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LOWER TRIASSIC POTASSIUM-RICH RHYOLITES OF THE SILICIC UNIT, WESTERN CARPATHIANS, SLOVAKIA: GEOCHEMISTRY, MINERALOGY AND GENETIC ASPECTS

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Abstract: Detailed study of Lower Triassic high-K rhyolites of the Drienok and Muráň Nappes, the Silicic Unit, Inner Western Carpathians, reveals their alkaline and anorogenic nature. The rhyolites occur within shallow-marine to continental shale, sandstone and limestone platform sequences. The rocks are unusually K-rich (4.9–8.7 wt.% K_2O), enriched in Si, Rb, REE's, Y and Zr and depleted in Al, Ca, Na, P and Sr. Rhyolite phenocrysts are represented by β-quartz and alkali feldspars. Zircon typology (mainly P_5 and D types) indicates a hot and dry magma environment which corresponds to a high zircon saturation temperature: 820–895 °C. Accessory monazite-(Ce), xenotime-(Y), rutile, ilmenite, magnetite, hematite and barite were identified. The results indicate an origin of the high-K rhyolites in an extensional tectonic regime during the early-Alpine rifting stage. The exceptionally high K in contrast to very low Ca and Na contents in the rhyolites is probably a result of late-magmatic and/or post-magmatic (hydrothermal) overprint by K-rich fluids. This K-enrichment of Early to Middle Triassic volcanic rocks is a characteristic feature of the South Alpine–Inner Carpathian domaine during their Early Alpine continental rifting stage.

Key words: Western Carpathians, Silicic Unit, rhyolites, geochemistry, mineralogy, alkali feldspars, zircon.

Introduction

Occurrences of acid volcanic rocks within Lower Triassic clastic to carbonate sequences of the Silicic Unit, in the Muráň and Drienok nappes were known for many years (e.g. Štúr 1868; Oppenheimer 1931; Grenar & Kotásek 1956; Zorkovský 1959a,b; Losert 1963; Slavkay 1965, 1981; Zuberec 1968; Klinec 1976; Hovorka & Spišiak 1988). The authors mentioned mainly their petrographic features, locally with bulk-rock compositions (Zorkovský 1959a,b). A sole petrographical and geochemical study is available for the Lower Triassic acid volcanites of the Drienok Nappe near the Poniky village (Slavkay 1965, 1981); the author characterized (trachy)andesite–trachyte–rhyolite lava and pyroclastic sequences as belonging to the "K-alkalic association" (after de La Roche classification). The sequence was named the Skálie Formation and correlated with the Lower Triassic volcanic suite of the Bükk Unit, Hungary (Hovorka & Spišiak 1988). However, trace-element and accessory mineral data from the Triassic acid volcanites in the Silicic Unit are still missing.

The aim of this study is to present new geochemical and mineralogical data on the Lower Triassic rhyolites of the Drienok and Muráň nappes of the Silicic Unit in comparison with older results as well as analogous occurrences in the Alpine-Carpathian belt.

Regional geology

All the studied acid volcanites form lava flows or ignimbrite layers in Lower Triassic siliciclastic and carbonate sequences of the Muráň and Drienok nappes of the Silicic Unit.

The Silicic Unit represents the tectonically uppermost Alpine nappe structures in the Western Carpathians. It overlies the Veporic, Hronic and Gemeric units. The Silicic Unit involves Upper Permian to Upper Jurassic (Malmian) mainly

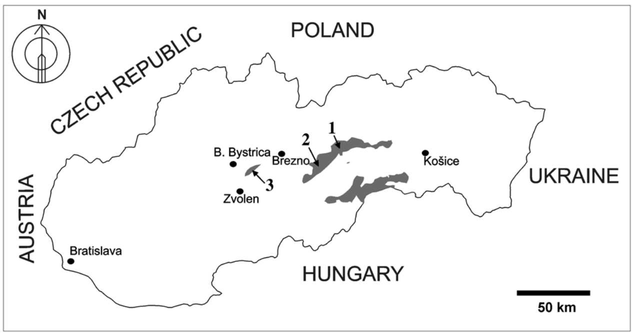

Fig. 1. Schematic map of Slovakia with the Silicic Unit (grey) and localities of Lower Triassic volcanites: 1 — Telgárt, 2 — Veľká Stožka, 3 — Poniky.

sedimentary sequences which are facially analogous with the Schneeberg and Mürzalpe nappes of the Juvavic Unit of the Northern Calcareous Alps (Mello Ed. 1997). A lower part of the Silicic Unit consists of a 1200–1600 m thick sequence of Lower Triassic continental to shallow marine sediments: varicoloured, mainly violet, reddish-brown and greenish-grey shales to sandstones, locally shales and limestones with siliciclastic admixture (Bystrický 1959, 1964; Slavkay 1965; Biely Ed. 1997; Mello Ed. 1997). The volcanic rocks occur in the upper part of the Lower Triassic (Scythian) members of the Werfen Formation, which belongs to the Szin Member of Upper Nammalian to Middle Spathian age (according to Kovács et al. 1989; cf. Mello Ed. 1997), formerly designated as "Campilian Beds" (e.g. Bystrický 1959, 1964). The total thickness of the Szin Member is 300–400 m (Mello Ed. 1997); ca. 200 m of the thickness of this member was revealed by the PO-1 borehole near Poniky village in the Drienok Nappe (Slavkay 1965).

Volcanic rocks of the Silicic Unit occur in several localities (Figs. 1–3):

(1) The Gregová hill near Telgárt (formerly Švermovo) village represents the largest continuous volcanic body (3.3 by 1.8 km, Fig. 2) probably of a laccolith shape (Pouba 1953), accompanied by smaller volcanic outcrops. The rhyolite body lies amidst Griensbachian to Spathian shales to fine-grained sandstones and limestones of the Muráň Nappe (Biely Ed. 1992, 1997).

(2) The Veľká Stožka hill locality, ca. 9 km SSE of Závadka-nad-Hronom village represents a smaller rhyolite body (ca. 500 m in size) concordant with Lower Triassic violet and greyish-green shales, locally sandy or clayish shales of the Werfen Formation (Zorkovský 1959a) in the Muráň Nappe (Fig. 2). A geological map 1:50,000 by Klinec (1976) does not show this occurrence, but another rhyolite oucrop, 2 km S of the Pohorelská Maša village (ca. 300 m in size) is depicted here.

(3) The largest area of Lower Triassic acid volcanites in the Silicic Unit is situated in the vicinity of Poniky village. Volcanic and volcanoclastic rocks form a non-continuous belt, ca. 7 km long and up to 300 m wide plus a continuous 1200 by 300 m outcrop S of the Žiarec hill (Fig. 3).

