GEOLOGICA CARPATHICA, APRIL 2018, 69, 2, 187–198 doi: 10.1515/geoca-2018-0011

Permian A-type rhyolites of the Muráň Nappe, Inner Western Carpathians, Slovakia: in-situ zircon U–Pb SIMS ages and tectonic setting

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(Manuscript received November 6, 2017; accepted in revised form February 15, 2018)

Abstract: Three representative A-type rhyolitic rock samples from the Muráň Nappe of the inferred Silicic Unit of the Inner Western Carpathians (Slovakia) were dated using the high-precision SIMS U–Pb isotope technique on zircons. The geochronological data presented in this paper is the first in-situ isotopic dating of these volcanic rocks. Oscillatory zoned zircon crystals mostly revealed concordant Permian (Guadalupian) ages: 266.6±2.4 Ma in Tisovec-Rejkovo (TIS-1), 263.3±1.9 Ma in Telgárt-Gregová Hill (TEL-1) and 269.5±1.8 Ma in Veľká Stožka-Dudlavka (SD-2) rhyolites. The results indicate that the formation of A-type rhyolites and their plutonic equivalents are connected to magmatic activity during the Permian extensional tectonics and most likely related to the Pangea supercontinent break-up.

Keywords: Permian volcanism, Western Carpathians, Muráň Nappe, A-type rhyolites, zircon, SIMS U–Pb age.

Introduction

Numerous occurrences of acid volcanic rocks, mainly rhyolites in Permian to Lower Triassic siliciclastic to carbonate sequences of the inferred Silicic Unit Muráň and Drienok nappes have been reported by many authors (e.g., Stur 1868; Oppenheimer 1931; Grenar & Kotásek 1956; Zorkovský 1959a, b; Losert 1963; Slavkay 1965, 1981; Klinec 1976; Hovorka & Spišiak 1988; Uher et al. 2002a, b; Ondrejka et al. 2007, 2015; Demko & Hraško 2013). The (trachy)andesite–trachyte–rhyolite lava and pyroclastic sequences as belonging to the K-alkalic association (according to de La Roche et al. 1980 classification) were characterised in the PO-1 borehole near Poniky village in the Drienok Nappe (Slavkay 1965, 1981). The sequence was named the Skálie Formation and it correlates with the Lower Triassic volcanic suite of the Bükk Unit in Hungary (Hovorka & Spišiak 1988). The major and trace element geochemical and mineralogical characteristics of these volcanic rocks (Uher et al. 2002b) are compatible with analogous occurrences of post-Variscan anorogenic A-type magmatic rocks in the Alpine-Carpathian belt (e.g., Bonin 1990; Beltrán-Triviño et al. 2016).

The lack of convincing radiometric dates has confused previous authors about the stratigraphic position of these rhyolites and their inferred Early Triassic age (Biely 1956; Slavkay 1965, 1981; Mello et al. 2000b; Uher et al. 2002a, b; Ondrejka et al. 2015). However, the age of these volcanic rocks was deduced only from their close geological position to adjacent Triassic sediments (Klinec 1976; Slavkay 1981; Mello et al. 2000a, b). Determination of the exact age of these volcanites resulted in EPMA monazite dating of the Gregová rhyolite body which gave a Guadalupian age of 263±3.5 Ma (Demko & Hraško 2013). This geochronological data was supported by comprehensive petrographical, lithofacial, and volcanological study which reported the close volcanics relationship to Permian sedimentary succession upwards followed by Triassic sediments (Demko & Hraško 2013). However, a precise geochronological solution is required to place these volcanites in stratigraphic successions of the inferred Silicic Unit Muráň Nappe in the southern part of the Inner Western Carpathians. The aim of this paper is to yield accurate radiometric ages for these acid volcanic rocks by in-situ zircon U–Pb SIMS isotopic dating. We selected three typical occurrences of the rhyolites from Muráň Nappe: Tisovec-Rejkovo, Veľká Stožka-Dudlavka, and Telgárt-Gregová Hill for this dating (Fig. 1).

Geological setting, mineral composition, geochemistry and petrology of A-type rhyolites

The Silicic Unit (e.g., Plašienka et al. 1997) includes the structurally highest, non-metamorphosed nappe stack restricted to the Vepor-Gemer Belt of the Inner Western Carpathians and to the Slovak-Aggtelek Karst to the south. (i.e. Drienok, Muráň, Vernár, Stratená, Silica, Szőlősardó,

