

Early Carboniferous successive I/S granite magmatism recorded in the Malá Fatra Mountains by LA-ICP-MS zircon dating (Western Carpathians)

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Abstract: In situ U–Pb zircon dating by the ICP-MS technique from tonalite located in the southern margin of the Kriváňská Malá Fatra granite massif records a Concordant age of 353 ± 3 Ma for zircon cores, 342 ± 3 Ma for their rims but the zircons from granodiorite on the northern margin of the massif show only coeval Concordant age of 342 ± 3 Ma from both cores and rims. The obtained ages establish successive Tournaisian and Visean magmatic events in the Variscan Malá Fatra crystalline basement and an intimate relationships between two Early Carboniferous intrusions. The Th/U ratio from zircon cores of Tournaisian tonalite shows a magmatic value of 1.0, whereas the ratio with value of 0.2 from zircon rims most likely represent the thermal imprint from emanated hydrothermal fluids from identified Visean granodiorite intrusion with similar Th/U zircon ratio of 0.4. The short time span of about 11 Ma for the origin of these two granitoid intrusive phases in the Malá Fatra Mountains advocates a relatively rapid Variscan convergence from a probably terminated Tournaisian arc magmatic regime to Visean collisional setting.

Keywords: Western Carpathians, Malá Fatra granites, ICP-MS zircon dating, Variscan orogeny, Tournaisian and Visean ages.

Introduction

The Variscan belt in Europe exposes numerous volumetric granite massifs (Franke 1989) and their multistage evolution is well documented in the Massif Central (Faure et al. 2009), Vosges and Schwarzwald (Altherr et al. 2000) and the nearby Bohemian Massif (e.g. Janoušek et al. 1995, 2004; Holub 1997; Žák et al. 2005; Finger et al. 2007; Schulmann et al. 2009; Breiter 2010; Trubač et al. 2017; Janoušek 2019). Behind the Alpine front, which separates the Variscan and Alpine Europe terrains, the Variscan granites of the present West-Carpathian mountain belt are preserved only in crystalline segments included as fragments in the Alpine edifice during the Cretaceous period. Thus, understanding of Variscan granite evolution in the present Western Carpathians must be based on mineralogical, geochemical and geochronological data that are compared with evolution of the classical Variscan magmatic domains. Variscan granitoids in crystalline fragments of the Western Carpathians occur in the Alpine Tatric and Veporic units and they are also present in the Tatric Core mountain Malá Fatra (e.g. Petrík & Kohút 1997; Bezák et al. 2011). The zircon geochronological data indicate the origin of the Variscan West-Carpathian granites during the Upper Devonian/Mississippian period in the quite large time span of ca. 365–340 Ma (e.g. Bibikova et al. 1988; Král' et al. 1997; Petrík & Kohút 1997; Poller & Todt 2000; Finger et al. 2003; Burda & Klötzli 2007; Broska et al. 2013; Gawęda et al. 2016). The followed felsic magmatism in the Western Car-

pathians is mainly from the Permian period (Uher & Broska 1996; Kohút & Stein 2005; Putiš et al. 2016; Broska & Kubiš 2018; Ondrejka et al. 2018 and references therein) and basic Permian magmatism is also present in the Malá Fatra Mts in the form of intruded lamprophyre dykes in granitoids (Spišiak et al. 2018).

The Malá Fatra granite massif as a part of the Alpine Tatric Unit of the Western Carpathians is formed by at least two magmatic bodies formerly identified from mapping work and petrographic research of Ivanov & Kamenický (1957). They distinguished “hybrid to oligoclase–biotite granitoids” and relatively younger “Magura granite” as a product of Variscan thermal activity present in two mapped belts. Later Kamenický et al. (1987) described an intensively metasomatic alteration of the hybrid as well as the Magura granites, both on the northern margin of the Malá Fatra massif. Broska et al. (1997) evaluated in the sense of the classification of Chappell & White (1992) the hybrid and oligoclase–biotite granitoid as an I-type and the Magura granites as affiliated to an S-type granite suite. The granitoids in the Malá Fatra Mts. intruded high grade crystalline basement (Janák & Lupták 1997; Putiš et al. 2003).

U–Pb zircon conventional multigrain dating for hybrid granites performed on four zircon concentrates of different grain size showed age of 353 ± 5 (–11) Ma (Shcherbak et al. 1990). The ICP-MS age of zircons taken from Magura granite in area of the Kľačianska Magura hill near a chalet recorded significant younger intrusive activity 346 ± 10 Ma (Hrdlička et

al. 2005; Hrdlička 2006). The existence of the two individual granite bodies in the Malá Fatra pluton proven lithologically and geochronologically meant a challenge to re-evaluate their chronological sequence by one geochronometer method. This contribution reports results from ICP-MS laser ablation U–Pb dating on zircons from the mentioned Malá Fatra granite bodies.