According to the Poniky borehole material, the greyish-green and violet-brown "Werfenian" shales with intercalations of marly limestones and calciferous shales containing "Campilian" fauna are superposed by ca. 30 m thick volcanic layer of subaqueous andesite tuff and (trachy)andesite (Slavkay 1965). This volcanic layer is superposed ca. 5 m thick bed of pyroclastic material with calcareous claystone to marly limestone and two rhyolitic layers, 5 and 38.5 m thick with 1 m thick intercalation of calcareous claystone to marly limestone (Slavkay 1965).

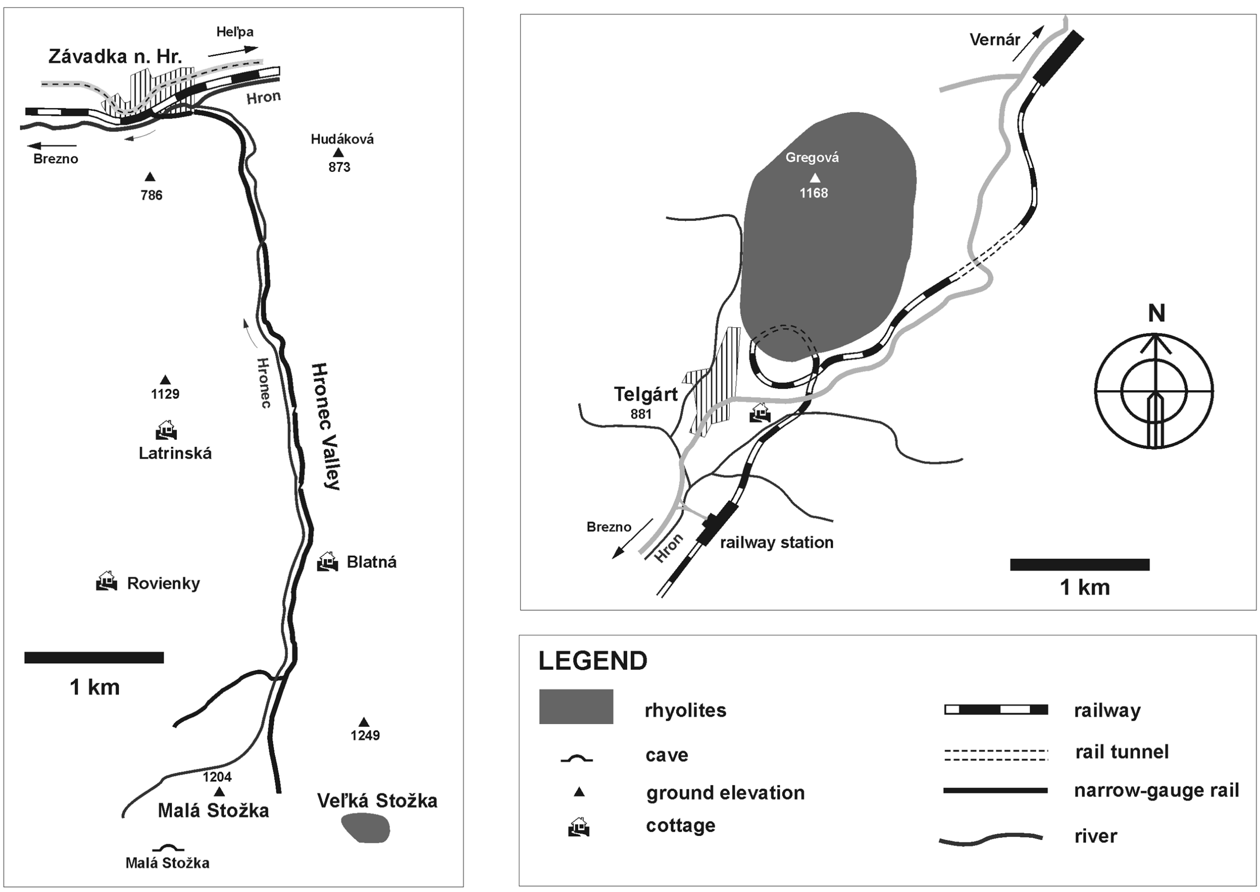

Fig. 2. Schematic map of the Telgárt and Veľká Stožka rhyolite bodies.

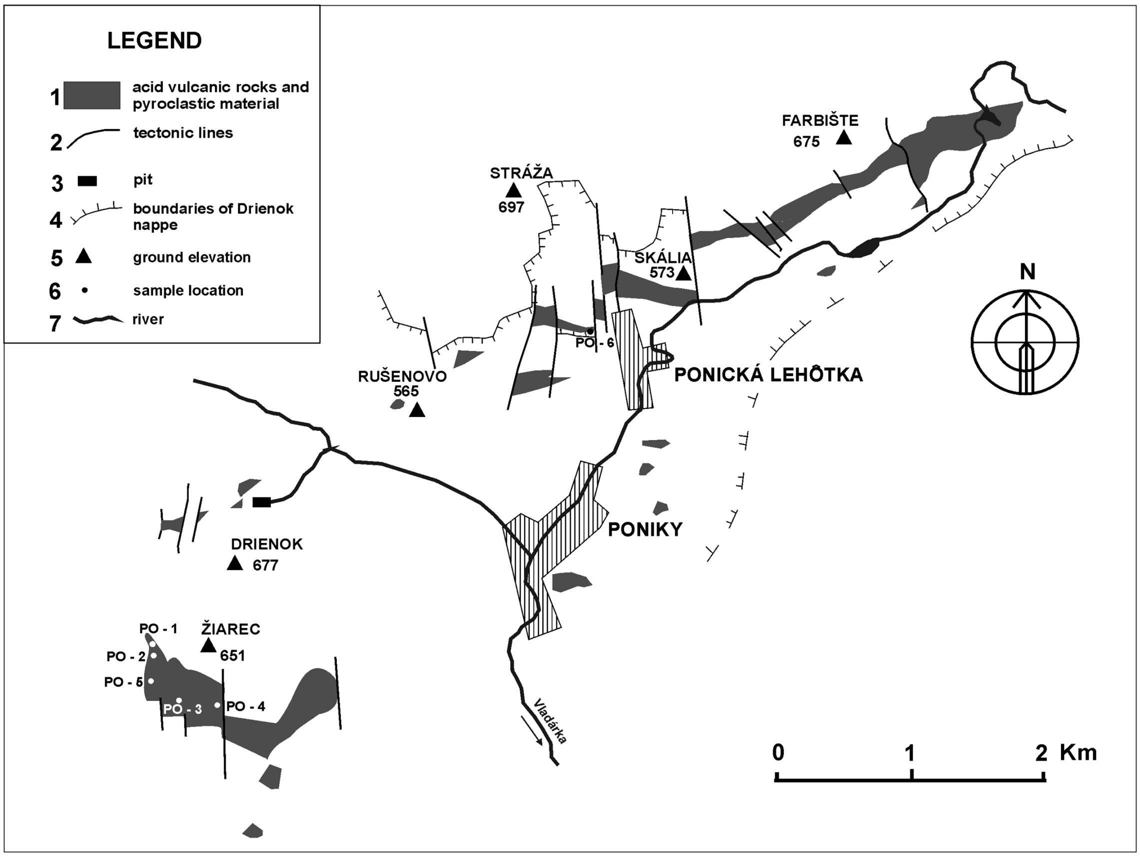

Fig. 3. Schematic map of the Poniky rhyolites.

