

PETROLOGY AND PROVENANCE STUDY OF THE QUATERNARY CLASTIC SEDIMENTS FROM HERSO KILKIS (MACEDONIA, GREECE)

Georgiadis I. K.¹, Tsirambides A.¹, Kassoli-Fournaraki A.¹, and Trontsios G.¹

¹ Aristotle University of Thessaloniki, School of Geology, Department of Mineralogy-Petrology-Economic Geology, iogeorgi@geo.auth.gr, ananias@geo.auth.gr, kassoli@geo.auth.gr, trontzos@geo.auth.gr

Abstract

The sediments analysed are generally coarse grained, sand gravels to gravel sands. The silt and clay content of the samples is low and their textural study revealed a fluvial deposition environment. The amounts of quartz, feldspars and lithic fragments range from 33% to 56%, 8% to 18% and 28% to 52%, respectively. The samples studied may be classified as garnet-mica bearing litharenites. Quartz, plagioclases and micas are the predominant constituents. Detrital calcite and pyroxenes are present in small amounts. The samples are texturally and mineralogically immature. Detailed polarized microscopy revealed the presence of garnet, staurolite, kyanite, zoisite, rutile, epidote, zircon, apatite and tourmaline, as well as of opaque minerals. These accessory minerals are considered indexes of metamorphic provenance. Geochemically the samples are classified as sublitharenites and subarkoses, all being rich in SiO₂. The overall percentages of quartz, feldspars and rock fragments designate intense physical weathering and rapid transport and deposition in the Herso Basin which is part of a passive continental margin (recycled orogen).

Key words: drilling cuttings, paragenesis, mineral indexes, origin.

Περίληψη

Τα ιζήματα που αναλύονται είναι γενικά αδρόκοκκα, από αμμώδη χαλίκια έως χαλικώδεις άμμοι. Το περιεχόμενό τους σε ιλύ και άργιλο είναι μικρό, ενώ η ιστολογική τους μελέτη αποκαλύπτει περιβάλλον ποτάμιας απόθεσης. Το περιεχόμενό τους σε χαλαζία, αστρίους και θραύσματα πετρωμάτων κυμαίνεται από 33% έως 56%, 8% έως 18% και 28% έως 52%, αντίστοιχα. Τα ιζήματα που εξετάζονται μπορούν να ταξινομηθούν ως γρανато-μαρμαρυγιούχοι λιθαρενίτες. Χαλαζιάς, πλαγιόκλαστα και μαρμαρυγίες είναι τα επικρατέστερα συστατικά. Κλαστικός ασβεστίτης και πυρόξενοι βρίσκονται σε μικρά ποσά. Τα δείγματα είναι ιστολογικά και ορυκτολογικά ανώριμα. Λεπτομερής πολωτική μικροσκοπία αποκάλυψε την παρουσία γρανάτη, σταυρόλιθου, κνανίτη, ζοϊσίτη, ρουτίλιου, επιδότου, ζirkονίου, απατίτη και τουρμαλίνη, καθώς και αδιαφανών ορυκτών. Αυτά τα επουσιώδη ορυκτά θεωρούνται δείκτες μεταμορφικής προέλευσης. Γεωχημικά τα δείγματα ταξινομούνται ως υπολιθαρενίτες και υποαρκώζες και όλα είναι πλούσια σε SiO₂. Το συνολικό ποσοστό του χαλαζία, των αστρίων και των θραυσμάτων των πετρωμάτων δείχνει έντονη φυσική αποσάθρωση και ρα-

γδαία μεταφορά και απόθεση στη Λεκάνη του Χέρσου που θεωρείται τμήμα ενός παθητικού ηπειρωτικού περιθωρίου (ανακυκλωμένο ορογενές).

Λέξεις κλειδιά: θρύμματα γεώτρησης, παραγένεση, ορυκτά δείκτες, προέλευση.

1. Introduction

The Neogene and Quaternary sediments, along with the molassic sediments of Eocene-Miocene of Greece lie unconformably over the folded alpine basement and are of fluvial, lacustrine or marine origin. Especially, the Neogene and Quaternary sediments are deposited into grabens or other neotectonic basins and are not connected to orogenic procedures. The Post Alpine formations are widespread and are characterized by a wide lithological and facies variation (Mountrakis 1985).

The sediments studied were deposited into the Axios-Thessaloniki neotectonic graben, overlying the alpine basement and the Tertiary molasses. The graben has a NNW-SSE general direction and the detrital sediments filling it are generally loose alluvial, fluvial and lacustrine formations (mainly sandstones). These formations are medium to coarse grained gravel sands to gravel mud sands, moderately to poorly sorted and rich in feldspars and quartz (Mountrakis *et al.* 1993, Tsirambides 1997).

