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Article

Morphometric characteristics, shapes and provenance of Holocene pebbles from the Sava River gravels (Zagreb, Croatia)

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Abstract: Morphometric analysis of Holocene pebbles from the Sava River gravels, in Zagreb alluvial aquifer system (NW Croatia), revealed distribution of their shapes along 30 km long observed watercourse. Limestones, dolomites and sandstones are determined as major (> 4%), and effusive magmatics, cherts and tuffs as minor lithotypes of the pebbles (up to 4%). Their distributions indicate mainly distant Alpine provenance for carbonate (limestones and dolomites) pebbles and local input for sandstones and minor lithotypes, laterally from the Samoborska gora and Medvednica Mts. Carbonates have predominately disc and sphere shapes, implying also their mainly distant sources. Scattered distributions of pebble shapes (sphere, disc, blade and rod) for sandstones and minor lithotypes indicate multiple sources, some of them probably local. Original sedimentary environments for main pebble lithotypes are tentatively interpreted from their flatness ratios, indicating predominant lake shore environments, followed by moraine and riverbed.

Keywords: Quaternary, Holocene, alluvial sediments, Sava River, gravels, morphometry, Zagreb, Croatia

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1. Introduction

Morphometric research of gravels is often conducted to determine weathering, transporting and depositional mechanisms/processes of their formation, as well as their provenance. Non-lithified alluvial sediments deposited in Quaternary braided or meandering river systems, such as Holocene sediments deposited in the Sava River alluvial terraces near the City of Zagreb (Croatia), are especially suitable for such studies.

Holocene deposits, that make up the youngest parts of the Zagreb alluvial aquifer system [1-7], were used for a case study that analyses morphometric and lithological characteristics of gravel pebbles. It aims to describe their transport and depositional mechanisms as well as potential of applied method for analysis of deposits with complex deposition and transport history. Besides morphometric analysis, the research included petrographic analysis and description of pebbles, as well as interpretation of their provenance and transport directions.

The extent of possible contribution of eroded material with local source brought by lateral streams from nearby Samoborska gora Mt., Marijagorička brda Hills and Medvednica Mt. was compared to contribution of material from more distant upstream Alpine area brought by the Sava River. The research was performed along the 30 km long traverse following the Sava River and the aim of this paper is to present and evaluate obtained results.

2. Geological settings

The Sava River originates in Slovenia, at the foot of the Southern Calcareous Alps. It flows through Slovenia, enters Croatia about 15 km west of Zagreb (Figure 1) and flows further towards

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east along the border between Croatia and Bosnia and Herzegovina. After its app. 950 km long run, it finally enters the Danube River in Serbia, near Belgrade. Following transition in the underlying geomorphology, Sava changes their riverbed characteristics. While flowing through generally higher area in Slovenia, their riverbed is generally shallow and deposits are predominantly coarse (mainly gravels), resembling braided river transport and depositional mechanisms. West of Zagreb and downstream toward East, it becomes predominantly meandering river. Recent watercourse (blue streamline and modern lakes/gravel pits in Figure 1) has been highly regulated and embanked at the beginning of the 20th century and after the major flooding of the City of Zagreb, in the year 1964. Deposits of meandering Sava River system are nowadays mainly exploited in gravel pits and exposed during foundation works for buildings and infrastructure.

According to Geology of Zagreb and Ivanić-Grad Sheets [8-9], accompanying texts for respective Basic geological maps of the area [10-11], Quaternary deposits in Zagreb alluvial plain can be distinguished on those of Pleistocene and Holocene ages, forming three lithostratigraphic units: 1) the oldest unit (defined as of Pliocene to Lower Pleistocene age), consisting mainly of gravels, sands and clays; 2) the middle unit (of Middle to Upper Pleistocene age), consisting of loess deposits and fine clayey silts, with some interlayers of sands and gravels, and occasionally peat and swamp sediments; and 3) the youngest unit, consisting of alluvial deposits, deposited within the last 10 Ka, since the Sava River formed their recent watercourse.

Deposits of the youngest unit are mainly gravels and sands, and subordinately silty clays. Predominant pebbles in gravel deposits are carbonates (limestones and dolomites), sandstones, effusive magmatics, cherts and tuffs. Surrounding hills are built of various Palaeozoic, Mesozoic and Cenozoic (Cainozoic) rocks – magmatic, metamorphic add sedimentary (Figure 1), which can be compared with gravel pebbles. These results are also well documented by several studies [11-17].

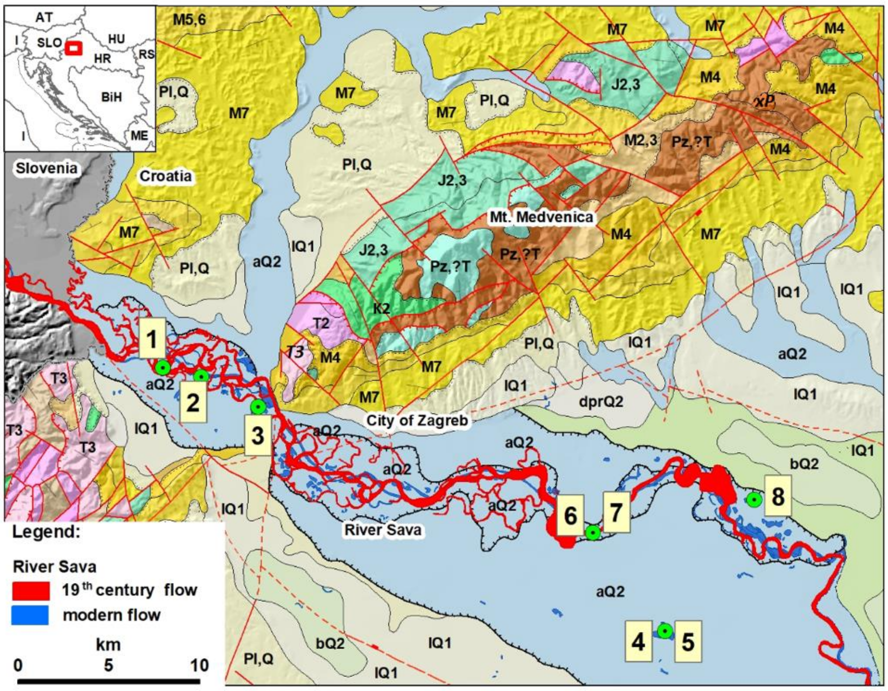

Figure 1. Geographical location and geological map of the study area. Sava River watercourses: non-regulated (red) and regulated (blue), Sampling locations (green dots: 1-8): **1-Samobor; 2-Savršćak; 3-Orešje; 4-Novo Čiče1; 5-Novo Čiče2; 6-Novi Petruševec1; 7-Novi Petruševec2; 8-Ivanja Reka.** Modified, after [18]. Legend for geology, after [19]: **xP:** Permian (magmatics: quartz diorites, granodiorites); **?Pz?T-P**: Palaeozoic to Triassic (parametamorphites); **T2:** Middle Triassic (carbonates, clastic and pyroclastic deposits); **T3:** Norian to Rhaetian (dolomites); **J23**: Middle to Upper Jurassic (ophiolites); **K2**: Upper Cretaceous (carbonate clastics and „Scaglia" limestones); **M23:** Otnangian to Carpathian (clastics, carbonates with clastics); **M4**: Badenian (*Lithothamnium* limestones and similar

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rocks); **M5,6:** Sarmatian to Pannonian (carbonate clastics); **M7:** Pontian (clastics and coal); **PlQ**: Plio-Quaternary (clastic deposits); **lQ1**: Pleistocene (loess sediments); **dprQ2**: Holocene (diluvial and proluvial sediments); **aQ2**: Holocene (fluvial deposits); **bQ1:** Holocene (pond deposits).

Later researches defined these deposits more precisely. For Middle Pleistocene gravels in the area west of Zagreb it is determined that their predominant sandstone pebbles originated from nearby source area, i.e. from Medvednica Mt., Samoborsko gorje Mt. and Marijagorička brda Hills, and for the overlying alluvial Sava gravels predominantly carbonate lithology of the Alpine provenance is defined [20]. Four Pleistocene-Holocene units were precisely distinguished [21]: (I) Lower Pleistocene loess-like deposits, with some paleosols characteristics; (II) Middle Pleistocene sandy gravels determined as lake deposits, with the transition into sandstones and pelitic sediments (even to loess with paleosols); (III) Upper Pleistocene loess, followed by swamp and lake deposits; and (IV) Holocene alluvial gravels. These deposits are later well correlated with the deposits investigated towards east [22], showing mainly quartz/quartzite/chert pebbles assemblage of Pleistocene gravels, and predominantly carbonate pebbles assemblage of Holocene sandy gravels.

3. Materials and methods

To ensure quality and reliability of the obtained results, following field and laboratory procedure were conducted. In the field, representative locations for sampling of the Holocene gravel beds were chosen, starting from the west and downstream to the east of the City of Zagreb (green dots in Figure 1). Sampling sites (Table 1) were located at nearby gravel pits, at the banks of the Sava River and at riverbed gravel bars as well (Figures 2a-b).

Table 1. Investigated locations, their GPS coordinates and sampling sites

Location	GPS - x	GPS - y	Sampling site
1 Samobor	55 606 24	50 769 92	Riverbank
2 Savršćak	55 588 28	50 774 05	Gravel pit bank
3 Orešje	55 636 03	50 751 42	Gravel pit bank
4 Novo Čiče 1	55 863 16	50 635 96	Gravel pit bank
5 Novo Čiče 2	55 863 16	50 635 96	Gravel pit bank
6 Novi Petruševec 1	55 822 69	60 688 48	Riverbed bar
7 Novi Petruševec 2	55 822 84	50 688 84	Riverbank
8 Ivanja Reka	55 906 34	50 707 51	Gravel pit bank

Samples were taken from within the single visible bedforms/layers as bulk samples, i.e. they are not discriminately taken according to the size of their clasts.

