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GENESIS OF THE UPPER PLEISTOCENE GRAVEL FROM THE ABESINIJA PIT SE FROM ZAGREB (CROATIA)

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Abstract. Polymictic gravels exploited in the vicinity of Rugvica, SE from Zagreb, comprise clasts of various lithology, colour, shape, and size. Pebbles are composed of sedimentary, volcanic and, sporadically, metamorphic rocks. During the field work we recognized fossils in the abundant carbonate pebbles. Most of the carbonate clasts are rounded, discoidal in shape, varying in colour from white to dark grey, almost black. Pebbles were measured by a calliper and petrographic thin sections were prepared from fossiliferous pebbles. Numerical analyses pointed to some minor differences in their shape and size, but micropaleontological analyses revealed clasts of Carboniferous, Permian, Triassic, Jurassic, Cretaceous, Paleogene and Neogene age. Most of the Mesozoic and Cenozoic clasts originate from the two local mountain areas (Medvednica Mt. and Samobor Hills), with part of the Jurassic-Cretaceous pebbles possibly derived from SW Slovenia. Irregularly shaped and sometimes poorly rounded clasts of the Paleogene/Neogene ages seem to be abruptly transported to short distances by torrents or streams. The most enigmatic were the clasts of Carboniferous-Permian age. The nearest Palaeozoic outcrops occur upstream in Central Slovenia, but some fossils point to the even longer transport route, from the Karavanks in the upper flow of the Sava River. Gravels are overlain by fine-grained lake sediments and peat coal. Peat comprises significant amount of pine pollen, pointing to the warming period within the Late Pleistocene, which was additionally confirmed by the radiocarbon dating.

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Fig. 1 - A) A map of the rivers draining the Alps (Winterberg & Willet 2019). Zagreb area is marked with red rectangle on the map; B) position of the research area (Abesinija gravel pit) SE from Zagreb, coordinates: 45°46’34.54”N; 16°09’38.92”E (Google Maps, 2024).

Introduction

The Sava River, formed by the fusion of the Sava Dolinka and the Sava Bohinjka, is one of the longest rivers in Europe and the largest tributary of the Danube, considering the volume of water (Winterberg & Willet 2019, Fig. 1A). The Sava River Basin extends into the territory of six countries: Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Montenegro and, marginally, northern Albania. Quaternary deposits of the eastern part of the Zagreb alluvial plain are presented on the Basic Geological Map, Sheet Ivanić Grad (Basch 1983 a,b). They are composed of loose clays, silts, sands, and gravels. Gravels provide the potentially valuable building material, which is excavated in several gravel pits and host the largest underground drinking water reserves in the area, the Zagreb aquifer system. They are often exposed during the preparation of foundations for large buildings. Due to all these features, alluvial deposits of the Sava River were studied by various authors (e.g., Marić et al. 1954; Borčić et al. 1968; Crnković & Bušić 1970; Šimunić & Basch 1975; Čakarun et al. 1987; Velić & Saftić 1991; Velić & Durn 1993; Velić et al. 1999; Brkić et al. 2003; Nakić et al. 2013; Brkić 2017; Kovač et al. 2017; Trenc et al. 2019; Barudžija et al. 2020; Sremac et al. 2020; Meaški et al. 2021).

Some of the early published detailed studies were dedicated to the petrographic composition and distribution of the Holocene clastic deposits in the Sava River valley (e.g., Marić et al. 1954; Crnković & Bušić 1970).

Barudžija et al. (2020) studied the modal composition of the Holocene gravels and the distribution of different lithotypes along the Sava watercourse, from the Samobor City in the west, to Ivanja Reka in the east. They give significant credit to the previously published data, and emphasize the dominance of limestones, dolostones, and sandstones among the studied pebbles, with less abundant effusive volcanic rocks, cherts, and

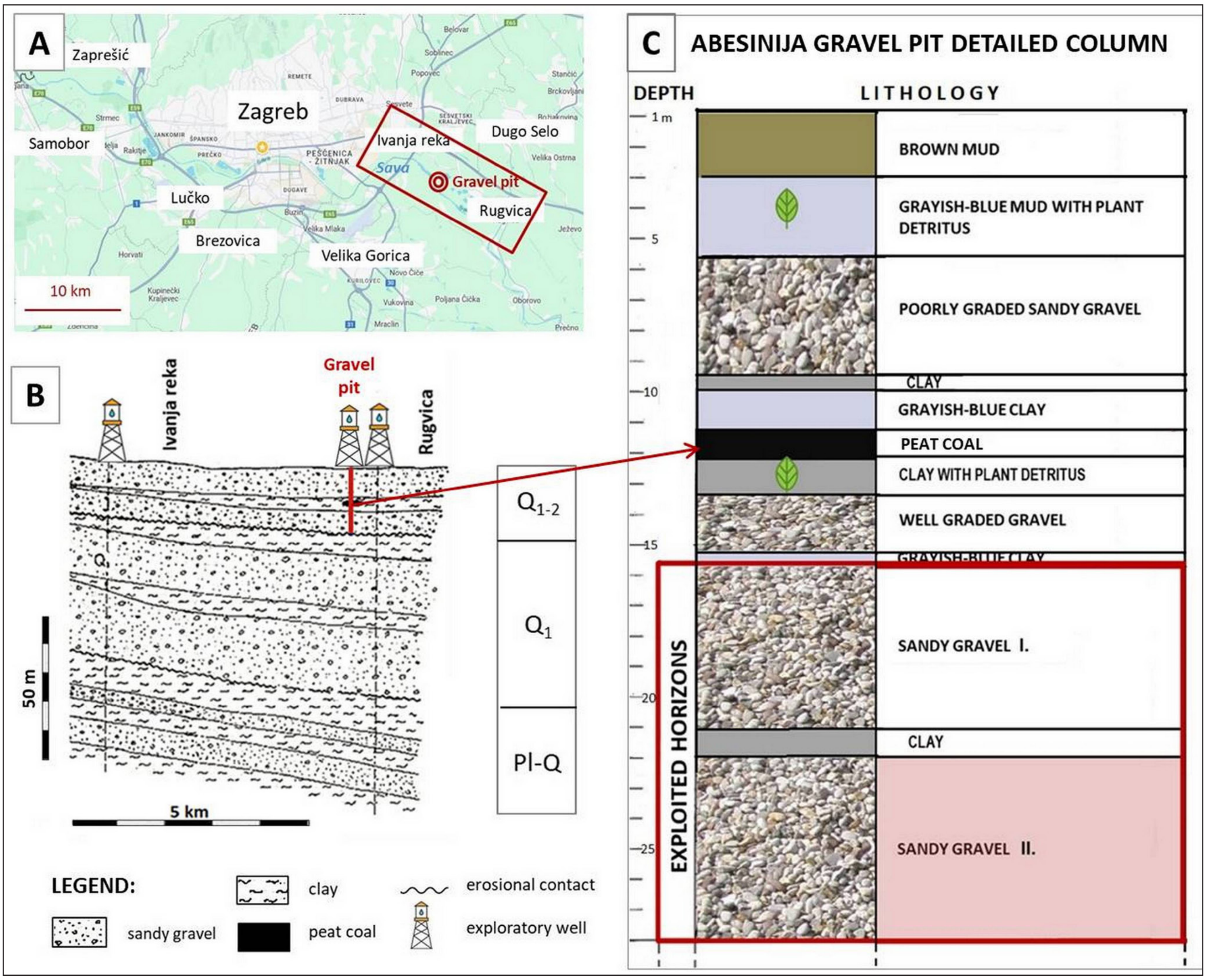


Fig. 2 - A) Position of the geological profile on the topographic map of Zagreb (Google Maps, 2024); B) geological profile through the clastic deposits between Ivanja Reka and Rugvica (after Čakarun et al. 1987; modified), with the position of Abesinija gravel pit bore-holes. It is sometimes hard to distinguish the Quaternary deposits from the Pliocene (Pl) clastic sequence, therefore this horizon is often described as of the Plio-Quaternary age. Pleistocene (Q_1) and Holocene (Q_2) horizons are dominantly composed of sandy, poorly sorted gravels. This horizon also comprises loess, peat, and swamp sediments, as well as fine-grained argillaceous silts and clays. Holocene deposits are also heterogeneous, with dominance of alluvial gravels and sands and, subordinately, silty clays; C) a detailed column of the Abesinija gravel pit (drawn after the archives of the Company IGM "Šljunčara Trstenik d.o.o."). Sampled horizon, Sandy gravel II. (from 22 to 28 m depth) is marked by pink colour. Black peat above the exploited horizons was taken for the carbon-14 dating and palynological analyses.

tuffs. The distribution and abundance point to a possible combination of local sources, together with distant Alpine pebble provenance.

Velić et al. (1999) were among the first to offer an insight into the deeper horizons, analysing the data from a 101 m deep borehole at the "Jakuševec" waste disposal site. They determined six lithological units of Middle-Late Pleistocene and Holocene ages, separated by erosional unconformities. Units are composed of gravels, sandy gravels, sands, silts, and clays. They distinguished a Holocene gravel horizon with predominantly carbonate clasts from an older, presumably Pleistocene horizon, which comprises a significant amount of siliciclastic rocks.

Gravels from the wider area of Trstenik, SE from Zagreb (Figs. 1B, 2A-B), have been surveyed and exploited by the Company IGM "Šljunčara Trstenik d.o.o." for almost half a century. The two most important sandy gravel horizons were unearthed after removing the surface dirt, clay and peat deposits and poorly sorted gravels (Fig. 2C).