Analytical methods

Chemical analyses of the volcanic rocks were carried out by X-ray fluorescence method (XRF: main oxides), optical emission spectrography (OES: Be, Sr, Ba, B, Ga, Sn, Pb, Zr, V, Cr, Mo, Co, Ni, Cu, Sc and Y), atomic absorption spectroscopy (AAS: Rb), instrumental neutron activaction analysis and inductively coupled plasma (INAA, ICP: REE's). Measurements using XRF, OES and AAS methods were performed at the Geological Institute, Slovak Academy of Sciences, Bratislava; INAA at IGEM, Russian Academy of Sciences, Moscow and ICP at the Geological Survey of the Slovak Republic, Spišská Nová Ves (Slovakia).

Feldspars and zircon were analysed by electron microprobe analysis (EMPA). JEOL Superprobe 733 apparatus was used in wave-length dispersion mode and following analytical conditions: accelerating voltage of 15 kV (feldspars) and 20 kV (zircon), respectively, beam current of 20 nA, beam diameter: 3–5 μm. Standards used: wollastonite (Si Kα, Ca Kα), Al_2O_3 (Al Kα), chromite (Fe Kα), albite (Na Kα) and orthoclase (K Kα) for feldspars; zircon (Si Kα, Zr Lα, Hf Mα) and YAG (Y Lα) for zircon. EMPA compositions were done at the Geological Survey of the Slovak Republic, Bratislava.

Zircon was separated by conventional heavy-mineral separation technique (rock crushing, sieving, heavy liquid and electromagnetic separation) from large samples (ca. 5–7 kg in weight).

Zircon morphology was studied under the Tesla BS-300 scanning electron microscope (SEM) at the Geological Institute, Slovak Academy of Sciences, Bratislava, internal zoning of zircon and other minerals was investigated under the JEOL JSM-825 scanning electron microscope in back-scattered electrons mode (BSE) at the Geological Survey of the Slovak Republic, Bratislava.

Results

Petrography and mineral composition

The studied rhyolitic rocks reveal common features of acid volcanics. The texture is porphyric with granolepidoblastic, locally microfelsic groundmass. In some cases, also fluidal texture occurs. Phenocrysts, 2–4 mm in size, are represented by corroded bipyramidal β-quartz and euhedral alkali feldspars. The feldspars are commonly replaced by chessboard albite, late K-feldspar or fine-grained white mica aggregates.

The devitrificated groudmass consists of very fine-grained (~10 μm) aggregate of quartz, feldspar, white mica, hematite pigment, rarely biotite, chlorite and accessory zircon, EDS analyses reveal also rare monazite-(Ce), xenotime-(Y), rutile, ilmenite, magnetite and barite. Microscopic hydrothermal veinlets of quartz are locally common.

The studied rocks are volcanic rocks, however, volcanoclastic rocks are also mentioned in the Poniky area (Slavkay 1965).

Chemical composition

The results of the new and published bulk-rock chemical analyses of volcanics are presented in Tables 1 and 2. Generally, the investigated volcanic rocks are enriched in Si (72.8–77.2 wt.% SiO_2) and especially in K (4.9–8.7 wt.% K_2O) and depleted in Ti (0.08–0.30 wt.% TiO_2), Mg (0.09–1.0 wt.% MgO), Ca (0.03–1.1 wt.% CaO), Na (0.19–2.8 wt.% Na_2O) and P (0.01–0.11 wt.% P_2O_5) — Table 1. TAS diagram (Le Bas et al. 1986) discriminates the studied rocks into rhyolite field, the more basic members of the Poniky area (trachytes, trachyandesites to andesites after Slavkay 1965) fall into dacite, andesite and on the boundary between the trachydacite (trachyte) and rhyolite fields (Fig. 4). Remarkably high potassium and low calcium and sodium contents resulted in their designation as potassium-rich rhyolites. Despite the relatively low Al contents, due to depletion in Ca and Na, the rhyolites are peraluminous with A/CNK = 1.15 to 1.7 (Fig. 5). High Si contents connected with low Mg and Ca caused anomalously high R1 parameter and very low R2 parameter in R1-R2 multicationic diagram (Batchelor & Bowden 1985) with a trend concordant with anorogenic magmatic suites (Fig. 6).

Trace-element geochemistry of the rhyolites (Table 2) shows a slight enrichment in Rb, Zr, Y and REE, depletion in Sr, Ba and V, as well as elevated Rb/Sr and Ga/Al ratios, which are typical for alkaline-rich (A-type) post-orogenic and anorogenic Si-rich magmatic suites (cf. Whalen et al. 1987). The A-type tendency is also evident in chondrite-normalized REE distribution; the chondrite-normalized curves show characteristic pronounced negative Eu-anomaly and slightly LREE enrichment (Fig. 7). Conspicuously high Ba content (1200 ppm), in PO-2/97 sample in comparison to the others (Table 2) is caused by a presence of hydrothermal barite which was identified in Poniky as well as the Telgárt rhyolites.

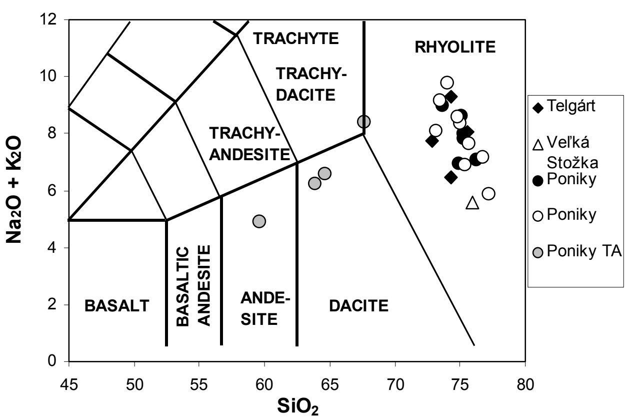

Fig. 4. Total alkali-silica diagram of the rhyolites (Le Bas et al. 1986). Full symbols: our analyses; Open and grey symbols: older analyses (Zorkovský 1959a,b; Slavkay 1965). Poniky TA — more basic members of the Poniky volcanics ("trachyte-andesite" members according to Slavkay 1965).