Dott (1964) supports that textural maturity and compositional stability provide the clearest guides in the sandstone classification. In general, sandstones are classified into arkoses, litharenites, greywackes and quartz arenites. Arkoses are terrigenous coarse grained sandstones formed from intense physical weathering of granites and gneisses and rapid transport and deposition of the clastic materials at small distance. They generally contain abundant feldspars (>25 %), usually altered and are mineralogically and texturally immature. Litharenites are sandstones with a great mineralogical diversity, rich in rock fragments and quartz with a lesser amount of feldspars than arkoses and significant amount of detrital mica. The litharenites are indicators of relatively adjacent provenance. Greywackes are marine sandstones and quartz arenites are mineralogically mature cratonic sandstones (Pettijohn *et al.* 1973). In arkoses, the clay fraction is a minor constituent, whereas in quartz sandstones the sand fraction is abundant in detrital quartz (Blatt *et al.* 1972).

This study considers the detailed mineralogical and chemical study of clastic sediments from the Herso Basin (Kilkis Prefecture). Using a variety of petrographic, mineralogical and geochemical techniques it is attempted to elucidate the processes under which these sediments were formed and the parent rocks which constitute the supplier of these clastic materials.

2. Geological Setting

The Herso Basin is located approximately 13 km N-NW of the city of Kilkis. It has an elongated shape, covers an area of approximately 100 km², and it is drained mainly from Doiranis River and several torrents. Serbomacedonian Massif constitutes the eastern margin of the Basin (Disoro Mountain), whereas Circum Rhodope Belt constitutes the western margin (Fig. 1). The Quaternary detrital sediments under study overlie unconformably the alpine basement (I.G.M.E. 1990).

The eastern margin of Herso Basin (Disoro Mountain) constitutes the western part of the Serbomacedonian Massif. Disoro Mountain, being a part of the Vertiskos Unit, consists of the following Paleozoic metamorphic rocks: a) medium grained pelitic mica schists rich in quartz, micas and to a lesser extent plagioclase and metamorphic minerals (mainly garnet altered to chlorite, kyanite, clinozoisite and staurolite); b) meta-arkosic rocks rich in quartz, plagioclase, micas, apatite, titanite and opaque minerals; c) coarse augen gneiss comprised of quartz, feldspars, biotite, zoisite, epidote, apatite, zircon and opaque minerals; and d) banded amphibolites. In all the petrographic types the plagioclase is usually altered to sericite. In addition, Paleozoic ultramafic rocks are present in small bodies, mainly consisting of serpentine, accessory titanite and opaque minerals. Finally, a Mesozoic granite is found tectonically emplaced between Serbomacedonian

Massif and Circum Rhodope Belt at the North part of the Basin. This granite is mainly composed of quartz, perthitic microcline, plagioclase, chloritized biotite and zircon, allanite, apatite, fluorite and titanite as accessory minerals. Hydrothermal alteration of the constituents of this granite is very evident (Sidiropoulos 1991, Christofides *et al.* 1999).

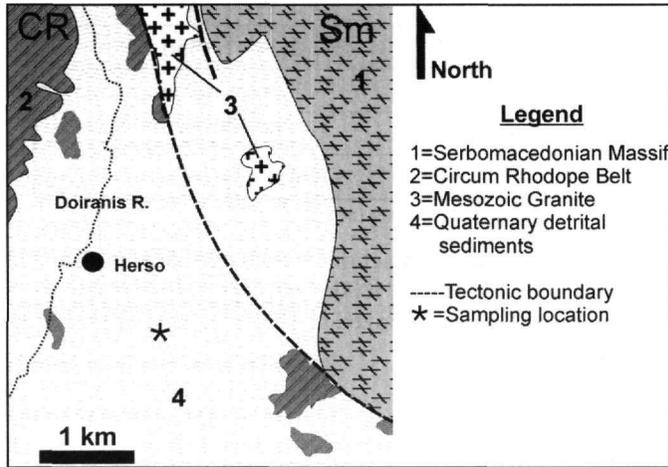


Figure 1 - Petrographic sketch map of the Herso Basin

The western margin of Herso Basin (Mavros Vrahos and Megali Toumpa Hills) actually is the eastern boundary of the Circum Rhodope Belt. The latter generally consists of Permotriassic volcanic rocks and meta-clastic sediments which are accompanied by Mesozoic sediments (Doumbia Unit). It is a succession of Permian turbidity meta-clastics (Examili Formation) comprised of meta-sandstones, quartzites and breccias in the lower part, a Permotriassic volcanisedimentary series with alternating acid volcanics and meta-clastics in the middle and Mesozoic neritic and marine carbonates in the upper part. Usually, the above mentioned formations show silicification and are schistosed (Asvesta 1992).

