Late Permian volcanic dykes in the crystalline basement of the Považský Inovec Mts. (Western Carpathians): U–Th–Pb zircon SHRIMP and monazite chemical dating

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Abstract: This paper presents geochronological data for the volcanic dykes located in the northern Považský Inovec Mts. The dykes are up to 5 m thick and tens to hundreds of metres long. They comprise variously inclined and oriented lenses, composed of strongly altered grey-green alkali basalts. Their age was variously interpreted and discussed in the past. Dykes were emplaced into the Tatricum metamorphic rocks, mostly consisting of mica schists and gneisses of the Variscan (early Carboniferous) age. Two different methods, zircon SHRIMP and monazite chemical dating, were applied to determine the age of these dykes. U–Pb SHRIMP dating of magmatic zircons yielded the concordia age of 260.2±1.4 Ma. The Th–U–Pb monazite dating of the same dyke gave the CHIME age of 259±3Ma. Both ages confirm the magmatic crystallization at the boundary of the latest Middle Permian to the Late Permian. Dyke emplacement was coeval with development of the Late Paleozoic sedimentary basin known in the northern Považský Inovec Mts. and could be correlated with other pre-Mesozoic Tethyan regions especially in the Southern Alps.

Key words: Permian volcanism, dykes, zircon dating, monazite dating, Western Carpathians, Tatricum.

Introduction

The occurrence of Upper Paleozoic sequences overlying the Variscan crystalline basement is documented in various regions of Europe from the Bohemian Massif to the Pyrenees (e.g., Wilson et al. 2004). A similar situation is also known in the Western Carpathians, an Alpine thrust belt located in the eastern continuation of the Eastern Alps. The Western Carpathians represent north-vergent nappes that are traditionally divided into Outer and Inner zones. The Inner Western Carpathians consist of both thick- and thin-skinned Mesozoic nappes and in the north are rimmed by the Cenozoic belt consisting of the thin-skinned Outer Carpathians (Biely et al. 1996; Mišík 1997; Plašienka et al. 1997; Lexa et al. 2000; Hók et al. 2014). The northern part of the Inner Western Carpathians exposed in the so-called Tatra–Fatra Belt (or simply the "Core mountains") comprises Cenozoic horsts of the Tatricum crystalline basement and its autochthonous sedimentary cover overridden by the Mesozoic Fatricum and Hronicum cover nappes. The Tatricum, mostly consisting of Variscan crystalline basement, is known for locally preserved Upper Paleozoic continental volcano-sedimentary sequences found in several of the mountain ranges within the Tatra-Fatra Belt (Vozárová & Vozár 1988; Vozár 1997; Ivan et al. 2002; Vozár et al. 2010).

However, only the region of the northern part of the Považský Inovec Mountains is known for the presence of Carboniferous terrigenous clastics and Permian volcanoclastic and volcanic rocks (Putiš 1983; Štimmel et al. 1984; Olšavský 2008). Occurrences of volcanic and/or sub-volcanic dykes in the Western Carpathian Tatricum and Veporicum crystalline basement are known from the Malé Karpaty Mts., Strážovské vrchy Mts., Malá Fatra Mts., Nízke Tatry Mts. and Veporic Kohút zone. They form a heterogeneous rock group usually classified as the quartz porphyrites or lamprophyres (Hovorka 1967; Hovorka et al. 1982). Some of them are dated as Mesozoic (e.g., Spišiak & Balogh 2002) but the exact age of most of them is still unknown.

The studied dykes occur in the crystalline basement of the Selec (northern) Block of the Považský Inovec Mts. (Figs. 1, 2; Ivanička et al. 2007, 2011). The pre-Alpine crystalline basement of the Tatricum in the Selec Block is predominantly composed of monotonous Variscan chlorite-muscovite (mica) schists (dated as late Carboniferous, 307–310 Ma by Kráľ et al. 2013), and only locally accompanied by quartz-rich paragneisses and amphibolites (cf. Krist et al. 1992). The basement is covered by Upper Paleozoic to Jurassic and Upper Cretaceous complexes (Ivanička et al. 2007, 2011). The Upper Paleozoic volcano-sedimentary Kálnica Group is known for

the occurrences of the Permian basalts and rhyolites (Fig. 3; Vozárová & Vozár 1988; Rojkovič & Novotný 1993; Korikovsky et al. 1995; Vozár 1997; Putiš et al. 2008; Olšavský 2008). The volcanic dykes scattered along numerous localities in the crystalline basement of the northern Považský Inovec Mts. were reported for the first time by Kamenický (1956) and described in more detail by Polák (1956), who formerly

Fig. 1. Location of the Považský Inovec Mts. in the territory of Slovakia.

regarded them as products of Miocene volcanic activity. Dyke rocks were classified as quartz porphyrites (dacites) and referred to as post-Variscan, early Mesozoic in age (Hovorka 1960, 1967). In the following decades, several authors proposed their age being Miocene (Hovorka & Spišiak 1988, 1990; Plašienka & Marko 1993). The more recent research (Konečný 2005; Ivanička et al. 2011) brought more detailed information about the spatial distribution of the dykes and correlated them with quartz-bearing trachyandesites (TAQ), which are unlikely to occur within the Miocene Central Slovak Volcanic Field. This excluded a possibility of a Miocene age and suggested an older (Cretaceous?) age. Remaining controversy regarding the age of dykes and their relationship to the other late Paleozoic or possibly Mesozoic volcanites in the Považský Inovec Mts. (cf. Soták et al. 1993 and Putiš et al. 2008) as well other Permian volcanites in the Western Carpathians (Vozár 1997) were the main reasons for our attempt to date the dykes. These assumptions have been disproved first by authors of this paper (Uher in Pelech 2015, p. 59) who dated the dykes using monazite chemical dating as approx. 259 Ma old. The 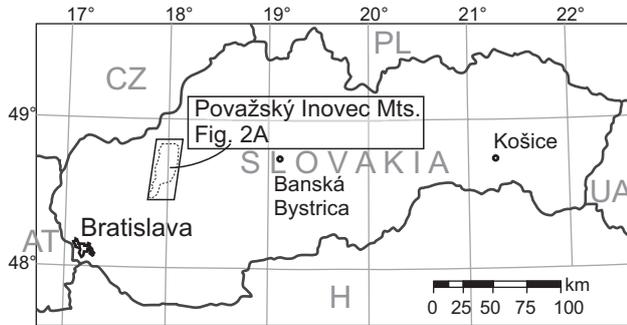same results were later obtained by the monazite CHIME method by other researchers (Putiš et al. 2016a) and U–Pb SIMS zircon dating (Putiš et al. 2016b).

The main aim of this paper is to present new geochronological data obtained from the dykes in the crystalline basement of the northern (Selec) block of the Považský Inovec Mts. by the means of U–Th–Pb zircon SHRIMP and monazite CHIME dating.

