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Sources of Pleistocene to Recent Alluvial Sediments of Northwestern Bilogora and Surrounding Areas (Croatia)

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Abstract

This study aims to determine the provenance of Pleistocene to recent alluvial sediments in the area of NW Bilogora. The research area includes Pannonian inselbergs of northern Croatia with a major focus on Bilogora Mountain. Framework composition and heavy mineral assemblages of sand samples, together with micropetrographical characteristics and whole-rock geochemistry of volcanic and volcaniclastic pebbles and rocks are used to explore sources of Lower-Middle Pleistocene deposits of the oldest Drava River terrace, along with local stream and river sediments. The development of this area is closely linked to local and regional tectonic processes, as well as the formation of the Drava-Mura River system which has supplied detrital material from the Eastern Alps, at least since Miocene times. The composition of Pleistocene sands points to extensive recycling from local Neogene sedimentary units, a process which is still ongoing today. Silicic pebbles correlate well with the widespread Permian-Triassic igneous activity in the Austroalpine units and Tisia, though the pebbles are likely recycled from Miocene conglomerates. Findings of mafic volcanic lithoclasts indicate the possibility of erosion of the pre-Neogene basement of mountains Kalnik and Ivanščica as well. During the Early-Middle Pleistocene, the Drava River basin of today's northern Bilogora area received material from the Alps, along with local supply from units exposed on uplifting local inselbergs. Intermittent changes in sediment supply dynamics could have been affected by climatic changes and local uplift tectonics, coupled with hydrological dynamics in the Drava River during the Pleistocene.

Keywords:
NW Bilogora, SW Pannonian Basin, Pleistocene, recent stream sediment, provenance

1. Introduction

The SW region of the Pannonian Basin System (PBS), specifically the area of the Drava River basin in Croatia (see **Figure 1**), has been supplied with detrital material from the long-standing sediment source area in the Eastern Alps at least since Early Miocene times. This is reflected in the composition of the Neogene and Quaternary sediment successions (**Mutić, 1975a; 1975b; Šćavnićar, 1979; Šimunić and Šimunić, 1987; Kovačić and Grizelj, 2006; Kovačić et al., 2009; Matošević et al., 2023**), and is still evident today in the material carried by the modern Drava and Mura rivers (**Arato et al., 2021**). The more recent Quaternary period is characterized by particularly intense climate oscillations, with transitions between glacial and interglacial episodes dictating changes in sediment yield, transport, and deposition over local to regional scales. Pleistocene glacial periods have been characterized by intense physical weathering in highland regions. With waning glacial conditions sediment yield from such areas was greatly enhanced during paraglacial conditions that followed (**Church and Ryder, 1972; Ballantyne, 2002; Sommerwerk et al., 2009**). In the Drava depression and surrounding areas, such periods characterized by a sediment-laden and water-rich paleo-Drava River produced considerable accumulations of coarse-grained clastic deposits, contrary to glacial periods during which aeolian depositional environments dominated (**Galović and Magdalenić, 1975; Mutić, 1975a; Babić et al., 1978; Mutić, 1989; Peh et al., 1998; Wacha et al., 2018**). In addition to climate changes, local tectonic uplift has also caused reorganization of paleo-environments and sediment pathways (**Peh et al., 1998; Kovačić and Grizelj, 2006; Mrinjek et al., 2006; Kovačić et al., 2009; Man-**

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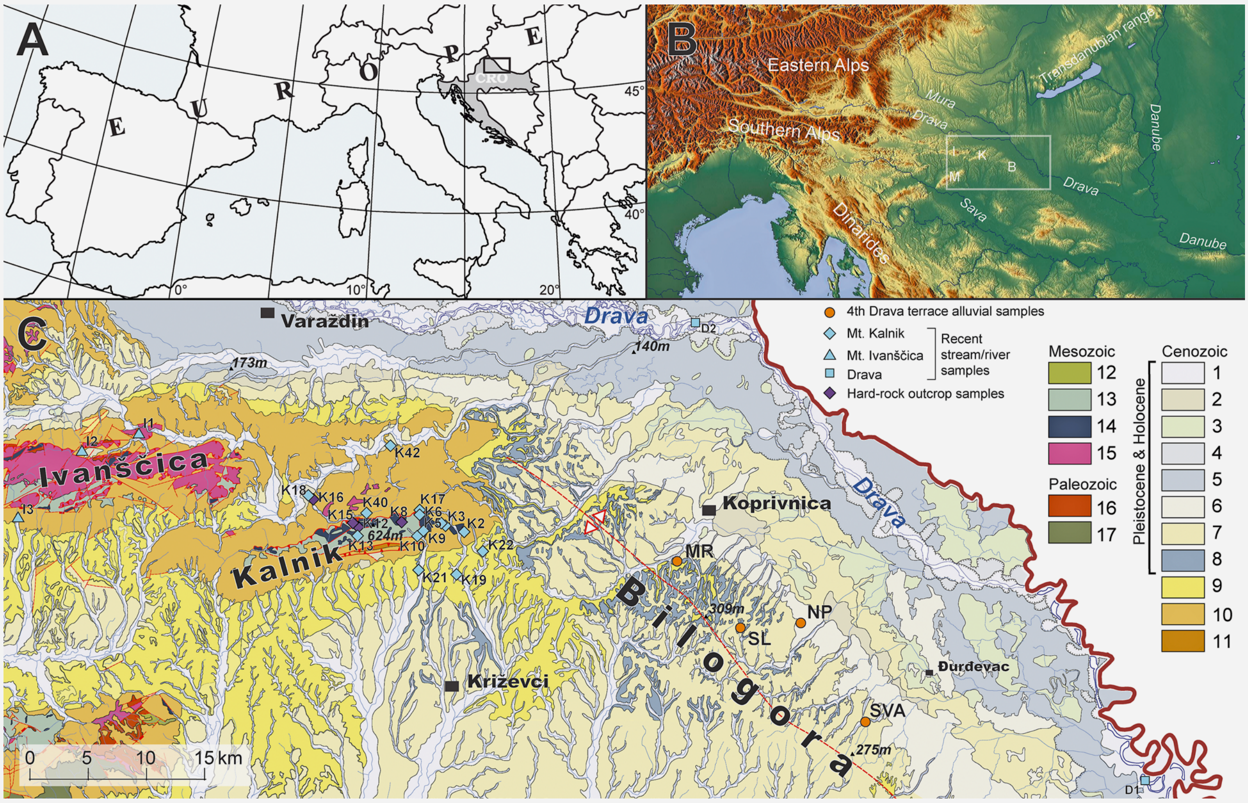

Figure 1. **(A)** Reference map of southern Europe with the position of the study area indicated by a rectangle; **(B)** Morphological map depicting the Eastern and Southern Alps, Northern Dinarides, and SW region of the Pannonian Basin. The location of the study area is indicated by the rectangle. B-Mt. Bilogora, K-Mt. Kalnik, I-Mt. Ivanščica, M-Mt. Medvednica; **(C)** Simplified geological map of Bilogora Mountain and the surrounding area with sampling locations (after **Galović and Marković, 1979; Basch, 1981; Šimunić et al., 1983, 2014; Korolija and Crnko, 1985; Hećimović, 1986; Jamičić, 1989**). Geological units in the study area-Cenozoic: 1-River and stream alluvium (silt, sand, gravel), 2-Proluvial and alluvial sediment, 3-Lake-swamp organogenic sediment, 4-1st alluvial terrace of Drava River, 5-2nd alluvial terrace of Drava River, 6-Eolian sands, 7-Loess and swamp loess, 8-4th alluvial terrace of Drava River, 9-Pontian and Pliocene clastics (gravel, sand, sandstone, marl, clay), 10-Early and Middle Miocene clastics (breccia, conglomerate, sandstone, marl, clay), marly limestone, sandy limestone, 11-Paleocene-Eocene carbonate breccia; Mesozoic: 12-Upper Cretaceous sediments, 13-Jurassic sediments - ophiolitic melange (shales, sandstones, limestones, chert), 14-Jurassic igneous rocks (diabase, basalt, serpentinite), 15-Triassic clastics, carbonates, and volcanics; Paleozoic: 16-Permian low-grade metasediments, 17-Devonian-Carboniferous low-grade metasediments. Abbreviations: MR-Mučna Reka, SL-Selinec, NP-Novigrad Podravski, SVA-Sv. Ana.

dic et al., 2015; Matoš et al., 2016; Wacha et al., 2018; Mencin Gale et al., 2019; Kurečić et al., 2021). While the overall tectonic evolution of the PBS is complex and characterized by alterations of extensional and compressional/transpressional tectonic phases through the Neogene and Quaternary (**e.g. Royden et al., 1983; Huismans et al., 2001; Brückl et al., 2010; Schmid et al., 2020 with references**), the tectonic stage that had the most profound effect on Quaternary landscape formation in the SW area of the PBS was Pliocene-Quaternary tectonic inversion/structural reactivation during which Bilogora and other nearby mountains were tectonically uplifted at the scale of few hundreds of meters (**Šimunić and Šimunić, 1987; Tomljenović and Csontos, 2001; Matoš et al., 2016, 2017; Wacha et al., 2018**).

While Upper Pleistocene aeolian deposits in the Drava River area have received some attention in the past (**Galović and Magdalenić, 1975; Mutić, 1975b; Babić et al., 1978; Galović, 2016**), very little information exists on the Early to Middle Pleistocene coarse-grained deposits that characterize the oldest Drava River terrace exposed on the NE slopes of the Bilogora. Only a few studies have been reported on the composition and provenance of these sediments, most of them briefly emphasizing an Alpine source of detrital material (**Mutić, 1975a; Brenko et al., 2020, 2021**). The possibility of intermittent local supply of the Drava River terraces has been hinted at by a few authors (**Babić et al., 1978; Peh et al., 1998; Šimunić et al., 2014**), implicating possible oscillations in sediment supply between different source areas.

The investigated area is located in the hilly landscape region of northern Croatia, along the southwestern margin of the Drava depression, in the area of northwestern portions of Bilogora, near mountains Kalnik and Ivanščica, as well as the modern Drava River course (see

Figure 1). In this study, we focus on the determination of the petrographic and heavy mineral composition of Pleistocene sands and the geochemistry of assorted volcanic and volcaniclastic pebbles from the oldest Drava River terrace, in combination with comparable data from recent stream and river sediment from surrounding areas. The aim of the research is to gain a better understanding of the interplay between distal and local sediment source contribution to the study area during the Quaternary in relation to tectonics and climate changes.