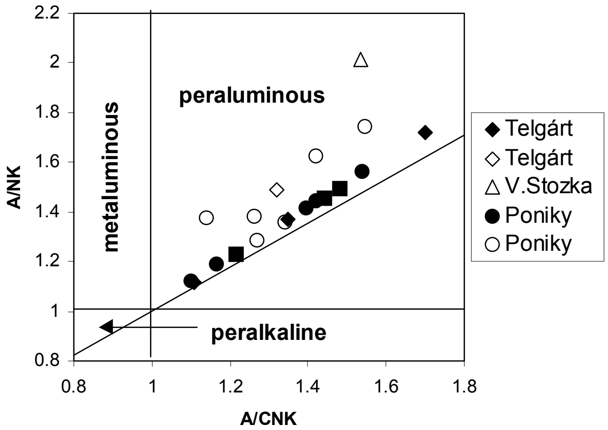

Fig. 5. A/NK vs. A/CNK diagram of the rhyolites.

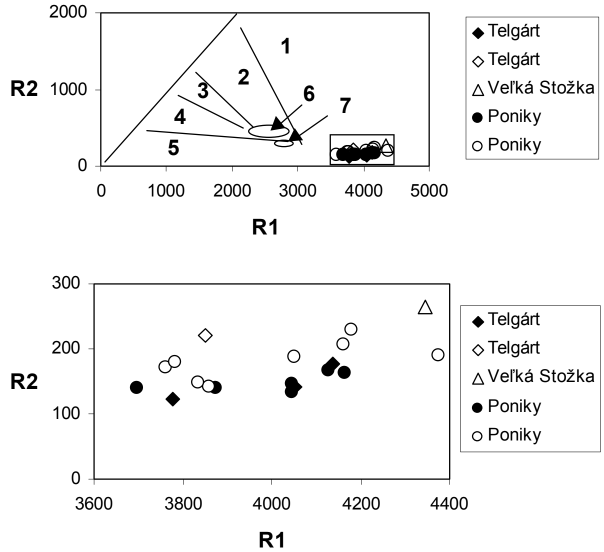

Fig. 6. R1-R2 diagram (Batchelor & Bowden 1985) of the rhyolites. Analyses are compared to the fields of major granite associations: 1 — mantle fractionates, 2 — pre-plate collision, 3 — post-collisional uplift, 4 — late-orogenic, 5 — anorogenic, 6 — syn-collision, 7 — post-orogenic.

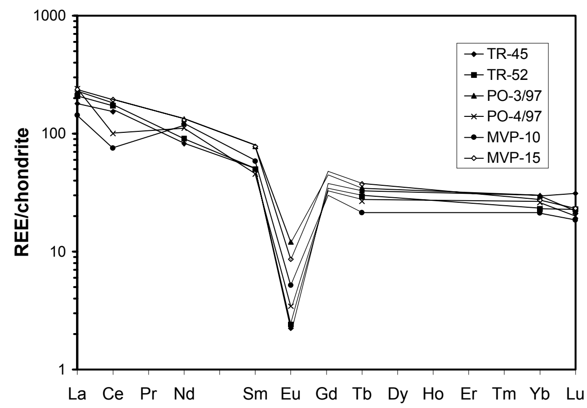

Fig. 7. REE/chondrite normalized diagram of the rhyolites. REE chondrite values after Taylor & Mc Lennan (1985). Sample location: TR — Telgárt; PO, MPV — Poniky.

Table 1: Chemical analyses of the Lower Triassic volcanites from the Silicic Unit (wt. %). References: A — our results; B —Zorkovský (1959b); C — Zorkovský (1959a); Slavkay (1965).

Unit	MURÁŇ NAPPE					DRIENOK NAPPE						
Location	Telgárt, Gregová: rhyolites				V. Stožka	Poniky area: rhyolites						
Reference	A	A	A	B	C	A	A	A	A	A	A	A
Sample	TR-45	TR-52	PV-1/90	Tel-1	VS-1	PO-1/97	PO-2/97	PO-3/97	PO-4/97	PO-5/97	PO-6/99	MVP-10
SiO_2	74.28	74.25	75.60	72.80	75.98	75.29	74.89	73.65	75.26	75.11	76.25	75.01
TiO_2	0.08	0.14	0.14	0.22	0.30	0.13	0.13	0.21	0.14	0.14	0.12	0.12
Al_2O_3	11.70	12.46	12.09	13.13	12.51	12.65	11.94	12.19	12.33	12.14	11.82	12.20
Fe_2O_{3total}	2.48	1.69	2.02	3.10	2.72	1.38	2.28	2.13	1.77	1.50	1.89	1.74
MnO	0.01	0.01	0.03	0.01	trace	0.02	0.03	0.01	0.01	0.01	0.02	0.01
MgO	0.12	1.03	0.31	0.50	0.56	0.26	0.84	0.16	0.09	0.18	0.78	0.23
CaO	0.03	0.05	0.08	0.62	1.06	0.09	0.07	0.11	0.07	0.11	0.07	0.09
Na_2O	0.74	0.43	0.19	0.75	0.34	0.17	0.19	1.98	0.37	1.59	0.92	2.15
K_2O	8.58	6.04	7.85	7.00	5.23	7.83	6.77	7.03	7.48	7.03	6.17	6.23
P_2O_5	0.11	0.07	n.a.	0.01	trace	0.02	0.02	0.03	0.04	0.03	0.01	0.02
LOI	1.53	3.01	1.10	1.17	1.27	1.06	1.54	1.15	1.32	1.07	1.17	1.62
H_2O^-	0.34	0.79	0.20	0.18	0.05	0.44	0.51	0.50	0.45	0.38	0.11	0.10
Total	100.00	99.97	99.61	99.49	100.02	99.34	99.21	99.15	99.33	99.29	99.33	99.52

Unit	DRIENOK NAPPE										
Location	Poniky area: rhyolites							Poniky area: (trachy)dacites, andesites			
Reference	A	A	D	D	D	D	D		D	D	D	D
Sample	MVP-13	MVP-15	KP-12	KP-14	KP-15	KP-18	KP-25	KP-26	KP-22	KP-16	KP-19	KP-21
SiO_2	74.82	74.04	75.33	76.67	75.65	77.23	73.44	73.14	67.67	63.89	64.66	59.60
TiO_2	0.12	0.14	0.14	0.13	0.14	0.16	0.14	0.17	0.55	0.96	0.85	0.83
Al_2O_3	12.80	12.01	12.35	11.53	12.18	12.02	13.08	13.18	14.87	15.62	15.35	15.16
Fe_2O_{3total}	1.75	1.73	2.29	1.24	2.11	1.40	1.95	2.73	5.04	5.72	5.16	8.72
MnO	0.02	0.01	0.02	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.02	0.09
MgO	0.27	0.29	0.41	0.33	0.42	0.41	0.70	0.84	0.47	1.93	1.63	3.28
CaO	0.08	0.12	0.60	0.94	0.45	0.48	0.07	0.07	0.83	2.73	1.86	4.09
Na_2O	1.99	2.77	0.26	1.10	1.00	0.96	0.45	1.64	2.54	3.46	2.80	2.62
K_2O	6.58	7.00	6.64	6.08	6.64	4.92	8.72	6.47	5.88	2.80	3.80	2.30
P_2O_5	0.02	0.03	0.05	0.04	0.05	0.03	0.06	0.10	0.16	0.05	0.21	0.24
LOI	1.50	1.31	1.79	1.90	1.27	1.57	1.06	1.25	2.07	3.58	3.81	6.04
H_2O^-	0.15	0.02	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total	100.10	99.47	99.88	99.97	99.92	99.19	99.69	99.61	100.11	100.77	100.15	102.97

Table 2: Trace-element analyses of the Lower Triassic rhyolites from the Silicic Unit (ppm).