Regional geology

The studied dykes are intruded into the crystalline basement rocks, which are mostly composed of chlorite-muscovite schists and paragneisses (Fig. 4A and B), only locally with amphibolite lenses. Particularly the studied locality is remarkable for contact of dyke rocks with Permian terrigenous sediments of the Tatricum cover succession. The dykes are 0.5 to 3m (locally up to 5m) thick, lenticular bodies of grey-green to grey-brown, volcanic rocks with phenocrysts of quartz, feldspars and mafic minerals. Their length in map view varies between tens of metres and approx. 500 m. The orientation of
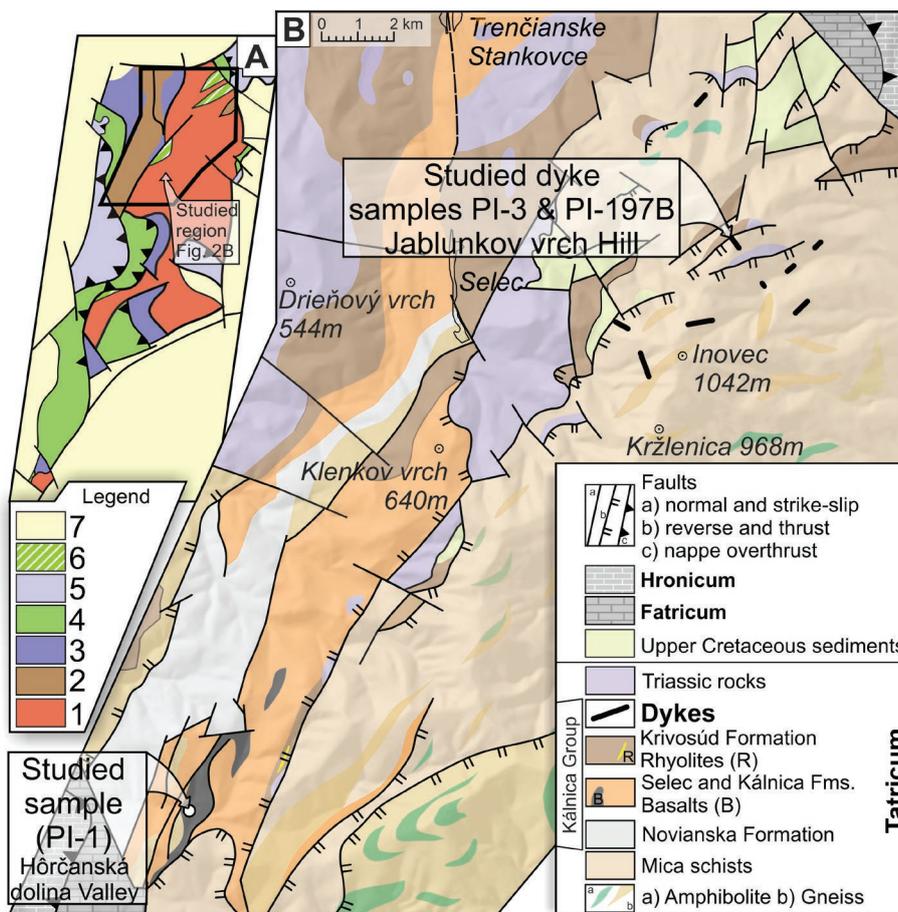

Fig. 2. A — Simplified tectonic map of the Považský Inovec Mts. with the studied area outlined. Legend: **1** – Crystalline basement; **2** – Upper Paleozoic rocks of Tatricum; **3** – Triassic rocks of Tatricum; **4** – Fatricum; **5** – Hronicum **6** – Upper Cretaceous rocks; **7** – Cenozoic sediments. **B** — Geological map of the studied area in the northern Považský Inovec Mts. (modified after Elečko et al. 2008). For the stratigraphy of particular Upper Paleozoic formations see Fig. 3.

dykes is variable, generally NW–SE to E–W. Intrusive contacts are generally sharp (Fig. 4A and B), often marked by chilled margins (Fig. 4C). Intrusion breccias along the dyke walls containing clasts of the Upper Permian sandstones (Krivosúd Formation) and underlying chlorite-muscovite (mica) schists were observed at the Jablunkov vrch Hill locality (Fig. 4D). The occurrence of Permian sediments at the dyke contact could be explained as a result of dyke propagation along the former normal or strike-slip faults. The dykes contain up to 5cm thick quartz and hematite veinlets. Some samples are lithologically similar to the Permian mafic volcanites occurring in the Hôrčanská dolina Valley in the western part of the Považský Inovec Mts. (sample PI-1, Fig. 2B). According to chemical composition, the dykes were characterized as andesite to basaltic andesite (Hovorka 1960, 1967), basaltic trachyandesite to trachyandesite (Konečný 2005) or rhyodacite (Putiš et al. 2016b).

Several volcanic dykes were investigated in the Selec Block of the Považský Inovec Mts. One rock sample PI-3 (approx. 10 kg weight) from the dyke at Jablunkov vrch Hill (elevation 794 m a.s.l.; GPS: N 48.7903°, E 18.0524°; Fig. 2), was collected for U–Pb dating. Another sample PI-197B (approx. 1 kg) from the same outcrop was used for the electron-microprobe U–Th–Pb dating of monazite. Additionally, the sample PI-1 representing the Permian volcanites (Selec Formation, Figs. 2 and 3) from the Hôrčanská dolina Valley (GPS: N 48.70738°, E 17.93374°) was used for petrographic and geochemical correlation.

Analytical methods

Zircon crystals from the PI-3 sample were separated using standard methods involving grinding, heavy liquid and magnetic separation procedures. The half-sectioned zircon crystals were mounted in the epoxy resin puck with chips of the reference zircons TEMORA-1 (Black et al. 2003) and 91500 (Wiedenbeck et al. 1995). These were imaged by optical microscopy, BSE and CL, in order to guide the positioning of analytical spots. *In situ* U–Pb analyses were performed on a SHRIMP-II at the Centre for Isotopic Research (CIR) at VSEGEI in St. Petersburg, Russia. Each analysis consisted of 5 scans through the 196–254 AMU mass range; analytical pit diameter was ~25 µm, with a primary O^- beam intensity of ca. 6 nA. The data have been reduced using the SQUID Excel macro of Ludwig (2000). Common lead was corrected using the measured $^{204}Pb/^{206}Pb$ ratio and the Stacey & Kramers (1975) model Pb evolution. Age calculations and plotting was done with ISOPLOT/EX (Ludwig 2003). The uncertainties given for individual analyses (ratios and ages) are at the one-sigma level, but the uncertainties in calculated concordia ages are reported at two-sigma levels.

The monazite age of the PI-197B sample were investigated by electron microprobe in polished thin sections using a Cameca SX100 electron microprobe (WDS mode) at the Dionýz Štúr State Geological Institute, Bratislava. Further
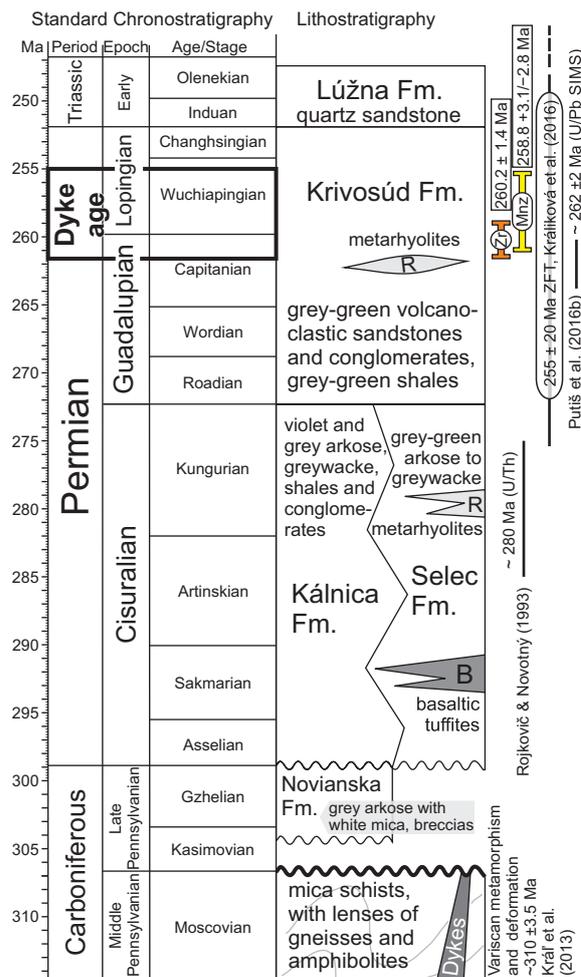

