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TEXTURAL AND PETROLOGICAL STUDY OF MODERN SANDS FROM THE VERTISKOS UNIT OF SERBOMACEDONIAN MASSIF (MACEDONIA, GREECE)

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Abstract

The sediments analyzed are in general coarse grained gravelly sands to slightly gravelly muddy sands poor in mud content and texturally and mineralogically immature to submature. They have been deposited in a fluvial environment. They are feldspathic and in all samples detrital minerals of metamorphic origin are found along with minor amounts of detrital calcite. These sediments are deposited rapidly near their source which comprises the Vertiskos Unit. The mineral constituents of the samples show that Vertiskos Unit is rapidly weathered under a seasonably wet and warm climate. All the samples may be considered as constituting one sedimentary petrologic province, comprised of one mineral association, namely the amphibole-garnet.

Key words: *Vertiskos Unit, metamorphic rocks, fluvial, modern sands.*

1. Introduction

Five are the basic processes that lead to the formation and release of sand-sized grains (Pettijohn et al., 1987); weathering (including both disintegration and decomposition), explosive volcanism, crushing (not including ordinary abrasion), pelletization and precipitation from solution. In general, sands accumulate in environments of high kinetic energy, such as sections of stream channels, alluvial fans and marine environments (Ehlers and Blatt, 1982). Especially the medium of transport and deposition, along with climate and source areas, are the most important factors for the accumulation of a sedimentary deposit (Reineck and Singh, 1986).

Studies on modern sand contribute to our understanding of the effects of processes controlling the composition of sand-size sediment, this information being useful for better paleogeographic interpretations of ancient source area and basin systems (Dickinson, 1985). According to Suttner (1974) the factors that combine to produce detrital assemblages found in modern and ancient sediments include source-rock composition, tectonics, climate and relief. These factors grouped together are referred to as provenance (Dickinson, 1970). In a more descriptive way, Pettijohn et al. (1987) consider provenance of including the paleogeography of a region, the identification of possible source areas for the clastic material under study and the revealing of details about the paleocurrents and the paleoslope. The above mentioned authors also state furthermore that the study of the mineralogy of modern sands may disclose valuable minerals and if the provenance is understood, we may prospect

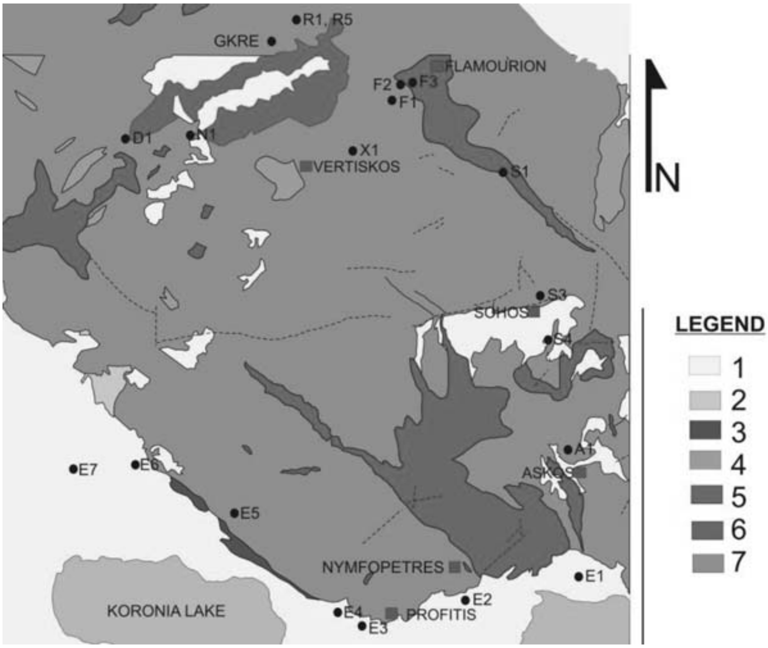

Fig. 1: Petrographic sketch map of the study area (Vertiskos Unit). 1=Quaternary and Neogene gravels, sands and sandy muds, 2= Neogene molassic sediments, 3=Quartzites (Examili Formation), 4=hornblend-quartz diorite, 5=biotite-quartz diorite to granodiorite, 6=two-mica and biotite granite and 7=Alpine metamorphic basement.

them more accurately. Also, sand petrology is helpful in developing a systematic quantitative approach to the problem of optimizing sampling procedures in sedimentary petrography (Weltje, 2004).

