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Provenance of the Upper Miocene clastic material in the southwestern part of the Pannonian Basin

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Abstract: Upper Miocene clastic material in the SW part of the Pannonian Basin originates from two clearly different source areas. The mineralogy and texture of the detritus of the older part of the deposits (Croatica, Ozalj and Medvedski Breg units) are immature. These sediments originated from intense mechanical weathering of the hinterland. Detrital composition varies greatly and clearly reflects the composition of the source rocks. The mineralogy and texture of the detritus of younger deposits (Andraševec, Hum Zabočki, Cernik and Pluska units) are relatively mature, showing a uniform composition in the entire study area. The sediments were generated by weathering of various sources, mainly siliciclastic sediments and metamorphic rocks, and to a lesser degree, basic and ultrabasic magmatic rocks. The composition of the main detrital modes of the arenites and paleotransport measurements suggest that the source rocks were part of an orogenic belt located to the NW, W and NE of the studied area, namely the Eastern Alps and Carpathians. On the SW edge of the Pannonian Basin, in the Hrvatsko Zagorje and Mt Žumberak area, at the contact between the Upper Miocene and Pliocene deposits, a gradual change of the heavy mineral assemblage was determined. This change could be linked with structural changes in the Alpine-Carpathian orogen when rocks from deeper parts were brought to the surface, or with a rearrangement of source areas within the orogen area. Towards the east, in the area of the Slavonian Mts, sands in the Upper Miocene and lowest part of Pliocene deposits do not show similar changes, and probably belong to a separate clastic system, which, contemporaneously prograded towards the south.

Key words: Upper Miocene, Pannonian Basin, framework petrography, paleotransport, heavy mineral analysis, provenance of clastic material.

Introduction

The Pannonian Basin, surrounded by the Alps, Carpathians and Dinarides, paleogeographically belongs to the area of the Central Paratethys (Fig. 1A). Its formation commenced in the Early Miocene, due to continental collision and subduction of the European Plate under the Apulian Plate (Royden 1988; Tari et al. 1992; Horváth 1995; Kováč et al. 1998). At the end of the Middle Miocene, the Pannonian Basin became isolated from the formerly marine Paratethys, which resulted in the formation of a brackish Lake Pannon (Rögl & Steininger 1983; Rögl 1998; Magyar et al. 1999). During the Late Miocene, as a result of prograding clastic systems, Lake Pannon experienced a large-scale reduction in size and a relevant expansion of terrestrial areas (Rögl & Steininger 1983; Magyar et al. 1999; Kovačić et al. 2004). The direction of progradation of the clastic systems and their composition in the NW, middle and E part of the Pannonian Basin point to an Alpine-Carpathian provenance of the major amount of detritus (Mattick et al. 1988; Juhász 1991; Juhász & Magyar 1992; Magyar et al. 1999; Thamó-Boszó & Juhász 2002).

The composition and provenance of clastic material filling the SW part of the Pannonian Basin during Late Miocene times has not yet been studied in detail. The provenance of the clastic material could be related to large mountain chains, such as the Dinarides, representing the closest highly uplifted area to the southern margin of the basin during the Late Miocene, as well as to the more distant Alps and Carpathians or to the islands within the basin itself (Fig. 1A,B). Vertical changes in composition obtained for the Sava Depression arenites show that granitoid source rocks were substituted by metamorphic rocks, limestones and cherts at the Early/Late Pannonian boundary (Šćavničar 1979). The composition of Upper Miocene sands of the Ilova Depression (Fig. 1B) suggests a provenance linked to the dismantling of local uplifted magmatic and metamorphic blocks within the basin. Vertical changes in composition are the result of climatic changes and changes in source rocks (Blašković 1982). The composition of Pontian sands in Hrvatsko Zagorje and Mt Kalnik, on the other hand, shows that the sources were mostly of metamorphic and sedimentary type. The uniformity of their composition suggests that the source area of the detritus was a large mountain massif, most probably the Alps (Šimunić & Šimunić 1987).

Reconstruction of the provenance and composition of the source rocks for clastic material is a complex problem. It can be solved correctly only by integrating data of petrographic sediment composition and paleotransport measurements. The composition of source rocks primarily depends on the geotectonic position of the source area (Dickinson & Valloni 1980; Dickinson et al. 1983; Dickinson 1985; Valloni 1985). However, when reconstructing provenance, one must also consider factors such as physical and chemical weathering, relief, length and type of transport as well as cli-

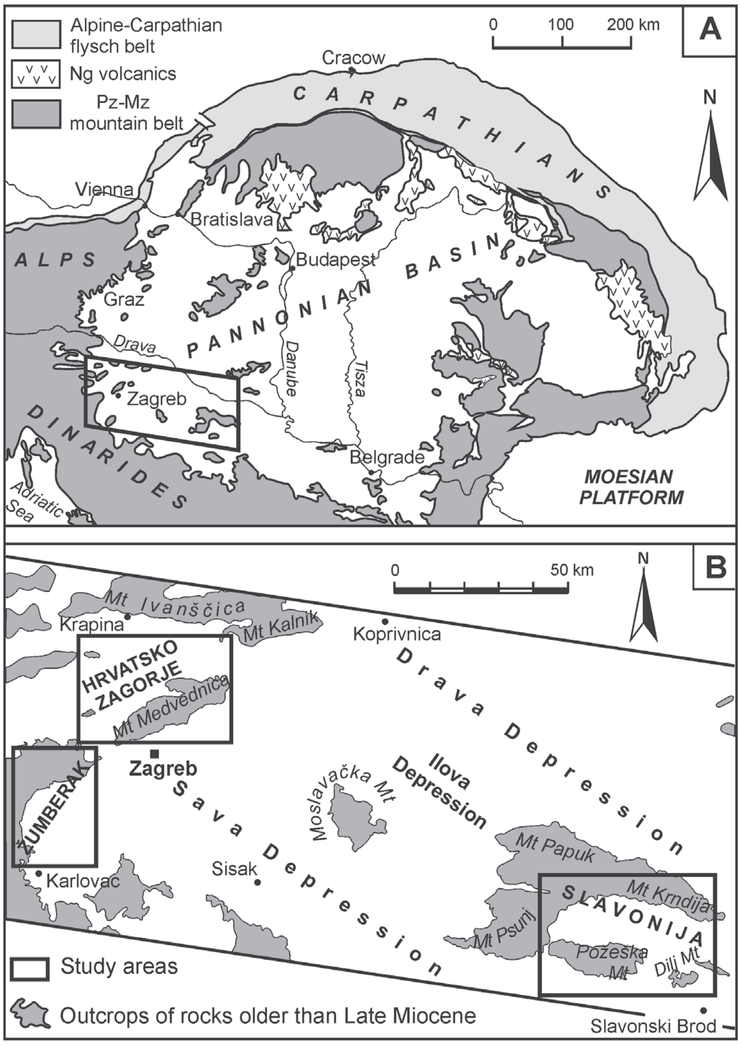

Fig. 1. A — Sketch of the Pannonian Basin and its surroundings (after Royden 1988). The area framed is shown in B. **B** — South-western part of the Pannonian Basin with the location of the study areas.

mate. All these factors can change the composition of the material at the location of weathering, as well as during transport and sedimentation (Basu 1985; Morton & Hallsworth 1994, 1999). Therefore, the objective of this paper is to reconstruct the provenance and composition of the source rocks for the clastic material that was filling the SW part of the Pannonian Basin during the Late Miocene, by synthesizing data from petrographic analysis of gravel and sand, and data from the paleotransport analysis in the sedimentary basin. Research was performed on outcrops in Hrvatsko Zagorje including Mt Medvednica, in Mt Žumberak and Slavonian Mts (Fig. 1B).

Geological setting

The Miocene deposits of the SW part of the Pannonian Basin unconformably overlie a strongly tectonized Paleozoic-Mesozoic-Paleogene basement (Fig. 2A,B and C) consisting of various magmatic, metamorphic and sedimentary rocks, belonging to the northern margin of the Inner Dinarides, and to the Tisza block (Šikić et al. 1979; Šparica et al. 1980; Basch 1983; Jamičić et al. 1986; Korolija & Jamičić 1989; Herak et al. 1990; Šikić 1995a; Pamić 1998). The Early Miocene to Middle Badenian syn-rift phase of the basin formation was well marked by strong tectonic and volcanic activities and by the deposition of different clastic and carbonate sediments (Horváth & Royden 1981; Royden 1988; Pavelić 2001). The post-rift phase started in the Upper Badenian and was characterized by subsidence due to lithosphere cooling with occasional inversions of the basin caused by tectonics (Horváth & Royden 1981; Royden 1988; Pavelić 2001).

At the end of the Middle Miocene (Late Sarmatian) a tectonic compaction was recorded in the SW part of the Pannonian Basin, mainly linked to intra-plate stress, to uplifting of tectonic blocks and to the narrowing of sedimentary accommodation space (Horváth 1995; Kováč et al. 1997, 1998; Fodor et al. 1999; Tomljenović & Csontos 2001). Contemporaneously, connection between the Pannonian Basin and the Mediterranean was closing, and Lake Pannon was formed as a separate depositional area with low salinity (Steininger et al. 1988; Rögl 1996). At the beginning of the Pannonian, during a period of low tectonic activity, mostly limestones and marls were deposited. Rising of the water level in the lake during the Pannonian caused the flooding of tectonic blocks uplifted at the end of the Sarmatian and the deposition of coarse-grained clastic sediments in coastal lacustrine areas. Gradual infilling of Lake Pannon initiated with the progradation of clastic deltaic systems from the north. In Hrvatsko Zagorje it started already in the Pannonian, on Mt Žumberak at the beginning of Pontian, and in the Slavonian Mts in Late Pontian (Magyar et al. 1999; Kovačić 2004; Kovačić et al. 2004). The progradation of clastic systems, shallowing and finally infilling of the basin was probably caused by deceleration of basin subsidence. Subsidence was slowed down by forming a balance in a late stage of the post-rift phase of basin formation. At the end of the Miocene, during the Pliocene, and intensively in the Quaternary, a new compressional phase took place in the evolution of the Pannonian Basin, in which by inversion of inherited normal faults, counterclockwise (CCW) rotation and lifting of individual blocks, recent uplifted areas of the SW part of the Pannonian Basin were formed (Jamičić 1995; Horváth & Cloetingh 1996; Prelogović et al. 1998; Tomljenović & Csontos 2001; Márton et al. 2002).