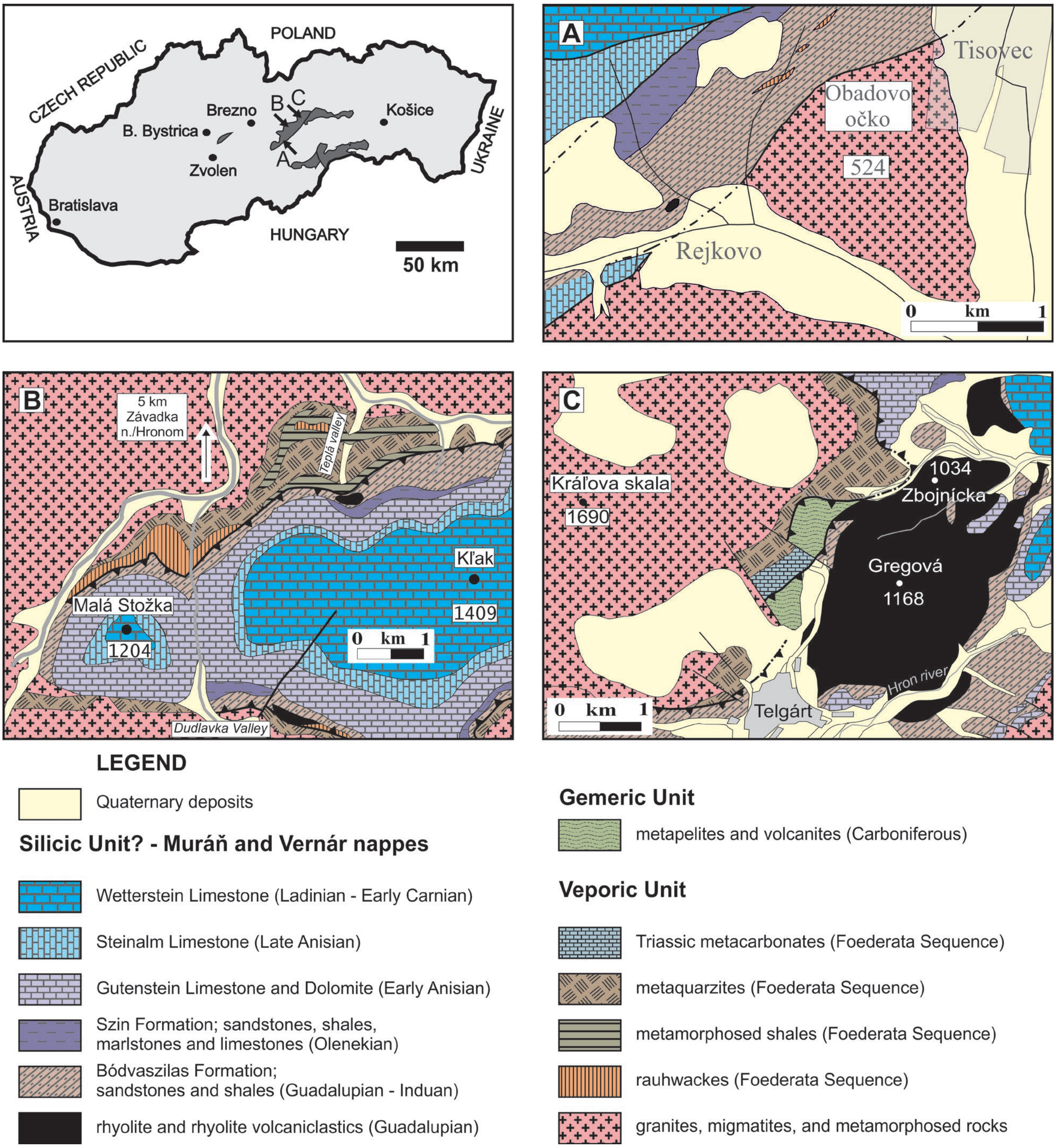

Fig. 1. Position of investigated rhyolites of the Muráň Nappe in the Inner Western Carpathians: **A** — Tisovec-Rejkovo (TIS-1), N 48°40'7.89", E 19°55'28.96"; **B** — Veľká Stožka-Dudlavka (SD-2), N 48°46'9.42", E 19°56'32.47"; **C** — Telgárt-Gregová Hill (TEL-1), N 48°51'21.41", E 20°12'16.13": The geological maps are modified after Klinec (1976).

and Bódva nappes). Lithostratigraphy establishes Late Permian to Late Jurassic sedimentary successions dominated by extensive Middle to Late Triassic platform-type carbonates, and the unit is facially analogous to the Schneeberg and Mürzalpe nappes of the Upper Tirolic and/or Juvavic nappes of the Northern Calcareous Alps (Mello et al. 1997).

The original sedimentary position of the Silicic Unit is not well constrained. Facially, it could be placed on the northern passive margin of the Meliata (Neotethys) Ocean (Haas et al. 1995) but the structural position on the top of the nappe stack would infer origin from the southern margin of the Ocean (as in Hók et al. 1995, 2014; Putiš et al. 2014; Lačný et al. 2016; Plašienka et al. 2016).

The lower part of the Silicic Unit is composed of the Werfen Formation. This ranges from tens to hundreds of metres thick sedimentary succession of continental to shallow marine deposits, mainly shales to sandstones with marlstones, limestones and a siliciclastic admixture of Late Permian to Early Triassic age (Bystrický 1964; Slavkay 1965; Klinec 1976; Biely et al. 1992, 1997; Mello et al. 2000a, b; Vojtko 2000). From this group of nappe stack, the Muráň, Vernár, and Drienok nappes contain the rhyolite bodies in the lower portion of the formation (Fig. 2; Bódvaszilas Member; Hips 1996).

The A-type rhyolitic rocks have the common features of acid volcanics. The texture is commonly porphyric with a microfelsitic to felsitic groundmass. Fluidal texture also occurs in some places. Phenocrysts, 0.5–4 mm in size, are represented by euhedral mesoperthitic alkali feldspars (Fig. 3a) and corroded ß-quartz (Fig. 3b). The feldspars are commonly replaced by post-magmatic chessboard albite or fine-grained aggregates of white mica (Uher et al. 2002b; Ondrejka et al. 2007). The groundmass consists of a very fine-grained aggregate of quartz, alkali feldspar, white mica, hematite pigment, and occasionally biotite, chlorite, and accessory zircon, monazite-(Ce), xenotime- (Y), rutile, ilmenite, magnetite, hematite, and barite (Uher et al. 2002b; Ondrejka et al. 2015) (Fig. 3c). Moreover, the rhyolite body at Tisovec-Rejkovo contains a unique REE–Y–(Th)–P–As–(Si)–(Nb)–(S) accessory assemblage comprising REE arsenate-phosphate-silicate solid solutions, REE carbonates and rarely cerianite-(Ce) (Ondrejka et al. 2007).

All studied rhyolites are rich in Si and especially K, and depleted in Ti, Mg, Ca, Na, and P (Uher et al. 2002a, b; Ondrejka et al. 2007). 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. High Si contents connected with low Mg and Ca resulted in anomalously high R1 parameter and very low R2 (after Batchelor & Bowden 1985) with a trend concordant with anorogenic magmatic suites (Uher et al. 2002b). The rhyolites trace element geochemistry has slight enrichment in Rb, Zr, Y and REE, depletion in Sr, Ba and V, as well as elevated Rb/Sr and Ga/Al ratios (Uher et al. 2002b) which are typical for alkali-rich post-orogenic and anorogenic Si-rich magmatic suites of A-type affinity (Whalen et al. 1987). The A-type tendency is also evident in chondrite-normalised REE distribution patterns with pronounced negative Eu-anomaly and slightly enriched LREEs (Uher et al. 2002b; Ondrejka 2004).

Zircon typology of the rhyolites shows dominant high alkaline and high temperature (800–900 ± 50 °C) types and subtypes (Fig. 3d, e; Uher et al. 2002b; Ondrejka et al. 2015) which are characteristic for anorogenic alkaline magmatic

