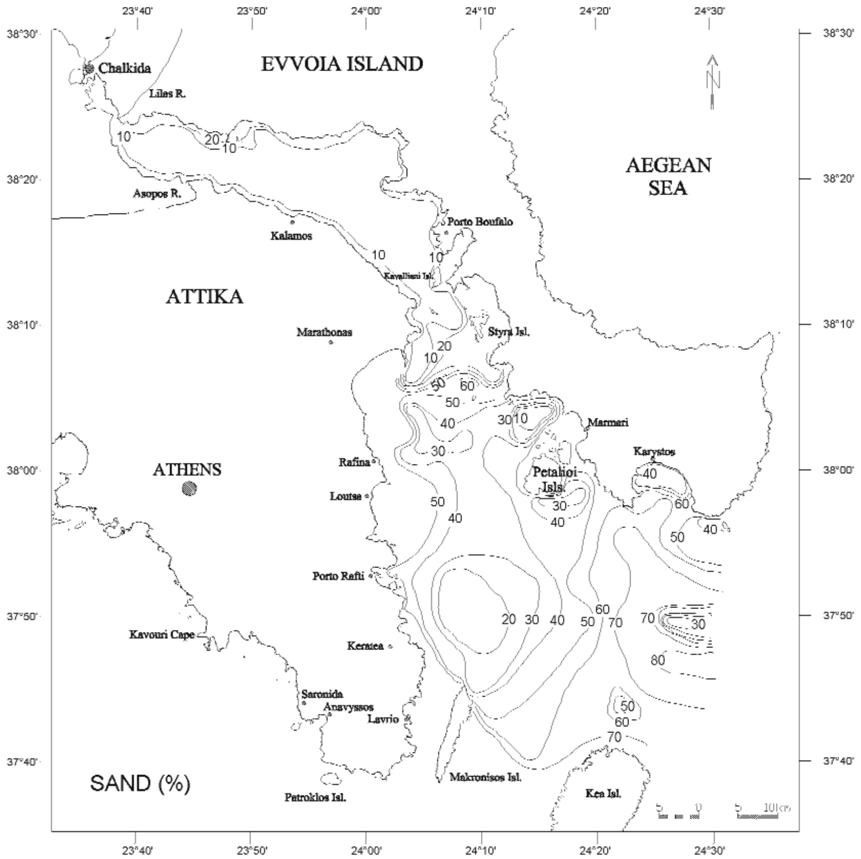

Fig. 3: Sand distribution (wt. %).

in the range of 5-10 cm/sec. In the Southern Petalioi Gulf bottom currents with velocities >40 cm/sec were measured (KONTOYIANNIS & PAPADOPOULOS, 1997).

Materials and methods

Fieldwork was carried out with the R/V AEGAEO of the National Centre for Marine Research, within the framework of the "Program of Open Hellenic Seas", during two oceanographic cruises (October 1986, December 1988). In a dense sampling network 123 samples of surficial sediments were collected with a Reineck stainless-steel grab.

All samples were dried overnight at about 65° C and then ground to a fine powder. Total carbonates were determined according to the method of MULLER (1964). Prior to particle size analysis, each sample was subject to: (a) organic matter elimination (digestion in 10% H_2O_2); and (b) carbonates elimination (10% HCl), (FOLK, 1974). Subsequently, the sand fraction (O > 63 □m) was separated by wet sieving, while the silt and clay fractions were determined by the X-Ray particle sizer Sedigraph (Micromeritics 5000 ET), at the Laboratoire Sedimentologie et Geochimie Marine of Perpignan (France).

Smear slides of all 123 samples were prepared for examination under the polarised microscope, along with 22 thin sections. Twenty-three samples were analysed by X-Ray Diffraction using a Rigaku D/Max B