Modern sediments from Doirani Lake (NW margin of Vertiskos Unit) are coarse to medium grained and poorly sorted feldspathic wackes and arkoses, deposited in a lacustrine environment with little transportation, since they contained ferromagnesian minerals (Tsirambides, 1997). Drilling cuttings (fluvial sand gravels to gravel sands) from Herso, Kilkis (West margin of Vertiskos Unit) are also minerallogically immature, litharenites to feldspathic litharenites or orthoquartzites, formed under intense physical weathering with rapid transport and deposition, under semi-arid climate or under the influence of a high relief (Georgiadis, 2006; Georgiadis et al., 2007). All the above detrital sediments have as exclusive source, the metamorphic basement of the Unit.

The detrital sediments studied are deposited onto the Vertiskos Plateau, overlying the alpine gneissic basement. These are soil profiles along with generally loose alluvial, fluvial and some lacustrine formations. This study considers the detailed textural, petrological and mineralogical study of modern sands from the Vertiskos Unit. Using mechanical, petrographic and mineralogical techniques it is attempted to indicate the processes under which these sediments were formed, the petrology of the source areas and the current state of weathering of the Vertiskos Unit, Serbomacedonian Massif.

2. Geological setting

The study area belongs to the Serbomacedonian Massif and more specifically comprises the Northern and major part of the Vertiskos Unit. The Vertiskos mountain is located in the centre of this Unit,

Table 1. Peak heights used for mineral semi-quantitative determination (Tsirambides, 2008).

Mineral	Angle (2θ)	d (Å)	Counts/second
Quartz	20.8	4.26	765
Plagioclase	28.0	3.18	1350
Alkali feldspar	27.5	3.24	1350
Calcite	29.4	3.04	1370
Pyroxene	29.9	2.99	1250
Amphibole	10.5	8.45	1250
Garnet[1]	34.7	2.57	1250
Micas	19.7	4.50	260

[1]d-value varies slightly according to composition.

with an altitude of approximately 1,103 m. This mountain is drained from several rivers and torrents. This complex drainage system is generally of dendritic pattern, discharging its detrital load to Gallikos and Strymon Rivers (West and East ends of the Massif, respectively), to Doirani and Kerkini Lakes to the North and to Koronia and Volvi Lakes to the South (North and South ends of the Unit, respectively) (Fig. 1).

The Alpine basement of the Vertiskos Unit is mainly comprised of Paleozoic metasediments and metabasic rocks, along with Eocene to Miocene granites. The Unit has been metamorphosed during the Paleozoic to the amphibolite facies, followed by a Cretaceous retrograde metamorphosis to the greenschist facies (Mountrakis, 2002). In detail the petrographic types that consist the Unit (excluding granites, pegmatites and marbles), are (Kourou, 1991; Sidiropoulos, 1991; Chatzidimitriadis et al., 1993): A) Amphibolites, amphibolitic gneisses and banded amphibolites. B) Medium grained pelitic to semi-pelitic mica schists. C). Fine grained meta-arkosic rocks. D) Fine-grained and massive meta-sandstones in bands with migmatitic gneisses. E) Calsic silisic rocks with no typical composition, developed between the contact of the marbles and the semi-pelitic schists. F) Augen gneisses and banded gneisses. G) Medium to coarse grained garnet mica gneisses. H) Small eclogitic bodies. I) Ultrabasic rocks (typical serpentinites and talc-chlorite schists) and J) Poorly sorted Tertiary massive graywackes along with poorly sorted and massive arkoses.