Fig. 3. Lithostratigraphy of the Upper Paleozoic Kálnica Group of the northern Považský Inovec Mts. with marked occurrences of volcanic rocks. R — Rhyolite; B — Basalt. The age of the investigated dyke as indicated by zircon (Zr) and monazite (Mnz) dating (this paper) and data by Putiš et al. (2016b).

details regarding the dating technique were published by Konečný et al. (2004) and Petrík & Konečný (2009). A sample current of 180 nA, counting times of 300 s for Pb, 80 s for U and 35 s for Th and the accelerating voltage of 15 kV were used. The beam diameter was typically 3–5 µm. For monazite dating, we used $ThM\alpha_1$, $UM\beta_1$, $PbM\alpha_1$, $YL\alpha$ X-ray lines. The interferences between $PbM\alpha_1$–$YL\gamma_1$ and $UM\alpha_1$–$ThM\beta_1$ were corrected by empirically measured correction coefficients; interferences between REE X-ray lines were also corrected, but these have no impact on the monazite dating (Konečný et al. 2004). The statistical approach of Montel et al. (1996) was applied for the final age determination and the DAMON program was used for the age recalculations, histograms and isochron plots (Konečný et al. 2004). Moreover, the U/Pb vs. Th/Pb isochron method for monazite dating (CHIME; Cocherie & Albarède 2001) was used.

The PI-3 and PI-1 samples were also analysed for major and trace elements including REEs at the AcmeLabs Ltd. Vancouver, Canada. Following a lithium metaborate/tetraborate
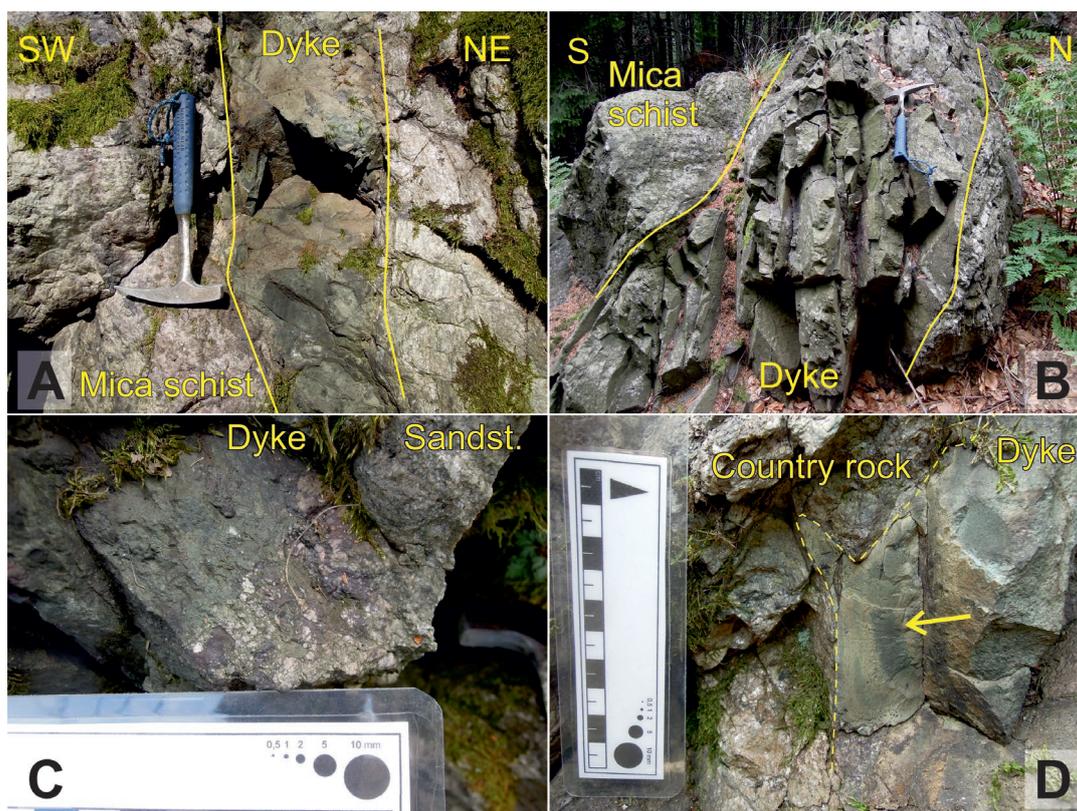
Fig. 4. A — Thinner dyke at the investigated locality Jablunkov vrch Hill. **B** — Thicker dyke at the northern slope of the Inovec Hill. **C** — Brecciated contact of dyke and Permian sandstone at the investigated locality Jablunkov vrch Hill. **D** — Chilled margin of dyke on the contact with the country rocks, marked by an arrow.

fusion and dilute nitric digestion, two instrumentation techniques, inductively coupled plasma emission spectrometry (ICP-ES) and inductively coupled plasma mass spectrometry (ICP-MS), were used for whole-rock geochemical analyses. Loss on ignition (LOI) represents weight difference determined separately after ignition at 1000 °C.

Results

Petrography

The dykes are composed of microporphyritic, grey-green altered volcanic rocks (Fig. 4A–D). Textural evidence, especially the intersertal texture (Fig. 5A–B) points to a shallow level of emplacement. The largest part of the PI-3 rock sample consists of fine-grained aggregates of chlorite, Fe-oxide/hydroxide minerals, calcite, albite, quartz and rare muscovite. Fine needles of rutile and crystals of apatite are frequent. Laths and needles of plagioclases are replaced by aggregates of albite and muscovite. Mafic phenocrysts are totally replaced by chlorite, Fe-oxides/hydroxide and quartz. Quartz crystals, occurring in some thin-sections, show distinct magmatic corrosion (Fig. 5C–F). Individual quartz crystals have embayed margins and are wrapped by fine aggregates of chlorite and

opaque minerals (Fig. 5C–F). The majority of them are represented by volcanogenic β-quartz, but isolated polycrystalline grains are also present (Fig. 5D). These partially dissolved β-quartz grains represent relics of phenocrysts that were incorporated into the ascending basalt dykes.

