RGNZ/MGPB

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
DOI: 10.17794/rgn.2025.4.13

Original scientific paper

Stratigraphic Age and Morphometric Features of Upper Pleistocene Flow Till Pebbles from the Papuča Gravel Pit (Gospić, Croatia)

Josipa Velić[1*], **Ivo Velić**[2]

[1] *University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10000 Zagreb, Croatia;*
[2] *Croatian Summer School, Pančićeva 5, 10000 Zagreb, Croatia.*

Abstract

This research was conducted in the Papuča gravel pit southeast of Gospić (Croatia). The fan-shaped sediment body, up to 14 m thick, is composed of poorly sorted, coarse-grained, and unconsolidated sandy gravel. Over 200 blocks and pebbles were selected from the gravel pit. The main criteria for sample selection were based on their potential for determination of their stratigraphic age. The clasts are Jurassic, Triassic, and Permian provenance. Selected clasts were measured for morphometric analyses. According to the median (Md = 7.5 mm), the gravel is medium-grained, with 50% gravel size clasts. The Trask coefficient (So = 6.44) indicates poor sorting, while the skewness coefficient (Sk = 0.313) indicates an asymmetric clast size distribution, with a prevalence of clasts larger than the median value. The Zingg diagram points to a predominance of spheroidal clasts followed by discoidal and rod-shaped clasts while blade-shaped clasts are scarce. The flatness ratio of clasts is 1.7, which is consistent with traditional calculations for fluvio-glacial and moraine deposits. The clast lithological analysis (macro and micro) was performed. The results indicate the dominance of limestone clasts. Glacially formed troughs, including ravines Ljutik and Široka Draga on the northern, steep slope of Mt. Velebit, served as pathways for meltwater, which transported clasts of various sizes and stratigraphic ages, originating from the glacier base and from the hillsides. The age of the gravel is estimated at 20,700 ± 200 years, during the glacier retreat at the beginning of Greenland Interstadial No. 1 of the Late Pleistocene.

Keywords:
flow till, pebble stratigraphy, size and shape, Upper Pleistocene, Mt. Velebit, Croatia

1. Introduction

The purpose of this study is to explain the circumstances of the origin of the Papuča gravel pit. Research was conducted in the Papuča gravel pit in the central part of the Lika region, at the foothill of Mt. Velebit, 22 km southeast of Gospić (see **Figure 1a**). The site is located beneath the deeply incised erosional valleys Široka Draga (marked with a blue arrow, see **Figure 1b**) and Ljutik, which extend from the northwestern slopes of Vaganski Vrh (1,757 m) to Lika Field (approximately 600 m elevation) (see **Figures 1b, 2a**). The gravel pit is accessible via a 20 km-long state road from Gospić to the Papuča settlement, followed by a 2 km local macadam road heading south (see **Figure 1b**). The exploitation gravel field, which has been actively mined for several decades, is situated in the northern, frontal part of the sandy gravel lobe called Vedrine, between the villages of Potrebići and Križajica, at elevations ranging between 700 and 590 m (see **Figures 2b, 3a**). **Figures 2b** and **Figures 3a** show the differences in the appearance of the gravel pit created during 13 years of exploitation. The company operating the site produces aggregates sorted by fractions: 0–4 mm, 4–8 mm, 8–16 mm, 16–31.5 mm, 0–16 mm (mixed), 0–31.5 mm (mixed), and natural gravel. A certain weathering and fracture of the clast can be seen in **Figure 3c**. Data on aggregate fractions can be used for further research by some newer or different methods (see **Figure 3b, c**).

Discussions about glacial landscapes in the Karst Dinarides and studies of the glaciation of Mt. Velebit date back to the late 19th century and continued through the 20th and 21st centuries (e.g. **Gavazzi, 1903; Schubert, 1909; Milojević, 1922; Roglić, 1963; Nikler, 1973; Belij, 1985; Bognar & Faivre, 2006; Hughes et al., 2010; Marjanac, 2012; Krklec et al., 2015**). More recent studies have focused on the early glacial maximum and sedimentology of glacial deposits in the southern part of the former ice margin at Mt. Velebit, as published by **Velić et al., 2011, 2014, 2017; Velić & Velić, 2019; Žebre et al., 2019; Sarıkaya et al., 2020**.

Climate changes during the glacial period (Würm III) significantly influenced the formation of glacio-nival

* Corresponding author: Josipa Velić
e-mail address: josipa.velic@rgn.unizg.hr
Received: 20 January 2025. Accepted: 14 April 2025.
Available online: 27 August 2025

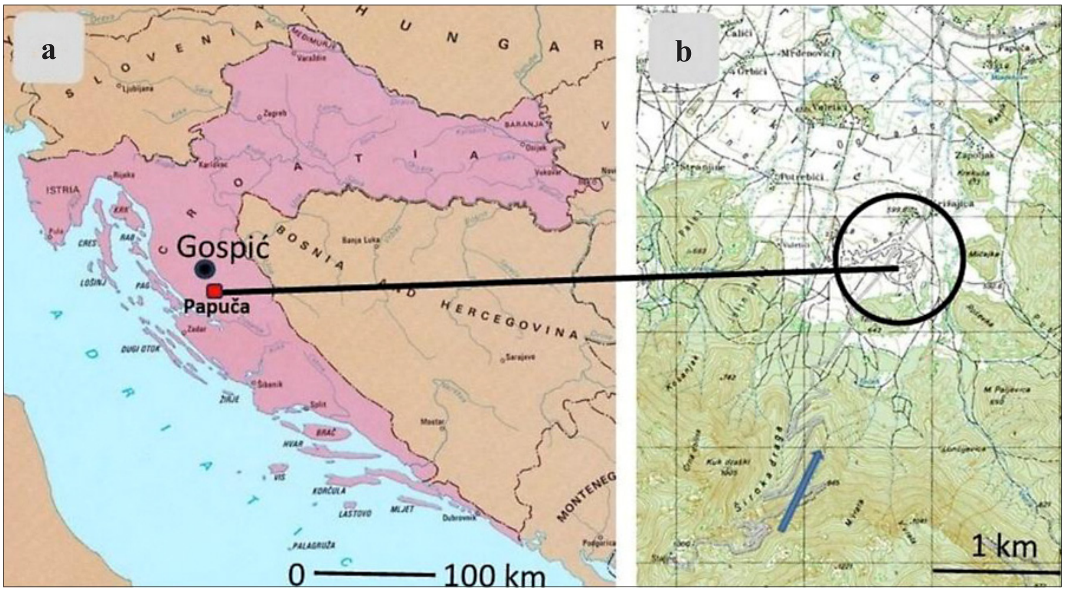

Figure 1. Location of the Papuča gravel pit: a) position on the map of the Republic of Croatia; (b) topographic map (1:25 000, sheet 470-1-1); the blue arrow marks the transport direction along the Široka Draga incised valley-torrent.

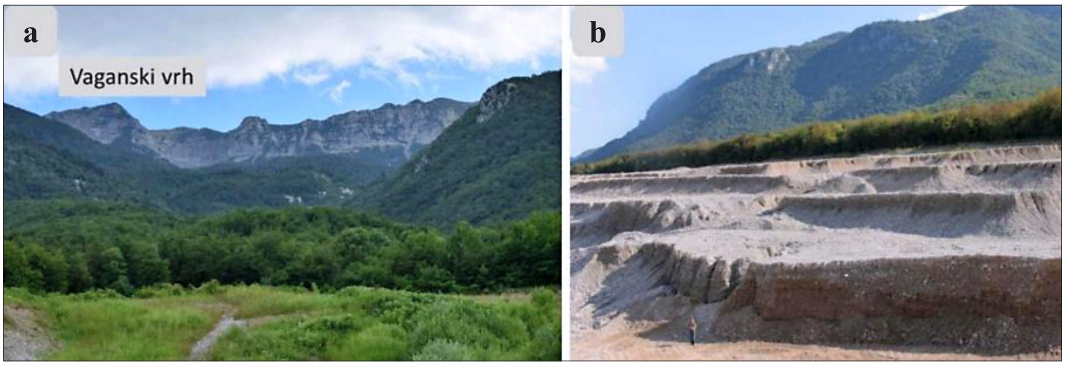

Figure 2. Field photos: a) panoramic view of the Široka Draga valley on the north Mt. Velebit slope with the highest Mt. Velebit peak, i.e. Vaganski Vrh (1762 m); b) the middle part of the Papuča gravel pit (photos from the year 2007).