3. Materials and Methods

From different horizons of a water drilling performed to a depth of 150 m, 16 cutting samples were taken. They were analyzed in detail by the use of X-ray diffraction (XRD), polarizing microscopy and geochemical techniques. The samples were separated into consecutive size fractions by sieving in order their textural properties to be studied. Prior to the mineralogical analysis the collected samples were disaggregated by the use of an agate mortar and pestle, gently in order to retain to the extent possible their intrinsic grain sizes. The fraction of 0.5-1 mm was chosen for the X-ray diffraction, microscopical and geochemical study, due to its extended abundance in all samples.

X-ray diffraction was performed on a Philips diffractometer with Ni-filtered CuK_α radiation. Randomly oriented mounts of the untreated fraction of 0.5-1 mm of the samples were scanned over the interval $3-43^\circ 2\theta$ at a scanning speed 1° per minute. Semi-quantitative estimates of the minerals present are based on peak heights and intensity factors on XRD patterns, without the employment of any correction factors (Table 1), using the methods described by Schultz (1964), Cook *et al.* (1975) and Tsirambides (2004).

Polarizing microscopy analysis was performed by the use of thin sections prepared from grains of the fraction 0.5-1 mm of each sample. In this way the paragenesis of the samples was determined in detail. In addition, the thin sections were point counted in order the percentages of monocrystalline and polycrystalline quartz, feldspars and lithic fragments as well as of all minerals present to be calculated and the samples to be classified.

Table 1 - Peak heights used for mineral semi-quantitative determination (Tsirambides 2004)

Mineral	Angle (2 θ)	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
Total micas ¹	19.7	4.50	260

¹Total micas including chlorite

The geochemistry of the above mentioned fraction of each sample was also studied. The chemical analysis was performed on a Perkin Elmer 5000 flame spectrometer apparatus. Quantity of the fraction 0.5-1 mm of each sample was pulverized and the major oxides were measured by the use of atomic absorption spectrometry (AAS).

4. Results

4.1. Lithology and Petrology

The samples analysed are generally coarse grained, sand gravels to gravel sands. All samples present unimodal frequency curves except X1, X2 and X10 that show bimodal patterns and poorer sorting. All grains present low sphericity and are angular to subangular. The lithic fragments which are constituted of finer quartz grains are generally more rounded than those constituted of coarser quartz grains. The same trend is noticed for these lithic fragments constituted of fine white mica embracing altered metamorphic minerals. Finally, the single crystals of metamorphic minerals (i.e. garnet, kyanite and staurolite) are present as euhedral crystals with more angular shape (Georgiadis 2006). All samples are texturally and mineralogically immature. The silt and clay content of the samples is low (generally <15 %) and their textural study revealed a fluvial deposition environment, except for the sample X3 (~70 m depth) which is lacustrine.

Table 2 - Main constituents (wt. %) of the samples analysed

Sample	Depth (m)	Q	F	L	Sample	Depth (m)	Q	F	L
X1	0.15	33	15	52	X9	102-108	54	18	28
X2	40-46	42	15	42	X10	108-114	56	8	37
X3	66-72	43	16	41	X11	114-120	48	12	39
X4	78-84	48	16	36	X12	120-126	52	10	38
X5	84-90	50	11	39	X13	126-132	51	15	34
X6	90-94.5	52	14	34	X14	132-138	50	12	39
X7	94.5-96	54	10	36	X15	138-144	48	11	41
X8	96-102	52	12	36	X16	144-150	46	17	38

Q=monocrystalline and polycrystalline quartz, F=feldspars and L=lithic fragments

Table 2 presents the percentages of monocrystalline and polycrystalline quartz, feldspars and lithic fragments of the samples studied. These are classified as litharenites and feldspathic litharenites according to Folk *et al.* (1970) and Pettijohn *et al.* (1973). Generally, the amounts of quartz, feldspars and lithic fragments range from 33 % to 56 %, 8 % to 18 % and 28 % to 52 %, respectively. According to Tucker (2001) the samples are mineralogically immature due to their

high content in lithic fragments and feldspars, indicative of an adjacent source of the clastic load. The litharenites definitely designate a surface weathering mainly of volcanic, sedimentary and low grade metamorphic rocks, the latter reflected in their mineral constituents (Pettijohn *et al.* 1973).

4.2. Mineralogy

The X-ray diffraction semiquantitative determination of the samples is shown in table 3. Quartz is the predominant constituent of the samples. This is due to its abundance in the surrounding metamorphosed rocks, to its mechanical resistance, as well as to the chosen fraction studied (Blatt 1992). The amount of quartz in the samples shows an increasing trend up to the depth of approximately 90 m, and then remains above 70 % in the deeper ones.