2. Geological settings

The geological history of the study area is closely associated with the tectonic evolution of the Drava depression, an integral part of the North Croatian Basin (NCB) which represents a SW segment of the PBS (**e.g. Matoš et al., 2016, 2017; Pavelić and Kovačić, 2018, and references therein**). The formation of the PBS initiated due to the Adria Microplate - European plate collision (Late Oligocene-Early Miocene) that yielded lateral extrusion of the Alpine-Carpathian-Pannonian (ALCAPA) crustal block and E-W "back-arc type" extension (**e.g. Ratschbacher, 1991a; Ratschbacher et al., 1991b; Horváth and Tari, 1999, and references therein**). Formation of fault-related troughs within the PBS, which were affected by thermal subsidence through the Middle and Upper Miocene **(e.g. Horváth and Tari, 1999; Saftić et al., 2003**), resulted in high sedimentation rates and formation of thick sedimentary successions (**Horváth and Tari, 1999; Saftić et al., 2003, and references therein**). However, during the Pliocene and the Quaternary regional stresses within the PBS changed from extension to compression/transpression (**e.g. Bada et al., 2007**). This resulted in structural reactivation and tectonic inversion of inherited faults, including the Drava depression normal fault, which was reactivated and tectonically inverted as a dextral fault forming the Bilogora cogenetic transpressional structure (**Matoš, 2014; Wacha et al., 2018**). In the NCB, this tectonic inversion was initiated during the Late Pannonian (**e.g. Prelogović et al., 1998; Matoš 2014, and references within**), whereas tectonic uplift of Bilogora climaxed during the mid-Pleistocene (**e.g. Matoš et al. 2016, 2017; Wacha et al., 2018**). Along with the Bilogora structure, in the Late Pontian (c. 7.5 Ma) tectonic inversion also uplifted the nearby mountains Kalnik, Ivanščica, and Medvednica (see **Figure 1**). With an average altitude in the range of 300 to 500 m, the E-W striking structure of Mt. Kalnik resembles a lithological mosaic of Jurassic, Cretaceous, and Paleogene complexes that were affected by previous Hercynian and Alpine tectogenesis (**Šimunić and Hećimović, 1979; Šimunić et al., 1982; Tomljenović et al., 2008**). The Late Miocene tectonic uplift of Mt. Kalnik climaxed during the Pliocene and Quaternary due to N-S directed shortening when Mt. Kalnik experienced an uplift of several hundred meters (**Hećimović, 1995**), involving thrusting and overlapping which exposed pre-Neogene and Neogene units surrounded by Plio-Quaternary sediments. Tectonic uplift of the Bilogora and Mt. Kalnik during the Pliocene and Quaternary were in a range of c. 200 to 700 m respectively, contributing to the final landscape formation of the study area (**Kranjec et al., 1971; Prelogović, 1974; Prelogović and Velić, 1988; Matoš, 2014; Matoš et al., 2016**).

The Neogene and Quaternary stratigraphy of the study area, which includes parts of the North Croatian Basin and Hrvatsko Zagorje Basin, is well established from outcrops along uplifted inselbergs and subsurface data (see **Figure 1; Babić et al., 1978; Lučić et al., 2001; Saftić et al., 2003; Pavelić and Kovačić, 2018; Avanić et al., 2021**). The Early Miocene syn-rift phase was characterized by deposition in varied continental and shallow marine environments producing dominantly coarse-grained deposits (**e.g. Pavelić et al., 2001; 2024; Avanić, 2012; Avanić et al., 2021**). Continued regional subsidence during the Middle Miocene led to more uniform open lacustrine, followed by marine deposition of dominantly fine-grained and carbonate sediments, with sporadic influxes of coarse-grained material. The Late Miocene was characterized by isolation from marine realms and the establishment of the brackish Lake Pannon. At the time it covered much of the wider region but was slowly infilled by prograding delta systems from the NW, which gave way to widespread continental environments by the Pliocene (**Kovačić et al., 2004; Kovačić and Grizelj, 2006; Sebe et al., 2020**). In the western Drava depression and surrounding areas, depositional environments were characterized by general delta plain (e.g. channels, marsh lagoons) environments; firstly, fluvial, alluvial fan, marsh, and isolated lacustrine environments during Pliocene, while during Pleistocene and Holocene these environments transitioned to prevailing aeolian environments (**Kranjec et al., 1971; Galović and Magdalenić, 1975; Kovačić et al., 2009; Grizelj et al., 2017; Kurečić et al., 2021**). In the Sava depression and Slavonia, to the S and SE of the study area, lacustrine environments of the large fresh-water Lake Slavonia persisted until the Early Pleistocene, when they were replaced by alluvial, marsh and aeolian deposits (**Mandic et al., 2015; Kurečić, 2017**).

Through the Pleistocene and Holocene, the Drava River constructed four aggradational terraces (**Šimunić et al., 2013**). Terrace formation was a result of increased sediment influx conditioned by tectonic uplift in the source area(s), climate oscillations from glacial to interglacial conditions, and spatial migration of the braided paleo-Drava River system. The studied fourth Drava terrace, which is today exposed on Bilogora consists of up to 80 m of gravel, sand, and silt layers (**Šimunić et al., 2014; Wacha et al., 2018**). In NW Bilogora, the gravels are composed largely of sub to well-rounded quartz pebbles and lithoclasts of metamorphic, magmatic, and sedimentary origin, mostly ranging in size from 4 to 6 cm in

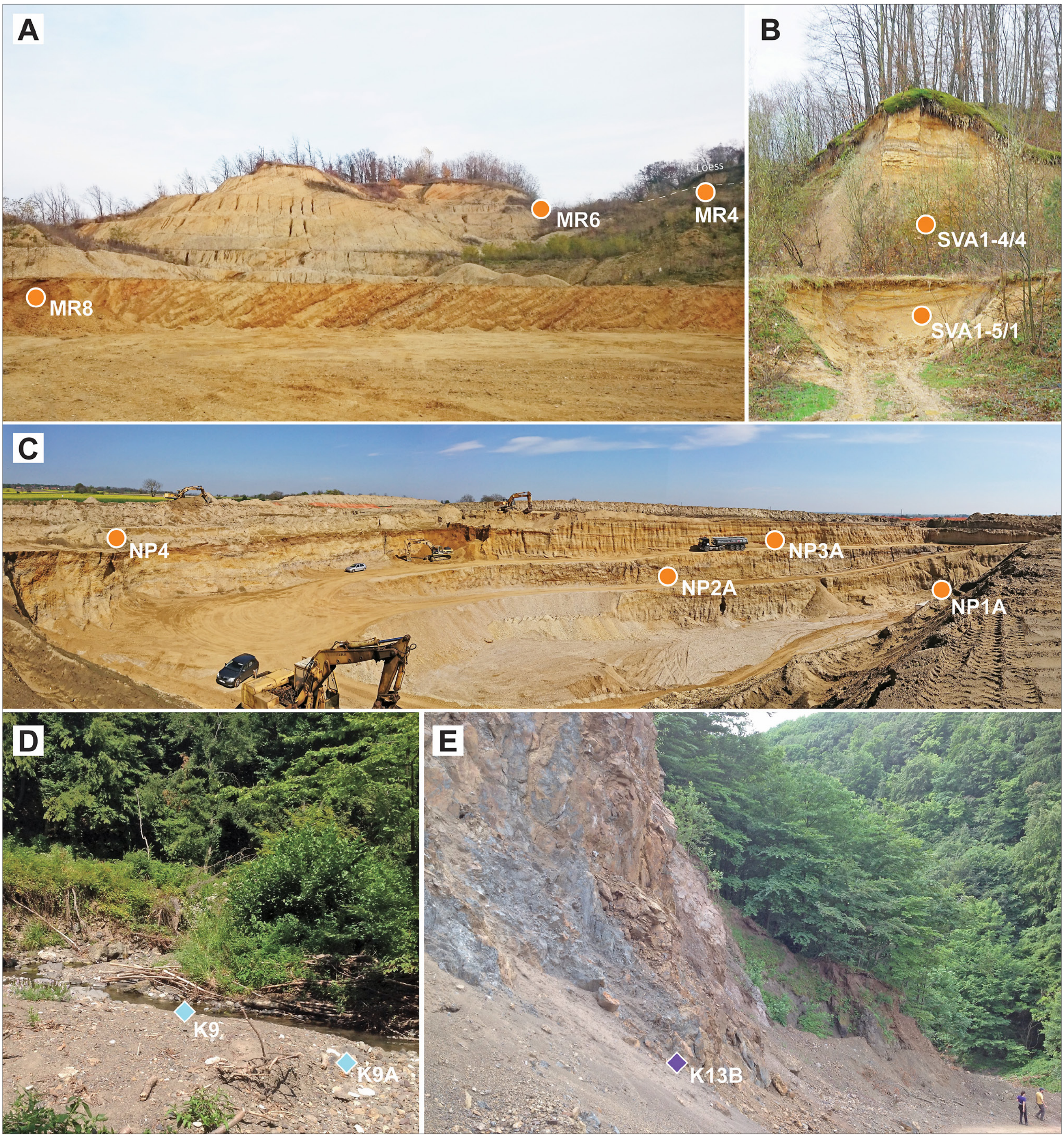

Figure 2. Field photos of sand and gravel quarries and pits exposing Pleistocene alluvial deposits within the NW Bilogora area at **(A)** Mučna Reka, **(B)** Sv. Ana and **(C)** Novigrad Podravski. **(D)** A gravel and sand bar in Kamešnica Creek, southern Mt. Kalnik. **(E)** Pillow basalts exposed in the quarry near Ljubelj Kalnički, Mt. Kalnik. Points indicate sampling locations. See **Figure 1** for geographic locations.

diameter, occasionally up to 12 to 25 cm. The gravel is intercalated with lenses and layers of coarse to medium-grained, medium to poorly sorted sand. **Wacha et al. (2018)** reported a minimum age of >359 ka based on luminescence dating of a sand sample from the Mučna Reka location, suggesting a Middle Pleistocene or older age. On the official geological map of Croatia 1:100 000 (Koprivnica sheet) these deposits are identified as belonging to the Lower and Middle Pleistocene (**Šimunić et al., 2013**). The described coarse-grained deposits are usually topped by a few meters thick loess-like cover dated as Upper Pleistocene, with ages corresponding to the Last Glacial (**Wacha et al., 2018**). Based on IRSL ages **Wacha et al. (2018)** also suggested that uplift in the northwestern portions of Bilogora probably climaxed in the Middle Pleistocene when the deposits of the fourth Drava River terrace were relatively uplifted (between 200 and 450 m) to elevations between 160 and 309 m a.s.l. There are certain discrepancies in the stratigraphic assignment of the fourth Drava terrace in older publications and geological maps. Authors in the past have commonly included the sediments of the fourth Drava terrace in the so-called "Belvedere gravel" (**Soklić, 1943, 1952**) which are of Pliocene age, while on certain geological maps, they are included in the Pliocene-Quaternary succession (**Korolija et al., 1986**). The deposits of the three younger terraces have been ascribed by different authors to the Middle-Upper Pleistocene and Holocene (**Mutić, 1975a; Babić et al., 1978; Šimunić et al., 2014**). In the Drava depression and up to the NE slopes of Mt. Bilogora in the Koprivnica area, deposits of this period make up approximately 100 m of the sediment succession (**Babić et al., 1978; Šimunić et al., 2013**).