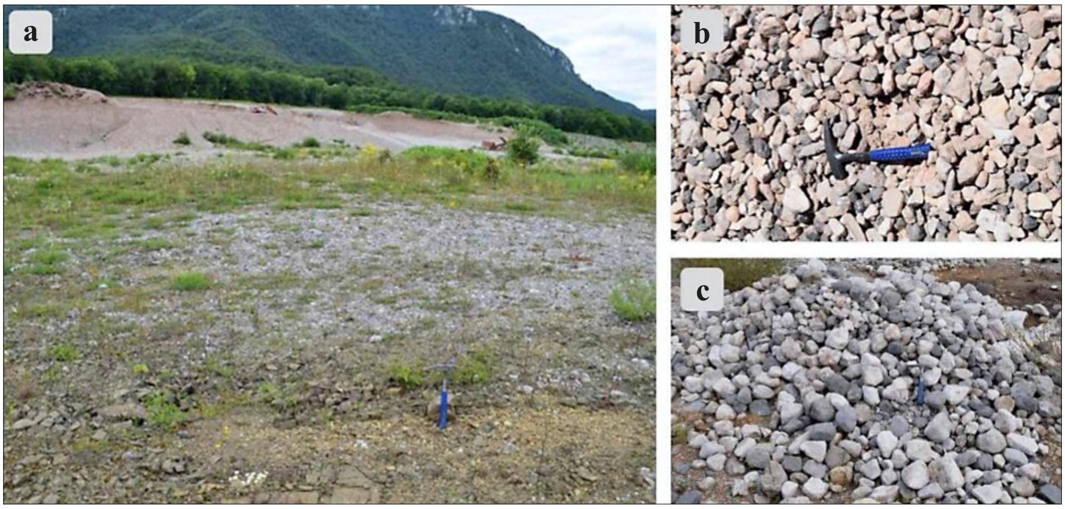

Figure 3. Field photos from the Papuča gravel pit: a) panoramic view on part of the gravel pit, photo from the year 2020; in the lower part of the photo there are brownish "*Triticites*" (fossil foraminifers) sandstones; b) sorted gravels (for scale: hammer length 33 cm); c) unsorted gravels (for scale: hammer length 33 cm).

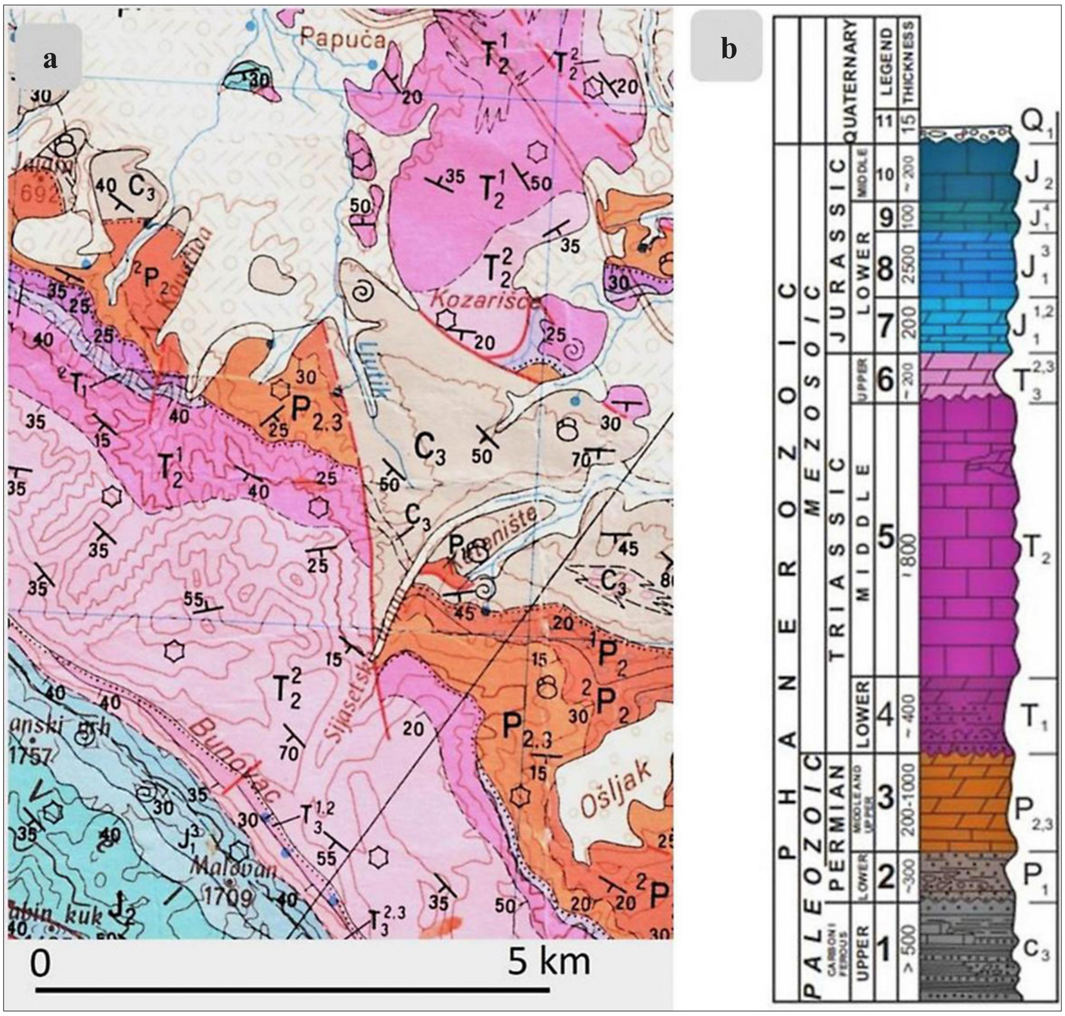

Figure 4. a) fragment from the Basic Geological Map, sheet Udbina (**Šušnjar et al., 1973**).
Map symbols: C_3 = Upper Carboniferous sandstones and shales; $^2P_2$ = Middle Permian sandstones; $P_{2,3}$ = Middle and Upper Permian dolomites; $^1T_1$ = Lower Triassic dolomites, micaceous sandstones and shales; $^2T_1$ = Lower Triassic limestones, marls and dolomites; T_2^1 = Middle Triassic (Anisian) dolomites; T_2^2 = Middle Triassic (Ladinian) limestones and dolomites; $T_3^{1,2}$ = Upper Triassic conglomerates and tuffaceous clastic deposits; $T_3^{2,3}$ = Upper Triassic dolomites and limestones; $J_1^{1,2}$ = Lower Jurassic limestones and dolomites; J_1^3 = Lower Jurassic limestones; J_1^4 = Lower Jurassic spotty limestones; J_2 = Middle Jurassic limestones and dolomites; pr = proluvial gravels and sands
b) Stratigraphic column of the area Vaganski Vrh-Papuča.

karst landforms, particularly at heights over 1300 m. Almost 12°C lower temperatures than today enabled the formation of an ice sheet at the topmost parts of Velebit Mt., which slightly moved towards the lower slope parts – karst holes, valleys, and channels, forming and changing their relief by exaration (**Perica & Orešić, 1999**). Excellent examples are the deeply incised torrent-creek valleys Široka Draga, Ljutik, and a valley with a hiker's path situated slightly to the west, leading from Grubišni Dolac towards the foothill of Badanj (1638 m).

After the cognition of the Velebit glaciation during the Pleistocene, a rather detailed field study was conducted by **Belij (1985)**, whose research became an important basis for interpreting the genesis of the Papuča pit gravels. According to the geomorphological map of the glacial relief of the Southern Velebit Mt., the ice-sheet margin was situated between Badanj (1638 m) in the west and Babina Vrh (1738 m) in the east. This means it was approximately 4.5 km from Papuča. The approximation is following the data from **Krklec et al. (2015, fig. 1)**, who estimated the ice-sheet size at 19.5 km². Symmetrically situated between the two aforementioned peaks, **Belij (1985)** detected the trough along the northern, relatively steep slope of Velebit Mt., through which subglacial water and meltwater flows transported clasts of various sizes and stratigraphic ages.

Sarıkaya et al. (2020), based on the glacial chronology of cosmogenic ^{36}Cl from the Southern Velebit Mt., from Rujanska kosa, approximately 7 km from Papuča, dated the retreat of the glacier during the Late Pleistocene (i.e. the last glacial maximum), which positions the minimal age of the ice retreat to before 20,700 ± 200 years.

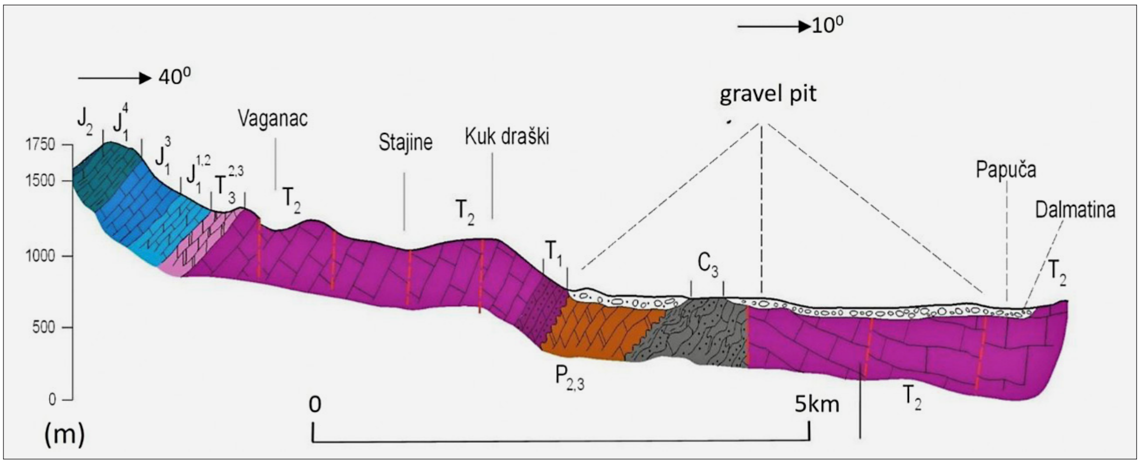

Figure 5. Geological profile along the transport route of the glacio-fluvial sediments - torrent Široka Draga (the vertical unit of this profile is "m" i.e. meters)

2. Geological Setting

The geological setting of the gravel pit area is shown according to the data Basic Geological Map, sheet Udbina (**Šušnjar et al., 1973**). The bedrock of gravels from the Papuča gravel pit consists of Upper Carboniferous, Middle and Upper Permian, Lower, Middle, and Upper Triassic, and Lower and Middle Jurassic rocks (see **Figures 4, 5**). Geological descriptions are summarized from the Basic Geological Map and according to the findings of the second author of this article, who has been researching the geological features of Velebit for several decades. Nevertheless, the largest part of the exploitation field lies over Upper Carboniferous shales and sandstones, with clearly visible gravelly-sandy deposits overlying the brownish-yellow Carboniferous deposits, marked by a hammer (see **Figure 3a**).

