

Research Paper

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TEXTURE AND MINERALOGICAL COMPOSITION OF QUATERNARY TERRESTRIAL AND MARINE SEDIMENTS FROM MACEDONIA AND THRACE, GREECE

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Abstract

Clastic sediments collected from land and gulfs of Macedonia and Thrace in Greece are examined on the basis of their texture and mineral composition. All terrestrial samples are coarse-grained and poorly sorted, with angular to sub-angular grains. These are mainly composed of quartz and feldspars, followed by micas, calcite and Fe-Mg minerals. Among the clay minerals illite predominates over smectite and smectite over vermiculite (+chlorite+kaolinite). In addition, the interstratified phases illite/smectite, chlorite/vermiculite, and smectite/vermiculite are present in significant amounts in the clay fraction (<2 μm), signifying the incomplete weathering of the primary minerals. Mixing during transportation, flocculation, differential settling processes and organic matter are the main mechanisms for the distribution of the discharged terrigenous load into the North Aegean Gulfs. All gulf bottom samples are coarse to fine grained and medium sorted, and their grains are angular to sub-angular. Quartz and feldspars predominate. In addition, biogenic calcite, micas and various Fe-Mg minerals exist as primary and/or accessory minerals. Among clay minerals, illite predominates over smectite and smectite over kaolinite (+chlorite+vermiculite). Almost in all gulf sediments the interstratified phase illite/smectite is apparent. The presence of feldspars and Fe-Mg minerals, as well as the high content of clay minerals and the polymodal grain-size distribution with angular to sub-angular grains, signify mineralogical and textural immaturity of all the examined sediments, as well as predominance of mild climatic conditions and thus mild weathering processes. The quartz content in these sediments is usually <70%. Therefore, a sedimentation cycle of these materials has not been completed.

Keywords: texture, mineralogical composition, immaturity, sedimentation cycle.

Περίληψη

Κλαστικά ιζήματα τα οποία συλλέχθηκαν από την ξηρά και τους κόλπους της Μακεδονίας και Θράκης στην Ελλάδα εξετάζονται με βάση την υφή και την ορυκτολογική σύστασή τους. Όλα τα χερσαία δείγματα είναι αδρόκοκκα και κακώς ταξινομημένα, με γωνιώδεις έως υπογωνιώδεις κόκκους. Αυτά αποτελούνται κυρίως από χαλαζία και αστρίους, ακολουθούμενα από μαρμαρυγίες, ασβεστίτη και Fe-Mg ορυκτά. Μεταξύ των αργιλικών ορυκτών, ο ιλίτης επικρατεί του σμεκτίτη και ο σμεκτίτης του βερμικουλίτη (+ χλωρίτη + καολινίτη). Επιπλέον, οι ενδοστρωματωμένες φάσεις ιλίτη/σμεκτίτη, χλωρίτη/βερμικουλίτη και σμεκτίτη/βερμικουλίτη είναι παρούσες σε σημαντικές ποσότητες στο κλάσμα αργίλου (<2 μm), σημαίνοντας τον ατελή χαρακτήρα της αποσάθρωσης των πρωτογενών ορυκτών. Η ανάμιξη κατά τη μεταφορά, η κροκίδωση, οι διαφορετικές διεργασίες καθίζησης και η οργανική ύλη είναι οι κύριοι μηχανισμοί για την κατανομή του εκφορτισμένου χερσαίου φορτίου στους κόλπους του Βορείου Αιγαίου. Όλα τα δείγματα των πυθμένων των κόλπων είναι αδρό- έως λεπτόκοκκα και μέτρια ταξινομημένα και οι κόκκοι τους είναι γωνιώδεις έως υπογωνιώδεις. Ο χαλαζίας και οι άστρια επικρατούν. Επιπλέον, ο βιογενής ασβεστίτης, οι μαρμαρυγίες και διάφορα Fe-Mg ορυκτά υπάρχουν ως κύρια και / ή επουσίωδη ορυκτά. Μεταξύ των αργιλικών ορυκτών, ο ιλίτης επικρατεί του σμεκτίτη και ο σμεκτίτης του καολινίτη (+ χλωρίτη + βερμικουλίτη). Σχεδόν σε όλα τα ιζήματα των κόλπων η ενδοστρωματωμένη φάση ιλίτη/σμεκτίτη είναι εμφανής. Η παρουσία των αστρίων και των Fe-Mg ορυκτών, καθώς και το υψηλό περιεχόμενο αργιλικών ορυκτών και η πολυπληθυσμιακή κατανομή του μεγέθους των κόκκων με γωνιώδεις έως υπογωνιώδεις κόκκους, υποδηλώνουν ορυκτολογική και ιστολογική ανωριμότητα όλων των εξεταζόμενων ιζημάτων, καθώς και επικράτηση ήπιων κλιματολογικών συνθηκών και συνεπώς ήπιων διεργασιών αποσάθρωσης. Ο περιεχόμενος χαλαζίας σε αυτά τα ιζήματα είναι συνήθως <70%. Επομένως, δεν έχει ολοκληρωθεί ένας κύκλος ιζηματογένεσης αυτών των υλικών.