3. Materials and Methods

From different locations of the Vertiskos Unit samples of modern sands were taken. They were analyzed in detail mineralogically by the use of powder X-ray diffraction (PXRD). The samples when moisten were left to dry at room temperature and then separated into consecutive size fractions by sieving in order their textural properties to be studied. Powder X-ray diffraction was performed on a Philips diffractometer with Ni-filtered CuK_{α} radiation. Randomly oriented mounts of the untreated sand sized fraction of the samples were scanned over the interval 3-63° 2θ at a scanning speed of 1.2° per minute. Semi-quantitative estimates of the minerals present are based on peak heights and intensity factors of XRD patterns (Table 1), using the methods described by Hower et al. (1976), Moore and Reynolds (1997) and Tsirambides (2008). In addition, polarizing microscopy analysis was performed by the use of thin sections prepared from grains of the fractions 1Φ, 2Φ, and 3Φ of samples R1 and G1. In this way the shape of the grains along with the distribution of minerals in each fraction was examined.

Table 2. Statistical parameters of grain size populations for the modern sand samples, according to Folk (1974).

Sample	Mo (Φ)	Md (Φ)	M_z (Φ)	σ_I (Φ)	Sk_I	KG
E1	-1.0 & 2.0	-0.8	-0.49	1.82	0.17	0.83
E2	-1.0 & 2.0	-1.0	-0.41	1.82	0.21	0.92
E3	0.1	-0.5	-0.59	1.33	-0.07	1.06
E4	-0.3	-0.8	-0.62	1.69	0.08	0.88
E5	-2.0 & 0.0	-0.9	-0.93	1.68	0.02	0.86
E6	-2.8 & -0.7	-1.2	-1.35	1.52	-0.02	1.04
E7	0.6	-0.2	-0.21	1.59	0.00	0.97
X1	-2.9 & 0.9	-0.1	-0.41	1.68	-0.29	1.11
A1	-0.1	-0.7	-0.55	1.30	0.10	1.08
S1	-2.0 & 1.0	0.0	-0.17	1.64	-0.18	0.91
S3	-1.1 & 2.0	1.0	-0.75	1.84	0.22	0.93
S4	1.9	-0.2	0.94	1.79	-0.10	1.00
F1	0.1	-0.6	-1.12	1.11	0.16	1.18
F2	-0.1	-0.5	-1.64	0.97	-0.02	1.04
F3	0.0	-0.3	-0.44	1.02	0.07	1.00
N1	0.4	-0.5	-0.26	1.04	0.00	0.98
D1	0.0	0.5	-0.50	0.99	0.05	1.05
R1	5.0	2.1	2.19	2.17	-0.11	0.74
R5	1.0	0.5	0.13	1.83	-0.01	0.95
G1	1.8	1.1	0.94	1.35	-0.30	1.54

Mo=mode, M_d=median, M_Z=graphic mean, σ_I=inclusive graphic standard deviation, Sk_I=inclusive graphic skewness and K_G=graphic kurtosis.

4. Results

4.1 Texture and Lithology

Macroscopically all the modern sand samples are generally brown and grey coloured coarse grained loose sands, showing a sandy gravel to gravely sand texture, with little or no mud. Exceptions are the samples R1 and R5, which demonstrate a muddier suite.

All grains macroscopically present low sphericity and are angular to subangular, with easily identified more rounded lithic fragments of metamorphic origin, usually schist, along with some round shaped granite pebbles. The statistical parameters of grain size populations of the modern sand samples analysed are presented in Table 2.

The equations adopted for their calculation along with their interpretation are according to Folk (1974). In figure 2 the lithological classification of the modern sand samples is shown, according to Folk (1974).

According to the variation amplitude of the inclusive graphic standard deviation, the modern sands appear to be moderately sorted to very poorly sorted. The degree of sorting along with the content of mud in the samples, designates them as texturally immature to submature (Weller, 1960; Folk,