Mafic volcanites (sample PI-1), formerly mostly tuffs and lava flows (Olšavský 2008), from the Selec Formation in the Hôrčanská dolina Valley are represented by the dark green unevenly foliated fine-grained rocks, where foliation obliterated the initial rock texture. Microlites of plagioclases are totally replaced by fine chlorite-sericite mixed layers and albite. The interstices between feldspar microlites are occupied by micro-crystalline aggregates of chlorite and Fe-Ti oxides, associated with smaller amount of sericite, albite and quartz. Mafic phenocrysts are pseudomorphically replaced by Fe-Mg chlorite, Fe-Ti oxides, and scarce calcite and quartz. Magnetite and ilmenite were detected as primary magmatic phase, either as inclusions in mafic phenocrysts or as individual grains in the groundmass. Ilmenite was totally or partially decomposed in rutile and hematite. According to the preserved shape and system of cleavage, both rimmed or filled by hematite, the observed phenocrysts correspond to amphibole (Fig. 6). Rare square chlorite pseudomorphoses, occasionally with inclusion of Cr-spinel, could have originated after pyroxenes.
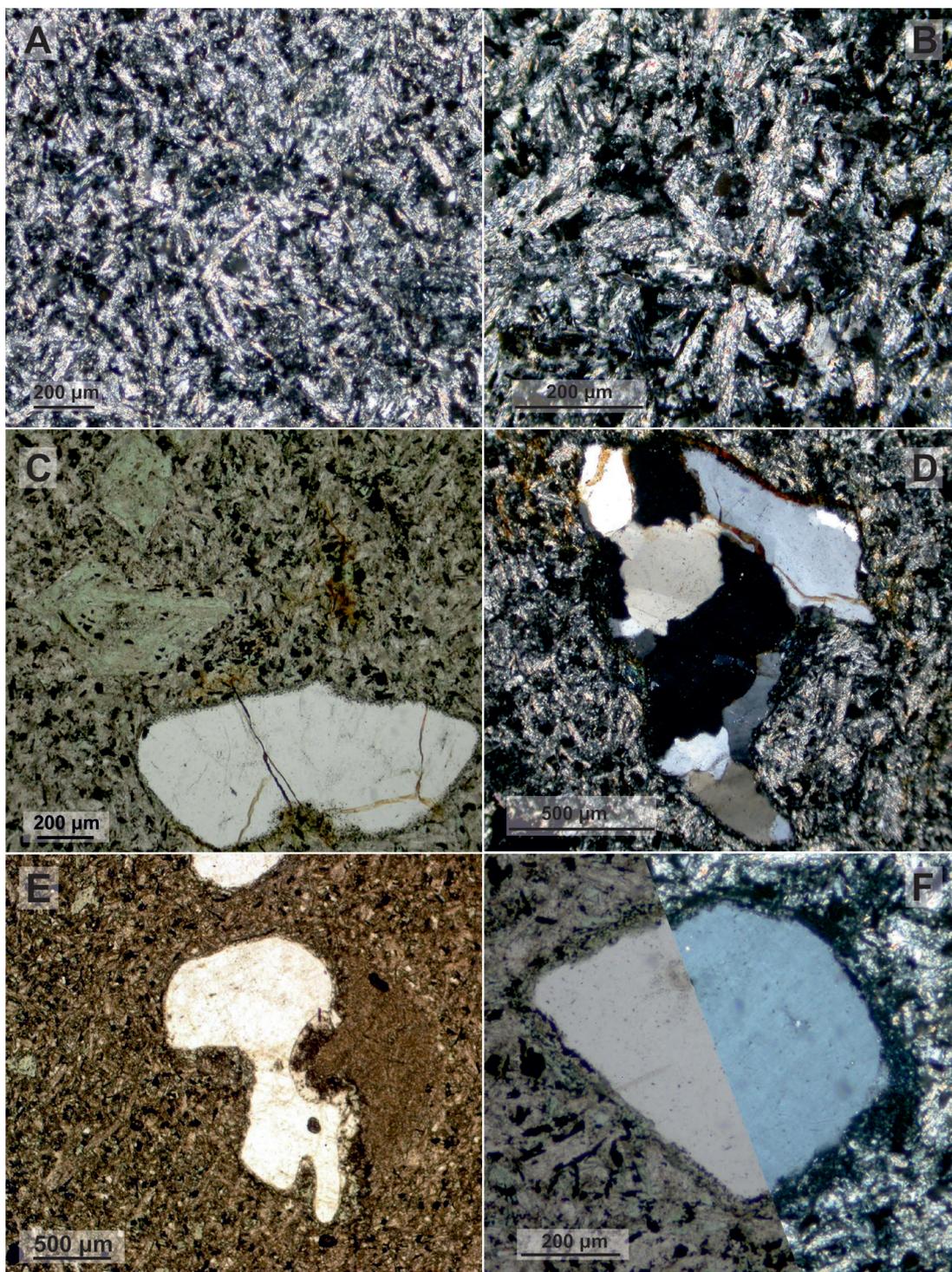
Fig. 5. Photomicrographs of sample PI-3. **A, B** — Intersertal texture of basaltic dyke, XPL. **C** — Chlorite pseudomorphs after mafic phenocrysts of ß-quartz, PPL. **D** — Xenolith of polycrystalline quartz grain with indication of magmatic dissolution, XPL. **E** — Magmatically corroded quartz crystal, PPL. **F** — Corroded ß-quartz with felty texture around rim, PPL (left) and XPL (right).

Geochemistry

Major- and trace-element compositions, including rare earth elements of sample PI-3 (dated dyke) and the mafic volcanite of the Selec Formation (sample PI-1) are given in Table 1.

The high value loss on ignition (LOI) suggests high degrees of post-magmatic alteration (4.6 wt. % for dyke PI-3 and 8.6 wt. % for mafic avolcanite PI-1 (Table 1). In order to make a more reliable classification of the studied rocks, we used a classification, based on ratios of Zr/TiO_2 vs. Nb/Y

(Winchester & Floyd 1977; Pearce 1996; Fig. 7). These immobile elements classify the studied dyke as an alkali basalt (sample PI-3) and volcanite to sub-alkaline basalt (sample PI-1).

On the whole, both display chondrite-normalized rare earth element (REE) patterns characterized by a slight enrichment of light REEs (La_N/Yb_N=4.56 and 5.36, respectively) and weak negative Eu-anomalies (Eu/Eu*=0.80 and 0.91, respectively), with no significant heavy REE fractionation (Fig. 5A; Gd/Yb_N=1.55 and 1.58, respectively).

In the primitive mantle normalized multi-element diagram (Fig. 5B) these rocks show a higher enrichment in Cs, Rb, Th, U, Nb, K, Ta, LREE and Pb compared to Ba, Sr, P, Zr, Hf, Ti and middle and heavy REE with distinct peaks for Cs, U, Th and Pb and troughs for Ba, Nb, La-Ce, Sr and Ti. The studied dyke rock (sample PI-3) has a low 0.51 Nb_N/Ta_N ratio, similar to 0.71 from the Selec Formation volcanite (sample PI-1). These values are close to the 0.71 crustal ratio (Rudnick & Fountain 1995), implying that crustal material has been assimilated. Equally, the crustal involvement is indicated by Nb/U ratio (7.1 and 16, respectively) that confirms an assimilation of crustal material (9.7 value for continental crust and 34 for mantle source according to Rudnick & Fountain 1995).

The primitive mantle normalized 0.18 (PI-3) and 0.67 (PI-1) Ce_N/Pb_N ratios are consistent with the continental crust (<1; Rudnick & Fountain 1995).

Zircon SHRIMP dating

Zircons mostly occur as short-prismatic crystals with complicated oscillatory growth zoning. Zircon crystals ca. 200–400 μm long and 100–200 μm wide were used for dating.

Intricate compositional growth zoning was identified within the dated magmatic zircon grains by CL and BSE images (Fig. 8A). Zircon crystals have a rather uniform internal texture, characterized by a narrow fine oscillatory growth zoning. In some zircon crystals, the regular growth zoning is interrupted by textural discontinuities along which the original zoning is resorbed or truncated and succeeded by new-growth of zoned zircon rims (Fig. 8A, spots PI3-4, 6, 7). A very old xenocrystic core ($^{207}Pb/^{206}Pb$ 2101±17 Ma) was identified, mantled by the newly grown magmatic zircon (Fig. 8A, spot PI3-5).