Λέξεις-κλειδιά: υφή, ορυκτολογική σύσταση, ανωριμότητα, κύκλος ιζηματογένεσης.

1. INTRODUCTION

During weathering of a wide range of rocks, dissolution of primary minerals and formation of new mineral phases takes place within a weathering profile. Factors controlling the intensity of the weathering processes are climate (temperature and rainfall), topography, tectonics, mineralogical and physical characteristics of parent rocks, the presence of organisms, etc.

In middle latitude regions, mild temperatures, rainfall ranging from 50 cm/yr to 100 cm/yr and chemical weathering predominate (Chamley, 1989). The resulting soils typically exhibit a brown colour that tends to become reddish in the warmer areas (e.g. red Mediterranean soils). In the sub-humid region of the Mediterranean, degradation is moderate. In lowland areas, where the rainfall is between 30 cm/yr and 50 cm/yr, the ions removed from primary silicates during humid seasons are re-concentrated during dry seasons giving genesis to discrete and interstratified clay minerals. In temperate areas, detrital illite is the predominant clay mineral, signifying low to medium intensity of weathering processes (Weaver, 1989).

Red beds are sedimentary strata deposited on land under a strongly oxidizing environment. They may be composed of breccias, sandstones, silts and clays and are predominantly red in colour due to the presence of ferric oxide, which coats individual grains. The main source of iron in the pigment is the in-place alteration of iron-rich primary minerals such as amphiboles, pyroxenes, chlorites, epidote, micas, etc. Red beds are indicative of climates that are warm and dry or seasonal with respect to rainfall. Red beds that occur under temperate climates have been considered relict soils, formed under warmer paleoclimates (Chamley, 1989; Weaver, 1989; Parrish, 1998; Sheldon, 2005).

Illite is the dominant clay mineral in argillaceous rocks, especially in shales. It is formed by the weathering of silicates, mainly of feldspars and muscovite. Formation of illite is generally favoured by alkaline conditions and by high concentrations of Al and K. Illite also may precipitate in the pores of sandstone reservoirs, impeding fluid flow. The climatic and topographic conditions necessary for the formation of smectite are basically the opposite of those that favor the formation of kaolinite. Thus, low relief and/or low permeability, low rainfall and/or low water flux, and low temperature, favor the formation of smectite (Weaver, 1989). Smectite can be formed by the alteration of feldspars, micas, and various Fe-Mg-silicates.

When the dominant clay mineral in a fine-grained sediment (e.g. shale) is smectite, it means that the paleoclimate was cool and arid or warm and humid with low relief, the soil in the source area had low permeability, and the source rock was volcanic, plutonic, metamorphic or shale. Nearly half the soils in the temperate zone contain more than 50% smectite (+illite/smectite). However, it is unlikely that smectite produced by the weathering of layer silicates would be the dominant clay mineral in a detrital clayey suite, because during erosion clay minerals may be normally removed from the whole

soil profile. Under conditions of poor drainage thick sections of smectite can be produced (Weaver, 1989).

Vermiculite phases are found in outcrop terrigenous sediments where they are commonly products of recent weathering. Vermiculite occurs in variable amounts in all major soil groups but is most common in soils of temperate climates, where the dioctahedral variety is more abundant than the trioctahedral. Its genesis is usually ascribed to the supergene alteration of biotite, phlogopite, or chlorite. Vermiculite can be found anywhere biotite is found. It is an extremely common mineral in the well-drained soils of humid regions if the parent material contains trioctahedral micas (Moore and Reynolds, 1997).

The general scarcity of clay sized sediments in shallow waters, due to winnowing through the action of waves, tides and currents, contrasts with the huge accumulations of argillaceous deposits in the rest of the oceans. Where they do occur, source mixing during transportation, flocculation and differential settling processes appear to be the main mechanisms for their distribution (Griffin et al., 1968; Chamley, 1989). The aggregation of clay particles by marine organic matter appears to be a widespread phenomenon, mainly responsible for the rapid sinking of land-derived materials. Clay is mainly incorporated in faecal pellets and other mucous matter within the surface water masses where high planktonic productivity develops seasonally (Chamley, 1989).

The coastline of Macedonia and Thrace in Greece incorporates the mouths of many small and large rivers. Most of them drain the mainland of Greece, except four (Evros, Nestos, Strymon, Axios) that expand their network to neighboring countries (Poulos and Chronis, 1997). Evros River is the largest supplier of continental clastic material (8.5×10^6 tons/yr) in the coastal region of NE Aegean. Similarly, in the Thermaikos Gulf, the rivers Gallikos, Axios, Aliakmon, and Pinios unload $(25-30) \times 10^6$ tons/yr of clastic terrestrial material (Poulos et al., 2000). The total suspended material in the NW Aegean Sea is $(484-830) \times 10^3$ tons/yr (Karageorgis and Anagnostou, 2003).