Plagioclase is the second in abundance mineral after quartz, with the exception of sample X1. Alkali feldspar is always present in minor amounts. According to Blatt (1992) feldspars constitute the 10-15 % of sandstones, a general rule that seems to apply in the studied samples. Even though the plagioclases are considered less stable in weathering compared to the alkali feldspars, in all samples studied the plagioclases are more abundant than the alkali feldspars. This is due to intense weathering of the parent rocks and to the rapid transport and deposition of the clastic materials at small distance. Plagioclase content along the depth of the drilling shows exactly the opposite trend compared to that of the quartz, whereas no distinct trend is obvious for the alkali feldspar.

Table 3 - Mineralogical composition (wt. %) of the samples analysed

Sample	Q	Pl	Kf	M	C	Px	Sample	Q	Pl	Kf	M	C	Px
X1	58	14	6	22	nd	nd	X9	80	8	8	4	tr	tr
X2	70	18	4	6	1	1	X10	82	9	3	6	nd	nd
X3	68	15	3	11	1	2	X11	83	9	5	3	tr	tr
X4	75	12	3	8	tr	2	X12	76	12	9	3	tr	tr
X5	67	12	14	6	2	1	X13	84	9	5	2	tr	nd
X6	86	7	1	5	nd	1	X14	78	11	8	3	nd	nd
X7	84	8	4	4	tr	tr	X15	82	10	5	3	nd	nd
X8	84	9	3	4	nd	tr	X16	78	12	5	5	nd	nd

Q=quartz, Pl=plagioclase, Kf=alkali feldspar, M=mica, C=detrital calcite, Px=pyroxene, tr=traces and nd=not detected

In all samples mica is present mostly as muscovite. Its increased abundance is due to its extended presence in the adjacent metamorphic parent rocks. Chlorite was also detected in traces in all samples. Generally, the mica content of the samples decreases downwards and below approximately 90 m is practically constant and less than 6 %.

Detrital calcite was detected in minor amounts (<2 %) in most of the samples. Almost in all samples pyroxene was found in amounts from traces up to 3 %, with a decreasing tendency to the deeper horizons. In the sample X2 traces of garnet (with almandine composition) were found and in the sample X8 traces of hematite were detected, too. The presence of garnet and pyroxene reveals a metamorphic provenance for the clastic sediments studied, whereas hematite may have formed from the alteration of the opaque minerals of the metamorphic parent rocks (Blatt 1992, Deer *et al.* 1998).

The samples are mineralogically immature since they contain great amounts of feldspars and ferromagnesian minerals (i.e. micas and pyroxenes). Because the clastic sediments under study contain these vulnerable to weathering minerals, it may be assumed that these were deposited near their source origin (Pettijohn *et al.* 1973, Sawyer 1986, Tsirambides 2004).

The samples studied may be classified as garnet-mica bearing litharenites according to Folk *et al.* (1970).

From the detailed polarized microscopy study, the following results were taken concerning the composition of the studied samples:

Their paragenesis is mainly constituted of monocrystalline and polycrystalline quartz, plagioclase usually altered to sericite, perthitic microcline, orthoclase and individual euhedral crystals of muscovite or in combination with quartz. The quartz is most commonly present with undulatory extinction, whereas when it is present in fine quartzose aggregates it shows characteristic lobe sutures. Biotite crystals are found always chloritized. Opaque minerals are always present in small amounts. Finally, rock fragments composed of quartz, biotite, muscovite and titanite or rock fragments with clinopyroxene, muscovite and detrital calcite, are contained in the studied clastic sediments.

Other accessory minerals found are: garnet in single euhedral crystals or in rock fragments along with quartz and plagioclase; euhedral single crystals of tourmaline; staurolite altered to fine muscovite; single crystals of kyanite (some times altered to fine muscovite) or kyanite in rock fragments with plagioclase; epidote in single crystals or in rock fragments with garnet and feldspars; zircon; apatite (in single crystals or aggregated with quartz); zoisite; rutile. Especially, in sample X1 amphibole is present as accessory mineral, always in rock fragments with quartz and plagioclase, and clinopyroxene in rock fragments with quartz and small zircon crystals.

4.3. Geochemistry

Chemical analysis results are presented in table 4. It is evident that all the samples studied are rich in SiO₂. This can be attributed to the high content of quartz, to the fact that the majority of the minerals constituting the samples are silicates and because of the coarse fraction chosen for this study. Pettijohn *et al.* (1973) and Chuhan *et al.* (2001) correlate the amounts of Al₂O₃ with feldspars, micas and pyroxenes. According to Deer *et al.* (1998) micas, titanite, rutile, garnet, staurolite, epidote (along with zoisite and clinozoisite), tourmaline and opaque minerals are responsible for the amounts of TiO₂ present in the samples.