Figure 6. Natural clasts from the Papuča gravel pit prepared for cutting and making thin sections, bottom right scale in centimeters

3. Methods

Field research was carried out in several phases between 2007 and 2023. During fieldwork, rocks forming the base of the gravels were examined in the lower parts of the Široka Draga gully, along the forest road, on the slightly hilly plateau near the northern boundary of the pit (see **Figure 3a**), at the western pit boundary beneath Jelin Palež, and an altitude of 850 m at the southern boundary of the sandy gravel body. From the gravels, blocks, and pebbles large enough to enable stratigraphic and lithological determinations were selected, together with randomly collected clasts from the 16–31.5 mm fraction (see **Figure 3b, 3c, Figure 6**). Namely, the mentioned fraction is the largest in the separation process and thus suitable for macroscopic determination of the type and age of clasts in the field.

Sixteen pebbles were selected for the preparation of thin sections to determine lithology, fossils, and microfacies which the field examination assumed that they contained interesting and important details for interpretation (see **Figure 6**).

Three perpendicular axes of clasts were measured in situ and was followed by morphometric analysis with the aim to prepare the Zingg diagrams to interpret transport mode, depositional processes, and pebble provenance. Based on field observations, it was concluded that approximately 200 measured clasts would be sufficient for this study.

Based on the field data, values were calculated to prepare the Zingg diagram and identify the dominant clast forms. Clast shape was defined qualitatively and quantitatively (numerically), with the latter applied in this research. Clast shape was determined by the relationship between the longest axis (a = length), medium axis (b = width), and shortest axis (c = thickness). By calculating the b/a and c/b ratios, **Zingg (1935)** classified clasts into four basic shapes: discoidal, spheroidal, blade-shaped, and rod-shaped (see **Table 1**).

The results of additional morphometric calculations include the flatness ratio and granulometric data: median (Md), Trask sorting coefficient (So), skewness

Table 1. Basic clast shapes according to **Zingg (1935)**

Class	b/a	c/b	Clast type
I.	> 2/3	< 2/3	discoids
II.	> 2/3	> 2/3	spheroids
III.	< 2/3	< 2/3	blades
IV.	< 2/3	> 2/3	rods

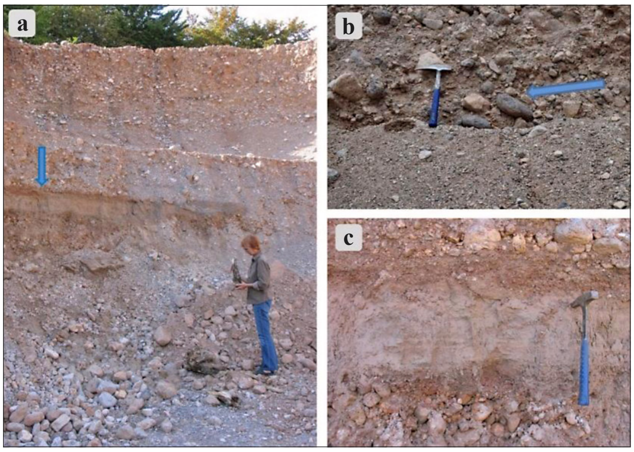

Figure 7. Field photos from the Papuča gravel pit (from the year 2007): a) detail from the pit showing the combination of sand and gravel with unsorted limestone pebbles; b) detail with rare, imbricated pebbles – the blue arrow shows the direction of the gravel flow; c) a bed of the fine-grained sand. In a) the height of the person serving as scale is 165 cm, b) and c): the geologic hammer is 33 cm long.

(Sk; a measure of distributional asymmetry), and excess kurtosis.

The flatness ratio is calculated during the geomorphological and paleogeographic research of gravels, according to the formula:

$$F = (a+b)/2c \quad (1)$$

where:

F – flatness ratio,
a – length of the longest axis,
b – length of the median axis,
c – length of the shortest axis.

The calculated values, in most cases varying between 1.2 and 5 (**Müller, 1967**), can help in the determination of the depositional environment. The traditional interpretations are shown in **Table 2**.

Table 2. The values of the Flatness ratio and depositional environment (modified after **Müller, 1967**)

Depositional environment	Flatness	Category
Potholes in river channel	1.2 – 1.6	A
Ground moraine	1.6 – 1.8	B
Fluvio-glacial	1.7 – 2.0	C
Frost river	2.0 – 3.1	D
Marine beach	2.3 – 3.8	E
Lake beach	2.3 – 4.4	F
River in moderately warm climate	2.5 – 3.5	G

4. Results and Discussion

Based on the results of field, laboratory, and cabinet research, sedimentary, stratigraphic, petrographic, and morphometric characteristics and the degree of flattening the genesis of the gravel pit were determined.

4.1. Sediment characteristics

The Papuča gravel pit covers a total area of 88,400 m². To calculate gravel reserves, 11 boreholes were drilled, with depths ranging from 7.70 to 14.0 m. The boreholes are located approximately in the center of the lobed sedimentary body, perpendicular to the Široka Draga torrent, directly beneath the foothill, or more specifically between 640 and 645 m above sea level. Based on field observations and the results of drilling the schematic lithological column is as follows (**BIGROM, 2021**):

- 0.00 to 0.20 m: brown humus
- 0.20 to 0.70 m: gravel and sand mixed with humus and clay
- 0.70 to 13.50 m: poorly sorted gravel and sand, with clasts of various shapes, primarily limestones and dolomites
- 13.50 to 14.00 m: yellow clay; Palaeozoic rocks – Carboniferous sandstones and shales

At the exposed excavation face, up to 10 m high (see **Figures 2b, 3a**), extremely poor sorting is evident (see **Figure 7**), which is also reflected in the cumulative granulometric curve from the company archives (**BIGROM, 2021**) (see **Figure 8**). The average sediment composition includes 55% gravel, 20% sand, 15% silt and clay, and 10% blocks. Granulometric measurements data, i.e. granulometric curve, yielded the following results: according to the median (Md = 7.5 mm), 50% of clasts are of 7.5 mm size, corresponding to medium-grained gravel. The Trask sorting coefficient (So = 6.44) points to poor sorting. The asymmetry coefficient (skewness) (Sk = 0.313) indicates that clasts larger than the median prevail, and the curve is asymmetrical on the coarse clast side. The interesting result for the kurtosis (excess) (K mm = 0.24) shows that the coarse- and very coarse-grained sand is better sorted than the clasts in the fine- and very fine-grained sand, which indicates that they were transported over a longer distance.

Sediment is indistinctly layered (see **Figure 7**), a feature attributed to grain size sorting. Carbonate clasts dominate all size fractions – their content in the gravel fraction ranges from 77% to 91% (see **Figure 9a**). In various sand fractions (see **Figure 9b**), carbonate grains comprise 24 to 58%, except in the finest fraction (0.50–0.125 mm), where quartz grains dominate. Clasts are generally angular to subangular and only rarely slightly rounded (see **Figure 3c**).