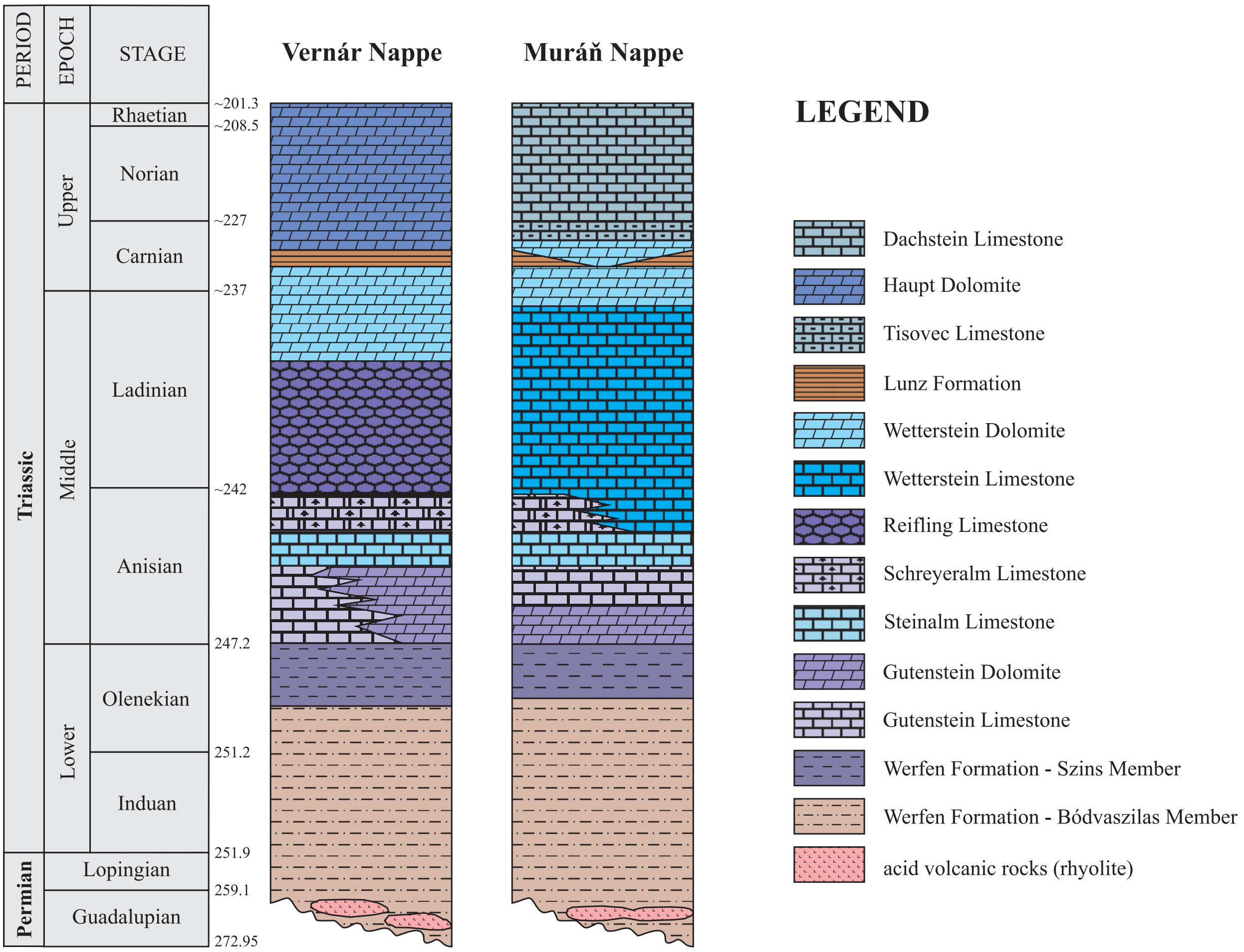

Fig. 2. Simplified Permian to Triassic lithostratigraphic column of the Vernár Nappe and Muráň Nappe.

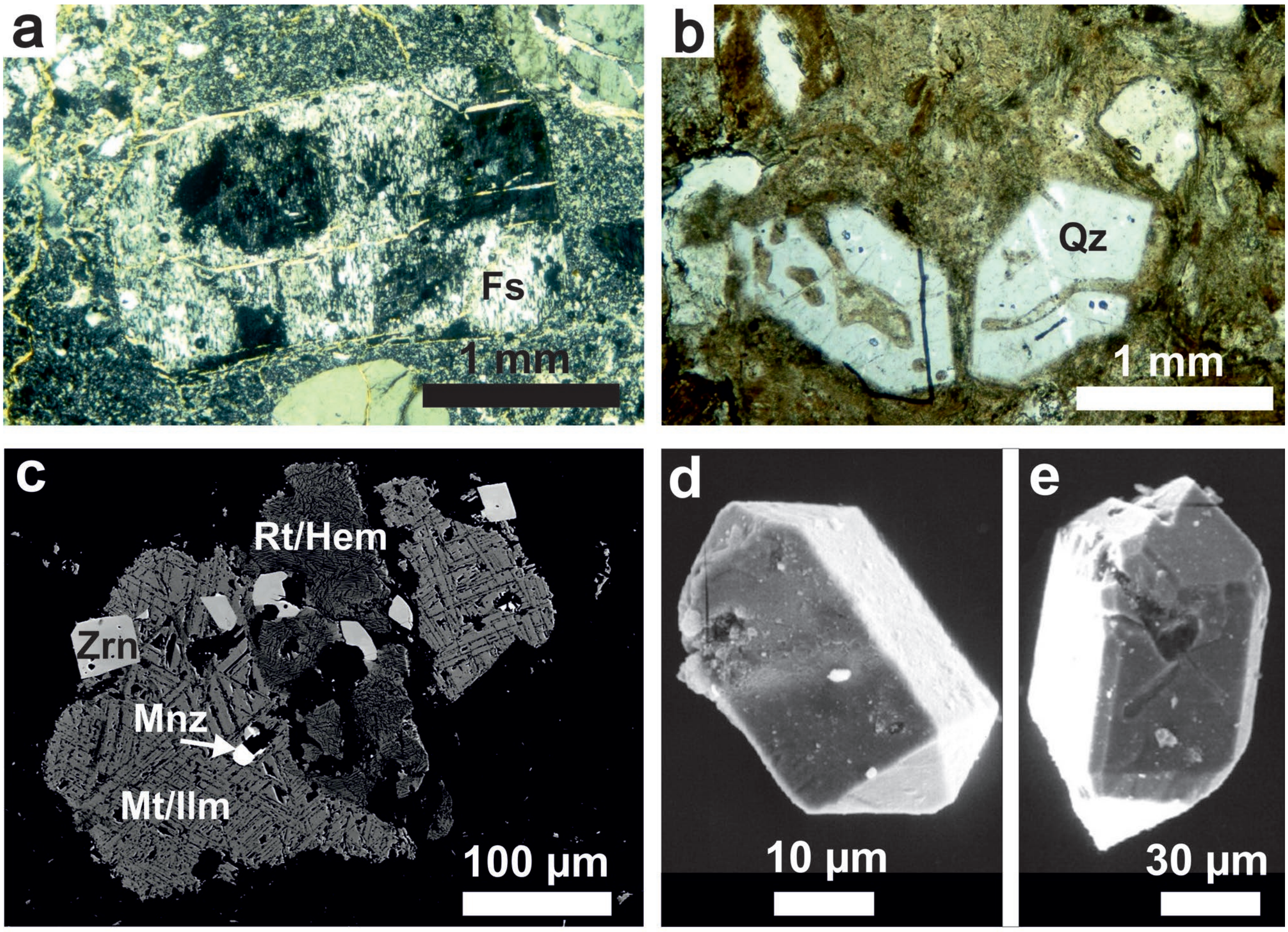

Fig. 3. Microphotographs, BSE and SEM images showing textural aspects and mineral composition of A-type rhyolites of the Muráň Nappe: **a** — phenocryst of euhedral chessboard albite (Fs) and fine-grained aggregates of white mica (X polaroids); **b** — phenocrysts of corroded ß-quartz (II polaroids); **c** — zircon (Zrn) and monazite-(Ce) (Mnz) enclosed in Fe-Ti oxide trellis aggregates represented by magnetite, ilmenite (Mt/Ilm) and rutile, hematite (Rt/Hem); **d** — zircon crystal of D type morphology; **e** — zircon crystal of P_5 subtype morphology.

suites (Pupin 1980). These results correspond with the zircon saturation temperatures (T_{Zr}) of the rhyolites, calculated from bulk-rock chemical composition (Watson & Harrison 1983), where T_{Zr}=820–895 °C (Uher et al. 2002b; Ondrejka et al. 2015). The study of Fe–Ti oxide mineral assemblage reveals late magmatic to (sub)solidus evolution of the rhyolites, 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).