The total iron (Fe₂O_{3i}) content can be mainly attributed to micas, amphiboles and opaque minerals, and to a lesser extent to feldspars (Blatt *et al.* 1972, Pettijohn *et al.* 1973). The same writers consider that almost the bulk of alkalis in coarse sandstones are concentrated in alkali feldspars and muscovite, with K⁺ generally being more abundant than Na⁺. The latter seems to apply in the samples studied.

According to Pettijohn *et al.* (1973) the amounts of Ca²⁺ are mainly due to the presence of calcite and plagioclases, whereas chlorite and dolomite are responsible for the Mg²⁺ present. They also consider Ca²⁺ more abundant than Mg²⁺, a fact which also applies to the samples studied. Micas, pyroxenes and amphiboles must also be included to the minerals controlling the amounts of CaO and MgO (Huang 1982, Deer *et al.* 1998). Because of the absence of detrital calcite and dolomite, plagioclases and micas are responsible for the CaO and MgO content in the samples.

P₂O₅ and MnO are present in minor amounts. The former can be attributed to the apatite present and the latter mainly to the tourmaline, garnet and to a lesser extent to the clinopyroxene and epidote present (Deer *et al.* 1998).

The loss on ignition (LOI) is generally due to the removal of OH⁻ from the crystal lattice of the minerals present, the organic carbon and CO₂ from the carbonate minerals. Since carbonate minerals and organic matter are absent, the contained hydroxyl minerals (especially micas) may be considered responsible for the LOI amounts.

Table 4 - Chemical composition (wt. %) of the samples analysed

Oxide	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16
SiO ₂	88.47	86.34	84.29	86.43	84.27	88.22	88.45	89.5	86.8	88.02	88.77	89.39	89.49	88.17	88.22	87.06
Al ₂ O ₃	5.32	6.27	5.97	5.45	6.59	5.2	4.3	4.17	4.68	4.55	4.35	4.18	4.27	5.44	4.39	5.18
TiO ₂	0.17	0.13	0.35	0.16	0.2	0.21	0.22	0.08	0.24	0.25	0.23	0.2	0.11	0.12	0.13	0.23
MnO	0.02	0.04	0.06	0.03	0.04	0.02	0.06	0.04	0.05	0.07	0.03	0.06	0.1	0.03	0.15	0.09
Fe ₂ O ₃	1.42	2.09	3.83	3.13	2.08	1.65	2.02	1.58	3.38	2.89	1.94	2.29	1.22	1.47	2.52	2.66
MgO	0.3	0.31	0.39	0.27	0.47	0.3	0.26	0.24	0.25	0.25	0.23	0.22	0.19	0.15	0.19	0.21
CaO	0.43	0.69	0.8	0.51	1.53	0.62	0.53	0.45	0.4	0.32	0.35	0.32	0.29	0.23	0.36	0.27
Na ₂ O	0.87	1.12	0.93	0.95	1.37	0.92	0.81	0.89	1.07	0.82	0.92	0.82	1.09	0.82	0.91	0.8
K ₂ O	1.17	1.35	1.37	1.07	1.55	1.25	1.1	1.09	1.24	1.2	1.18	1.15	1.68	1.67	1.46	1.64
P ₂ O ₅	0.03	0.04	0.07	0.16	0.05	0.05	0.04	0.05	0.06	0.07	0.04	0.04	0.07	0.1	0.05	0.06
LOI	1.31	1.4	1.7	1.42	1.39	1.37	1.74	1.68	1.75	1.4	1.49	0.87	1.14	1.41	1.26	1.49
Total	99.53	99.78	99.76	99.58	99.54	99.8	99.53	99.77	99.91	99.84	99.53	99.55	99.65	99.61	99.64	99.68

LOI=loss on ignition, Fe₂O₃=total iron as Fe³⁺

The SiO₂ content of the samples studied shows a decreasing trend up to a depth of approximately 90 m, and then increases. The opposite trend is observed for Al₂O₃, MgO, CaO and the alkalis. TiO₂, Fe₂O₃, P₂O₅ and LOI do not show any distinctive trend, whereas MnO shows a slight increasing trend with depth.

According to the geochemical classification of Herron (1988) all samples are classified as sublitharenites, except of two (X13 and X14) that are classified as subarkoses (Fig. 2). Pettijohn *et al.* (1973) consider sublitharenites as lithic sandstones containing 5-25 % labile constituents (i.e. rock fragments and feldspars) and subarkoses as sandstones containing 10-25 % feldspars and limited amounts of rock fragments. The petrographic classification of Folk *et al.* (1970) is not in complete agreement with the geochemical one of Herron (1988).