The deltaic sediments of northern Greece are climatically uniform in their setting and prograde into the north Aegean Sea. Tidal activity is negligible and the waves play a secondary role compared to the high sediment discharge of the rivers. Sand is the predominant (>60%) constituent of the river mouths (top sets), while the prodelta area consists mainly of silt- and clay-sized (>70%) particles (Poulos and Chronis, 1997). Relict sediments are found in the Thermaikos Gulf (Karageorgis and Anagnostou, 2001) and in the NE Aegean Sea (Kanellopoulos et al., 2008).

Hundreds of analyses of fine grained sediments and soils with Cenozoic age, collected from various land areas of Greece, confirm their textural and mineralogical immaturity. Terrestrial sediments or soils with a quartz content >70% are very rare in Greece. Therefore, a sedimentation cycle of these materials has not been completed (Tsirambides, 2005).

2. GEOLOGICAL SETTING

The Quaternary sediments of Greece lie unconformably over the folded alpine basement and are of fluvial, lacustrine or marine origin. These sediments are deposited into grabens or other neotectonic basins. The Post Alpine formations are widespread and are characterized by a wide lithological and facies variation. The Holocene sedimentation in the eastern Mediterranean is strongly affected by changes in the sea surface level associated with global paleoclimatic changes at the end of the Quaternary (Mountrakis, 2010).

In the Circum-Rhodope Belt, the flysch of Svoula (Units of Melisochoi and Cholomontas) is of Lower-Middle Jurassic age. It is characterized by alternations of meta-sediments (sandstones, marls, limestones). In the Peonia Belt (Units of Vafiochoi and Artzan), there is flysch of Upper Jurassic-Lower Cretaceous age, which is mainly made of conglomerates, sandstones and mudstones (Mountrakis, 2010).

The alpine basement must be an important source of the examined sediments beyond the molassic ones found in some troughs of the studied areas. The Evros trough in the past covered larger area extending into the northeastern Aegean. The molasse is mainly conglomerates, sandstones, marls and marly limestones of Middle Eocene-Oligocene age. In addition, molasse occurs in the area of Peonia that belongs to the Axios trough. It is believed that the trough is larger extending into the Thermaikos Gulf. Most of this molasse is covered by the terrestrial Neogene and Quaternary deposits of the Axios valley and the broader plain of Thessaloniki. The molasse is composed of conglomerates, breccias, sandstones, marls and limestones of Upper Eocene age (Mountrakis, 2010).

The area of Northern Greece is a complex of grabens and horsts (mountains) arranged in a primary NW-SE trend. Intermountain high-level basins (e.g. Ptolemais-Florina) with elevation 400–500 m or low-level basins (e.g. Mygdonia) with elevation 150–250 m, large coastal basins and plains (e.g. Axios-Thessaloniki, Serres-Strymon) were filled

with Neogene and Quaternary sediments. Red beds are the most characteristic of them. They are terrestrial-fluvial clastic sediments of red-brown colour that are exposed along basin sides, at surface, or can be traced in the central parts of the basins, in the subsurface by drilling. The widespread red beds and the associated rich mammalian fauna offer a good basis for stratigraphic and paleogeographic correlation with other sedimentary deposits in the Mediterranean (Psilovikos et al., 1987).

The terrestrial and marine sampling sites are shown in Figure 1. Grain-size distribution data and mineralogical composition of the examined sediments are shown in Tables 1 and 2.



Fig. 1: Sketch map of the regions of Macedonia and Thrace with the sampling sites.

3. MATERIALS AND METHODS

The samples were ground in a mortar to disaggregate them and left to dry at room temperature prior to X-ray diffraction (XRD) analysis. Powder X-ray diffraction was performed in a Philips diffractometer with Ni-filtered $\text{CuK}\alpha$ radiation. Randomly oriented mounts of some untreated samples were scanned over the interval $3\text{-}63^\circ 2\theta$ at a scanning speed of 1.2° per minute.

In addition, parallelly oriented, glycolated and heated at 550°C for 2.5 hours of bulk or specific grain-size mounts of selected samples were scanned over the interval $3\text{-}33^\circ 2\theta$ at the same scanning speed (Jackson, 1974). Semi-quantitative estimates of the minerals present are based on peak heights and intensity factors of the XRD patterns, using the methods described by Hower et al. (1976) and Moore and Reynolds (1997).

Table 1. Average grain size (μm) distribution (wt.%) of the samples analyzed.

