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Original scientific paper

Composition and provenance of Gröden sandstone from the Velebit Mts.

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Abstract
Six samples of Gröden sandstones (Middle Permian) were analysed: Five of them were from Pikovac Creek valley (in the vicinity of Brušane village at Velebit Mts., Croatia) and one was from the locus typicus Gröden/Val Gardena (Italy). Based on the micropetrographical characteristics of sandstones, as well as on the modal composition and heavy mineral association, origin of material, weathering index of source rocks, climate and relief in the period of deposition have been supposed. Four samples from Pikovac Creek were petrographicaly determined as lithic greywackes, one as densely packed lithic arenite, while a specimen from Gröden locus typicus represents feldspar greywacke. Lithic greywackes/arenites imply very low maturity and suggest a close proximity of source rocks as well as the active tectonics in the hinterland of the depositional basin. Heavy mineral association in the samples from Pikovac Creek valley, with a large amount of fairly rounded stable grains (zircon, tourmaline and rutile), indicate that clastic material was derived from recycled orogen, and probably from reworked sedimentary rocks. The presence of kyanite and chlorite in the heavy mineral assemblage suggest their origin is from metamorphic rocks. This data assumes that Gröden sandstones from Pikovac Creek were possibly deposited in the fan delta or braided delta depositional environment as a part of a rift system (recycled orogen). The composition of the sample Gröden s. locus typicus (light and heavy mineral fractions) suggests the vicinity of magmatic rocks in the source area. All analysed samples are red coloured and have a large amount of limonitized grains in the heavy mineral assemblage, that point to the arid climate at the time of deposition. A weathering index diagram for Pikovac sandstones implies an arid/semiarid climate and high relief of the source area where metamorphic or sedimentary rocks dominate, while an arid/semiarid climate and high relief with plutonic source rocks were supposed for the provenance of Gröden s. *locus typicus*.

Keywords
Gröden sandstone, Middle Permian, Velebit Mts., heavy mineral assemblage, provenance study

1. Introduction

Middle Permian Gröden sandstones (terminology after **Salopek, 1942, Sokač et al., 1974, 1976**) from Velebit Mts. have been investigated. Five samples were collected in Pikovac Creek valley near Brušane (**Figures 1** and **2**) and their petrographic characteristics have been compared with the sandstone of the Gröden Formation, from the locus typicus near Gröden/Val Gardena in the Dolomites (Italy).

Petrographic analyses of Gröden sandstones from Croatia are scarce. Data dealing with Gröden sandstones from Velebit Mts. was given by **Salopek (1942)**, who defined Gröden sandstones as Middle Permian and described them as lateral equivalent of Košna conglomerates (formerly called *verukano)*. According to the same author, Gröden sandstones are red, occasionally green, fine-to-medium grained. In the Pikovac Creek valley Gröden sandstones are younger than Permian carbonate breccias and they are overlain by red pelitic sedimentary rocks. The total thickness of Gröden sandstones unit is, according to **Salopek (1942)**, estimated to 100 m. In the wider realm, between Raduč and Medak, Gröden sandstones are clayey, poor in micas, and fine grained. They vary in colour from red, yellow and purple to greenish-brownish varieties **(Salopek, 1948)**.

In the vicinity of the Košna locality, **Kochansky-Devidé et al. (1982)** found Gröden sandstones that have been determined as medium- to coarse-grained greywackes. Quartz, lithic fragments, feldspars and bioclastic detritus occur in their composition. Matrix is chloritic or sericitic, rarely calcitic. The same authors claim that Gröden greywackes are

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more common at the transition to Upper Permian dolostones and their total thickness was estimated to 150-200 m. New contributions regarding palaeomagnetism and rock magnetism of Permian sandstone on Velebit Mts. were given recently by **Werner et al. (2015)**.

While mapping for the Basic Geological Map of SFRY 1:100000 sheet Gospić, **Sokač et al. (1976)** differentiated Gröden sandstones as the Middle Permian lithostratigraphic unit (P_2). Sandstones have been defined as medium- to coarse-grained greywackes that embrace poorly sorted angular siliciclastic detritus composed of quartz, lithic fragments (grains of sedimentary, metamorphic and volcanic rocks), feldspars, muscovite and chlorite. Matrix is chloritic to sericitic. Some varieties have carbonate cement (dolomite and ankerite). **Sokač et al. (1976)** interpreted Gröden sandstones as being deposited in the marine environments. In the composition of heavy mineral association **Sokač et al. (1976)** found zircon, tourmaline and rutile. Apatite grains occur sporadically while garnet, epidote, brookite, titanite and chloritoid are rare.

Analysing samples of Gröden sandstones from Pikovac Creek valley, we aim to ascertain more specific petrographic characteristics concerning composition, the source of siliciclastic material, type of climate during weathering/deposition and relief in the hinterland. All petrographic characteristics were compared with the sample of Gröden sandstone from locus typicus in the Southern Alps (Dolomites), in order to see similarities/differences in the depositional setting between the Velebit Mts. and the Dolomites. This paper represents the preliminary research of petrographic features from the two localities. Far more samples will be needed for further studies.

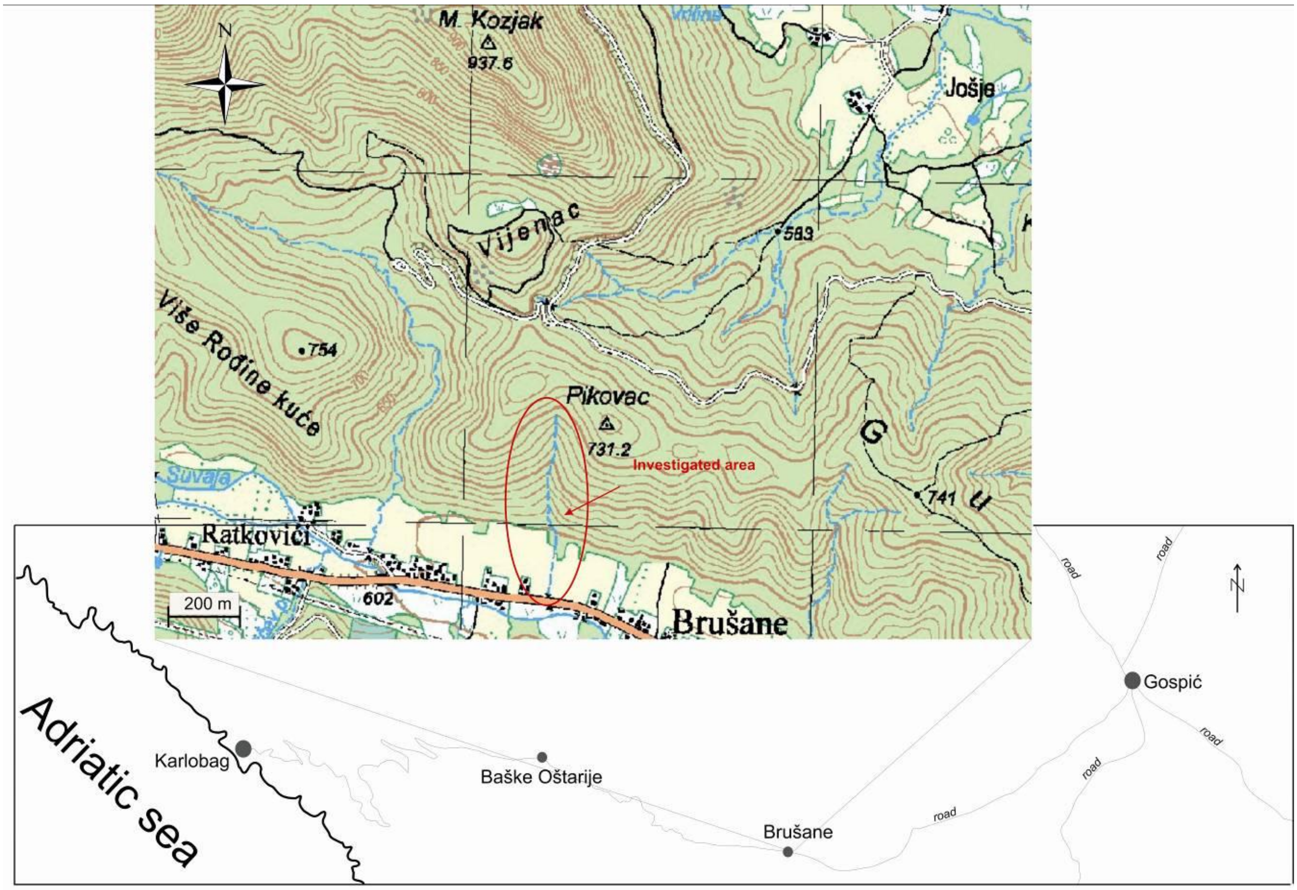


Figure 1. Topographic map of the Velebit Mts. near Brušane village. Investigated area is circled in red. Scale is 200 m. Modified after DGU (2007).