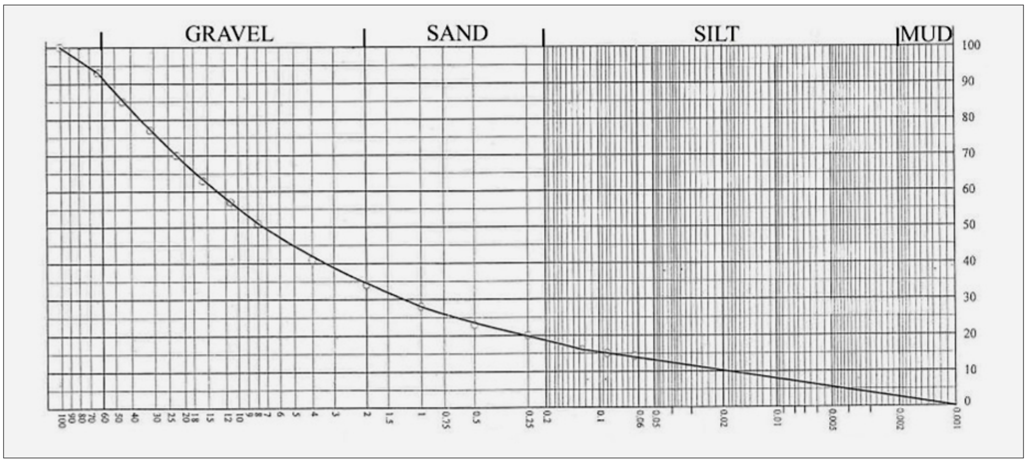

Figure 8. Granulometric curve (**BIGROM, 2021**)

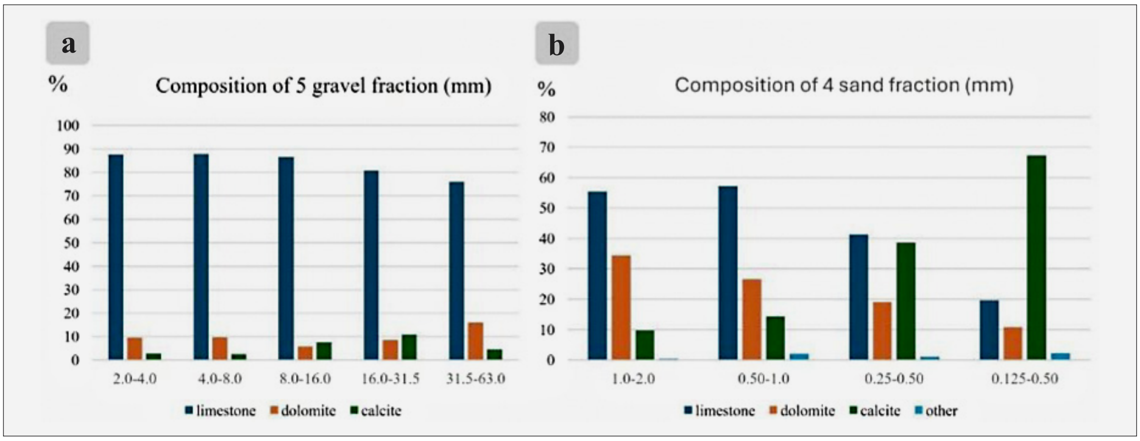

Figure 9. Histograms presenting the lithological composition of a) gravel and b) sand

4.2. *Stratigraphic and lithological determinations from collected clasts*

Gravels in the open parts of the gravel pit contain predominantly pebbles composed of limestones of the Middle Triassic and Lower Jurassic age (see **Figures 2a, 3a, 4, 5**), which crop out along the Široka Draga torrent. Late-diagenetic dolomitic pebbles, in most cases originating from Triassic or Jurassic rocks, were observed, although their precise age could not be determined. Conversely, early- diagenetic dolomites, with preserved fossils, were identified in the field as Permian *Mizzia* Dolomite and Upper Triassic Main Dolomite.

Upper Carboniferous deposits are dominated by clastic sedimentary rocks include shales and sandstones (see **Figure 10**). Dark grey and black shales predominate, with intercalations of dark grey sandstones (see **Figure 10a**). During weathering, these rocks broke into thin plates with upper surfaces marked by small mica particles. Some sandstone intercalations are brownish and contain numerous fossils of the *Triticites*-type fusulinid foraminifera. A fine-grained greyish-brown quartz breccia-conglomerate, probably of Upper Carboniferous age, is shown in **Figure 10b**. These clastic deposits crop out in the southern part of the gravel pit, at the boundary of the Carboniferous sandstones and Quaternary gravels (see **Figure 3a**).

Deposits of the Middle and Upper Permian age are represented by stratified grey dolomitic limestones (see **Figures 10c, d, e**). Bed thickness varies between 40 and 80 centimeters. These deposits contain numerous microfossils, with the most common being calcareous algae of the genera *Mizzia*, *Vermiporella*, *Salopekiella*, *Likanella*, and *Velebitella*, some of which were earlier described from this region, like what **Schubert (1909)**, **Kochanski-Devide (1965)** and **Sokač et al. (1974)** among fusulinid foraminifera, genera such as *Neoschwagerina* and *Eoverbeekina* were also identified.

Triassic deposits crop out in this area above the Poljana Kranjska Valley. They comprise dark purple, platy, well-stratified micaceous and sandy dolomites (see **Figures 11a, b**). Macrofossils are visible on the bedding surfaces, including preserved bivalves and their molds belonging to the taxa *Posidonomya clarae* (**Emmrich, 1844**) and *Unionites fassaensis* (**Wissmann, 1841**).

Lower Triassic sandstones are overlain by gray, recrystallized Middle Triassic Diplopora limestones (see **Figure 11c**). These limestones are highly karstified and

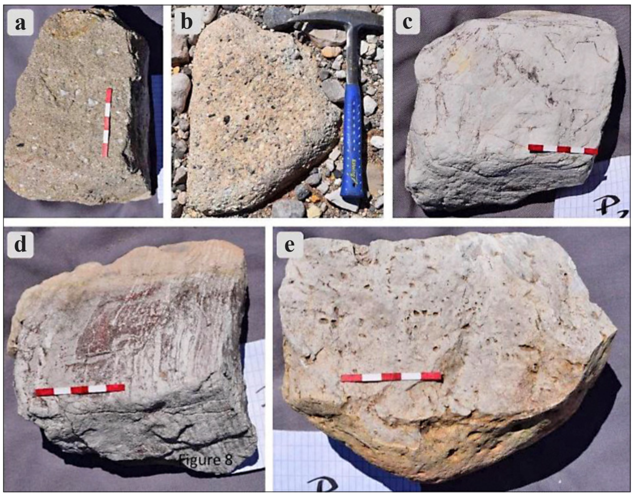

Figure 10. a) Upper Carboniferous C_3, coarse-grained sandstone to fine-grained breccia; b) Upper Carboniferous C_3, fine-grained quartz conglomerate; c), d), e) Middle to Upper Permian early diagenetic dolomite, scale in centimeters

sometimes exhibit a marble-like appearance with poorly developed stratification. When stratified, bed thickness ranges between 40 and 80 cm but can reach up to 2 meters. Limestones contain calcareous algae, with *Diplopora* being the most common genus, along with *Macroporella*, *Physoporella*, *Teutloporella*, and others.

By the end of the Middle Triassic and the beginning of the Upper Triassic, the area emerged from the sea, and erosional and karstification processes occurred. This is particularly visible in the Diplopora limestones (see **Figure 11c**). In the middle part of the Upper Triassic, a major transgression took place, flooding the whole area of present-day Mt. Velebit. Transgressive breccias and conglomerates mark the base of this transgression. These deposits are overlain by the Main Dolomite (Hauptdolomit), which accumulated up to the end of the Triassic (see **Figures 11e, f**).

In continuation, Lower Jurassic stratified limestones and dolomites occur in an undisturbed succession, alternating with one another. These rocks contributed to the

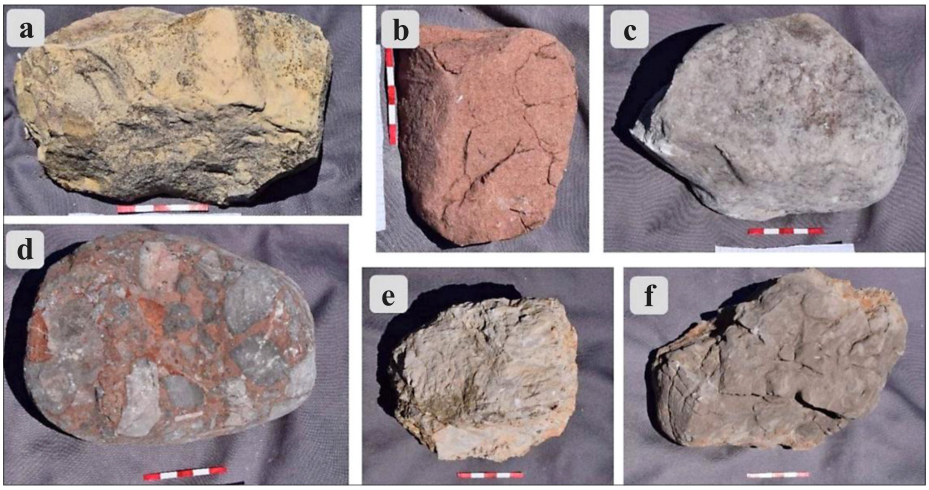

Figure 11. a) Lower Triassic – T_1 sandy dolomite; b) Lower Triassic – T_1 ooid sandstone; c) Middle Triassic – T_2, Diplopora limestone; d) Upper Triassic, Carnian – T_3^1, breccia composed of the T_2 Diplopora limestone clasts; e), f) Upper Triassic, Norian and Rhaetian – $T_3^{2,3}$ the Main dolomite, scale in centimeters

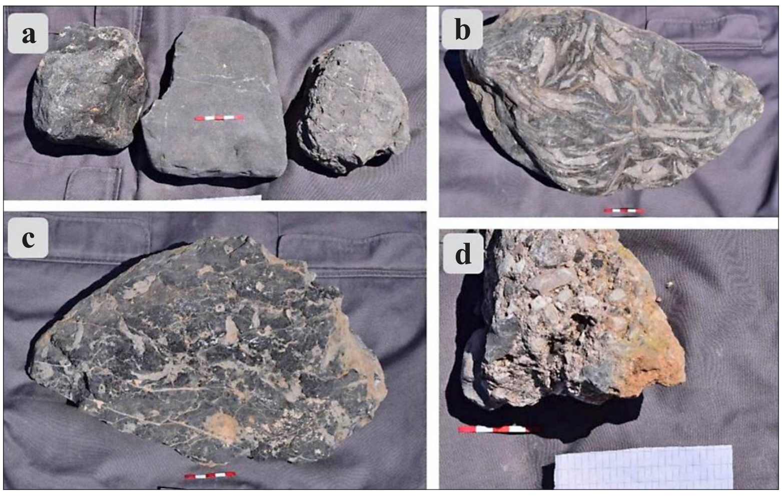

Figure 12. a) Lower Jurassic ($J_1^{1,2}$) limestones and dolomites; b) Lower Jurassic (J_1^3) Lithiotid limestones; c) Lower Jurassic (J_1^4) bioturbated limestones and dolomites; d) Quaternary (Q) carbonate conglomerate/breccia with clasts of Jurassic limestones and dolomites, scale in centimeters.