Our research team studied the morphometric features and modal composition of pebbles from the Sandy gravel II. (Fig. 2C), using more

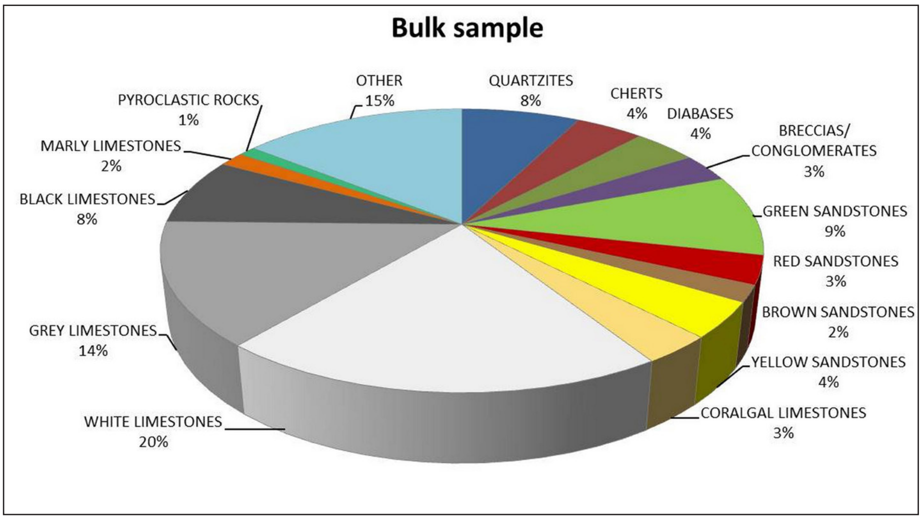


Fig. 3 - Modal composition of the Sandy gravel II. from the Abesinija gravel pit (after the data from Sremac et al. 2020).

than 2000 randomly collected clasts (Sremac et al. 2020) sized from 6.8 till 110.25 mm along the longest axis. We concluded that the investigated gravels are polymictic, with domination of carbonate pebbles (Fig. 3). Carbonate and sandstone pebbles are dominantly discoidal in shape, while the quartzite, chert and diabase clasts are often sharp-edged and generally smaller.

This study represents the continuation of the above mentioned research, with aim to reveal the provenance of pebbles and recognize the probable transport modes, based on the detailed lithological and paleontological features of the fossiliferous carbonate pebbles. Furthermore, we collected the peat coal from the overlying horizon (Fig. 2C), for radiometric and palynological analyses, to depict the climate conditions and the timing of depositional processes.

Materials and Methods

Gravels studied during this research were collected at the Abesinija gravel pit in the Rugvica area, located in the Sava River valley SE from Zagreb (Figs. 1B, 2A). Gravels were sampled from the excavated Sandy gravel II (Fig. 2C). Coordinates of the sampling site are 45°46'34.54''N; 16°09'38.92''E (Fig. 1B).

Materials for this research include 144 carbonate pebbles from the bulk sample collected during the previous study (Sremac et al. 2020) and 49 fossiliferous carbonate pebbles newly collected in the field. Carbonate pebbles were chosen among all other groups, because they comprise fossils important to recognize the age and provenance of these clasts. Two samples of the overlying peat coal (Fig. 2C) were taken for palynological and radiometric studies.

Fourty-five thin-sections were prepared from fossiliferous carbonate pebbles, at the Department of Geology, Faculty of Science in Zagreb. Palynological samples from the peat were prepared in the laboratory of the Croatian Geological Survey according to the standard techniques described in Moore et al. (1991). For palynofacies analyses slides were mounted in glycerine jelly, and the rest of the material was mixed in silicon oil for palynomorph analysis.

We used the Cannon COOLPIX P900 V1.5 camera for the field- and macrophotography (photo: R. Drempetić) and Canon EOS 1100D camera, associated with the Olympus SZX10 microscope, for photomicrographs of thin-sections prepared from the pebbles (University of Zagreb, Faculty of Science). Palynological analyses were performed using the Leica DM2500 microscope at ×50, ×100, ×200, ×400 and ×630 magnifications combined with the differential interference contrast (DIC). Photomicrographs were taken using a Leica MC190 HD camera connected to the Leica LAS EZ software. Sediment samples, organic residues and palynological slides are curated at the Croatian Geological Survey in Zagreb.

Numerical methods applied in this study represent an upgrade of analyses performed by Sremac et al. (2020). Flatness ratios (defined by equation $F = (a + b)/2c$, with a, b and c being the pebble axes) (after Cailleux 1952 and Müller 1967, from Barudžija et al. 2020) was calculated for each subcategory of carbonate pebbles. Furthermore, principal component analysis (PCA) (first introduced by Pearson 1901, developed by Hotelling 1933, from Jolliffe & Cadima 2016) was also applied. New data on the Compositional Data Analysis are summarized in Pawlowsky-Glahn & Buccianti (2011).

Two gross samples were tested using the abrasion tests in the Laboratory for Stone and Aggregate in Institut IGH, d.d. Micro-Deval (Md) analysis was applied to the wet samples from the fraction 10/14 mm for the lithological groups: (1) limestones, (2) magmatic rocks, (3) sandstones and (4) quartzites, applying HRN EN 1097-1:2011 standard. The first three lithological groups from the fraction 10/40 mm were additionally tested by the Los Angeles (HRN B.B8.045:1978 standard) test.

The two peat coal samples were exposed to the radiocarbon dating (LNA-PS 7.2/1 determination of 14C specific activity/age by LSC technique) in the Division of experimental physics, Laboratory for low-level radioactivities at the Ruđer Bošković Institute in Zagreb. A liquid scintillation counter Quantulus 1220 was used during these analyses. Calibrated dates were determined on the basis of dendrochronological calibration curve IntCal20 (Reimer et al. 2020) by the current version of the OxCal program (available at https://c14.arch.ox.ac.uk/).

Fig. 4 - Types of carbonate pebbles from the Abesinija gravel pit: A) grey limestones (V1); B) white limestones (V2); C) black limestones (V3); D) biocalcarenites (VM). Limestone pebbles (V1, V2 and V3) are well rounded, while the biocalcarenite pebbles (VM) occur in different shapes and sizes. Fossils can be seen by a bare eye in some pebbles.

Results

Facies, microfacies and paleontological analyses

During the initial research in the Abesinija gravel pit (Sremac et al. 2020) we recognized fossils in carbonate pebbles and divided them into the four main groups: grey limestones (V1), white limestones and dolostones (V2), black limestones (V3) and highly fossiliferous white biocalcarenites (VM) (Fig. 4).

Carbonate pebbles from groups V1, V2 and V3 are generally well sorted, rounded and discoidal in shape, while biocalcarenite pebbles (VM) appear in rather irregular shapes, in various sizes, they are not well rounded and their surface is sometimes a bit rough (Fig. 4). We decided to prepare the thin-sections from fossiliferous pebbles in order to recognize their age, microfacies and, when possible, determine the provenance.

Paleozoic pebbles. Dark grey, almost black pebbles are not very common in the gravel pit. We collected altogether 28 pebbles, some of them with fossil remnants (e.g., Fig. 5A) and chose 8 pebbles to prepare the thin-sections (Figs. 5B-J).

Pebble microfacies is usually wackestone to packstone (Figs. 5B, C), sometimes grainstone.

Foraminifera from the suborder Fusulinina prevail among the microfossils, including *Montiparus* sp. (Fig. 5C), *Zellia*? sp. (Fig. 5D), *Triticites umbonoplicatiformis* Leven & Davydov, 2001 (Fig. 5E), *Bradyina* sp. (Fig. 5F), *Deckerella* sp. (Fig. 5G) and *Lasiodiscus granifer* Reichel, 1946 (Fig. 5H). Echinoids remains (Fig. 5I) and phylloid algae (Fig. 5J) are also present.

Microfossil assemblage is typical for limestones of Late Carboniferous (Kasimovian) to Early Permian age of the Alpine sedimentary succession (e.g., Leven & Davydov 2001; Novak & Krainer 2022 and references therein; Ueno 2022).

Mesozoic pebbles. Vividly coloured sandstone pebbles (e.g., Fig. 6A) are abundant and easily recognizable in the field. They are probably derived from Triassic rocks, exposed in the upstream areas.

Green pyroclastic rocks (“pietra verde”), diabase pebbles and green sandstones deposited after the weathering of the diabase are also present, pointing to the Jurassic-Cretaceous age.

Numerous light grey and white, dominantly discoidal carbonate pebbles with smooth surfaces sometimes comprise visible microfossils. Among 117 collected carbonate pebbles (48 grey and 69 white) we chose 16 of them to prepare thirty thin sections.

One of the grey pebbles comprises the cross sections of the green alga *Diplopora* sp. (Chlorophyta: Dasycladales: Diploporaceae) (Fig. 6B). Middle Triassic age is therefore presumed for at least one part of the grey limestone pebbles.

White limestone/dolostone pebbles represent the most common group in the Abesinija grav-