Description and relationship between the different units

On the basis of lithological and paleontological characteristics, the Upper Miocene deposits of the SW Pannonian

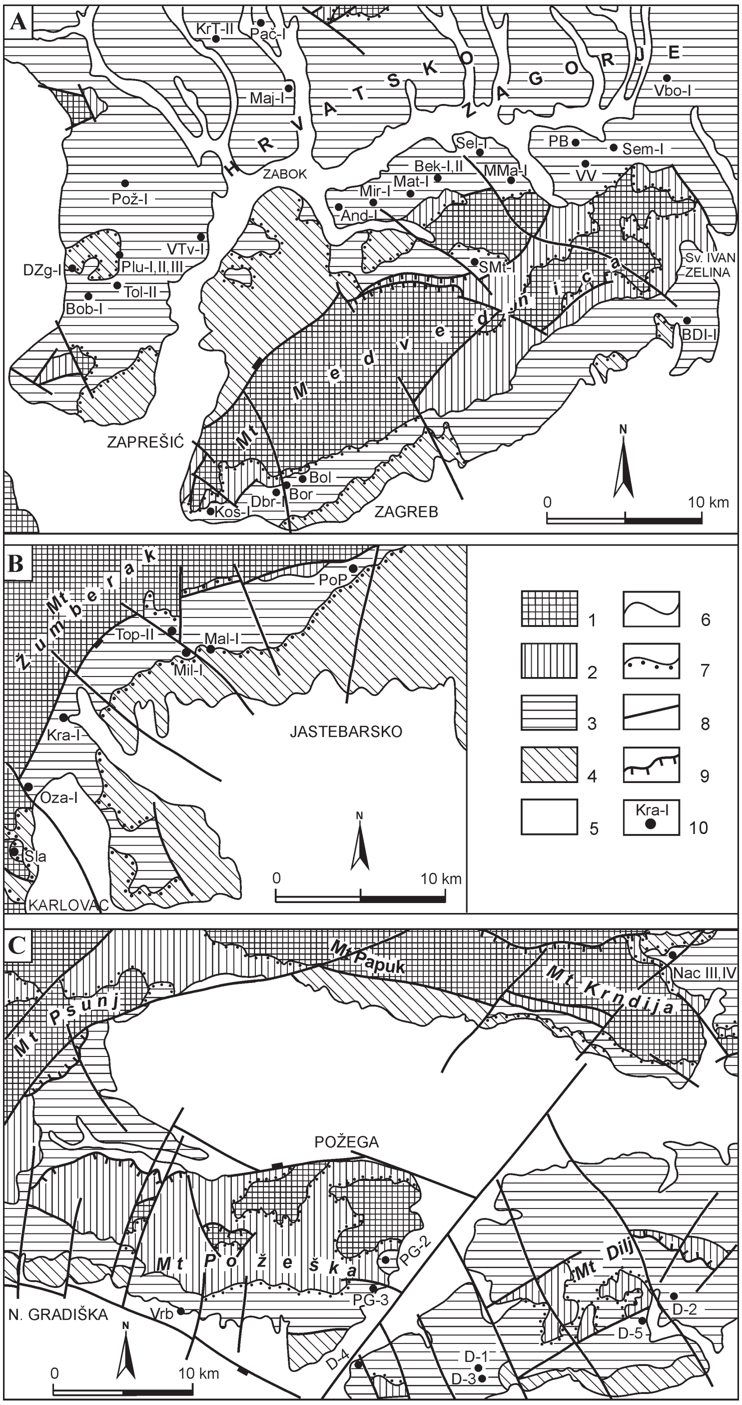

Fig. 2. Geological sketch-maps of: **A** — Hrvatsko Zagorje and Mt Medvednica, **B** — Mt Žumberak, **C** — Slavonian Mts. **1** — Pre-Neogene rocks, **2** — Neogene rocks older than Sarmatian, **3** — Sarmatian, Pannonian and Pontian deposits, **4** — Pliocene and Pliocene-Quaternary deposits, **5** — Quaternary deposits, **6** — normal boundary, **7** — transgressive boundary, **8** — fault, **9** — nappe, **10** — locations of measured sections, sampling and paleotransport measurements. From unpublished Geological Map of the Republic of Croatia 1:300,000.

Basin are commonly subdivided into (a) Croatica- and Banatica-beds (Lower to Upper Pannonian), and (b) Abichi- and Rhomboidea-beds (Lower to Upper Pontian) (Sokač 1972; Kranjec et al. 1973) (Fig. 3). The Pliocene deposits are also known as Paludina-beds. This subdivision of Upper Miocene and Pliocene sediments, not yet chronostratigraphically confirmed, is based on a vertical change of endemic fauna.

In this paper, the Upper Miocene deposits are divided into the following five informal lithostratigraphic units, from bottom to top: Croatica, Medvedski Breg, Ozalj, Andraševec and Hum Zabočki units. The boundaries between the newly defined lithostratigraphic units and the previous units do not coincide. Their correlation is shown in Fig. 4.

In the Hrvatsko Zagorje and Žumberak area, the Hum Zabočki unit is followed by the Pluska unit assigned to the Pliocene, with the exception of its lower part, doubtedly referred to the Miocene (Fig. 4A,B,E). The deposits of the Pluska unit are thought to be of Pliocene–Quaternary age (Fig. 2A and B) (Šikić et al. 1979; Basch 1983). In the Slavonian Mts area, the Hum Zabočki unit is followed by the Cernik unit (Fig. 4F) which could correspond to the Pliocene Paludina-beds (Figs. 2C and 3).

The Croatica unit (Cro unit) (20 to 40 m thick) has been assigned to the Early Pannonian in the Hrvatsko Zagorje, Mt Medvednica and Slavonian Mts areas (Fig. 4A–D and F). It consists of thin-bedded clayey limestones and marls with rare intervals of massive marls and sands, deposited in a shallow-water lake environment with low salinity (summarized in Kovačić 2004). The contact with the underlying Sarmatian deposits is mostly sharp and conformable, whereas this unit grades upwards into marls of the Medvedski Breg unit and rarely into the clastic deposits of the Ozalj and/or Andraševec units.

The Medvedski Breg unit (MeB unit) (Lower Pannonian–Upper Pontian, Fig. 4B–F), about 120 to 160 m thick, is widespread in the studied area and mainly consists of massive marls deposited in a deep-water brackish environment (summarized in Kovačić 2004). Within these marls there are rare occurrences of sand-gravel deposits. This unit conformably overlies the Croatica and Ozalj units (Hrvatsko Zagorje and Slavonian Mts Area), or Sarmatian deposits (Mt Žumberak) (Fig. 4B–F). It is conformably overlain by the Andraševec unit.

The Ozalj unit (Oza unit) (Žumberak and Medvednica Mts; 1 to 90 m thick and Early and Middle Pannonian in age) consists of medium- to coarse-grained clastic sediments deposited in a nearshore lacustrine, river or distribution channel environment (summarized in Kovačić 2004). This unit disconformable rests on Middle Miocene and older deposits or occurs as a lateral equivalent of the Cro unit and lower part of the MeB unit (Fig. 4B,D,E).

The Andraševec unit (And unit) deposited over the entire studied area, shows the largest stratigraphic span

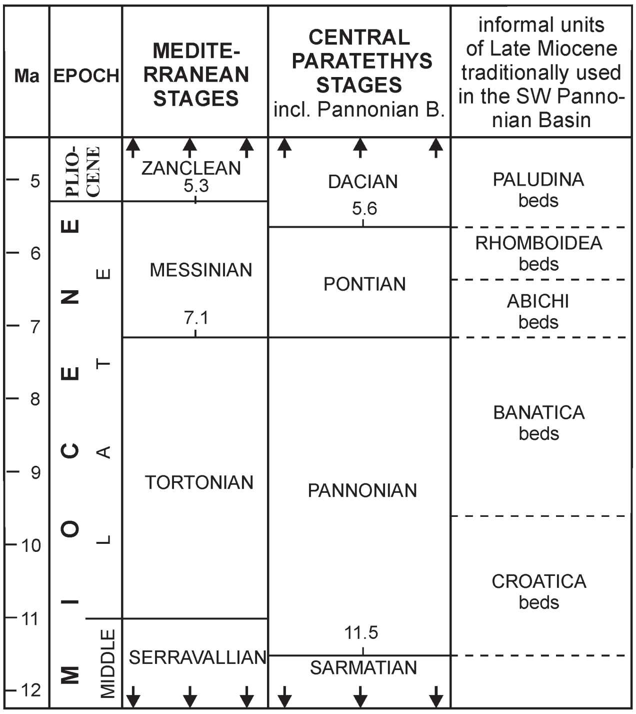

Fig. 3. Chronostratigraphic correlation between Mediterranean and Central Paratethys during Late Miocene (after Rögl 1996), with the subdivisions traditionally used in the SW Pannonian Basin (after Sokač 1972; Kranjec et al. 1973; Šikić et al. 1979; etc.).