Samples	COI ¹	>2000	2000-63	63-2	<2
Platamonas Pierias (3)	20		48	38	14
Moudania (6)		24	73	3	
Chalkidiki (16)			44	25	31
Kalamaria (8)	14		40	31	29
Thessaloniki Cedar Hills (8)	10		46	32	22
Vertiskos Langada (46)		30	60	10	
Herso Kilkis (16)		8	88	4	
Doirani Kilkis (12)		6	77	13	4
Strymi Rhodope (5)	26		9	25	66
Evros River (5)	6		40	45	15
² Thermaikos Gulf (27)	29		30	29	41
³ Thermaikos Gulf (7)	24		43	25	32
Alexandroupolis Gulf (13)			24	48	28

¹Total percentage of cement material (Carbonates + Organics + Fe oxides and Fe- and Al- hydroxides).
²Lykousis et al. (1981), ³Pehlivanoglou et al. (2004).
The number of samples analyzed is presented in parenthesis.

4. TERRESTRIAL SEDIMENTS

4.1. Platamonas Pierias

The soil samples were collected from different sites of the new opening of the national road of Athens - Thessaloniki in the area of Platamonas. The sediments are consisted of abundant friable and earthy aggregates. They may be characterized as sand-muddy soils. The main minerals present in decreasing abundance are: carbonates (calcite+dolomite), quartz, feldspars (plagioclases > K-feldspars), Fe-Mg minerals, micas, and clay minerals. Among the clay minerals illite predominates, while smectite, vermiculite and their interstratified phases follow. The sediments are mineralogically immature because of the high content in Fe-Mg minerals and feldspars. The sediments are texturally immature because of their poor sorting, the angular morphology of the grains and the high content of the clay size grains (>5%) (Tsirambides, 1999).

The presence of amphiboles and pyroxenes, as well as the high content of clay minerals and feldspars in these soils, signify their mineralogical immaturity and the predominance of mild climatic conditions and thus, mild weathering processes. The

above mineralogical paragenesis is indicative of the mineral composition of the adjacent parent rocks the weathering products of which are transported and deposited on the lower slopes of the hills (Tsirambides, 1999).

4.2. Chalkidiki

The surface samples were collected from road slopes and stream beds. The sediments consist of abundant friable and earthy aggregates. They may be characterized as sandy muds to muddy sands. The main minerals present in decreasing abundance are: quartz, feldspars (plagioclases > K-feldspars), carbonates (calcite+dolomite), Fe-Mg minerals, micas, and clay minerals. Among the clay minerals illite predominates, while smectite, vermiculite, chlorite, kaolinite, and their interstratified phases, follow. The sediments are texturally and mineralogically immature (Kastrinaki et al., 2004).

The presence of pyroxenes and amphiboles, as well as the high content of clay minerals and feldspars in these muddy sediments, signify their mineralogical immaturity and the predominance of mild climatic conditions, and thus mild weathering processes (Kastrinaki et al., 2004).

4.3. Moudania

The Quaternary red beds are incoherent, coarse grained and poorly sorted. They belong to the arkosic facies and their depositional environment is fluvial-lacustrine. Angular to sub-angular rock fragments derived from the adjacent parent rocks are very common. These sediments may be characterized as gravelly sands. They are texturally and mineralogically immature (Tsirambides et al., 2007).

The samples were collected from well-exposed red bed outcrops and were analyzed in detail using petrographic (stereoscope and microscope), X-ray diffraction (XRD) and geochemical techniques. The extended presence of sand size grains suggests high intensity of weathering of the parent rocks and rapid transport and deposition of the weathered materials close to the source area. The main minerals present in decreasing abundance are: quartz, feldspars (plagioclases > K-feldspars), micas (+clay minerals), calcite, pyroxene, amphibole, and pyrite. The presence of illite, smectite (+illite/smectite), and chlorite (+vermiculite) in the <0.063 mm fraction is evident (Tsirambides et al., 2007).

The source minerals for the formation of the studied red beds are quartz, feldspars, micas, and various Fe-Mg silicates, which are primary constituents of the Mesozoic basement igneous and metamorphic rocks predominating in the adjacent area. The samples may be considered ferromagnesian and potassic sandstones. A felsic igneous provenance signature is justified for most of the samples. The climate under which these Quaternary red beds were formed was warm and semiarid (Tsirambides et al., 2007).

4.4. Kalamaria

Neogene and Quaternary clastic sediments and alluvial deposits cover all the Alpine petrographic formations in Kalamaria in thicknesses exceeding 250 m. The samples of Holocene age were collected from different depths of four excavations, for foundation of constructions. They are mainly marly sediments and may be characterized as clayey to sand-muddy. The main minerals present in decreasing abundance are: quartz, feldspars (plagioclases > K-feldspars), amphiboles, pyroxenes, and epidote. Among the phyllosilicates micas and clay minerals predominate. The clay fraction consists of illite, smectite, vermiculite, chlorite, and their interstratifications, as well as of kaolinite. The sediments are texturally and mineralogically immature (Tsirambides, 2001).

