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Permian A-type rhyolites of the Drienok Nappe, Inner Western Carpathians, Slovakia: Tectonic setting from in-situ zircon U–Pb LA–ICP–MS dating

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Abstract: Two representative peraluminous A-type rhyolite samples from the Poniky area (the Drienok Nappe) in the Inner Western Carpathians (central Slovakia) were dated using the LA–ICP–MS U–Pb zircon method. These geochronological data represent the first in-situ isotopic dating study undertaken on these volcanic rocks. Oscillatory zoned zircon crystals yielded concordant Permian (Guadalupian) ages of 271.0 ± 1.5 Ma and 267.5 ± 1.6 Ma for the Poniky rhyolites, which supports their genetic link to the analogous mid-Permian (Guadalupian) rhyolites of adjacent Muráň and Vernár nappes. The Ti-in-zircon geothermometry (corrected using the activities of SiO_2 and TiO_2 using the rhyolite-MELTS thermodynamic software) indicate mean zircon crystallization temperatures of ~910 to 935 °C for the Poniky rhyolites. The results indicate pulses of anorogenic A-type rhyolitic magmatism were coeval with intrusions of granitic rocks associated with an intraplate extensional tectonic regime triggered by asthenospheric upwelling in the Western Carpathian region. The A-type magmatism was most likely related to the break-up of the Pangea supercontinent during the mid-Permian (~270–260 Ma).

Keywords: zircon, U–Pb LA–ICP–MS dating, rhyolite, Permian, Western Carpathians.

Introduction

Post-Variscan (Permian ~280–250 Ma) granitic rocks represented by A-type granites, granite porphyries and rhyolites to rhyodacites, and rare metal-bearing S-type leucogranites are documented through the entire Western Carpathian-Pannonian area and occur in the Tatric, Veporic, Gemeric, Oravic, Silicic and Transdanubic units (e.g., Uher & Marschalko 1993; Uher & Broska 1994, 1996; Uher & Pushkarev 1994; Uher et al. 1994, 2002, 2009, 2015; Petrík et al. 1994, 1995; Buda & Nagy 1995; Broska & Uher 2001; Gyalog & Horváth 2004; Radvanec et al. 2009; Ondrejka et al. 2015, 2018a, b, 2021; Sobocký et al. 2020; Villaseñor et al. 2021). A-type granitic rocks are the most common expression of this Permian felsic magmatism and are mainly represented by peraluminous biotite leucogranites, syenogranites to granite porphyries and very fine-grained aplitic leucogranites rich in Si, K, Rb, Ga, Zr, REE, Y, and Nb and with hypersolvus-transsolvus (Turčok, Upohlav and Hrončok microgranites) to subsolvus (Velence, Hrončok other varieties) alkali feldspar compositions (Uher & Broska 1996; Ondrejka et al. 2021).

The Permian volcanic rocks show a transitional calc-alkaline (Harnobis rhyodacites) to alkaline chemistry (Uher et al. 2002). U–Pb in-situ zircon dating yields ages of ~267–262 Ma for the Western Carpathian A-type granites. These include the Turčok granite (Gemeric Unit), Hrončok granite (Veporic Unit), pebbles of the Upohlav granite Cretaceous conglomerates (Klippen Belt, Oravic Unit) and rhyolites of the Muráň and Vernár nappes (Silicic Unit). An age of ~280 Ma for the Pannonian granites (Velence) has also been obtained (Ondrejka et al. 2021).

The occurrence of felsic volcanic rocks, mainly rhyolites, in the Poniky area within the Permian to Lower Triassic siliciclastic to carbonate sequences of the Drienok Nappe has been documented by earlier studies, which focused primarily on detailed petrography along with mineral and whole-rock compositions (Grenar & Kotásek 1956; Zuberec 1968; Hovorka & Spišiak 1988; Uher et al. 2002). The (trachy)andesite–trachyte–rhyolite lavas and pyroclastic sequences in the borehole near Poniky village were classified a “K-alkalic association” (Slavkay 1965, 1981). The sequence was named the Skálie Formation and correlated with the Lower Triassic volcanic suite of the Bükkic Unit in Hungary (Hovorka & Spišiak 1988). The major and trace element geochemical and mineralogical characteristics of these volcanic rocks (Uher et al. 2002) are similar to occurrences of post-Variscan anorogenic

A-type magmatic rocks in the Alpine–Carpathian belt (e.g., Bonin 1990; Beltrán-Triviño et al. 2016; Ondrejka et al. 2021). However, these volcanic rocks in the Drienok nappe have not been isotopically dated, and they were usually considered as Lower Triassic (e.g., Slavkay 1965; Mello et al. 2000b; Uher et al. 2002; Ondrejka et al. 2015).

This study aims to determine accurate radiometric ages for these felsic volcanic rocks by in-situ zircon U–Pb LA–ICP–MS isotopic dating and to constrain the lithostratigraphic succession of the Drienok Nappe in the southern part of the Inner Western Carpathians (*sensu* Hók et al. 2014). Moreover, Ti-in zircon geothermometry has been applied to determine crystallization temperatures of the rhyolite melt. Two typical occurrences of rhyolites from the Drienok Nappe located in the Poniky, Piesky (PO-1 sample) and Poniky, Žiarec (PO-2 sample) outcrops (characterised by Uher et al. 2002) were selected for this study (Fig. 1).

Geological setting

The lithostratigraphy of the Drienok Nappe is comprised of a Permian to Lower Triassic siliciclastic sedimentary succession followed by Middle Triassic platform and open marine carbonates. Horizons of Permian volcanic and volcanoclastic rocks are mostly in tectonic contact with the adjacent Lower Triassic sedimentary rocks. The lowermost portions of the succession are comprised of fine-grained quartz arkose and sandstone which are overlain by a sequence comprised of alternations (heterolithic bedding) of sandstone and siltstone, with extensive *Diplocraterion paralellum* ichnofossils (Olšavský & Šimo 2007). These units are considered equivalent to the Bodvaszilas Formation (cf. Hips 1996). The upper part of Lower Triassic succession in the Drienok Nappe is comprised of alternations of calcareous shales with sandy limestones. It represents a carbonate platform environment based on its mollusc fauna and exhibits a similar facies to the Szin Formation (Hips 1996). The uppermost portions of the succession in the Drienok Nappe section are composed of Middle Triassic massive and bedded shallow water to open marine carbonates.

The largest area of Permian felsic volcanic rocks of the Drienok Nappe is located near the villages of Poniky and Ponická Lehôtka. Volcanic and volcanoclastic rocks form a non-continuous belt, exposed in a region ~7 km long and up to 300 m wide between the hills of Drienok and Driekyňa and a continuous 1200×300 m large outcrop south of Žiarec Hill (Fig. 1). The geological position of the volcanic and adjacent sedimentary rocks in the Poniky area is illustrated in Fig. 2. Greyish-green and violet-brown shales with intercalations of marly limestones and calciferous shales containing a Olenekian (Lower Triassic) fauna of the Šuňava/Szin Formation (e.g., Olšavský 2004 and references therein) are in tectonic contact with the Permian volcanic and volcanoclastic rocks. At the base of the Permian volcanics, a layer of subaqueous andesite tuff and (trachy)andesite (~30 m thick) is overlain by a 5 m thick bed of pyroclastic material with calcareous claystone to marly limestone and overlain by two rhyolite layers, 5 m and 38.5 m thick separated by a 1 m thick intercalation of calcareous claystone to marly limestone (Slavkay 1965).