(Lower Pannonian–Upper Pontian), ranging in thickness between 10–40 m (Slavonian Mts) and 600 m (Hrvatsko Zagorje area; Fig. 4). It consists of an alternation of sand beds, silts and silty marls deposited in a prodelta–deltaic slope lacustrine environment (Kovačić 2004; Kovačić et al. 2004). It is conformable with the underlying MeB and Cro units, and the overlying Hum Zabočki unit (Fig. 4).

The Hum Zabočki unit (HZb unit) is widespread in the entire study area, is assigned to the Late Pontian and its thickness varies from 5 m in the Slavonian Mts area to 160 m in the eastern part of the Hrvatsko Zagorje area (Fig. 4). It consists of an alternation of sand beds and silts deposited in a delta front in the shallow brackish lacustrine environment (Kovačić 2004; Kovačić et al. 2004). This unit is conformable with the underlying And unit and the overlying Pluska and Cernik units.

The Pluska unit (Plu unit) (Pontian-Pliocene), detected in the Hrvatsko Zagorje and Mt Žumberak, consists of clay, silt and sands with layers and lenses of gravel and coal, deposited in a river or distribution channel, flood plain, coastal lagoon and swamp environment (summarized in Kovačić 2004). This unit conformably overlies the HZb unit. Upper boundary and unit thickness are not defined (Fig. 4B,C,E).

The Cernik unit (Cer unit) (Early Pliocene) crops out in the Slavonian Mts area overlying the HZb unit (Fig. 4F). It consists of clay, silt and sand deposits with layers and lenses of gravel similar to those of the Plu unit, but with different composition. Deposition took place in a fresh water lacustrine environment, in deltas and on alluvial plains (summarized in Kovačić 2004).

Sampling and methods

During fieldwork, 42 geological sections were investigated. On the basis of geological mapping, facies analysis, and environmental interpretation, the vertical position and lateral correlation of sections were reconstructed. These relationships were used in the construction of the schematic geological sections and the definition of the informal lithostratigraphic units of the Upper Miocene deposits (Fig. 4). Erosion channel axes and current ripple lamination were measured to determine the sediment paleotransport direction in the depositional basin.

Samples for petrographic analysis of clastic sediments were collected in order to cover all the studied areas as well as the entire time span of all the Upper Miocene deposits. The compositions of gravel, conglomerate pebbles and sandstones were determined by means of analysis of 40 thin sections using a polarization microscope. Composition of the unconsolidated sand-silt sediments was performed in the 0.09–0.16 mm carbonate-free fraction. Heavy and light mineral fractions (HMF and LMF, respectively), were obtained using bromoform ($CHBr_3$; $\delta = 2.84\ g \cdot cm^{-3}$).

Qualitative and quantitative analysis of HMF and LMF compositions were performed by determination of 300–400 grains per sample using the ribbon counting method (Menge & Maurer 1992). Opaque minerals were determined in reflected light.

Finally, the LMF of 28 samples of sands, selected to represent all the three studied areas, were analysed according to the Dickinson's (1985) criteria in order to obtain the QtFL, and QmFLt (Total Quartz-Feldspars-Lithic Fragments, Monocrystalline Quartz-Feldspars-Total Lithic Fragments, respectively).

Results

Ozalj, Croatica and Medvedski Breg units

Clastic sediments of the Oza, Cro and MeB units are medium- to coarse-grained and poorly sorted. In the studied area their composition varies, from siliciclastic to mixed carbonate-siliciclastic as well as to mainly carbonate.

Conglomerates and gravels

On the SW slopes of Mt Medvednica (Kos-I and Dbr-I sections in Fig. 2A and Fig. 4D), the Ozalj and MeB units gravels (1–2 cm average size with a maximum of 8 cm) are represented by pebbles of quartzites, green schists, sandstones and volcanic rocks. Carbonate pebbles, less represented, are composed mostly of biocalcarenites or mollusc fragments. On the N slopes of Mt Medvednica, in the SW part of Hrvatsko Zagorje (SMt-I on Fig. 2A and Fig. 4B),

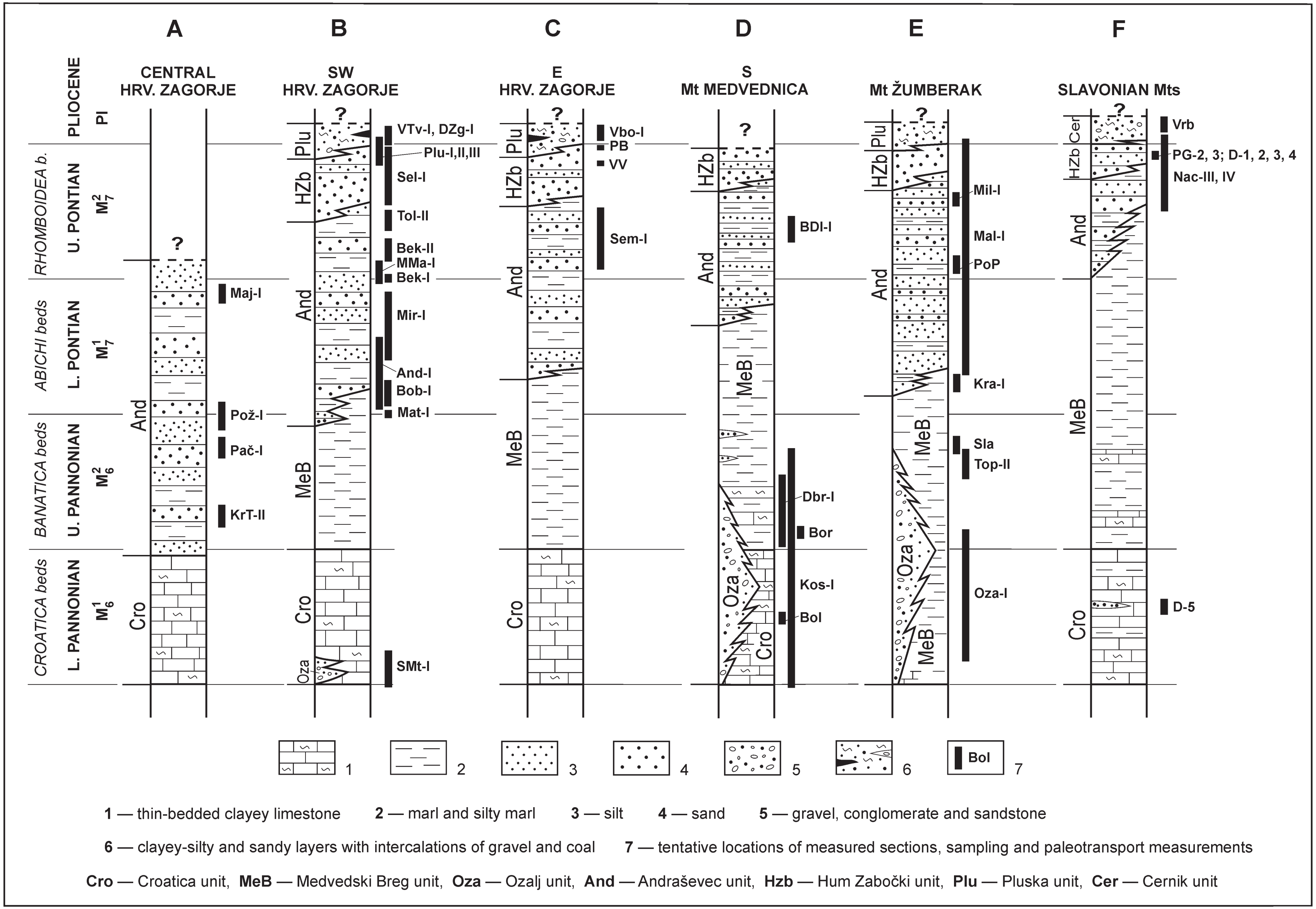

Fig. 4. Schematic geological sections of the Late Miocene deposits with informal lithostratigraphic units of **A** — Central Hrvatsko Zagorje, **B** — SW Hrvatsko Zagorje, **C** — E Hrvatsko Zagorje, **D** — S Mt Medvednica, **E** — Mt Žumberak and **F** — Slavonian Mts. Tentative locations of measured sections, sampling and paleotransport measurements are given on the right side of sections.

the Oza unit gravels are coarse-grained and poorly sorted. The most common pebble lithotypes are shales, chert, sandstones and siltstones, while bioclastic limestones are rare.

The conglomerates and gravels of the Oza and MeB units cropping out on Mt Žumberak (Oza-I and Top-II on Fig. 2B and Fig. 4E) are composed of 0.5–3 cm sized pebbles (maximum 35 cm), mainly represented by recrystallized micrite, microsparite and sparite limestones and often dolomites. Pebbles of other types of rock (quartzite, chert) are rare.

Sands and sandstones

The modal composition of sands (Tables 1, 2 and Fig. 5) and sandstones corresponds to the litharenites.

Sandstones on the SW slopes of Mt Medvednica (Kos-I, Dbr-I, Bor and Bol sections on Fig. 2A and Fig. 4D) are characterized by a mixed carbonate-siliciclastic composition. The carbonate fragments are mostly redeposited Badenian fossil fragments of red algae, bryozoans, echinoids, mollusks and foraminifers. The siliciclastic material consists mostly of quartz with undulatory extinction and quartzite fragments. There are smaller amounts of quartz grains with uniform extinction, epimetamorphic and volcanic rock fragments, feldspars, chert and siltstones. The sandstones on the Mt Žumberak have a similar composition to the conglomerates and gravels of the same area, but they also partially contain redeposited carbonate fragments of Badenian age-red algae, foraminifers and corals.

Sands of the Oza unit (SW slopes of Mt Medvednica) are characterized by a distinct domination of epidote in a composition of translucent heavy minerals (THM) (group A in Table1). In the light mineral fraction (LMF) sub-angular to sub-rounded quartz grains, usually with undulatory extinction and low-rank metamorphic rock fragments (quartz-chlorite schists, quartz-sericite schists) are dominant. Feldspars appear mostly in very altered grains.