2. Geological setting

Pikovac Creek valley, where samples of Gröden sandstones were collected, is the part of a large anticline, located in the vicinity of Brušane village (**Figure 2**). Pikovac Creek is the left tributary of Suvaja Creek. A geological map of Brušane area is presented by **Salopek (1948)** – **Figure 2** and **Sokač et al., (1974, 1976)**.

The oldest rocks in the area are Carboniferous clastics that occur in the northern limb of the Brušane anticline (**Sokač et al., 1976**). Among clastic deposits, sandstones and clayey shales intercalate with quartz-rich conglomerates and limestones. Carbonaceous clastics are conformably overlain by Early Permian clastics and carbonates. Clastic deposits prevail at the very beginning of Early Permian, while in the late Early Permian, limestones dominate over clastics.

Fossil association preserved in limestone layers corresponds well with Rattendorf beds and therefore the whole interval was determined as Early Permian (**Sokač et al., 1976**).

Middle Permian sandstones were continuously deposited after Early Permian clastics and carbonates. Pyrite rich sandstones occur in the older Middle Permian strata. They laterally pass to sandstones of Gröden type, quartz and petromict conglomerates or limestones in the upper part of the Middle Permian (**Sokač et al., 1976**). The age of Gröden sandstones is discerned according to superposition. In the hanging wall of Gröden sandstones, Late Permian carbonates (predominantly dolomites and rare limestones) occurred.

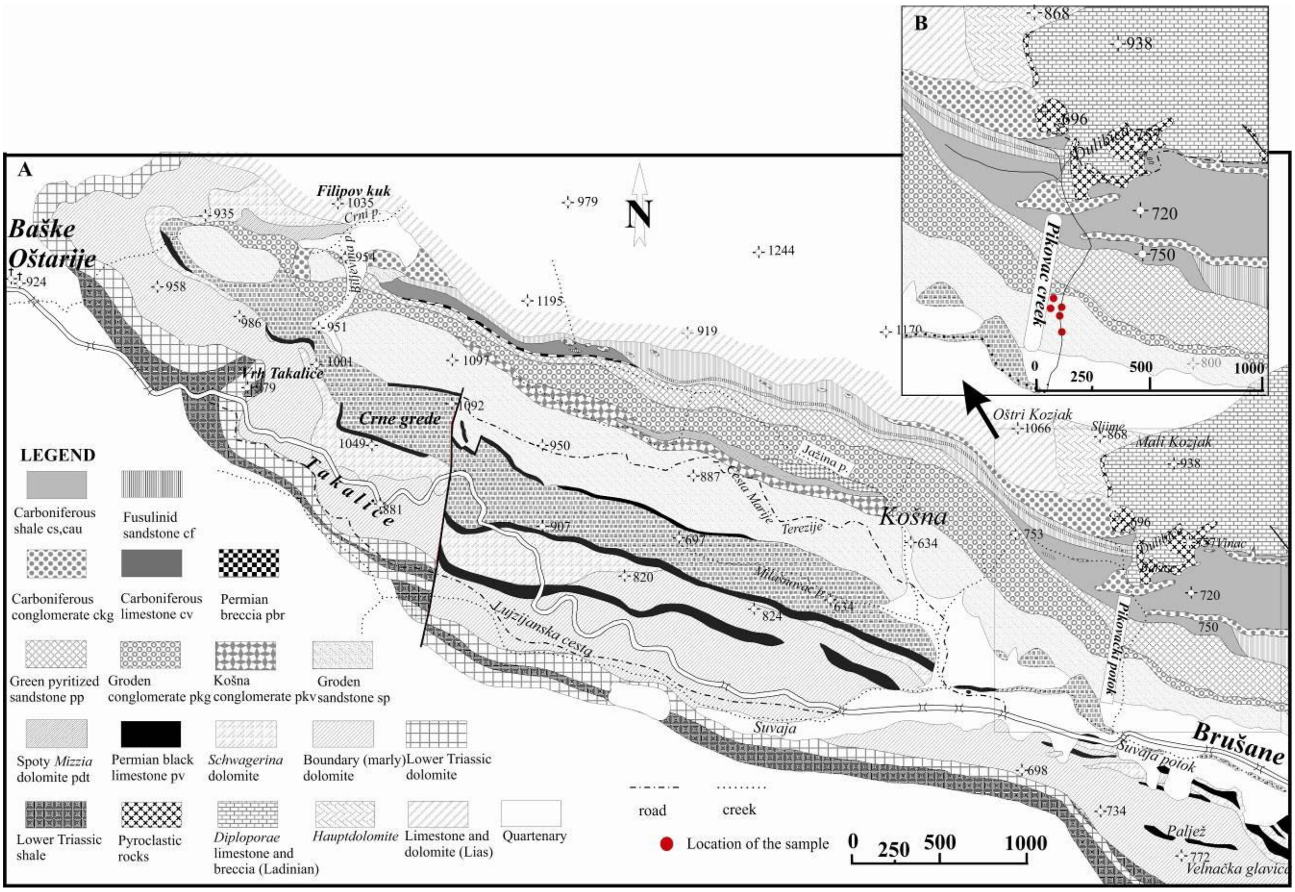


Figure 2.A) A geological map of the Brušane area, Velebit Mts., after Salopek (1942); B) Aclose view of the Pikovac Creek valley, with the positions of analysed samples.

3. Methods

The investigation was carried out using filed and laboratory methods. Five samples were collected in Pikovac Creek valley (Velebit Mts.). One sample represents Middle Permian sandstone from the Gröden Formation collected at locus typicus Gröden (Val Gardena) in the Dolomites (Italy). Thin sections were analysed under a polarising microscope. The composition of main mineral constituents was analysed in thin sections by using a point counter (**Chayes, 1949**). For the heavy minerals analyses separation of heavy and light mineral fractions was done using sodium tungsten dihydrate [Na_2WO_4 x $2H_2O$] with a 2.89 g/cm^3 density. All samples were disintegrated by crushing them into small pieces and for further disintegration an ultrasonic bath was used. The disintegrated material was sieved to achieve fractions 0.063 – 0.125 mm (fraction 0.063) and 0.125 – 0.2 mm (fraction 0.125). Heavy minerals were mounted with Canada balsam (slide mounts). Modal analysis of total heavy mineral composition was performed by counting 300 grains, aiming to determine the percentage of limonitized grains, opaque minerals and transparent grains. For the composition of transparent grains we used counting on 150 grains or less, if a small amount of heavy minerals was available. All mineral phases were determined and expressed in percentages.

4. Results

A total of six samples were micropetrographicaly investigated. Samples of Gröden sandstones collected in Pikovac Creek valley (Velebit Mts.) differ from the locus typicus sample, collected in the Dolomites.

Five samples collected in Pikovac Creek valley are red to yellow, fine- to medium-grained sandstones. Four samples were determined as lithic greywackes, and one sample was determined as lithic arenite (**Table 1**).