3. Methodology

Field investigation included an inspection of the available outcrops and the sampling of sands and individual pebbles in the Pleistocene alluvial sands and gravels from NW Bilogora. Samples were mostly collected from active or abandoned sand and gravel quarries and pits. Three sand samples were collected at Mučna Reka, one from Selinec, four from Novigrad Podravski, and two from Sveta Ana (see **Figures 1** and **2**). Pebbles of volcanic rocks were collected at Mučna Reka and Novigrad Podravski. Detrital material from modern streams of Mt. Kalnik, Mt. Ivanščica, and the Drava River was sampled and analyzed to explore compositions of potential local and distal sedimentary sources (see **Figures 1** and **2**). This included stream sand samples and individual volcanic pebbles. Additionally, volcanic pebbles from Middle Miocene conglomerates along the margins of Mt. Kalnik, and samples of volcanic rocks from the ophiolitic mélange of Jurassic age on Mt. Kalnik were also sampled (see **Figures 1** and **2**). Petrographic analysis was performed on all collected samples, heavy mineral analysis was performed on sand samples, while selected pebbles of volcanic and volcaniclastic rock samples were subjected to whole-rock geochemical analysis. Volcanic lithologies (both as detrital pebbles and hard rock outcrops) were specifically chosen as the focus of analyses since they represent a distinct group consistently encountered in all studied units. Furthermore, such material lends itself to suitable petrographic and geochemical discrimination. The complete list of collected samples, their basic data and performed analyses is given in **Supplement 1**.

For quantitative framework petrographic analysis, sand samples were sieved, and grains within the 250-500 μm and 500-1000 μm fractions were artificially cemented using resin and hardener. Microscope thin sections were produced from the prepared sand samples. Grains were optically determined using a polarizing microscope and an average of 500 points were counted for each thin section according to the Gazzi-Dickinson method (**Ingersoll et al., 1984; Zuffa, 1985, 1987**). Metamorphic lithic grains were subdivided using criteria proposed by **Garzanti and Vezzoli (2003)** into metapelite, metapsammite/metafelsite, metacarbonate, and metabasite grains.

For quantitative heavy mineral analysis, sand samples were treated with 5% acetic acid, sieved, and ultrasonically cleaned from adhering clays. Sodium polytungstate ($3Na_2WO_4$ x $9WO_3$ x H_2O) with a density of 2.895 was used for mineral separation of the 63 to 125 μm fraction. A small amount of each heavy mineral fraction was mounted on microscope slides using Meltmount (n=1.66). About 250-300 translucent grains were optically determined in each sample using a polarizing microscope by ribbon counting.

Collected pebble and rock samples of volcanic and volcaniclastic lithology were micropetrographically analyzed. For that purpose, 44 thin sections were prepared from volcanic recent stream pebbles, Middle Miocene conglomerate pebbles and Jurassic hard rock samples, using standard procedure in the Laboratory for the preparation of geological materials of the Department of Mineralogy, Petrology and Mineral Resources, Faculty of Mining, Geology and Petroleum Engineering (University of Zagreb). Thin sections were stained using K-ferricyanide and Alizarine Red S by the procedure of **Dickson (1965)**, for easier determination of calcite and dolomite. After the preparation, thin sections were analyzed using a polarizing microscope Leica 120 DM/LSP and Zeiss Axiolab at the Division for Mineralogy and Petrography at the Department of Geology, Faculty of Science (University of Zagreb). For whole-rock geochemical analysis, 20 samples (pebbles and rock samples) were chosen based on their petrographic characteristics and sampling area. The samples were cut using a rock saw to discard the weathered zones on the sample surface. The freshest parts of the samples were then manually disintegrated into smaller fragments, quartered, and finally ground to powder in an agate mill. The powdered samples were sent to Bureau Veritas Mineral Laboratories for whole-rock geochemical analysis. Major element concentrations were analyzed by ICP-ES (Inductively Coupled Plasma Emission Spectrometer) and the results are shown in percentages. Minor elements, including rare earth elements (REE), were analyzed by the ICP-MS method and their concentrations are expressed in ppm or ppb units. Internal standards (STD) DS11, GS311-1, GS910-4, OREAS262, SO-19 were used. The whole-rock results were analyzed using GCDkit 6.1. software (**Janoušek et al., 2006**).

4. Results

4.1. Framework composition and heavy mineral assemblages of sand samples

Results of the quantitative petrographic and heavy mineral analysis of the studied sand samples are availa-

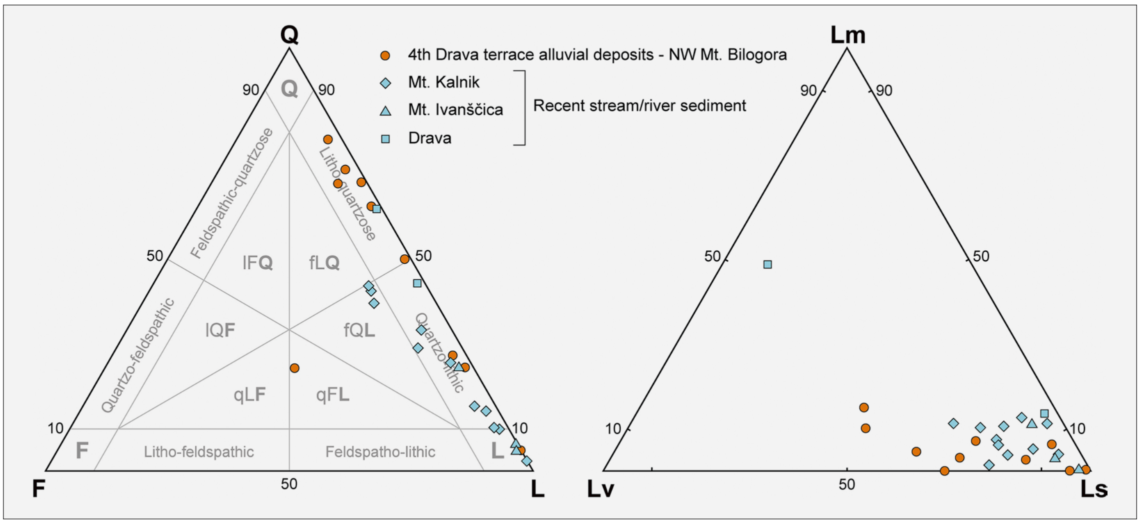

Figure 3. Framework composition of studied sand samples based on the Gazzi-Dickinson point counting method. QFL diagram (left) displays the proportions of major detrital components (fields after **Garzanti, 2019**), and the LmLvLs diagram (right) displays metamorphic, volcanic, and sedimentary lithic fragments.

ble in **Supplements 2** and **3**. Quartz and lithic grains dominate the framework compositions of the studied sands. Based on the classification proposed by **Garzanti (2019)** most samples can be classified in the range of lithic, quartzo-lithic to litho-quartzose sands (see **Figure 3**). Only three samples with feldspar content slightly above 10% classify as feldspatho-quartzo-lithic and one sample from Mučna Reka (MR4) with high feldspar content as quartzo-feldspatho-lithic. Almost all sands from recent streams of Mt. Kalnik, Mt. Ivanščica, and the Drava River contain more than 50% of lithics (see **Figure 4a-d**). Pleistocene samples from NW Bilogora display variable quartz-to-lithic ratios, but are comparably more quartz-rich, with half of the samples having quartz content well above 50% (see **Figures 3** and **4e, f**). Quartz is present as both monocrystalline and polycrystalline varieties, the latter being slightly more dominant in most samples. Among the lithic grains, sedimentary lithoclasts dominate all samples except one from the Drava River (see **Figures 3** and **4a**). These are mostly fragments of fine-grained clastic rocks, while carbonate lithoclasts were identified in recent stream sands from Mt. Ivanščica (see **Figure 4b**). The proportion of metamorphic lithics is less or slightly above 10% in almost all samples, while volcanic lithics are more represented in some of the Pleistocene samples from NW Bilogora. Volcanic lithic grains are most commonly felsic volcanics, while mafic volcanic grains were regularly encountered in stream sand samples from Mt. Kalnik.

The most common heavy mineral species in the analyzed sand samples are garnet, rutile, staurolite, zircon, epidote, tourmaline, and amphibole with minor amounts of kyanite, apatite, pyroxene, Cr-spinel, and titanite (see **Supplement 3**). However, their relative proportions vary considerably among the studied groups and locations of samples. These differences are illustrated in the diagrams presented in **Figure 5**.

Sand samples from the Pleistocene alluvial deposits of NW Bilogora are characterized by a high ZTR (zircon, tourmaline, and rutile) index, with rutile being consistently the dominant ultrastable mineral in all samples. RuZi (rutile-zircon) index is above 50 in all Pleistocene samples, with values up to 88. The garnet content varies considerably ranging from a few percent up to 69%, while epidote/zoisite is abundant but also variable among the individual Pleistocene samples. The GZi (garnet-zircon) index varies extensively from 8.8 to 98.4, even within individual groups of samples. Among the Pleistocene alluvial samples from Bilogora all of the samples from Mučna Reka (MR4, MR6, MR8), two samples from Novigrad Podravski (NP4, NP3A), and one from Sveta Ana (SVA 5/1) have GZi values lower than 40. Conversely, several samples from the same Pleistocene localities have high indices, as do most of the samples from Mt. Kalnik and the Drava River. Sand samples from modern streams of Mt. Kalnik and Mt. Ivanščica have consistently high garnet and ZTR content, while amphibole, staurolite, and epidote/zoisite are highly variable from a few percent up to a maximum 33%, 29%, and 17%, respectively in individual samples. Sands of the modern Drava River have heavy mineral assemblages dominated by garnet, with a common occurrence of amphibole and epidote/zoisite, and low ZTR.