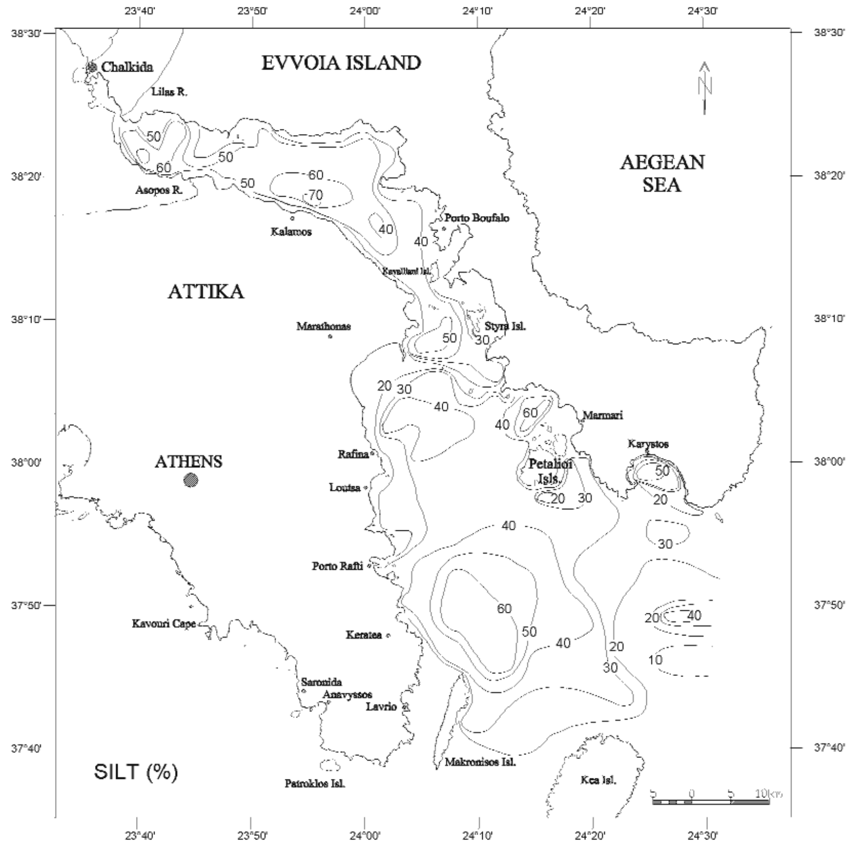

Fig. 4: Silt distribution (wt. %).

diffractometer with Ni-filtered CuK□ radiation. Randomly oriented samples were scanned over the interval 2-40^{o} 2□ at a scanning speed of 1^{o}/min.

Results

The grain size distribution (sand - silt - clay) of the samples analysed is given in Table 1; it should be noted that all samples were chemically treated for the removal of organic matter and carbonates. Carbonates mainly originate in the calcareous skeletons of various marine organisms as well as in the weathering products of the carbonate formations in the adjacent land. Thus, some information can be obtained concerning the origin and the hydrodynamic conditions that contributed to the processes of sediment transport and deposition.

The sand fraction distribution (Fig. 3) in the Southern Evoikos Gulf is particularly uniform, with low percentages in the range of 10-20%. This distribution follows the smooth bathymetry of the gulf (Fig. 2), with the relatively small depths and subdued seafloor relief. On the contrary, a different trend appears in the Northern Petalioi Gulf, with zones of increased sand percentage (40-60% at the western and central section). Local minima following the bathymetry are observed NW of Marmari. The Northern Petalioi Gulf may be considered that constitutes a transition zone from the shallow Southern Evoikos Gulf to the deeper Southern Petalioi Gulf, where the higher percentages of sand are observed. Specifically, in the Southern Petalioi Gulf a