All samples from Pikovac Creek valley are densely packed and moderately- to well-sorted. They contain red argillaceous to quartz-sericitic matrix, except sample G-2 that is tightly packed and the amount of matrix is < 15% (**Figure 3 a-f**). In the same sample, due to tight grain packing and pressure solution, cement cannot be clearly seen. Clastic grains are mainly rounded or sub-rounded, rarely angular. In the mineral composition lithic fragments prevail (58.9-82.2 % **- Table 2**) while quartz is also an important constituent whose amount varies in all samples from 15.4-37.7 % (**Table 2**). Feldspar grains (plagioclase and K-feldspars) are rare (0.7-3.6 %). Among lithic grains, quartzite, shale/slate, schist and microcrystalline quartz-rich volcanic or chert fragments have been identified (**Figure 3 d, f**). Muscovite and chlorite dominate among mica particles (**Table 2**).

Sample Gröden s. locus typicus is determined as a medium grained feldspathic greywacke (**Figure 4 g, h**). Their clasts are angular to rounded, and moderately sorted. In composition, feldspar grains prevail (59%) – **Table 2**. Quartz and lithic fragments are present in similar amounts (Q-20.7% and Lt-20.3%) – **Table 2**. Feldspar grains have rounded hollows resembling vesicles. Moderate alteration to clays occur (**Figure 3 h**). Lithic particles predominantly represent polymineral quartz fragments. Muscovite, chlorite and hornblenda crystals are very rare. Matrix is quartz-sericitic, red.

Table 1. Determination of investigated samples

Sample	**Determination**
G-1	**lithic greywacke**
G-1 Gröden	**lithic greywacke**
G-2	**lithic arenite**
G-2a	**lithic greywacke**
G-3	**lithic greywacke**
Gröden s. *locus typicus*	**feldspar greywacke**

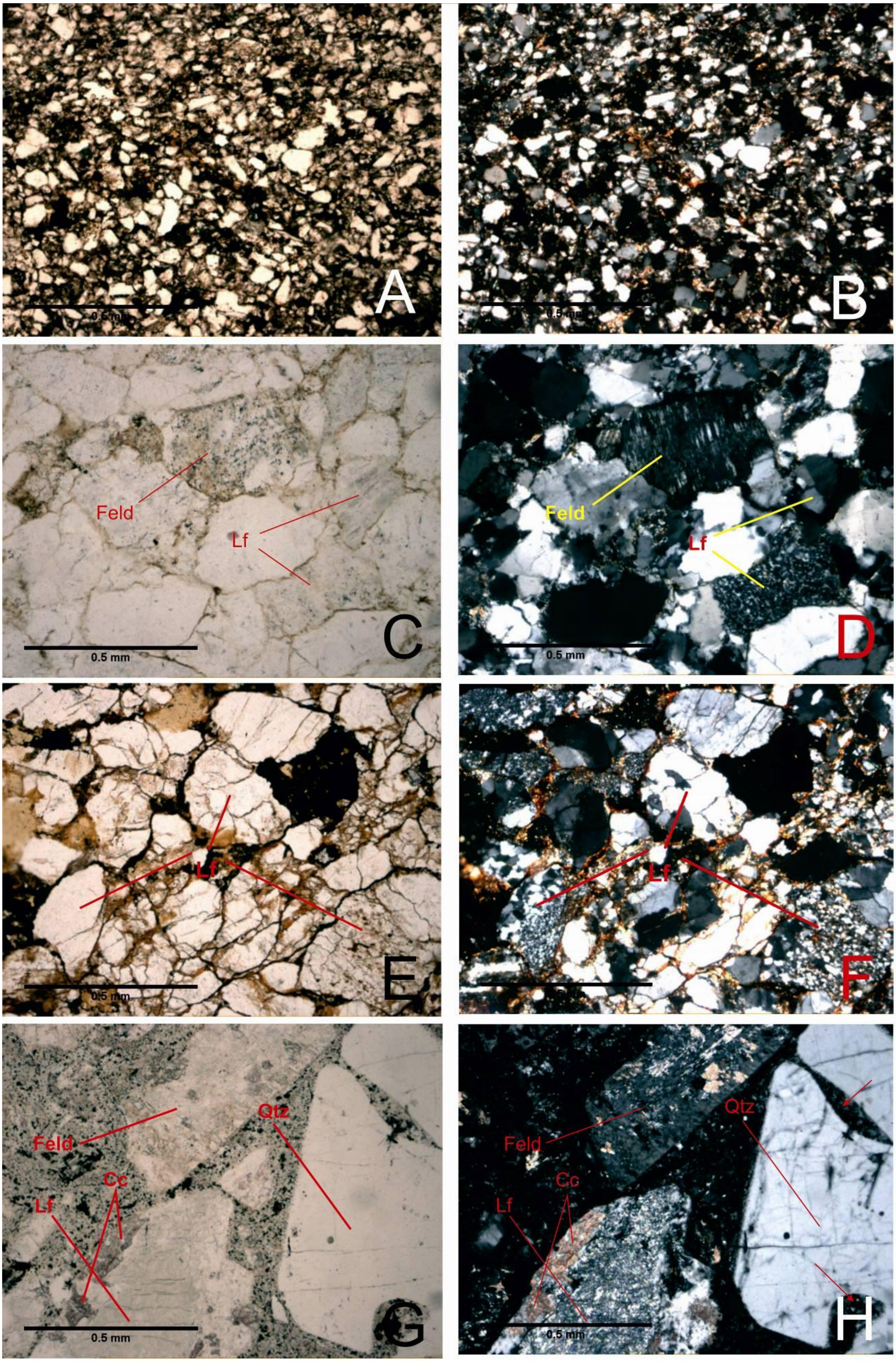

A
0.5 mm
B
0.5 mm
Feld
Lf
C
0.5 mm
Feld
Lf
D
0.5 mm
Lf
E
0.5 mm
Lf
F
Feld
Qtz
Cc
Lf
G
0.5 mm
Feld
Qtz
Cc
Lf
0.5 mm
H

Figure 3. Micropetrographical features of analysed samples; Left are microphotographs under polarized light, right with crossed nicols. Legend: Qtz – quartz, Feld – feldspar, Lf – lithic fragments, Cc calcite (as a product of alteration). Scale bars = 0.5 mm. A, B – Well sorted lithic greywacke (sample G-1 Gröden); C, D - Tightly packed subangular grains in lithic arenite. Lithic fragments prevail in composition (sample G-2); E, F – Composition of moderately sorted lithic greywacke (sample G-2a). Note different type of lithic fragments composed of polymineral quartz indicating their metamorphic origin; G, H - Photomicrograph of feldspathic greywacke composed of angular to rounded feldspar, quartz and lithic fragments and quartz-sericitic matrix (sample Gröden s. locus typicus). Note spherical hollows in quartz grains resembling vesicles (arrows) and microcrystalline quartz with calcitic alteration (Lt, Cc) indicating altered glass-rich volcanic fragment.

Table 2. Mineral composition of analysed samples. Number of all counted grains and percentage of components included in the classification of sandstones (after **Pettijohn et al., 1987**).