Analytical methods

Zircon crystals were extracted using standard density and magnetic separation techniques. Zircons and zircon U–Pb age standards were mounted in 2.5 cm diameter epoxy polished to expose the crystal interiors for analysis. Zircon crystals were documented with transmitted and reflected light microphotographs, followed by cathodoluminescence (CL) imaging under a field emission scanning electron microscope equipped with Gatan MonoCL4 detector at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGG-CAS) in Beijing. After imaging, the zircon mount was coated with high purity gold to reach <20 Ω resistance prior to SIMS analysis.

Measurement of U, Th, and Pb isotopes was conducted using a Cameca IMS-1280HR SIMS at the Institute of Geology and Geophysics, Chinese Academy of Sciences in Beijing. The instrument description and analytical procedure follow Li et al. (2009), and we give only a brief summary. The primary O_2^- ion beam spot is approximately 20×30 µm in size. Positive secondary ions were extracted with a 10 kV potential. A 60 eV energy window was used in secondary ion beam optics with mass resolution of approximately 5400 (at 10 % peak height) to separate Pb^+ peaks from isobaric interferences. A single electron multiplier was then used in ion-counting mode to measure secondary ion beam intensities by peak jumping mode. Each measurement consists of 7 cycles. The Pb/U calibration was performed relative to the Plešovice zircon standard ($^{206}Pb/^{238}U$ age=337.13±0.37 Ma; Sláma et al. 2008); U and Th concentrations were calibrated against zircon standard 91500 (Th=29 ppm, and U=81 ppm, Wiedenbeck et al.

1995). A long-term uncertainty of 1.5 % (1s RSD) for $^{206}Pb/^{238}U$ measurements of the standard zircons was propagated to the unknowns (Li et al. 2010), although the measured $^{206}Pb/^{238}U$ error in a specific session is generally ≤1% (1σ RSD). Measured compositions were corrected for common Pb using non-radiogenic ^{204}Pb. Corrections are sufficiently small to be insensitive to the choice of common Pb composition, and the average of present-day crustal composition (Stacey & Kramers 1975) is used for the common Pb; assuming that the common Pb is largely surface contamination introduced in sample preparation. Data reduction was performed by Isoplot/Ex version 2.49 program (Ludwig 2001). Uncertainties on individual analyses in data tables are reported at 1σ level, and Concordia U–Pb ages are quoted with 95 % confidence interval except where otherwise noted. The Qinghu (China) zircon standard and samples were alternately analysed as unknowns in order to monitor the external uncertainties of SIMS U–Pb zircon dating calibrated against the Plešovice standard. Twenty-two Qinghu zircon measurements yielded concordia age of 160±1 Ma which is identical within error to the 159.5±0.2 Ma recommended value (Li et al. 2013).

Results

Zircon descriptions

Zircon crystals were separated from the A-type rhyolites from Tisovec (TIS-1 sample), Telgárt (TEL-1 sample), and Veľká Stožka (SD-2 sample). The highest quality zircon crystals in all samples were selected for measurement to avoid fractures and mineral inclusions. The apparent zircon morphology ranges from euhedral and long-prismatic to subhedral, stubby grains. Among them, the euhedral crystals are the most common. Some zircons have slightly resorbed shapes with varying degree of crystal-edge rounding. Zircons crystals are transparent, mostly 100–200 μm in length with length/width ratios of ~1.5:1 to ~3:1. While magmatic regular fine oscillatory and sector zoning are common features of the investigated zircon crystals, irregular (subsolidus?) domains are also visible in CL imaging (Fig. 4).

SIMS zircon U–Pb ages

A total of 58 spot analyses were performed on zircon crystals from samples TIS-1, TEL-1 and SD-2. The zircons reveal variable concentrations of uranium (~40 to 930 ppm) and thorium (~15 to 1220 ppm) which give a relatively wide Th/U ratio between 0.05 and 2.33 for all three samples (Tables 1 to 3). Values for f_{206} (the proportion of common ^{206}Pb in total measured ^{206}Pb) are in the range of 0.09–3.19 % (TIS-1, Table 1), 0.24–1.25 % (TEL-1, Table 2) and 0.04–1.66 % (SD-2, Table 3).

A total of 19 spot analyses were obtained from the Tisovec-Rejkovo rhyolite, TIS-1 sample (Table 1). Apart from a single zircon crystal (spot TIS-1-1) which shows a different morphology (S-subtypes), the remaining 18 zircon crystals exhibit D or P_{4-5} morphology (according to typology of Pupin 1980) (Fig. 4). Their U–Pb isotope analyses are concordant within analytical errors; yielding a concordia age of 266.6±2.4 Ma (MSWD of concordance=1.3) (Fig. 5). Spot TIS-1-1 gives a clearly older age of 462.7±6.6 Ma (1σ) which is interpreted as an inherited xenocryst.

A total of 19 spot analyses were obtained from the Telgárt-Gregová Hill rhyolite, TEL-1 sample (Table 2). One analysis (spot TEL-1-5) yields a clearly older date of 781.2±11.6 Ma (1σ) than the majority of the population. This zircon has unambiguously resorbed shape with irregular zoning under CL, thus indicating a potential inherited xenocryst in origin. The remaining 18 zircons are mostly euhedral crystals with concentric zoning (Fig. 4). They give concordant U–Pb results within analytical errors; yielding a concordia age of 263.3±1.9 Ma (MSWD of concordance=0.16) (Fig. 6).

A total of 20 spot analyses were conducted for the Veľká Stožka-Dudlavka, SD-2 sample (Table 3). One analysis (spot SD-2-2) gives a clearly younger date of 239.0±3.5 Ma (1σ) than others, possibly due to partial loss of radiogenic Pb. The remaining 19 analyses are concordant within analytical errors, yielding a concordia age of 269.5±1.8 Ma (MSWD of concordance= 0.19) (Fig. 7).

Discussion and conclusion

Acid volcanic rocks of the inferred Silicic Unit Muráň Nappe in the Inner Western Carpathians were investigated mainly from the view-point of their stratigraphic position and determination of their petrographic composition (Zorkovský 1959a,b; Slavkay 1965, 1981) and mineralogical–geochemical characteristics (Uher et al. 2002a,b; Ondrejka et al. 2007, 2015). Lithological and stratigraphic correlations without radiometric data prompted previous authors to deem the rhyolites of the Silicic Unit as Early Triassic (Biely 1956; Slavkay 1965, 1981; Mello et al. 2000b; Uher et al. 2002a,b; Ondrejka et al. 2015).