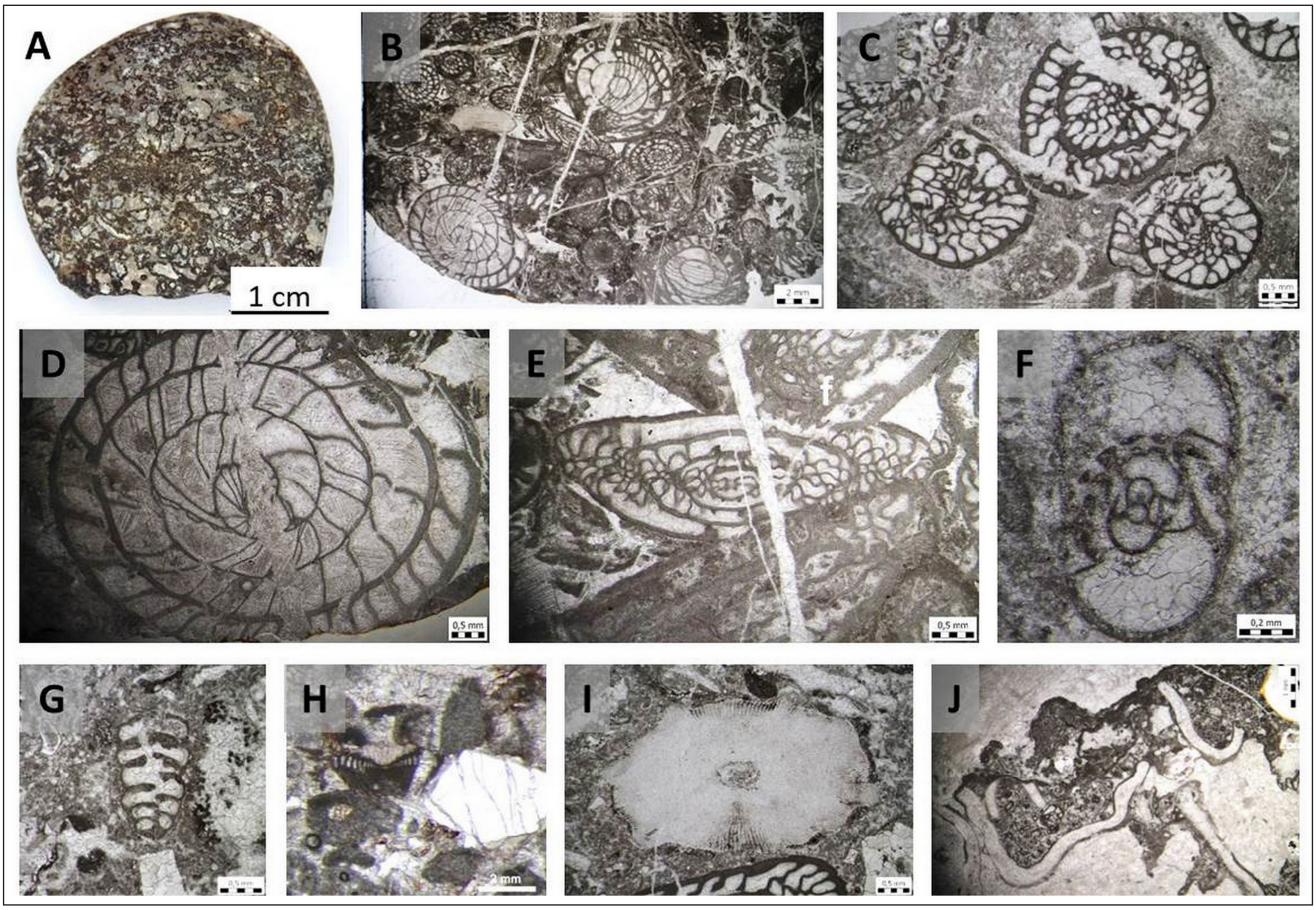


Fig. 5 - A) One of the pebbles with Paleozoic fossils; B) packstone with fusulinid foraminifera; C) wackestone with *Montiparus* sp. (Fusulinida: Triticitidae); D) pseudoschwagerinid foraminifera *Zellia* ? sp. (Fusulinida: Triticitidae); E) *Triticites umbonoplicatiformis* Leven & Davydov, 2001 (Fusulinida: Triticitidae); F) *Bradyina* sp. (Endothyrida: Bradyinidae); G) *Deckerella* sp. (Endothyrida: Palaeotextulariidae); H) *Lasiodiscus granifer* Reichel, 1946 (Archaediscida: Lasiodiscidae); I) cross section of echinoid spine (Echinodermata); J) phylloid algae (Chlorophyta: Bryopsidales: Halimedaceae).

el pit. Under the microscope, the following microfacies types could be distinguished: (1) radiolarite with thin shells, often described as "filaments" (Fig. 6C); (2) oolitic grainstone with brachiopods (Fig. 6D); peloid wackestone with crustacean coprolites (*Favreina* sp.), green alga *Lithocodium* and microproblematica *Thaumatoporella* (Figs. 6E, F).

Cenozoic pebbles. Powder-white and yellowish-white highly fossiliferous pebbles can be easily recognized in the field. They appear in a variety of shapes and sizes and their surface is variably smooth (Fig. 4D).

Coralline algae are the most common microfossils in these pebbles. Study of thin-sections revealed abundant microfossils. The most common in larger, less rounded clasts are coralline algae, genera *Spongites* (Rhodophyta: Corallinales: Spongitaceae) (Fig. 7A) and *Lithothamnion* (Rhodophyta: Corallinales: Hapalidiaceae) (Fig. 7B). Green algae from the family Halimedaceae occur sporadically (Fig. 7C). Red algae are often associated with bryozoans (Figs. 7D, E) and balanoid crustaceans (Fig. 7E).

Smaller and better rounded highly fossiliferous pebbles also comprise red algae as bioconstructors, producing the macroids in association with *Polystrata alba* (Pfender) (Denizot 1968), (Rhodophyta: Peysonellaceae) and acervulinid foraminifera. In such deposits rotaliid foraminifera also occur (Figs. 7F, G).

Palynomorphs from the peat coal. Two samples of the peat coal from the neighbouring gravel pits: Abesinija and Trstenik were studied. The sample from Abesinija gravel pit did not comprise palynomorphs, but the peat from Trstenik was suitable for further analyses.

Palynofacies of the Trstenik sample is dominated by phytoclasts, mostly degraded non-woody

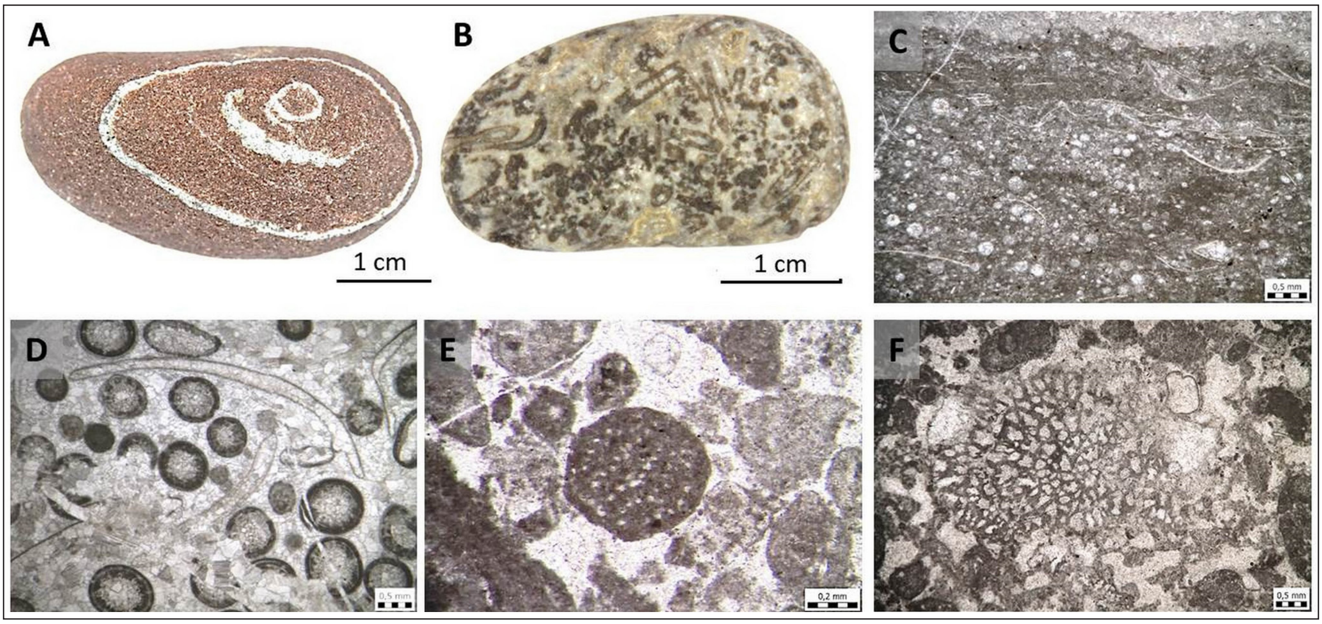


Fig. 6 - A, B - Common Lower to Middle Triassic pebbles in the Abesinija gravel pit: A) red sandstone; B) Middle Triassic grainstone with *Diplopora* sp. (Chlorophyta: Dasycladales: Diploporaceae); C-F - Photomicrographs of thin sections comprising fossils: C) radiolarite with "filaments"; D) oolitic grainstone with brachiopods; E) peloid wackestone with *Favreina* sp. (ichnofamily Favreinidae; crustacean coprolite); F) peloid wackestone with *Lithocodium* (Chlorophyta: Ulotrichales?: Ulvophyceae) and *Thaumatoporella* sp. (Incertae sedis: Thaumatoporellaceae).