The largest amount of the sands in the Oza unit in Mt Žumberak (Oza-I 3/2 and Oza-I 6/1 in group B in Table 1) is characterized by a predominance of opaque minerals in the HMF and dominance of ultra stable minerals (zircon, rutile, tourmaline) in the THM. A part of the unit (Sla 3/4 in group C in Table 1) is characterized by an abundance of dolomite in the HMF. Zircon is present as either very rounded grains or grains with no signs of rounding. Rutile is mostly well rounded, and tourmaline less rounded. The LMF in the sands consists of well rounded ultra-stable fragments like quartz, quartzite and chert. In the sand of the MeB unit rock fragments prevail, with fragments most commonly of devitrified volcanic glass and tuff. The content of the HMF of these sands is very similar to that of the sands in the Oza unit (B in Table 1), except that MeB unit sands also contain idiomorphic fresh biotite (Top-II 3/1 and Top-II 6/4 in group B in Table 1).

In the Slavonian Mts area (D-5 in Fig. 2C and Fig. 4F) within limestones of the Cro unit a layer of coarse-grained poorly sorted limy sand was determined. The sand consists of redeposited carbonate fossil fragments of Badenian age, represented by fragments of red algae, echinoids bryozoans and benthic foraminifers.

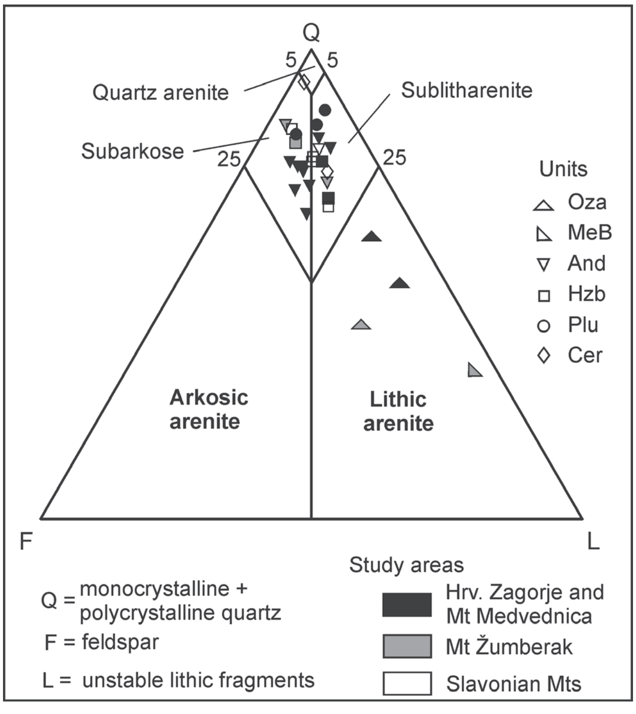

Fig. 5. Modal composition of siliciclastic material of the sands compared within Pettijohn et al. (1987) sandstone classification.

Andraševec, Hum Zabočki, Pluska and Cernik units

The clastites of the And, HZb, Plu and Cer units consist mostly of medium- to coarse-grained well-sorted sands, rarely cemented, while gravels are very rare. The main characteristics of the detritus of the units are a dominance of siliciclastic fragments (>90 %) and the uniformity of composition throughout the whole studied area during a longer period of time. Fragments of fossils and dolomite, the most frequent carbonate components of detritus, are rare. The modal composition of the sands (Fig. 5) and sandstones corresponds to the sublitharenites and subarkose groups. Monocrystaline quartz grains with undulatory extinction and rock fragments are abundant (Table 1); the last being mainly represented by polycrystalline quartz (Table 2). The content of muscovite varies significantly, while feldspar and unstable rock fragments are rare (Tables 1, 2).

The gravels consist of well-rounded pebbles of quartzite and chert with a maximum size of 2 cm.

Heavy and light minerals associations

On the basis of characteristics of the HMF assemblage, the sands of the And, HZb, Plu and Cer units are classified into 4 groups (C, D, E and F in Table 1).

Group C (Lower Pontian sands of the And unit, Mt Žumberak, Table 1) shows a heavy mineral assemblage very similar to that of the Oza unit.

Table 1: Modal composition of the heavy and light mineral fractions (0.09–0.16 mm) of siliciclastic material of Upper Miocene sands from the SW part of the Pannonian Basin. Abbreviations: **op** — opaque min., **ch** — chlorite, **b** — biotite, **do** — dolomite, **thm** — translucent heavy minerals, **tu** — tourmaline, **zr** — zircon, **rt** — rutile, **am** — amphibole, **ep** — epidote, **g** — garnet, **ky** — kyanite, **st** — staurolite, **oth** — other translucent heavy minerals, **q** — quartz, **f** — feldspar, **l** — lithic fragments, **ms** — muscovite, **+** — minerals with occurrence < 1 %. For Age and Unit see Fig. 4. *Continued on the next page.*

Group	Sample	Age	Unit	Heavy minerals (%)					Translucent heavy minerals (%)									Light minerals (%)			
				op	**ch**	**b**	**do**	**thm**	**tu**	**zr**	**rt**	**am**	**ep**	**g**	**ky**	**st**	**oth**	**q**	**f**	**l**	**ms**
A	Bol 1/2	M_6^1	Oza	34	+			66	2		+		87	1	+	4	5	52	8	40	
	5/4	M_6^1	Oza	40				60	2		2		88	+		5	2	54	11	34	1
	Dbr-I 2/1	M_6^2	Oza	23				77		+	+	+	91			4	3	42	8	50	
	4/1	M_6^2	Oza	29				71	1	+			92	1		2	3	40	8	52	
	12/1	M_6^2	Oza	16				84				+	95			1	3	47	11	42	
	Bor 1/1	M_6^2	Oza	23				77	+	+		3	87	2		1	6	46	15	39	
B	Oza-I 3/2	M_6^1	Oza	92			2	6	11	48	38		+		+	2		74	13	13	
	6/1	M_6^1	Oza	93			1	6	14	53	27		+		2	2	1	62	16	22	
	Top-II 3/1	M_6^2	MeB	92		+	2	6	18	27	35		3		1	12	4	18	4	78	
	6/4	M_6^2	MeB	56		10	17	7	13	43	28	1		10		3	2	9	2	89	
C	Sla 3/4	M_6^2	Oza	27			70	3	25	6	4		9	40	2	9	5	34	20	46	
	Kra-I 13/1	M_7^1	And	6	1		91	2	46	5	13		15	8	2	6	5	73	11	15	1
	Mal-I 5/2	M_7^1	And	11	1		70	18	10	3	7		31	24	2	15	8	73	4	23	
	7/1	M_7^1	And	11	17		41	31	8	1	4	1	34	28	3	14	7	49	30	16	5
D	KrT-II 16/1	M_6^2	And	8	1		61	30	4	+	7	+	20	49	3	11	5	63	9	25	3
	8/1	M_6^2	And	13	5		34	48	6		4		34	25	5	21	5	62	8	24	6
	11/1	M_6^2	And	18	5		11	66	5		3		26	41	2	19	4	65	6	22	7
	16/1	M_6^2	And	12	3			85	4		3	4	27	42	4	12	4	61	8	28	3
	Pač-I 1/1	M_6^2	And	13	7		11	69	3		5		13	65	1	7	6	61	7	29	3
	20/1	M_6^2	And	11	2		5	82	2		5		11	72	3	5	2	61	13	25	1
	39/1	M_6^2	And	14	18		11	57	8	+	3		14	53	2	16	3	59	3	29	9
	Pož-I 1/2	M_6^2	And	8	1		5	86	6	1	5	5	11	62	1	7	2	65	7	27	1
	6/1	M_6^2	And	13	21		10	56	4	+	3	4	34	36	1	13	4	40	8	26	26
	Mat-I 1/1	M_6^2	And	10	4	2		84	6		4	+	14	57	3	3	12	53	15	31	1
	Bob-I 10/1	M_7^1	And	9	41		27	23	6		2		37	28	7	12	8	55	14	16	15
	25/1	M_7^1	And	7	35		31	27	5		2	2	35	28	5	18	5	52	16	25	7
	Pož-I 23/1	M_7^1	And	14	15		24	47	3	+	2	4	35	32	3	17	3	47	12	26	15
	And-I 2/1	M_7^1	And	14	+	+		85	1	+	2		26	63	1	2	4	38	22	39	1
	29/1	M_7^1	And	32	19	1		48	5	1	1		21	54	+	7	10	39	11	44	+
	Mat-I 8/1	M_7^1	And	10	+			89	4		3		8	74	1	4	6	51	15	32	2
	14/1	M_7^1	And	11	1			88	5		2		10	71	2	4	6	39	28	32	1
	Mir-I 2/1	M_7^1	And	21	13	1		65	8		9	+	26	37	6	6	7	34	17	41	8
	6/1	M_7^1	And	8	+			92	2		3	+	28	57	4	3	2	49	18	30	3
	6/3	M_7^1	And	16				84	2		4		31	57	2	2	2	52	18	28	2
	7/4	M_7^1	And	17	8	+		75	7		2		38	26	5	8	14	40	13	41	6
	12/1	M_7^1	And	13	2			85	3		3		39	39	3	7	6	47	15	32	1
	Maj-I 1/2	M_7^1	And	7	29		31	33	4	+	1	2	40	36	2	12	2	48	12	25	15
	3/1	M_7^1	And	12	15		16	57	6		1	3	34	33	3	17	3	56	14	27	3
	Tol –II 8/1	M_7^2	And	4	21		39	36	5		5	16	27	20	4	16	7	55	10	28	7
	14/1	M_7^2	Hzb	6	24		37	33	3		2	8	29	28	3	19	5	42	5	21	32
	Bek-I 2/3	M_7^2	And	9	3	1		87	2		1	4	46	31	1	3	12	61	15	20	4
	MMa-I 5/1	M_7^2	And	8				92	5		2	3	57	7	2	12	12	56	14	27	3
	11/1	M_7^2	And	6	1			93	2		2	3	44	26	1	10	12	60	15	24	1
	Bek-II 3/1	M_7^2	And	8	21	15		56	2		5	1	59	17	+	3		44	11	21	24
	11/1	M_7^2	And	12	39			49	5		1	13	51	12	1	5	12	39	9	31	21
	Sel-I 1/1	M_7^2	And	10	7			83	3	+	1	20	28	28	2	7	10	65	9	22	4
	30/1	M_7^2	Hzb	18	47			35	4	1	4	9	58	18		3	3	30	6	15	49
	38/1	M_7^2	Hzb	11	2	+		87	2		2	7	43	27	3	6	10	49	11	35	5
	45/1	M_7^2-Pl	Plu	24				76	2	1	6	3	38	32	5	5	8	50	8	33	9
	Sem-I 12/1	M_7^2	And	18	3	+		78	5		2	4	39	22	4	10	14	62	17	20	1
	22/1	M_7^2	And	12	1	1		86	4		1	3	51	15	2	9	15	63	15	20	2
	VV 1	M_7^2	Hzb	14	+			85	4	1	6	2	41	19	3	13	11	63	13	22	2
	BDl-I 5/1	M_7^2	And	15	2			83	2		3	9	32	41	2	6	5	69	12	17	2
	6/3	M_7^2	And	11	1			88	2		2	7	32	40	2	4	11	57	26	17	
	Plu-I 1/1	M_7^2	Hzb	6	33	+	32	28	2		4	21	20	23	6	12	12	64	10	16	10
	8/1	M_7^2	Hzb	3	27		39	31	6	+	1	26	15	18	6	17	10	58	5	27	10
	11/1	M_7^2	Hzb	10	7		4	79	4	+	3	14	23	28	3	15	9	65	9	21	5
	19/1	M_7^2	Hzb	14				86	4	+	2	22	42	+	6	14	9	69	8	22	1
	Plu-III 1/1	M_7^2	Hzb	11	2		+	86	3		4	6	28	38	6	7	8	50	16	34	
	Mil-I 1/3	M_7^2	And	15	17		5	63	6		4	3	40	19	2	20	6	57	11	30	2
	3/1	M_7^2	And	13	6		11	70	3		4	1	40	20	1	27	4	47	20	32	1
	PoP 1/1	M_7^2	And	7	2		2	89	1	1	4	3	25	35	7	19	5	78	13	8	1
	5/4	M_7^2	And	6	7		10	77	3		1	1	33	23	3	33	3	75	11	11	3
	Mal-I 12/2	M_7^2	Hzb	18	9		11	62	2		2	6	26	40	4	12	8	66	13	19	2
	PG-2	M_7^2	Hzb	14	2		8	76	2	+	1	7	28	48	4	5	4	52	13	35	
	D-1	M_7^2	Hzb	7			+	93	3		2	11	19	46	4	10	5	64	12	23	1
	D-2	M_7^2	Hzb	8				92	3		2		64	2	6	19	4	60	12	28	