The magmatic crystallisation ages of ca. 270–263 Ma presented in this paper are the first in-situ isotopic ages of these volcanic rocks constrained by the U–Pb SIMS method on zircon. However, already the first preliminary geochronological results indicated a Permian age for the rhyolites in question. These were obtained from the Poniky-Drienok (261±15 Ma) and Veľká Stožka (258±12 Ma) rhyolite bodies by the in-situ EPMA U–Th–Pb method on monazite (Ondrejka 2004). The ages are relatively imprecise due to low Th, U contents measured by EPMA and the restricted number of analytical spots (12 and 15 respectively) which resulted in relatively large 2σ errors. Moreover, recent monazite EPMA chemical dating from the Telgárt-Gregová Hill rhyolite body gave a more precise Permian age (Guadalupian) of 263±3.5 Ma (Demko & Hraško 2013) which is in good agreement with our presented SIMS U–Pb ages.

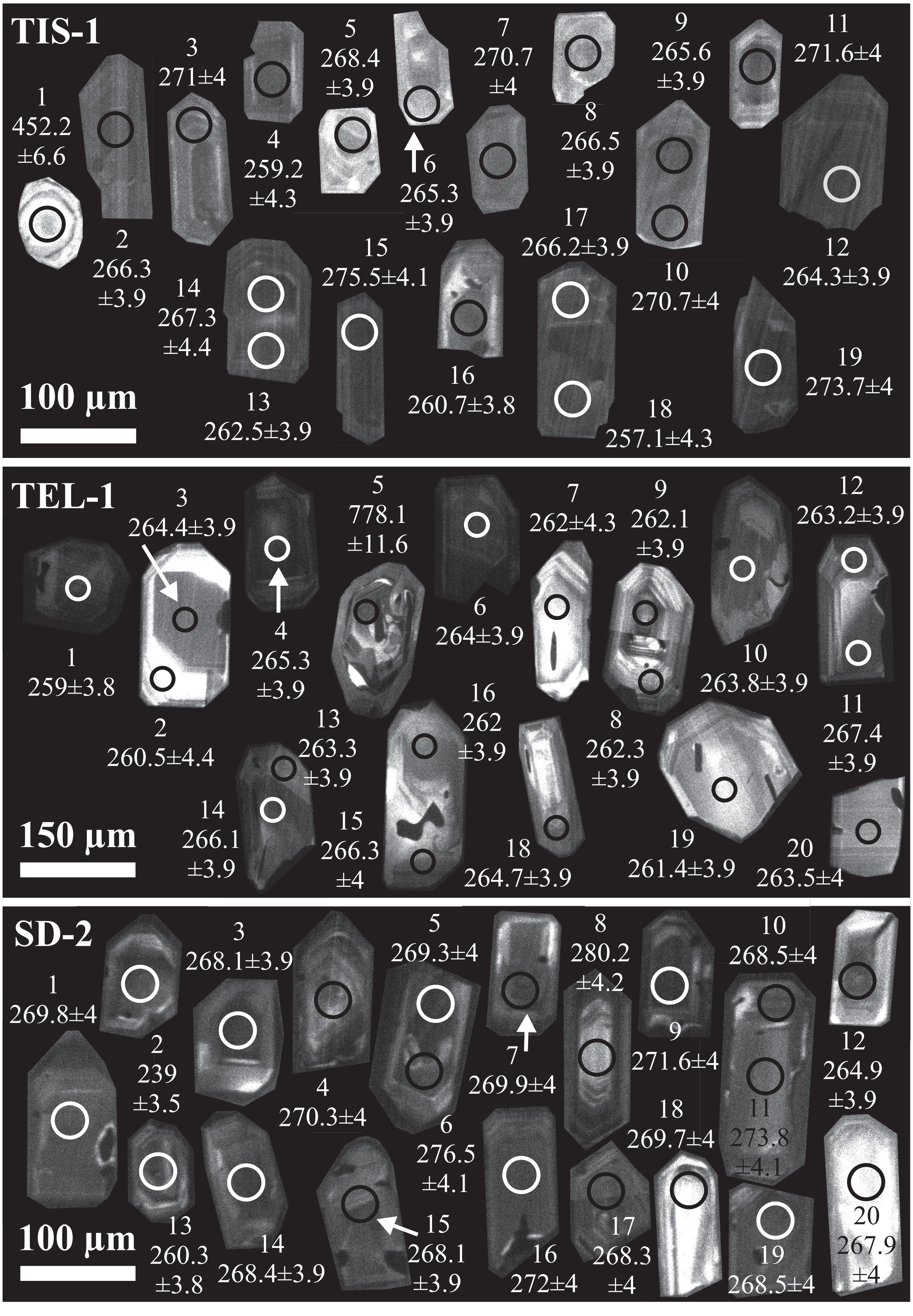

Fig. 4. CL images of zircons from the A-type rhyolite from Muráň Nappe with illustrated analytical spots and corresponding $^{206}Pb/^{238}U$ age values.

Table 1: SIMS zircon U–Th–Pb data of the rhyolite sample TIS-1 (Tisovec-Rejkovo).

sample/spot	U (ppm)	Th (ppm)	Pb (ppm)	Th/U	f_{206} (%)	$^{207}Pb/^{235}U$	±σ (%)	$^{206}Pb/^{238}U$	±σ (%)	$^{206}Pb/^{238}U$ age (Ma)	±σ (Ma)	$^{207}Pb/^{235}U$ age (Ma)	±σ (Ma)
TIS-1/1	266.5	14.2	20.8	0.053	0.09	0.57731	2.17	0.0727	1.50	452.2	6.6	462.7	8.1
TIS-1/2	620.3	412.6	33.0	0.665	0.18	0.30316	1.69	0.0422	1.50	266.3	3.9	268.9	4.0
TIS-1/3	474.0	274.8	25.1	0.580	0.26	0.30312	1.77	0.0429	1.50	271.0	4.0	268.8	4.2
TIS-1/4	557.9	427.2	28.8	0.766	3.19	0.29134	4.14	0.0410	1.71	259.2	4.3	259.6	9.5
TIS-1/5	740.2	434.9	39.0	0.588	0.41	0.30447	1.67	0.0425	1.50	268.4	3.9	269.9	4.0
TIS-1/6	548.7	326.2	28.5	0.595	0.18	0.29541	1.87	0.0420	1.51	265.3	3.9	262.8	4.3
TIS-1/7	428.2	235.0	22.4	0.549	0.34	0.30453	1.78	0.0429	1.50	270.7	4.0	269.9	4.2
TIS-1/8	432.2	351.8	23.8	0.814	0.40	0.29153	2.30	0.0422	1.50	266.5	3.9	259.8	5.3
TIS-1/9	933.0	978.4	54.1	1.049	0.35	0.29292	1.90	0.0421	1.50	265.6	3.9	260.9	4.4
TIS-1/10	492.6	293.1	26.2	0.595	0.10	0.30421	1.81	0.0429	1.50	270.7	4.0	269.7	4.3
TIS-1/11	902.3	892.9	53.0	0.990	0.36	0.30256	2.29	0.0430	1.50	271.6	4.0	268.4	5.4
TIS-1/12	466.5	279.9	24.2	0.600	0.20	0.29882	1.77	0.0419	1.50	264.3	3.9	265.5	4.1
TIS-1/13	426.1	255.3	21.7	0.599	0.67	0.27534	2.78	0.0416	1.50	262.5	3.9	247.0	6.1
TIS-1/14	525.1	1223.6	40.1	2.330	1.91	0.29241	4.65	0.0423	1.69	267.3	4.4	260.5	10.7
TIS-1/15	638.3	516.9	36.4	0.810	0.14	0.30881	1.70	0.0437	1.51	275.5	4.1	273.3	4.1
TIS-1/16	482.7	282.3	24.6	0.585	0.41	0.28907	2.15	0.0413	1.50	260.7	3.8	257.8	4.9
TIS-1/17	341.2	165.8	17.3	0.486	0.32	0.30253	1.83	0.0422	1.50	266.2	3.9	268.4	4.3
TIS-1/18	376.0	204.7	18.6	0.544	0.42	0.27788	2.34	0.0407	1.70	257.1	4.3	249.0	5.2
TIS-1/19	750.9	496.8	41.1	0.662	0.35	0.30995	1.66	0.0434	1.50	273.7	4.0	274.1	4.0