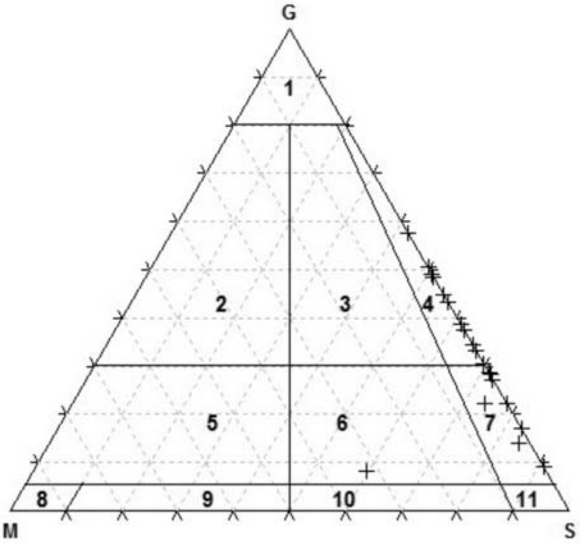

Fig. 2: Textural classification of modern sand samples, according to Folk (1974). G=percentage of gravel, S=percentage of sand, M=percentage of silt+clay, 1=gravel, 2=muddy gravel, 3=muddy sandy gravel, 4=sandy gravel, 5=gravelly mud, 6=gravelly muddy sand, 7=gravelly sand, 8=slightly gravelly mud, 9=slightly gravelly sandy mud, 10=slightly gravelly muddy sand and 11=slightly gravelly sand.

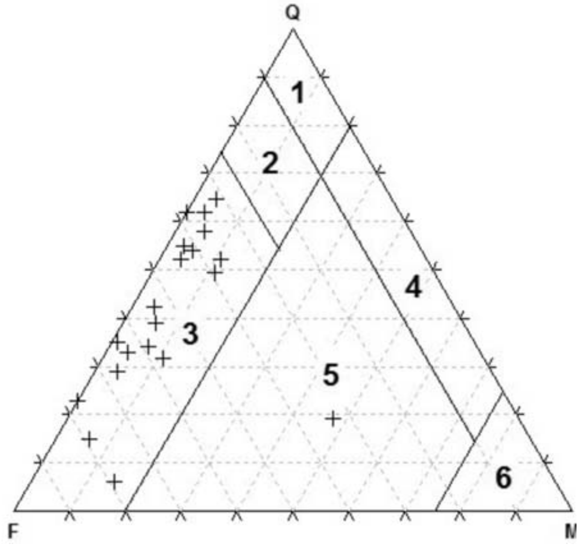

Fig: 3: Ternary diagram for the classification of detrital sediments according to Stewart et al. (1959). 1=orthoquartzite, 2=feldspathic orthoquartzite, 3=arkose, 4=subgraywacke, 5=greywacke (phyllarenite), 6=pelite, Q=quartz, F=feldspars and M=micas (+chlorite).

1974). The inclusive graphic skewness implies that they have grain size curves from coarse skewed, to symmetrical and fine skewed. Modern sands have graphic kurtosis with positive value, ranging from 0.74 to 1.54, so being platykurtic to leptokurtic.

According to Folk (1974), the modern sand samples analyzed are classified as sandy gravels to gravely sands, with the exception of the sample R1 which plots to the field of gravelly muddy sand.

4.2 Mineralogy and Petrology

The powder X-ray diffraction semiquantitative mineralogical composition of the modern sand samples is shown in Table 3. The petrographical classification adopted is that of Pettijohn (1957) and

Table 3. Mineralogical composition (wt. %) of the modern sands analyzed.

Sample	Q	Pl	Kf	M	Am	Px	Grt	Cc	Q_n	F_n	M_n
E1	22	23	49	tr	6	nd	nd	tr	23	77	0
E2	19	33	nd	47	nd	nd	1	nd	19	81	0
E3	55	23	11	tr	10	nd	1	nd	62	38	0
E4	33	37	20	7	nd	2	nd	1	34	59	7
E5	37	49	4	6	2	nd	2	nd	39	55	6
E6	44	26	5	9	7	2	nd	7	52	37	11
E7	61	31	4	3	1	nd	nd	nd	62	35	3
X1	30	18	6	7	33	2	4	nd	53	4	43
A1	45	25	9	4	12	1	1	3	54	41	5
S1	59	13	24	5	nd	nd	nd	nd	58	37	5
S3	17	29	4	6	43	nd	nd	nd	30	60	10
S4	27	42	8	1	19	3	nd	nd	35	64	1
F1	13	63	3	5	15	tr	nd	nd	16	80	4
F2	39	41	9	4	3	3	2	nd	43	53	4
F3	33	40	21	4	3	nd	nd	nd	34	62	4
N1	51	35	8	4	nd	2	nd	nd	52	44	4
D1	54	20	20	3	2	2	nd	1	56	41	3
R1	21	33	15	3	21	1	6	nd	29	67	4
R5	6	66	8	14	3	1	2	nd	7	78	15
G1	57	19	9	4	9	2	nd	nd	64	31	5

Q=quartz, Pl=plagioclase, Kf=alkali feldspars, M=micas including chlorite, Am=amphibole, Px=pyroxene, Grt=garnet, Cc=calcite, Q_n=normalized percentage of quartz, F_n=normalized percentage of total amount of feldspars, M_n=normalized percentage of micas, tr=traces and nd=not detected.