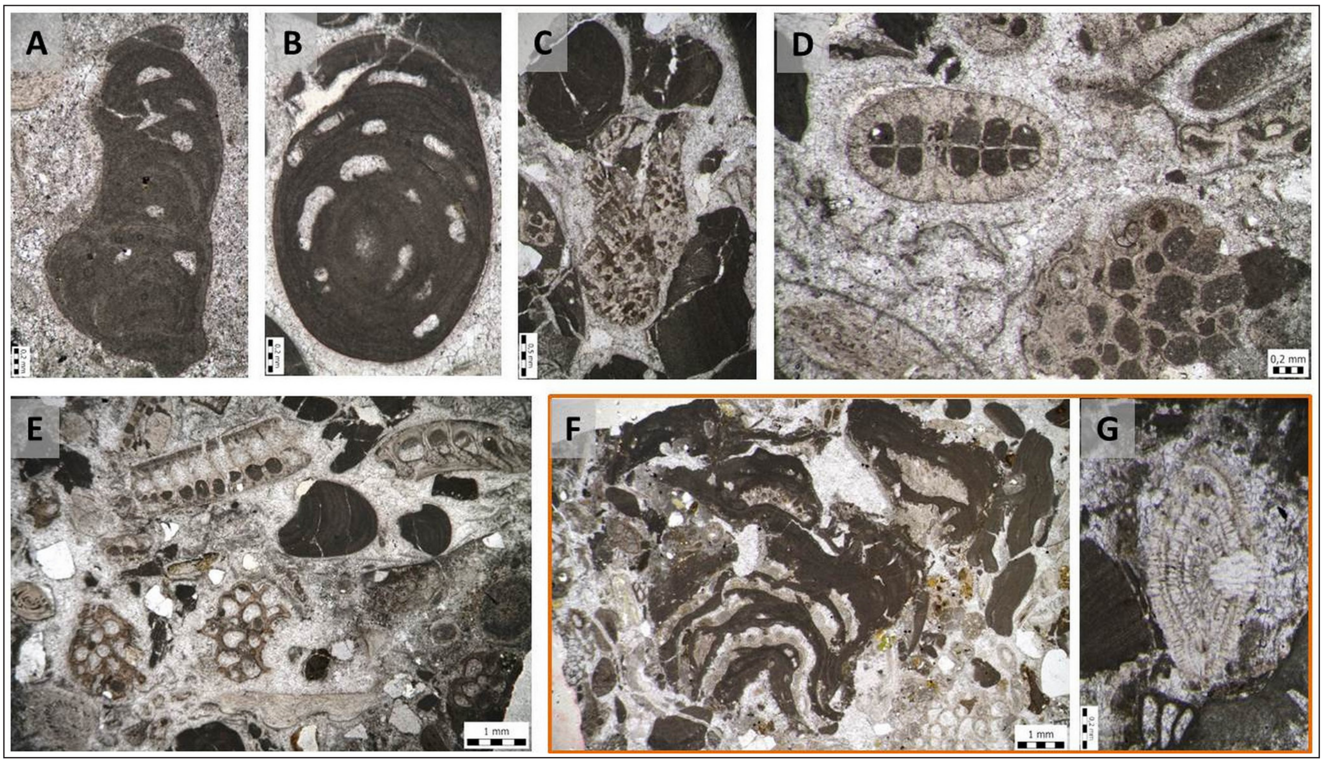


Fig. 7 - A-E - Fossils from the Neogene pebbles: A) red alga *Spongites* sp.; B) red alga *Lithothamnion crispatum* Hauck, 1878; C) green alga from the Halimedaceae family; D) bryozoans; E) bryozoans and cirripedes in wackestone to grainstone; F-G - Fossils from the Paleogene pebbles: F) a combined peysonellae-corallinacean macroid; G) large benthic rotaliid foraminifera.

plant debris (Fig. 8), indicating pronounced input of the terrestrial organic material (Tyson 1995). Domination of transformed particles points to high plant-derived content (Sebag et al. 2006).

Palynomorph concentration is calculated to 30985 palynomorphs per gram (Tab. 1).

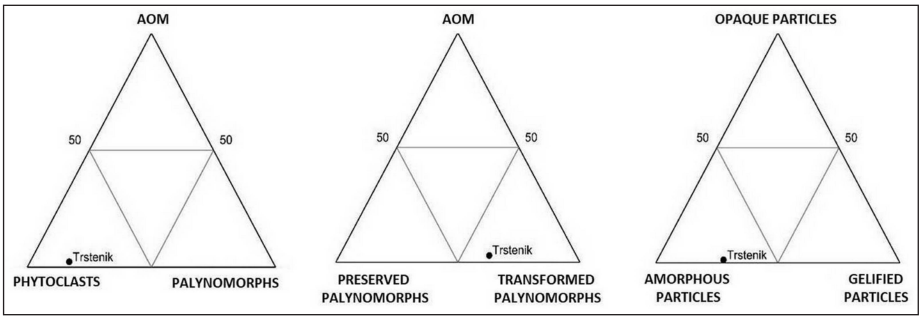


Fig. 8 - Palynofacies ternary diagrams presenting the relationships among the amorphous OM-phytoclasts-palynomorphs, amorphous OM/preserved phytoclasts/transformed phytoclasts and opaque/amorphous/gelified particles.

TRSTENIK																								
GENUS	*Juniperus*	*Pinus*	*Picea*	*Buxus*	*Quercus*	Cyperaceae	Poaceae	*Artemisia*	Asteraceae	*Filipendula*	*Knautia*	*Sphagnum*	monolete fern spore	*Sigmopollis*	*Gloeotrichia*	*Mougeotia*	Fungi	NPP	undiff.	ex. *Lycopodium*	**WEIGHT (g)**	**Ls18584**	**PALYNOMORPHS SUM**	**CONCENTRATION**
Grains	48	201	3	1	2	1	1	3	4	2	1	2	1	16	71	5	2	2	13	16	21	2	**379**	**30985**

Tab. 1 - Number of palynomorphs grains and their concentration in the peat sample Trstenik.

Numerical analyses of carbonate pebbles

After the micropaleontological analyses, it become clear that the pebbles originate from different areas, and probably underwent different shaping and transport processes. In order to find the additional evidence for such interpretations, authors decided to apply the numerical methods on different groups of carbonate pebbles.

Flatness ratio. Flatness ratio was used as a proxy for the mode of transport of pebbles by several authors (Cailleux 1952 and Müller 1967, from Barudžija et al. 2020), although today it is known to mainly depend on the pebble lithology (e.g. in Pawlowsky-Glahn & Buccianti 2011). During this study, authors calculated the flatness ratio for the carbonate pebbles with different fossils (white, grey,

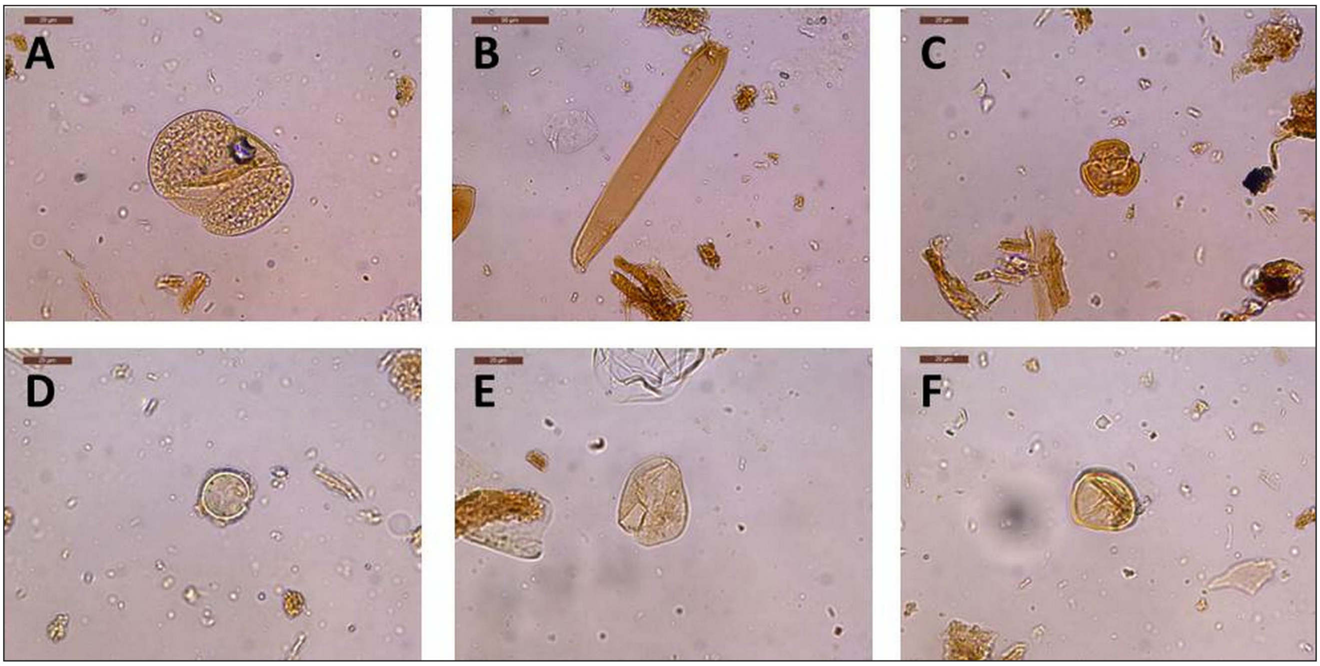


Fig. 9 - Palynomorphs from the peat sample Trstenik: A) *Pinus*; B) *Gloeotrichia*; C) *Artemisia*; D) *Sigmopollis*; E) *Juniperus*; F) *Sphagnum*. Scale bar is 20 μm, except on B) where is 50 μm.

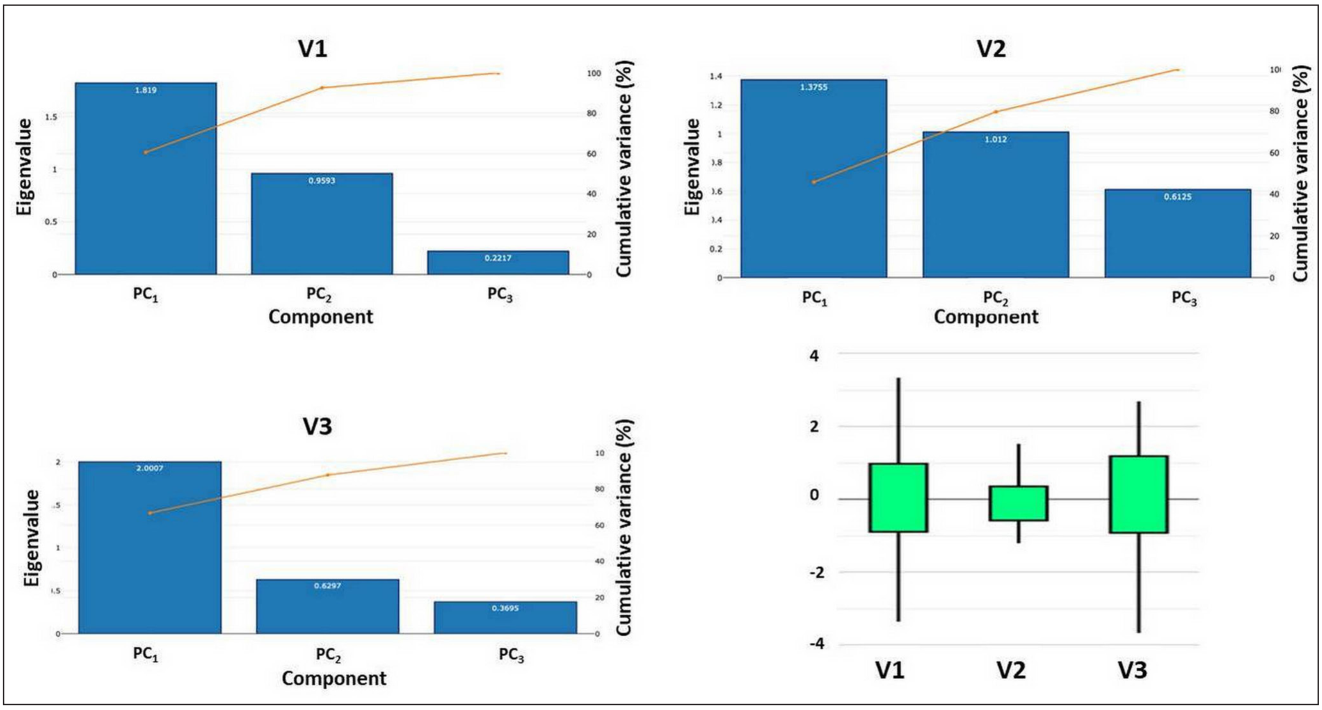


Fig. 10 - Results of PCA analyses for the groups of carbonate pebbles V1, V2 and V3 (grey, white, and black carbonate pebbles).

and black carbonate rocks and highly fossiliferous calcarenites) (raw data available in Supplement 1), but the analysis has shown only the slight differences between the pebble groups. Grey limestones (V1), altogether 43 pebbles, have the highest average Flatness ratio (1.977506). The most common group, white carbonate pebbles (V2, 69 pieces), show the average Flatness ratio of 1.9473039. Black carbonate pebbles (V3, 28 pieces) measure 1.8955713; while the less rounded, variably large biocalcarenite pebbles (VM, 20 pieces) have the lowest values of the Flatness ratio, 1.816849.