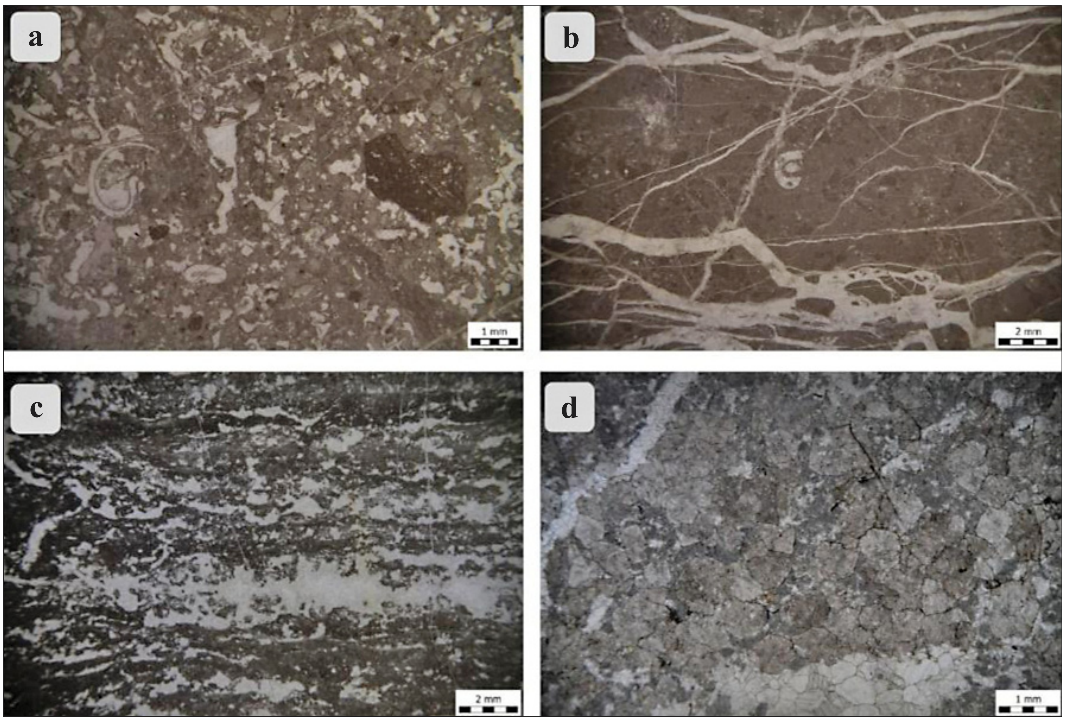

Figure 13. a) pebble1, biocalcarenite with fenestral fabric (recrystallized floatstone), contains gastropods; b) pebble 2, pelloidal mudstone to wackestone with dessication cracks and scarce foraminifera; c) pebble 3, laminated boundstone with fenestral fabric; d) pebble 4, medium to coarse-grained late diagenetic dolomite.

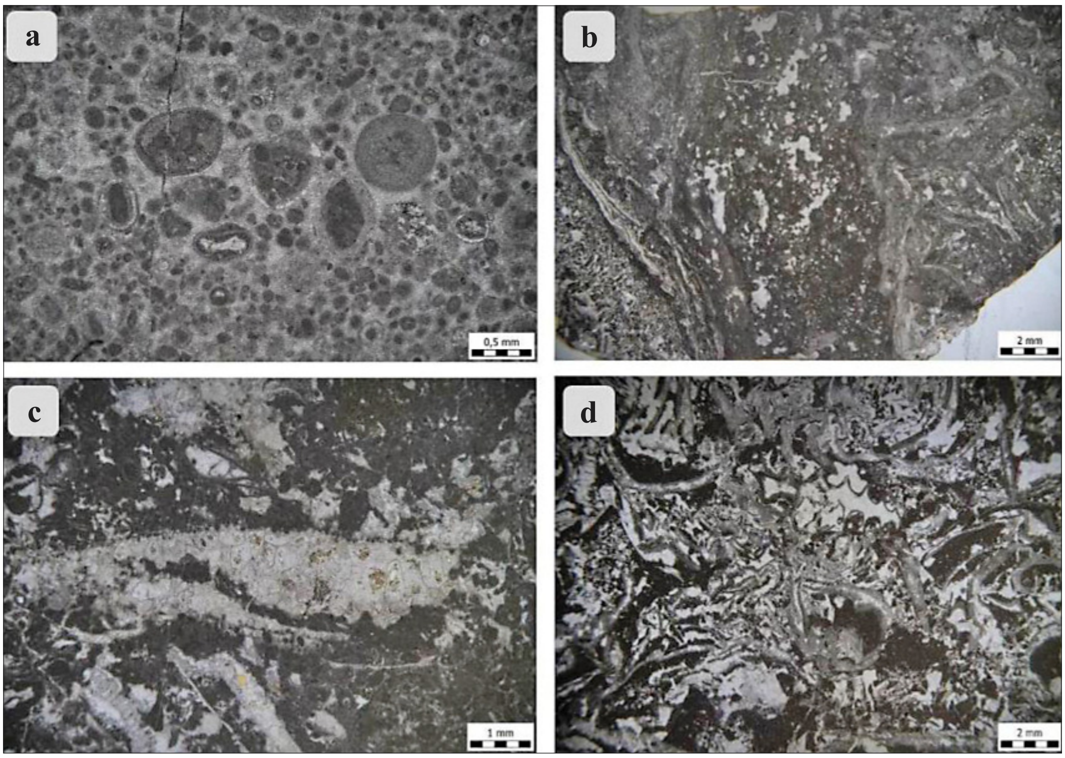

Figure 14. a) pebble 5, ooid grainstone, recrystallized; b) pebble 6, boundstone, in the middle of the picture there is a fenestral fabric; c) pebble 8, floatstone with sections macrofossils: gastropods, brachiopods, sponges and foraminifers, selective dissolution of aragonite can be seen; d) pebble 9: coquina (rudstone).

dark gray and black pebbles (see **Figure 12a**) found in the Quaternary gravels. Among them, highly fossiliferous Lithiotid limestones are present, characterized by cross-sections of large lithiotid bivalves (see **Figure 12b**).

The youngest exposed bedrock is the Lower Jurassic bioturbated limestone, known as "Fleckenkalk" (see **Figure 12c**), originating from the uppermost parts of the Vaganski Vrh ridge. Younger Jurassic clasts were not found in the gravel, which suggests that the material source was the exposed rocks eroded by ice and torrential flow.

4.3. Petrographic features of clasts

Thin sections were prepared from 16 pebbles (see **Figure 6**) to determine lithology, fossils, and microfacies (see **Figures 13−16**). For pebbles 7 and 17, it was impossible to make a thin section; during preparation for the making thin section the pebbles were cracked by small cracks. A variety of facies types were identified: biocalcarenite with fenestral fabric, pelloidal mudstone to wackestone (pebble 1), pelloidal mudstone to wackestone with dessication cracks and scarce foraminifera (pebble 2), laminated boundstone with fenestral fabric (pebble 3), medium to coarse-grained late-diagenetic dolomite (pebble 4), ooid grainstone (pebble 5), boundstone (pebble 6), floatstone with macrofossils (gastropods, brachiopods, sponges, and foraminifera) (pebble 8), coquina (rudstone) (pebble 9), floatstone to rudstone with algae (pebble 10), floatstone with foraminifera and macrofossils (pebble 11), floatstone with *Thaumatoporella* or codiacean algae (?*Pseudolithocodium carpathicum*) (pebble 12), pelloidal wackestone with juvenile serpulid clusters in pelloidal micrite (pebble 13), boundstone (partly recrystallized laminated sediment, possibly stromatolite) (pebble 14), limestone with laminated fenestral fabric (pebble 14), and floatstone with undetermined algae and fenestral fabric (pebbles 15 and 16). Therefore, most of the pebbles represent various varieties of limestones.