Table 1: *Continued.*

Group	Sample	Age	Unit	Heavy minerals (%)					Translucent heavy minerals (%)									Light minerals (%)			
				op	ch	b	do	thm	tu	zr	rt	am	ep	g	ky	st	oth	q	f	l	ms
D	Nac-III 6/1	M_7^2	And	21				79	3	+	4		57	2	3	21	9	65	9	26	
	6/3	M_7^2	Hzb	9				91	33		14		2		23	24	4	57	12	28	3
	12/2	Pl	Cer	11				89	25	1	18		3		26	23	4	51	12	20	17
	Nac-IV 1/1	Pl	Cer	17				83	18	+	12	+	10		25	27	7	71	9	21	
	5/1	Pl	Cer	29				71	20	2	18		4		21	30	5	60	13	25	2
	7/1	Pl	Cer	20				80	13	2	14	1	17		17	33	3	73	5	21	1
	Vrb 7/1	Pl	Cer	29	2			69	12	3	26		2		22	32	3	62	9	27	2
	13/1	Pl	Cer	21	2		32	45	15		23		+		24	35	2	49	16	34	1
	17/1	Pl	Cer	26			6	68	29	2	13			+	29	24	2	55	10	35	
	22/1	Pl	Cer	21			9	70	18	1	15		+		26	37	2	38	15	47	
	27/1	Pl	Cer	14	1		13	72	33	2	12		2		22	27	2	46	17	37	
	39/1	Pl	Cer	25	1			74	29	1	15		3		21	29	2	49	15	36	
E	Plu-II 1/1	M_7^2	Hzb	21				79	9	2	5	4	40		5	27	8	57	6	31	6
	4/1	M_7^2	Hzb	14				86	5	1	2	3	52		5	29	3	61	15	21	3
	6/2	M_7^2-Pl	Plu	25				75	11	+	11	+	43		10	21	3	70	12	17	1
	Plu-III 2/1	M_7^2	Hzb	16	+			86	5		4	5	56	1	7	15	7	65	5	25	
	3/1	M_7^2	Hzb	22				78	6		8		52	+	7	22	4	65	9	26	
	4/1	M_7^2	Hzb	34				66	7	+	8	+	39	+	13	28	3	57	14	27	
	6/1	M_7^2-Pl	Plu	17			+	82	7		8	+	29	2	11	38	4	58	17	25	
	PB 1	M_7^2	Hzb	32				68	8	+	17		43		11	18	2	72	5	23	
	Vbo-I 17/1	M_7^2-Pl	Plu	7	12			81	23		1	3	33	1	10	26	3	55	5	18	22
	Mal-I 14/2	M_7^2	Hzb	29				71	9	+	7		47		5	24	7	69	6	24	1
F	Dzg-I 3/1	M_7^2-Pl	Plu	47				53	33		14		2		23	24	4	69	6	25	
	10/1	M_7^2-Pl	Plu	48				52	25	1	18		3		26	23	4	66	3	29	2
	20/2	M_7^2-Pl	Plu	46			+	54	18	+	12	+	10		25	27	7	68	4	26	2
	21/2	M_7^2-Pl	Plu	63			+	36	20	2	18		4		21	30	5	69	4	24	3
	Plu-II 7/2	M_7^2-Pl	Plu	39				61	13	2	14	1	17		17	33	3	81	4	15	+
	VTv-I 1/1	M_7^2-Pl	Plu	53				47	12	3	26		2		22	32	3	81	7	12	
	6/1	M_7^2-Pl	Plu	51				49	15		23		+		24	35	2	70	7	23	
	9/1	M_7^2-Pl	Plu	55				45	29	2	13			+	29	24	2	77	4	15	4
	17/1	M_7^2-Pl	Plu	48				52	18	1	15		+		26	37	2	73	8	19	
	Mal K/1	M_7^2-Pl	Plu	49				51	33	2	12		2		22	27	2	70	7	22	+
	K/2	M_7^2-Pl	Plu	51				49	29	1	15		3		21	29	2	77	5	18	

Group D comprises the sands of the Cer unit, of the largest portion of the And and HZb units and of a smaller part of the Plu unit (Table 1), ranging between Upper Pannonian and Pliocene. The main characteristic of these sands is the dominance of garnet and epidote and the significant occurrence of staurolite, tourmaline, amphiboles, kyanite and rutile within the THM. Other significant minerals in the HMF are opaque minerals (magnetite, chromite, limonite), chlorite and dolomite. The chemical composition of the largest part of the garnets is closest to almandine and, subordinately to grossular (Kovačić 2004). Rutile is well rounded, tourmaline less rounded. The major part of the amphiboles, according to their chemical composition, belongs to the hornblende group (tschermakite, Mg-hornblende), while actinolite, pargasite and magnesiocatoforite are very rare (Kovačić 2004). In the LMF the most abundant is quartz, followed by rock fragments, feldspars and muscovite. Quartz grains are mostly semi-angular rarely well rounded or not rounded at all. Grains with low undulatory extinction prevail. Grains with homogeneous extinction are rare and those with distinct undulatory extinction are very rare. Quartzite type fragments are the most abundant rock fragments. Fragments of chert are numerous, with radiolarian fragments clearly still visible in some fragments. Unstable rocks like shales, quartz-chlorites, quartz-sericite slates and fragments like slate-phyllites are rare. Fragments with considerably altered ophiolite and vitrophyre structure, probably belonging to diabase-spilite rocks, are very rare as well as quartz-feldspar fragments (granitoid and/or gneissic rocks) and fine-grained sandstone and siltstone fragments. Feldspar grains, usually not well preserved, are mainly represented by orthoclase, while microcline and polysynthetically twinned plagioclase are rare.

Group E comprises a smaller part of the Upper Pontian-Pliocene sands of the HZb and Plu units cropping out in the Hrvatsko Zagorje and Mt Žumberak areas (Table 1). According to their characteristics, these deposits represent a transition between those of groups D and F. This group is in fact characterized by the abundance of epidote and staurolite, by the significant occurrence of tourmaline, rutile and kyanite and by the absence of garnets within the THM fraction. The composition and characteristics of the fragments of its LMF are very similar to those of the group D.

Group F consists of a larger part of the Upper Miocene–Pliocene sands in the Plu unit in Hrvatsko Zagorje and Mt Žumberak (Table 1). This group is characterized by the

Table 2: Modal composition of the light fraction (0.09–0.16 mm) of sands from the Oza, MeB, And, HZb, Plu and Cer units. Results are recalculated on 100 %. Abbreviations: **Qm** — monocrystalline quartz, **Qp** — polycrystalline quartz, **Qt** — total quartz grains (Qm+Qp), **F** — feldspar fragments, **L** — unstable lithic fragments, **Lt** — total lithic fragments (Qp+L). Other abbreviations as in Fig. 4.