Principal Component Analysis (PCA). PCA analysis was applied to the limestone groups V1, V2 and V3 (raw data available in Supplement 1). For these groups of pebbles we presumed that they might originate from multiple provenance areas and/or had different depositional and transportation history. PCA as a tool creates artificial values that were created for each sampling site as single variable derived from original x, y, z values of grain axes (dimensions). Such artificial value showed similar variances and averages (Fig. 10) as well as the most follow normal distribution for all 3 sites. Consequently, specific PCA results did not firm assumption that source areas were (significantly) different for each group of samples, based on their dimensions. In details, the PC1 component in all 3 cases explains between 46 and 67%, as dominant PCA variable. In addition, two-tailed t-test with pooled variance had been calculated for all three pairs: V1-V2, V1-V3, V2-V3 retrospectively, with H_0 hypothesis of similarity of sample's grain as result of similar source area(s). Since p-value > α, H_0 cannot be rejected. Additionally, the average of Group 1's population is assumed to be equal to the average of Group 2's population in all 3 calculations.

Abrasion/toughness tests. Results of the Los Angeles test provided the coefficients for limestones and sandstones (LA=20), while the coefficient for the magmatic rocks is LA=17. Micro-Deval tests were performed for four pebble categories: limestones (Md=8), sandstones (Md=20), magmatic rocks (Md=19) and quartzites (Md=5) (Fig. 11).

Age of the overlying peat horizon

The age of the two peat coal samples, one from the Abesinija gravel pit (laboratory identifica-

LAB. ID	TESTING ITEM	^{14}C AGE (BP)	CALIBRATED DATE (cal BP)	PROBABILITY
Z-8614 / B1939	Lignite from Abesinija (AB)	28720 ± 360	33661 – 32774 cal BP	51,40%
			32598 – 32259 cal BP	16,80%
Z-8615 / B1940	Lignite from Trstenik (TR)	26470 ± 260	30980 – 30431 cal BP	68,30%

Tab. 2 - Results of radiocarbon dating of the two peat samples performed in the Division of experimental physics, Laboratory for low-level radioactivities at the Ruđer Bošković Institute in Zagreb.

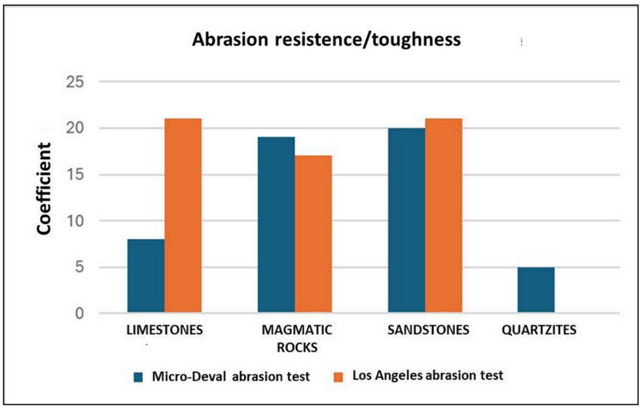


Fig. 11 - Comparison of the abrasion tests results obtained by Micro-Deval and Los Angeles methods.

tion Z-8614/B1939) and the other from the neighbouring Trstenik gravel pit (Z-8615/B1940), was obtained from radiocarbon dating (Tab. 2). The conventional ^{14}C age of the sample from Abesinija was 28 720 ± 360 BP, while the value obtained for the Trstenik sample is 26 470 ± 260 BP (before 1950).

Calibrated date for the Abesinija peat is: 33661 – 32774 cal BP (51.4%), 32598 – 32259 cal BP (16.8%), and for the Trstenik peat 30980 – 30431 cal BP (68.3%) (Tab.2, Fig. 12). Advanced calibration curves present the more precise age (with probability of 95.4%) of Abesinija peat to 34046 – 31956 cal BP and Trstenik peat to 31109 – 30193 cal BP (Fig. 13).

Discussion

Pebble provenance and transport modes

Most of the authors who studied the youngest, Holocene gravels of the Sava floodplain, concluded that they originate from local and distal source areas (e.g., Marić et al. 1954; Crnković & Bušić 1970; Barudžija et al. 2020). It was generally considered that the Alps are the source of smaller, chert and quartzite pebbles and sandy matrix, while the larger carbonate and sandstone pebbles are derived from the Medvednica Mt. and Žumberak/Samobor Hills. Studying a borehole at the Jakuševec waste disposal site, Velić et al. (1999) based the stratigraphic division of Quaternary clastic deposits on their lithology. They presumed that the Pleistocene sediments comprise a significant amount of siliciclastic component, which was partly derived from the Alps, while the Holocene deposits are dominantly composed of the carbonate pebbles from the local sources.

"Šljunčara Trstenik d.o.o." company archives comprise the data which show that carbonate and

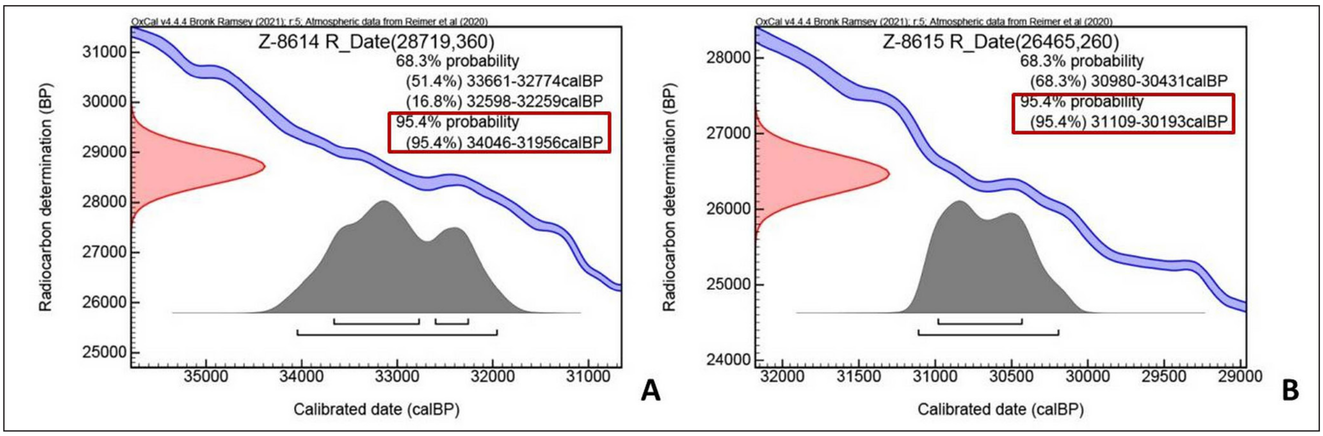


Fig. 12 - Advanced calibration curves for absolute ages of peat samples: A) Abesinija; B) Trstenik. The most probable age data (95.4%) are presented within red rectangles.

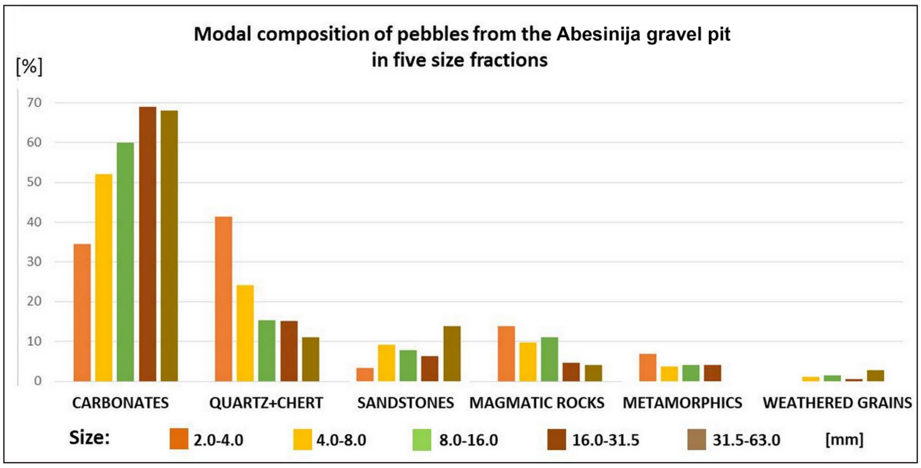


Fig. 13 - Distribution of pebbles from the bulk sample of the Sandy gravel II from the Abesinija gravel pit by size, based upon the archive data of the Company "Šljunčara Trstenik d.o.o.". Size categories are not standardly used, but they clearly reflect the abundance of different lithological categories according to their size.

sandstone clasts in Sandy gravel horizons I. and II. are more abundant in coarse fractions, while the siliceous pebbles (quartz, chert) and magmatic rocks are more common in finer fractions (Fig. 13). Such results point to the probable proximity of the carbonate and sandstone source areas, while the quartz/chert clasts were probably transported to longer distances.