The extended presence of clay minerals and their interstratifications is due to their terrigenous transport from the adjacent drainage basin where rocks rich in feldspars and Fe-Mg minerals predominate. The main alteration products of these rocks are the above mentioned phases. The extended presence of smectite and illite/smectite in some layers may be the result of alteration of plagioclases of volcanic origin. Rounded volcanic fragments with sizes from some millimeters up to 4 cm have been found inside the examined sediments (Tsirambides, 2001). The nearest volcanic centers were in Almopia. Their volcanic activity affected the surrounding areas and the north-west Aegean since Tertiary (Fytikas et al., 1984).

The high participation of feldspars, Fe-Mg minerals and clay minerals signify mineralogical immaturity. The polymodal grain-size distribution (poor sorting), the sub-angularity of the grains, and the high content of the clay fraction, signify textural immaturity (Tsirambides, 2001).

4.5. Thessaloniki Cedar Hills

The red beds studied extend over an area of about 5 km². The samples were collected from well-exposed red bed outcrops with thickness up to 15 m and were analyzed in

detail using petrographic and X-ray diffraction (XRD) techniques. The red beds are poorly sorted. They are consisted of coarse grained and friable components and present earthy lustre. Angular to sub-angular rock fragments derived from the metamorphic bedrock are very common. The examined sediments belong to the clayey sands. The extended presence (41–66%) of coarse silt- and sand-size grains suggests a mild intensity of in situ weathering of the bedrock. The main minerals present in decreasing abundance are: quartz, feldspars (plagioclases > K-feldspars), epidote, micas, chlorite, pyroxenes, amphiboles, and talc. In the clay fraction (<2 μm) illite, smectite, and chlorite predominate. The presence of mixed-layer minerals is limited, testifying intense weathering of the primary minerals. The clay minerals are the in situ weathering products of the primary minerals of the greenschists, gneisses, and gabbros that predominate in the area (Tsirambides, 2004).

The formation of red beds took place on low relief land under alternating wet and dry seasons, which prevail in the eastern Mediterranean region since Neogene. The poor sorting of the red beds, the sub angular morphology of their grains and their high content in clay size grains (11–26%), indicate that these red beds are texturally immature. In addition, the great abundance of feldspars and Fe-Mg minerals reflects mineralogical immaturity. The extended presence of clay minerals in the red beds signifies low intensity of leaching. The low relief and the long-lasting tectonic stability in the Thessaloniki region were essential for the significant thickness of the red beds. The most likely source materials for the formation of the red beds are feldspars, micas, and various Fe-Mg silicates, which are primary constituents of the metamorphic and ultramafic rocks predominating in the adjacent area. Dissolved ions liberated during the wet seasons are re-concentrated in the dry seasons participating in the formation of clay minerals. Most of the illite and smectite present were formed in situ by the weathering of the above primary minerals of the bedrock that consists especially of greenschists, gneisses and gabbros (Tsirambides, 2004).

4.6. Vertiskos Langada

The samples were collected from different Holocene outcrops. They are generally brown, reddish and grey coloured loose fluvial sands. Their grains demonstrate, at macroscopic level, low sphericity and are angular to sub angular. More rounded lithic fragments are of metamorphic origin. Most of the samples yield a polymodal grain-size distribution. Texturally they are moderately sorted to very poorly sorted and immature to submature. They are mainly sandy gravels and gravelly sands. These sediments accumulated close to their source under intense to mild tectonic activity, under rapid

weathering, and comprise a diverse mixture of detrital populations. They are composed of quartz, feldspars, micas, and accessory minerals (e.g. amphibole and garnet), mainly of metamorphic origin (Georgiadis et al., 2012).

The mineral abundances indicate that the Vertiskos Unit was rapidly weathered in a temperate and seasonable climate primarily through the action of physical weathering factors (Georgiadis et al., 2012).

4.7. Herso Kilkis

The sediments of the Herso basin consist part of the Axios-Thessaloniki neotectonic graben. This graben has an NNW-SSE general direction and the detrital sediments filling it are generally loose alluvial, fluvial and lacustrine formations (mainly sandstones) (Mountrakis et al., 1993).

The samples were collected from different Holocene outcrops of the Herso plain. The coarse grained sediments present poor sorting and sub angular morphology of the grains. They may be characterized as gravelly sands. Their silt and clay content is low and their textural study reveals a fluvial-lacustrine deposition environment. The main minerals present in decreasing abundance are: quartz, feldspars (plagioclases > K-feldspars) and mica. Detrital calcite and pyroxenes, as well as the accessory minerals garnet, staurolite, kyanite, zoisite, rutile, epidote, zircon, apatite, tourmaline, and opaque minerals, are present in small amounts. These accessory minerals are considered indexes of metamorphic provenance. Geochemically the samples are classified as sublitharenites and subarkoses, all being rich in SiO₂. The sediments may be classified as garnet-mica bearing litharenites. The overall percentages of quartz, feldspars and rock fragments imply intense physical weathering and rapid transport and deposition in the Herso basin. The sediments are texturally and mineralogically immature (Georgiadis et al., 2007).