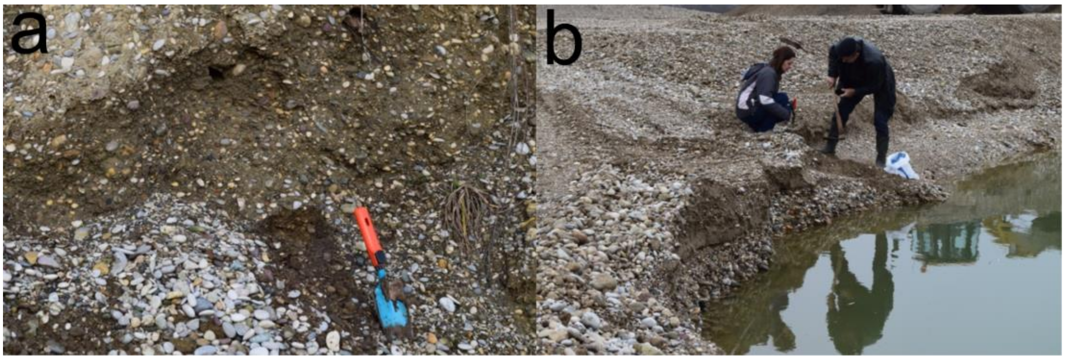

Figure 2. (a-b) Sampling at gravel pit banks: a) Ivanja Reka; b) Savršćak

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In the laboratory, total of 8 bulk samples were dried on air and sieved on 6 mm, 4 mm and 2 mm sieves. Statistical representative sets of 300 pebbles [23-25] of various sizes were taken from the largest separated fractions (> 6 mm) of each sample, making total set of 2400 pebbles prepared. Macroscopic lithological determinations were made, and pebbles are grouped according to determined lithotypes (Figures 3a-h).

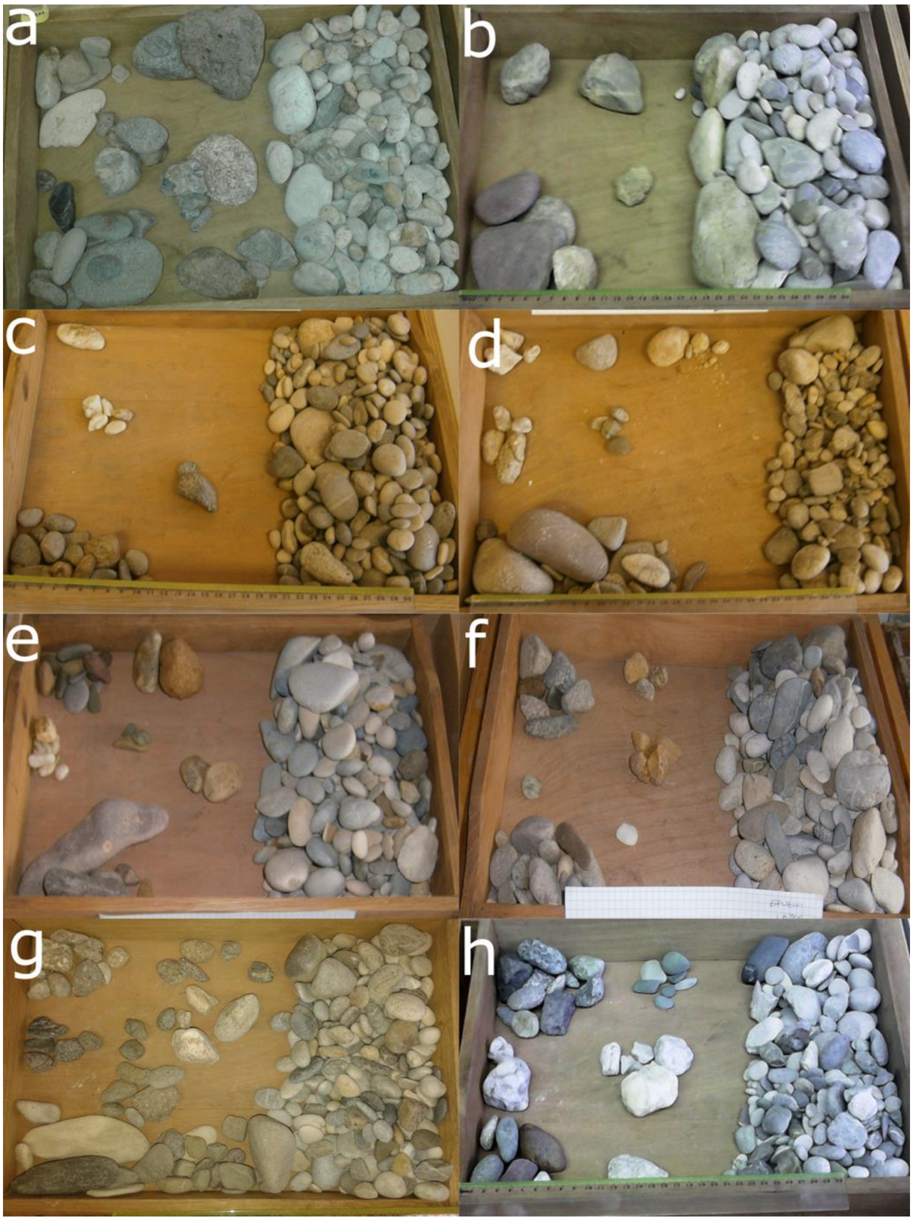

Figure 3. (a-h) Analysed pebbles grouped into lithotypes, at locations: a-Samobor; b-Savršćak; c-Orešje; d-Novo Čiče1; e-Novo Čiče2; f-Novi Petruševec1; g-Novi Petruševec2; h-Ivanja Reka. Divison on the yellow scale, visible on the lower width of Figs. b, c, d & h, is in centimetres.

Additionally, thin sections from the most common pebbles at one representative site (Samobor location) were analysed by polarizing microscope, in order to support macroscopic determinations of the lithotypes. Micropetrographic analysis confirmed major lithotypes determined (Figures 4a-f).

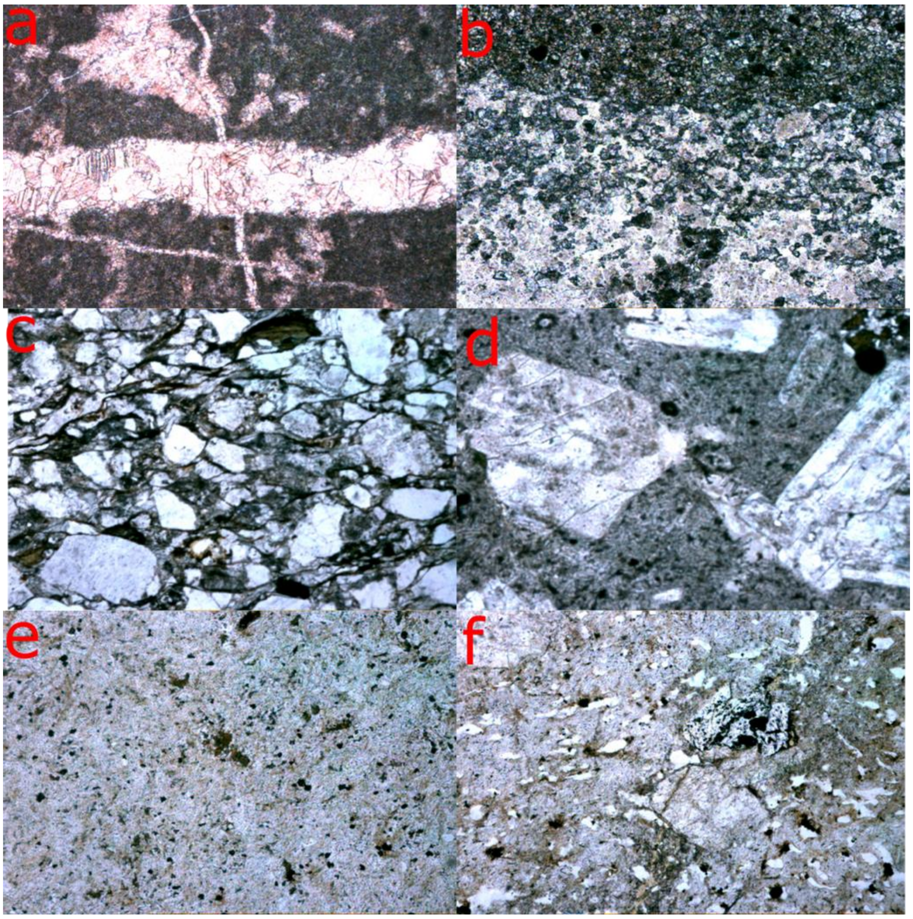

Figure 4. (a-f) Microphotographs of thin sections for main determined lithotypes in Samobor location: a) limestone, b) dolomite; c) sandstone (greywacke); d) effusive magmatic; e) tuff; f) chert. Width of the microphotographs is 1.7 mm.

Direct measurements of geometrical axes on the pebbles (the longest diameter/length a; the middle diameter/width b; and the shortest diameter/height c) were made with Vernier calliper on all selected pebbles, according to well-established procedure [23-24, 26-28]. By comparing the results of these measurements (b/a and c/b ratios), basic grain shape names were attributed: disc, sphere, blade or rod (Table 2) to all measured pebbles. All results of the measurements are further statistically processed with MS Excel® software.

Although various methods of characterization and classification of pebble shapes have been developed since [29-36], the original method, as described by [27] and upgraded by [23], attributing original sedimentary environments from flatness ratios, were the most appropriate to present the results of this study.

Table 2. Basic types of pebble shapes, after [27]

	b/a	c/b	shape
I.	> 2/3	< 2/3	disc
II.	> 2/3	> 2/3	sphere
III.	< 2/3	< 2/3	blade
IV.	< 2/3	> 2/3	rod

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Flatness ratios, defined by equation F = (a + b) / 2c, were also calculated for each selected pebble. They usually vary for gravel pebbles between 1.2 and 5, after [23]. Original sedimentary environments are further discussed and attributed, according to Table 3.