Petrography and mineralogy

The investigated rhyolites show porphyric, locally fluidal textures with a grano-lepidoblastic and microfelsitic to felsitic groundmass. Based on optical point counting (average of six samples), the rock-forming minerals comprise devitrified and limonitised groundmass (59 vol. %), phenocrysts (2–4 mm in size) of corroded bipyramidal ß-quartz (16 vol. %) (Fig. 3a), albitic plagioclase ($Ab_{90–100}Or_{00–10}An_{00-01}$) (15 vol. %), euhedral/subhedral mesoperthitic alkali feldspar ($Or_{55–65}Ab_{35–45}An_{01}$) and sanidine ($Or_{90–99}Ab_{01–10}An_{00–02}$) (9 vol. %), and accessory minerals (1 vol. %). The feldspars are commonly replaced by post-magmatic chessboard albite or fine-grained aggregates of white mica (Fig. 3b). The groundmass consists of a very fine-grained (~10 µm) aggregates of quartz, alkali feldspar, white mica, hematite staining, and occasionally biotite and chlorite. The accessory assemblage consists of zircon, monazite-(Ce), xenotime-(Y), Fe–Ti oxides, and rare fluorapatite (Uher et al. 2002; Ondrejka et al. 2015, 2018b, 2021). The Fe–Ti oxide textures and assemblages commonly encountered in the rhyolites constrain the late-magmatic to sub-solidus evolution, with estimated equilibrium temperatures from ~750 to ~400 °C and oxygen fugacity values approaching the NiNiO buffer from −0.76 $\Delta\log fO_2$ (~626 °C) to +1.53 $\Delta\log fO_2$ (~655 °C) (Ondrejka et al. 2015). Microscopic hydrothermal veinlets of quartz are locally common (Uher et al. 2002; Ondrejka et al. 2015, 2018b). A stockwork zone of hydrothermal copper mineralization within a complex supergene zone is hosted by rhyolites at the Farbište ore occurrence near Poniky (e.g., Števko et al. 2011).

The zircon typology of the rhyolites shows dominant high alkaline and high temperatures (800–900±50 °C) D and P morphological types (Fig. 3c–e); (Uher et al. 2002; Ondrejka et al. 2015), which are characteristic of anorogenic alkaline magmatic suites (Pupin 1980). These results are compatible with zircon saturation temperatures (T_{Zr}) of the rhyolites calculated from the bulk-rock chemical compositions (using the formulation of Boehnke et al. 2013) of T_{Zr}=800–840 °C. These data are from (i) the newly obtained whole-rock analyses in Table 1 and (ii) the older published values from Uher et al. 2002 based on the Watson & Harrison 1983 formulation and recalculated in this study.

Analytical methods

Zircon crystals were extracted using standard density and magnetic separation techniques. Zircon crystals were mounted in epoxy and polished to expose the crystal interiors. Zircons

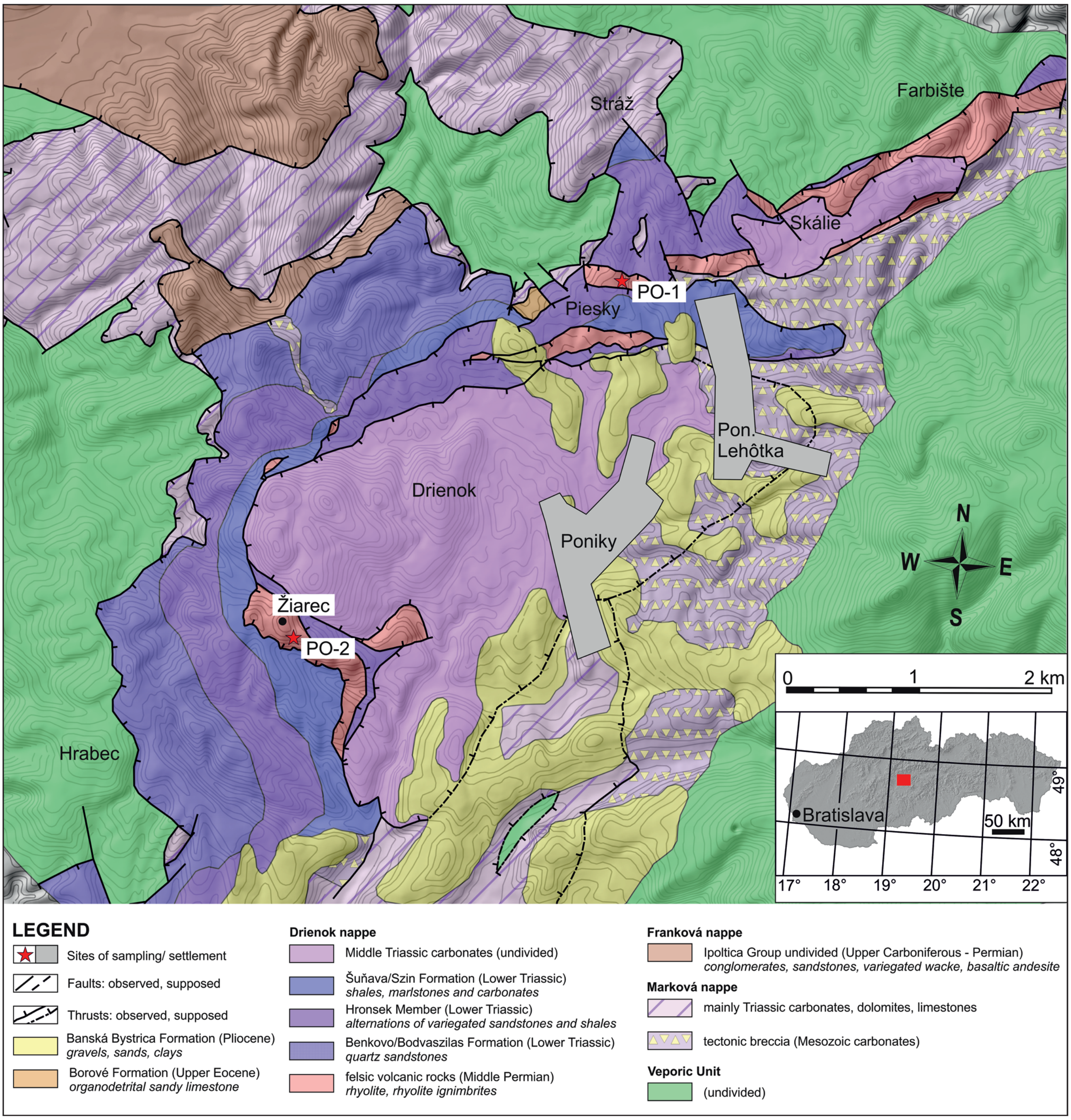

Fig. 1. Geological map of the Poniky area (Slavkay 1968, modified) and the position of investigated rhyolites of the Drienok Nappe in the Inner Western Carpathians: **a** — Poniky, Piesky (PO-1), 48°43'28.74"N, 19°17'19.571"E; **b** — Poniky, Žiarec (PO-2), 48°38'16.687"N, 19°21'26.764"E.