Unit	MURÁŇ NAPPE			DRIENOK NAPPE								
Location	Telgárt, Gregová: rhyolites			Poniky area: rhyolites								
Sample	TR-45	TR-52	PV-1/90	PO-1/97	PO-2/97	PO-3/97	PO-4/97	PO-5/97	PO-6/99	MVP-10	MVP-13	MVP-15
Rb	n.a.	n.a.	219	228	251	222	263	230	222	230	255	241
Be	n.a.	n.a.	3.6	4	4.4	4.9	4.5	4.9	2	n.a.	n.a.	n.a.
Sr	n.a.	n.a.	<3	<3	10	14	<3	12	8	14.5	18	35
Ba	n.a.	n.a.	224	178	1200	295	234	257	141	330	250	360
B	n.a.	n.a.	204	100	107	91	110	91	60	83	72	75
Ga	n.a.	n.a.	18	17	18	18	20	21	14	n.a.	n.a.	n.a.
Sn	n.a.	n.a.	4.7	3.3	<3	<3	4.7	<3	6	5.1	4.2	4
Pb	n.a.	n.a.	10.1	10	6	14	10	13	5	28.2	15	10.2
Zr	n.a.	n.a.	360	162	190	234	170	240	204	145	155	150
Hf	9	8.3	n.a.	n.a.	n.a.	8	6	n.a.	n.a.	7	8	7
Th	22	23	n.a.	n.a.	n.a.	19	24	n.a.	n.a.	23	19	17
V	n.a.	n.a.	3.6	11	6	11	12	<3	6	8.1	5	4.3
Ta	1.3	1.5	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.4	n.a.	n.a.
Cr	n.a.	n.a.	<3	<3	<3	<3	<3	<3	3	3.9	3.2	3.8
Mo	n.a.	n.a.	1.3	<1	1.1	1	1	1	1	<3	<3	<3
Co	0.9	1.3	<3	3.6	3.6	3.2	<3	<3	3	3.4	<3	<3
Ni	n.a.	n.a.	4.7	4.9	9.6	5.4	<3	3	5	3.9	3.2	3
Cu	n.a.	n.a.	<3	13	30	7	3	3	17	15.1	14	10.2
Sc	4	5.2	<3	3	4.8	6.4	4.3	4.2	5	4.6	4.8	6.2
Y	n.a.	n.a.	39	34	22	36	32	49	44	34	32	30
La	44	51	n.a.	n.a.	n.a.	56	59	n.a.	n.a.	35	55	58
Ce	98	110	n.a.	n.a.	n.a.	116	64	n.a.	n.a.	48	101	124
Nd	39	43	n.a.	n.a.	n.a.	63	53	n.a.	n.a.	57	60	62
Sm	7.7	7.7	n.a.	n.a.	n.a.	12	7	n.a.	n.a.	9	11	12
Eu	0.13	0.14	n.a.	n.a.	n.a.	0.7	0.2	n.a.	n.a.	0.3	0.3	0.5
Tb	1.2	1.1	n.a.	n.a.	n.a.	1.3	1	n.a.	n.a.	0.8	1.1	1.4
Yb	4.9	3.8	n.a.	n.a.	n.a.	4.9	4.3	n.a.	n.a.	3.5	4.1	4.5
Lu	0.79	0.58	n.a.	n.a.	n.a.	0.56	0.51	n.a.	n.a.	0.47	0.55	0.59

Feldspars composition

Electron microprobe analyses of alkali feldspar phenocrysts from the Poniky rhyolites revealed three distinct phases: (1) K>Na alkali feldspar ($Or_{55-65}Ab_{35-45}An_{\sim01}$), (2) nearly pure K-feldspar ($Or_{90-99}Ab_{01-10}An_{00-02}$), and (3) albite ($Ab_{90-100}Or_{00-10}An_{00}$) replacing primary K-rich feldspars (Table 3, Fig. 8). The feldspar crystals are compositionaly homogeneous without distinct changes from centre to rim of the crystals.

Table 3: Representative microprobe compositions of alkali feldspars from the Poniky rhyolite (wt. %).

Phase	K>Na feldspar				K-feldspar				Albite			
Sample	PO-5	PO-5	PO-6	PO-6	PO-3	PO-3	PO-6	PO-6	PO-3	PO-3	PO-5	PO-5
Crystal/pos.	center	rim	center	rim	center	rim	center	rim	center	rim	center	rim
SiO_2	66.95	67.28	67.11	67.13	66.05	64.79	64.26	64.80	69.30	69.33	69.58	69.47
Al_2O_3	18.71	18.29	18.46	18.15	18.05	18.03	18.77	18.55	19.33	19.21	18.96	19.04
FeO^+	0.20	0.03	0.06	0.14	0.03	0.00	0.00	0.00	0.00	0.38	0.00	0.00
CaO	0.24	0.23	0.26	0.25	0.00	0.09	0.16	0.00	0.04	0.04	0.00	0.02
Na_2O	5.19	4.79	4.87	4.00	0.30	0.39	0.27	0.38	11.85	11.78	12.23	12.31
K_2O	9.39	9.32	9.07	10.66	16.16	15.93	16.49	16.52	0.13	0.00	0.01	0.00
Total	100.68	99.94	99.83	100.33	100.59	99.23	99.95	100.25	100.65	100.74	100.78	100.84
Formulae based on 8 oxygen atoms												
Si	3.002	3.028	3.021	3.027	3.026	3.012	2.978	2.991	3.007	3.008	3.016	3.011
Al	0.989	0.970	0.980	0.965	0.975	0.988	1.025	1.009	0.988	0.982	0.969	0.973
Fe	0.007	0.001	0.002	0.005	0.001	0.000	0.000	0.000	0.000	0.014	0.000	0.000
Ca	0.012	0.011	0.013	0.012	0.000	0.004	0.008	0.000	0.002	0.002	0.000	0.001
Na	0.451	0.418	0.425	0.350	0.027	0.035	0.024	0.034	0.997	0.991	1.028	1.035
K	0.537	0.535	0.521	0.613	0.944	0.945	0.975	0.973	0.007	0.000	0.001	0.000
Total	4.998	4.963	4.962	4.972	4.973	4.984	5.010	5.007	5.001	4.997	5.014	5.020