Table 3. Flatness ratios in various sedimentary environments, after [23]

SEDIMENTARY ENVIRONMENT	*FLATTNESS RATIO*
riverbed	**1.2 – 1.6**
moraine	**1.6 – 1.8**
sea shore	2.3 – 3.8
lake shore	**2.3 – 4.4**

4. Results

The results of lithological determinations and major (> 4%) defined lithotypes (limestones, dolomites, sandstones), as well as minor (< 4%) lithotypes (effusive magmatics, cherts and tuffs), are statistically presented for all samples. Pebbles of breccias, conglomerates, marls, shales and quartz are determined as accessories (< 1%). Distributions of major lithotypes at locations along Sava River watercourse, from the West downstream to the East (from Samobor to Ivanja Reka), are presented in Figure 5, and distributions of minor lithotypes in Figure 6.

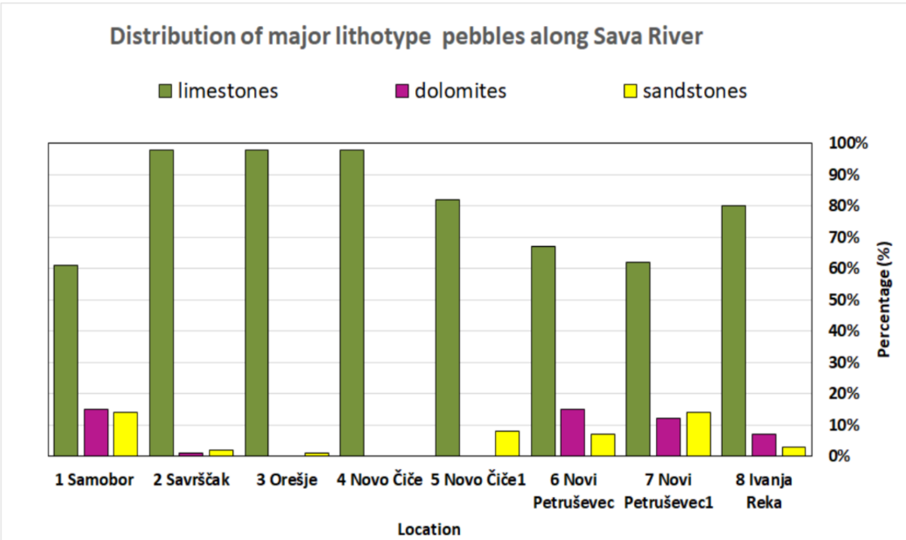

Figure 5. Distributions of major lithotypes of the pebbles at locations

The most common lithotype in all samples and at all locations are limestones, ranging from 63% (Samobor) to 97% (Savršćak, Orešje and Novo Čiče) in the west, and progressively decreasing towards east (down to 62%, in Novi Petruševec 1). Along with the major contribution from the Alpine region upstream of the Sava River, an additional contribution in the west is attributed to Triassic carbonates, documented in nearby Samoborska gora Mt. and Marijagorička brda Hills and in SW parts of Medvednica Mt. [9, 37-40]. Together with the predominance of limestone pebbles in the west, dolomites are the second most common lithotype determined, significantly abundant in Samobor (15%), which indicates local contributions as well. Shares of dolomites strongly decrease downstream (< 1%), but significant increase (7-16%) in Novi Petruševec and Ivanja Reka locations is determined. Sandstones are the next common lithotype, with shares up to 15% in Samobor (west) and Novi Petruševec (east) locations, as well as up to 7% in other locations. Effusive magmatics, cherts and tuffs are irregularly distributed, with shares up to 3-4%. Pebbles from breccias, conglomerates, quartz,

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shales and marls are also determined in minor amounts (< 1%), showing no significant distribution patterns.

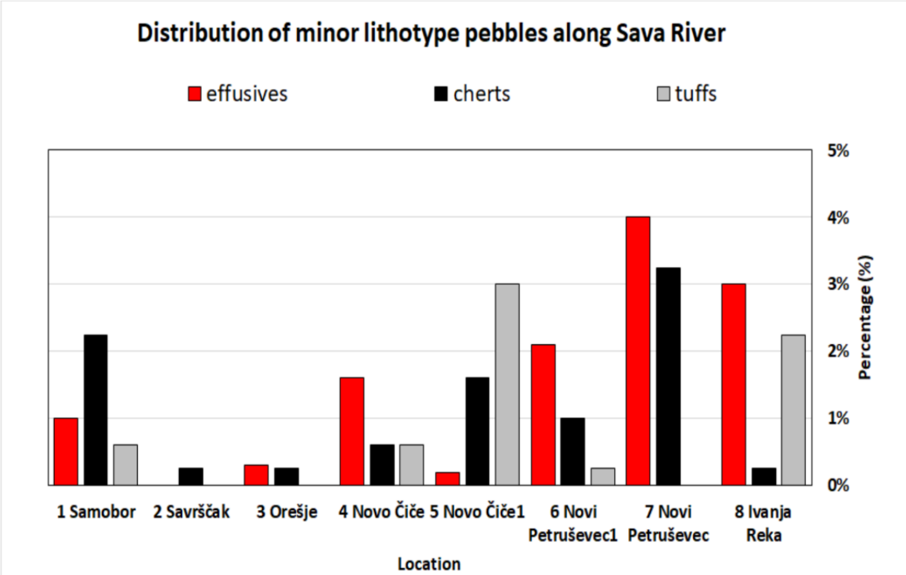

Figure 6. Distributions of minor lithotypes of the pebbles at locations

By comparing their measured axes (according to Table 2), pebble shapes (disc, sphere, blade or rod) were quantitatively defined in each sample. Pebble shapes were determined for all main lithotypes and the results are presented in the Zingg diagrams and histograms (Figures 7-14) for all locations, from the west downstream to the east.

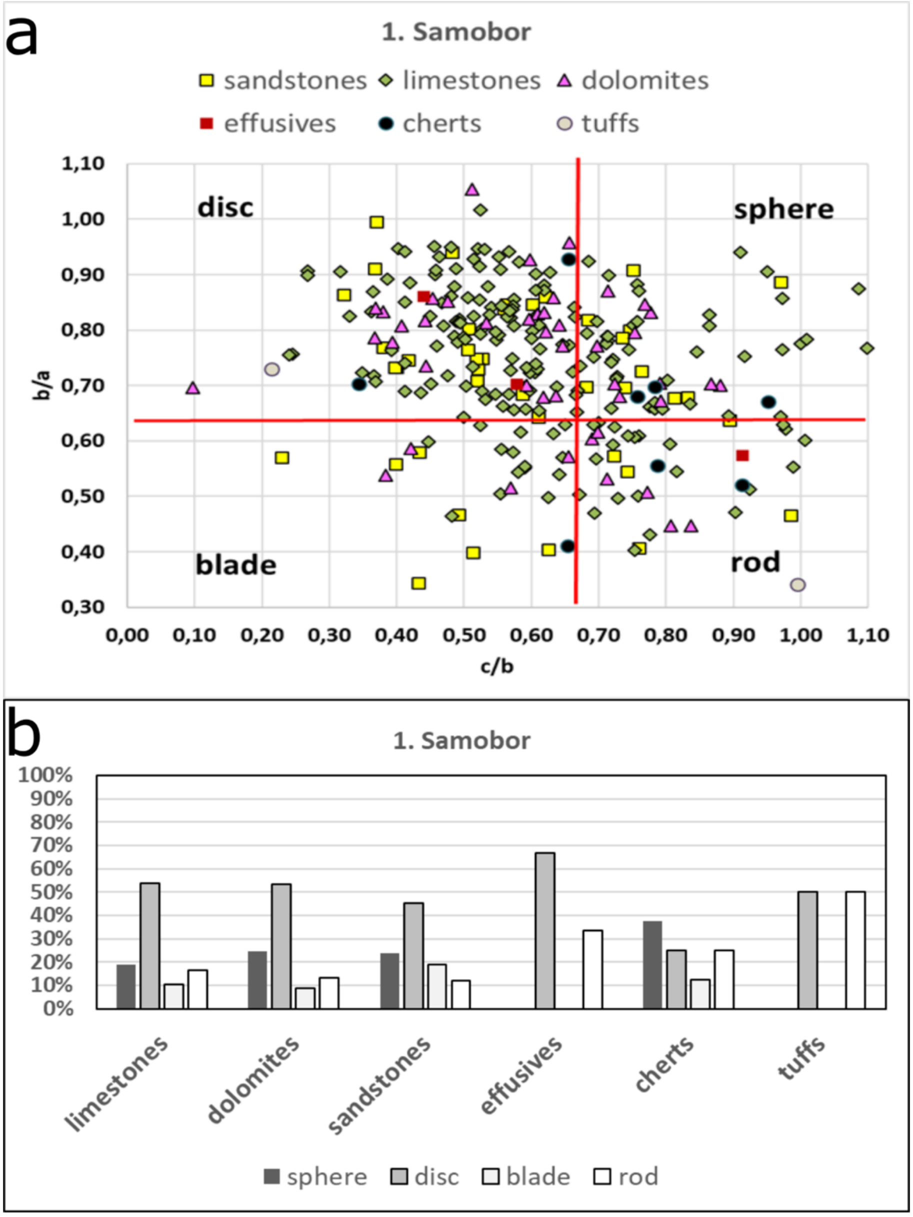

Figure 7. Pebble shapes of main lithotypes in Samobor: Zingg diagram (a), histograms (b)

In Samobor, predominant limestone and dolomite pebbles have mainly disc to mildly sphere shapes (Figure 7). Subordinate lithotypes (sandstones, effusives, cherts and tuffs) show more scattered distributions of their pebble shapes, with sandstones being the most diverse among them.