Stewart et al. (1959), shown on figure 3. These authors use the percentages of quartz, total feldspars and micas, avoiding the use of rock fragments, thus making this scheme suitable for bulk X-ray analyses.

In the petrographical classification scheme adopted in this study, the term greywacke is used for sandstones rich in micaceous material. Depending though on the textural examination of the samples which revealed that they are poor in muddy matrix, the term phyllarenites should be adopted according to Folk (1974). Accessory minerals which participate in the assemblage of the samples with percentages greater than 3%, are included as prefixes to the rock naming.

In the modern sand samples analyzed the quartz content varies significantly, ranging from 6% to 61%. The same variation width is observed also in the plagioclase content (13-66%) and the alkali feldspar content (3-49%), with the mica content being also diverse (1-47%). Accessory ferromagnesian minerals (amphiboles and pyroxenes), along with detrital garnet and calcite, are almost always present in the composition of the above samples, sometimes in great amounts.

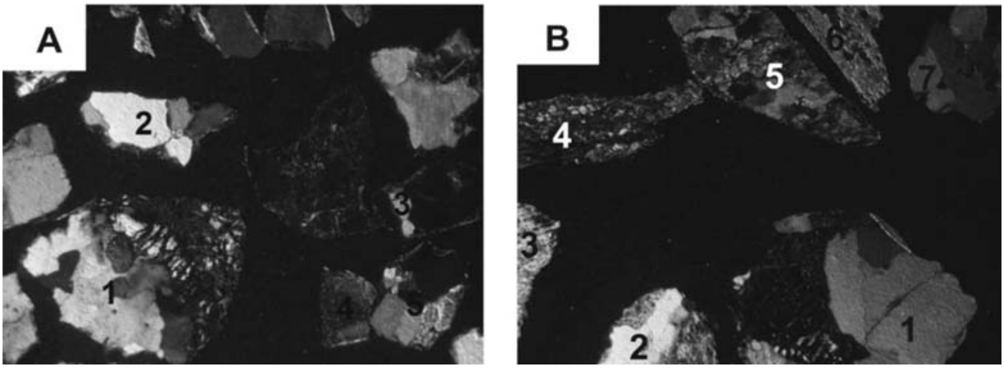

Fig: 4: A) Microphotograph of fraction 1Φ from sample R1. 1=rock gragment with undulatory quartz, biotite and garnet, 2=rock fragment with undulatory quartz and biotite, 3=rock fragment with quartz and biotite crystal showing extinction, 4=monocrystalline biotite and 5=rock fragment with quartz and amphibole. Nicol+. B) Microphotograph of fraction 0Φ from sample G1. 1=rock fragment with undulatory quartz and garnet, 2=rock fragment with undulatory quartz, fine biotite and fine white mica, 3=fragment with fine white mica, 4=rock fragment with biotite and quartz, 5=polycrystalline fine quartz with minor white mica, 6=muscovite fragment and 7=polycrystalline quartz.

All of the samples presented in this study are mineralogically immature according to Weller (1960) since they contain feldspars, ferromagnesian and heavy minerals (i.e. micas, amphibole, pyroxene and garnet). Their high content in lithic fragments and feldspars, is indicative of an adjacent source of the clastic load (Tucker, 2001). From the petrographic examination of the samples it is obvious that the modern sand samples demonstrate controversial composition. This can be attributed to rapid erosion and mixing of sand populations from different but adjacent sources.