5. Provenance Study

For the determination of the source of the detrital sediments, the diagrams of Dickinson *et al.* (1983) and Roser and Korsch (1988) are used.

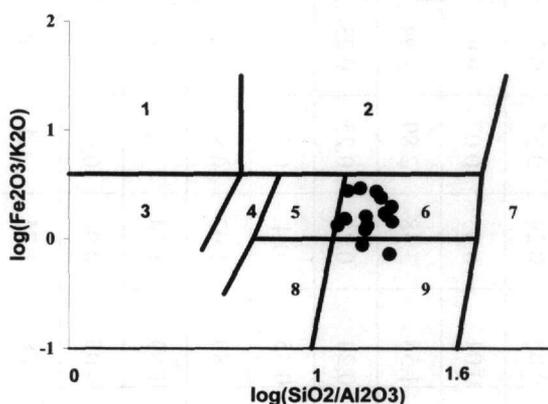


Figure 2 - Geochemical classification of terrigenous sandstones and shales (Herron 1988).
 1=Fe-shale, 2=Fe-sand, 3=shale, 4=wacke, 5=litharenite, 6=sublitharenite,
 7=quartz arenite, 8=arkose and 9=subarkose

The former has the advantage of incorporating the percentages of monocrystalline and polycrystalline quartz, feldspars and lithic fragments, parameters readily determined for the petrological classification. All the samples fall in the field of recycled orogen, except for sample X1 that projects in the field of dissected arc (Fig. 3).

The latter makes use of two discriminant functions, based on the major oxide chemical analysis. On this diagram the samples studied project in the field of quartzose sedimentary provenance (Fig. 4). According to Faundez *et al.* (2002) this source is indicative of quartzose metamorphosed sediments. The field of quartzose sedimentary provenance incorporates detrital sediments typical of passive continental margins (Roser and Korsch 1988). In general, Nesbitt and Young (1982) and Harnois (1988) consider Na⁺, K⁺ and Ca²⁺ useful provenance indicators, on the basis that Na⁺ and Ca²⁺ are mobile elements during weathering, whereas K⁺ is immobile and enriched, during transport and deposition, in the clastic load.

Especially, useful for the provenance determination are the heavy minerals, such as garnet, tourmaline, staurolite, kyanite, epidote and zircon. These minerals are considered indexes of low to high grade metamorphic rocks. All these minerals are present as accessory ones in the paragenesis of the studied samples and their presence is consistent with the metamorphic rocks east of the Herzo Basin. In addition, the increased amounts of detrital quartz, feldspars, chlorite, muscovite, staurolite and garnet, are indicative of a metamorphic provenance (Moorehouse 1985).

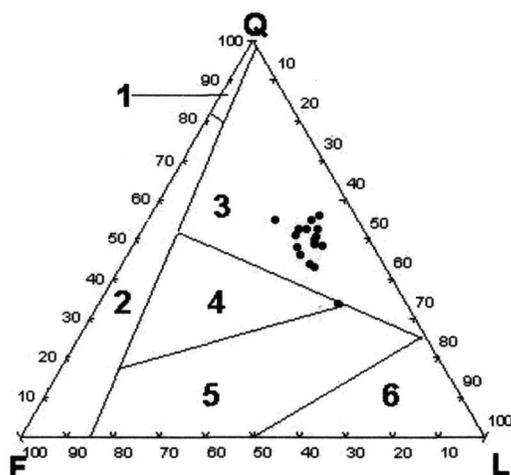


Figure 3 - Provenance discrimination of detrital sediments according to Dickinson et al. (1983). 1=craton interior, 2=basement uplift, 3=recycled orogen, 4=dissected arc, 5=transitional arc, 6=undissected arc, Q=quartz, F=feldspars, L=lithic fragments

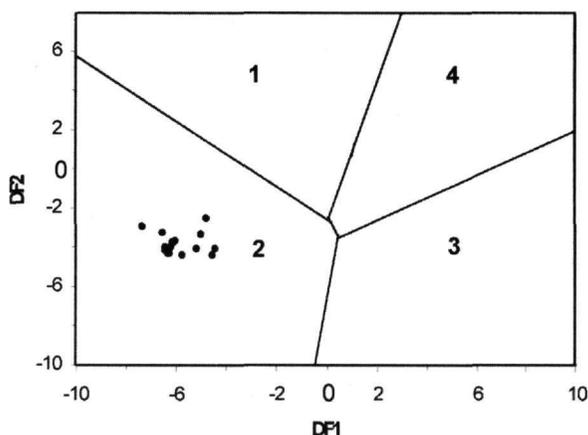


Figure 4 - Discriminant function diagram for the provenance signatures of sandstone-mudstone suites (Roser & Korsch, 1988). 1=felsic igneous provenance, 2= quartzose sedimentary provenance, 3=mafic igneous provenance, 4=intermediate igneous provenance.