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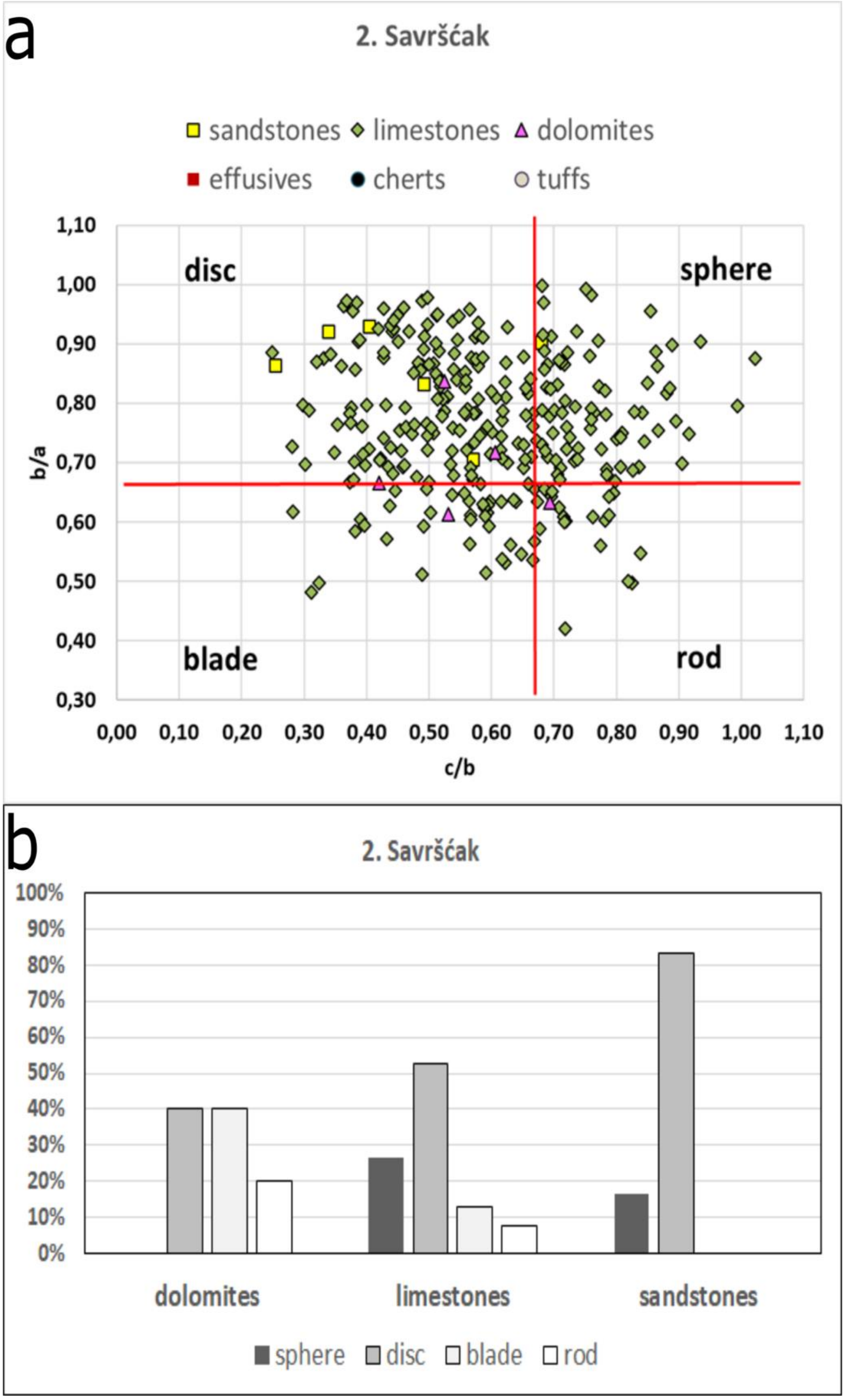

Figure 8. Pebble shapes of main lithotypes in Savršćak: Zingg diagram (a), histograms (b)

In Savršćak, predominance of limestone pebbles is significant, and they are mainly of disc to sphere shapes (Figure 8). Subordinate dolomite and sandstone pebbles show similar distributions, with the slight shift of dolomites toward more elongated shapes (blade to rod).

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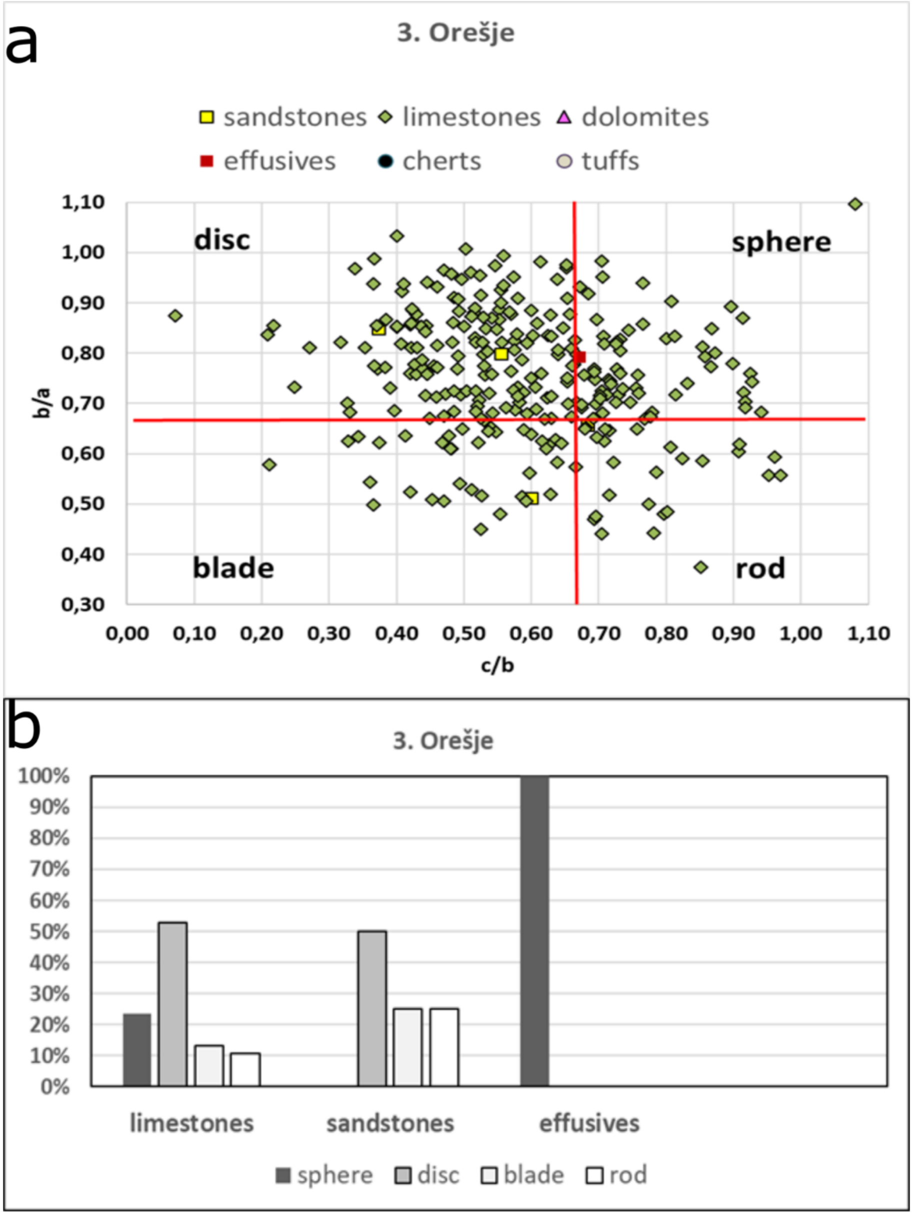

Figure 9. Pebble shapes of main lithotypes in Orešje: Zingg diagram (a), histograms (b)

In Orešje, predominant limestone pebbles also have mainly disc shapes (Figure 9). Other lithotypes present are insignificant, as well distributions of their pebble shapes. Sandstone pebbles have mainly disc shapes, followed by blade and rod shapes.

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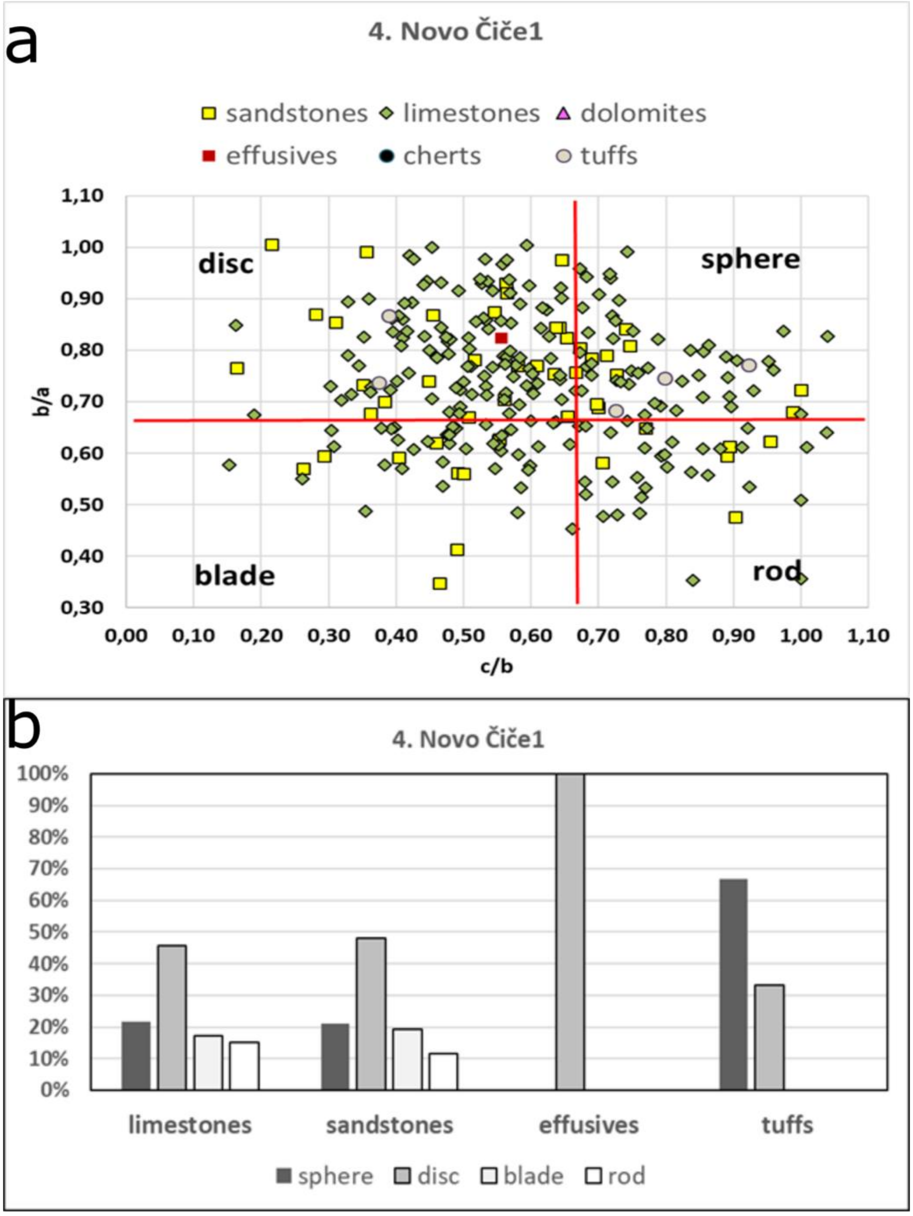