The abundance of plagioclase, compared with that of alkali feldspar, implies intense physical weathering and rapid transport and deposition at small distance. This tectonic regime is concluded from the percentages of quartz, feldspars and rock fragments in the paragenesis of the examined clastic sediments. The limited presence of detrital carbonate minerals suggests that there was no contribution of clastic load from the carbonate rocks outcropping to the west of the Herso basin (Georgiadis et al., 2007).

4.8. Doirani Kilkis

The samples were collected from different Holocene outcrops of the Doirani basin. The coarse grained sediments present poor sorting and sub angular morphology of their grains. They may be characterized as gravelly sands. The main minerals present in decreasing abundance are: feldspars (plagioclases > K-feldspars), quartz, micas, tremolite, and small amounts of clay minerals. The average clay mineral composition is: 90% illite, 10% (chlorite+kaolinite). Smectite is missing. The sediments may be classified as feldspathic wackes and arkoses. They are texturally and mineralogically immature (Tsirambides, 1997).

The poor sorting of these sediments, the sub angularity of their grains and the extensive presence of mud matrix justify textural immaturity. The co-existence of gravel, sand, silt and clay is due to the fluvial-terrestrial transport of the weathering products from the adjacent mountains towards the lake. The significant presence of illite and the limited of kaolinite+chlorite in the matrix confirm the deposition of the weathering materials in a terrestrial-lacustrine environment (Tsirambides, 1997).

4.9. Strymi Rhodope

The friable soils are very fine-grained and present earthy luster. The main minerals present in decreasing abundance are: quartz, calcite, clay minerals, and to a less extent feldspars. The clay minerals in decreasing abundance are: illite, vermiculite, smectite, and their interstratifications (Xeidakis et al., 2004).

Micaceous material (especially muscovite and/or illite) is present in nearly all soils. In recent geological time most of the illite and illite/smectite has been transported by rivers draining the adjacent bedrock. The most likely source materials for the formation of clay minerals present are K-feldspars and plagioclases as constituents of metamorphic and acid volcanic rocks that predominate in the drainage basin of the Filiouris River. The climatic conditions in the source area could have ranged from cold to temperate (Xeidakis et al., 2004).

Table 2. Mineralogical composition (wt.%) by XRD method of the samples examined.

Samples	Grain-size	C+D	Q	F	M	Fe-Mg	Z	I	S	Ch+K+V
Platamonas Pierias (3)	bulk	29	18	12		6		20	9	6
Moudania (6)	bulk	2	43	42	11	2		tr	tr	tr
Chalkidiki (16)	bulk	11	41	25		3		13	4	3
Kalamaria (8)	20-2 μm		23	55		5		10	4	3
Thessaloniki Cedar Hills (8)	20-2 μm		26	22		10		20	9	13
Vertiskos Langada (46)	bulk	tr	44	29	19	8				
Herso Kilkis (16)	1-0.5 mm	tr	77	16	6	1				
Doirani Kilkis (12)	30-2 μm		24	55	18	3				
Strymi Rhodope (5)	bulk	17	21	9				24	13	16
Evros River (5)	bulk		25	32		4	9	20	5	5
¹ Thermaikos Gulf (27)	<2 μm							50	35	15
² Thermaikos Gulf (7)	<2 μm							48	22	16
Ierissos Gulf (37)	<2 μm		4	7		3		63	19	18
Strymonikos Gulf (118)	<2 μm							59	24	17
Alexandroupolis Gulf (13)	<2 μm							65	18	17

C=calcite D=dolomite, Q=quartz, F=feldspars, M=micas, Fe-Mg=ferromagnesian minerals, Z=zeolites, I=illite, S=smectite, Ch=chlorite, K=kaolinite, V=vermiculite, tr=trace.
¹Lykousis et al. (1981), ²Pehlivanoglou et al. (2004).
Other symbols as in Table 1.

4.10. Evros River

The samples were collected from sand bars of the western bank of the river, 5 km south of the Monastiraki village. The reworking of the weathered materials is limited because of the large discharge load in short time intervals and its rapid transport and deposition. The fluvial deposits present poor sorting and sub angular morphology of their grains. These clastic sediments are mineralogically immature because of the extensive presence of feldspars and unstable Fe-Mg minerals. The examined sediments may be characterized as sandy silts. The main minerals present in decreasing abundance are: quartz, feldspars (plagioclases > K-feldspars), micas, zeolites, and clay minerals. In the clay fraction (<2 μm) and in decreasing abundance illite/smectite, illite, chlorite, vermiculite, and chlorite/vermiculite are present. The limited abundance of smectite and kaolinite is due to the unfavourable physicochemical or climatic conditions for their formation (Tsirambides and Kantiranis, 1998). The extensive presence of quartz, feldspars and micas is expected because they constitute the weathering products of the large drainage basin of Evros River (extended in NE Greece and south Bulgaria), where igneous and metamorphic rocks predominate. The presence, in significant amounts, of zeolites is justified by the extended presence of volcanoclastic sediments in this drainage basin (Tsirambides and Kantiranis, 1998).