Similar results were obtained in our previous study (Sremac et al. 2020). We counted a high percentage (ca. 45%) of carbonate clasts in the bulk sample of Sandy gravel II. Among the carbonate clasts, grey limestones (V1) counts 14%, white limestones (V2) 20%, black bioclastic limestones (V3) 8% and yellowish-white bioclastic limestones (VM) 3% of all pebbles. In the fine fraction separated by the Company (<5 mm) the values are smaller: V1 – 6%; V2 – 18%, V3- and VM 3%, supporting the presumption that some groups of the carbonate pebbles (particularly the grey limestones, V1) were derived from proximal sources.

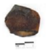
The next step of our research was the quest for the provenance of carbonate pebbles, based upon the microfossils.

Paleozoic (Rattendorf Group) highly fossiliferous pebbles were the biggest enigma, because today they do not outcrop in the local upstream areas.

Genus *Montiparus* occurs in the Kasimovian of the Carnic Alps and Karavanks (Krainer & Davydov 1998; Forke 2002). Genus *Triticites* was reported from the Kasimovian and Lower Permian of the Southern Alps (Carnic Alps and Karavanks) (Krainer & Davydov 1998; Forke 2002; Novak 2007; Novak & Krainer 2022 and references therein). Genus *Zellia* occurs from the Asselian-Sakmarian (Ramovš & Kochansky-Devidé 1979; Vachard & Krainer 2001a) up to the Artinskian of the Carnic Alps (Krainer & Davydov 1998). Genus *Pseudoschwagerina* occurs in the Asselian and Sakmarian of the Carnic Alps (Forke 2002; Novak & Krainer 2022). The genera *Bradyina* and *Deckerella* are common and occur in Carboniferous and Permian deposits all over the world. They are particularly common in the Upper Carboniferous of the Carnic Alps (Vachard & Krainer 2001b) and uppermost Carboniferous deposits of Slovenia (Novak & Krainer 2022; Ramovš and Kochansky-Devidé 1979, 1981). Representatives of the Lasiodiscidae family occur throughout the Upper Carboniferous (e.g. Ramovš & Kochansky-Devidé 1979; Vachard & Krainer 2001ba), but are also present in the Permian deposits of the Carnic Alps (Schaffshauser et al. 2015). The genera *Bradyina*, *Deckerella* and *Lasiodiscus* were also determined from the Middle Permian Beds from Slovenia (Flügel et al. 1984), while the Permian species *Lasiodiscus granifer* Reichel, 1946 (Reichel 1946), was not previously recorded from the Sava River upstream areas.

All these data mark the Karavanks, situated along the Slovenian/Austrian border, and the upper Sava flow (Source area 1 in Fig. 14A) as the most probable source of the Paleozoic pebbles, which means that some of the pebbles could have been transported more than 180 km towards the gravel pit. Besides the Sava, the rivers of its watershed (e.g., Tržiška and Kamniška Bistrica) played the important role in transporting the Paleozoic pebbles towards their recent position (Fig. 14A). At least part of the angular, small quartz/chert clasts were also derived from the Alps.

Late Paleozoic rocks also crop out in Central Slovenia, in the vicinity of Ljubljana (Source area

<table>
<tr><th rowspan="2">LITHOLOGY</th><th rowspan="2">PHOTO</th><th rowspan="2">AMOUNT</th><th colspan="3">AGE</th><th colspan="5">PROVENANCE</th></tr>
<tr><th>Pz</th><th>Mz</th><th>Kz</th><th>NW SLO</th><th>CENT SLO</th><th>S SLO</th><th>SAMOB</th><th>MEDV</th></tr>
<tr><td>GREY LIMESTONE (V1)</td><td></td><td>14%</td><td></td><td>T</td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td><td bgcolor="#c0c0c0"></td><td bgcolor="#c0c0c0"></td></tr>
<tr><td>WHITE LIMESTONE (V2)</td><td></td><td>20%</td><td></td><td>J-K</td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td><td bgcolor="#c0c0c0"></td><td bgcolor="#c0c0c0"></td></tr>
<tr><td>BLACK LIMESTONE (V3)</td><td></td><td>8%</td><td>C-P</td><td></td><td></td><td bgcolor="#c0c0c0"></td><td bgcolor="#c0c0c0"></td><td></td><td></td><td></td></tr>
<tr><td>BIOCALCARENITE (VM)</td><td></td><td>3%</td><td></td><td></td><td>M</td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td><td bgcolor="#c0c0c0"></td></tr>
<tr><td>SANDSTONE</td><td></td><td>18%</td><td></td><td>T,J,K</td><td>M</td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td><td bgcolor="#c0c0c0"></td></tr>
<tr><td>BRECCIA/CONGLOMERATE</td><td></td><td>3%</td><td></td><td>J,K,M</td><td></td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td><td bgcolor="#c0c0c0"></td></tr>
<tr><td>CHERT/QUARTZITE</td><td></td><td>12%</td><td>Pz</td><td></td><td></td><td bgcolor="#c0c0c0"></td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td></tr>
<tr><td>DIABASE/PYROCLASTIC</td><td></td><td>5%</td><td></td><td>J-K</td><td></td><td></td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td></tr>
</table>

Tab. 3 - Age and the main provenances (from NW to SE) of the studied pebbles: NW SLO = Northern Slovenia; CENT SLO = Central Slovenia; S SLO = Southern Slovenia; SAMOB = Samobor Hills; MEDV= Medvednica Mt.

2 in Fig. 14A) (e.g., Kolar-Jurkovšek & Jurkovšek 2012 and references therein) and, therefore, some of the Carboniferous pebbles might originate from that region.

Mesozoic pebbles might have come from the different source regions in Slovenia and Croatia (Tab. 3; Fig. 14A – source area 3, Fig. 15 – source area Medvednica Mt.).

Radiolarites with filaments occur in Croatia in the Triassic, as well as in the Middle Jurassic deposits. The closest findings are on NW slopes of the Medvednica Mt. (Fig. 15) and in Žumberak and Samobor Hills (Fig. 16) (Halamić & Goričan 1995; Halamić et al. 1999, 2001; Dragičević & Velić 2002).

Oolitic grainstone occurs sporadically along the NE margin of the Adriatic Carbonate Platform, including some localities in Žumberak-Samobor area (e.g., Bucković et al. 2001; Dragičević & Velić 2002). It marks the high-energy depositional environment and can be found in deposits of different age.

Favreinid coprolites occur since the Triassic, pointing to a lagoonal environment. Pelletal-bioclastic wackestone was described from the Sošice locality in Žumberačka Gora Hills, W from Zagreb (e.g. Bucković 2006) and from SE Slovenia (Fig. 14A – source area 3). Genus *Favreina* was detected in the Triassic to Lower Jurassic (Bukovac & Sokač 1989) and Middle Jurassic lagoonal deposits (Dozet & Šribar 1998). Medvednica is also a source of the Mesozoic sandstone, diabase and pyroclastic pebbles (Fig. 15).

Pebbles of Paleogene age, with red alga *Polystrata alba*, outcrop at NW slopes of the Mt. Medvednica (e.g., Šikić et al. 1972 a, b; Gušić & Babić 1973; Halamić & Goričan 1995; Halamić et al. 1999; Slovenec & Pamić 2002) (Tab. 3; Fig. 15).

Whitish, irregularly shaped biocalcarenite pebbles comprise the abundant red algae, which, together with bryozoans, represent the common bioconstructors in the Middle Miocene deposits of the marginal areas of the Paratethys Sea, including northern Croatia (e.g., Kochansky 1944; Vrsaljko et al. 2006; Piller et al. 2007; Harzhauser & Piller 2007; Basso et al. 2008; Martinuš et al. 2013; Posedi et al. 2014; Sremac et al. 2016, 2018; Pavelić & Kovačić 2018). The most common occurrence of bryozoan-rhodalgal facies is in the Langhian and early Serravallian (Badenian in local stratigraphy). Such Miocene shallow marine deposits occur upstream the research area in a rather narrow belt around the Medvednica Mt. and Žumberak-Samobor Hills, therefore revealing the probable provenance of these pebbles (Tab. 3; Figs. 15, 16).

Pebbles from the NW slopes of the Medvednica Mt. near Zagreb (Tab. 3, Fig. 15), were transported by the River Krapina and its tributaries (Fig. 14A) towards the Sava River. On the SE slopes pebbles were probably transported by streams (Fig. 15 - blue arrows), some of which still exist (e.g., creeks Dolje, Vrapčak, Črnomerec, Bliznec, Trnava).

Summarizing the results we can conclude that the amount and diversity of pebbles increases with the proximity of the source regions (Tab. 3).