Figure 10. Pebble shapes of main lithotypes in Novo Čiče 1: Zingg diagram (a), histograms (b)

In Novo Čiče 1, scattered pattern of sandstone pebble shapes appeared again (Figure 10), as previously in Samobor (Figure 7). Predominant limestone pebbles retained mainly disc and sphere shapes.

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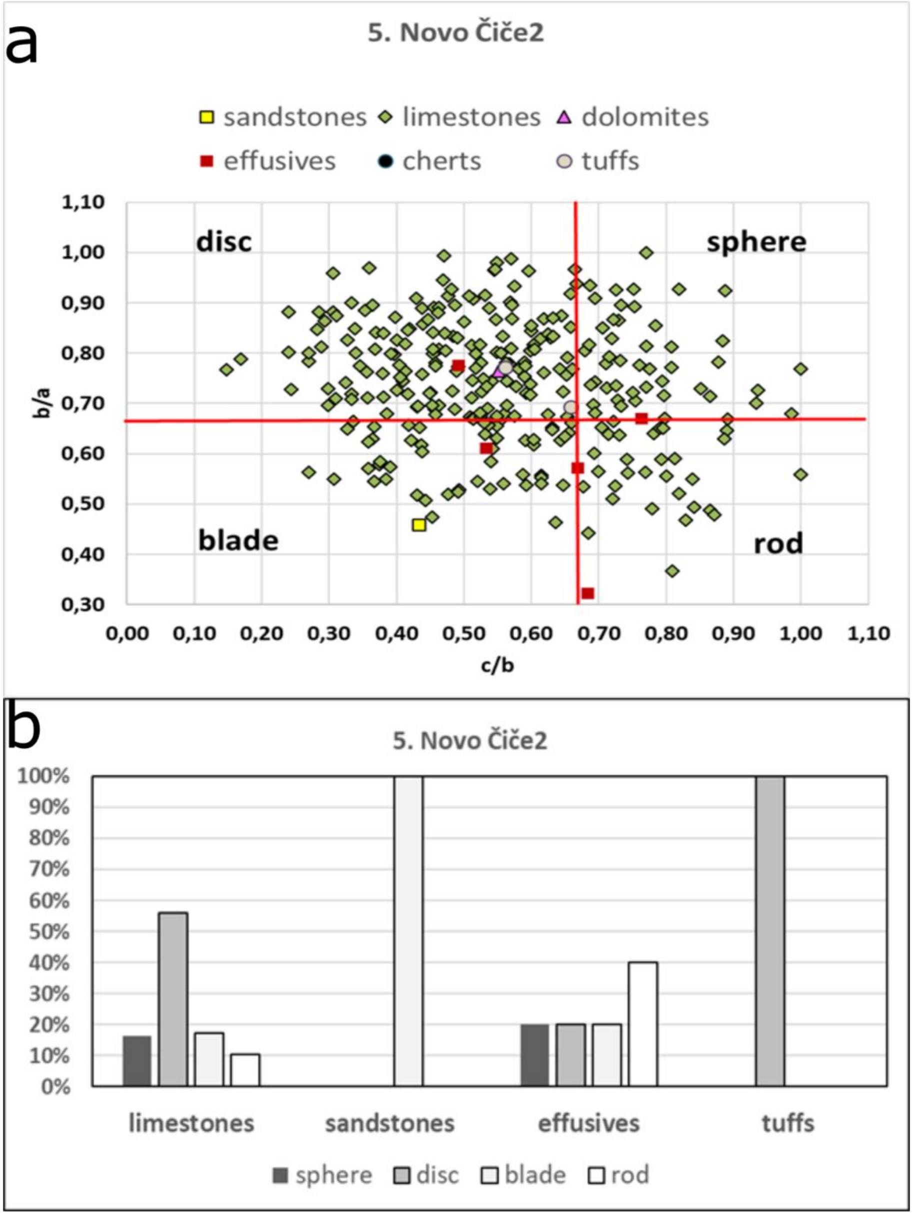

Figure 11. Pebble shapes of main lithotypes in Novo Čiče 2: Zingg diagram (a), histograms (b)

In Novo Čiče 2, effusive magmatic pebbles suddenly increase, having more elongated (blade to rod) shapes (Figure 11). Predominant limestones retained mainly disc shapes.

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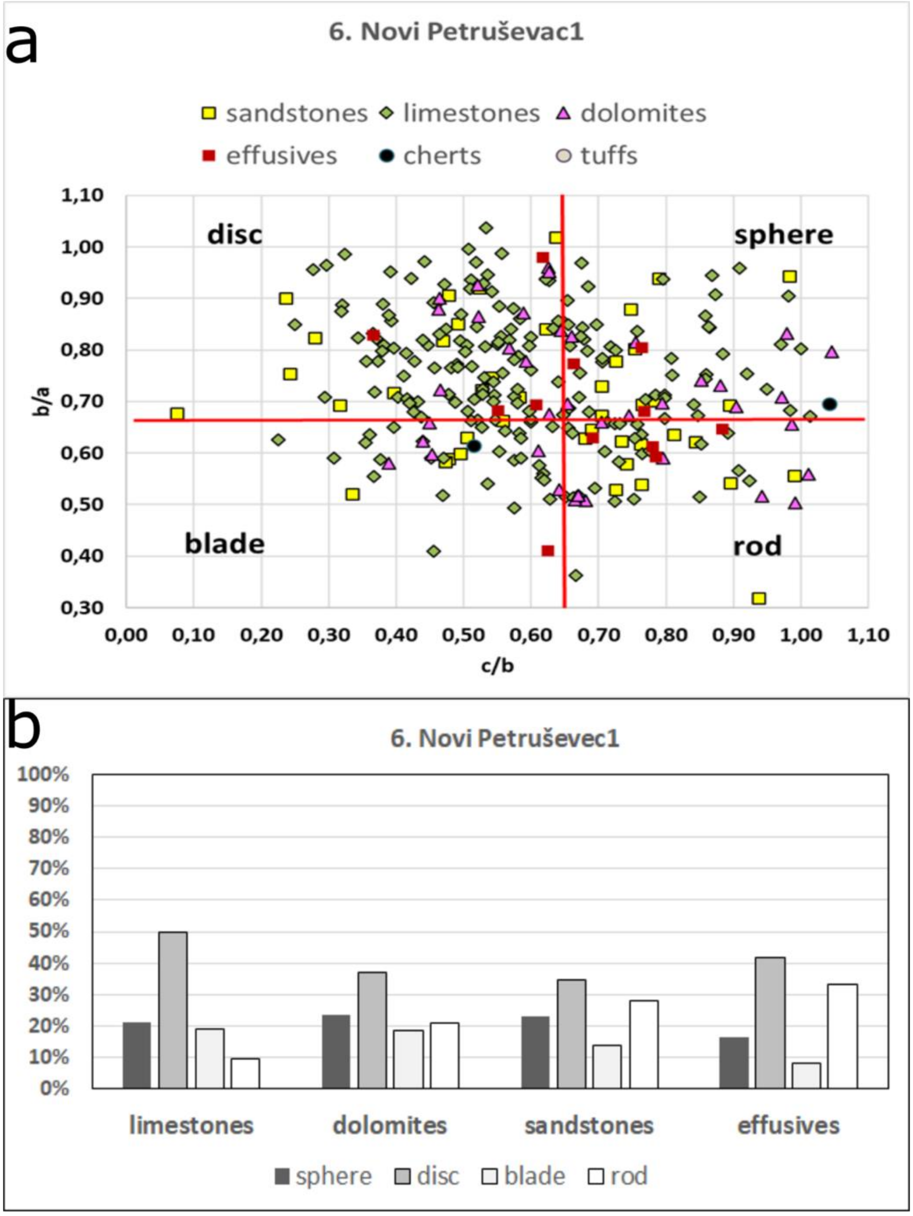

Figure 12. Pebble shapes of main lithotypes in Novi Petruševec 1: Zingg diagram (a), histograms (b)

Downstream toward the East, in Novi Petruševec 1, limestone pebbles slightly decrease, retaining mainly disc shapes (Figure 12). All other lithotypes increase, showing scattered distributions of their pebble shapes.