4.2. Petrography of volcanic and volcaniclastic pebble and rock samples

Based on the micropetrographical analysis, volcanic and volcaniclastic pebble and hard rock outcrop samples, can further be grouped into two petrographic categories: 1) samples composed dominantly of felsic mineral phases and 2) samples composed dominantly of mafic mineral phases.

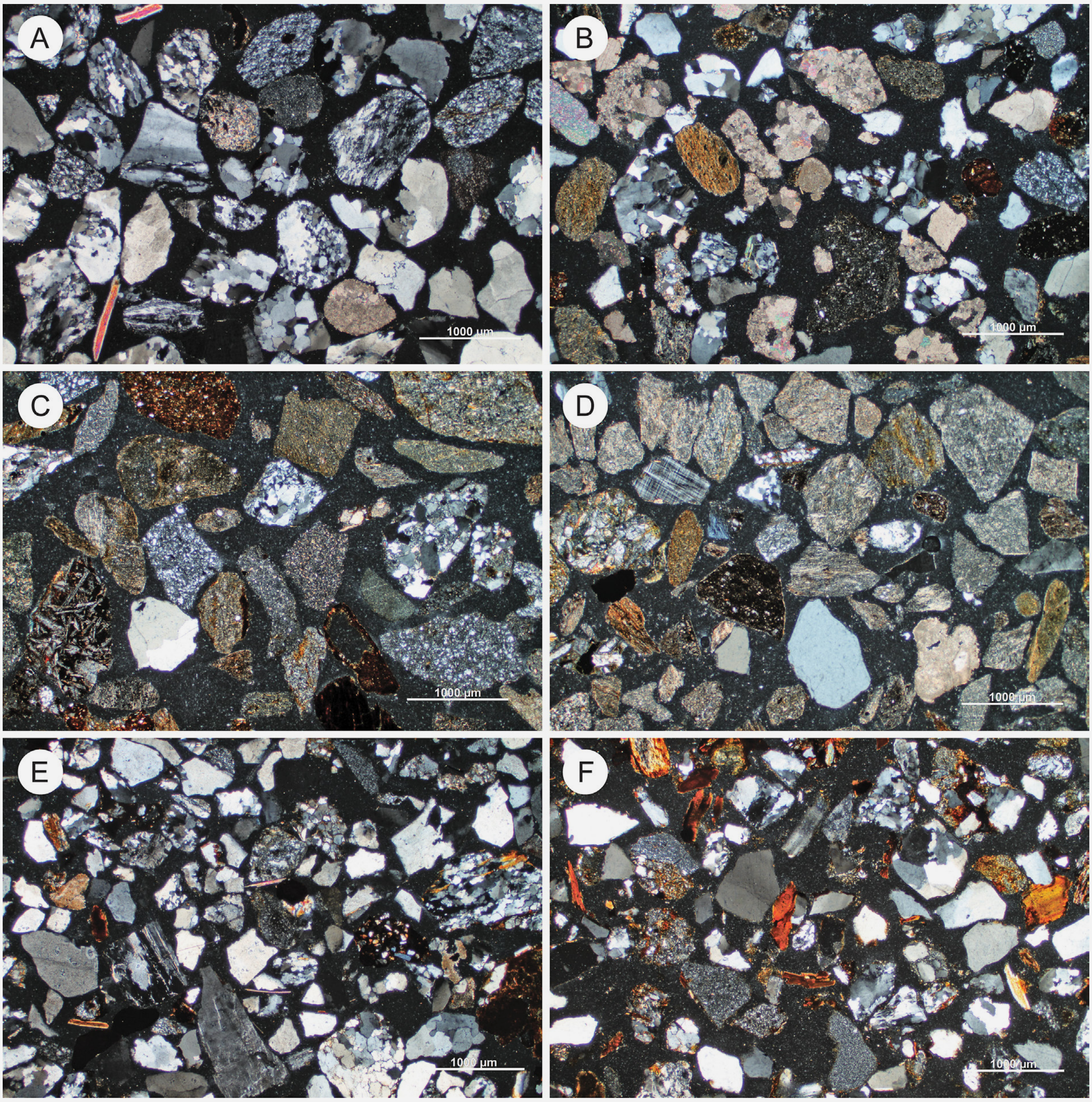

Figure 4. Selected microphotographs of analyzed sand samples. (A) Drava River sand - sample D2, (B) Stream sand from Mt. Ivanščica – sample I1 (C) Stream sand from Mt. Kalnik – sample K12 (D) Stream sand from Mt. Kalnik – sample K9 (E) Pleistocene sand from Mučna reka – sample MR4 (F) Pleistocene sand from the Novigrad Podravski gravel pit – sample NP2a

Samples from category 1 are K-5, K-8A, K-8B, K-8C, K-9A, K-9B, K-16A, K-16B, K-16E, K-17A, BM-2, BMR-3, NP-1, NP-2, NP-3 and MR-2. The main characteristic of these samples, except samples K-16A and K-16B, is the presence of flow textures. This texture is visible due to a significant amount of elongated pumice fragments, often exhibiting fiamme texture, and imbrication of elongated mineral grains (see **Figure 6a**). This group of samples is composed of crystalloclastic and vitroclastic particles. The most dominant crystalloclast is quartz of varying sizes. Most of the quartz crystalloclasts are rounded, often with embayments and oval cavities filled with microcrystalline aggregates. Resorption rims are also seen. A certain extent of quartz crystalloclasts are broken and exhibit jig-saw fit crystal texture (see **Figure 6a**). Idiomorphic to hipidiomorphic plagioclase crystalloclasts are present. Plagioclase grains are altered to microcrystalline aggregates of prehnite, sericite, and calcite, to various extents, but generally follow the pattern of extensive alteration towards the center of the grain. Vitric particles are present in the form of pumice fragments mostly of coarse-sized ash, but fragments of lapilli size can also be observed (see **Figure 6a**). Pumice fragments are mostly devitrified to microcrystal-

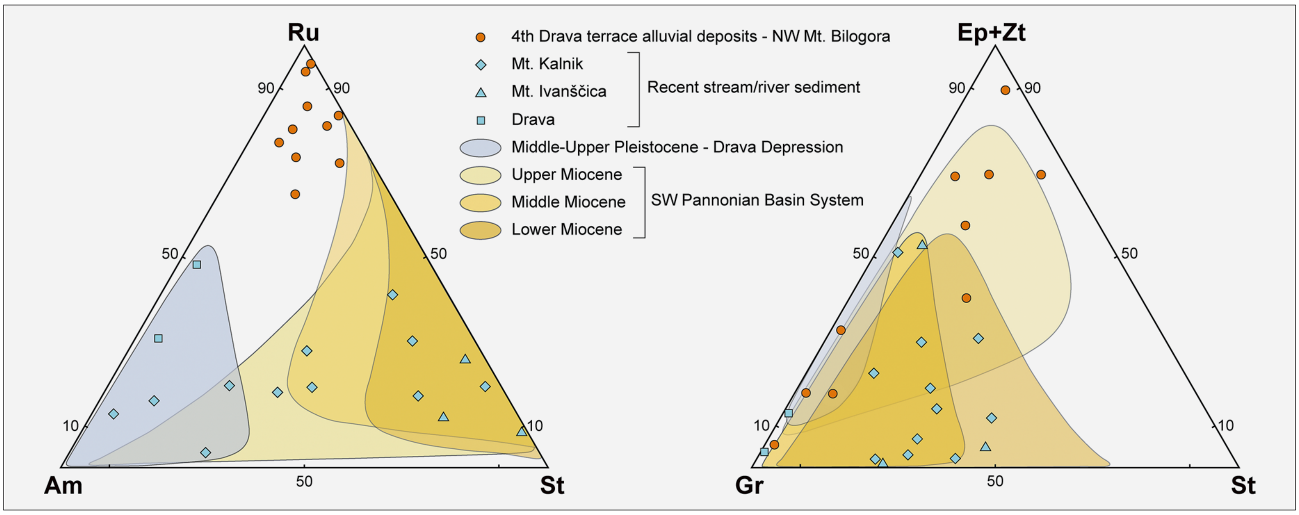

Figure 5. Ternary diagrams showing relative proportions of chosen heavy minerals in the studied sand samples. Colored fields represent published data from major stratigraphic intervals of the SW PBS area (data are displayed as 90% predictive regions; Mutić, 1975a: Middle-Upper Pleistocene sediments from the B-12 borehole near Podravska Slatina, Drava depression; Kovačić and Grizelj, 2006: Upper Miocene Andraševac Formation from the Hrvatsko Zagorje, Žumberak and Slavonia areas; Mutić, 1981: Middle and Lower Miocene units from the Hrvatsko Zagorje area)

line quartz and albite aggregates, and sometimes to chlorite and celadonite. The orientation of pumice fragments differs, but are mostly organized in a flow texture. Plastic deformations of pumice fragments in contact with other grains are noticed (see **Figure 6a**). Densely packed, welded, glass shards of medium-sized ash are present in most of the samples and exhibit V, X, Y, and bubble-wall forms (see **Figure 6b**). In sample MR-2 a small amount of lithoclasts is present (see **Figure 6c**). These lithoclasts are composed of very fine- to fine-sized ash composed of glass shards, and rare crystalloclasts of quartz, albite, and feldspar. Lithoclasts are determined as fine-sized ash vitroclastic tuff. The volcaniclastic material in this group of samples is supported by the matrix composed dominantly of fine-sized ash glass shards and fine mica crystals. Fine-sized ash glass shards from the matrix are mostly platy, and less common X and Y shaped. Most of the shards are devitrified to microcrystalline quartz and albite aggregates, but also some remain vitric. This group of samples is determined to belong to pyroclastic density current deposits (PDC).

Samples K-16A and K-16B show similar characteristics and only slightly differ from the PDC deposit. They are composed of coarse sanidine phenocrystals (larger than 1 mm) of hipidiomorphic structure. Sanidine phenocrystals are altered to sericite and clay mineral aggregates with rims being extensively more altered than the core of the grain. Sanidine grains are often organized into a glomeporphyre texture. Also, smaller plagioclase phenocrystals are noticed, with idiomorphic forms. They are almost completely altered to microcrystalline quartz, prehnite, and opaque mineral aggregates. The volcanic matrix of these effusive samples is composed of microcrystalline quartz, albite, and sericite. These samples belong to an effusive igneous rock determined as sanidine dacite.