were characterised by transmitted and reflected light petrography, followed by cathodoluminescence (CL) imaging using a CAMECA SX 100 at the Department of Electron Microanalysis at the State Geological Institute of Dionýz Štúr, Bratislava, Slovak Republic. LA–ICP–MS U–Pb age zircon data were acquired using a Photon Machines Analyte Excite 193 nm ArF excimer laser-ablation system with a HelEx 2-volume ablation cell coupled to an Agilent 7900 ICP–MS at the Department of Geology, Trinity College Dublin. The instruments were tuned using NIST612 standard glass to yield Th/U ratios of unity and low oxide production rates (ThO^+/Th^+ typically <0.15 %). A quantity of 0.4 l min^{-1} He carrier gas was fed into the laser cell, and the aerosol was subsequently mixed with 0.6 l min^{-1} Ar make-up gas and 11 ml min^{-1} N_2. Data reduction of the raw U–Pb isotope data was performed through the "VizualAge" data reduction scheme (Petrus & Kamber 2012) in the freeware IOLITE package (Paton et al. 2011). Sample-standard bracketing was applied after the correction of downhole fractionation to account for long-term drift in isotopic or elemental ratios by normalising all ratios to those of the U–Pb reference standards. Final age calculations were made using the Isoplot add-in for Excel (Ludwig 2012). A repetition rate of 11 Hz and a circular spot of 24 μm were employed. Eleven isotopes (^{49}Ti, ^{91}Zr, ^{175}Lu, ^{202}Hg, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th, ^{235}U and ^{238}U) were acquired during each analysis, which comprised 27 s of ablation (300 shots) and 10 s washout, the latter portions of which were used for the baseline measurement. 91500 zircon (^{206}Pb/^{238}U TIMS age of 1065.4±0.6 Ma; Wiedenbeck et al. 2004) was used as the primary U–Pb calibration standard. The secondary standards GZ-7 zircon (^{206}Pb/^{238}U TIMS age of 530.26 Ma±0.05 Ma; Nasdala et al. 2018), Plešovice zircon (^{206}Pb/^{238}U TIMS age of 337.13±0.37 Ma; Sláma et al. 2008) and WRS 1348 zircon (^{206}Pb/^{238}U TIMS age of 526.26±0.70; Pointon et al. 2012) yielded LA–ICP–MS ages of 533.1±1.5 Ma, 335.9±1.6 Ma and 526.8±2.4 Ma respectively.

Zircon crystallization temperatures were calculated using the method of Watson et al. (2006). To avoid underestimating the calculated temperatures, we calculated activity (*a*) of corresponding oxides ($aSiO_2$ and $aTiO_2$) using the rhyolite-MELTS thermodynamic software (ver. 1.0.2, Gualda et al. 2012) and applied the necessary corrections as recommended by Schiller & Finger (2019). We used a water content of 2.5 wt. % for all our calculations, as this is considered a realistic initial value for many A-type magmas (Klimm et al. 2003). However, varying the amount of water did not significantly change the calculated activities (Schiller & Finger 2019).

Whole-rock multi-element geochemistry was performed by Bureau Veritas (AcmeLabs) in Vancouver, Canada, by lithium borate fusion coupled with inductively coupled plasma emission spectrometry (ICP–ES) for major elements, and the trace and rare earth elements (REE) were determined by inductively coupled plasma mass spectrometry (ICP–MS) and ICP–ES. Some trace elements have been analysed by modified aqua regia digestion coupled with ICP–ES/MS.

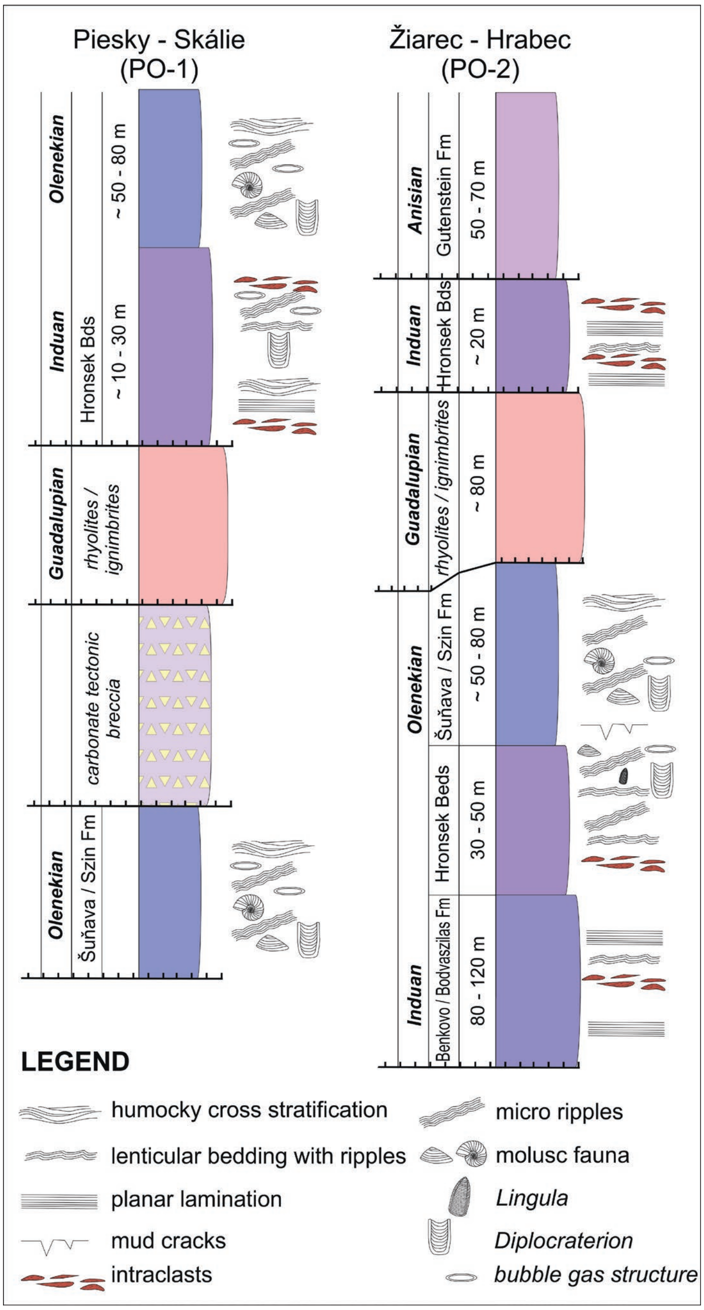

Fig. 2. Simplified Permian to Triassic lithotectonic columns of the Drienok Nappe in the Poniky, Piesky and Poniky, Žiarec area.

Results

Whole-rock major and trace element geochemistry

The representative results of the whole-rock chemical analyses are given in Table 1. The studied rhyolites are rich in Si and especially K, and depleted in Ti, Mg, Ca, Na, and P. Despite the relatively low Al contents due to depletion in Ca and Na, the rhyolites are dominantly peraluminous with A/CNK=1.24–1.28 and A/NK=1.26−1.33 (Fig. 4). The high Si contents connected with low Mg and Ca resulted in an anomalously high R1 and very low R2 values (multi-cationic parameters of Batchelor & Bowden 1985) with a trend similar to anorogenic magmatic suites. The rhyolite trace element geochemistry has a slight enrichment in Rb, Th, Zr, and REE (except Eu), depletion in Sr (Fig. 5, Table 1), as well as elevated Y/Nb≥3, Th/U≥3.8, Rb/Sr≥10.3 and Ga/Al≥2.7 ratios which are typical of alkali-rich post-orogenic and anorogenic Si-rich magmatic suites of A-type affinity (Fig. 6) (Whalen et al. 1987). The A-type affinity is also evident in chondrite-normalised “V-shaped” REE distribution patterns with pronounced negative Eu-anomalies (Eu_N/Eu^*_N= 0.17−0.18) and slightly enriched LREEs (Fig. 7).