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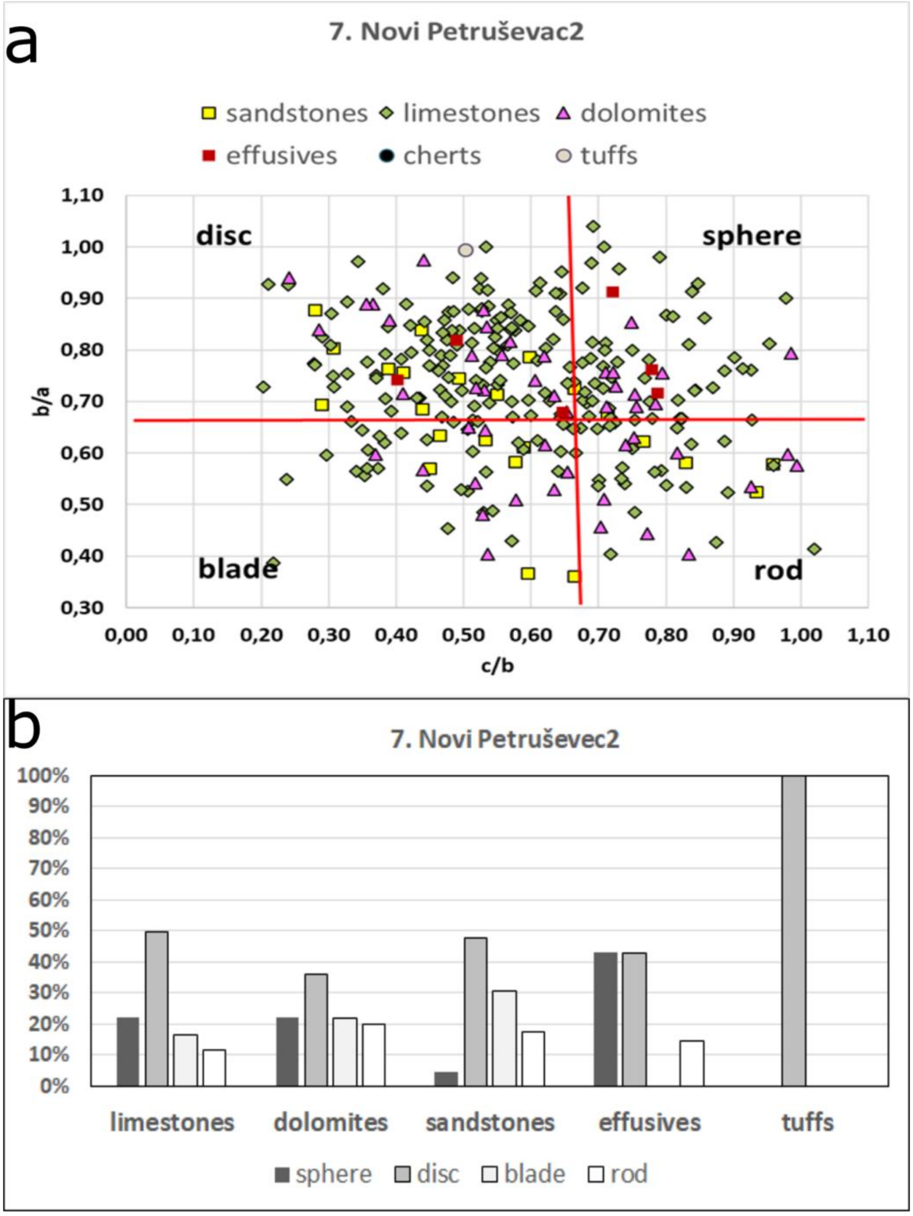

Figure 13. Pebble shapes of main lithotypes in Novi Petruševec 2: Zingg diagram (a), histograms (b)

In Novi Petruševec 2 (Figure 13), similar shares of lithotypes present and distributions of their pebble shapes appear as in Novi Petruševec 1 (Figure 12). Limestones, dolomites and sandstone pebbles have mainly disc shapes, and effusive magmatic pebbles have disc and sphere shapes.

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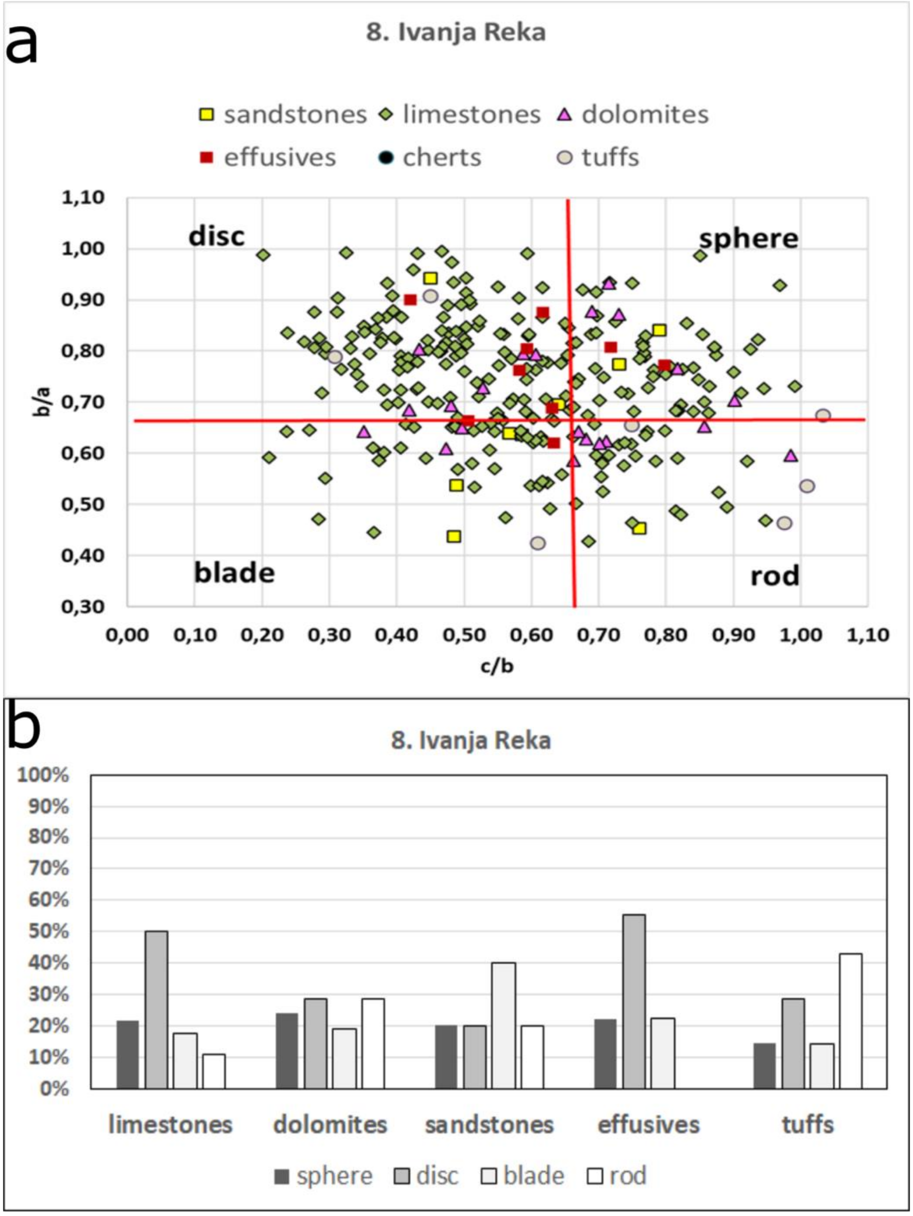

Figure 14. Pebble shapes of main lithotypes in Ivanja Reka: Zingg diagram (a), histograms (b)

In Ivanja Reka, the far east location, all main lithotypes are significantly present again. Limestones are predominant and slightly increase again, having mainly disc to sphere pebble shapes (Figure 14). Sandstone pebbles with mainly blade shapes prevail.

Generally, regardless of their lithotypes, disc pebbles prevail (45-50%) in all locations along observed traverse (Figure 15). Sphere pebbles are less abundant (16-26%), while blade (11-16%) and rod (8-15%) pebbles are subordinately present. Disc, sphere and rod pebbles are more or less equally distributed along observed the Sava River watercourse, while blade pebbles discretely increase downstream toward east.

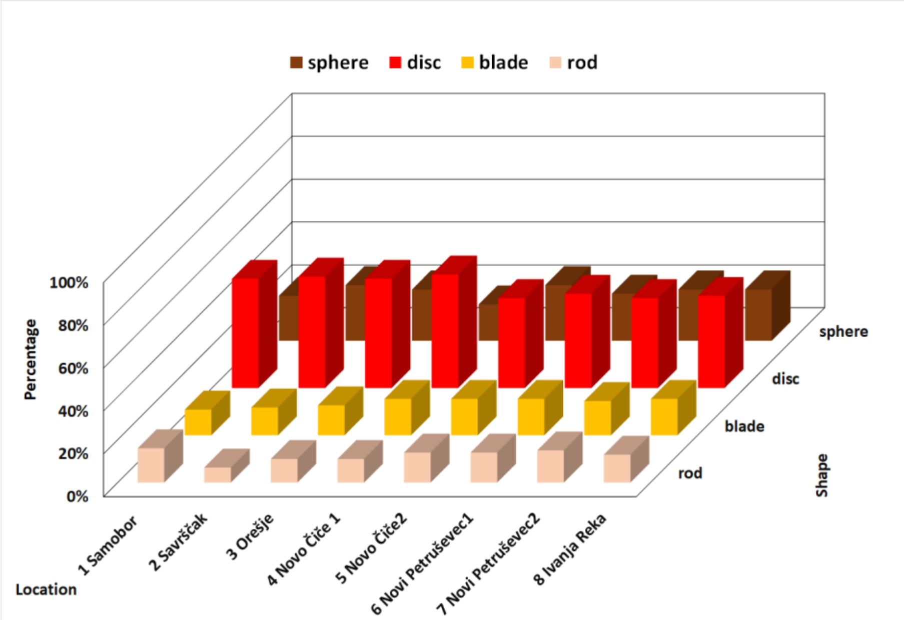

Figure 15. Distribution of all pebble shapes at locations

Original sedimentary environments (moraines, riverbeds and lake shores), determined by measuring their diameters and calculating flatness ratios of the pebbles (according to [23], see Table 3), were attributed (Figure 16). Since these ratios depend also on their different lithologies and hydrodynamic conditions during the transport of the pebbles, comparisons of lithotypes distributions (Figures 5-6), pebble shapes distributions according to their lithotypes (Figures 7-14) and regardless of lithotypes (Figure 15), as well as distribution of attributed original sedimentary environments (Figure 16), were made and further discussed.