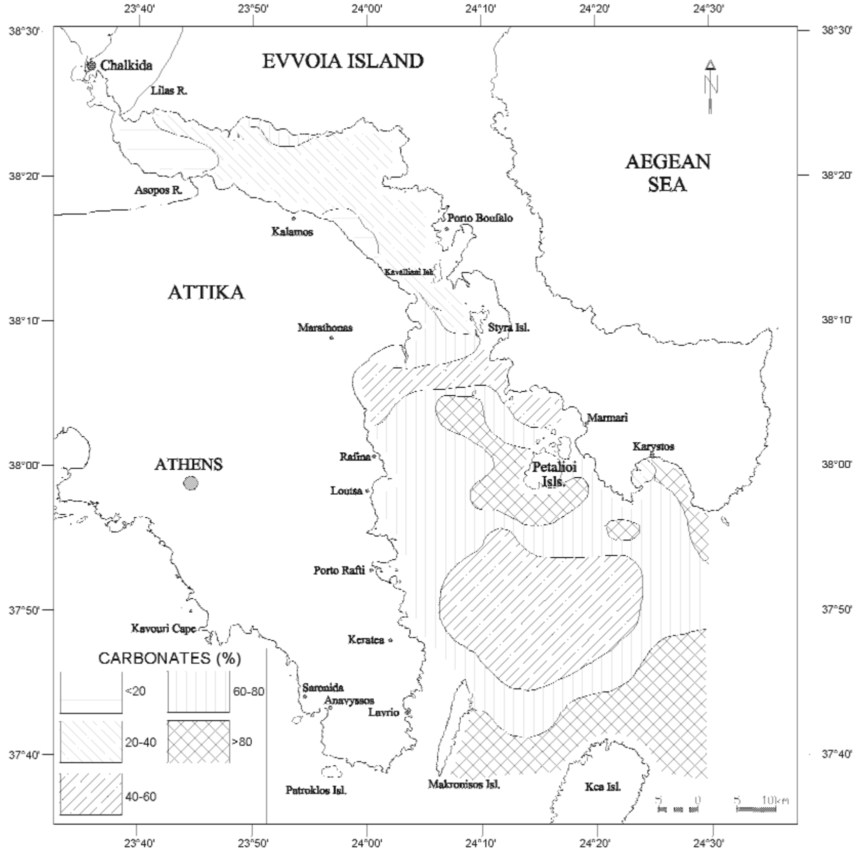

Fig. 5: Total carbonates distribution (wt. %).

gradual increase of sand percentage eastwards is noticed (from 20 to 80%), which is independent of depth fluctuations. The lower values are noticed offshore Porto-Rafti and Keratea, while the higher ones between Kea Isl. and Karystos. The mean size of sand grains (Table 1) in the Northern Petalioi Gulf ranges from very fine-grained sand to fine-grained sand (0.063-0.250 mm). The very fine-grained sand (0.063-0.125 mm) predominates at the inner section of the Southern Petalioi Gulf. This area is surrounded by zones of medium to coarse-grained sand (0.5 to >1 mm), particularly at the southern and eastern section. The most coarse-grained sands are related to the steep gradients of the seabed and also the strong bottom currents that prevail in the area.

The distribution of the silt fraction (Fig. 4) generally presents reverse trend in comparison to the sand distribution. The higher percentages (> 70%) occur in the Southern Evvoikos Gulf, which is characterised by the dominance of silty sediments. The Northern Petalioi Gulf constitutes again a transition zone, where low to medium percentages of silt occur at the west (20-40%) and higher percentages close to Marmari, generally following the seabed gradients. The Southern Petalioi Gulf presents at its western section a space of silt deposition (40-60%), while at the central and eastern sections the silt fraction is minimum (up to 10%).

The finest-grained sediment fraction (clay), presents similar geographic distribution with the silt, with percentages up to

70% in the Southern Evoikos Gulf and much lower in the Petalioi Gulfs.

The content of the surficial sediments in total carbonates is given in Table 1 and their geographic distribution in figure 5. Under the polarised microscope we recognised that the carbonate constituents of the studied sediments mainly originate in skeletal debris of marine organisms (foraminifers, gastropods, bivalves, etc.) The Southern Evoikos Gulf is characterised by the lower percentages of carbonates, which are < 20% at the western section and 20-40% at the inner section. In the area of Southern Evoikos Gulf diatoms (siliceous skeleton) are abundant. Carbonate content from 40 to 60% by weight is observed in the deepest part of the basin, surrounded by a zone of higher values (60-80%). Particular increased values exceeding 80% are observed close to Petalioi Isles and the southern section of the study area, from the Makronisos Isl. to Kea Isl. and eastwards.

The mineralogical composition of the sediments is fairly homogeneous in all the study area. The most abundant mineral is quartz. Feldspars (mainly plagioclase) and micas follow. Among the clay minerals illite, chlorite and kaolinite predominate. From the group of carbonate minerals, calcite, Mg-calcite and small amounts of aragonite appear in the samples. The origin of calcite is mainly biogenic as well as terrigenous, while the other carbonate minerals are wholly biogenic. The geographic distribution of the different minerals is correlated to the lithologic types of the adjacent land and the weathering materials of its drainage basins. In the Southern Evoikos Gulf the terrigenous calcite is increased, as a consequence of the weathering of the extended carbonate land formations. Its preservation in the marine environment is due to the small distance of transport from the source area and also to the mild hydrodynamic regime. Towards the south, an increase of heavy minerals content, such as epidote, hornblende, glaucophane and zircon, is noticed. These minerals come from the metamorphic formations of the eastern Attica and the southern Evoia Isl.

Discussion and Conclusions

The processes of transport and deposition of the clastic materials from the land into the sea are controlled by various factors such as the size of the grains, their specific weight, the hydrodynamic regime (currents and waves) and the bottom morphology. Thus, the geographic distribution of sand, silt and clay may provide some information pertaining to the sedimentation mechanisms.