Table 2: SIMS zircon U-Th-Pb data of the rhyolite sample TEL-1 (Telgárt–Gregová Hill).

sample/spot	U (ppm)	Th (ppm)	Pb (ppm)	Th/U	f_{206} (%)	$^{207}Pb/^{235}U$	±σ (%)	$^{206}Pb/^{238}U$	±σ (%)	$^{206}Pb/^{238}U$ age (Ma)	±σ (Ma)	$^{207}Pb/^{235}U$ age (Ma)	±σ (Ma)
TEL-1/1	112.1	79.5	5.9	0.709	1.25	0.29439	2.38	0.0410	1.51	259.0	3.8	262.0	5.5
TEL-1/2	43.5	16.0	2.1	0.368	0.37	0.29479	4.75	0.0412	1.74	260.5	4.4	262.3	11.0
TEL-1/3	181.0	105.8	9.4	0.585	0.68	0.29764	2.08	0.0419	1.50	264.4	3.9	264.6	4.8
TEL-1/4	220.5	179.4	12.0	0.813	0.61	0.29205	1.99	0.0420	1.51	265.3	3.9	260.2	4.6
TEL-1/5	283.7	191.0	46.6	0.673	0.62	1.15836	2.18	0.1283	1.58	778.1	11.6	781.2	11.9
TEL-1/6	179.9	125.8	9.5	0.699	0.55	0.29307	2.09	0.0418	1.50	264.0	3.9	261.0	4.8
TEL-1/7	119.3	82.0	6.3	0.688	0.76	0.29592	2.43	0.0415	1.68	262.0	4.3	263.2	5.7
TEL-1/8	141.5	79.5	7.2	0.562	0.91	0.27857	4.42	0.0415	1.51	262.3	3.9	249.5	9.8
TEL-1/9	234.0	202.5	12.7	0.865	0.69	0.27604	3.36	0.0415	1.51	262.1	3.9	247.5	7.4
TEL-1/10	128.1	89.9	6.8	0.702	0.72	0.29547	2.27	0.0418	1.50	263.8	3.9	262.9	5.3
TEL-1/11	230.3	148.8	12.1	0.646	0.42	0.30028	2.06	0.0423	1.50	267.4	3.9	266.6	4.9
TEL-1/12	281.0	131.1	14.0	0.466	0.38	0.30170	1.89	0.0417	1.50	263.2	3.9	267.7	4.5
TEL-1/13	216.5	123.2	11.1	0.569	0.36	0.29609	1.98	0.0417	1.50	263.3	3.9	263.3	4.6
TEL-1/14	239.6	150.5	12.7	0.628	0.44	0.30755	1.95	0.0421	1.50	266.1	3.9	272.3	4.7
TEL-1/15	89.5	47.6	4.6	0.532	0.53	0.28974	2.56	0.0422	1.53	266.3	4.0	258.4	5.8
TEL-1/16	92.0	52.6	4.7	0.571	0.72	0.28760	2.53	0.0415	1.50	262.0	3.9	256.7	5.8
TEL-1/18	198.5	107.4	10.2	0.541	0.24	0.29556	2.55	0.0419	1.50	264.7	3.9	262.9	5.9
TEL-1/19	223.0	144.0	11.5	0.646	0.41	0.29354	1.98	0.0414	1.50	261.4	3.9	261.3	4.6
TEL-1/20	112.0	77.2	5.9	0.689	0.73	0.29815	2.71	0.0417	1.54	263.5	4.0	265.0	6.3

Analogous zircon U–Pb SIMS ages of ca. 270 to 260 Ma were determined from the following locations; a rhyolite lava flow in Permian siliciclastics and rhyodacite dyke in crystalline basement micaschist-gneisses of the Infratatric Unit in the Považský Inovec Mts. (~267–262 Ma; Putiš et al. 2016), a quartz-bearing, magmatically mixed and/or contaminated volcanic dykes of alkaline basalt in the Tatric Unit of the Považský Inovec Mts. (~260 Ma; Pelech et al. 2017), the A-type Turčok metagranite (~263 Ma; Radvanec et al. 2009) and rare metal S-type granites in the Gemeric Unit ~275–250 Ma (Finger & Broska 1999; Kohút & Stein 2005; Radvanec et al. 2009). Permian ages of acid magmatism were also documented in the Northern Veporic Unit, including the eastern part of the Nízke Tatry Mts. (Kotov et al. 1996; Bezák et al. 2008; Vozárová et al. 2016). Very similar age intervals (~275–255 Ma) were also obtained from volcanic and volcano-sedimentary rocks in the Permian successions of the Gemeric unit and in the Meliatic Bôrka nappe in the Inner Western Carpathians (Vozárová et al. 2009, 2012; Kohút et al. 2013).

The specific geochemistry of the dated rhyolites also reveals their origin in an extensional regime of the crust. Despite their unusual K-enrichment, the geochemistry indicates affinity to alkali volcanic suites rich in Si, Rb, Zr, Y and REE and depleted in Mg, Ca, Na, P, Sr, Ba and V; closely comparable to hot and dry anorogenic A-type granitic rocks (Whalen et al. 1987; Eby 1990; Frost & Frost 1997; Frost et al. 2001). Zircon typology (Pupin 1980) and saturation thermometry (Watson & Harrison 1983) also support the solidification from high temperature and alkali magma (Uher et al. 2002b).