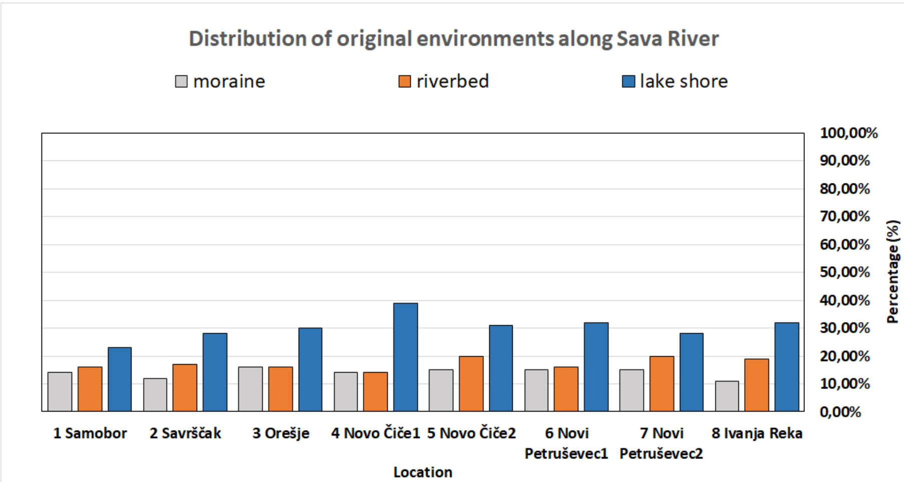

Figure 16. Attributed original sedimentary environments for the pebbles at locations

5. Discussion

Comparisons of lithotypes distributions (Figures 5-6) show predominance of carbonate lithologies (limestones and dolomites) of mainly Alpine provenance, with possibly significant input from local sources in the West (Triassic deposits of Medvednica and Samoborska gora Mts. – left side on Figure 1, see also [9, 37]). Nearby Location 3 (Orešje), significant change of Sava River watercourse is visible: through the narrowing between Medvednica and Samoborska gora Mts. at Podsused, it

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enters Zagreb alluvial plain and flows further toward east as slower, meandering river. This change of watercourse also reflects mainly on the distribution of Holocene gravel pebbles and partly on their morphometric characteristics, which mostly depend on their lithologies. Accumulation of predominately carbonate pebbles occurred at locations 1-3. Incision and deep erosion of the riverbed (down to the underlying Pleistocene deposits) at knickpoint near Podsused followed. These two processes influenced distribution of lithotypes at downstream locations. Sandstones are also abundant in the west and in the far east locations, while almost lacking in the middle part of observed traverse. This implies probable local inputs from the SW limbs of Medvednica and Samoborska gora Mts. in the west, and from SE parts of Medvednica Mt. in the east. Minor lithotypes (effusive magmatics, cherts and tuffs) increase significantly towards east, suggesting also possible lateral input from the eastern parts of the Medvednica Mt. (see [8, 37], as well as [41-42]).

Pebble shapes in alluvial sediments are primarily influenced by their lithology, fabric and sedimentary structures, and then by hydrodynamic conditions during transport. Shale and schist pebbles are usually prone to form platy pebbles, and not likely to form rod or sphere shapes, and the same can be stated for thin layered/laminated limestones, cherts, siltites and sandstones. More homogeneous rocks (thick layered and massive limestones and dolomites, quartzites or marbles) tend to form sphere, disc or generally isometric pebble shapes. Approaching to ideal sphere pebble shape correlates also well with the increasing hydrodynamic conditions or with relatively long transport [24].

When pebble shapes and corresponding lithotypes are compared (Figures 7-14), disc and sphere pebble shapes distributions correlate well with two major lithologies - limestones and dolomites (compare with Figure 5). Contribution of limestone and dolomite pebbles and their predominately disc and sphere shapes is therefore significant characteristic of overall pebble distribution (Figure 15), and it implies their similar sources (predominately more distant, and possibly some local) and similar transport conditions as well. On the other hand, third major lithotype - sandstones, show more scattered pebble shapes distributions, in all locations where they are significantly present: in the West, as well as in the far East locations. Their almost equally present sphere, disc, blade and rod shapes, reflect possible heterogeneity of their fabrics and/or sedimentary structures, thus implying multiple sources. Considering that fact, together with their significant abundance in the West and East (compare with Figure 5), local sources and possible lateral input by streams from Medvednica and Samoborska gora Mts., are likely. Pebble shapes distributions of minor lithotypes (effusive magmatics, cherts and tuffs) are also scattered, and together with their abundances (compare with Figure 6) suggest, at least some, local sources.

Flatness ratios in the pebbles of the same lithotypes vary according to their original sedimentary environments and hydrodynamic conditions [23-24]. Distribution of original sedimentary environments - moraines, riverbeds and lake shores - show that pebbles originated at lake shores prevail in all locations (see Figure 16). Sandy gravel lake deposits are often recorded in the underlying Middle Pleistocene deposits [21-22], and predominance of the pebbles from such environments indicate their redeposition further downstream during Holocene. Sea shore environments were not considered and attributed, due to previously determined and described geology of the area, which does not includes marine environments that could be possibly re-deposited during Quaternary, and also due to overlapping of theoretical flatness ratios for sea shores with those for lake shores (compare in Table 3). Pebbles originated in moraine environments are almost equally distributed and indicate glacial weathering and transport, prior to Holocene alluvial transport along Sava River watercourse and riverbed deposition. Climatic changes with glacial and interglacial periods, followed by sudden warming and increased tectonic dynamics in Holocene [22] favour intensive riverbed transport and sedimentation of relatively well sorted gravels. Therefore, Holocene gravels contain predominantly carbonate pebbles of Alpine provenance, which are overlying Pleistocene deposits.

Pebbles with flatness ratio indicating original riverbed environment are usually expected in Holocene gravels of the Sava River. However, their similar shares (15-20%) as pebbles from moraine environments (11-18%), as well as predominance of lake shore pebbles (20-40%) over both, indicate influence of riverbed environment processes on morphometric characteristics of gravel pebbles along observed traverse, but less than expected for riverbed gravels. Older moraine pebbles of Alpine

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provenance (predominantly limestones and dolomites), and lake shore pebbles redeposited from the underlying Pleistocene lake deposits, did not significantly change their morphometric characteristics in Holocene lower energy meandering river environments along observed Sava River watercourse. They mainly retained their flatness ratios, which helped us to recognize and tentatively interpret their original sedimentary environments and their provenance.

Holocene the Sava River gravels thus represent a kind of environmental products, similar as products of "Los Angeles Abrasion Resistance Test" [43-44], which is applied on various types of rocks in simulated conditions at the laboratory. Morphometric characteristics and pebble shapes of predominate carbonate lithotypes thus can be compared in the future studies with the physicomechanical properties of carbonates from nearby the Samoborska gora and Medvednica, Mts. described by [40-41] and [45].

6. Conclusions

Limestones, dolomites and sandstones are major lithotypes in observed Holocene pebbles from the Sava River gravels, while effusive magmatics, cherts and tuffs are minor lithotypes present. Their distributions vary along observed traverse, downstream from Samobor to Ivanja Reka, indicating distant Alpine provenance, as well as possible local input in the west for two main lithologies, limestones and dolomites. Sandstone pebbles distribution indicate probable local sources at both ends of the traverse, in the west, as well as in the east. Minor lithotypes distributions indicate probable local input in the east.

Predominately disc and sphere shapes of limestone and dolomite pebbles imply their similar sources and transport conditions (mainly distant, and some local). Scattered distributions of sandstones pebble shapes indicate multiple sources, some of them highly probable as local, from the SW parts of Medvednica and Samoborska gora Mts. in the west, and from the SE Medvednica Mt. in the east. Scattered distributions of pebble shapes for minor lithotypes suggest similar provenance.

Original sedimentary environments for main pebble lithotypes are tentatively interpreted from their flatness ratios, indicating predominant lake shore environments, followed by moraine and riverbed environments.