FeO^+ = total Fe as FeO

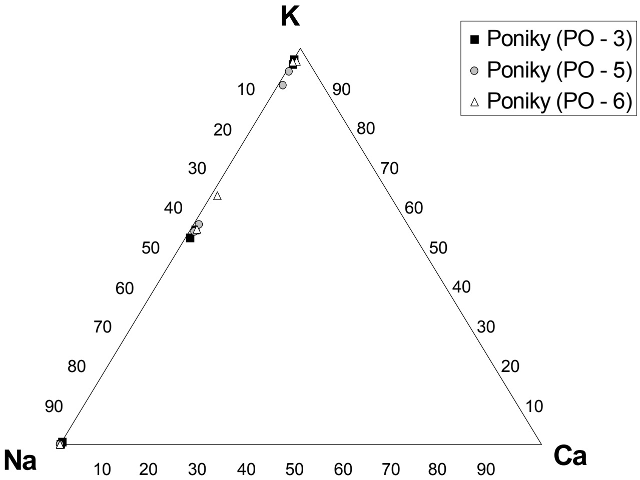

Fig. 8. Feldspar ternary diagram of the rhyolites (atom. %).

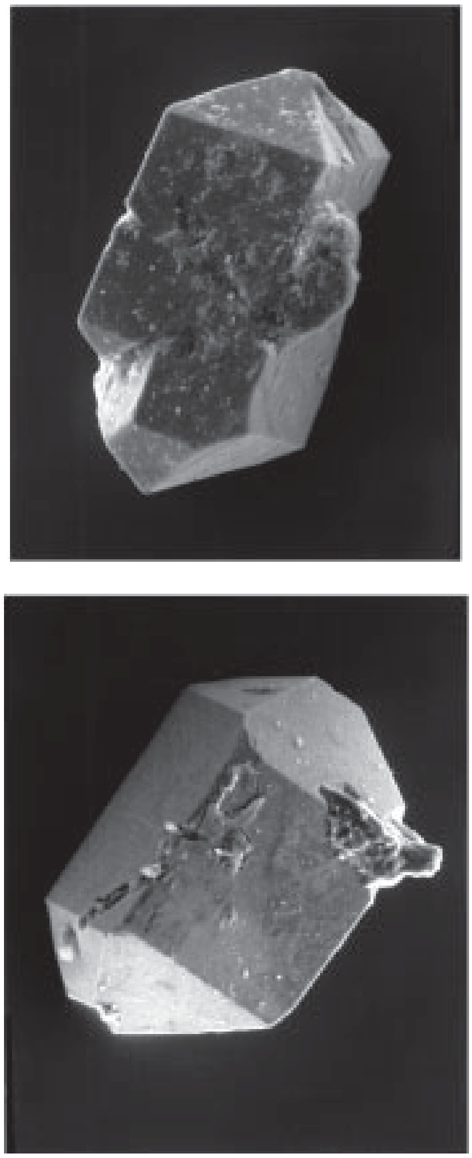

Fig. 9. Zircon BSE microphotographs, Poniky rhyolite. Size of crystals: 110 (upper) and 170 (lower) μm.

Zircon typology and composition

The zircon typology method (Pupin 1980) exhibits types and subtypes typical for hot and dry alkali magmas: mainly P_4–P_5 and D (Figs. 9–10). Such zircon morphology indicates a temperature of zircon crystallization of 800–900±50 °C (cf. Pupin 1980). These results are in concordance with zircon saturation temperatures (T_{Zrn}) calculated from bulk-rock chemical composition (Watson & Harrison 1983): the T_{Zrn} = 820–845 °C for the Poniky rhyolites (6 samples) and 895 °C for the Telgárt rhyolite.

BSE shows slightly oscillatory zoning of zircon, locally with small inherited (?) oval core. EMPA reveals Hf contents common for continental crustal granite zircon: 1.0–1.7 wt.% HfO_2 (cf. Pupin 1992) — Table 4. The contents of Y are slightly elevated: 0.4–1.0 wt.% Y_2O_3, and the concentration of other elements (P, U, Th, REE, etc.) is below the EMPA detection limit (<0.1 wt.%). Profils across zircon crystals do not show distinct variations of Zr, Hf and Y contents or systematic Hf enrichment in the rims of zircon crystals.

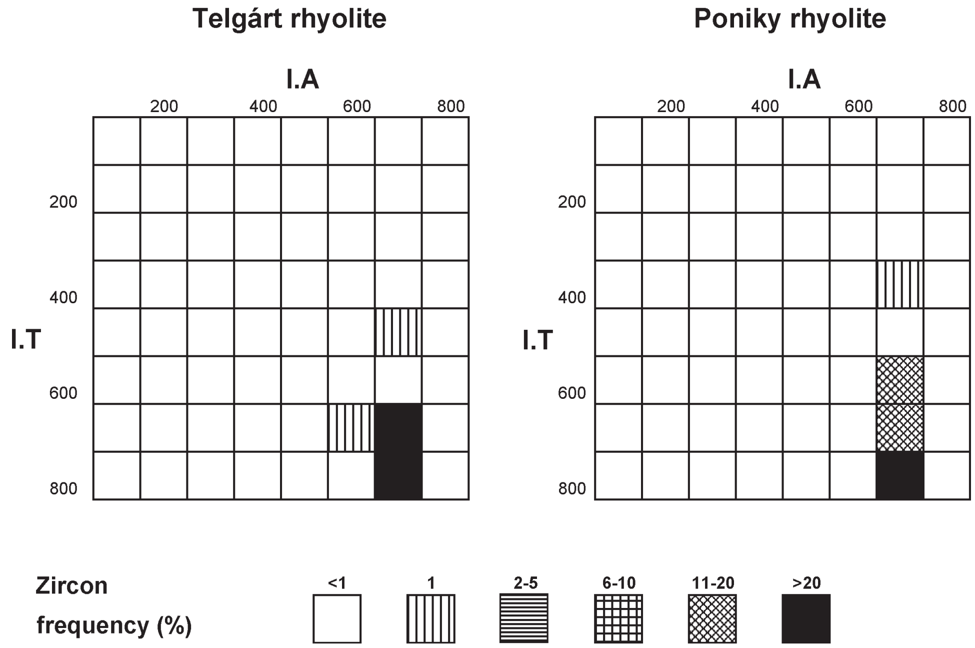

Fig. 10. Zircon typograms of the rhyolites. Left — Telgárt rhyolite (PV-1); Right — Poniky rhyolite (PO-6).