4.4. Results of the morphometric analysis of grain measurements

Measured pebbles, according to the b/a and c/b ratios, were classified into four groups (spheres, discs, rods, and blades) (see **Figure 17a**). **Table 3** presents the number of pebbles and the percentage of clasts from each of the four categories. The "boundary values" include the ratios that are in between the Zingg classes. **Figure 17b** presents the number of pebbles according to shape and **Figure 17c** presents the percentage (%) of the sample according to shape.

According to the Zingg graph (see **Figures 17 b, c**), the largest part of pebbles is spheroidal in shape (37%, 74 pebbles). Discoidal pebbles are the second most abundant group (27.5%, 55 pebbles), followed by rod-shaped (20.5%, 41 pebbles), while blade-shaped pebbles are rather scarce (6%, 12 pebbles). Clasts with the "boundary values" in the Zingg diagram represented 9% (18 pebbles) of the studied sample (see **Table 3**). The geological composition is dominated by carbonate sediment of relatively homogeneous texture and structure in all fractions of the clast (see **Figures 9a and b**), which were weathered into spheroidal, discoidal, or isometric clasts during weathering and transport, as shown in the histograms according to **Zingg (1935)**.

Table 3. Number of clasts and percentage within the whole sample according to the four Zingg classes

Class	b/a	c/b	Shape	No. of pebbles	Percentage
I.	> 2/3	< 2/3	discoidal	55	27.5
II.	> 2/3	> 2/3	spheroidal	74	37
III.	< 2/3	< 2/3	bladed	12	6
IV.	< 2/3	> 2/3	rod-shaped	41	20.5
Boundary values				18	9

4.5. Flatness

Flatness was commonly calculated in traditional sedimentological papers as a tool to depict the transport mode (**Müller, 1967**). The value of such calculations is the subject of debate, but they can be useful when applied within unified lithological groups (e.g. **Sremac et. al., 2024**). The flatness ratio of pebbles of the same lithological composition depends on the depositional environment and hydrodynamic conditions. In the Papuča gravel pit, clasts are dominantly composed of carbonate rocks (see **Figure 9a, 9b; BIGROM, 2021**), therefore the obtained values can be considered indicative of the deposition mode (see **Tables 2, 4**).

Based on the results of all research, it is possible to reconstruct the genesis of gravel. Stratigraphic and petrographic features of clasts from the analysed sediment body undoubtedly point to their provenance – cracked and strongly weathered rocks from the Southern Velebit Mt. (see **Figures 6, 7, 8**). Clasts originate from the ice-cap bedrock but also from the surrounding hills. They were carried over short distances along steep slopes and were likely redeposited multiple times during heavy rain episodes, especially with periodic high-energy flows, i.e. torrential flows (**Tišljar, 2004**). For the processes of washing and dredging, the intensity of precipitation is very significant. Namely, short-term but heavy precipitation prevailed on Velebit, which, due to increased slopes (slopes of more than 12 degrees dominate), quickly drained on the surface (**Perica & Orešić, 1999**). This interpretation of genesis is supported by **Belij (1985)** with his conclusion that at the maximum of the Wurm cooling, the glaciers of southern Velebit belonged to the type of hanging glaciers. Their tongues of hanging glaciers descended down the subvertical sections on the Lika slope, hollowing out steep hanging ditches, and then broke, crashed down the section, and melted.

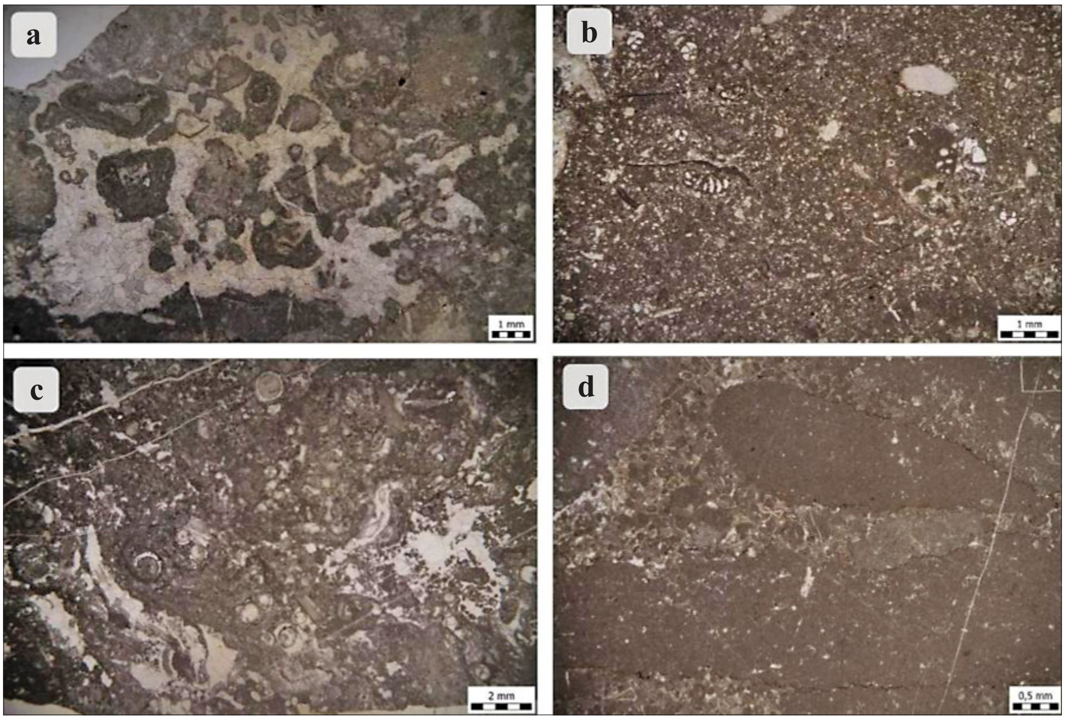

Figure 15. a) pebble 10, floatstone to rudstone with algae; b) pebble 11, floatstone with sections of foraminifera and macrofossils; c) pebble 12, floatstone with thaumatoporellas or codiacean algae (Ulvophyceae, ?*Pseudolithocodium carpathicum* **Mišik, 1979**); d) pebble 13, pelloidal wackestone with sections of juvenile serpulid turfs in pelloidal micrite.

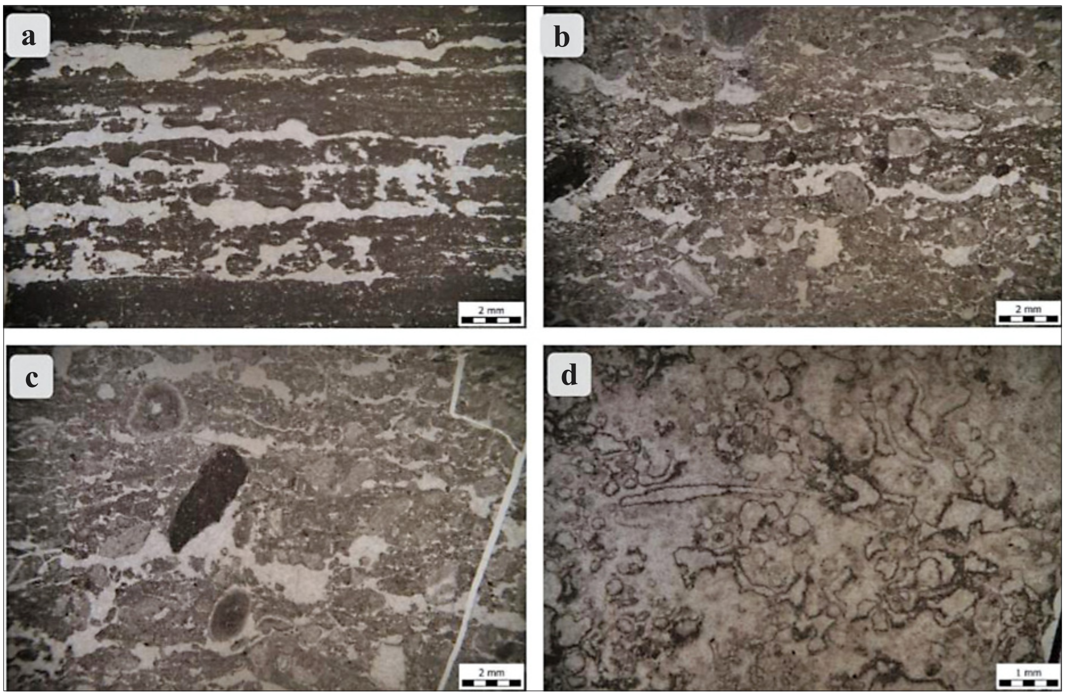

Figure 16. a) pebble 14, boundstone (partly recrystallized laminated sediment, probably stromatolite); b) and c), pebble 15: limestone with the laminated fenestral fabric of the LF-A type (according to Flügel), probably stromatolite limestone of the bindstone type; d) pebble 16, floatstone with undeterminable sections of algae and fenestral fabric.

The sediment within the lobe can be described as poorly sorted, mid-grained gravels, with 50% of clasts being 7.5 mm in size. However, in the field, blocks larger than 10 cm also occur, representing 10% of the deposit when observing the granulometric curve. This size distribution points to high water energy, and short transport with rolling and falling, while the discrete differences in clast size (see **Figure 4**) indicate the pulsation

Table 4. The flatness ratio for pebbles from the Papuča gravel pit. A = river channel; B = ground moraine; C = fluvio-glacial; D = frost river; E = marine beach; F = lake beach; G = moderate/warm river. Some values overlap, so combined columns are added to the table.