Samples from the category 2 are K-2, K-2A, K-3B, K-10A, K-10B, K-10C, K-10D, K-12A, K-12B, K-12C, K-13B, K-15B, K-16C, K-16D, BMR-1, and BMR-2. Furthermore, this category of samples can also be subdivided into samples of coherent lava flows presented by samples of effusive rocks, mostly basalts; and volcaniclastic, autoclastic rocks formed by in-situ fragmentation or mixing of magma and unconsolidated sediments (subdivision according to **McPhie at al., 1993**). Samples K-2, K-2A, K-10D, K-12B, K-12C, K-13B, K-15B, K-16C, K-16D present coherent facies rocks of basaltic composition (see **Figure 6d**). Their texture varies from microporphyritic, aphire, aphanitic, homogenous, and ophitic. The samples are dominantly composed of fine plagioclase crystals with alotriomorphic to hipidiomorphic structures, mostly of lath shapes with lamellas. The plagioclase crystals are sometimes organized into radial aggregates forming bow-tie spherulites (see **Figure 6d**). The alteration pattern in the plagioclase shows greater progress from rims toward the core, with alteration products being microcrystalline aggregates of calcite, prehnite, and clay minerals. Sometimes in this group of samples pyroxene crystals up to 0.5 mm in size can be noticed. They often form glomeroporphyric texture and are often completely altered to microcrystalline aggregates of chlorite and serpentine. The volcanic matrix between the crystal phases is composed of volcanic glass, zeolite, and fine opaque minerals, with extensive alterations into a mixture of chlorite, epidote, calcite, prehnite, sericite, and clay minerals. Sample K-10D exhibits amygdaloidal texture with rare zones of orange-brown domains probably presenting altered olivine crystals. The amygdales are filled with polycrystalline calcite aggregates, with their rims showing radial needle-shaped pyroxene crystals.

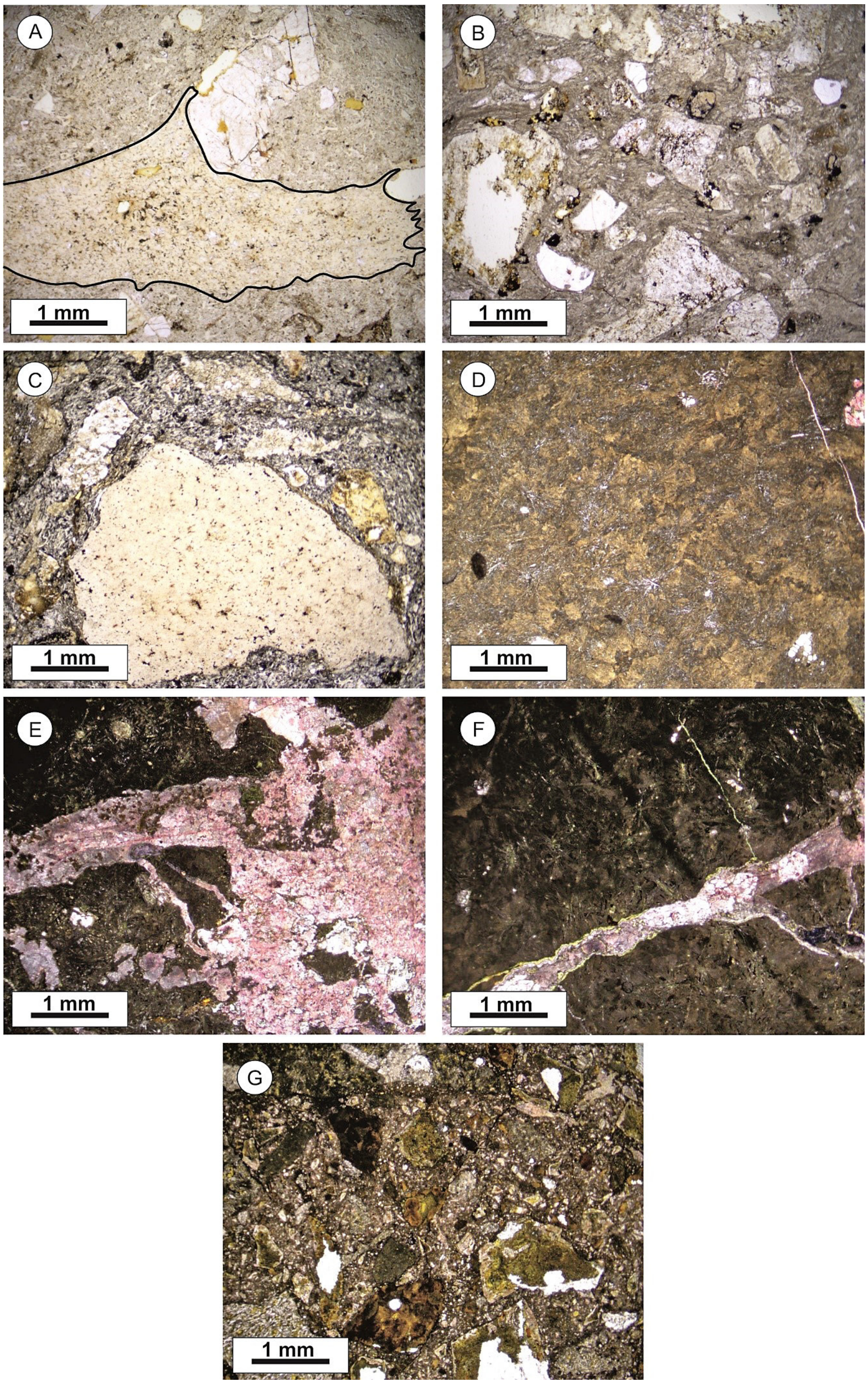

Figure 6. Microphotograph of analyzed volcanic and volcaniclastic rock samples. **(A)** Felsic volcaniclastic rock with pumice fragments of lapilli size and plagioclase crystalloclasts in the fine-ash matrix. Notice the plastic deformations of the pumice fragment in contact with the crystalloclast. Sample NP-1. **(B)** Microphotograph of sample K-17a belonging to the group of felsic volcaniclastic rocks. The sample is composed of medium-sized crystalloclasts, pumice fragments, and glass shards. The preferred orientation of glass shards indicates flow texture characteristics for PDC deposits. **(C)** Lithoclasts in the group of felsic volcaniclastic samples are composed of fine glass shards, probably belonging to vitroclastic tuffs. Sample MR-2. **(D)** Sample K-13b represents a basalt from the second group of rocks. This basalt exhibits spherulite forms in a dark hyaline matrix. **(E)** The contact between calcite and volcanic domain in sample K-10c. This sample belongs to the mafic group and represents peperite rocks. The contact is diffused and indicative of hot magma-wet sediment mixing. **(F)** Sample K-10c, belonging to the peperite rocks of the mafic group. The reaction zones in the calcite veins support the interpretation of hot contact. **(G)** Milimetre-sized clasts of different basalt types are found in the finer matrix composed of crystalloclasts and hyaline lithoclasts. Sample K-10b belongs to the autoclastic breccia rocks of the mafic group of samples.

Samples K-3B, K-10A, K-10B, K-10C, K-12A, BMR-1, and BMR-2 represent an autoclastic group. Samples K-10A, K-10B, K-10C, and K-12A are composed of two different phases. These phases are clearly distinguished even in the hand specimens. One phase is presented by the dark basaltic material, while the other phase is composed of calcite minerals arranged in the samples as veins or irregular domains (see **Figure 6e**). The magmatic phase is presented by rounded to angular zones, sometimes with dispersed edges composed of dark homogenous material (see **Figure 6e**). In the thin sections, the fine crystalline hyaline matrix can be distinguished with a various amount of small plagioclase crystals. The plagioclase crystals are sometimes radially oriented and are altered to chlorite and calcite. The hyaline matrix is devitrified into chlorite, zeolite, palagonite, and calcite aggregates to a various extent. The basaltic domains can also have rare amygdales filled with calcite crystals. Calcite is seen in veins of different thicknesses or irregularly shaped domains with different contacts with the magmatic material (see **Figure 6e**). Thin veins are filled with calcite crystals exhibiting type 1 twinning and sharp contacts with the basaltic material. Thicker veins are filled with type 2 calcite twins and mostly have irregular and diffuse contact with the basaltic material (see **Figure 6e**). In these types of veins opaque minerals and volcanic glass can also be seen. Also, domains with signs of interaction between the calcite and the plastic volcanic glass can be observed, and as transition of alteration patterns from the edges toward the center of the calcite domains (see **Figure 6f**). The volcanic material found in the veins can sometimes contain small fragments of other rock types and orthopyroxene phenocrystals. In the sample K-12A, the carbonate component is presented by irregular domains of large subhedral dolomite crystals. The carbonate component is often silicified. Contacts between the dolomite domains and the hyaline domains are mostly diffuse and exhibit transitions from chlorite to quartz to dolomite. The characteristics of this group of samples indicate that they are generated from the basaltic-limestone peperite rock.

Samples K-3B, BMR-1, and BMR-2 are composed of poorly sorted basalt clasts (see **Figure 6g**). The size of clasts varies from 2 mm to 1 cm. Clasts belong to different types of basalts, all described before in the coherent basalt group of samples. A certain amount of plagioclase and scarcer pyroxene crystalloclasts are also present. Clasts are mostly matrix-supported or exhibit point contacts (see **Figure 6g**). The dark matrix between the clasts is composed of finely ground hyaline basalt material and smaller plagioclase crystalloclasts (see **Figure 6g**). These samples are determined as autoclastic basalt breccia.

4.3. Whole-rock geochemistry of volcanic and volcaniclastic pebble and rock samples

Major and trace elements (including REE) were analyzed on the 20 selected samples of both volcanic/volcaniclastic petrographically defined groups from pebbles and rock outcrops (see **Supplement 4**). The geochemical data correlate well with the observed petrography**.** Geochemical group 1 (G1) corresponds to samples in the petrographic category 1 (see **Figures 6a, b, c**) composed dominantly of felsic mineral phases (K8A, K8B, K9A, K17A, NP1, NP2, MR2, K16A, K16B), whereas geochemical group 2 (G2) corresponds to samples in petrographic category 2 (see **Figures 6d, e, f, g**) composed dominantly of mafic mineral phases (K2A, K10A, K10B, K10C, K10D, K12A, K12B, K12C, K13B, K15B). Samples from the geochemical group 1 (G1, silicic) are characterized by loss on ignition values (LOI) between 0.7 and 2.2% wt. % whereas Group 2 (G2, basic) samples have much higher LOI values (4 to 19.1 wt. %) which is at least partly caused by their origin i.e. petrography (presence of carbonates). This fact might have been responsible for the mobilization of certain elements and hence geochemical interpretations will rely predominantly on the immobile trace element concentrations (HFSE and REE).