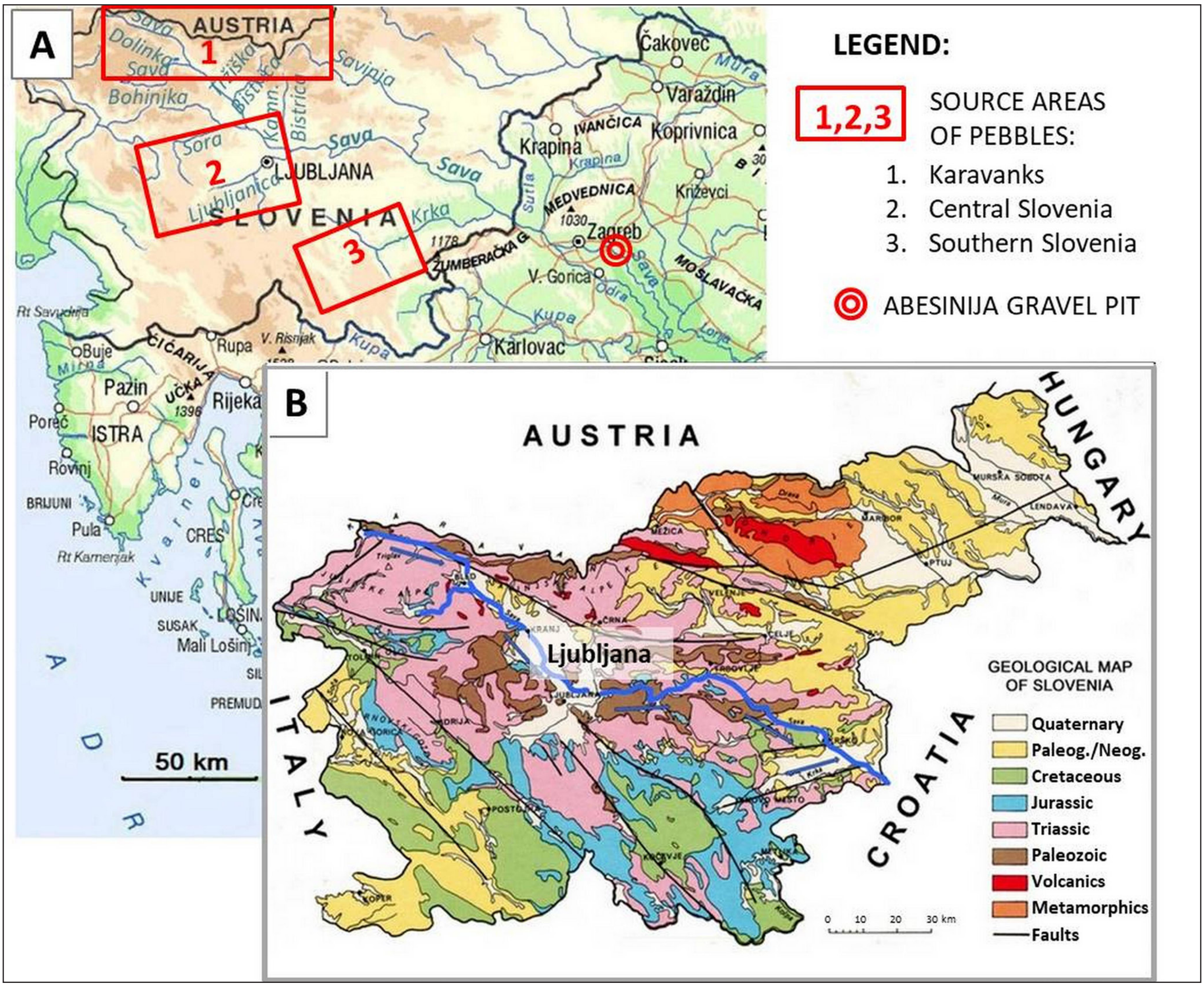


Fig. 14 - A) Geographic map of Slovenia and a part of Croatia (https://croatia.eu/index.php?view=article&id=7&lang=2), modified by adding the names of the Slovenian rivers involved in the pebble transport, with the position of probable pebble source areas and the position of the Abesinija gravel pit; B) a simplified geological map of Slovenia (Basic Geological Map of Slovenia) modified, with emphasized pebble routes (blue arrows).

Scarce and small Palaeozoic pebbles (V3) had the longest transport route, remaining a bit enigmatic. If they were transported all the way from the Alps by the Sava River and its tributaries, the differences in size from the local white and grey carbonate pebbles would be more expressed. Theoretically, they could have been partly transported by the Sava glacier, which extended to the Central Slovenia during some stadials (Fig. 16), as it was presumed by Jamšek Rupnik et al. (2020) for the Last Glacial Maximum (LGM).

Numerical analyses

During our research, numerical methods, contrary to the paleontological analyses, did not yield clear results.

Flatness ratio measured for the limestone pebbles with different fossils pointed only to some minor differences (calculated values: V1:1.977506, V2:1.9473039; V3:1.8955713; VM: 1.816849). Nevertheless, presenting the calculated flatness ratios (Supplement 1) for each pebble on histograms with traditional flatness categories (Fig. 17), some differences among the limestone pebble groups are evident, particularly for the Palaeozoic and Triassic pebbles (V1,V3).

Results of the PCA analyses also did not clearly confirm the presumption that source areas were (significantly) different for each group of samples, based on their dimensions. In details, the PC1 component in all 3 cases explains between 46

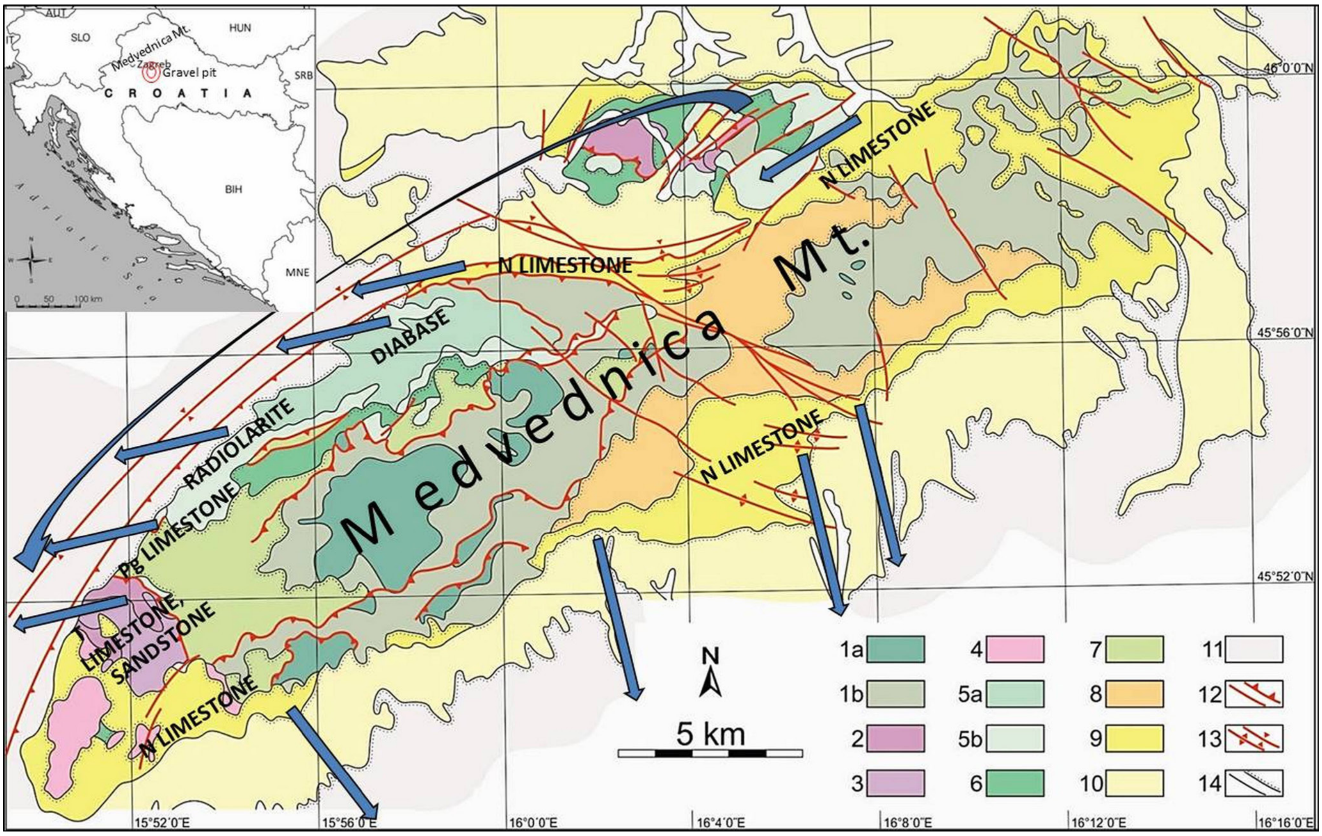


Fig. 15 - Geological map of the Medvednica Mt. (after Tomljenović 2002) with marked probable source areas and transport routes for several lithological groups of pebbles.
Legend: 1a – Silurian to Upper Triassic low-grade metamorphic complex (greenschists); 1b – Silurian to Upper Triassic parametamorphic deposits; 2 – Lower Triassic sandstones, siltites, shales, ooid limestones and calcarenites; 3 – Middle Triassic dolomites with limestone, shale, chert and pyroclastic intercalations; 4 – Upper Triassic stromatolitic dolomites; 5a – Mesozoic ophiolitic complex volcanics (basalts, diabases, gabbros and peridotites); 5b – Mesozoic ophiolitic complex sedimentary rocks; 6 – Aptian to Cenomanian marine clastic deposits, limestones and marls; 7 – Uppermost Cretaceous to Paleocene fluvial and marine clastic and carbonate deposits; 8 – Lower Miocene fluvial deposits with coal intercalations; 9 – Middle Miocene shallow-marine (Badenian), and brackish sedimentary rocks (Sarmatian); 10 – Upper Miocene brackish deposits (Pontian); 11 – Pliocene and younger gravels, sands and clays; 12 – faults; 13 – fold axis; 14 – normal and transgressive stratigraphic contacts.

and 67%, as dominant PCA variable. In addition, two-tailed t-test with pooled variance had been calculated for all three pairs: V1-V2, V1-V3, V2-V3 retrospectively, with H_0 hypothesis of similarity of sample's grain as a result of similar source area(s). Since p-value > α, H_0 cannot be rejected. Additionally, the average of Group 1's population is assumed to be equal to the average of Group 2's population in all 3 calculations.

Even more unclear results were obtained by the abrasion tests. Limestones and sandstones analysed by LA method showed similar values, while the Micro-Deval tests yielded similar values for sandstones and magmatic rocks. Diagenetic, and tectonic processes (causing the formation of microfractures and cracks in pebbles) could partly affect the toughness result, but not in such amount, as presented in the abrasion test results.

Unclear or even paradoxical numerical results point to the complex history of pebbles, some of which underwent multiple cycles of transport and redeposition. Although we discovered their probable source areas, these pebbles could also originate from older beach conglomerates, e.g., in the base of the multiple Cenozoic transgressive/regressive cycles of the Paratethys Sea, as described from the Medvednica Mt. (e.g. Pavelić & Kovačić 2018; Sremac et al. 2022 and references therein).