Category	A	B	C	D	E	F	G	A, B	B, C	C, D	E, F	D, E, F	D, E, F, G	?
No. of pebbles	77	1	12	12	0	0	0	20	45	4	2	8	17	2

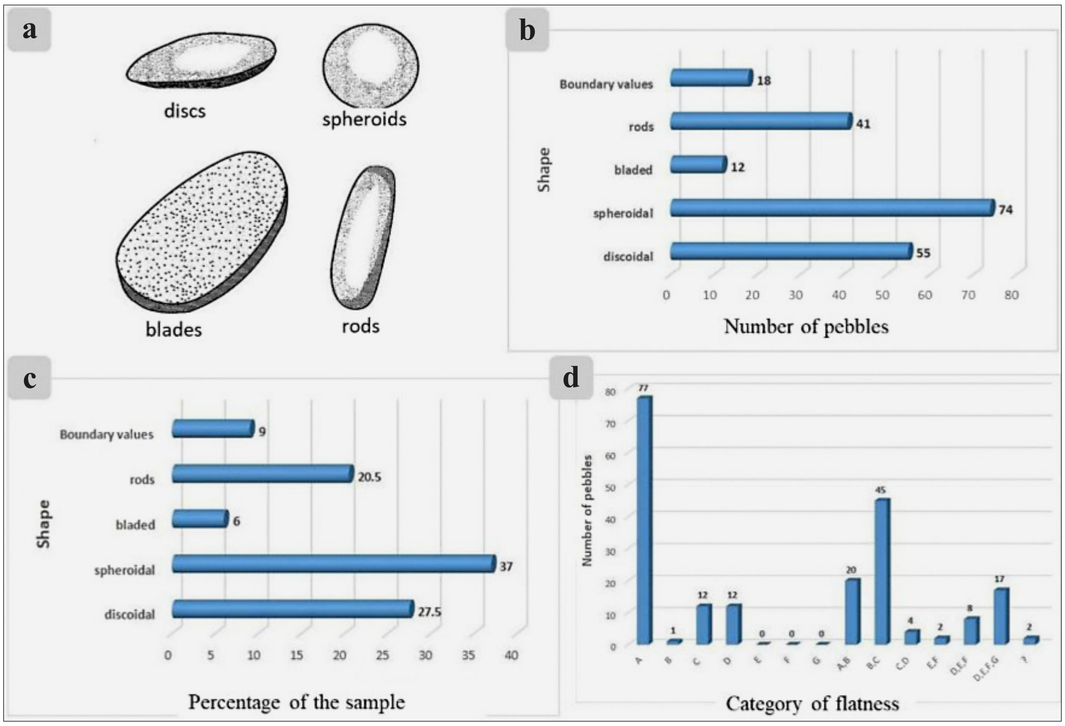

Figure 17. a) shapes according to **Zingg (1935);** b) number of pebbles according to shape; c) percentage (%) of the sample according to shape; d) flatness (distributed in categories, as shown in **Table 4**).

of water energy. The kurtosis (excess) Kmm = 0.24 reveals the fact that coarse and very coarse sand grains are better sorted, which means they were transported over longer distances. In most cases, clasts do not show preferred orientation, but occasionally, imbrication occurs (see **Figure 4c**), indicating transport from the south, i.e. from the Velebit Mt. slopes). The flatness degree of the largest number of pebbles (45 in total) points to river potholes, moraines, and glaciofluvial environments.

The studied gravel, according to all listed features, can be classified as a flow till (**Bennett & Glasser, 2009, Table 8**), forming a single or coalesced fan (**Lawson, 1982; Zielinski & van Loon, 1999**). Additional evidence for this interpretation includes angular or poorly rounded clasts, not striated or faceted, unsorted and poorly consolidated sediment, variable lithological composition, poorly developed, as well as the important finding of individual flow packages (see **Figure 4c**). Far-travelled erratic blocks occur at the lower edge of the investigated sediment body.

In the upper part of the torrent, at a height of 850 m, a scar occurs, marking the boundary between the flow till and the bedrock. Below the scar, a channel with approximately 5 m thick levees can be traced. At the bottom of the Velebit Mt. slope, at around 650 m in height, a fan consisting of single or coalesced small lobes forms (see **Figure 18**).

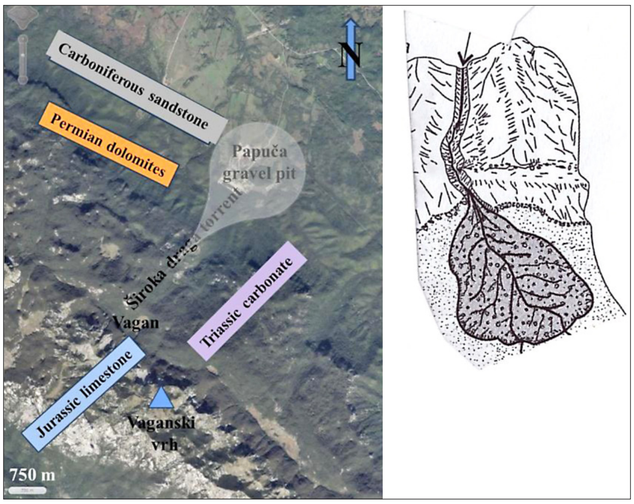

Figure 18. Reconstruction sketch of the flow-till genesis: zone of the Carboniferous sandstone; zone of Permian dolomite; zone of Triassic carbonate; zone of J = limestones; the shape in transparent gray represents the flow till distribution (https./preglednik.arkod.hr)

According to the previous authors, like **Sarıkaya et al., 2020**, the glacier retreat occurred over 21,000 years ago, and the likely beginning of the formation of this flow-till occurred at the end of the Pleistocene, i.e. at the beginning of Greenland Interstadial No.1 (**Cohen et al., 2013**).

5. Conclusions

Melting of the Velebit hanging glaciers began at the end of the Pleistocene, i.e. at the beginning of the Greenland Interstadial No. 1. The torrents Široka Draga and Ljutik, sloping towards the Lika region, were the paths where poorly-sorted unconsolidated debris flow till was deposited, creating small fans in the form of stacked coalesced lobes. The lithology and modal composition of clasts point to local provenance, i.e. the most abundant clasts in the Papuča gravel pit, limestone pebbles of the Middle Triassic and Lower Jurassic age, were derived from the local rocks (see **Figures 9-11**), which compose the largest part of the Široka Draga incised valley. Furthermore, some of the pebbles were determined to be early-diagenetic *Mizzia* dolomites with Permian calcareous algae and other shallow marine fossils and Upper Triassic Main Dolomite. Gravel transport mode can be explained by abrupt high-energy torrents, associated with the redeposition of clasts by tearing off, falling, rolling, and flowing.

Acknowledgement

This research was supported by the project "Mathematical Methods in Geology VI, VII, and VIII" (2021, 2022, 2023), led by Tomislav Malvić (University of Zagreb, Faculty of Mining, Geology, and Petroleum Engineering). The authors wish to thank for the financial, technical, and other kinds of support. We are grateful to Professor Uroš Barudžija who helped in the determination of petrographic slides, and honorary assistant professor Marija Bošnjak who calculated and interpreted all numerical values and prepared the related figures (Zingg diagram and flatness). The authors also express their gratitude to Professor Jasenka Sremac, who significantly helped in writing the manuscript with her valuable advice and helped in the determination of the fossil content of petrographic slides, and Zlatko Špoljar, whose help in the field was immensely important and effective.

The authors express their gratitude to reviewers for their constructive suggestions, which significantly improved the paper.

6. References

Belij, S. (1985). Glacijalni reljef južnog Velebita (Glacial relief of Southern Velebit). *Geografski glasnik, 47*, 71-85. (in Croatian).

Bennett, M.R. & Glasser, N.F. (2009). Glacial Geology. Ice Sheets and Landforms. *Wiley-Blackwell*, 2nd ed., XI+384 p.

BIGROM (2021). Elaborat o rezervama građevnog pijeska i šljunka na eksploatacijskom polju „Papuča". Gospić. (in Croatian).

Bognar, A. & Faivre, S. (2006). Geomorphological traces of the younger Pleistocene glaciation in the central part of the Velebit Mt. *Hrvatski geografski glasnik, 68*(2), 19-30. https://doi.org/10.21861/HGG.2006.68.02.02

Cohen, K.M., Finney, S.C., Gibbard, P.L. & Fan, J.-X. (2013; updated). The ICS International Chronostratigraphic Chart. *Episodes*, *36*: 199-204. URL: http://www.stratigraphy.org/ICSchart/ChronostratChart2022-10.pdf

Gavazzi, A. (1903). Tragovi oledbe na Velebitu. *Glasnik hrvatskog naravoslovnog društva, 14*, 459-460. (in Croatian).