Sample	Quartz (monomineral)		Feldspar		Lithic fragments		sum (QmFLt)	Opaque fragments	Micas	Hbl	Chlorite	Total number of analysed grains
Gröden s. locus typicus	62	20.7%	177	59.0%	61	20.3%	300	9	-	13	9	331
G-1	114	37.7%	10	3.3%	178	58.9%	302	3	14	-	15	334
G-1 Gröden	100	32.9%	2	0.7%	202	66.4%	304	7	26	-	13	350
G-2	50	15.4%	8	2.5%	267	82.2%	325	-	-	-	-	325
G-2a	91	29.6%	2	0.7%	214	69.7%	307	17	1	-	2	327
G-3	101	32.7%	11	3.6%	197	63.8%	309	12	16	-	9	346

4.1 Provenance study

Ternary provenance diagram modified after **Dickinson et al. (1983)** (**Figure 4**) and **Weltje (2006)** aims to determine the provenance of the clastic material in analysed sandstones. Provenance diagram Q_mFL_t (**Dickinson et al., 1983** –**Figure 4**) shows percentage ratios of monomineral quartz, feldspar and lithic fragments in each analysed sample. According to their composition, samples were plotted in different provenance areas, as follows:

G-1 – **Transitional recycled orogen**,
G-1 Gröden – **Transitional recycled orogen**,
G-2 – **Lithic recycled orogen**,
G-2a – **Transitional recycled orogen**,
G-3 – **Transitional recycled orogen**,
Gröden s. locus typicus –marginal position between **Basement uplift of continental block** and **Transitional magmatic arc.**

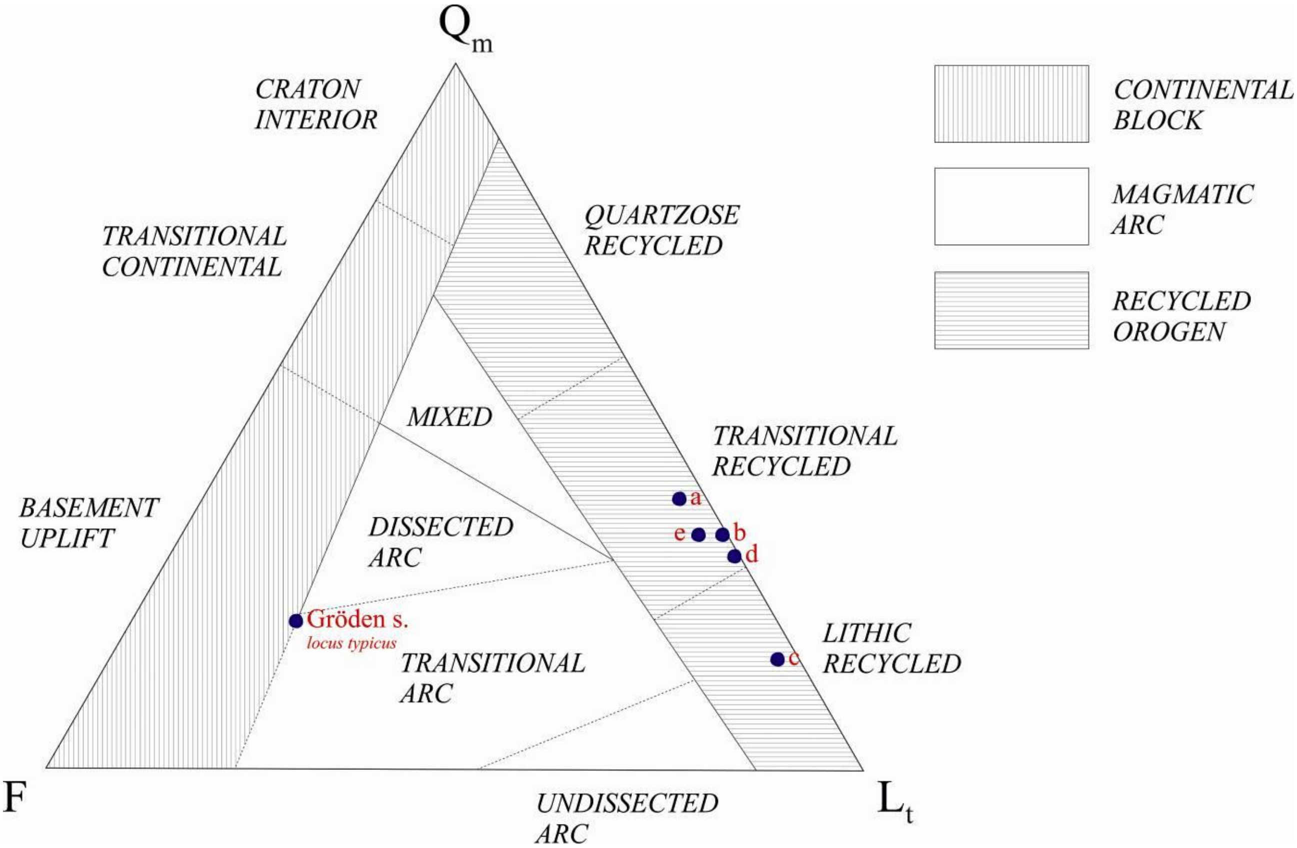


Figure 4. Provenance Q_mFL_t diagram modified by **Dickinson et al. (1983)** and **Dickinson (1985)**; Qm - monomineral quartz grains; F – feldspar grains; Lt – total lithic fragments. Samples: Gröden s. locus typicus; Pikovac Creek valley: a - G-1; b - G-1 Gröden; c - G-2; d - G-2a; e - G-3.

From the ternary diagram by **Dickinson et al. (1983)** it can be clearly seen that samples from Pikovac Creek valley were all plotted in the area of transitional/lithic recycled orogen, while the composition of sample Gröden s. locus typicus plots at the marginal position between "Basement uplift of continental block" and "Transitional magmatic arc". This assumes different source areas for samples from Pikovac Creek valley and the sample from the locus typicus locality in the Dolomites. Nevertheless, the described marginal position of sample Gröden s. locus typicus required that Dickinson's model should be tested using the ternary diagram modified after **Weltje (2006) (Figures 5 a, b)**.

Provenance ternary diagrams (**Figure 5 a**) modified after **Weltje (2002)** shows that sample G-1 from Pikovac creek valley was plotted in the field of recycled orogen with 90% confidence, while samples G-1 Gröden, G-2, G-2a and G-3 were plotted in the field of recycled orogen with 50% confidence. On the contrary, the composition of sample Gröden s. locus typicus plots with 50% confidence in the field of magmatic arc. For additional testing of these results, another ternary diagram was used (**Weltje, 2006**) – **Figure 5 b**. Plotted position of analysed samples confirmed that clastic material of sandstones from Pikovac Creek was derived from the recycled orogen, while sample Gröden s. locus typicus was fed from the magmatic arc (**Figure 5 b**).