Age of the clastic succession

After the deposition of gravels, a paleo-lake was established in the research area, slightly turning the alluvial environment into the marsh and peat. Therefore, the swamp processes influenced the final phases of clastic deposition. Such successions could repeatedly occur during the warming periods,

Fig. 16 - A summary of the source areas and simplified presumed pebble transport routes (blue-green arrows) along the Sava River and its tributaries, towards the Abesinija gravel pit. Map source: Wikimedia Commons. Presumed ice extent drawn partly after Jamšek Rupnik et al. (2020).

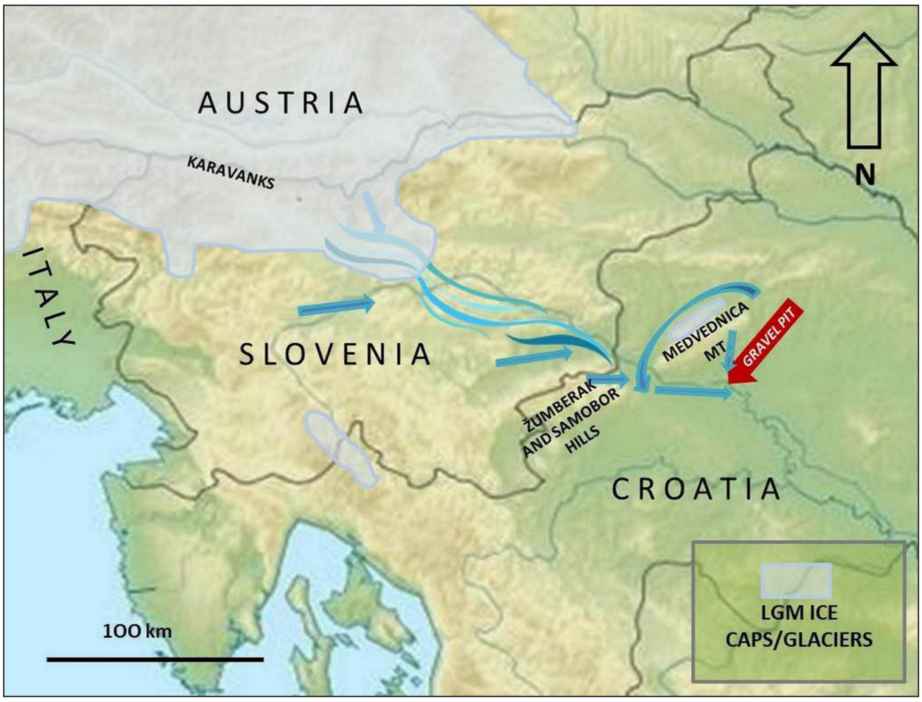
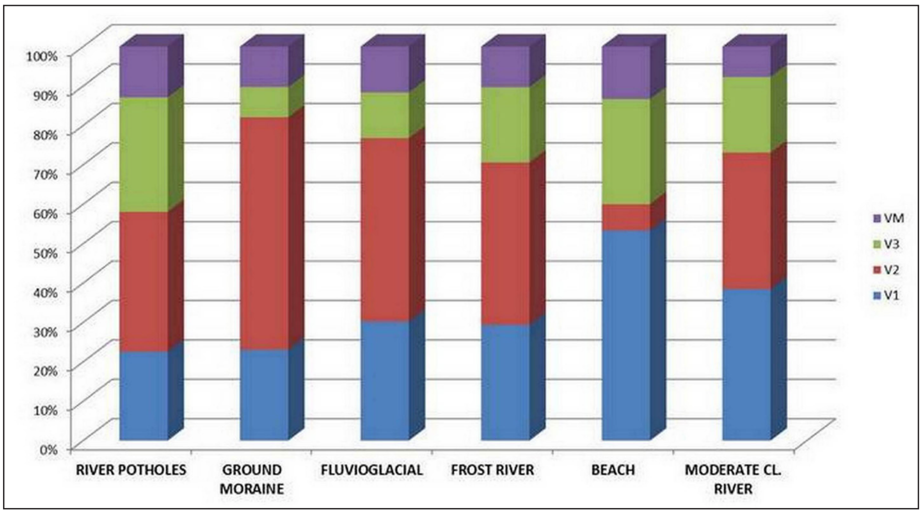


Fig. 17 - Distribution of the possible depositional environments of the studied carbonate pebble groups V1 (grey), V2 (white), V3 (black) and VM (biocalcarenite pebbles) from the Abesinija gravel pit, according to the traditional interpretations of the Flatness ratio. Raw data are available in the Supplement 1.



being temporarily interrupted by terrestrial phases, as was already noted by Velić et al. (1999).

During the preparation of technical documentation for the neighbouring exploitation fields Abesinija and Trstenik by the maintaining company, it was presumed that the older part of the clastic succession, including the exploited gravels, belongs to the Pleistocene, and the younger part, above the clay and peat layer, to the Holocene.

Numerical ages obtained during this study, by carbon−14 dating (Tab. 2) of the two peat samples from the horizon overlying the sandy gravels (Fig. 2C) dated the peat coals to the Upper Pleistocene, Abesinija peat to 34046 – 31956 and neighbouring Trstenik peat to 31109 – 30193 years before present, placing the peat formation into the two warming episodes (equivalents of the Greenland interstadials 5 and 6) (positions of A and T in Fig. 18). That means that the deposition of gravels might have taken place during the interstadials 6, or, more likely, 7 (Fig. 18), because, during the stadials, no alluvial deposition occurred in this area (Velić et al. 1999).

Palynoflora from the Trstenik peat sample

After the flooding episodes shallow swamp vegetation and an open juniper-dominated vegetation characterized a landscape in the surroundings of Abesinija and Trstenik, while trees were mainly pine. Mire vegetation is marked by *Sphagnum*. The drier areas hosted a steppe vegetation, dominat-

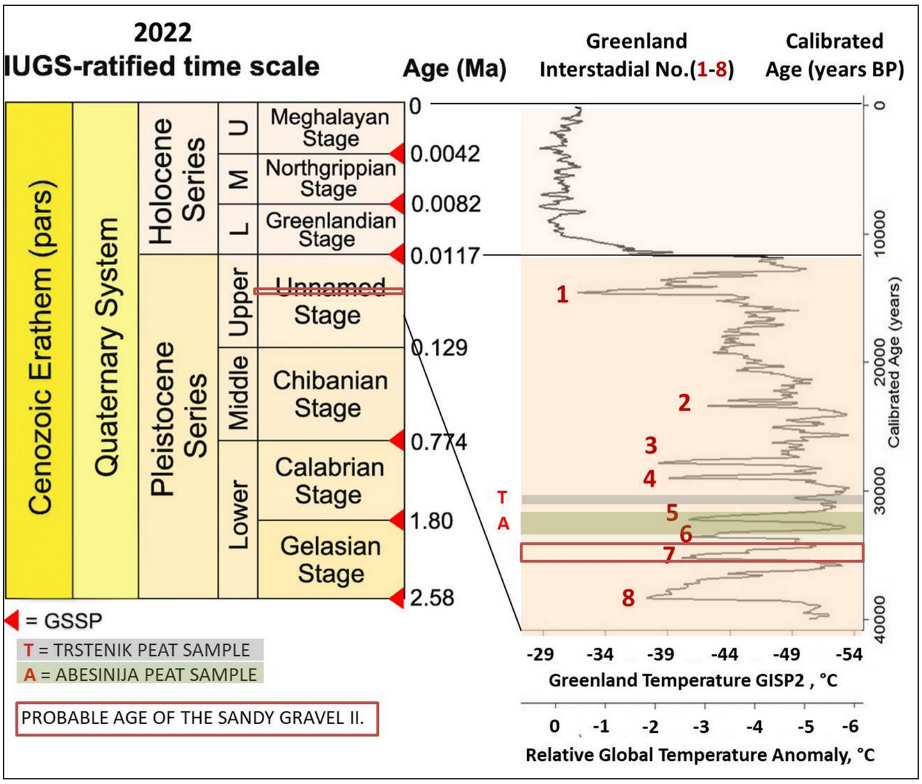


Fig. 18 - IUGS-ratified time scale (Cohen et al. 2013) and global temperature curve with warming episodes (Greenland Interstadials 1-8) (Martin 2020). Red letters mark the age of the overlying peat samples (A for the Abesinija and T for the Trstenik sample), determined by radiometric methods, with probability of 95.4%. Probable age of the Sandy Gravel II is marked by a red rectangle.

ed by sagebrush (*Artemisia*) accompanied by other herbaceous species (Asteraceae, meadowsweet *Filipendula*). Very rare occurrence of *Quercus* may indicate the local presence of isolated trees (potential refuge areas for temperate trees), or a distant source.

Aridification interval (stadial) is characterized by a peat-bog installation, marked by *Sphagnum,* while wet interval (interstadial) is characterized by a lacustrine phytoplanktonic production and the occurrence of higher plants on the land (Sebag et al. 2006). During that period *Gloeotrichia* colonies, known as nitrogen fixers, created more favourable conditions for aquatic plants to colonize the swampy areas. After that, *Sigmopollis* appeared associated with eutrophic to mesotrophic open waters (Van Geel et al. 1983). A similar, but younger succession was described from the Fimon site, northern Italy, at around 27.0 ± 0.3 ka (Pini et al. 2022).

Conclusions

- Sandy gravels exploited in the Abesinija gravel pit comprise a high amount of carbonate pebbles (up to 45% of the bulk sample).
- Microfossil analyses indicate the age of pebbles from the Carboniferous to the Neogene (Middle Miocene).
- Pebbles were derived from the distant Alps (Karavanks), central and southern Slovenia and from the local sources - Medvednica Mt. and Žumberak-Samobor Hills.
- Local carbonate areas played much more important role in deriving the coarse clastic material than previously considered, not only in the Holocene, but also in the Late Pleistocene.
- Mathematical methods were not helpful enough in distinguishing the different pebble sources, due to the complex pebble history and possible redeposition.
- After the deposition of gravels, swamps were formed in the Sava flood-plain and the surrounding areas were covered by pine forests.
- The age of the overlying peat coals place the deposition of the studied clastic sequence into the Late Pleistocene (possibly the equivalents of the Greenland Interstadials 6 or 7).

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