Table 3: SIMS zircon U-Th-Pb data of the rhyolite sample SD-2 (Veľká Stožka-Dudlavka).

sample/spot	U (ppm)	Th (ppm)	Pb (ppm)	Th/U	f_{206} (%)	$^{207}Pb/^{235}U$	±σ (%)	$^{206}Pb/^{238}U$	±σ (%)	$^{206}Pb/^{238}U$ age (Ma)	±σ (Ma)	$^{207}Pb/^{235}U$ age (Ma)	±σ (Ma)
SD-2/1	531.3	358.4	28.7	0.674	0.37	0.30681	1.81	0.0427	1.50	269.8	4.0	271.7	4.3
SD-2/2	333.1	621.6	18.3	1.866	1.66	0.26071	3.85	0.0378	1.51	239.0	3.5	235.2	8.1
SD-2/3	732.5	626.0	40.8	0.855	0.10	0.30108	1.72	0.0425	1.50	268.1	3.9	267.2	4.1
SD-2/4	290.6	208.2	16.0	0.716	0.25	0.30484	1.88	0.0428	1.50	270.3	4.0	270.2	4.5
SD-2/5	530.7	246.8	27.1	0.465	0.19	0.30571	1.74	0.0427	1.50	269.3	4.0	270.8	4.1
SD-2/6	393.4	118.8	19.8	0.302	0.08	0.31167	1.85	0.0438	1.50	276.5	4.1	275.5	4.5
SD-2/7	620.2	483.5	34.4	0.780	0.04	0.30307	1.69	0.0428	1.50	269.9	4.0	268.8	4.0
SD-2/8	391.8	187.6	20.9	0.479	0.10	0.31258	1.81	0.0444	1.54	280.2	4.2	276.2	4.4
SD-2/9	575.4	445.6	32.0	0.774	0.33	0.30986	1.77	0.0430	1.50	271.6	4.0	274.1	4.3
SD-2/10	524.9	256.6	26.8	0.489	0.19	0.30338	1.72	0.0425	1.50	268.5	4.0	269.0	4.1
SD-2/11	397.1	275.6	21.8	0.694	0.32	0.31154	1.81	0.0434	1.53	273.8	4.1	275.4	4.4
SD-2/12	748.3	706.3	41.7	0.944	0.55	0.29073	2.11	0.0420	1.50	264.9	3.9	259.1	4.8
SD-2/13	412.6	330.9	21.5	0.802	0.48	0.29523	2.35	0.0412	1.50	260.3	3.8	262.7	5.4
SD-2/14	516.6	349.9	27.8	0.677	0.37	0.30374	1.73	0.0425	1.50	268.4	3.9	269.3	4.1
SD-2/15	526.3	372.2	28.5	0.707	0.23	0.30162	1.91	0.0425	1.50	268.1	3.9	267.7	4.5
SD-2/16	565.0	389.9	30.9	0.690	0.23	0.30448	2.20	0.0431	1.50	272.0	4.0	269.9	5.2
SD-2/17	605.0	295.4	31.0	0.488	0.21	0.30560	1.73	0.0425	1.52	268.3	4.0	270.8	4.1
SD-2/18	257.2	172.6	13.9	0.671	0.86	0.30208	2.11	0.0427	1.50	269.7	4.0	268.0	5.0
SD-2/19	474.4	412.6	26.6	0.870	1.00	0.29340	2.08	0.0425	1.50	268.5	4.0	261.2	4.8
SD-2/20	333.3	128.1	16.6	0.384	0.31	0.29651	1.88	0.0424	1.51	267.9	4.0	263.7	4.4

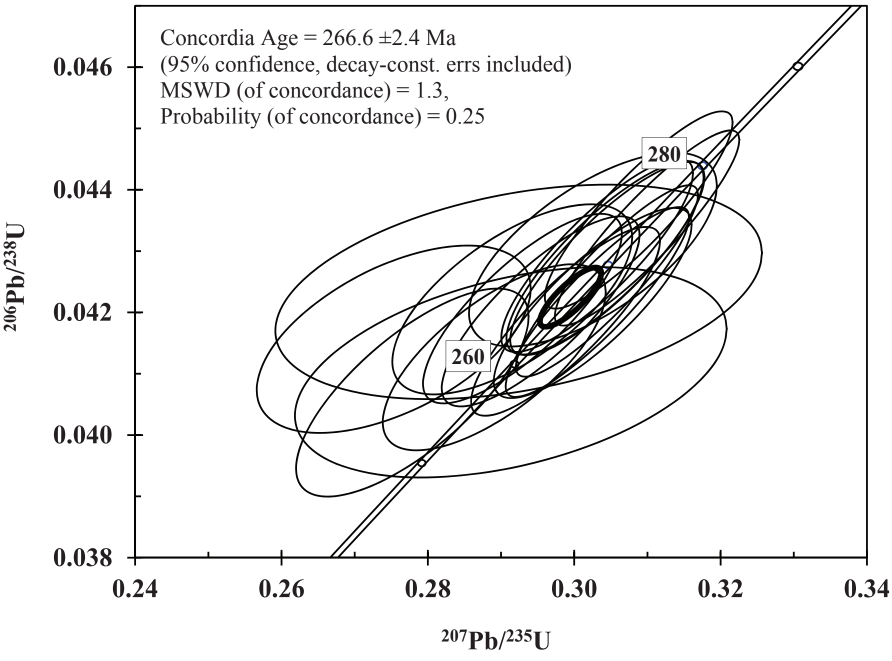

Fig. 5. SIMS zircon U–Pb concordia age plots for rhyolite sample TIS-1 (Tisovec-Rejkovo).

Finally, it should be noted that the portrayed rhyolites occur only in the Muráň nappe and its equivalent Vernár and Drienok nappe fragments thrust far to the north over the Veporic thick-skinned thrust sheet. However, the typical Silicic Unit, overlying the Meliata and Gemeric units, does not contain rhyolite volcanics. For that reason, the aforementioned nappes with the signatures of the rhyolite volcanism do not necessarily belong to the Silicic Unit (cf. Havrila 1997; Vojtko 2000; Mello et al. 2000b; Vojtko et al. 2015), but potentially to a specific group of higher nappes in the Inner Western Carpathians derived from the northern margin of the Neotethys Meliata(-Hallstatt) Basin, with lacking the HP Meliatic (Bôrka Nappe) fragments in the footwall.