G1 silicic samples show major element variation characterized by a relatively narrow range of SiO_2 (70.5-79.71 wt. %) accompanied by low MgO (0.14-0.61 wt. %), CaO (0.03-1.91 wt. %) and TiO_2 (0.1-0.46 wt. %) and high K_2O (6.67-9.99 wt. %) content. G2 basic samples show greater scattering of the major element data i.e. SiO_2 (28.78-47.3 wt. %), higher MgO (3.27-1.52 wt. %), CaO (6.04-20.28 wt. %) and TiO_2 (0.82-1.89 wt. %) and high K_2O (0.04-2.28 wt. %) content (see **Supplement 4**).

According to the immobile trace element classification diagram Nb/Yb – Zr/TiO_2 (**Winchester and Floyd, 1977;** see **Figure 7a**) that is less sensitive to secondary processes, samples from the G1 i.e. silicic group classify mostly in the rhyolite and rhyodacite/dacite fields and are thus designated as G1A (K-8A, K-8B, K-9A, K-17A, MR-2, NP-1, NP-2, BMR-3). Sanidine-rich volcaniclastic rocks fall into the trachyte field i.e. form the G1B subgroup (K-16A, K-16B). Part of the G2 basic samples plot into the andesite/basalt and subalkaline basalt fields forming the G2A subgroup (K10A, K10B, K10C, K12A, K12B, K12C, K13B), while others into the alkali basalt field and are members of the G2B subgroup (K2A, K10D and K15B).

The geochemical distinction between G1 and G2 groups is supported by the chondrite-normalized REE patterns (see **Figure 7b, c**). All of the G1 samples show prominent negative Eu anomalies (Eu/Eu*=0.09-0.61). Differences between subgroups G1A and G1B are also evident. Most of the G1 samples pertain to the G1A subgroup characterized by fractionated REE trends with La_N/Yb_N ranging from 4.92-11.78, although one sample from the Drava alluvial terrace (BMR-3) shows significantly less fractionated signature in comparison to other G1A samples (La_N/Yb_N=2.67). Samples from the G1B subgroup are characterized by even higher La_N/Yb_N values (18.78-18.83). Among G2 samples the two geo-

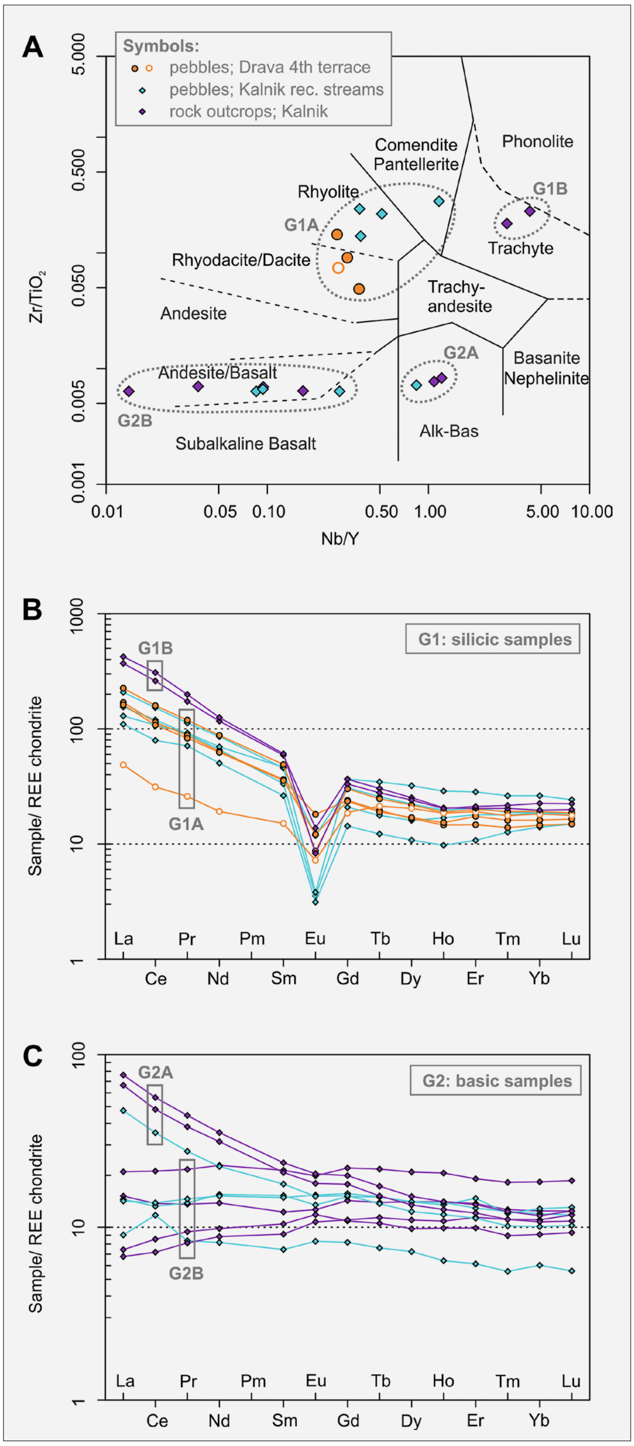

Figure 7. General geochemical characteristics of pebble and hard rock samples. **(A)** Nb/Yb – Zr/TiO2 diagram (**Winchester and Floyd, 1977**) classifies G1 samples as rhyodacites to trachites and G2 samples classify as andesite/basalts to alkaline basalts. **(B)** Chondrite normalized REE patterns for G1 (silicic) samples (after **Boynton, 1984**). **(C)** Chondrite normalized REE patterns of G2 (basic) samples (after **Boynton, 1984**). Sample symbols correspond to their sampling location and occurrence (pebbles vs. hard rock outcrops).

chemical subgroups are also discernable. G2A samples display generally less fractionated REE trends (La_N/Yb_N=0.62-1.50) while G2B samples show La_N/Yb_N values (4.70-6.52) between those for G1A and G2A subgroups. Europium anomaly for all G2 samples is not very pronounced (Eu/Eu*=0.88-1.11).

5. Discussion

The persistent Alpine supply of detrital material active since Miocene times has left its prevailing signature on both Neogene and Quaternary deposits in the study area. This complicates attempts at discriminating between local vs. alpine sediment source origin during the Quaternary due to overall similarities in the composition of potentially recycled local material of paleo-Alpine origin (e.g. from Miocene units exposed on nearby inselbergs) and that arriving directly from the Alps. However, considering the depositional and tectonic setting of the studied Lower-Middle Pleistocene Drava alluvial terrace deposits of Bilogora, local sediment sources should be considered as an important factor, at least in certain periods. The high proportion of lithoclasts in the analyzed modern stream sands from Mt. Kalnik and Mt. Ivanščica, which are further strongly dominated by sedimentary lithotypes (see **Figure 3**) indicates that present sediment production and dispersal from these areas is largely influenced by the recycling of material from existing Miocene sedimentary units. Heavy mineral suits identified in these stream sands reflect Lower to Upper Miocene sandstone compositions for which a large volume of published data exists (**Mutić, 1975a, 1981; Kovačić and Grizelj, 2006**; see **Figure 5**). Sand samples from modern creeks of Mt. Kalnik and Mt. Ivanščica have consistently high garnet and ZTR content, while amphibole, staurolite, and epidote/zoisite are highly variable. The presence of mafic lithoclasts in the sand fraction of modern streams (see **Figure 4c**) suggests that basement lithologies also supply material to local streams, although this is not always evident in the heavy mineral signature. Mafic pebbles identified in modern stream sediments of Mt. Kalnik are comparable based on their composition to lithologies forming the part of the Jurassic ophiolitic mélange complex exposed on both inselbergs, i.e., Mt. Kalnik and Mt. Ivanščica (see **Figure 7**). Pebbles of similar petrographic composition (samples BMR-1 and BMR-2) identified in the studied Middle to Late Pleistocene sediments suggest that these basement highs may have contributed material to the area of northwestern Bilogora within this earlier timeframe as well. Similar to the current sediment generation and dispersal patterns, the inselbergs of Mt. Kalnik and Mt. Ivanščica undergoing recent tectonic uplift were likely important source areas of sediment for the northwestern Bilogora area during the Early Pleistocene. Notable Pliocene to Quaternary tectonic uplift in the SE Pannonian basin area (**e.g. Prelogović et al., 1998; Tomljenović and Csontos, 2001; Matoš et al., 2016, 2017**) combined with the interchange of interglacial and glacial periods (**Wacha et al., 2018 with references**) has inevitably spurred erosion of widespread sedimentary cover, as well as to some extent of older basement rocks, particularly in the areas of local inselbergs (**Šimunić and Šimunić, 1987**). The importance of local supply has been previously mentioned mainly for the end of the Pliocene and early Pleistocene (**Šimunić et al., 2014**). **Šimunić et al. (2014)** suggested a local provenance for Lower Pleistocene sands and gravels in fluvial-lacustrine deposits exposed along the southern foothills of Mt. Kalnik, noting their high epidote content and absence of garnet, as well as the gravel clast compositions reflecting lithologies exposed on Mt. Kalnik. **Peh et al. (1998)** only briefly mentioned that the source area of the oldest Drava terrace deposits is most probably the zone of high-grade metamorphic rocks of Pohorje Mt. (Slovenia), but that another possible source area could be Mt. Papuk. **Babić et al. (1978)** suggested partial local supply during the Middle and Upper Pleistocene due to the reduced inflow of material from the Alps caused by climate change. The high proportion of quartz and sedimentary lithoclasts in the studied Pleistocene sands from Bilogora (see **Figure 3**) supports extensive recycling from local sedimentary units. Field observations of poorly lithified sediment pebbles within coarse-grained deposits at Mučna Reka support such conclusion. Furthermore, all of the studied Middle Pleistocene alluvial terrace sand samples from NW Bilogora are distinguished by their high ZTR content dominated by rutile, while in addition, some are low or almost devoid of garnet and amphibole (samples MR4, MR6, MR8, SVA5/1, NP3A, NP4; see **Figures 2** and **5**). It is improbable that this material arrived by the Drava River which carries heavy mineral assemblages dominated by garnet and containing common amphibole and epidote group minerals, with consistently very low percentages of other species, particularly ZTR. The Drava River has been delivering sediment with equivalent heavy mineral suits since at least the Middle Pleistocene as evidenced by reported borehole samples (**Mutić 1975a; Babić, et al., 1978; Šimunić et al., 2014**). This would require a considerable alteration of the sediment composition by processes such as weathering or hydraulic sorting, involving almost complete removal of garnet as well as other heavy mineral species. Although garnets can be affected in extreme weathering conditions within silicic soils (**Bateman and Catt, 2007**), they are generally resistant to weathering in surface conditions (**Mange and Maurer, 1992; Morton and Hallsworth, 1999**). Considering that significant etching has not been observed on individual garnet grains, it is unlikely that weathering alone could have consumed them to such a degree in just a single sedimentary cycle. The conspicuously high ZTR index in Lower-Middle Pleistocene samples instead may reflect multiple recycling stages involving local Mt. Kalnik and Mt. Ivanščica Neogene sediments and/or older basement units. Jurassic sandstones occurring within the ophiolitic mélange units, common on local inselbergs, are highly mature and have heavy mineral suits dominantly of ZTR (**Babić and Zupanič, 1978**). The streams of Mt. Kalnik and Mt Ivanščica, as well as Neogene sediments of the area, display higher ZTR content than the Drava River sediment, although they too are sometimes abundant in garnet, as well as staurolite (**e.g. Kovačić and Grizelj, 2006; Mutić, 1975a**; see **Figure 5**). However, **Kovačić and Grizelj (2006)** have reported sedimentary units with a conspicuously high proportion of ZTR and/or epidote group minerals, while devoid of garnet within Upper Miocene and Pliocene deposits of Hrvatsko Zagorje and Žumberak and interpreted for some of them a local provenance.