The sample PI-3 yielded a cluster of $^{206}Pb/^{238}U$ ages, ranging between 258 Ma and 263 Ma, for nine magmatic zircon
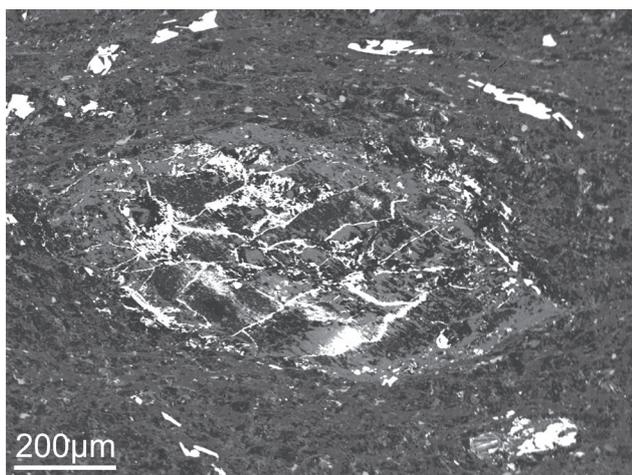

Fig. 6. BSE image of pseudomorph after mafic phenocryst of amphibole, sample PI-1.
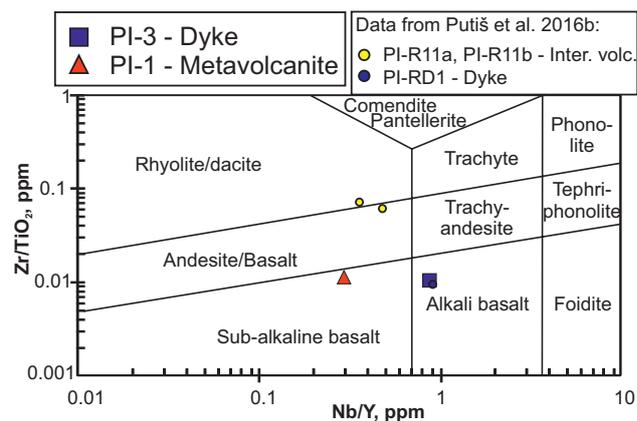

Fig. 7. Zr/TiO_2 vs. Nb/Y diagram (Pearce 1996) showing classification of dyke (PI-3) and volcanites (PI-1) from Považský Inovec Mts. based on immobile elements. Circles represent data published by Putiš et al. (2016b).

Table 1: Major (wt. %) and trace-element (ppm) whole rock analyses of the Považský Inovec Mts. dated dyke sample PI-3 and volcanite PI-1 sample. Sum of iron (Fe_{tot}) was measured as Fe_2O_3.

| Sample | major oxide (wt. %) | | | | | | | | | | | % | | |
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3	LOI	sum	C_{tot}
PI-3	55.06	16.86	9.14	6.19	0.72	3.40	1.60	1.70	0.42	0.07	0.03	4.60	99.78	0.06
PI-1	48.5	14.3	9.61	4.18	8.09	3.36	1.13	1.85	0.34	0.16	0.02	8.60	99.82	1.76

| | trace element (ppm) | | | | | | | | | | | | | |
	Ni	Ba	Co	Cs	Ga	Hf	Nb	Rb	Sr	Ta	Th	U	V	Zr	Y
PI-3	111.0	118.0	34.8	2.5	18.5	4.1	27.7	93.0	69.8	3.1	2.9	3.9	142.0	174.6	30.0
PI-1	25	106	28.5	3.9	18.3	5.1	12.9	51	147.9	0.9	4.0	0.8	207	194.8	42.8
	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Pb
PI-3	22.10	43.30	5.6	22.60	5.19	1.60	5.48	0.93	5.35	1.8	2.96	0.45	2.80	0.41	9.80
PI-1	26	55.6	7.1	29.6	6.73	1.86	7.43	1.22	7.3	1.46	4.8	0.6	3.87	0.6	3.3

crystals (Table 2; Figs. 8A and 9). The ^{232}Th/^{238}U ratios are mostly between 0.40 and 1.34, typical for zircons of a magmatic origin. U and Th contents are relatively low, 107–463 ppm and 69–427 ppm, respectively. The concordia age, calculated from the clusters along the concordia curve, is 260.2 ±1.4 Ma (95 % confidence, decay-constant errors included; MSWD=0.63, probability=0.43).

Monazite electron-microprobe dating

Monazite is a very rare accessory mineral in the studied dyke rocks. It forms euhedral to subhedral crystals, 20 to 50 μm across, hosted by in K-feldspar and quartz phenocrysts (Fig. 8B and C). Monazite associates with zircon, apatite and rarely xenotime-(Y). Monazite crystals show regular oscillatory zoning in BSE images. Locally, tiny inclusions of ThSiO$_4$ phase (thorite or huttonite) occur in monazite. Electron-microprobe dating of monazite using the calculation method of Montel et al. (1996) shows a weighted average age of 255 ± 4 Ma (26 point analyses, MSWD=1.58). The histogram of individual ages (Fig. 10A) shows an asymmetrical distribution slightly skewed to younger ages with the maximum age intervals between 250–260 and 260–270 Ma. Deconvolution of this histogram (Fig. 10B) gives 258.6 ± 4 Ma for the main fraction (94 %, Isoplot 4.15) Standard Suzuki-type isochron (Fig. 10 C) provides a good fit, but with the positive intercept
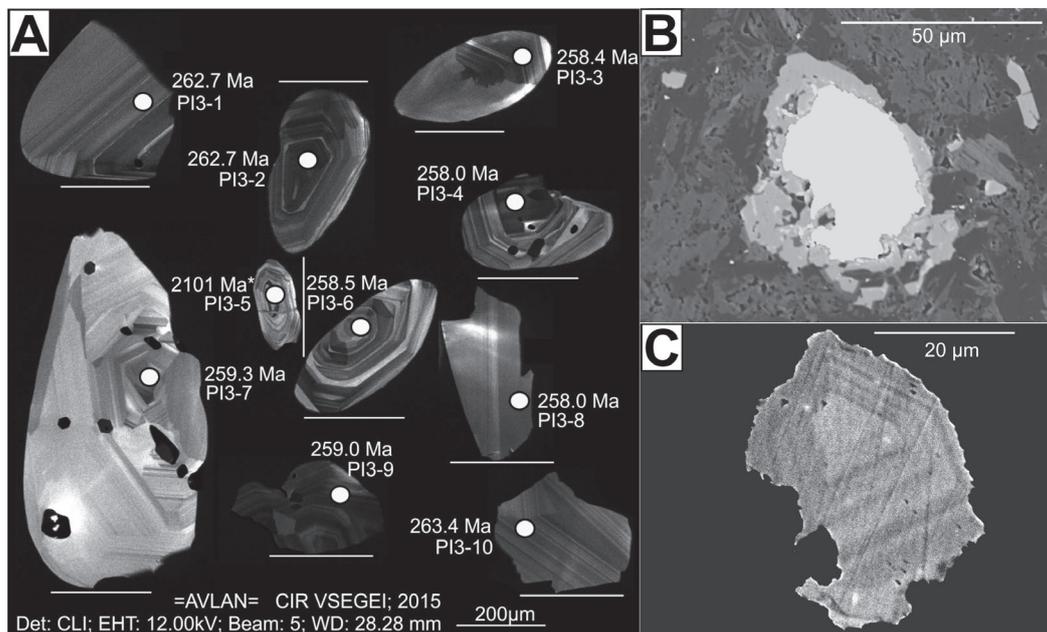

Fig. 8. A — Selected cathodoluminiscence magmatic zircon images from the Považský Inovec Mts. Permian dyke (sample PI-3) with indication of the age data (in Ma) based on ^{206}Pb/^{238}U ratios. Zircon indicated by asterisk corresponds to the ^{207}Pb/^{206}Pb age value of the Palaeoproterozoic xenocrystic grain. **B-C**: BSE images of monazite-(Ce) from the studied volcanic rock, sample PI-197B. **B** — Crystal of monazite (white), partly replaced by fluorapatite along the rims (grey) in chlorite-rich groundmass (dark grey). **C** — Regular oscillatory zoning of the same monazite crystal.