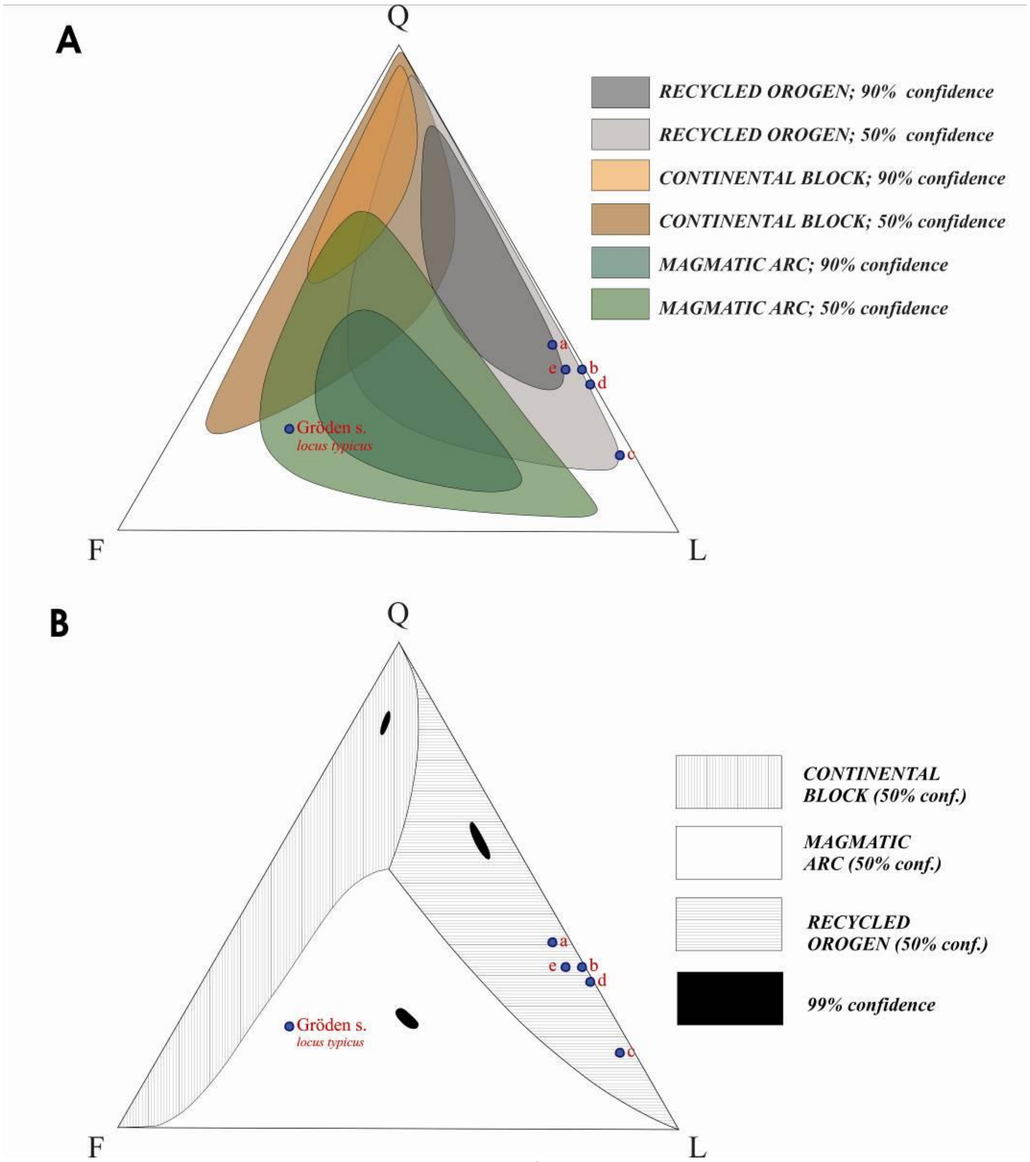
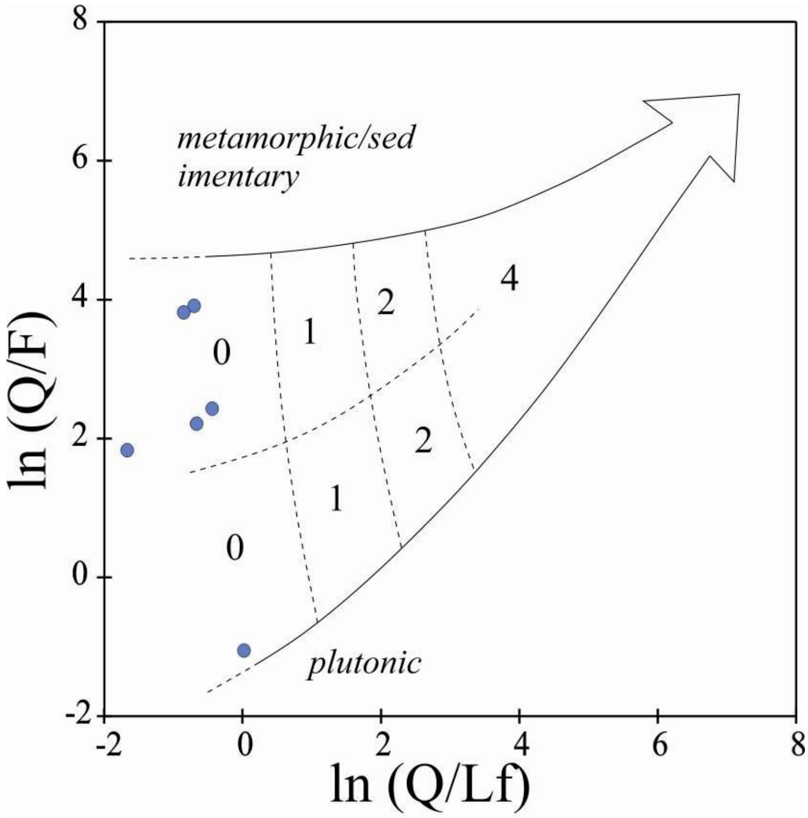


Figure 5. Provenance QFL diagrams with confidence regions (Q – quartz grains; F – feldspar grains; L – lithic fragments) modified by **Weltje (2002)** (A) and **Weltje (2006)** (B) and positions of analysed samples; Gröden s. *locus typicus* - Gröden s. locus typicus*;* Samples from Pikovac Creek valley: a - G-1; b - G-1 Gröden; c - G-2; d - G-2a; e - G-3;

4.1.1. Weathering index diagram

Weathering index diagrams (after **Weltje, 1994; Weltje et. al., 1998**) were constructed to determine the climate conditions, physiology (relief) and origin of siliciclastic material – **Figure 6**. A weathering index diagram shows the natural logarithm of quartz and feldspar ratio versus the natural logarithm of quartz and lithic fragments ratio. The diagram is divided in two areas, regarding the rock type (metamorphic/sedimentary and plutonic). Each of these areas is divided into four fields, pointing to the climate and relief conditions.

Samples G-1, G-1 Gröden, G-2, G-2a and G-3 from the Pikovac Creek valley (**Figure 2**) are grouped and plotted in the area of metamorphic/sedimentary rocks. The field of projection is marked "0" that also implies high relief and weathering in arid to semiarid climatic conditions. The composition of sample Gröden s. locus typicus is plotted in the area of plutonic rocks suggesting also weathering of high relief in the arid/semiarid conditions. These results are well confirmed by the high amount of feldspar in the Gröden s. locus typicus sample.



semi-quantitative weathering index		Physiology (relief) High (Mountains)	Moderate (Hills)	Low (Plains)
(semi) Arid and mediteranean	0	0	0	0
Temperate subhumid	1	0	1	2
Tropical humid	2	0	2	4

Figure 6. Weathering index diagram with the explanation of semi-quantitative weathering index and physiology (relief). Samples: G-Gröden s. locus typicus, a-G-1, b-G-1 gröden, c-G-2, d-G-2a and e-G-3. Modified after **Weltje (1994)** and **Weltje et al. (1998)**.

4.2 Heavy mineral assemblage

Analysis of the heavy mineral composition was possible only for four samples (G-1 Gröden, G-2a and G-3 and Gröden s. locus typicus). Two of the analysed samples (G-1 and G-2) did not have enough grains for analysis, and therefore they were omitted in the paper. Results of the heavy mineral analysis are summarized in **Table 2** and **Figure 7**.

Heavy mineral assemblage of all analysed samples is similar. In the composition the main constituents, counted on 300 grains, are limonitized grains (grains that have a thin film of Fe-oxides on the surface and therefore they cannot be differentiated). Opaque grains are also commonly present. The amount of transparent grains varies from 2-11% in the total composition. Heavy mineral grains from Pikovac Creek (G-1 Gröden, G-2a i G-3) are fairly rounded, while sample Gröden s. locus typicus has angular grains.

The main constituent in the transparent grains composition of all analysed samples is zircon. Zircon grains are prismatic, with high relief (**Figures 8 a, b**). Their shape vary from highly rounded (samples from Pikovac Creek – **Figure 8 a**) to planar, not rounded crystals from Gröden s. locus typicus – **Figure 8 b**. In the Gröden s. locus typicus sample prismatic or bipyramid planes and often zonal zircon crystals are nicely visible. Zircon grains from the same sample are also rich in inclusions. Sample G-2a has the highest percentage of zircon grains (56%) while in sample G-3 the percentage is 36%. Two samples (Gröden s. locus typicus and G-1 Gröden have the lowest content of zircon grains (15% and 13% respectively) compared to the amount of other transparent heavy mineral grains.