5. MARINE SEDIMENTS

5.1. Thermaikos Gulf

The annual solid supply of all rivers (Gallikos, Axios, Aliakmon, Pinios), flowing into the Gulf, amounts to $(25\text{--}30) \times 10^6$ tons/yr. The maximum thickness of the sediments in the Gulf reaches 25–30 m. The discharged load presents polymodal grain-size distribution signifying a mild intensity of weathering of parent rocks on land. The average content of the non-silicate phases (Carbonates + Organics + Iron oxides and iron and aluminum hydroxides) is 24%. The main minerals present in decreasing abundance are: quartz, feldspars (plagioclases > K-feldspars), Fe-Mg minerals, micas, and clay minerals. On average, the clay fraction ($<2 \mu\text{m}$) consists of: 48% illite, 26% smectite, 18% (chlorite + kaolinite), 3% quartz, 3% feldspars, and 2% Fe-Mg minerals. Ordered and randomly interstratified phases of illite/smectite are present. Smectite predominates over the rest of the clay minerals in front of the pro-delta platform and close to the coast at depths not exceeding 30 m. All these minerals are the weathering products of the rocks from the drainage basins of the rivers flowing into the Gulf, as well as of the Neogene and Quaternary unconsolidated sediments of the surrounding coasts (Lykousis and Chronis, 1989; Karageorgis and Anagnostou, 2001; Pehlivanoglou et al., 2004).

Parts of the bed of central and eastern Thermaikos Gulf are covered by relict sands (up to 80%). The terrigenous input, the water mass circulation and to a lesser extent the quality of the discharged material and the differential settling of grains, control the sedimentation rate and the grain size distribution within the NW Aegean Sea (Lykousis et al., 1981).

The examined sediments are medium sorted and have sub-angular grains. These characteristics signify their textural immaturity. In addition, the extensive presence of feldspars and ferromagnesian minerals confirm and their mineralogical immaturity. The origin of all silicate minerals is terrigenous. The origin of calcite is mostly biogenic. The presence of clay minerals is due to the very large suspended load of the rivers derived from the weathering of parent rocks in the drainage basins. In addition, some of the clay minerals are derived from the weathering of unconsolidated Neogene and Quaternary coastal sediments. Chlorite (+kaolinite) content expresses the strong climatic dependence controlled by the intensity of weathering of parent rocks, which occur in the drainage basins. The low content of kaolinite may be due to unfavorable climatic and physicochemical conditions, as well as to the detrital origin, rapid transport

and deposition of the weathered material in the Gulf. Furthermore, the presence of amphiboles observed even in the coarse clay fractions confirms the limited reworking and weathering of the primary ferromagnesian minerals because of the high river discharge over short time periods and rapid deposition in the Gulf. Finally, the significant presence of interstratified illite/smectite confirms the limited reworking and weathering of the primary minerals during their transport and deposition from the drainage basins to the Gulf (Lykousis and Chronis, 1989; Karageorgis and Anagnostou, 2001; Pehlivanoglou et al., 2004).

The abundance of smectite is enhanced by the high Fe and organic content of the terrigenous input, as well as by the physico-chemical conditions of the seawater (e.g. salinity, temperature, pH and Eh), which result in rapid flocculation and settling of smectite flocs (Chronis, 1986).

The recent sediments of the Thermaikos Gulf have adopted their characteristic zone distribution in response to the coastal topography, the water circulation, and the prevailing climate in the region. The composition and dispersal of the suspended load of the rivers into the Gulf is controlled by the prevailing seasonal meteorological conditions at their catchment areas and the coastal area. The aggregation and distribution of clay particles in the Thermaikos Gulf is least controlled by the organic content of the terrigenous input because its presence is limited (Poulos et al., 2000).

5.2. Ierissos Gulf

The sea floor is covered by sands and silty to clayey sands. The minerals present in the sand fraction are: quartz (14–72%), feldspars (6–35%), calcite (4–77%), Mg-calcite (2–4%), and muscovite (2–20%). The average clay mineral content is: 63 wt.% illite, 19 wt.% smectite, and 18 wt.% (kaolinite+chlorite). Low content of illite/smectite is detected in some samples. The distribution of clay minerals on the sea floor is mainly related to the composition of the drained land rocks and the unconsolidated Neogene and Quaternary coastal sediments, to the dispersion of clay minerals by currents and to the eustatic movements (Conispoliatis and Perissoratis, 1987; Pehlivanoglou and Sourikouroubali, 1987).