$$DF_1 = -1.773TiO_2 + 0.607Al_2O_3 + 0.76Fe_2O_{3r} - 1.5MgO + 0.616CaO + 0.509Na_2O - 1.224K_2O - 9.09$$

$$DF_2 = 0.445TiO_2 + 0.07Al_2O_3 - 0.25Fe_2O_{3r} - 1.142MgO + 0.438CaO + 1.475Na_2O + 1.426K_2O - 6.861$$

6. Discussion

From the petrographic analysis of the samples it is found that these are rich in metamorphic rock fragments and are classified as quartz sandstones according to Dott (1964), as garnet-mica bearing litharenites according to Folk *et al.* (1970), or as lithic sandstones according to Pettijohn *et al.* (1973). All the samples are texturally and mineralogically immature.

Their paragenesis is mainly composed of quartz and plagioclase, followed by mica (mainly muscovite) and alkali feldspar (mainly microcline). The accessory minerals include abundant meta-

morphic minerals (i.e. garnet, tourmaline, staurolite, kyanite, epidote, zircon, apatite, zoisite and rutile), along with few detrital calcite and clinopyroxene. The abundance of plagioclase, compared with that of alkali feldspar, designates intense physical weathering and rapid transport and deposition at small distance along passive continental margins. This tectonic regime is concluded from the percentages of quartz, feldspars and rock fragments in the paragenesis of the samples under study (recycled orogen).

Comparing the petrography of the samples with the petrography of the adjacent rocks, there is readily an affiliation of the former with the metamorphic rocks of the Vertiskos Unit. Especially, the above mentioned accessory metamorphic minerals are indicative of their source. The apatite present in the samples may be attributed to the weathering either of the igneous body at the north of the Basin, or of the metamorphic rocks of the Vertiskos Unit. Tourmaline is considered by Petti-john *et al.* (1973) and Blatt (1992) an igneous mineral, but it is not a component of the acid igneous body at the North of the Basin (Christofides *et al.* 1999), whereas it is a common constituent of the metamorphic rocks of the Vertiskos Unit (Sidiropoulos 1991). The source of the characteristic metamorphic minerals and of fine white mica may be attributed only to the metamorphic rocks of the eastern margin of the Basin.

The absence of detrital carbonate minerals is notable and declares none contribution of clastic load from the carbonate rocks outcropping to the West of the Basin. Also, the absence of sanidine and rock fragments with aphanitic mass designates that the volcanic rocks of the Circum Rhodope Belt did not contribute to the formation of the litharenites studied. The latter could be used as an indication of the streams flow direction through the Basin, though the flow direction of Doiranis River must be considered as the main stream controlling the contribution of clastic load.

The chemical analysis of the samples revealed that these are rich in SiO_2 . K_2O is more abundant than Na_2O and CaO more abundant than MgO . The amount of SiO_2 in the samples seems to be controlled mainly by quartz, whereas the amount of Al_2O_3 , CaO , MgO and the alkalis is controlled by feldspars and micas.

7. Conclusions

- All samples are generally coarse grained, sand gravels to gravel sands. Their grains present low sphericity and are angular to subangular.
- All samples are texturally and mineralogically immature and were deposited in a fluvial environment.
- They contain quartz as a predominant mineral (58-86 %), plagioclase (7-18 %), mica (2-22 %), K-feldspar (1-14 %) and the accessory minerals (of metamorphic provenance) garnet, tourmaline, staurolite, kyanite, epidote, zircon, apatite, zoisite and rutile.
- The above mineral paragenesis means the almost exclusive contribution of clastic load from the metamorphic rocks to the East of the Basin and the igneous body to the North.
- These clastic sediments were formed by intense physical weathering of the parent rocks and by rapid transport and deposition of the clastic load at small distance.
- The Herso Basin may be considered part of a passive continental margin (recycled orogen).

8. References

- Asvesta, A., 1992. The magmatism and its related sedimentation during the first stages of the opening of the ocean basin of Axios in Triassic, *PhD Thesis*, Aristotle University, Thessaloniki, 436pp.
- Blatt, H., 1992. *Sedimentary petrology*, New York, Freeman & Co, 250pp.