Sample	Locality	Age	Unit	Light minerals (%)					
				Qm	Qp	Qt	F	L	Lt
Bol-I 1/2	Hrvatsko Zagorje and Mt Medvednica	M_6^1	Oza	52	8	60	8	32	40
Dbr-I 2/1		M_6^2	Oza	42	7	49	8	43	50
KrT-II 16/1		M_6^2	And	63	18	81	8	11	29
Pač-I 20/1		M_6^2	And	61	14	75	13	11	25
Pož-I 1/2		M_6^2	And	66	13	79	7	14	27
Bob-I 10/1		M_7^1	And	65	11	76	16	8	19
MMa-I 1 11/1		M_7^1	And	60	15	75	15	10	25
Mir-I 2/1		M_7^1	And	48	17	65	18	17	34
Mir-I 6/3		M_7^1	And	54	16	70	18	12	28
Bek-II 3/1		M_7^2	And	58	13	71	15	14	27
Maj-I 3/1		M_7^1	And	58	16	74	14	12	28
Plu-I 11/1		M_7^2	HZb	68	8	76	10	14	22
Sel-I 38/1		M_7^2	HZb	51	17	68	13	19	36
Dzg-I 21/2		M_7^2-Pl	Plu	71	16	87	4	9	25
Plu-II 6/2		M_7^2-Pl	Plu	71	11	82	12	6	17
VTv-I 6/1		M_7^2-Pl	Plu	70	14	84	7	9	23
Sla 3/4	Mt Žumberak	M_6^2	Oza	34	8	42	20	38	46
Top-II 3/1		M_6^2	MeB	18	14	32	4	64	78
Mil-I 1/3		M_7^2	And	58	14	72	11	17	31
PoP-I 1/1		M_7^2	And	79	5	84	13	3	8
Mal-I 12/2		M_7^2	HZb	68	12	80	13	7	19
Nac-III 6/1	Slavonian Mts	M_7^2	And	65	14	79	9	12	26
Nac-III 6/3		M_7^2	HZb	59	17	76	12	12	29
PG-2		M_7^2	HZb	52	15	67	13	20	35
D-1		M_7^2	HZb	65	12	77	12	11	23
D-2		M_7^2	HZb	60	23	83	12	5	28
Nac-IV 7/1		Pl	Cer	74	19	93	5	2	21
Vrb-I 17/1		Pl	Cer	55	19	74	10	16	35

abundance of a staurolite–kyanite–tourmaline–rutile mineral association (about 90 % in average of the THM fraction). The LMF fraction is represented mostly by quartz, and subordinately, by low amounts of rock fragments, feldspar and muscovite.

Paleotransport

Due to an often poor outcrop quality of the Upper Miocene deposits in the studied area a reconstruction of the detritus transport direction in the sedimentary basin by systematic measurements of current ripple lamination and channel axes was only possible in deposits of the Andraševec and Hum Zabočki units.

Andraševec (And)

Measurements of the cross-lamination direction in Hrvatsko Zagorje (Fig. 6A–E), southern slope of Mt Medvednica (Fig. 6F) and northern slope of Mt Krndija in Slavonija (Fig. 6G), show a main paleocurrent direction from the NW, N and NE, partially according to the WNW paleotransport direction determined in the same deposits in Hrvatsko Zagorje on the basis of flute casts by Kovačić et al. (2004).

Hum Zabočki (HZb)

The position of the distributary channel axes in the delta front in Hrvatsko Zagorje (VV on Figs. 2A and 4C) shows a NNE–SSW paleotransport direction similar to the current ripple lamination measurements performed in Slavonija on Mt Dilj and indicating a direction towards the SSW (Fig. 6K,L). These data also coincide with detritus transport towards the S obtained by the cross-bedding position in the Gilbert-type delta foreset in the Miocene deposits on Mt Dilj (Pavelić 2001). Current ripple lamination measurements in Hrvatsko Zagorje (Fig. 6H–J) and Mt Požega (Fig. 6M) show very different directions of paleotransport, which can be explained as deflection of distributary channels, or as the impact of waves and currents in the shallow lacustrine environment.

Discussion

Composition of source rocks and provenance

Gravel, sandstone and sand analysis show that the clastic material, deposited in the SW part of the Pannonian Basin, originated from the weathering of different sedi-

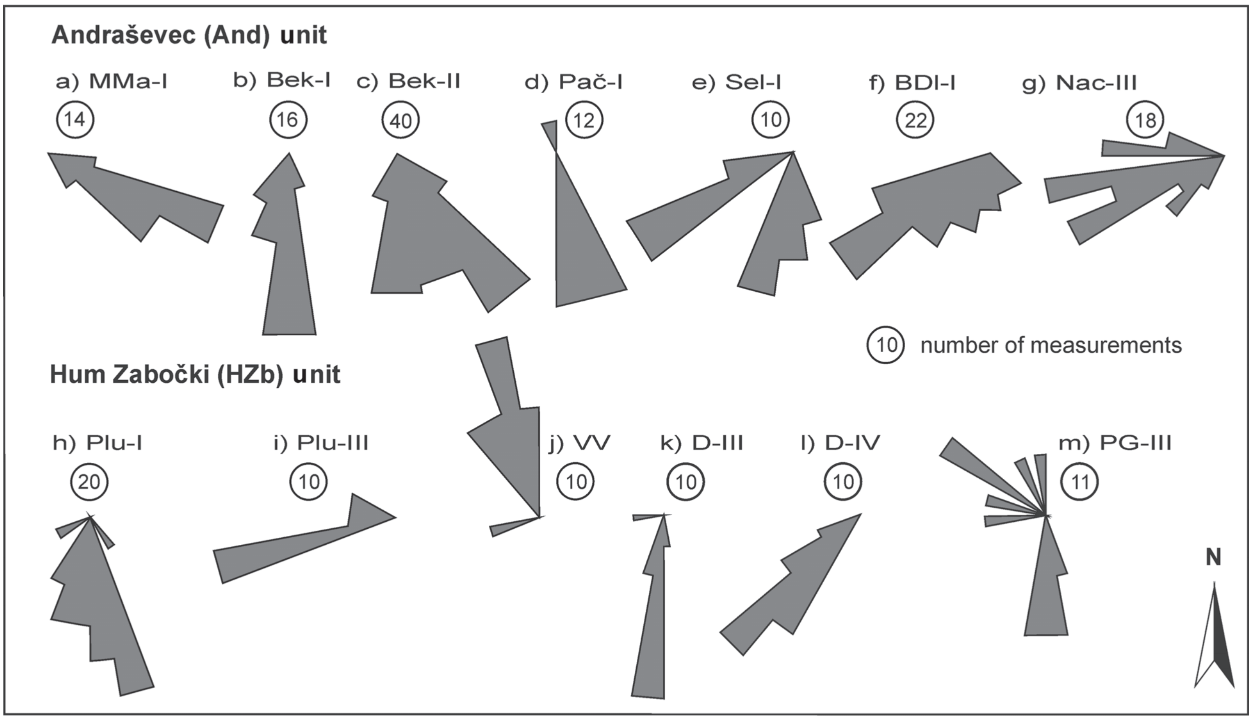

Fig. 6. Measured ripple marks in the rose diagrams indicate paleotransport towards S, SE and SW. These opposite directions in the HZb unit can be explained by reworking of material by waves and streams in the lake.

mentary, metamorphic and magmatic rocks of two different source areas. Thus, two different petrological provinces can be distinguished, responsible for supplying the Oza, Cro and MeB unit and the And, HZb, Cer and Plu unit groups. There are also clastites composed of detritus from both source areas (group C on Fig. 7).

Ozalj, Croatica and Medvedski Breg units

The very diverse modal composition of sands (groups A and B in Table 1) and (also) petrographic composition of sandstones and gravels, indicate different types of source rocks for the clastic material of Oza, Cro and MeB units (province I on Fig. 7).

Mt Medvednica. The modal and granulometric composition of the clastic material of the Oza and MeB units reflects its connection with the proximate hinterland. Gravel in the SW part of Mt Medvednica originates from quartzites, green schists, sandstones, metabasalts and Middle Miocene bioclastic limestones. All of them probably originated from rocks whose primary outcrops are exposed in the SW and central part of Mt Medvednica (Basch 1995; Šikić 1995b). Quartz with undulatory extinction and fragments of quartz-chlorite and quartz-sericite schists (group A in Table 1 and in Fig. 7), frequent siliciclastic components of sand detritus from the same area, also probably originated from quartzite and green schists from Mt Medvednica. Epidote, the most abundant translucent heavy mineral in the Oza unit on the SW slopes of Mt Medvednica, probably also originates from widespread green schists on Mt Medvednica (group A in Table 1). The roundness of quartz grains and considerable alteration of feldspars suggest that a part of the sand detritus is derived from older sandstones also cropping out on Mt Medvednica. The carbonate fraction of the sand detritus consists of reworked fossil fragments derived from widespread Middle Miocene limestones.

The coarse-grained and poorly sorted gravels on the N side of Mt Medvednica indicate a very local origin. Most of the material (shales, cherts, sandstones, siltstones) probably originated from Mesozoic ophiolites, primary outcrops of which are located on the N slopes of Mt Medvednica (Basch 1995; Babić et al. 2002; Halamić et al. 2005). Limestone pebbles probably originated from Middle Miocene fossiliferous limestones that are widespread on Mt Medvednica.