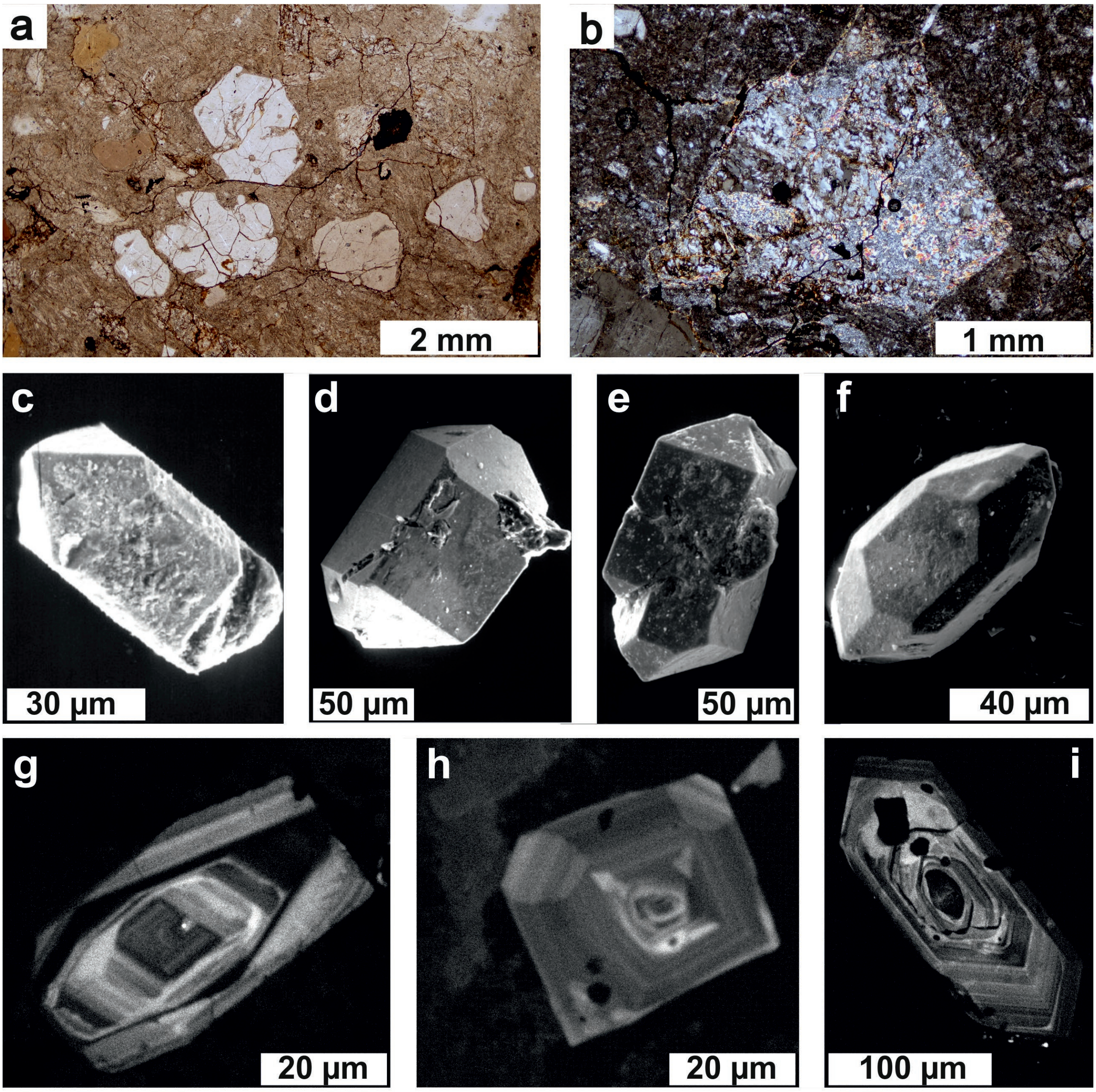

Fig. 3. Photomicrographs (**a**, **b**), SEM (**c**–**f**) and CL (**g**–**i**) images showing rock microtextural aspects and morphology and internal zoning of zircon from A-type rhyolites of the Drienok Nappe: **a** — phenocrysts of corroded ß-quartz (parallel polaroids); **b** — phenocryst of strongly altered feldspar with fine-grained aggregates of white mica (crossing polaroids); **c** — zircon crystal of P_4 subtype morphology; **d** — zircon crystal of P_5 subtype morphology; **e** — zircon crystal of D type morphology; **f** — zircon crystal of S_{17} subtype morphology; **g** — fine oscillatory zoning in a zircon crystal; **h** — combination of fine oscillatory and sector zoning in a zircon crystal; **i** — fine oscillatory zoning of zircon with rounded inherited core of Proterozoic zircon.

Zircon characterisation

Primary magmatic zircon is the most common accessory mineral in the investigated A-type rhyolites. The highest quality transparent zircon crystals of the PO-1 and PO-2 samples were selected for dating, and zircons exhibiting metamict alteration, fractures and possible mineral inclusions were avoided. The zircon crystals are prismatic, usually transparent, occasionally weakly pink in colour, and are mostly ~100–200 µm in length. Euhedral zircon crystals have predominantly P_4–P_5 and D (Fig. 3c–e), rarely S_{17}–S_{19} (sub)type morphologies (Fig. 3f) according to the Pupin (1980) typology classification. While the internal texture of the zircon crystals comprises magmatic, fine oscillatory (Fig. 3g–i) and sector zoning (Fig. 3h), irregular, most likely late-magmatic to subsolidus rim domains are present to a lesser extent. Some zircon crystals also contain small round core zones and represent remnants of older inherited zircon (Fig. 3i).

Table 1: Chemical analyses of whole-rock samples from A-type rhyolites (Poniky area).

Location	Piesky	Žiarec
Sample	PO-1	PO-2
SiO_2 (wt. %)	75.31	75.17
TiO_2	0.16	0.15
Al_2O_3	11.86	12.33
Fe_2O_3	2.23	1.83
MnO	0.01	<0.01
MgO	0.41	0.3
CaO	0.19	0.09
Na_2O	0.57	1.09
K_2O	7.39	7.38
P_2O_5	0.03	0.04
LOI+H_2O^-	1.7	1.5
Total	99.86	99.88
$FeO_{tot}/(FeO_{tot}+MgO)$	0.83	0.85
A/CNK	1.28	1.24
A/NK	1.33	1.26
V (ppm)	11	8
Sc	5	5
Cs	6.6	6.9
Ga	17.9	17.6
Zr	263.2	235.2
Hf	7.9	7.3
Sn	3	3
Nb	16.2	16.2
Ta	1.2	1.3
Rb	238.9	233.1
Sr	20.2	22.7
Ba	179	237
Be	2	3
Mo	0.9	1.1
W	12.8	9.4
Co	2.7	4.1
Ni	2.9	2
Cu	2.8	7.2
Zn	9	13
Ag	<0.1	<0.1
Cd	<0.1	<0.1
Hg	<0.01	<0.01
As	7.8	8.8
Sb	0.4	0.5
Tl	<0.1	<0.1
Se	<0.5	<0.5
Bi	<0.1	<0.1
Pb	2.8	4
Th	19.5	21.8
U	5.2	4.5
Y	51.8	48.4
La	55.7	55.5
Ce	114.8	120.3
Pr	14.13	14.74
Nd	52.8	56.5
Sm	10.8	11.82
Eu	0.6	0.65
Gd	10.12	10.13
Tb	1.56	1.49
Dy	9.5	9.03
Ho	1.84	1.71
Er	5.41	5.03
Tm	0.73	0.73
Yb	4.83	4.64
Lu	0.71	0.7
Au (ppb)	3.7	4.7

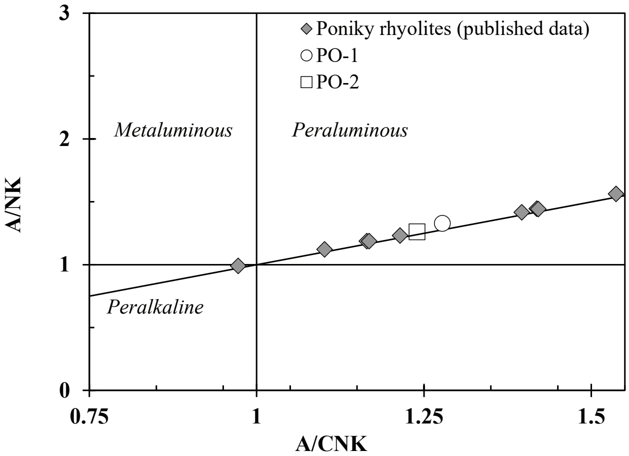

Fig. 4. Binary diagram of A/CNK vs. A/NK. A/CNK=Al_2O_3/(CaO+Na_2O+K_2O), A/NK=Al_2O_3/(Na_2O+K_2O) (mol. %). Grey symbols from Uher et al. (2002), Ondrejka et al. (2021).