According to petrographical classification scheme adopted in this study, the samples may be distributed under seven clans of rocks, namely: A) Arkose: samples E2, E4, E5, A1, S1, F1 and D1, all being rich in feldspars. B) Amphibole arkose: samples E1, E3, E6, E7, S3, F3, N1 and G1 due to their content in amphiboles and feldspars. C) Pyroxene amphibole arkose: samples S4 and F2. D) Garnet amphibole arkose: only the sample R1 is included as being rich in amphibole and garnet. E) Amphibole greywacke: the sample R5 due to its content in amphibole and mica and F) Garnet amphibole subgraywacke: X1 is the only member of this clan, being rich in amphibole and moderately rich in mica.

From the polarized microscopy study (Fig. 4) it is found that the assemblage of the 1Φ fraction of samples R1 and G1 is mainly constituted of monocrystalline and polycrystalline quartz, plagioclase always altered to sericite, few alkali feldspar usually found as orthoclase and individual euhedral crystals of muscovite and biotite or along with quartz. Quartz is present with undulatory extinction and when present in fine quartzose aggregates it shows characteristic lobe sutures. Single crystals of quartz and feldspar are generally angular to subangular. Opaque minerals are always present in small amounts. Rock fragments are generally subangular to subrounded and composed of quartz, biotite, muscovite, amphibole, plagioclase, epidote, kyanite, sillimanite, orthopyroxene and zoisite. Other accessory minerals found are garnet and kyanite in single euhedral crystals and single crystals of orthopyroxene and rutile.

In the fraction of 2Φ the amount of rock fragments decreases and they become more angular, maintaining though their mineral constitution. This fraction is rich in single angular to subangular crystals of muscovite, orthopyroxene, epidote, biotite, kyanite, plagioclase (altered in sericite), quartz, orthoclase, clinopyroxene, garnet, rutile and some amphibole. Fraction 3Φ is mainly constituted of single angular crystals of the above mentioned minerals, plus minor amounts of zoisite.

5. Discussion

The samples analyzed in general demonstrate unimodal patterns of grain size distribution, except samples E1, E2, E5, E6, X1, S1 and S3 with bimodal pattern. Samples F2 and D1 are moderately sorted, R1 is very poorly sorted, whereas the rest of the samples are poorly sorted. The previous designates them as being immature to submature (Folk, 1974). Folk (1974) and Tucker (2001) interpret this feature as being distinctive of sediments accumulated in loci of the source (rapid deposition), or the current action was weak (i.e. detrital material deposited from a viscous flow, such as a mud flow). The above acceptation also implies that these sediments were deposited under intense to mild tectonic activity (Folk, 1974). Taira and Scholle (1979) studied the origin of bimodal sands in modern environments and found that this feature of sediments in fluvial channels could be attributed to the mixing of two sorting processes, which have different sorting tendencies.

According to Friedman (1961) all samples are fluvial deposits. Fuchtbauer and Muller (1970) suggest that fluvial sediments demonstrate $\sigma_I > 1.2\Phi$ (or sometimes $>1.3\Phi$) and $Sk_I < 1$ (rarely >1), whereas flood plain sediments demonstrate mostly $\sigma_I > 2\Phi$ and always $Sk_I < 1$. This rule is not always followed by the samples studied. In general, the samples studied are poor in mud content (except sample R1), so they have arenitic character.

From the petrographic analysis of the samples it is found that quartz is present in all samples, but its content varies greatly. Its presence is due to its abundance in the surrounding metamorphosed rocks and granites and to its mechanical resistance (Blatt, 1992). When plotting the values acquired for inclusive graphic skewness versus the quartz content, a general trend is obvious with quartz content diminishing with increasing skewness. This is indicative that the bulk of the quartz content is accumulated in the coarse fraction of the sediment. Blatt et al. (1972) consider the mean size of detrital quartz to be approximately 2Φ in sandstones. The texture of the quartzose rock fragments, as revealed from the polarized microscopy, is indicative of a metamorphic gneissic and acid plutonic source: Quartz crystals show undulatory extinction and intercrystalline suturing in polycrystalline grains. Also, assuming a first-cycle origin of the modern sands, the fine monocrystalline quartz grains must have originated from foliated metamorphic rocks (Blatt et al., 1972).