Mt Žumberak. The abundance of very coarse-grained (up to 35 cm) and poorly sorted, carbonate fragments within the Oza and MeB units points to a relatively short transport. The limestone-dolomite composition of the sandstones, gravels and conglomerates indicates that most of the material originated from the huge Mesozoic Adriatic Carbonate Platform (Vlahović et al. 2005). During the Late Miocene, these rocks probably represented the SW margin of the Pannonian Basin and today they are the most prevalent rocks on Mt Žumberak (Šikić et al. 1979). Local redeposited fragments of red algae, foraminifers and corals in the sandstone composition show that part of the material originated from the Middle Miocene bioclastic deposits, also present on Mt Žumberak (Vrsaljko et al. 2005). The well-rounded quartz grains and stable rock fragments (chert, quartzite), dominance

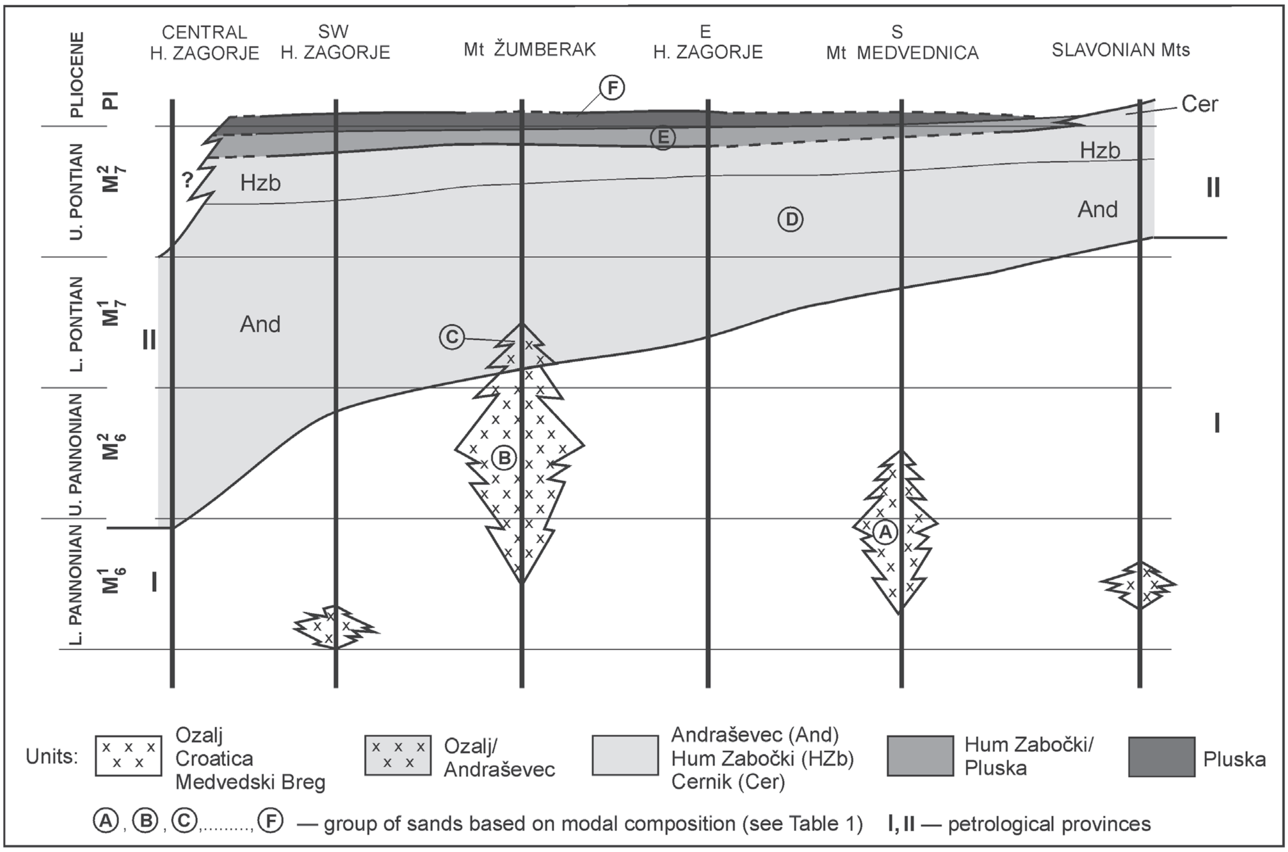

Fig. 7. The provenance of clastic material of Upper Miocene deposits in the SW part of the Pannonian Basin constrains from framework petrography and heavy mineral analysis. Provenance I represents clastic material of the Cro, Oza and MeB units developed by erosion of local uplifted blocks. Provenance II represents clastic material of the And, HZb, Plu and Cer units developed by erosion of distant mountains located NW, N and NE from the deposition areas.

of the ultra stable translucent heavy minerals (zircon, tourmaline, rutile) and their good roundness indicate that a minor part of the clastic material of the Oza and MeB units is recycled. This material most probably originated from older Cretaceous or Paleogene clastites, which are also present in Mt Žumberak (Šikić et al. 1979). The presence of devitrified volcanic glass, idiomorphic biotite and zircon crystals in the sands of the MeB unit shows that a minor amount of detritus probably originated from the Lower Miocene volcaniclastics from Mt Žumberak (Šikić et al. 1979). The sandy sediments of the upper part of the Oza unit and lower part of the And unit were probably a result of mixing of material from two different sources, because their composition represent a mixture of both provinces (group C in Table 1 and on Fig. 7). Most of the material in these deposits consists of the same limestone-dolomite and siliciclastic detritus as in the older part of the Oza unit, showing that it was also composed of the rocks forming Mt Žumberak, and is of local origin (province I on Fig. 7). A minor amount of material (epidote–garnet mineral association) originated from low to high regional metamorphism rocks, which do not outcrop on Mt Žumberak today, or in its vicinity. This material was probably transported from remote areas (province II on Fig. 7).

Slavonian Mts. The clastic material of the Cro unit on Mt Dilj (Fig. 7) is of local origin and consists of poorly sorted fossil fragments redeposited from Badenian fossiliferous limestones.

It may be concluded that clastic material of Oza, Cro and MeB units is of local origin (province I on Fig. 7). Its composition varies in different localities and clearly reflects the composition of source rocks.

Andraševec, Hum Zabočki, Pluska and Cernik units

The sandstone composition and LMF of the sands showed that the And, HZb, Plu and Cer units (province II in Fig. 7) have a similar composition in the entire studied area, whereas the Plu unit is characterized by a different heavy mineral assemblage.

According to these results the sand detritus of the And, HZb and Cer units is mainly recycled, as testified by the abundance of fine-grained sandstones and siltstones, highly alterated feldspars and rounded quartz grains and resistant THM.

A subordinate but significant portion of the detritus is derived from epimetamorphic sources as suggested by (i) numerous low rank metamorphic rock fragments, (ii) undulatory extinction of the quartz grains and (iii) abundance of epidote, chlorite, acid plagioclase and amphibole, very typical mineral assemblage of the green schists and epidote-amphibolite facies. Assemblage of the metamorphic index minerals, like chlorite, garnet, staurolite and kyanite suggests that paraschists of the Barow type metamorphism participated in the composition of the source area. The small amount of quartz with uniform extinction and fragments of quartz-feldspars indicates that acid magmatic rocks probably did not have significant portion in the composition of source rocks. The content of basic, ultrabasic and carbonate rocks, could not be estimated because of the chemical instability of their compounds in conditions of a moist and warm climate, as existed during the Late Miocene in the Pannonian Basin area (Pantić 1986; Planderová et al. 1993). However, the presence of chromite, magnetite, magnesiocatoforite and fragments of diabase-spilites and dolomite suggests that basic and ultrabasic rocks of oceanic crust also participated in the composition of the source area, as well as dolostones.

The homogeneity of the modal composition of the sands in the And, HZb and Cer units and their similarity are probably a consequence of modification of material during the weathering of source rocks, transport, and perhaps diagenesis. This conclusion could be supported by the low amount of physically and chemically unstable fragments, and by the fine grain size and relatively good sorting of detritus. The huge chronostratigraphic range of sand deposition (approximately 5 Myr), and the distance between the deposition areas of almost 200 km, indicate that the source area had to be a large mountain massif. This rules out the possibility that the clastic material originated from destruction of smaller local mountains, although some of them, like Mt Medvednica, Mt Psunj or Mt Papuk consist of very different rock types (Jamičić et al. 1986; Šikić 1995b), which could, theoretically, have provided sand detritus of similar composition. If the reconstructed paleotransport directions (Fig. 6) are corrected for approximately 20°, which is supposed as an average post-Miocene CCW rotation of the studied area (Márton et al. 2002), the results indicate that the clastic material was transported into the SW part of the basin from the NW, N and NE during the Late Miocene (Fig. 8).

The indicators of composition and direction of detritus transport suggest that its origin is in Eastern Alps and Carpathians (Fig. 8). The rock types in Eastern Alps support the theory that Alps were the source of the largest amount of the detritus. The Eastern Alps consist of regionally metamorphosed rocks with different degrees of metamorphism, from phyllites, chlorite-amphibole schists, amphibolites and gneisses to eclogites (Hinterlechner-Ravnik 1971, 1973; Bögel & Roeder 1978; Gizycki & Schmidt 1978; Mioč 1978; Žnidarčič & Mioč 1987; Godard et al. 1996). The composition of all these rocks support the theory that they were the source of the largest part of the detritus. The Carpathian Mts also consist of different sedimentary, metamorphic and magmatic rocks, which could have been a source of clastic material of And, HZb and Cer units (Royden & Báldi 1988; Krist et al. 1992; Hovorka 1996; Plašienka et al. 1997; Korikovsky et al. 1997a,b; Putiš et al. 1997; Petrík & Kohút 1997; Vozárova & Faryad 1997).