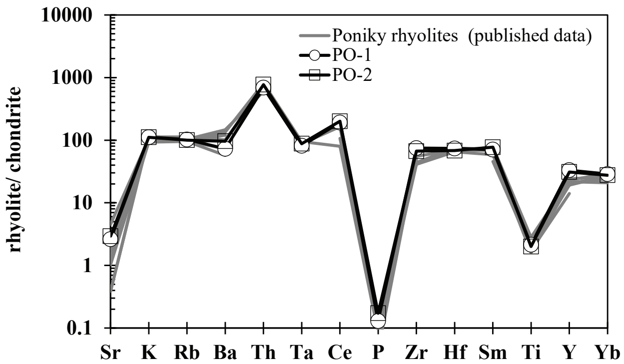

Fig. 5. Chondrite-normalised multi-element diagram of the rhyolites. Normalised values after Barrat et al. (2012). Grey patterns from Uher et al. (2002), Ondrejka et al. (2021).

LA–ICP–MS zircon U–Pb ages

We report the results of U–Pb LA–ICP–MS zircon dating of two rhyolite samples, PO-1 and PO-2 (Figs. 7, 8; Tables 2, 3). A total of 68 spot analyses were performed on the studied zircon crystals: 40 from the PO-1 sample and 28 from the PO-2 sample (Table 2). The f_{206} values (proportions of common ^{206}Pb in the total measured ^{206}Pb) of all data ranged from −0.004 to 0.105 % (PO-1) and −0.001 to 0.151 % (PO-2).

The PO-1 zircon crystals contain 10.6–391 ppm U and 4.88–235 ppm Th, with a Th/U ratio ranging between 0.38–0.66 (mean 0.53). The U–Pb Concordia age of the magmatic population is 271.0±1.5 Ma (MSWD of concordance=0.074) (Fig. 8). The PO-2 zircon crystals show 37.6–664 ppm U and 14.7–460 ppm Th, with a Th/U ratio ranging between

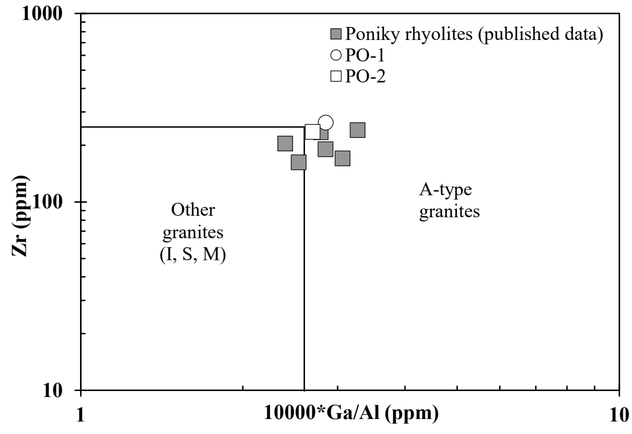

Fig. 6. Binary plot of 10,000*Ga/Al vs. Zr (Whalen et al. 1987). Grey symbols from Uher et al. (2002), Ondrejka et al. (2021).

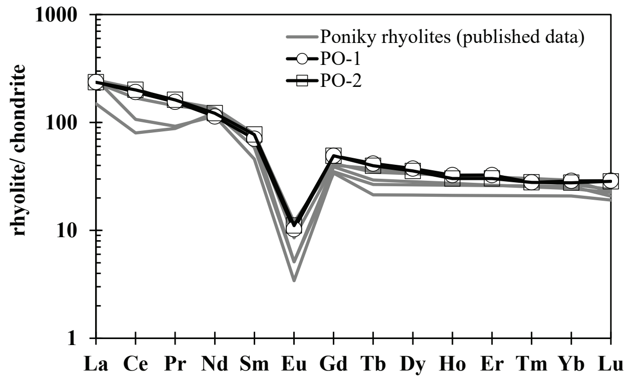

Fig. 7. Chondrite-normalised REE patterns of the rhyolites. Normalised values after Barrat et al. (2012). Grey patterns from Uher et al. (2002), Ondrejka et al. (2021).

0.39–0.85 (mean 0.56). The U–Pb Concordia age of the magmatic population is 267.5±1.6 Ma (MSWD of concordance= 1.50) (Fig. 9).

A subset of analyses in both samples (~18 %) represent inherited zircon cores. They yielded older $^{206}Pb/^{238}U$ ages, from Paleoproterozoic (2067±38 to 1034±Ma) to Neoproterozoic (960±16 to 573±15 Ma), and one Carboniferous age (341±16 Ma) (Tables 2, 3).

Ti-in-zircon crystallization temperatures

The PO-1 and PO-2 zircon crystals show Ti-in-zircon crystallization temperatures in the range of 656–873 °C (mean 768 °C) and 672–1187 °C (mean 782 °C), respectively (Tables 2, 3). However, calculated average temperatures for both samples appear underestimated for relatively hot and dry A-type rhyolitic magma. This suggests that the activity of SiO_2 and TiO_2 remained below unity over a large part of the magmatic zircon crystallization range and values must be corrected relative to the original TiO_2- and SiO_2-saturated calibration of the Ti-in-zircon thermometer (Schiller & Finger 2019).

The rhyolite-MELTS software indicates the following activities (*a*) for the rocks at 900–1000 °C and assumed water contents of 2.5 wt. %: aSiO$_2$ (PO-1)=0.6–0.7, aTiO$_2$ (PO-1)=0.2–0.3, aSiO$_2$ (PO-2)=0.6, aTiO$_2$ (PO-2)=0.2–0.3. These activity values result in a significant upward shift in the Ti-in-zircon temperatures on the order of 140 °C (PO-1) and 150 °C (PO-2). Corrected crystallization temperatures for PO-1 and PO-2 zircon crystals yield values of 798–1015 °C (mean 910 °C) and 824–1340 °C (mean 935 °C), respectively (Tables 2, 3).

Discussion and conclusions

Felsic volcanic rocks of the Drienok Nappe in the Inner Western Carpathians were previously investigated mainly in terms of their stratigraphic position and petrography (Slavkay 1965, 1981; Olšavský 2004), mineralogical and geochemical characteristics (Uher et al. 2002; Ondrejka et al. 2015), or their relationship to ore mineralisation and its associated low-T to supergene evolution (Števko et al. 2011). Similar to analogous occurrences of A-type rhyolites in the Muráň Nappe (Ondrejka et al. 2018b), they were previously considered as Early Triassic in age (Slavkay 1965, 1981; Uher et al. 2002; Ondrejka et al. 2015) based on their proximity to Lower Triassic sediments as no geochronological data was available at that time (Klinec 1976; Slavkay 1981; Mello et al. 2000a, b).

The magmatic crystallization ages of ~270 Ma presented here represent the first in-situ LA–ICP–MS U–Pb zircon ages of rhyolites from the Poniky area in the Drienok Nappe.

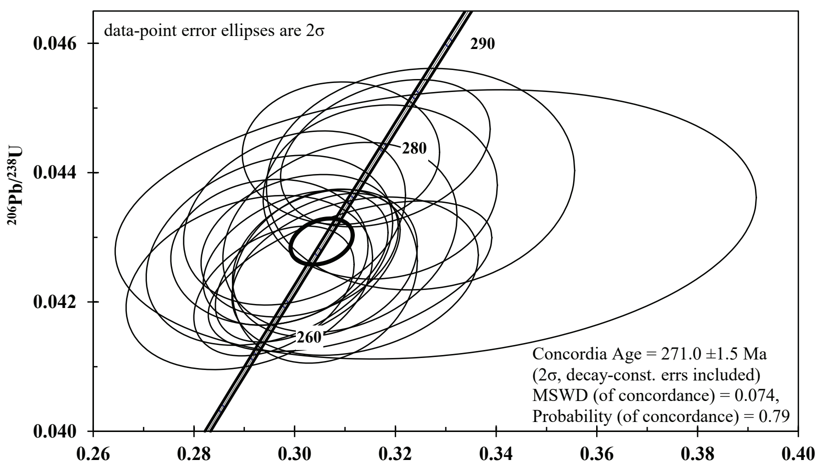

Fig. 8. LA–ICP–MS zircon U–Pb Concordia age diagram of the PO-1 rhyolite (Poniky, Piesky).