Table 2: SHRIMP zircon age data from the sample PI-3. Errors are 1-sigma; Pbc and Pb* indicate the common and radiogenic portions, respectively. Error in Standard calibration was 0.36 % (not included in above errors but required when comparing data from different mounts). (1) Common Pb corrected using measured ^{204}Pb.

| Spot	^{206}Pb$_c$	U	Th	^{232}Th/^{238}U	^{206}Pb*	(1) ^{206}Pb/^{238}U	±	(1) ^{207}Pb/^{206}Pb	±	Discor-dant	(1) ^{206}Pb/^{238}U	±	(1) ^{207}Pb*/^{206}Pb*	±	(1) ^{207}Pb*/^{235}U	±	(1) ^{206}Pb*/^{238}U	±	err corr
	%	ppm	ppm		ppm	Age		Age		%		%		%		%		%	
PI3-1	0.16	178	100	0.58	6.36	262.7	2.1	262	79	0	24.4	0.83	0.0515	3.4	0.295	3.5	0.0416	0.83	.235
PI3-2	0.20	420	242	0.59	15.10	262.7	1.4	179	53	−32	24.4	0.56	0.0497	2.3	0.2848	2.3	0.0416	0.56	.240
PI3-3	0.21	330	427	1.34	11.60	258.4	1.8	233	64	−10	24.45	0.72	0.0508	2.8	0.2866	2.9	0.0409	0.72	.251
PI3-4	0.30	463	279	0.62	16.30	258.0	1.6	236	62	−8	24.48	0.62	0.0509	2.7	0.2866	2.8	0.0408	0.62	.225
PI3-5	0.20	107	51	0.50	32.60	1958	12	2101	17	7	2.816	0.73	0.1302	10	6.40	1.2	0.355	0.73	.592
PI3-6	0.60	134	69	0.53	4.73	258.5	2.9	117	140	−55	24.44	1.10	0.0484	5.7	0.2730	5.9	0.0409	1.10	.193
PI3-7	0.18	134	62	0.48	4.74	259.3	2.8	337	88	30	24.36	1.10	0.0532	3.9	0.3010	4.0	0.0410	1.10	.273
PI3-8	0.86	136	91	0.69	4.83	258.0	2.8	110	140	−57	24.49	1.10	0.0482	6.0	0.2710	6.1	0.0408	1.10	.183
PI3-9	0.30	268	114	0.44	9.46	259.0	2.0	289	83	11	24.40	0.80	0.0521	3.6	0.2940	3.7	0.0409	0.80	.215
PI3-10	0.00	189	74	0.40	6.79	263.4	2.4	327	62	24	23.97	0.92	0.0530	2.7	0.3046	2.9	0.0417	0.92	.320
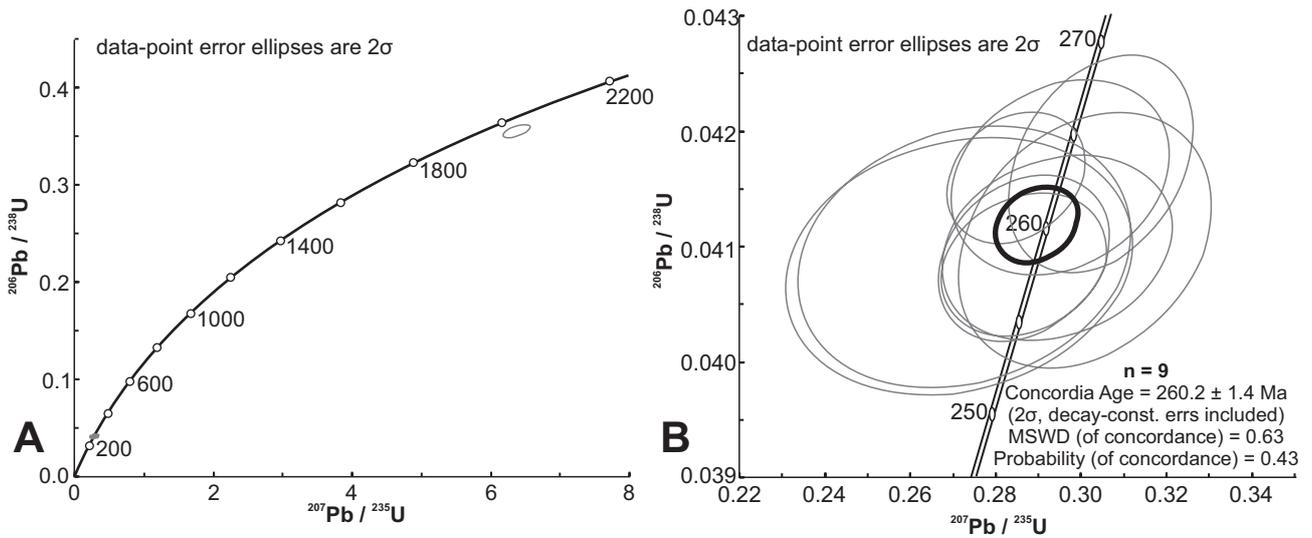
Fig. 9. U/Pb concordia plot showing the magmatic zircon ages from the sample PI-3 dyke. **A** — all data; **B** — detail on concordia age data.
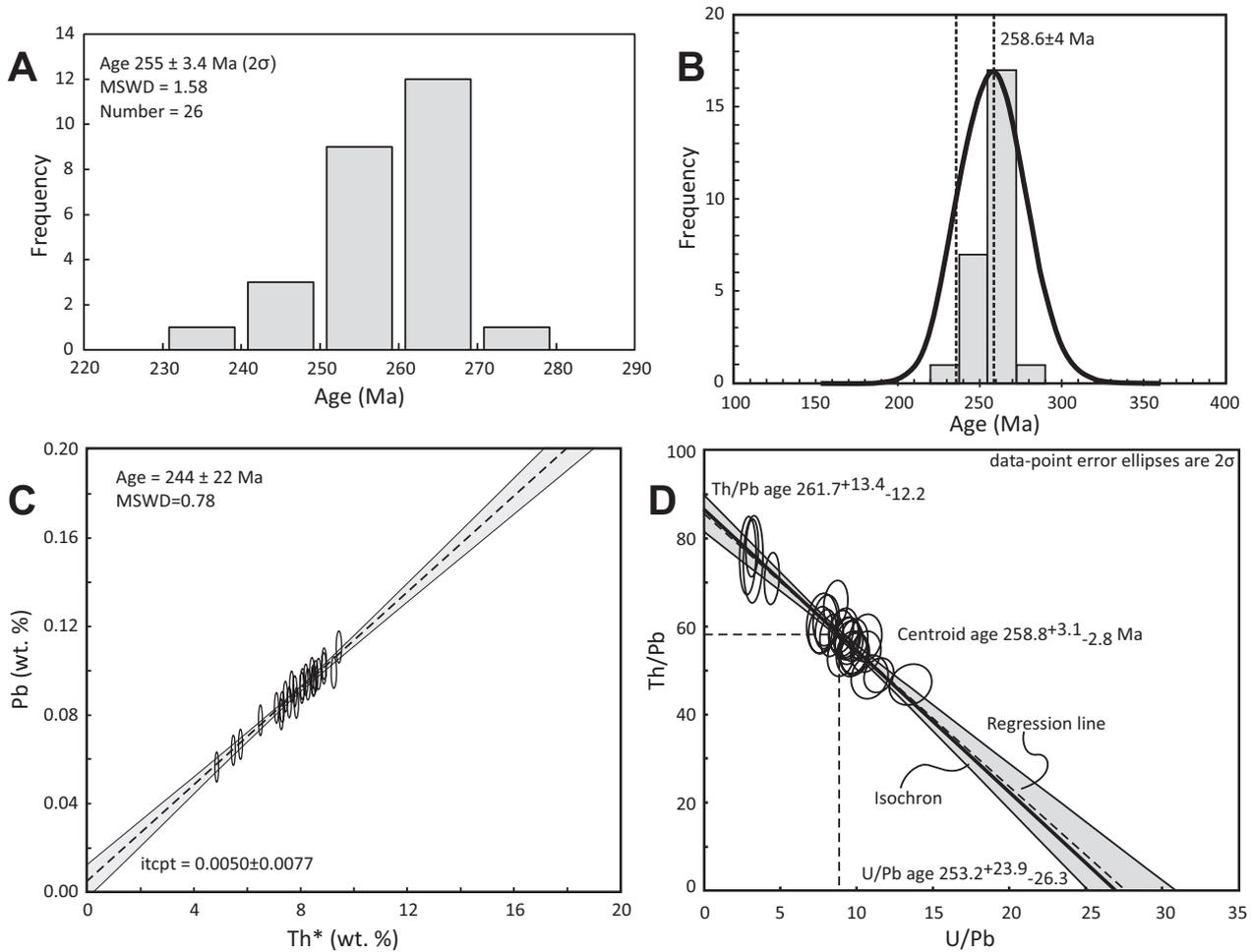