Table 4: Representative microprobe compositions of zircon from the Poniky rhyolite (wt. %).

Sample# Crystal/position	PO-2 center	PO-2 rim	PO-3 center	PO-3 rim	PO-5 center	PO-5 rim	PO-6 center	PO-6 rim
SiO_2	32.29	32.51	33.97	34.14	32.23	32.20	32.56	32.61
ZrO_2	65.35	65.15	64.98	64.31	64.52	64.97	64.94	65.66
HfO_2	1.45	1.35	1.21	1.23	1.73	1.71	1.57	1.69
$Y2O_3$	0.50	0.44	0.42	0.87	1.29	0.72	0.66	0.72
Total	99.59	99.45	100.58	100.55	99.77	99.6	99.73	100.68
Formulae based on 4 oxygen atoms								
Si	0.997	1.003	1.027	1.031	0.996	0.996	1.003	0.997
Zr	0.984	0.980	0.958	0.947	0.973	0.980	0.975	0.979
Hf	0.013	0.012	0.010	0.011	0.015	0.015	0.014	0.015
Y	0.008	0.007	0.007	0.014	0.021	0.012	0.011	0.012
Total	2.002	2.002	2.002	2.003	2.005	2.003	2.003	2.003
100*Hf/(Hf+Zr)	1.304	1.210	1.033	1.148	1.518	1.508	1.416	1.509
Zr/Hf atomic	75.69	81.67	95.80	86.09	64.87	65.33	69.64	65.27

Discussion and conclusions

Paleotectonic implications

The Early Alpine evolution of the Inner Western Carpathians links with the Late Paleozoic evolution of the Intra-Alpine terrain (Stampfli 1996). The Intra-Alpine terrain is a Variscan continental fragment accreted to Eurasia due to closure of the Paleotethys ocean in the Late Carboniferous. Northward subduction of the Paleotethys oceanic crust caused the Late Carboniferous and Early Permian calc-alkaline magmatic activity in an active margin setting as being related to subduction (Finger & Steyrer 1990). Some authors would regard this late- to post-Variscan calc-alkaline magmatism as being related to post-orogenic processes rather than to arc magmatism (Bonin 1990, 1993).

According to our opinion this plutonic-magmatic process, dated in the Western Carpathians Early Permian to Middle Triassic (Kotov et al. 1996; Putiš et al. 2000, 2001) is related to post-orogenic (post-Variscan) large-scale extension and hence represents a pre-orogenic Early-Alpine continental rifting. This riftogenesis is finally regarded as having given birth to the Meliata-Hallstatt ocean or marginal sea (Kozur 1991). One of the best arguments for such an interpretation is the changed geochemical trend of anorogenic magmatites; instead of the calc-alkaline, an alkaline trend is characteristic for the studied Permian-Triassic rhyolites of the Drienok Nappe as well as other magmatic occurrences regarded as related to this event (Uher & Broska 1996; Kotov et al. 1996; Putiš et al. 2000).

We have proposed (Putiš in Kotov et al. 1996) to divide the Permian sedimentary-magmatic complexes of the Central Western Carpathians into two different groups reflecting two stages of continental riftogenesis: One group comes from deep contemporary active transtensional furrows mainly filled by sandy-shale sediments. Psephitic intercalations indicate tectonic erosion of the marginal parts of furrows. So called bimodal volcanics (rhyolites, rhyodacites, andesites, basalts), with alkaline affinity, are characteristics of this group. They are contemporaneous with emplacement of small granitic plutons of the Hrončok type (A-type, Petrík et al. 1995; Uher & Broska 1996; Kotov et al. 1996; Putiš et al. 2000, 2001) in the upper crust. A thermal anomaly coupled with this stage of riftogenesis can also be determined by the numerous K-Ar and Rb-Sr ages clustering around 250–230 Ma (Cambel et al. 1990; Krist et al. 1992). The second group of the mainly Verucano-type Permian sediments reflects a dynamic setting connected with erosion of uplifted blocks.

Lower to Middle Triassic acid to basic volcanic activity is known from numerous localities of the internal and uppermost nappe units in the broader Alpine-Carpathian orogenic belt (Dercourt et al. 1990). Triassic alkaline K-rich rhyolites analogous to the Silicic rhyolites were described from the Southern Alps (Vecchi & Zanche 1982). On the other hand, calc-alkaline mainly andesite and younger alkaline basalt formations occur in Middle Triassic carbonate sequences of the Bükk Unit (Szoldán 1990). Moreover, thin acid tuffitic layers of the "Pietra Verde" type are known from the Middle Triassic Reifling Limestone near Silická Brezová and Hucín villages in the Silica Nappe of the Silicic Unit (Kuthan 1959; Mello 1997), these tuffs and tuffites are common in the Upper Austroalpine and Transdanubic Unit in Hungary (Ravasz 1973; Cros & Szabó 1984). Recently, a small occurrence of green tufite layer was also described in the Middle Triassic carbonates of the Hronic Unit near Valaská Dubová village (Olšavský 1999).

We can find a lot of analogical settings along the northern margin of Apulia, for example in the Southern and Eastern Alps (Thöni & Jagoutz 1993; Pfeifer et al. 1993). Paleotectonically, they indicate a rifted and unstable platform in the Permian to Middle Triassic, leading at last to opening of the Middle Triassic–Early Jurassic Meliata-Hallstatt ocean. A similar, but diachronous paleotectonic situation occurred in the northern Tatric domain of the Central Western Carpathians, where syn-rift mid-Jurassic limburgites and basanites are related to the rifting stage of the Jurassic-Cretaceous Tethys ocean (Hovorka & Spišiak 1988).

Geochemical features

The above mentioned geochemical and mineralogical results of the investigated Lower Triassic volcanites of the Silicic Unit show the specific and similar character of all the studied volcanic rocks. Our study described only rhyolites and not members of the andesite–trachyte or trachyandesite–trachyte differentiation sequences in the Poniky area of the Drienok Nappe. However, the (trachy)andesite and trachyte members occur in the older volcanic layer and they were rec-