Tourmaline (**Figures 8 c, d**) is present in the samples from Pikovac Creek while sample Gröden s. locus typicus lacks tourmaline. Tourmaline grains are often isometric, fairly rounded, with strong pleochroism that vary from colourless to dark green (**Figures 8 c, d**). Sample G-2a has the highest percent of tourmaline grains (20%), while in the rest of the samples the percentage is <10 %. Rutile was determined only in samples G-3 (18%) and G-2a, while other samples lack rutile. Rutile grains are yellow to brown grains with very weak pleochroism (**Figure 8 e**). Apatite is present in all the samples but with various amounts and the highest amount was found in the sample Gröden s. locus typicus (14%). Sample G-1 Gröden has 6% of apatite grains, sample G-3 has 7%, and in sample G-2a amount of apatite is only 2%. Apatite grains are fairly rounded, elongated or isometric (**Figure 8 f**). Apatite from sample Gröden s. locus typicus has hollows resembling vesicles (**Figure 8 f**). Grains of kyanite are usually angular, colourless or pale green. Green kyanite crystals are short prismatic (that is atypical for kyanite) and show weak pleochroism. Interference colours are low (grey and yellow). Biotite is present only in the composition of two samples: Gröden s. locus typicus (8%) and G-2a (8%). Biotite platy crystals are brown and pleochroitic. Chlorite has platy habitus, and weak pleochroism. Chloritic component varies in analysed samples from very high in Gröden s. locus typicus (50%) and G-1 Gröden (59%) to low in G-3(11%), while in sample G-2a chlorite was not present. In the samples of Pikovac Creek valley leucoxene grains occur sometimes in a significant amount. We use the name "leucoxene" for the translucent to opaque, yellow to brown grains, composed of needles or laths that possibly represent Ti-bearing mineral phases (routile, anatase, sphene). Grains that represent clusters of needles or thin laths may indicate authigenic origin of Ti-bearing minerals in sediments, thus implying origin from older sedimentary rocks (**Mange & Wright, 2007**).

Table 3. Heavy mineral composition of the analysed samples. The legend is the same as in Figure 4.

Sample	Locality	Age	Total composition (%) counted on ca. 300 grains			Transparent grains (%) counted on ca. 150 grains														
			Limonitized grains	Opaque grains	Transparent grains	Ch	Zr	Tr	Ru	Lx	Bt	Mc	Hbl	Ap	Ky	Co	Gt	Sp	An	others
Gröden s. locus typicus	Gröden locus typicus	P_2	86	3	11	50	15	0	0	0	8	9	0	14	0	1	0	0	2	1
G-1 Gröden	Pikovac Creek	P_2	96	+	4	59	13	6	0	3	0	0	0	6	9	0	1	0	0	3
G-2a	Pikovac Creek	P_2	90	9	2	0	56	20	6	6	8	0	0	2	0	0	0	1	0	1
G-3	Pikovac Creek	P_2	87	8	5	11	36	9	18	11	0	0	2	7	5	1	+	0	0	0

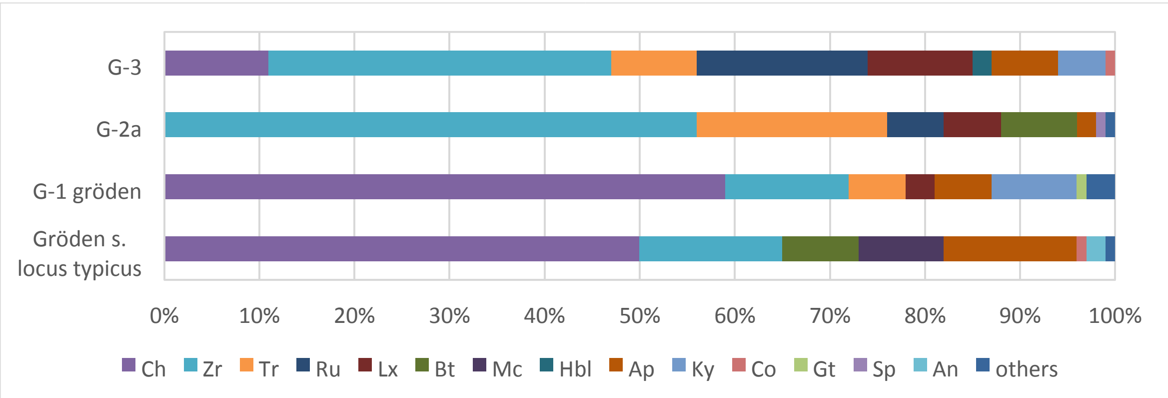


Figure 7. Heavy minerals composition of analysed samples; Ch – chlorite, Zr – zircon, Tr – tourmaline, Ru – rutile, Lx – leucoxene, Bt – biotite, Mc – muscovite, Hbl – hornblende, Ap – apatite, Ky – kyanite, Co – corundum, Gt – garnet, Sp – spinel, An – anatas, + - less than 1%**)**. (Abbreviations according to standards used by **Mange & Wright, 2007**)

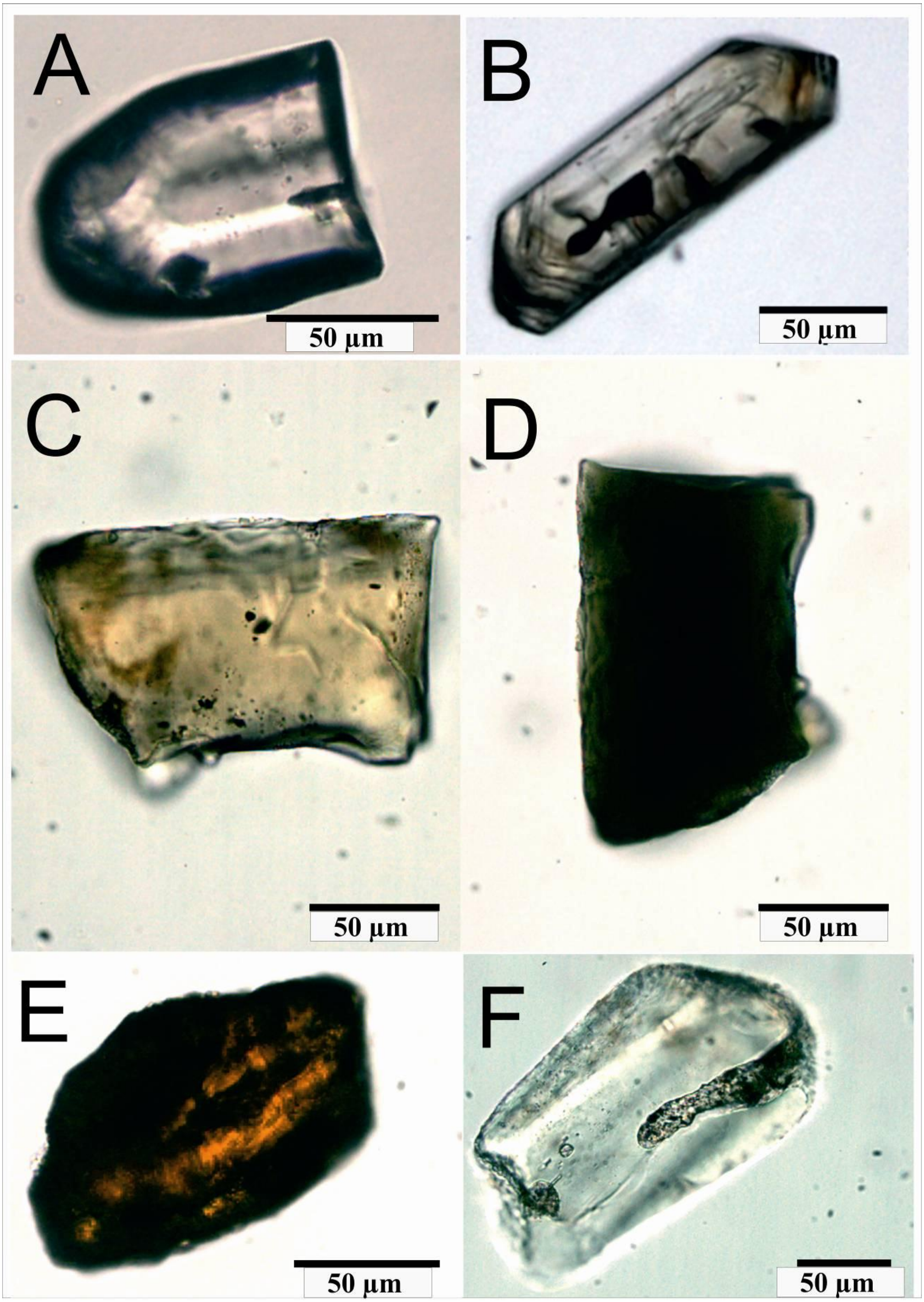


Figure 8. Heavy minerals assemblage. A – Rounded zircon, sample G-3. B – Long prismatic zircon grain from sample Gröden s. *locus typicus*. C, D – Pleochroitic tourmaline grain, G-2a, E – Rounded rutile, G-3. F - Apatite, Gröden s. locus typicus. Partly rounded prismatic grain, with possible vesicle hollow (right).