- Blatt, H., Middleton, G., and Murray, R., 1972. *Origin of sedimentary rocks*, New Jersey, Prentice-Hall, 634pp.
- Christofides, G., Koroneos, A., Pe-Piper, G., Katirtzoglou, K., and Chatzikirkou, A., 1999. Pre-Tertiary A-type magmatism in the Serbomacedonian Massif (N. Greece): Kerkini granitic complex, *Bull. Geol. Soc. Greece*, XXXIII, 131–148.
- Chuhan, F.A., Bjorlykke, K., and Lowrey, C.J., 2001. Closed system burial diagenesis in reservoir sandstones: Examples from the Garn formation at Haltenbanken area, offshore Mid-Norway, *J. Sed. Res.*, 71(1), 15–26.
- Cook, H.E., Johnson, P.D., Matti, J.C., and Zemmels, I., 1975. Methods of sample preparation and X-ray diffraction data analysis, Initial reports, *Deep Sea Drilling Project*, 28, 999–1007.
- Deer, W.A., Howie, R.A., and Zussman, J., 1998. *An introduction to the rock-forming minerals*—2nd Ed., Essex, Addison Wesley Ltd, 696pp.
- Dickinson, W.R., Beard, S.L., and Brakenridge, G.R., 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting, *Geol. Soc. Am. Bull.*, 94, 222–235.
- Dott, R.H., Jr, 1964. Wacke, greywacke and matrix-What approach to immature sandstone classification? *J. Sed. Petrol.*, 34(3), 625–632.
- Faundez, V., Herve, F., and Lacassie, J.P., 2002. Provenance and depositional setting of pre-Late Jurassic turbidite complexes, *N. Z. J. Geol. Geophys.*, 45, 411–425.
- Folk, R.L., Andrews, P.B., and Lewis, D.W., 1970. Detrital sedimentary rock classification and nomenclature for use in N. Zealand, *N. Z. J. Geol. Geophys.*, 13, 937–968.
- Georgiadis, I.K., 2006. Petrological and geochemical study of the Quaternary detrital sediments of Herso Basin, Kilkis Prefecture, *M.Sc. Thesis*, Aristotle University, Thessaloniki, 127pp.
- Harnois, L., 1988. The CIW index: A new chemical index of weathering, *Sed. Geol.*, 55, 319–322.
- Herron, M.M., 1988. Geochemical classification of terrigenous sands and shales from core log data, *J. Sed. Petrol.*, 58, 820–829.
- Huang, P.M., 1982. Feldspars, olivines, pyroxenes and amphiboles. In J.B. Dixon and S.B. Weed (eds), *Minerals in Soil Environments*, 553–595, Soil Sci. Soc. America, Madison, 948pp.
- I.G.M.E., 1990. *Geological map of Greece, Herso sheet, scale 1:50.000*, Athens.
- Moorehouse, W.W., 1985. *The study of rocks in thin sections*, Delhi, CBS Publishers and Distributors, 514pp.
- Mountrakis, D., 1985. *Geology of Greece*, Thessaloniki, University Studio Press, 207pp.
- Mountrakis, D., Syrides, G., Polymenakos, L., and Pavlides, S., 1993. The neotectonic structure of the eastern margin of Axios-Thermaikos graben in the area of western Chalkidiki (Central Macedonia), *Bull. Geol. Soc. Greece*, XXVIII(1), 379–395.
- Nesbitt, H.W., and Young, G.M., 1982. Early Proterozoic climate and plate motions inferred from major element chemistry of lutites, *Nature*, 299, 715–717.
- Pettijohn, F.J., Potter, P.E., and Siever, R., 1973. *Sand and sandstone*, New York, Springer-Verlag, 618pp.
- Roser, B.P., and Korsch, R.J., 1988. Provenance signatures of sandstone–mudstone suites determined using discriminant function analysis of major–element data, *Chem. Geol.*, 67, 119–139.

- Sawyer, E.W., 1986. The influence of source rock type, chemical weathering and sorting on the geochemistry of clastic sediments from the Quetico metasedimentary belt, Superior Province, Canada, *Chem. Geol.*, 55, 77-95.
- Schultz, L.G., 1964. Quantitative interpretation of mineralogical composition from X-ray and chemical data for the Pierre shale, *U.S.G.S. Spec. Paper 391C*, 33pp.
- Sidiropoulos, N., 1991. Lithology, geochemistry, tectonics and metamorphosis of the Northwestern part of Vertiskos group. The area of Mountain Disoro (Kroussia), North of Kilkis, *PhD Thesis*, Aristotle University, Thessaloniki, 592pp.
- Tsirambides, A.E., 1997. Study of the Quaternary sediments of Doirani basin, *Ann. Geol. Pays Hell.*, 37, 907-919.
- Tsirambides, A.E., 2004. *Petrology of sedimentary rocks-2nd Ed.*, Thessaloniki, University Publications, 261pp.
- Tucker, M.E., 2001. *Sedimentary petrology: An introduction to the origin of sedimentary rocks-3rd Ed.*, Oxford, Blackwell Publishing, 262pp.