Sporadic findings of volcanic pebbles in the Drava terrace sections further indicate the possibility of locally controlled colluvial insurgences of debris material from the surrounding inselbergs. Basic volcanic/volcaniclastic pebbles (petrographic category 2 i.e. geochemical G2 group) and their geochemistry are ascribed to the igneous activity recorded in mafic rock types from the massifs of Mt. Ivanščica, Kuna Gora and Kalnik (see **Figure 8**). They exhibit similar textural, structural and geochemical characteristics as the rocks belonging to the Middle Triassic age, that were reported in the Hruškovec quarry (Mt. Kalnik) by **Palinkaš et al. (2008)** and **Vrkljan (1994)**. **Palinkaš et al. (2008)** and **Kiss et al. (2008)** reported different basic volcanic and volcaniclastic lithotypes in the area of Mt. Kalnik, among others pillow basalts, peperites, fragmented pillow breccia, and peperitic hyaloclastite. Same lithologies are present in the pebble samples of the Mt. Kalnik stream system. Geochemistry of the G2A subgroup correlates well with these observations and the geochemical data on Middle Triassic volcaniclastic deposits from Hrvatsko Zagorje (Mt. Kuna Gora) and Mt. Ivanščica (see **Figure 8**) published by **Lugović et al. (2015)**, **Slovenec et al. (2019)**, **Slovenec and Šegvić (2019)** and **Smirčić et al. (2024)**. Similarly, the geochemical signature of the pebbles from the G2B subgroup correlates well with the Jurassic-Cretaceous gabbroic rocks from Mt. Kalnik ophiolitic melange described by **Lugović et al. (2015)**. Both of these facts point to a local erosion and deposition of fragmented material in the vicinity of the source area. The absence of Permian volcanic rock outcrops on Mt. Kalnik leads to the conclusion that these pebbles in local streams must be recycled from local Neogene coarse-grained units. Similarly, this could be the source for the mafic pebbles encountered in the Bilogora Drava Pleistocene terrace sediment as well, as testified by the presence of autoclastic mafic pebbles.

Silicic pebbles encountered and sampled in recent streams of Mt. Kalnik, as well as in Pleistocene coarse-grained deposits forming the Drava alluvial terrace at the Mučna Reka and Novigrad Podravski localities, form the geochemical subgroup G1A corresponding to pyroclastic density current deposits from the petrographic category

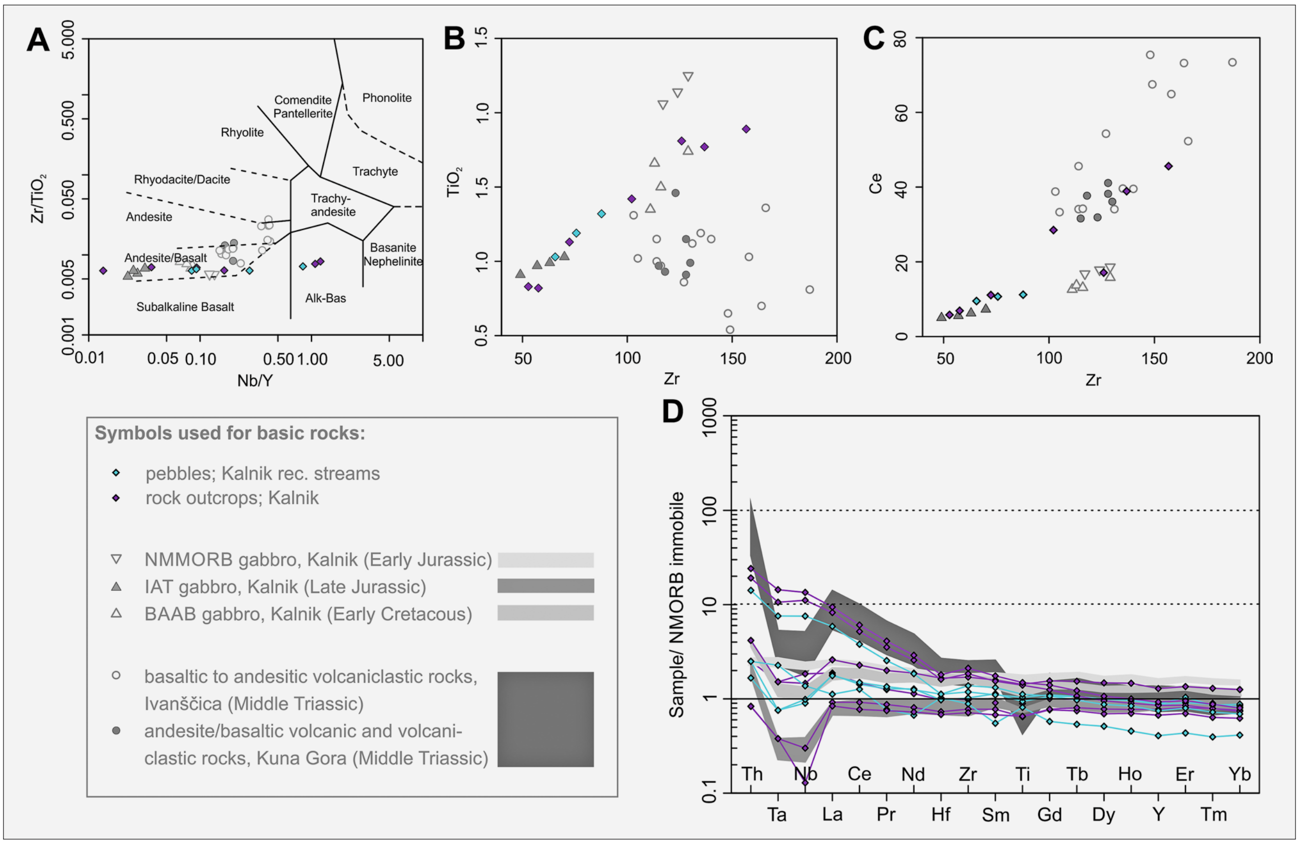

Figure 8. Selected bivariate and spider diagrams for the basic igneous rocks of the Drava/Mura drainage system. **(A)** Nb/Yb – Zr/TiO2 diagram (**Winchester and Floyd, 1977**). **(B, C)** Bivariate plots show the relation of G2 samples (blue and purple) to the basaltic to andesitic volcanic and volcaniclastic rocks from Mt. Ivanščica, Mt. Kuna Gora, and Mt. Kalnik (see text for details and sources of data used for comparison). **(D)** N-MORB immobile multi-element diagram after **Sun and McDonough (1989)** from **Pearce (2014)** shows a correlation between studied basic pebbles and previously mentioned basic volcanic to volcaniclastic rocks.

1. Their data is compared to the geochemical data for Permian felsic to intermediate rocks from the recent Drava/Mura drainage system (see **Figure 9**). Data for the Hungarian part of the Pannonian basin includes ALCAPA and Tisia basement rocks from **Szemerédi et al. (2020a, 2020b, 2023)**. Porphyry syenites of the Karavanke Granitic Belt are from **Bole et al. (2001)** and data on Permian rift-related granite magmatism from Eastern Alps from **Yuan et al. (2020)** are also included in the comparison. Volcanic rocks from the Miocene Pohorje igneous complex (**Poli et al. 2020**) in the Eastern Alps are also taken into consideration. According to the geochemical characteristics, G1 (felsic) samples are peraluminous and in general correlate well with the peraluminous widespread Permian-Triassic igneous activity documented in the Austoalpine units and Tisia. A N-MORB immobile multi-element diagram (see **Figure 9 d-g**) after **Sun and McDonough (1989)** from **Pearce (2014)** has been taken for characterization of a possible parental material of studied samples due to the obvious mobility of alkalis and LILE trace elements resulting from post-magmatic alteration processes. Samples show consistent grouping into previously defined G1A and G1B subgroups with a more pronounced distinction on the left-hand side of the diagram encompassing elements characterized by higher incompatibility during the melting of the mantle. G1A samples show greatest resemblance to the peraluminous Permian felsic volcanites and volcaniclastites from the Pannonian basin (see **Figure 9d**) and peraluminous Permian metagranites from the Eastern Alps (see **Figure 9e**). However, metalumionous rocks from Karawanken together with metalumionus Miocene volcanic rocks from the Pohorje igneous complex (see **Figures 9f, g**) cannot be excluded as an additional potential contributor of G1A type of pebbles.