On the basis of the data presented, two sedimentary provinces may be distinguished:

- The sedimentary province A characterising the Southern Evoikos Gulf, where the seabed is particularly smooth, the sand fraction is located close to the coast and the silt-clay fractions are distributed according to the depth;
- The sedimentary province B characterising the Petalioi Gulfs, where the grain-size distribution of the sediments presents irregularities, since the coarse-grained fraction of sand prevails in the deeper areas.

The Asopos R. and to a lesser extent Lilas R., supply the Southern Evoikos Gulf with terrigenous material. The rocks that constitute the source of the clastic materials are metamorphic rocks and limestones. The sedimentary province A is mainly the result of the Asopos R. solid discharge during Holocene. The fine-grained clastic material is transported and uniformly deposited in the region from Chalkida to Porto-Boufalo, covering the seabed with silty sediments. At the river mouth, most of the transported material is deposited, smoothing the bottom morphology and creating low seafloor gradients. Eastwards and southwards the depths are greater and the Southern Evoikos Gulf functions as a sediment trap. Moreover, the natural narrow strait of Kavalliani Isl., in combination with the low current velocities (5-10 cm/sec; KONTOYIANNIS & PAPADOPOULOS, 1997) prevent the sediments transport further to the south, towards the Petalioi Gulfs. Thus, it is inferred that most clastic material supplied by Asopos River is trapped within the Southern Evoikos Gulf, forming the characteristic silty Holocene cover.

The sedimentary province B is controlled by the limited supply of clastic material from the land. The solid discharge is low and is achieved by ephemeral streams and the wave action on the coast. The influence of the lithology of the drainage basin is confirmed by the increase of heavy minerals content, which come from the weathering of the metamorphic rocks predominating the area. The coarse-grained materials are deposited on the coastal zone, while the fine-grained materials are transported and deposited at the inner and deeper section of the basin, which is developed northern and northeastern of Makronisos Isl. However, the sediments that characterise this area are sandy, with sand content up to 80% by weight (Fig. 3). These sediments are not products of modern sedimentation, but older deposits (relict sediments).

A significant factor that highly influences areas with small solid discharge and subsequent low sedimentation rate is the fluctuation of the sea-level. At the last glacial lowstand (around 18 ka B.P.), sea-level was about 100-110 m lower than today (FAIRBANKS, 1989). A large section of the Southern Evoikos and Northern Petalioi Gulfs were land, while the paleo-coast was developed almost parallel to the isobath of 100 m (Fig. 2). Along this paleo-coast sandy sediments were deposited. Marine transgression began at around 14 ka B.P.; 11 ka-12 ka B.P. the sea over-passed the narrow strait of Porto-Boufalo, and gradually reached its present level (KARAGEORGIS, 1992). The sandy sediments remained uncovered or were mixed to a less extent with younger and modern sediments, however without losing their sandy character; this mechanism explains the presence of coarse-grained sediments in the deeper sections of the Southern Petalioi Gulf. The poor hydrographic network of the adjacent land and thus the small solid discharge contributed to the preservation of these sands on the bottom surface. In the area strong currents close to the bottom prevail (> 40 cm/sec; KONTOYIANNIS & PAPADOPOULOS, 1997), preventing the deposition of fine-grained material and favouring the preservation of relict sands. This parameter, coupled with the steep seabed gradients, is responsible for the increased mean size of sand grains at the southern and eastern section of the study area.

The relict sediments often occur on continental margins (EMERY, 1968). According to SWIFT (1976) the continental margin of the study area may be characterised as pathetic type with autochthonous sedimentation and high transgression rate. Thus, the preservation of the relict sands is favoured. Relict sediments occur in many Mediterranean Sea regions, such as on the continental shelf of Spain (GARDNER *et al.,* 1990, ERCILLA *et al.,* 1995, LOPEZ-GALINDO *et al.,* 1999), in the Tyrrhenian Sea (CHIOCCI & ORLANDO, 1996) or in the Nile delta (FRIHY & DEWIDAR, 1993, FRIHY *et al.,* 1994). In Greece, relict sediments have been referred in the Thermaikos Gulf (CHRONIS, 1986; LYKOUSIS & CHRONIS, 1989) and in the northern Aegean Sea (PERISSORATIS *et al.,* 1987).

GUTIERREZ-MAS *et al.* (1996) refer similar assemblages of relict sediments in the Gulf of Cadiz (SW Spain), which are related to the modern sea transgression. Finally, changes of the sea-level and relative sedimentary structures have been noticed in the neighbouring Turkey, with sedimentological and mineralogical methods (ERGIN *et al.,* 1997) or with the use of Side Scan Sonar (OKYAR & EDIGER, 1997).

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