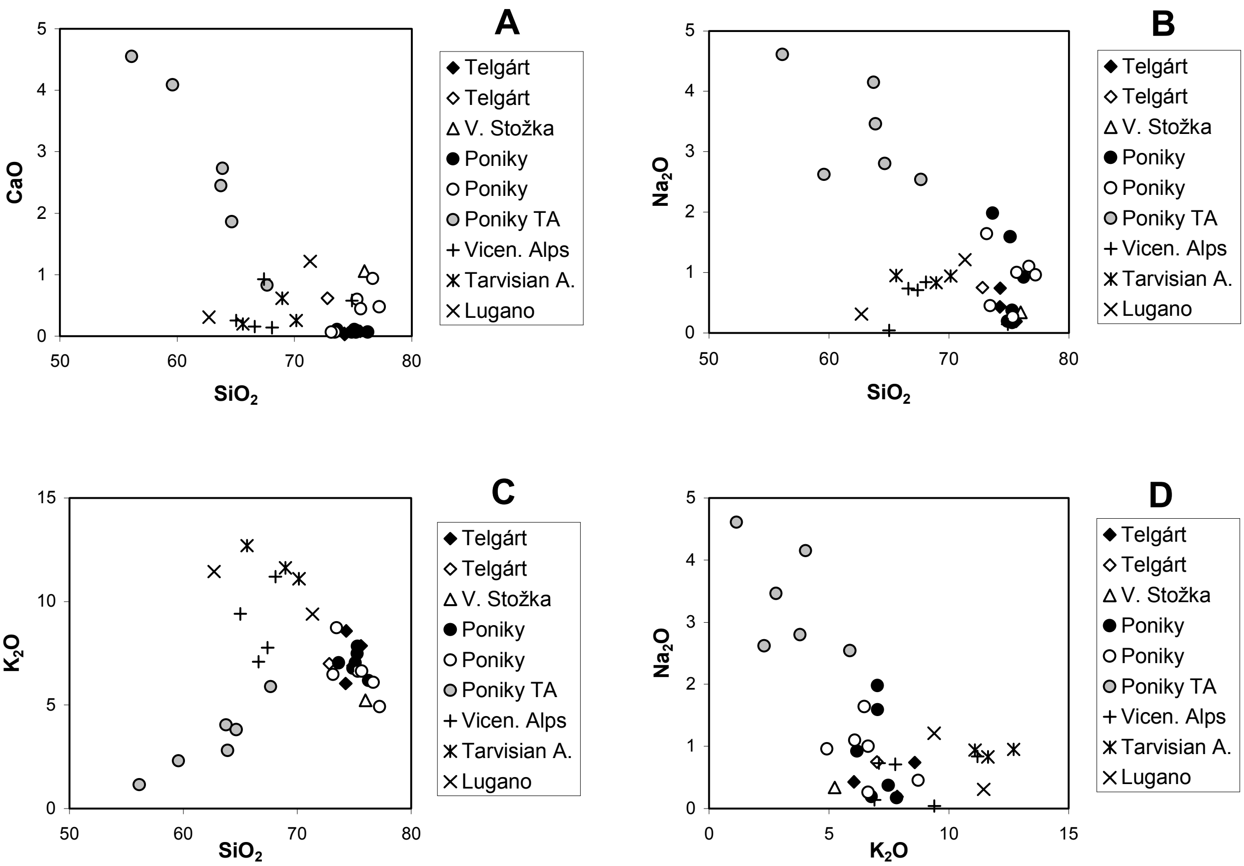

Fig. 11. Distribution of alkali elements in the Silicic rhyolites in comparison to the "trachyte–andesite" members of the Poniky area (Poniky TA; Slavkay 1965) and from the Middle Triassic high-K acid – intermediate volcanics and tuffs of the Southern Alps (Vicentinian and Tarvisian Alps, Lugano area; Vecchi & Zanche 1982). Other symbols as in Figs. 4–6.

ognized in the PO-1 borehole and also in some outcrops (Slavkay 1965, 1981).

The most conspicuous feature of all the studied rhyolites of the Silicic Unit is their unusually high potassium enrichment (4.9–8.7 wt.% K_2O, 6.8 wt.% K_2O in average), together with low Ca and Na contents (0.26 wt.% CaO and ~1 wt. % Na_2O in average). Such high K/Na ratio is unusual for common rhyolites of various geotectonic environments; rhyolites from various calc-alkaline and alkaline suites contain commonly ~1–6 wt.% K_2O, 1–5.5 wt.% Na_2O and 0.2–5.8 wt.% CaO (cf. Yarmolyuk & Kovalenko Eds. 1987). However, Middle Triassic rhyolites and dacites of the Southern Alps (Vicentinian and Tarvisian Alps, Lugano area) also contain similar K-enrichment and Na, Ca-depletion: 6.9–11.6 wt.% K_2O and only 0.04–0.95 wt.% Na_2O and 0.16–1.2 wt.% CaO; devitrification of glassy groundmass was connected with late orthoclase crystallization and the K-enrichment is explained mainly by magmatic gaseous transfer (Vecchi & Zanche 1982). The K-rich and relatively Na, Ca-poor Sarmatian rhyolites (5.9–9.0 wt.% K_2O) of the Jastrabá Formation (central Slovakia) are also connected with late magmatic to hydrothermal K-overprint and origin of adularia, a secondary K-feldspar (Konečný et al. 1998). The alkalies vs. SiO_2 and Na_2O vs. K_2O distributions of the Silicic rhyolites as well as the compared South-Alpine acid volcanics show rather irregular patterns without apparent linear trends, whereas the (trachy)andesites to trachytes of the Poniky area reveal a relatively regular linear pattern (Fig. 11). Consequently, the geochemical data indicate some late-magmatic and/or post-magmatic (hydrothermal?) overprint of the studied rhyolites by K-rich fluids. The origin of such fluids is probably closely connected with the parental rhyolite magma as a result of its fractionation, as the K-enrichment occurs only in rhyolites and not in the neighbouring dacites, trachydacites and andesites. On the other hand, the post-magmatic hydrothermal overprint is evident mainly in the andesitic and trachytic members of the Poniky area, as manifested by their strong chloritization and high Fe_2O_3 (4.4–5.7 wt.%) and LOI (3.5–6 wt.%) contents (Slavkay 1965).

Despite their unusual K-enrichment, the geochemistry of the studied rhyolites indicates affinity to alkalic volcanic suite enriched also in Si, Rb, Zr, Y, REE and depleted in Mg, Ca, Na, P, Sr, Ba and V, closely comparable to hot and dry post-orogenic to anorogenic A-type granitic rocks (cf. Whalen et al. 1987). Zircon typology and saturation temperatures also support the high temperature and alkalic character of the studied rhyolites. The Lower Triassic Drienok and Muráň nappe rhyolites also show geochemical and mineralogical similarities with Permian post-orogenic A-type rhyolites, granites and granite porphyries of the Western Carpathians (Broska et al. 1993; Uher & Broska 1996). The Lower to Middle Triassic Hrončok Granite also reveals A-type features (Petrík et al. 1995; Putiš et al. 2000).

Lower Triassic K-rich rhyolites of the Silicic Unit, together with analogous volcanic occurrences in the Alpine-Carpathian orogenic belt, represent the product of alkaline intra-plate volcanism connected with the initial Early-Alpine continental rifting stage and opening of the Meliata-Hallstatt oceanic trough in their vicinity.

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