Although widespread Miocene volcanic/volcaniclastic deposits of the Carpathian-Pannonian Region (CPR) could also represent source material for the G1 samples, this could not have been confirmed here. The main uncertainties lie in the fact that recent geochemical studies of Miocene volcanism in the CPR (e.g. **Brlek et al., 2023** and references therein) were based on the volcanic glass analyses and are not fully comparable to our data. Older data on Paleogene-Neogene volcanic rocks from the southern Pannonian basin (e.g. **Pamić et al., 1995**) suggest significant differences in petrography and major element data but the available datasets are too fragmentary to make any correlations. At this stage of research, the pre-

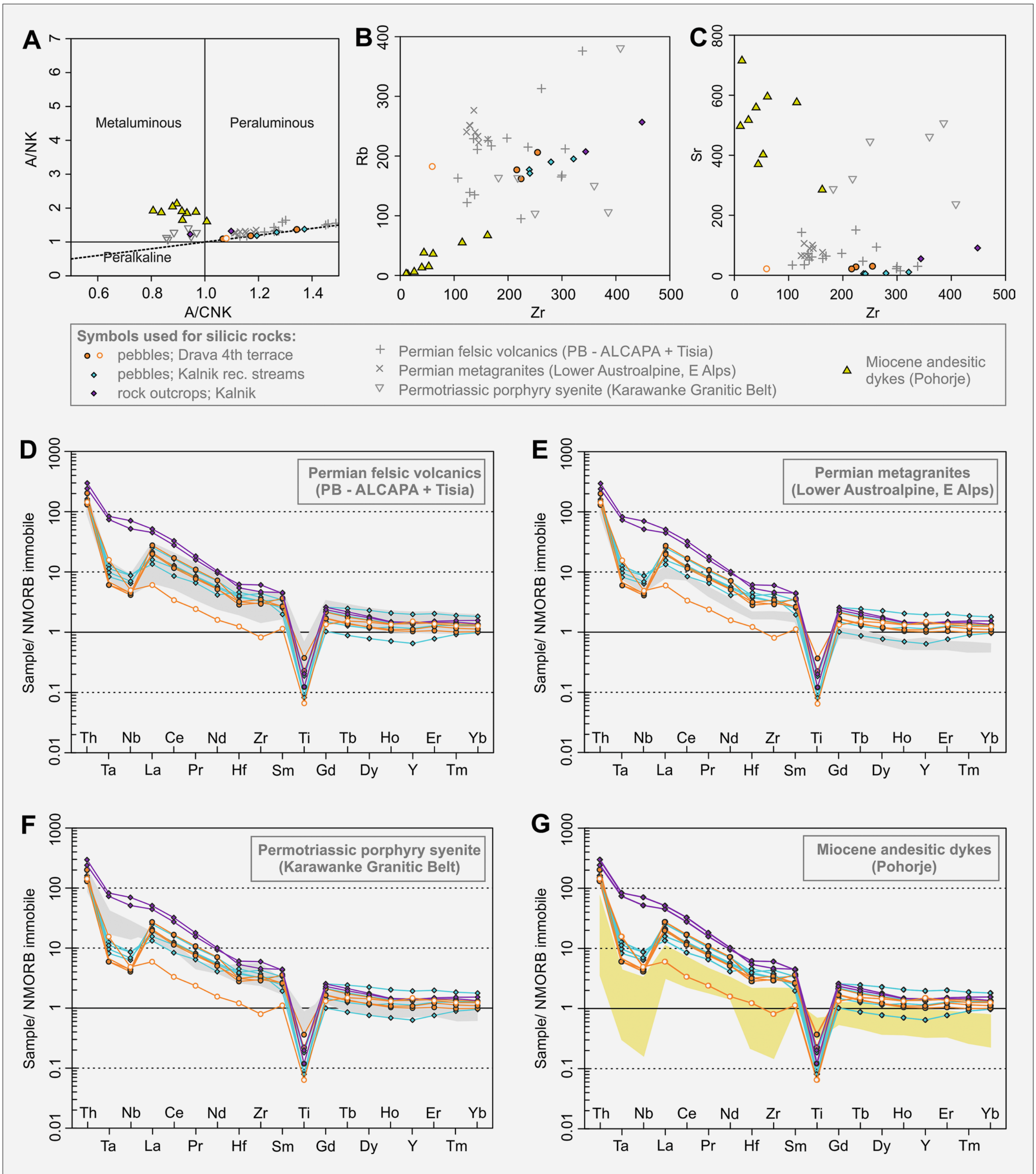

Figure 9. Selected bivariate and spider diagrams for the Permian-Triassic felsic igneous rocks of the Drava/Mura drainage system. See text for details and sources of data used for comparison. **(A)** In the A/NK vs. A/CNK diagram (**Shand, 1943**) G1 samples show peraluminous characteristics. **(B, C)** Bivariate plots show the relation of G1 samples to the Permian rock (grey) and Miocene Pohorje complex (yellow) addressed in the text according to their alteration intensity, fractionation processes, and source characteristics. **(D)** – **(G)** N-MORB immobile multi-element diagrams after **Sun and McDonough (1989)** from **Pearce (2014)** for each representative group of Permian and Miocene samples.

sented petrographic and geochemical dataset for the felsic pebbles make Permian-Triassic felsic igneous rocks or sediments containing such clasts a probable source of the studied felsic pebbles, although Miocene source rocks cannot be excluded completely as testified by the presence of the geochemically different BMR-3 sample. However, additional isotopic and geochronological data on the studied pebbles would be necessary to address this issue.

Though local sediment supply may have been an important contributing factor, heavy mineral suits in some of the analyzed samples from the Bilogora Drava alluvial terrace strongly resemble those of the modern Drava River sediment. Stark differences among samples from different horizons of the same localities may indicate a mixing of locally eroded material transported by streams and sediment from the Alps transported and deposited by the paleo-Drava River. There is a possibility that material transported by the River Drava was occasionally dominant, while in certain periods local material supply prevailed. Though traditional models envisage a significant decrease in sediment flux going into interglacials, additional subsequent interglacial peaks of increased sediment flux attributed to high-amplitude climate changes have been documented in the Alps for the period following the Last Glacial Maximum (**Savi et al., 2015**). Besides the tectonic uplift of Lower to Middle Pleistocene Drava River terrace deposits which partly dictated Quaternary landscape formation in NE Croatia, sediment influx dynamics of the paleo-Drava River drainage system pinpoint to the importance of Quaternary climate oscillations, i.e. glacial to interglacial conditions. The common occurrence of garnet-free and garnet-rich strata at the same sampling locations may reflect such pulses in climate changes and/or changes in local tectonic uplift dynamics, coupled with modifications in the course of the River Drava during the Pleistocene due to river dynamic processes.

6. Conclusions

The most significant conclusions of the present study with regards to the provenance of Pleistocene to recent alluvial sediments in the area of NW Bilogora may be summarized as follows:

1. Petrographic composition and heavy mineral suits from modern stream sands, together with geochemical and petrographic characteristics of individual volcanic and volcaniclastic pebbles, indicate that sediment production and dispersal from Mt. Kalnik and Mt. Ivanščica is presently largely influenced by recycling of material from Neogene sedimentary units, as well as from exposed basement units.

2. Petrographic composition and heavy mineral suits of Lower-Middle Pleistocene sands from the oldest Drava River terrace on northwestern Bilogora suggest extensive recycling from local sedimentary units. Sporadic findings of mafic pebbles in the gravels indicate the possibility of erosion of the pre-Neogene basement of local inselbergs.

3. The composition of silicic pebbles from Lower-Middle Pleistocene gravels on northwestern Bilogora correlates well with the widespread Permian-Triassic igneous activity in the Austroalpine units and Tisia. These volcanic units are a probable initial source, though the pebbles are likely recycled from Miocene conglomerates.

4. During the Middle Pleistocene the Drava River basin of today's northern Bilogora area received material from the Alps via the Drava River together with its tributary the Mura River, as well as by supply from units exposed on uplifting local Mt. Kalnik and Mt. Ivanščica inselbergs. Occasionally material transported by the River Drava was dominant, while in other periods local material supply prevailed. Changes in sediment supply dynamics could have been affected by climatic changes and local tectonics, coupled with the hydrological dynamics of the Drava River during the Pleistocene.

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SAŽETAK

Izvorište pleistocenskih i recentnih aluvijalnih sedimenata sjeverozapadne Bilogore i okolnih područja (Hrvatska)

Cilj je istraživanja odrediti izvorišta pleistocenskih i recentnih aluvijalnih sedimenata sjeverozapadne Bilogore. Područje istraživanja obuhvaća sjevernu Hrvatsku, odnosno panonske otočne gore s naglaskom na Bilogoru. Na temelju petrografije i sastava teških minerala uzoraka pijeska, zajedno s mikropetrografskim obilježjima i geokemijom vulkanskih i vulkanoklastičnih valutica i stijena, određivano je izvorište sedimenta najstarije dravske riječne terase starosti donji do srednji pleistocen. Razvoj ovoga područja usko je povezan s lokalnim i regionalnim tektonskim procesima, kao i formiranjem riječnoga sustava Drava – Mura koji ovo područje opskrbljuje materijalom iz Istočnih Alpa barem od vremena miocena. Sastav pleistocenskih pijesaka upućuje na intenzivno recikliranje lokalnih neogenskih sedimenata koje je prisutno još i danas. Felsične valutice dobro koreliraju s rasprostranjenom permsko-trijaskom magmatskom aktivnosti u austroalpinskim jedinicama i Tisiji, iako su vjerojatno reciklirane iz miocenskih konglomerata. Nalazi mafitnih vulkanskih litoklasta upućuju na mogućnost erozije predneogenske podloge Kalnika i Ivanšćice. Tijekom donjega i srednjega pleistocena porječje rijeke Drave na prostoru sjeverne Bilogore opskrbljivalo se materijalom iz Alpa, kao i s okolnih otočnih gora. Promjene u dinamici opskrbe sedimentom vjerojatno su bile uvjetovane klimatskim promjenama i lokalnom tektonikom, zajedno s hidrološkom dinamikom rijeke Drave tijekom pleistocena.

Ključne riječi:
SZ Bilogora, JZ Panonski bazen, pleistocen, recentni sedimenti potoka, provenijencija

Author's contribution

Tea Mendek (1) (PhD student, Sedimentology) prepared sand samples, provided the quantitative framework petrographic and heavy mineral analysis of sand samples, and interpretation of the results and preparation of the manuscript. **Borna Lužar-Oberiter** (2) (PhD, Associate professor, Sedimentology) performed the fieldwork, provided interpretation of the results, writing of manuscript chapters and preparation of figures, and consolidation of the paper. **Duje Smirčić** (3) (PhD, Assistant professor, Sedimentology, Igneous petrography) prepared samples and provided micropetrographical analysis of volcanic and volcaniclastic pebbles and rock samples, along with the interpretation of the results, writing of manuscript chapters and the preparation of figures. **Zorica Petrinec** (4) (PhD, Assistant professor, Igneous geochemistry) prepared samples for whole-rock geochemical analysis, along with the interpretation of the results, writing of manuscript chapters and the preparation of figures. **Bojan Matoš** (5) (PhD, Associate professor, Structural geology) performed the fieldwork, contributing to the geology of the Pannonian Basin System, and writing of manuscript chapters.
All authors have read and approved the final version of the manuscript.