Table 2: LA–ICP–MS zircon data of the PO-1 rhyolite (Poniky, Piesky). DT = detection limit, T_{corr} = corrected Ti-in-zircon temperature after Watson et al. (2006).

sample/ spot	^{207}Pb/^{235}U	±σ	^{206}Pb/^{238}U	±σ	rho	^{207}Pb/^{206}Pb	±σ	^{206}Pb/^{238}U age (Ma)	±σ (Ma)	^{207}Pb/^{235}U age (Ma)	±σ (Ma)	^{207}Pb/^{206}Pb age (Ma)	±σ (Ma)	U (ppm)	Th (ppm)	Th/U	f_{206}	Ti (ppm)	Ti DT (ppm)	T_{corr} °C
PO-1/1	0.3010	0.0160	0.0429	0.0009	0.28	0.0506	0.0026	271	5.7	267	14	223	11	1253	1064	0.85	−0.0013	11.2	1.6	893
PO-1/2	0.4630	0.0330	0.0436	0.0012	0.25	0.0759	0.0053	275	7.6	386	28	1092	76	68	32	0.47	0.0303	21.4	2.5	954
PO-1/3	0.2950	0.0200	0.0428	0.0012	0.26	0.0514	0.0034	270	7.6	262	18	259	17	107	57	0.53	−0.0003	17.1	2.0	932
PO-1/4	0.2950	0.0160	0.0428	0.0009	0.10	0.0498	0.0028	270	5.8	262	14	186	10	192	83	0.43	−0.0023	11.0	1.6	891
PO-1/5	0.3002	0.0150	0.0427	0.0009	0.44	0.0513	0.0023	269	5.4	267	13	254	11	283	163	0.58	−0.0004	10.4	1.5	886
PO-1/6	0.3250	0.0250	0.0439	0.0014	0.11	0.0538	0.0043	277	8.8	286	22	363	29	54	28	0.53	0.0025	15.9	2.4	925
PO-1/7	0.7950	0.0370	0.0951	0.0029	0.54	0.0606	0.0024	586	18	594	28	625	25	835	319	0.38	0.0014	8.3	2.3	867
PO-1/8	0.3060	0.0150	0.0426	0.0009	0.27	0.0521	0.0025	269	5.9	271	13	290	14	247	143	0.58	0.0006	13.8	1.5	912
PO-1/9	0.3170	0.0190	0.0437	0.0011	0.14	0.0535	0.0033	276	6.9	280	17	350	22	99	35	0.36	0.0022	12.1	1.7	900
PO-1/10	6.1000	0.2600	0.3638	0.0072	0.38	0.1211	0.0048	2000	40	1990	85	1972	78	325	282	0.87	−0.0025	18.8	2.1	942
PO-1/11	0.3000	0.0180	0.0433	0.0011	0.17	0.0508	0.0031	273	6.9	266	16	232	14	218	89	0.41	−0.0012	12.2	1.7	901
PO-1/12	0.2910	0.0200	0.0423	0.0011	0.14	0.0486	0.0034	267	6.9	259	18	129	9.0	97	54	0.56	−0.0038	21.2	2.5	953
PO-1/13	0.3140	0.0150	0.0404	0.0009	0.32	0.0571	0.0026	255	5.4	277	13	495	23	539	498	0.92	0.0073	21.6	2.9	955
PO-1/14	0.3180	0.0170	0.0443	0.0009	0.29	0.0525	0.0027	279	5.9	280	15	307	16	389	149	0.38	0.0008	6.3	1.5	844
PO-1/15	0.3280	0.0520	0.0432	0.0017	0.12	0.0580	0.0092	273	11	288	46	530	84	16	7	0.42	0.0079	35.0	3.4	1006
PO-1/16	0.3050	0.0280	0.0426	0.0012	0.08	0.0522	0.0049	269	7.6	270	25	294	28	58	22	0.38	0.0007	35.9	3.1	1009
PO-1/17	0.8650	0.0390	0.1035	0.0021	0.41	0.0606	0.0025	635	13	633	29	625	26	405	125	0.31	−0.0003	10.4	1.3	886
PO-1/18	0.3280	0.0240	0.0409	0.0011	0.25	0.0575	0.0041	258	6.9	288	21	511	36	92	37	0.41	0.0077	14.4	2.6	916
PO-1/19	0.3060	0.0150	0.0424	0.0011	0.30	0.0521	0.0025	268	6.9	271	13	290	14	186	105	0.56	0.0006	12.0	2.3	899
PO-1/20	0.3026	0.0150	0.0425	0.0009	0.44	0.0518	0.0023	268	5.9	268	13	277	12	276	161	0.58	0.0002	12.4	1.9	902
PO-1/21	0.8730	0.0420	0.1030	0.0020	0.37	0.0626	0.0028	632	12	637	31	695	31	139	79	0.57	0.0023	15.1	1.9	920
PO-1/22	0.8160	0.0350	0.0995	0.0017	0.45	0.0599	0.0023	611	10	606	26	601	23	875	677	0.77	−0.0003	7.0	1.3	852
PO-1/23	0.4240	0.0330	0.0450	0.0010	0.48	0.0671	0.0047	284	6.3	359	28	841	59	246	114	0.46	0.0190	22.1	6.8	958
PO-1/24	0.3120	0.0200	0.0424	0.0010	0.42	0.0549	0.0032	268	6.3	276	18	408	24	106	59	0.56	0.0041	19.7	3.4	946
PO-1/25	1.5860	0.0700	0.1605	0.0027	0.24	0.0716	0.0031	960	16	965	43	975	42	131	66	0.50	0.0007	12.1	1.4	900
PO-1/26	0.3050	0.0170	0.0431	0.0010	0.09	0.0514	0.0030	272	6.2	270	15	259	15	205	104	0.51	−0.0004	12.0	1.8	899
PO-1/27	1.7470	0.0760	0.1739	0.0036	0.41	0.0727	0.0029	1034	21	1026	45	1006	40	494	242	0.49	−0.0013	3.5	1.0	798
PO-1/28	0.8860	0.0740	0.0469	0.0014	0.50	0.1361	0.0100	295	8.8	644	54	2178	160	94	34	0.36	0.1055	11.1	1.9	892
PO-1/29	0.3090	0.0190	0.0430	0.0012	0.06	0.0530	0.0035	271	7.6	273	17	329	22	200	72	0.36	0.0017	10.3	1.8	885
PO-1/30	0.2959	0.0130	0.0422	0.0008	0.35	0.0508	0.0021	266	5.2	263	12	232	9.6	599	333	0.56	−0.0010	7.8	2.0	861
PO-1/31	0.3960	0.1000	0.0431	0.0077	1.00	0.0620	0.0044	272	49	339	86	674	48	135	76	0.57	0.0129	11.1	2.9	892
PO-1/32	0.6170	0.0620	0.0451	0.0014	0.39	0.0969	0.0090	284	8.8	488	49	1565	145	88	32	0.37	0.0565	27.7	3.2	981
PO-1/33	0.3110	0.0230	0.0424	0.0010	0.36	0.0520	0.0036	268	6.0	275	20	285	20	110	44	0.40	0.0005	15.6	3.7	923
PO-1/34	0.3092	0.0160	0.0443	0.0009	0.32	0.0509	0.0025	279	5.7	274	14	236	12	544	276	0.51	−0.0012	4.4	0.9	816
PO-1/35	0.7380	0.0490	0.0453	0.0015	0.18	0.1224	0.0084	286	9.5	561	37	1992	137	62	20	0.32	0.0885	37.9	4.0	1015
PO-1/36	0.3031	0.0150	0.0426	0.0008	0.37	0.0522	0.0024	269	5.0	269	13	294	14	360	222	0.62	0.0007	10.3	1.3	885
PO-1/37	0.3030	0.0210	0.0423	0.0010	0.40	0.0518	0.0033	267	6.0	269	19	277	18	101	54	0.54	0.0003	14.8	2.5	918
PO-1/38	0.3130	0.0190	0.0434	0.0010	0.34	0.0525	0.0030	274	6.3	277	17	307	18	233	115	0.49	0.0010	13.0	1.6	906
PO-1/39	0.3180	0.0160	0.0443	0.0010	0.40	0.0520	0.0024	279	6.1	280	14	285	13	253	148	0.58	0.0002	8.6	1.8	870
PO-1/40	6.6400	0.2900	0.3780	0.0070	0.44	0.1274	0.0050	2067	38	2065	90	2062	81	92	80	0.87	−0.0004	13.4	2.2	909