5. Discussion

Petrographic characteristics and composition of Gröden sandstones have been investigated. Five samples from Pikovac Creek valley (in the vicinity of Brušane village, Velebit Mts.) were analysed and their petrographic characteristics were compared with the sample of Gröden sandstone from the locality Gröden/Val Gardena in the Dolomites (Italy) thus named Gröden s. locus typicus. The composition of sandstones from these two localities were compared (regarding light and heavy mineral association) which enabled the interpretation of their composition and provenance of the clastic material, weathering index in the source area, characteristics of the climate during the deposition and relief in the hinterland as well.

Data interpreting depositional environment of Gröden sandstone from Velebit Mts., as well as the origin of clastic material, are poor. The composition of prevailing and subordinate constituents has been presented in **Sokač et al. (1976)**, but little is known about their depositional environment. On the contrary, Gröden sandstones in the Dolomites represents deposits of former alluvial fans, braided stream deposits, point-bar sequences, overbank deposits, and the sandy terminal lobes of fans that grade into coastal sabkha sequence (**Broglio Loriga & Cassinis, 1992** and references therein). Deposition indicates a markedly differentiated topographic setting that was repeatedly rejuvenated by synsedimentary tectonics (**Broglio Loriga & Cassinis, 1992; Cassinis et al., 1992** and references therein). In general, it is assumed that Gröden sandstones were deposited in the Middle Permian, as terrigenous alluvial deposits, and therefore characterized by a red colour. Source terrains were the underlying Permian volcanic rocks, the pre-Permian crystalline basement and granitic rocks (**Broglio Loriga & Cassinis, 1992**). Similar alluvial characteristics can be seen in Gröden sandstones from Slovenia (**Skaberne, 1995**).

Our analyses confirm some previous interpretations regarding Gröden sandstone from the Dolomites. An abundance of feldspars found in Gröden s. locus typicus (feldspatic greywacke) and a red colour due to the presence of Fe-oxides suggest arid climate in the Middle Permian (**Figure 6**). Regarding presence of quartz grains with vesicular hollows and K-feldspars, acidic volcanic rocks are considered as the source rocks from where the clastic material was derived. This assumption is also confirmed by plotting the composition in a provenance diagram (**Figures 5 a, b**), where a magmatic arc was supposed as a provenance area with a 50 % certainty (**Weltje, 2004, 2006**). Composition of the analysed sample Gröden s. locus typicus, plotted in the area of plutonic rocks within the weathering index diagram after **Weltje (1994)** and **Weltje et al. (1998) – Figure 6**, suggests weathering of the high plutonic relief in the arid/semiarid conditions. These results are well confirmed by the high amount of feldspars in the Gröden s. locus typicus sample. The presence of a high percentage of angular zonal zircons, apatite grains, muscovite and biotite, as well as a lack of kyanite, is in accordance with the supposed origin of detritus from a magmatic arc. Gröden-Bellerophon sequence unconformably overlies Lower Permian volcanics (Bolzano volcanic complex) or, where these are lacking, it rests directly on the Hercynian crystalline basement (**Broglio Loriga & Cassinis, 1992**). The tentatively analysed sample Gröden s. *locus typicus* is on the palaeogeographic reconstruction (after **Ziegler & Stampfli, 2001**) positioned close to the magmatic arc (**Figure 9**). Clay- and quartz-rich matrix and biotite, although altered, imply that the sandstone is immature, probably deposited near the source rock area.

Considering the mineral composition of the samples from Pikovac Creek valley, four sandstones were determined as lithic greywackes and one as lithic arenite. Presence of clayey and quartz-sericitic matrix in most analysed samples suggests a depositional environment that differs from fluvial. Fluvial sandstones are usually well sorted and matrix free, due to their long transport when fine-grained material is washed out. Matrix-rich sandstones accumulate in the environments more closely to the source area. An accumulation of matrix stems from short transport or from deposition not far from source areas. Mineral composition of sandstones from Pikovac Creek valley with a high percentage of lithic fragments and matrix imply immature sandstones, possibly deposited close to the source area. Deposition in fan deltas or braided deltas in a wrench-faulted graben/half graben system is supposed.

Using provenance diagrams (by **Dickinson et al. 1983; Weltje, 2002, 2006)** different source areas for Gröden sandstone from Pikovac Creek valley (recycled orogen) and from the locus typicus in the Dolomites (magmatic arc) have been suggested (**Figure 5 a, b**).

The assumption of the source provenance as presented can be validated by heavy mineral composition. In the heavy mineral association of samples from Pikovac Creek valley stable grains – zircon, tourmaline and rutile, prevail. Fair roundness of the grains (especially of zircons) suggests their origin from reworked sedimentary rocks that confirms the projection of composition in the field of recycled orogen. The origin of kyanite and chlorite in the composition of heavy mineral association, as well as abundant fragments of metamorphic rocks (slate, quartzite, schists) from light mineral fraction, suggest a metamorphic origin of these grains. This can be also confirmed by the plotting of their composition in the field of weathered sedimentary/metamorphic rocks of high relief in arid/semiarid climate (weathering index diagram after **Weltje, 1994** and **Weltje et al., 1998** – **Figure 6**). The origin of apatite is related, at least partly, to volcanic rocks. Volcanic rocks can also be present in recycled orogen or, more precisely, in a complex of a tectonically active region.

The assumption of weathering high mountains composed of sedimentary/metamorphic rocks in arid/semiarid conditions is confirmed for the samples from Pikovac Creek valley. This supposed different provenance area then for the sample Gröden s. locus typicus, which is composed of the material derived from a magmatic arc that has a high relief. Nevertheless, high relief assumes active tectonic area in the hinterland of both areas. Keeping in mind different provenance areas but weathering in the same climatic condition (arid/semiarid climate that has been proven by the weathering index and red colour due to presence of Fe-oxides) for these two investigated regions, we tentatively suggest their different palaeopositions (**Figure 9**). A palaeoreconstruction by **Ziegler & Stampfli (2001)** for Early Permian was used, assuming that similar distribution of depositional environments started in the Early Permian and continued to Middle Permian. The sample Gröden s. locus typicus is located close to the magmatic arc, due to a high influence of volcanic mineral components in its composition. A proposed position for Gröden sandstone from Pikovac Creek valley was more distant from the magmatic arc and located more closely to the initial graben, more to the South. Material for samples from Pikovac Creek was derived possibly from the recycled orogen located in Gondwana (**Figure 9**).