5.3. Strymonikos Gulf

Strymon River supplies by average 150,000 tons/yr of suspended material into the Gulf. The sea floor in the Gulf is covered by well to poorly sorted sands and silty clays. Some

parts are covered by relict sands. The sea floor sediments consist of quartz, feldspars, micas, calcite, amphiboles, epidote, clinopyroxenes, clay minerals, and opaque minerals. By average the clay minerals present are: 59 wt.% illite, 24 wt.% smectite, 17 wt.% (kaolinite+chlorite). In the sand fraction the authigenic mineral glauconite was found. The sea floor sediments contain organic matter from 0.2% to 6% by weight. The carbonate minerals (clastic and biogenic) vary from 2% to 40% by weight. The distribution of clay minerals is the result of differential settling and is controlled by the water circulation. The high concentrations of Zn and Pb are due to the mining activity of the adjacent mines of Olympias-Stratoniki (Conispoliatis, 1984; Pehlivanoglou and Souri-Kouroumbali, 1987).

5.4. Alexandroupolis Gulf

Evros is the largest supplier of fine grained Fe-Al-rich continental detritus to the offshore area. The modern sediments of the Gulf have adopted their characteristic zonal distribution in response to the coastal topography, the water motion, and the quality of the supplied material (Perissoratis et al., 1987). Felsic and mafic igneous (especially volcanic), as well as metamorphic rocks cover the western and central parts of the Evros river drainage basin; Neogene sediments cover the eastern part and the coastal zone (Pehlivanoglou, 1995).

The annual solid supply of the Evros River, flowing into the Gulf, amounts to at least 1,000,000 m³. The average clay mineral composition is: 65% illite, 18% smectite, and 17% kaolinite. Mixed-layer illite/smectite was detected in traces in some samples. All the above minerals are the weathering products of the Evros river drainage basin, as well as of the Neogene and Quaternary unconsolidated sediments of the coast. The hydrodynamic regime and physical grain size are the main mechanisms, which control the distribution of the clay minerals in the Gulf. The low content of kaolinite in all samples and the presence in traces of chlorite and amphiboles in some coarse clay fractions may be due to the unfavourable climatic and physicochemical conditions, as well as to the rapid transport and deposition of the weathered material (Pehlivanoglou et al., 2000).

The abundance of illite and smectite in the sediments is mainly due to the weathering of primary Fe-Mg minerals of the drainage basin rocks and their transport and deposition in the Gulf. Especially, the abundance of smectite is enhanced by the high Fe and organic content, which results in a rapid flocculation and settling out of smectite

grains. This flocculation process is enhanced by the physico-chemical conditions of the seawater (e.g. salinity, temperature, pH, and Eh) (Pehlivanoglou et al., 2000).

Kaolinite content expresses the strong climatic dependence controlled by the intensity of hydrolysis of continental rocks which occur in the drainage basin. However, the low content of kaolinite may be due to unfavorable climatic and physicochemical conditions, as well as to the detrital origin, rapid transport and deposition of the weathered material in the Gulf. Furthermore, the low percentage of the interstratified illite/smectite, as well as some presence of amphiboles even in the clay fractions of the discharged material, confirm the limited reworking and weathering of the primary ferromagnesian minerals because of the high river discharge over short time periods and rapid deposition in the Gulf (Pehlivanoglou et al., 2000).

In comparison to Evros River the Gulf sediments contain almost the same percentage of silt-size grains, about 50% less sand-size grains, and about 50% more clay-size grains (Table 1).

6. CONCLUSIONS

All terrestrial sediments from Macedonia and Thrace are coarse grained and poorly sorted, with angular to sub-angular grains. These are mainly composed of quartz and feldspars, followed by micas, calcite, and Fe-Mg minerals. Among the clay minerals illite predominates over smectite and smectite over vermiculite (+chlorite+kaolinite). In addition, the interstratified phases illite/smectite, chlorite/vermiculite, and smectite/vermiculite are present in significant amounts in the clay fraction (<2 μm), signifying the incomplete weathering of the primary minerals. Mixing during transportation, flocculation, differential settling processes, and organic matter are the main mechanisms for the distribution of the discharged terrigenous load into the North Aegean Gulfs.

All sea floor samples are coarse to fine grained and medium sorted, and their grains are angular to sub-angular. Quartz and feldspars predominate. In addition, biogenic calcite, micas, and various Fe-Mg minerals exist as primary and/or accessory minerals. Among clay minerals, illite predominates over smectite and smectite over kaolinite. In almost all sea floor sediments the interstratified phase illite/smectite is apparent.

The presence of feldspars and Fe-Mg minerals, as well as the high content of clay minerals and the polymodal grain-size distribution with angular to sub-angular grains,

signify mineralogical and textural immaturity of all the examined terrestrial and marine sediments, as well as predominance of mild climatic conditions and thus mild weathering processes. The quartz content in these sediments is usually <70%. Therefore, a sedimentation cycle of these materials has not been completed.

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