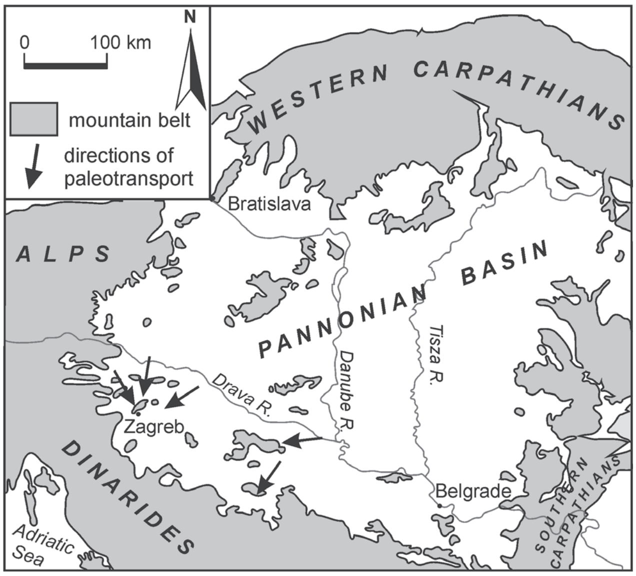

Fig. 8. Dominant directions of progradation of Upper Miocene siliciclastic detritus of the And and HZb units in the SW Pannonian Basin.

It should be emphasized that in the study area there are no indicators suggesting material influx from the south, namely from the Dinarides. The presence of various, very often coarse-grained, poorly sorted clastic sediments in the Upper Miocene deposits southwards of the studied area, in N Bosnia (Stevanović & Eremija 1977), shows that the Dinarides produced clastic material, but it was deposited in the proximity of land. The large thickness of Upper Miocene and Pliocene deposits, which in Sarajevo-Zenica Basin and Livno-Duvno Basin exceeds 500 m (summarized in Pavelić 2002), suggests that a considerable amount of detritus was probably deposited in fresh water basins inside the Dinarides, and only a small amount was transported towards the N into the Pannonian Basin.

The sands of the Plu unit (group F in Table 1 and Fig. 7) also have a homogeneous modal composition. The domination of well rounded quartz grains and resistant rock grains, together with the presence of most stable THM (tourmaline, rutile) shows that a considerable part of the detritus in the Plu unit originates from older sedimentary rocks. Abundant kyanite and staurolite indicate that a part of the detritus originates in metamorphic rocks formed in high pressure and temperature conditions. The existence of sand, which by its composition represents a transition from group D into group F (group E in Table 1 and Fig. 7), shows a gradual transition between HZb and Plu units. This transition is clearly visible in a gradual extinction of garnet and epidote, and contemporaneous increase in proportion of kyanite, rutile, tourmaline and staurolite. Considering the significant similarity of the granulometric composition and composition of the main detritic sand modes of the Plu unit and the sands of the And, HZb and Cer units, it may be supposed that they have the same provenance. However, differences in the HMF sand composition of the Plu unit and the sands of the And, HZb and Cer units show that during the time different rock types were eroded. Such change could be connected with structural changes in the Alpine-Carpathian orogen, with rocks from deeper levels reaching surface, or with translocation of source areas within the orogen. Eclogites rich in kyanite, metamorphosed in extremely high-pressure conditions, exist today on the surface of the Eastern Alps (Koralpe, Saualpe, Pohorje, Kozjak) (Fodor et al. 2003; Sassi et al. 2004), and could the represent source rocks for part of the material of the Plu unit.

The geotectonic setting of source areas of clastic material in the Andraševec, Hum Zabočki, Cernik and Pluska units

When inserted into diagrams for determination of the geotectonic setting of source areas (Fig. 9), the main detritic modes of sand in the And, HZb, Cer and Plu units, indicate that detritus source is an orogen.

The *QtFL* diagram and *QmFLt* diagram (Fig. 9A,B) show that the largest amount of sand detritus originated from a recycled orogen. The lower part of the sand in diagrams on Fig. 9A and B points to an inner craton on a continental block as a provenance of part of the detritus. However, the position of the Pannonian Basin, in between highly lifted orogens like the Alps, Carpathians and Dinarides, shows that even this material probably originated from a recycled orogen.

It may be concluded that analysis of the main detritic sand modes confirm the orogen origin of the clastic material of the And, HZb, Plu and Cer units and clearly show the origin of material from the Alpine-Carpathian orogenic belt. These mountain chains were formed by the Cretaceous-Miocene continental collision and subduction of the European Plate under the Apulian Plate (Tari et al. 1992; Horváth 1995; Kováč et al. 1998). During this process, different rocks of continental and ocean crust which developed in different geotectonic settings, were driven into contact, uplifted and eroded thus producing clastic material which subsequently filled the SW part of Pannonian Basin during the Late Miocene.

Conclusion

— The clastic material deposited during the Late Miocene in the SW part of the Pannonian Basin originated in two different source areas.

— The clastic material of the Ozalj, Croatica and Medvedski Breg units is mineralogically and structurally immature. It was produced by a mechanical erosion of rocks of the uplifted coastal hinterland and islands that were, because of the inversion of the basin at the end of Sarmatian, uplifted above lake water level. Its composition varies significantly, reflecting the composition of source rocks in the vicinity of the basin.

— The sand detritus of the Andraševec, Hum Zabočki, Cernik and Pluska units is mineralogically and structurally relatively mature. It was produced by weathering of different source rocks, that were mostly siliciclastic sedimentary and metamorphic rocks, and in a smaller amount acid magmatic rocks. The presence of basic and

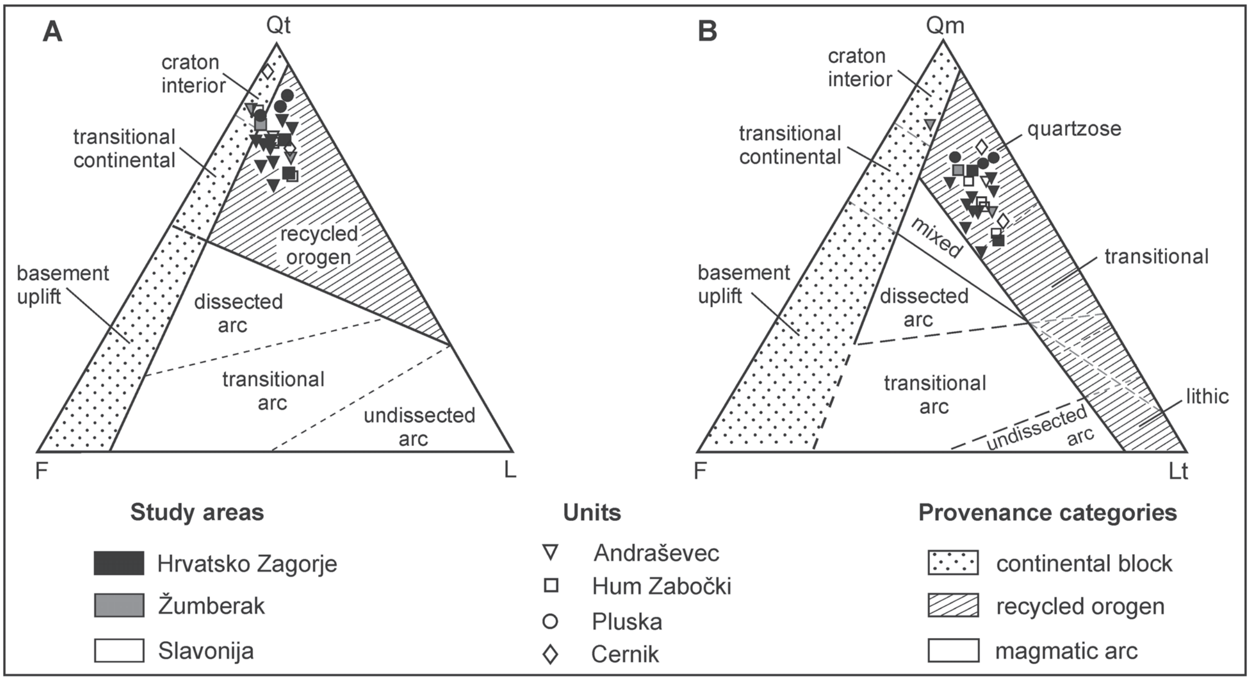

Fig. 9. Triangular diagrams with compositional fields indicating sands derivation from different types of provenances with emphasis on **A** — QtFL — maturity (Dickinson et al. 1983); **B** — QmFLt — source rocks (Dickinson et al. 1983). The diagrams suggest a recycled orogen provenance of the sand from the And, HZb, Plu and Cer units. Abbreviations as in Table 2.

ultrabasic magmatic rocks, and also carbonate rocks, is noticed. Their proportion could not be estimated because of distinct chemical instability of components. The types of components and ratio of the main detritic sand modes (QFL) suggests that the source rocks formed an orogenic belt. According to paleotransport measurements, the orogenic belt was situated NW, N and NE from the studied area, in the region of the Eastern Alps and Carpathians. This young region with high relief provided huge amounts of clastic material, which was significantly modified by mechanical and chemical processes under a warm and moist climate during the long transport. The composition of the main detritic ingredients is uniform in the whole studied area. However, the assemblage of the HMF shows gradual change from the sands of the Hum Zabočki unit to the sands of the Pluska unit, reflected in gradual loss of garnet and epidote, and relative increase in the portion of kyanite, tourmaline, rutile and staurolite. This change could be linked with structural changes in the Alpine-Carpathian orogen when rocks from deeper parts were brought to the surface, or with rearranging of source areas within the orogen area. Sands in Slavonian Mts area in the Cernik unit, which overlie the sands of the Hum Zabočki unit, do not show such changes, thus it could be presumed that they belong to some other clastic system, which contemporaneously prograded towards the S.

— The gradual change in the heavy minerals assemblage in the upper parts of the Upper Miocene deposits, which was determined in a few localities in Hrvatsko Zagorje, and partly in Mt Žumberak, offers new possibilities for stratigraphic correlation.

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