The presence of Permian granitic and rhyolitic magmatism in the Western Carpathian area indicates their similarity to the West-Mediterranean magmatic province (Bonin 1990, 1993, 1998; Deroin & Bonin 2003) and possible palaeogeographic position in the "southern" branch of Variscan and post-Variscan Europe, together with recent Alpine and Dinaride terrains. Evidence of metamorphism related to Permo–Triassic lithosphere thinning is documented in the neighbouring Eastern Alps (Thöni 1999; Schuster et al. 2001). Correspondingly, Permian acid volcanites and associated ignimbrites are also widespread in the Southern Alps and are correlated with the Bolzano Volcanic Complex (Cortesogno et al. 1998; Klötzli et al. 2003; McCann et al. 2008; Cassinis et al. 2012). Moreover, Permian (Cisuralian) volcanism was also documented in the Mecsek and Apuseni Mts. (Balogh & Kovách 1973; Bleahu et al. 1981; Stan 1984; Seghedi et al. 2001; Nicolae et al. 2014) and in the Eastern and Southern Carpathians and Carpatho–Balkanides to Balkanides (Stan 1987; Kräutner 1997; Krstić & Karamata 1992; Cortesogno et al. 2004). The Permian volcanic activity in all these areas suggests an extensional tectonic regime traditionally interpreted as being related to Pangea supercontinent break-up.

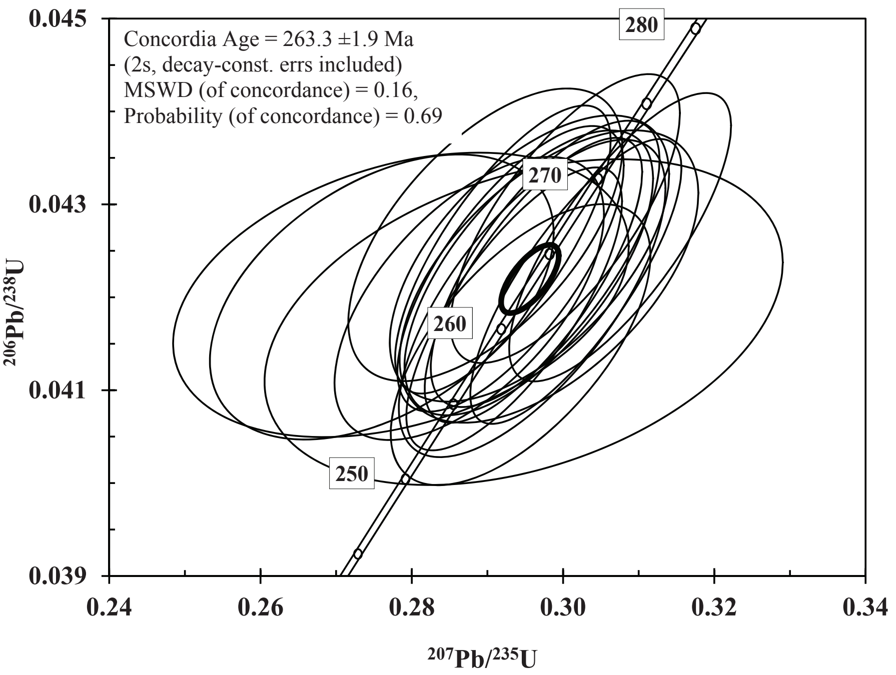

Fig. 6. SIMS zircon U-Pb concordia age plots for rhyolite sample TEL-1 (Telgárt).

The Muráň Nappe A-type rhyolites and their plutonic equivalents represented by A-type granites (Hrončok, Turčok, Upohlav, and Velence), and most likely also the rare metal S-type granites of the Gemeric Unit, originated under a transtensional or extensional regime (Petrík et al. 1995; Uher & Broska 1996). These plutonic-volcanic processes are related to post-orogenic (post-Variscan) large-scale crustal extension and contemporaneous overlap with the initial continental rifting stage of the new Alpine cycle (Putiš et al. 2000, 2016). These tectono–magmatic events are generally considered to have been related to the opening of the Neotethys Ocean (Ziegler & Stampfli 2001; Vai 2003; Muttoni et al. 2009; Cassinis et al. 2012) and the Pangea break-up (Isozaki 2009).

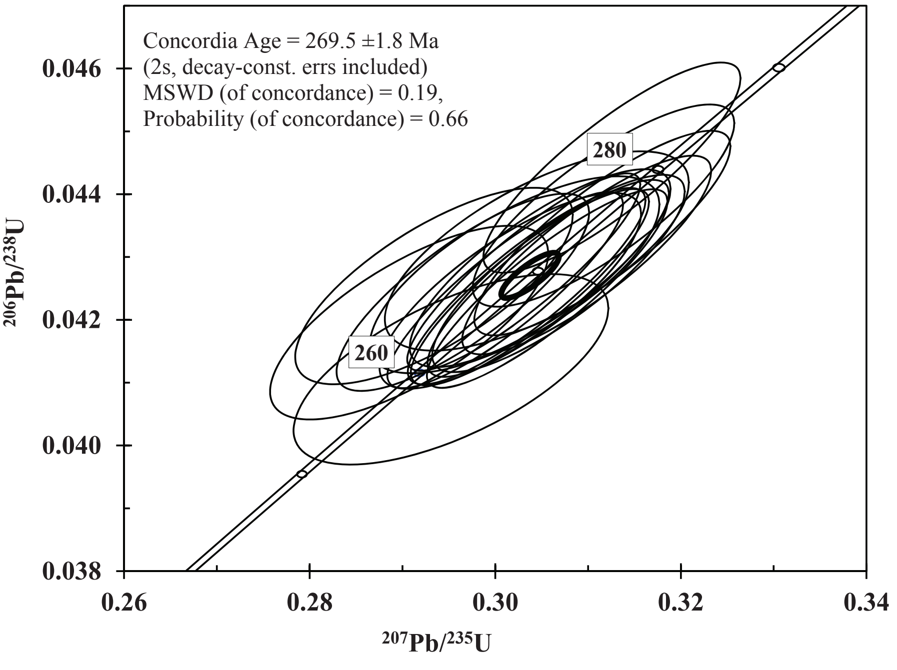

Fig. 7. SIMS zircon U-Pb concordia age plots for rhyolite sample SD-2 (Veľká Stožka-Dudlavka).

The change in geochemical trend from collision-related calc-alkaline to post-orogenic/anorogenic intracontinental alkaline magmatic suites is clearly documented across Variscan Europe (Bonin 1990, 1993, 1998) and also in other regions worldwide (e.g., Nikishin et al. 2002). New models of Permian magmatism and metamorphism suggest mantle plums triggering both the mantle and continental crust melting in the extensionally thinned underplated lithosphere (e.g., Nikishin et al. 2002; Sinigoi et al. 2011, 2016; Klötzli et al. 2014; Kunz et al. 2018).

Acknowledgments: We thank Xiaoxiao Ling, Jiao Li and Hongxia Ma for assistance in SIMS U–Pb zircon analysis and R.J. Marshall for polishing the English language. This work was supported by the Slovak Research and Development Agency (contracts APVV-14-0278, APVV-0315-12, APVV-15-0050), the China Ministry of Science and Technology (2016YFE0203000) and the VEGA Agency (Nos. 1/0257/13, 1/0279/15 and 1/0499/15). Finally, we thank Urs S. Klötzli, Ľubomír Hraško and Igor Petrík (Handling editor) for their constructive suggestions.

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