Fig. 10. A — Histogram of apparent EMPA monazite-(Ce) ages (n=26) from sample PI-197B. **B** — Deconvolution (by Isoplot 4.15) of the histogram provides 94 % fraction of older age 258.6±4 Ma, the younger age is neglected. **C** — Standard Suzuki-type CHIME weighed isochron shows a positive intercept of 0.005 % Pb, which indicates an apparently younger age 244±22 Ma. The shaded field is the 2SD error envelope of the regression line. **D** — Th/Pb vs. U/Pb CHIME isochron (Cocherie & Albarede 2001, solid line) gives an almost concordant age of 259±3 Ma. The shaded field is the 2SD error envelope of the regression line.

0.0050±0.0077 indicating an apparently younger age which is confirmed by the weighed isochron age of 244±22 Ma (Fig. 10B). Therefore, we prefer the U/Pb vs. Th/Pb isochron calculation method (Cocherie & Albarède 2001), suitable for monazite with variable U/Th ratios. In Fig. 10D, the spread of data defines a concordant isochron giving the age 259±3 Ma and low MSWD=0.97 (Table 3). One measurement point with an extremely high U content (3.8 wt. %) was excluded. Contrary to the standard isochron, this age is slightly higher than the weighted average and identical with the deconvolution age (Fig. 10B), and it is considered the best estimate.

Discussion

The age of volcanic dykes in the crystalline basement of the northern (Selec) block of the Považský Inovec Mts. was a matter of debate for a long time. Konečný (2005) compared the studied rocks with Miocene volcanites from the Central Slovak Volcanic Field. On the basis of petrographic and geochemical criteria, he discussed several contradictory features that excluded a Neogene age. The dykes from the Považský Inovec Mts. compared with similar Neogene rocks of the Central Slovak Volcanic Field, contain higher FeO tot (10.55−7.17 wt. % vs 5.69 wt. %), MgO (8.93−4.02 wt. % vs 2.39 wt. %), TiO (1.96−1.12 wt. % vs. 0.61) and P_2O_5 (0.77−0.37 wt. % vs. 0.28) (data from Konečný 2005 and present paper). A primary association of mafic minerals (pyroxenes?, amphiboles), represented by the chlorite+quartz +Fe mineral pseudomorphoses (very rare with inclusion of Cr-spinel; Konečný l.c.) was not found within the Neogene dykes. Correspondingly, the hydrothermal alterations of the compared rocks are different, chlorite+sericite+quartz±calcite in the Permian dykes versus biotite+K-feldspars+pyrite +sericite+argillite in the dykes of Neogene age. The zircon U/Pb concordia age (260.2±1.4 Ma; Fig. 9) as well as monazite chemical dating (259±3 Ma; Fig. 10) show latest a Middle Permian (Capitanian) to Late Permian (Wuchiapingian, according to Cohen et al. 2013 and ICS Chronostratigraphic chart 2017/2) crystallization age of the dyke in the Považský Inovec Mts. The 2101±17 Ma $^{207}Pb/^{206}Pb$ age value (Table 2) indicates a presence of xenocrystic Palaeoproterozoic zircon. It does not represent a primary constituent of the magma since it was assimilated from country rocks. The obtained late Permian age is in accordance with ages obtained by U/Pb SIMS dating of

dykes and volcanites (Putiš et al. 2016b). It is also supported by the zircon fission track analysis of the crystalline basement rocks which show late Permian post-Variscan cooling with no signs of Alpine metamorphic overprint (Králiková et al. 2016).

According to the present results, the studied dykes are the only dated representatives of late Paleozoic shallow volcanic intrusions in the Tatricum found *in situ* until now. The petrological and geochemical features differentiate the dykes from similar dykes occurring in the Tatricum crystalline basement which are mostly represented by lamprophyres (Hovorka 1967; Spišiak & Balogh 2002).

The volcanism of the Upper Paleozoic Kálnica Group is believed to be bimodal and concentrated mainly in the Lower Permian Selec Formation. The prevailing volcanic rocks are represented by the basaltic tuffs and lava flows exposed mainly in the Hôrčanská dolina and Hrádocká dolina Valleys. These bodies are represented by volcanite sample PI-1 which was correlated with the dated dyke (PI-3). Mafic volcanites from the Kálnica Group are represented by subalkaline within-plate type basalts (Korikovsky et al. 1995; Putiš et al. 2006). Less common rhyolites are known from the surface only in the Hôrčanská dolina Valley where they represent part of the Upper Permian Krivosúd Formation (Ivanička et al. 2007; Olšavský 2008). Other rhyolites were recorded in the boreholes around the Klenkov vrch Hill and in the former exploration galleries north of Selec village in the Lower Permian Selec Formation (Štimmel et al. 1984; Olšavský 2008). Unfortunately, these occurrences are not accessible at present. Rhyolites and their pyroclastic rocks of the Krivosúd Formation from the Hôrčanská dolina Valley were recently dated by Putiš et al. (2016b). They gained U–Pb zircon age data in the range of 266.5±1.9 Ma and 262.4±2.1 Ma (Putiš et al. l. c.) and confirmed the Upper Permian age of the Krivosúd Formation proposed earlier (e.g., Štimmel et al. 1985; Olšavský 2008). Putiš et al. (2016b) projected the studied volcanites in the rhyolite field (in the sense of Le Bas et al. 1986 and De La Roche et al. 1980 classifications). We classified these rocks as rhyodacite/dacite and basalt/andesite based on Zr/TiO_2 vs Nb/Y ratios (Pearce 1996; Fig. 7), for the high mobility of alkalis. They are enriched in LREE and more fractionated with the higher Eu anomalies in comparison with basic rocks (Fig. 11A). Correspondingly, in the multi-element diagram they are enriched in Th, La, Ce but depleted in Cs, Rb, U, Nb, K, Pb, Sr and Ti (Fig. 11) compared with basic volcanic rocks (sample PI-1; Fig. 11B).

The volcanic dyke that was formerly classified by Putiš et al. (2016b) as meta-rhyodacite (sample PI-RD 1) is geochemically identical with our sample PI-3. Based on Zr/TiO_2 vs Nb/Y ratios (Pearce 1996) it corresponds to alkali basalts (Fig. 7). Equally, distributions of REE and trace elements show an absolutely equal tendency (Fig. 11A and B).