Table 3: LA–ICP–MS zircon data of the PO-2 rhyolite (Poniky, Žiarec). DT = detection limit, T_{corr} = corrected Ti-in-zircon temperature after Watson et al. (2006).

sample/ spot	$^{207}Pb/^{235}U$	±σ	$^{206}Pb/^{238}U$	±σ	rho	$^{207}Pb/^{206}Pb$	±σ	$^{206}Pb/^{238}U$ age (Ma)	±σ (Ma)	$^{207}Pb/^{235}U$ age (Ma)	±σ (Ma)	$^{207}Pb/^{206}Pb$ age (Ma)	±σ (Ma)	U (ppm)	Th (ppm)	Th/U	f_{206}	Ti (ppm)	Ti DT (ppm)	T_{corr} °C
PO-2/1	0.2990	0.0110	0.0424	0.0012	0.15	0.0513	0.0022	268	7.6	266	9.8	254	11	177	99	0.56	−0.0004	7.6	1.4	870
PO-2/2	0.3052	0.0078	0.0427	0.0011	0.36	0.0518	0.0015	270	6.9	270	6.9	277	8	509	369	0.72	0.0002	8.6	1.4	880
PO-2/3	0.3030	0.0140	0.0424	0.0013	0.27	0.0521	0.0025	268	8.2	269	12	290	14	87	47	0.54	0.0006	20.6	2.3	961
PO-2/4	0.2940	0.0130	0.0421	0.0014	0.34	0.0507	0.0023	266	8.8	262	12	227	10	106	58	0.55	−0.0011	10.1	1.7	894
PO-2/5	0.3590	0.0350	0.0420	0.0017	0.23	0.0632	0.0061	265	11	311	30	715	69	18	8	0.43	0.0147	32.3	3.3	1008
PO-2/6	1.3000	0.2300	0.0543	0.0026	1.19	0.1730	0.0200	341	16	846	150	2587	299	111	55	0.49	0.1506	340	130	1340
PO-2/7	0.2970	0.0380	0.0421	0.0013	0.93	0.0510	0.0051	266	8.2	264	34	241	24	134	77	0.57	−0.0007	12.2	2.3	911
PO-2/8	0.3030	0.0140	0.0427	0.0013	0.38	0.0516	0.0023	270	8.2	269	12	268	12	109	59	0.54	−0.0001	14.6	1.7	928
PO-2/9	0.3220	0.0160	0.0414	0.0016	0.82	0.0560	0.0016	262	10	283	14	452	13	876	431	0.49	0.0057	10.8	2.3	900
PO-2/10	8.5400	0.6200	0.3420	0.0240	0.93	0.1808	0.0047	1896	133	2290	166	2660	69	277	126	0.46	0.0843	4.9	1.9	835
PO-2/11	0.3014	0.0099	0.0420	0.0011	0.33	0.0520	0.0018	265	6.9	267	8.8	285	9.9	474	335	0.71	0.0006	7.9	1.5	873
PO-2/12	0.3090	0.0250	0.0427	0.0015	0.20	0.0527	0.0043	270	9.5	273	22	316	26	34	12	0.36	0.0013	16.1	2	937
PO-2/13	0.3006	0.0078	0.0425	0.0012	0.26	0.0515	0.0017	268	7.6	267	6.9	263	8.7	463	203	0.44	−0.0001	5.02	0.97	836
PO-2/14	0.2950	0.0140	0.0407	0.0013	0.45	0.0528	0.0023	257	8.2	262	12	320	14	162	86	0.53	0.0018	11	1.5	902
PO-2/15	0.3230	0.0250	0.0427	0.0016	0.22	0.0549	0.0043	270	10	284	22	408	32	62	30	0.48	0.0041	13.4	3.4	920
PO-2/16	0.3120	0.0110	0.0430	0.0010	0.12	0.0526	0.0021	271	6.3	276	9.7	312	12	357	278	0.78	0.0012	7	1.7	863
PO-2/17	5.0650	0.0890	0.3259	0.0088	0.53	0.1128	0.0026	1818	49	1830	32	1845	43	197	294	1.49	0.0021	61	4.2	1082
PO-2/18	0.3900	0.0480	0.0425	0.0013	0.36	0.0666	0.0077	268	8.2	334	41	825	95	80	26	0.32	0.0188	17.7	3.5	946
PO-2/19	0.3006	0.0093	0.0424	0.0011	0.33	0.0514	0.0017	268	6.9	267	8.3	259	8.6	413	295	0.71	−0.0003	5.7	1.2	846
PO-2/20	0.3120	0.0250	0.0416	0.0014	-0.13	0.0550	0.0050	263	8.8	276	22	412	37	36	14	0.38	0.0044	19.2	2.4	954
PO-2/21	0.3530	0.2100	0.0414	0.0020	3.79	0.0618	0.0230	262	13	307	183	667	248	106	62	0.59	0.0130	16.2	2.4	938
PO-2/22	0.3150	0.0270	0.0427	0.0018	-0.56	0.0558	0.0064	270	11	278	24	444	51	35	15	0.44	0.0052	21.6	2.6	966
PO-2/23	0.2940	0.0130	0.0414	0.0012	0.10	0.0515	0.0026	262	7.6	262	12	263	13	148	103	0.70	0.0000	14	1.9	924
PO-2/24	0.3066	0.0078	0.0423	0.0010	0.23	0.0526	0.0016	267	6.3	272	6.9	312	9.5	558	198	0.36	0.0013	4.3	1.1	824
PO-2/25	0.3050	0.0110	0.0424	0.0010	0.37	0.0519	0.0018	268	6.1	270	9.7	281	9.7	650	286	0.44	0.0004	6.7	2.6	860
PO-2/26	0.5950	0.0810	0.0427	0.0019	0.29	0.0997	0.0130	270	12	474	65	1618	211	67	36	0.54	0.0604	153	22	1208
PO-2/27	4.3090	0.0930	0.2837	0.0074	0.52	0.1100	0.0026	1610	42	1695	37	1799	43	338	86	0.25	0.0137	9.4	2.2	888
PO-2/28	0.7740	0.0200	0.0930	0.0024	0.18	0.0605	0.0020	573	15	582	15	622	21	202	164	0.81	0.0017	9.4	1.5	888

However, analogous occurrences in the Tisovec-Rejkovo, Telgárt-Gregová and Veľká Stožka-Dudlavka sites in the Muráň Nappe have also been recently dated by the SIMS U–Pb zircon method at 270–263 Ma (Ondrejka et al. 2018b). The radiometric ages of the Poniky-Drienok rhyolites corroborate and further strengthen their genetic link to mid-Permian A-type magmatism in the Western Carpathian region (Demko & Hraško 2013; Ondrejka et al. 2021) as well as to similar occurrences on the ALCAPA Mega-unit of the Eastern Alps, Western Carpathians and basement of the Pannonian Basin and the Tisza Mega-unit (Kotov et al. 1996; Finger & Broska 1999; Pană et al. 2002; Lelkes-Felvári & Klötzli 2004; Kohút & Stein 2005; Bezák et al. 2008; Radvanec et al. 2009; Vozárová et al. 2009, 2012, 2016, 2021; Kohút et al. 2013; Bonin & Tatu 2016; Putiš et al. 2016; Pelech et al. 2017; Szemerédi et al. 2020a, b, 2021; Yuan et al. 2020).