In the modern sands, the content of feldspars follows an increasing trend along with the increase in the values of inclusive graphic skewness, showing that the former mainly contribute to the finer fractions of the samples. According to Blatt et al. (1972) the most altered feldspars in feldspathic sediments are the calcic ones and the freshest are the potassic, a general rule that seems to apply to all the samples studied. According to Pittman (1969) feldspar grains diminish in size by fracture along twin crystal planes, as they are transported in streams of high gradient. In the samples studied, feldspars do accumulate in the finer sand fractions but they also contribute to the coarser ones; this observation also favours the assumption of the accumulation of these sediments near their source.

Micas almost always contribute to the assemblage of the samples but in minor amounts, except sample R1 where it attributes a wacke character. Their abundance is due to the mica presence in the metamorphic parent rocks. Chlorite was also detected in traces in some of the samples along with some kaolinite. Their presence is associated with the alteration of micas and feldspars, respectively.

Detrital calcite was detected in some samples, its content ranging from traces to 7%. This can be attributed to minor contribution in carbonate clastic load from the carbonate rocks outcropping in the

Vertiskos Unit. Pyroxene when detected, always participate as a minor constituent of the samples analyzed. Garnet is a more common accessory mineral in the modern sands. The same is also true for amphiboles. All the three previous mentioned minerals are indicative of a metamorphic source and belong to the metastable group of heavy minerals (Folk, 1974). Morton and Johnsson (1993) showed that the abundances of garnet and pyroxene tend to decline with increased alluvial storage. Morton and Hallsworth (1999) consider heavy mineral assemblages in sandstones to be affected by physical sorting, mechanical abrasion and dissolution. These authors also note that source-area weathering does not significantly affect the diversity of heavy mineral suites prior to incorporation of sediment into the transport system, with the degree of enrichment of stable heavy minerals being greatest in transport-limited erosional regimes.

Suttner et al. (1981) and Suttner and Dutta (1986) correlated the framework composition and compositional maturity of fluvial sandstones with the climate setting, the more feldspathic (immature) being deposited near the source under a warm and dry climate and the more quartzose and mature being deposited under a wet climate. Girty (1991) showed that under semi-arid to mediterranean (hot summer) climate plutoniclastic sands produced are less ultered than under temperate and humid. Our samples due to their quartz content, may be considered to have been deposited under a wet climate, where chemical weathering readily acts, whereas according to von Eynatten (2003) the samples studied were deposited under a semi-arid climate with the effect of strong relief. The feldspar and heavy mineral content is more in agreement with the latter hypothesis (temperate and seasonable climate with the action mainly of physical weathering). Tsirambides (1999) also showed that the presence of amphibole and pyroxene in modern sediments is correlated with mild climatic conditions. The presence of unstable minerals (i.e. pyroxene, plagioclase) along with semistable ones (i.e. amphibole, orthoclase) also indicate the absence of chemical weathering (Garzanti et al., 2004).

According to Blatt et al. (1972) all the modern sand samples constitute a distinct petrologic province, correlated by age (modern), origin (the metamorphic basement) and distribution. This province could be furthermore mainly characterized by an amphibole association which includes all the modern sand samples.

6. Conclusions

The majority of the samples are coarse grained gravelly sands.

All samples are poor in mud content, demonstrate arenitic character and are texturally and mineralogically immature to submature. They have been deposited in a fluvial environment.

The sorting degree of the samples, along with their composition, is distinctive of sediments accumulated near the source under intense to mild tectonic activity. Especially, the bimodality of grain size in some of the samples is indicative of rapid weathering and mixing of different detrital populations.

Their assemblage is constituted mainly from quartz, feldspars and micas, along with accessory minerals of metamorphic and granitic origin. The studied sands are feldspathic and rich in heavy minerals. The latter feature verifies that these sands are deposited near their source. All the samples have as source the rocks comprising the Vertiskos Unit.

The mineral abundances described above designate Vertiskos Unit as being rapidly weathered under a seasonably wet and warm climate, with intense physical weathering. It is noticed a general trend of the samples becoming more quartzose and depleted in accessory minerals as they are transported from their source.

All the samples constitute a distinct sedimentary petrologic province on the Unit, comprised of an amphibole-garnet association.

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