The obtained ages correspond to the Guadalupian–Lopingian volcanic phase, possibly as a result of an extensional tectonic regime, also documented in other Western Carpathian units, as in the Northern Veporic (Vozárová et al. 2016), Hronic
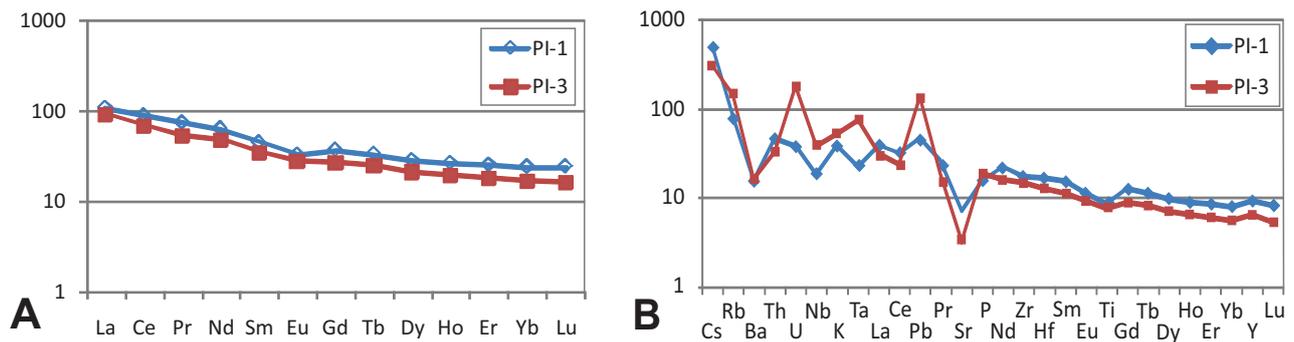
Table 3: EMPA (U+Th)–Pb ages of monazite in the studied sample PI-197B from the Považský Inovec Mts. Centroid age is the age corresponding to the crossing of functions y=f(x) and x=f(y), where x=U/Pb and y=Th/Pb.

	Age Ma	2σ Ma	−2σ Ma
Centroid age	258.8	3.1	2.8
Th/U age	261.7	13.4	12.2
U/Pb age	253.2	23.9	26.3

Fig. 11. A — Chondrite-normalized REE patterns of the Považský Inovec Mts. Permian volcanic rock (PI-1) and dyke (PI-3). Normalizing values are after McDonough & Sun (1995). **B** — Multi-elements variation diagram of the Považský Inovec Mts. Permian mafic volcanic rock (PI-1) and dyke (PI-3). Normalizing values are after Sun & McDonough (1989).

(andesite–basalts of the 2nd eruption phase; Vozár 1997; Dostal et al. 2003; Vozár et al. 2015) dated after the Illawara Reversal Magnetic Horizon (Vozárová & Túnyi 2003), as well as from the Bôrka Nappe (Vozárová et al. 2012) and Silicicum (Demko & Hraško 2013).

As was noted by Ivan et al. (2002), the Permian volcanism in the Western Carpathian region is analogous to the Ligurian and Southern Alps and Sardinia (Cortesongo et al. 1998; Dallagiovanna et al. 2009). However, Middle to Early Permian volcanites are not known in adjacent regions containing post-Variscan sedimentary basins, such as the Bohemian Massif (Ulrych et al. 2006), Eastern Alps (Krainer et al. 2005) or Eastern Carpathians (Seghedi et al. 2001).

The Považský Inovec Mts. dykes are located east of the main occurrence of the Upper Paleozoic rocks (Fig. 2). Older investigations described the dykes as NNE–SSW to NE–SW trending and unaffected by the Alpine metamorphic overprint (Maheľ 1986; Ivanička et al. 2011). This variation suggests the possibility of different ages of variously oriented dykes (cf. Shrivastava 2011) and will require further verification.

The oldest Upper Paleozoic sediments in the Tatricum are represented by 100–250 m thick grey-green and black white-mica bearing sandstones, black shales and conglomerates of the Novianska Formation found only in the Považský Inovec Mts. (Figs. 2B and 3). Its stratigraphic age was determined in the Novianska dolina Valley as Carboniferous based on the occurrence of microflora (Čorná & Kamenický 1976). The Novianska Fm. overlies Variscan chlorite-muscovite schists, dated by $^{40}Ar/^{39}Ar$ method around 310–302 Ma old, and so to the latest Carboniferous (Late Pennsylvanian, Kráľ et al. 2013). Additionally, the occurrence of clasts of the underlying basement rocks found in the conglomerates of the Novianska Fm. (Kamenický 1956; Putiš 1983; Olšavský 2008) indicates that their sedimentation took place directly after the meta-morphic event in the latest Carboniferous. This was a period of rifting characterized by formation of restricted, probably elongated, extensional basins as a result of post-collisional collapse of the Variscan orogen. The later subsidence, charac-terized by the deposition of continental sediments of the Selec

Fm. above the older Novianska Fm. or directly on the Variscan crystalline basement rocks was accompanied by bimodal subalkaline to alkaline volcanism in early Permian times (Broska et al. 1993). The rhyolitic volcanism of this stage in the Považský Inovec Mts. was accompanied by U-mine-ralization, the syngenetic stage of which was dated to approx. 280–270 Ma (Rojkovič & Novotný 1993; Rojkovič 1997). The latest Permian was characterized by subsidence affecting larger parts of the Tatric–Veporic region. In the Tatricum terrestrial clastics, usually with volcanic admixture are known (the Devín, Krivosúd, Stráňany, Vážna and Meďodoly Formations, cf. Vozárová & Vozár 1988; Vozárová 1996). Our data indicate that the dykes were emplaced during this period (~260 Ma), most probably along faults. The studied dykes (together with rhyolites dated by Putiš et al. 2016b) are there-fore the first representatives of the Upper Paleozoic volcanites in the Tatricum to be dated by the means of modern geochro-nological methods. The answer to the question whether they served as magma feeders is not entirely clear. At present, there is no documented occurrence of coeval (and comagmatic) extrusive mafic rocks in the studied region. The originally assumed uniform age of the dykes and basaltic volcanites from the Selec Formation is also unlikely. The volcanogenic admixture described in the late Permian Krivosúd Formation is only felsic in character (Putiš 1983; Štimmel et al. 1984; Olšavský 2008).

ß-quartz phenocrysts occurrence in the dyke rock in the sample PI-3 (Fig. 5C and E) remains unusual and causes problems for the petrographic classification of rocks (cf. Putiš et al. 2016b). Conditions for incorporation of quartz crystals can occur, when the basaltic melts enter the residual rhyolite magma chamber. The evidence of the interaction of mafic magma with crustal material and quartz dissolution were experimentally documented by Watson (1982) and Donaldson (1985). However, the occurrence of quartz in rocks of basaltic character could also be interpreted as a result of contamination by country rocks (cf. Hovorka 1967) as it is shown by the frequent presence of polycrystalline quartz (Fig. 5D).

Conclusions

A volcanic dyke of alkali basalt composition (Figs. 4, 5 and 7) from the crystalline basement of the northern Považský Inovec Mts. (Western Slovakia) was dated by the U–Pb zircon SHRIMP and monazite U–Th–Pb EMPA methods. Both U–Pb zircon SHRIMP (260.2±1.4 Ma) and monazite U–Th–Pb EMPA dating (259±3 Ma) provided (within error) latest Middle Permian to Late Permian (Capitanian/Wuchiapingian) ages for the studied rocks. The dykes, together with volcanites dated by Putiš et al. (2016b) in the northern Považský Inovec Mts., represent rare post-Variscan late Paleozoic volcanites, the only ones known from the Tatricum up to now. The obtained ages correspond to the Guadalupian–Lopingian extensional tectonic regime also documented in the Hronicum, Silicicum and Bôrka Nappe.

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