The investigated rhyolites reveal geochemical and mineralogical characteristics which clearly reflect their A-type affinity (Uher et al. 2002; Ondrejka et al. 2015). Despite their anomalously K-rich composition (due to strong K-metasomatic alteration), the bulk-rock geochemistry reveals a dominantly peraluminous, but also metaluminous, and even peralkaline character with high Si, K, Fe>Mg, K>Na, Rb, Nb, Zr, Th, Y, REE, F, Ga/Al and occasionally W and low Ti, Mg, Ca, P, Sr and V contents. The rhyolites are more alkali-calcic than alkalic and more ferroan than magnesian (according to Frost et al. 2001; Frost & Frost 2011), with high Fe/Mg ratios and are thus typical of A-type magmatic suites (e.g., Whalen et al. 1987; Sylvester 1989, 1994). The high amount of Fe–Ti oxide minerals (magnetite, ilmenite and hematite) also indicates iron enrichment in the rhyolite melt (Ondrejka et al. 2015). These aforementioned geochemical features are closely comparable to hot and dry anorogenic A-type granitic rocks that originated in an extensional tectonic regime of the crust (Whalen et al. 1987; Eby 1990; Frost & Frost 1997; Frost et al. 2001). The crystallization

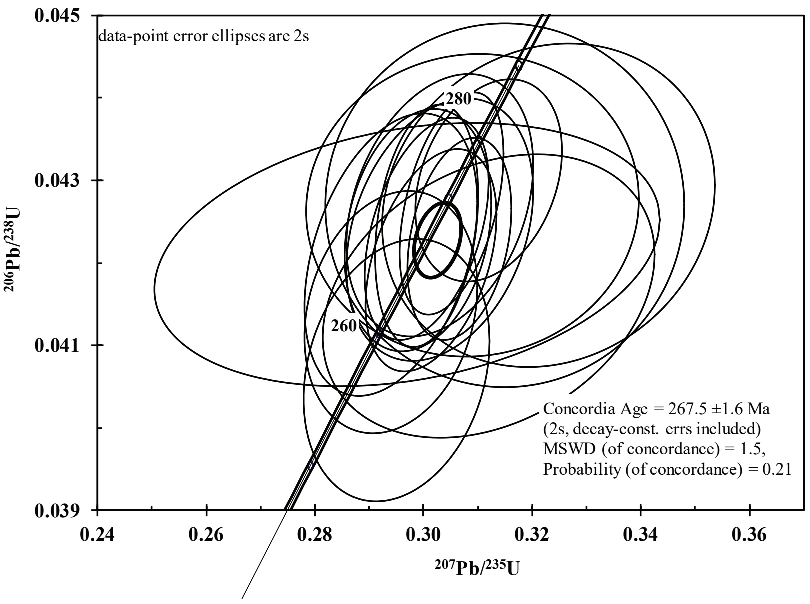

Fig. 9. LA–ICP–MS zircon U–Pb concordia age diagram of the PO-2 rhyolite (Poniky, Žiarec).

from a high temperature alkali magma (Uher et al. 2002; Ondrejka et al. 2021) that is mainly derived from the continental crust (A_2 group of Eby 1992) is indicated by zircon typology (Pupin 1980), and Ti-in-zircon thermometry (Watson et al. 2006).

Finally, it should be noted that the described rhyolites occur only in the Drienok Nappe and its equivalent Muráň and Vernár nappe fragments. These nappes are the structurally highest, unmetamorphosed nappes of the region, detached usually along Upper Permian to Lower Triassic evaporite-bearing horizons. For that reason, these nappes with rhyolite volcanism do not necessarily belong to the Silicic Unit (cf. Havrila 1997; Mello et al. 2000b; Vojtko 2000; Vojtko et al. 2015), but potentially to a group of higher nappes in the Inner Western Carpathians derived from the northern margin of the Neotethys Ocean.

Permian A-type granite and rhyolite originated under a transtensional or extensional tectonic regime (Petrík et al. 1995; Uher & Broska 1996; Uher et al. 2002; Ondrejka et al. 2018b, 2021) during post-Variscan times. The A-type granites include a wide range of felsic high-temperature, F-rich and water-poor, calc-alkaline to alkaline metaluminous to peraluminous suites where a mantle to crustal (meta)-igneous±meta-sedimentary source and a within-plate to plate boundary extensional tectonic setting is suggested (e.g., Collins et al. 1982; Creaser et al. 1991; Frost & Frost 1997, 2011; King et al. 1997; Bonin 2007; Sun et al. 2011; Dahlquist et al. 2014; Morales Cámera et al. 2018; Gao et al. 2020). Volcanic equivalents of A-type granitoids, especially rhyolites, show analogous geochemical features and tectonic settings and they also formed by various mechanisms from contrasting protoliths. They include extreme fractional crystallization of mantle-derived basaltic magma (McCurry et al. 2008; Medlin et al. 2015) or dehydration melting of older granitic rocks triggered by heat derived from the rising mafic magma (Dostal et al. 2021). In our case, partial melting of Cadomian and Variscan lower crustal quartzo–feldspathic meta-igneous and meta-sedimentary rocks with a possible minor contribution of mantle-derived material (e.g., Putiš et al. 2008) provides a likely origin for the Permian A-type rhyolites and related granites (Ondrejka et al. 2021). Moreover, this widespread Permian to Triassic magmatism is generally considered to have been the precursor and thus closely related to the opening of the Neotethys Ocean (Meliata–Hallstatt branch) (e.g., Kozur 1991; Ziegler & Stampfli 2001; Vai 2003; Muttoni et al. 2009; Cassinis et al. 2012) and to Pangea Supercontinent break-up and disintegration (Isozaki 2009; Putiš et al. 2019a,b).

The change from subduction-related calc-alkaline to post-orogenic/anorogenic intracontinental alkali-calcic/alkaline magmatic suites is clearly documented across the entire Variscan Europe (Bonin 1990, 1993, 1998) and in other regions worldwide (e.g., Nikishin et al. 2002; Konopelko et al. 2007; Shellnutt & Zhou 2007). Here, Permian magmatism and metamorphism documented in the Austroalpine units of the Eastern Alps and the Inner Western Carpathians suggest asthenospheric upwelling triggered partial melting of both mantle and deep crustal rocks in an extensionally thinned and underplated lithosphere (e.g., Nikishin et al. 2002; Shellnutt & Zhou 2007; Jeřábek et al. 2008; Sinigoi et al. 2011, 2016; Klötzli et al. 2014; Kunz et al. 2018; Putiš et al. 2018; Broska et al. 2022).

The presence of ~2070–570 Ma inherited cores in some zircon crystals from the rhyolites indicates the admixture of Paleoproterozoic to Neoproterozoic recycled magmatic and/or sedimentary material in the A-type melt source. The presence of older material is also supported by the sporadic inheritance of mostly Precambrian, 2800–450 Ma old monazite-(Ce) and zircon domains in the A-type granites as well as Carboniferous S- and I-type Variscan granitic rocks of the Western Carpathian and Pannonian region (Kohút et al. 2009; Broska et al. 2013; Sobocký et al. 2020; Kohút & Larionov 2021; Ondrejka et al. 2021).

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