Hughes, P.D., Woodward, J.C., van Calsteren, P.C., Thomas, L.E. & Adamson, K.R. (2010). Pleistocene ice caps on the coastal mountains of the Adriatic Sea. *Quaternary Science Reviews 29*, 3690-3708. https://doi.org/10.1016/j.quascirev.2010.06.032

Krklec, K., Domínguez-Villar, D. & Perica, D. (2015). Depositional environments and diagenesis of a carbonate till from a Quaternary paleoglacier sequence in the Southern Velebit Mountain (Croatia). *Palaeogeography, Palaeoclimatology, Palaeoecology 436*, 188-198. https://doi.org/10.1016/j.palaeo.2015.07.004

Kochanski-Devide, V. (1970). Die Kalkalgen des Karbons vom Velebit-Gebirge (Moskovien und Kassimovien). (Vapnenačke alge (moskovijen i kasimovien). *Palaeon. Jugosl., 10*, 1-32, Zagreb.

Lawson, D. E (1982). Mobilisation, movement and deposition of active subaerial sediment flow, Matanuska glacier, Alaska. *The Journal of Geology, 90*(3), 279-300.

Marjanac, L. (2012, unpublished). Pleistocene Glacial and Periglacial Sediments of Kvarner, Northern Dalmatia and Southern Velebit Mt. – Evidence of Dinaric Glaciation. PhD thesis. University of Zagreb, Croatia.

Müller, G. (1967). Methods in Sedimentary Petrology. *Schweizerbart*, Stuttgart, Germany, 1-283.

Milojević, B.Ž. (1922). Beleške o glečerskim tragovima na Raduši, Cincaru, Šatoru, Troglavu i Velebitu. *Glasnik Srpskog geografskog društva, 7–9*, 294-297. (in Serbian)

Nikler, L. (1973). Nov prilog poznavanju oledbe Velebita (Ein neuer Beitrag zur Kenntnis der Vereisung im Velebit Gebirge). *Geološki vjesnik, 25*, 109-112. (in Croatian, with German summary).

Perica, D. & Orešić, D. (1999). Klimatska obilježja Velebita i njihov utjecaj na oblikovanje reljefa. *Senjski zbornik: prilozi za geografiju, etnologiju, gospodarstvo, povijest i kulturu, 26*(1), 1-50. (in Croatian, with English summary).

Roglić, J. (1963). Glaciation of the Dinaric mountains and its effects on the Karst. *Report of the 6th International Congress on, Warsaw 1961, Panstwowe Wydawnictwo Naukowe*, Lodź, 293-299.

Sarıkaya, A., Stepišnik, U., Žebre, M., Çiner, A., Yıldırım, C., Vlahović, I., Tomljenović, B., Matoš, B., Klaus M. & Wilcken, M. K. (2020). Last glacial maximum deglaciation of the Southern Velebit Mt. (Croatia): insights from cosmogenic ^{36}Cl dating of Rujanska Kosa. *Mediterranean Geo-*

science Reviews, 2, 53-64. https://doi.org/10.1007/s42990-020-00030-9

Schubert, R. (1909). Geologija Dalmacije. *Matica dalmatinska*, 1-183, Zadar. (in Croatian)

Sokač, B., Nikler, L., Velić, I. & Mamužić, P. (1974). Osnovna geološka karta SFRJ, list Gospić 1:100 000, L 33-127; (Basic Geological Map SFRJ, The Gospić sheet 1:100 000, L 33-127). Institute of geology Zagreb, Federal institute of geology, Beograd.

Sremac J., Velić J., Bošnjak M., Velić I., Bakrač K., Šimičević A., Malvić T. & Fotović D. (2024). Genesis of the Upper Pleistocene gravel from the Abesinija pit SE from Zagreb (Croatia). *Rivista Italiana di Paleontologia e Stratigrafia, 130*(3): 613-631. https://riviste.unimi.it/index.php/RIPS/article/view/22533/22124

Šušnjar, M., Sokač. B., Bahun, S., Bukovac, J., Nikler., L., & Ivanović, A. (1973). Osnovna geološka karta SFRJ, list Udbina 1:100 000. (Basic Geological Map SFRJ, The Udbina sheet 1:100 000, Institute of geology Zagreb, Federal institute of geology, Beograd.

Tišljar, J. (2004): Sedimentologija klastičnih i silicijskih taložina. *Institut za geološka istraživanja*. 1-426. (in Croatian)

Velić, I. & Velić, J. (2019). Glacijalno-geološke značajke područja Nacionalnoga parka Paklenica; Od snježne pahuljice do moćnoga ledenjaka i natrag (Glaciogeological characteristics of The Paklenica national park; From snowflake to the powerful glacier and back). *JU Nacionalni park Paklenica, Starigrad Paklenica*, 1-123. (in Croatian)

Velić, J., Velić, I. & Kljajo, D. (2011). Sedimentary bodies, forms and occurences in the Tudorevo and Mirovo glacial deposits of northern Velebit (Croatia). *Geologia Croatica, 64*(1), 1-16.

Velić, I., Velić, J., Vlahović, I. & Cvetković, M. (2014). Geološki vodič kroz NP Paklenica (Geological Guide trough NP Paklenica). *JU Nacionalni park Paklenica, Starigrad Paklenica*, 1-331. (in Croatian)

Velić, J., Velić, I., Kljajo, D., Protrka, K., Škrabić, H. & Špoljar, Z. (2017). An geological overview of glacial accumulation and erosional occurrences on the Velebit and the Biokovo Mts., Croatia. *Rudarsko-geološko-naftni Zbornik, 32*(4), 77-96. https://doi.org/10.17794/rgn.2017.4.8.

Zielinski, T. & van Loon, A. J. (1999). Subaerial terminoglacial fans I: a semi-quantitative sedimentological analysis of the proximal environment. *Geologie en Mijnbouw, 77*, 1-15.

Zinng, T. (1935). Beitrag zur Schotteranalyse. *Schweiz. Miner. Petrol. Mitt., 15*, 39-140.

Žebre, M., Jež, J., Mechernich, S., Mušič, B., Horn, B. & Jamšek Rupnik, P. (2019). Paraglacial adjustment of alluvial fans to the last deglaciation in the Snežnik Mountain, Dinaric karst (Slovenia). *Geomorphology, 332*, 66-79. https://doi.org/10.1016/j.geomorph.2019.02.007.

URL 1. https://preglednik.arkod.hr

SAŽETAK

Stratigrafske i morfometrijske značajke klasta otjecajnoga tila iz ležišta šljunka „Papuča", Gospić, Hrvatska

Istraživano područje predstavlja eksploatacijsko polje šljunka „Papuča" u središnjemu dijelu Like, u podnožju Velebita, 22 km jugoistočno od Gospića. Terenskim radovima izabrano je više od 200 blokova i valutica kojima je bilo moguće odrediti stratigrafsku pripadnost – podrijetlo, a to su jurski, trijaski i permski karbonati. Na licu mjesta obavljeno je i mjerenje duljina triju međusobno okomitih osi potrebnih za izradbu Zinngovih dijagrama, tj. za morfometrijsku analizu. Prema Zinggovu grafu najveći broj valutica sferoidnog je oblika (37 %, 74 valutica), slijede valutice diskoidnoga (27,5 %, 55 valutica) i vretenastoga (20,5 %, 41 valutica) oblika te valutice pločasta oblika, koje su najmanje zastupljene (6 %, 12 valutica). Lepezu/lob debljine do 14 m izgrađuje loše sortirani krupnozrnati šljunak s pijeskom, slabo vezani, nekonsolidirani. Prema medijanu Md (7,5 mm) 50 % zrna čine veličinu od 7,5 mm što odgovara srednjozrnatom šljunku. Koeficijent sortiranja po Trasku (So 6,44) upućuje na lošu sortiranost, a koeficijent asimetrije (*skewness* Sk 0,313) na prevladavanje krupnijih zrna od medijana, tj. da je krivulja asimetrična na strani krupnijih zrna. Stupanj sploštenosti zrna iznosi 1,7, što odgovara fluvioglacijalnim okolišima i okolišima morena. Po koritastome reljefu s vrlo strmo urezanim bujičnjacima Ljutik i Široka draga na sjevernoj, razmjerno strmoj padini Velebita na područje današnjih lepeza/režnjeva tijekom zatopljenja, tj. otapanja ledenjaka s visokih dijelova Velebita, otjecale su velike količine sočnice noseći klaste različitih dimenzija i stratigrafske starosti podrijetlom iz podloge ledenjaka i dominantno iz obronaka. Sedimentiran je otjecajni loše sortiran i nekonsolidiran til – *flow till* – iz tokova stijenskoga krša stvarajući male lepeze odnosno režnjeve. Vrijeme povlačenja ledenjaka počelo je prije 20 700±200 godina, tj. na početku interstadijala Greenland INo. 1. – tijekom kasnoga pleistocena, što je i starost ležišta.

Ključne riječi:
otjecajni til, stratigrafija, veličine i oblici klasta, gornji pleistocen, Velebit, Hrvatska

Author's contribution

Josipa Velić (emeritus professor): organized the fieldwork, defined the boundaries of gravel sediment bodies, planned the pebble sampling, separated the pebbles for axis measurement, conceptualized the methods, titled, and wrote the manuscript. **Ivo Velić** (scientific advisor): defined the geological age and lithological features of pebbles and bedrocks in the field and under the microscope.
All authors have read and agreed to the published version of the manuscript.