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References

1. Nakić, Z., Ružičić, S., Posavec, K., Mileusnić, M., Parlov, J., Bačani A.; Durn, G. Conceptual model for groundwater status and risk assessment - case study of the Zagreb aquifer system. *Geol. Croat.* **2013**, *66, 1*, 55–77.
2. Vujević, M.; Posavec, K. Identification of groundwater level decline in Zagreb and Samobor-Zaprešić aquifers since the sixties of the twentieth century. *Rudarsko-Geološko-Naftni Zbornik* **2018**, *33, 4*, 55-64. https://hrcak.srce.hr/ojs/index.php/rgn/article/view/6776
3. Kapuralić, J., Posavec, K., Kurevija, T.; Macenić, M. Identification of River Sava temperature influence on groundwater temperature of the Zagreb and Samobor-Zaprešić aquifer as a part of shallow geothermal potential. *Rudarsko-Geološko-Naftni Zbornik* **2018**, *33, 5*, 59-69. https://hrcak.srce.hr/ojs/index.php/rgn/article/view/7575
4. Brkić, Ž. The relationship of the geological framework to the Quaternary aquifer system in the Sava River valley (Croatia). *Geol. Croat.* **2017**, *70, 3*, 201-213. https://doi.org/10.4154/gc.2017.12
5. Grizelj, A., Bakrač, K., Horvat, M., Avanić, R.; Hećimović, I. Occurrence of vivianite in alluvial Quaternary sediments in the area of Sesvete (Zagreb, Croatia). *Geol. Croat.* **2017**, *70, 1*, 41–52. https://doi.org/10.4154/gc.2017.01
6. Trenc, N., Matoš, B., Velić, J.; Perković, D. Application of GIS Procedure for River Terrace extraction from LiDAR- based DEM: Sava River Valley NW of Zagreb, Croatia. *Rudarsko-Geološko-Naftni Zbornik* **2018**, *34, 1*, 59-70. https://hrcak.srce.hr/ojs/index.php/rgn/article/view/7279
7. Ružičić, S., Kovač, Z.; Tumara, D. Physical and chemical properties in relation with soil permeability in the area of Velika Gorica well field. *Rudarsko-Geološko-Naftni Zbornik* **2018**, *33, 2*, 73-82. https://doi.org/10.17794/rgn zbornik.v33i2.5681
8. Šikić, K., Basch, O.; Šimunić, An. *Basic Geological Map of SFR Yugoslavia, 1:100000, Geology of the Zagreb sheet*. Geol. Institute Zagreb, Federal Geol. Institute Belgrade, 1979**,** pp 81. (in Croatian)
9. Basch, O. *Basic Geological Map of SFR Yugoslavia, 1:100000, Geology of the Ivanić-Grad sheet*. Geol. Institute Zagreb, Federal Geol. Institute Belgrade, 1983, pp. 66. (in Croatian)
10. Šikić, K., Basch, O.; Šimunić, An. *Basic Geological Map of SFR Yugoslavia, 1:100000, Zagreb sheet, L33-80*. Geol. Institute Zagreb, Federal Geol. Institute Belgrade, 1977. (in Croatian)
11. Basch, O. *Basic Geological Map of SFR Yugoslavia, 1:100000, Ivanić-Grad sheet, L33-81*. Geol. Institute Zagreb, Federal Geol. Institute Belgrade, 1983. (in Croatian)
12. Borčić, D., Capar, A., Čakarun, I., Kostović, K.; Miletić, P. Noviji podaci o zavisnosti vodostaja podzemne vode i vodostaja Save na području Zagreba [*New data on dependence of underground water levels and Sava River water levels in the area around the city of Zagreb*]. *Geol. Vjesn.* **1968**, *21*, 311-316. (in Croatian)
13. Crnković, B.; Bušić, M. Mineraloško-petrografski sastav nanosa rijeke Save. [*Mineralogical and petrological composition of the Sava River sediment*]. *Proceedings from 30th anniversary of the RGN Faculty (1939-1969)*, 1970, Zagreb, 133-140. (in Croatian)
14. Kovačević S.; Capar, A. Vodoistražni radovi u dolini Save kraj Samobora [*Underground water researches in Sava River alluvium near Samobor*]. *Proceedings of the 2nd Jugosl. Simp. Hidrogeol. & Eng. Geol.* 1, 1972, Belgrade. (in Croatian)
15. Šimunić, An.; Basch, O. Stratigrafija kvartarnih sedimenata Zagrebačkog Posavlja [*The stratigraphy of Quaternary sediments in the Zagrebačko Posavlje*]. *Geol. Vjesn.* **1975**, *28*, 153-164 (in Croatian)
16. Babić, Ž., Čakarun, I., Sokač, A.; Mraz, V. O geologiji kvartarnih naslaga porječja rijeke Drave [*About the geology of Quaternary deposits of the Drava River basin*]. *Geol. Vjesn.* **1978**, *30, 1*, 43-61. (in Croatian)
17. Šimunić, Al., Novosel-Škorić, S.; Piljurović, LJ. Litološka korelacija i kronostratigrafsko razgraničavanje kvartarnih naslaga na lokalitetu Prevlaka jugoistočno od Zagreba [*Lithological correlation and chronostratigraphic delimitation of Quaternary sediments at the location Prevlaka southeast of Zagreb*]. *Geol. Vjesn.* **1988**, *41*, 167-179. (in Croatian)
18. *Geological Map of the Republic of Croatia at a scale 1:300.000*. Croatian Geological Survey, Zagreb, 2009. (webGIS service: http://webgis.hgi-cgs.hr/gk300/default.aspx) (in Croatian)
19. *Guide to the Geological Map of the Republic of Croatia at a scale 1:300.000*. Velić, I.; Vlahović, I. (eds.); Croatian Geological Survey, Zagreb, 2009, pp. 141. (in Croatian)
20. Velić, J.; Saftić, B. Subsurface Spreading and Facies Characteristics of Middle Pleistocene Deposits between Zaprešić and Samobor. *Geol. Vjesn.* **1991**, *44*, 69–82.

Peer-reviewed version available at *Geosciences* **2020**, *10*, 92; doi:10.3390/geosciences10030092

21. Velić, J.; Durn, G. Alternating Lacustrine-Marsh Sedimentation and Subaerial Exposure Phases During Quaternary: Prečko, Zagreb, Croatia. *Geol. Croat.* **1993**, *46*, *1*, 71–90. doi: 10.4154/GC.1993.06
22. Velić, J., Saftić, B.; Malvić, T. Lithological Composition and Stratigraphy of Quaternary Sediments in the Area of the „Jakuševec" Waste Depository (Zagreb, Northern Croatia). *Geol. Croat.* **1999**, *52*, *2*, 119–130. doi: 10.4154/GC.1999.10
23. Müller, G. *Methods in Sedimentary Petrology*. Sedimentary Petrology-Part1, Schweizerbart, Stuttgart, 1967; pp. 283.
24. Tišljar, J. *Sedimentne stijene* [*Sedimentary rocks*]. Školska knjiga, Zagreb, 1994, pp. 421. (in Croatian)
25. Southard, J. *Sedimentary Geology*. MIT Open Course Ware, 2007; pp. 312.
26. Wentworth, C.K. The shapes of beach pebbles. *USGS Prof. Paper*, **1922**, *131-C*, 75-83.
27. Zingg, T. Beiträge zur Schotteranalyse. *Min. Petrog. Mitt. Schweiz.*, **1935**, *15*, 39–140.
28. Pettijohn, F.J. *Sedimentary Rocks* (2nd ed). Harper & Bros, New York, 1957; pp. 718.
29. Krumbein, W.C. Measurement and geologic significance of shape and roundness of sedimentary particles. *Jour. Sedim. Petr.* **1941**, *11*, 64–72.
30. Aschenbrenner, B.C. A new method of expressing particle sphericity. *Jour. Sedim. Petr.* **1956**, *26*, 15–31.
31. Sneed, E.; Folk, R.L. Pebbles in the lower Colorado River, Texas, a study in particle morphogenesis. *Journal of Geology* **1958**, *66*, 114–150.
32. Smalley, I.J. The presentation of subjective shape and roundness data. *Sedimentology* **1967**, *8*, 35–38.
33. Dobkins, J.E.; Folk, R.L. Shape development on Tahiti-Nui. *Jour. Sedim. Petr.* **1970**, *40*, 1167–1203.
34. Graham, D.J.; Midgley, N.G. Graphical representation of particle shape using triangular diagrams: an Excel spreadsheet method. *Earth Surface Processes and Landforms* **2000**, *25*, 1473–1477.
35. Blott, S.J.; Pye, K. Particle shape: a review and new methods of characterization and classification. *Sedimentology* **2008**, *55*, 31–63.
36. Szabó, T.; Domokos, G. A new classification system for pebble and crystal shapes based on static equilibrium points. *Central European Geology* **2010**, *53, 1*, 1–19. DOI: 10.1556/CEuGeol.53.2010.1
37. Šikić, K. Prikaz geološke građe Medvednice *[Overview of geological structure of the Medvednica Mt.*]. In: Šikić, K. (ed), Geološki vodič Medvednice *[Geological Guide through Medvednica Mt.*], 1995, Zagreb, 7-40. (in Croatian)
38. Tomljenović, B. *Structural Characteristics of Medvednica and Samoborsko gorje Mountains.* Ph.D. Thesis, 2002, University of Zagreb, Croatia. (in Croatian)
39. Pavičić, I., Dragičević, I., Vlahović, T.; Grgasović, T. Fractal analysis of fracture systems in Upper Triassic Dolomites in Žumberak Mountain, Croatia. *Rudarsko-Geološko-Naftni Zbornik* **2017**, *32*, *3*, 1-13. https://doi.org/10.17794/rgn zbornik.v32i3.4894
40. Maričić, A., Starčević, K.; Barudžija, U. Physical and mechanical properties of dolomites related to sedimentary and diagenetic features - case study of the Upper Triassic dolomites from Medvednica and Samobor Mts., NW Croatia. *Rudarsko-Geološko-Naftni Zbornik* **2018**, *33*, *3*, 33-44. https://hrcak.srce.hr/ojs/index.php/rgn/article/view/6147
41. Sremac, J., Kudrnovski, D., Velić, J., Bošnjak, M.; Velić, I. Statistical analyses of Late Cretaceous clastic deposits from Mali Potok Creek (Medvednica Mt., Northern Croatia). In: *Proceedings of the 2nd Croatian Congress on Geomathematics and Geological Terminology, Zagreb, Croatia, 6 Oct. 2018*; Zagreb, 2018, pp. 87–93.
42. Sremac, J., Velić, J., Bošnjak, M., Velić, I., Kudrnovski, D.; Troskot-Čorbić, T. Depositional Model, Pebble Provenance and Possible Reservoir Potential of Cretaceous Conglomerates: Example from the Southern Slope of Medvednica Mt. (Northern Croatia). *Geosciences* **2018**, *8*, *12*, 456-475. https://doi.org/10.3390/geosciences8120456
43. Ballivy G.; Dayre M. The mechanical behaviour of aggregates related to physicomechanical properties of rocks. *Int. Assoc. Eng. Geol. Bull.* **1984**, *29*, 339–342.
44. Teymen, A. Estimation of Los Angeles Abrasion resistance of igneous rocks from mechanical aggregate properties. *Bull. Eng. Geol. Environ.* **2019**, *78*, 837-846. https://doi.org/10.1007/s1006 4-017-1134-0
45. Tomašić, I., Ženko, T.; Aljinović, S. Otpornost dolomitnih agregata na udarno habajuća opterećenja i zamrzavanje [*Resistance of dolomite aggregates on percussive-wear load and freezing*]. *Rudarsko-Geološko-Naftni Zbornik* **1992**, *4*, 119-126. (in Croatian)