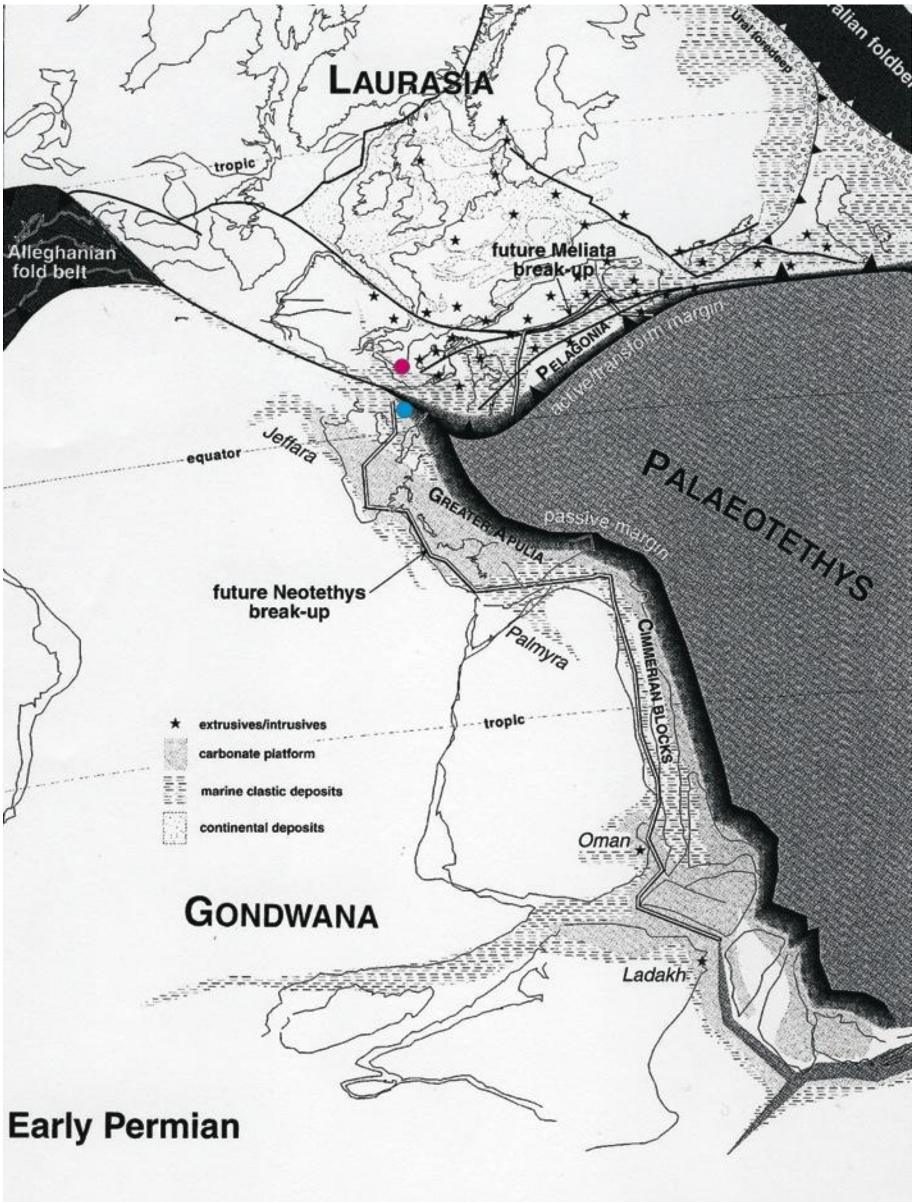


Figure 9. Palaeogeographic map after **Ziegler & Stampfli (2001)** with the assumed position of the Gröden sandstone sample from locus typicus in the Dolomites (red dot) and samples from Pikovac Creek valley in Velebit Mts. (blue dot)

6. Conclusions

Petrographic features, composition and provenance of Gröden sandstone have been analysed. Five samples were collected in the Pikovac Creek valley on the Velebit Mts. One sample was collected near Gröden/Val Gardena (locus typicus) in the Dolomites (Italy). All samples were compared by means of light and heavy minerals, provenance of detritic materials, climate and relief (weathering index) of the source rocks.

Four samples from Pikovac Creek were determined as lithic greywackes and one sample as densely-packed lithic arenite. Lithic greywackes/arenite imply very low maturity and suggest the close proximity of source rocks, as well as the active tectonics in the hinterland of the depositional basin. Regarding the provenance area, the composition of all samples from Pikovac Creek valley was plotted in the area of recycled orogin. Heavy mineral association with a large amount of fairly rounded stable grains (zircon and tourmaline), suggest that clastic material was derived from the older sedimentary rocks, although the presence of kyanite and chlorite in the heavy mineral assemblage suggests their metamorphic origin. Applying the diagram of **Weltje (1994)** sedimentary/metamorphic source rocks were supposed. This data assumes that Gröden sandstones from Pikovac Creek were possibly deposited in a fan delta or braided delta, probably in a rift system, and that material was derived from the recycled orogen composed mainly of sedimentary and metamorphic rocks.

The light and heavy mineral association of sample Gröden s. locus typicus, determined as feldspathic greywacke, suggests that the origin of material was magmatic arc. This assumption is well proven by prismatic zonal tourmaline grains and an abundance of apatite.

Concerning the weathering index and relief of the source area samples from the Pikovac Creek valley, as well as the sample Gröden s. locus typicus, suggests weathering of a high relief in arid/semiarid conditions.

Tentative palaeoposition of the Gröden sandstone from Pikovac Creek valley is located close to a rift system that started to develop in the Early Permian (palaeoreconstruction after **Ziegler & Stampfli, 2001**), while palaeoposition of the Gröden sandstones in the Dolomites is closely related to the proximity of the magmatic arc. Clastic material for Gröden sandstones in Pikovac Creek valley was possibly derived from Gondwana.

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Sažetak

Sastav i provenijencija gredenskih pješčenjaka Velebita

Analizirano je šest uzoraka srednjopermskih gredenskih pješčenjaka: pet uzoraka iz doline Pikovačkoga potoka u okolici Brušana na Velebitu i jedan uzorak s *locus typicus* lokaliteta Gröden/Val Gardena u Italiji. Na temelju mikropetrografskih karakteristika pješčenjaka, njihova mineralnog sastava te sastava teške i lake mineralne frakcije, interpretirano je podrijetlo materijala, indeks trošenja matičnih stijena te klima i reljef u vrijeme taloženja. Četiri uzorka pješčenjaka iz Pikovačkoga potoka petrografski su određena kao litične grauvake, a jedan uzorak kao gusto pakirani litični arenit, dok je uzorak pješčenjaka s *locus typicus* lokaliteta Gröden određen kao feldspatska grauvaka. Litične grauvake/areniti podrazumijevaju vrlo nisku zrelost i sugeriraju blizinu matičnih stijena, kao i aktivnu tektoniku u zaleđu sedimentacijskoga bazena. Asocijacija teških minerala u uzorcima iz Pikovačkoga potoka, s velikom količinom dobro zaobljenih stabilnih zrna (cirkon, turmalin i rutil), upućuje na to da klastični materijal potječe iz recikliranoga orogena, i to vjerojatno od pretaloženih sedimentnih stijena. Prisutnost distena i klorita u teškoj mineralnoj frakciji sugerira podrijetlo iz metamorfnih stijena. Rezultati upućuju na to da su gredenski pješčenjaci iz doline Pikovačkoga potoka možda taloženi u okolišu lepezne delte koja je dio riftnoga sustava (reciklirani orogen). Sastav lake i teške mineralne frakcije uzorka *Gröden s. locus typicus* sugerira podrijetlo iz magmatskih stijena. Svi analizirani uzorci crvene su boje i imaju veliku količinu limonitiziranih zrna u teškoj mineralnoj frakciji, što upućuje na aridnu klimu u vrijeme taloženja. Dijagram indeksa trošenja pješčenjaka iz Pikovačkoga potoka upućuje na aridnu/semiaridnu klimu i visoki reljef izvorišnoga područja koji je izgrađen od sedimentnih i metamorfnih stijena, dok uzorak *Gröden s. locus typicus* pješčenjaka ukazuje na aridnu/semiaridnu klimu i visoki reljef, s magmatskim matičnim stijenama i izvorišno područje magmatskoga luka.

Ključne riječi: gredenski pješčenjak, srednji perm, Velebit, teška mineralna frakcija, podrijetlo materijala