Sampling and methods

The representative I-type granite was sampled from the active quarry Dubná skala (MF-DS; GPS 49°08'19.2"N, 18°53'6.3"E, alt. 432 m), which is on the south part of a dated profile across the crystalline basement of the Malá Fatra Mts. Magura S-type granite (MF-S; GPS 49°10'19.8"N, 18°53'4.5"E, alt. 385 m) was taken from an outcrop by the abandoned former main road close to Strečno village (Fig. 1A). The structure and composition of the rock-forming and accessory minerals were analysed by the electron microprobe SX100 Cameca housed at the State Geological Institute and by FE microprobe JEOL at the Earth Science Institute of the Slovak Academy of Sciences in Banská Bystrica. Zircons from granites were mounted in epoxy, ground, polished and finally internal zircon structures were documented by BSE and cathodoluminescence imaging.

Two sets of zircon U–Pb analyses were performed using laser ablation ICP-MS technique at the Institute of Geology of the Czech Academy of Sciences in Prague. An Element 2 high-resolution sector field mass spectrometer (Thermo Scientific) coupled with a 193-nm ArF Analyte Excite excimer laser ablation system (Teledyne/Cetac) was used to acquire the Pb/U isotopic ratios. The Excite excimer laser is equipped with a HelEx II active 2-volume ablation cell and the laser was fired at a repetition rate of 5 Hz, using a spot size of 25 µm and a fluence of ca. 3.5 J/cm² (see Hanžl et al. 2019 for detail analytical procedure).

Results

I-type granite: Petrographic and geochemical characterization

Representative I-type is altered medium-grained biotite tonalite (sample MF-DS) with hypidiomorphic 2–6 mm long light greenish plagioclase with An_(30–45) (Fig. 1B). Biotite tonalite and granodiorite have been formerly described in the quarry, the tonalite is mostly in the central part (Macek et al. 1982). K-feldspars in the rock form local spots of antiperthite within plagioclase, interstitial K-feldspar is non-perthitic. Quartz shows undulose extinction and locally resorbs plagioclase or biotite forming ocelli (Fig. 2A). Biotite is strongly chloritized. Mg-rich Fe/(Fe+Mg)=0.4–0.5 is preserved but often folded as a response on the field stress (Fig. 2B). The local shearing is accompanied by formation of

white micas, epidote, titanite, and late zircon generation (Fig. 2C). Degradation of large titanite to ilmenite and rutile is an example of fluid overprint (Fig. 2D). Generally the most common primary accessory minerals in the rock are zircon, apatite, titanite, allanite-(Ce), Fe–Ti oxides, epidote, titanite. The rock is altered by late-magmatic fluids, biotite alters into chlorite but also tiny titanite, epidote and rutile.

Whole rock geochemical data from the Dubná Skala locality can be seen in the following works: Cambel & Walzel 1982; Broska et al. 1997; Hrdlička 2006. The tonalite and granodiorite from the quarry are typically enriched in incompatible LILE (Sr 660 ppm, Ba 1680 ppm) with Rb/Sr≈0.1 and steep chondrite normalized REE pattern. The REEs show Eu/Eu*=1.2 and (Ce/Yb)_N=28. The rocks are metaluminous/peraluminous (A/CNK≈0.8–1.1), with Na₂O/K₂O≈1.5–2 because tonalite is present. The ZrO₂/HfO₂(wt) ratio ≈40 for magmatic zircon cores is much higher than for rims ≈33. Low ZrO₂/HfO₂ values indicate late-post-magmatic zircons formed along shear zones (Table 1, Fig. 2C).

Magura S-type granite: Petrographic and geochemical characterization

Dated Magura granodiorite with S-type affinity (MF-S) is medium-grained slightly porphyritic, K-feldspar phenocrysts form hypidiomorphic to allotriomorphic individuals with local light red colouring (Fig. 1C). Primary K-feldspar precipitated as perthitic phenocrysts (up to 1 cm) in the interstitial position. The phenocrysts of K-feldspar enclose grains of sub- up to euhedral plagioclase (Fig. 2E). Plagioclase is mostly subhedral in size up to 1 cm and more acid in comparison to tonalite from Dubná Skala quarry: An-component rising up to 27 % in the cores, while on rims it is only to 18 %. Biotite contains inclusions of accessory Fe–Ti oxide which are commonly present interstitial and in very high amounts also in the plagioclases. Fe–Ti oxides have disintegrated during cooling (Fig. 2F). The granodiorite is imprinted by evolved post-magmatic alteration performed by intensive sericitization of plagioclases and almost complete chloritization and epidotization of biotite. Grains of quartz are anhedral with different degrees of undulatory extinction and they are dynamically recrystallized.

Granodiorite is peraluminous (ACNK≈1.3) with significant decrease ratio Na₂O/K₂O≈0.9 in comparison to MF-DS. The chondrite normalized REEs are less steep and (Ce/Yb)_N=15. The pronounced difference in values of zircon ZrO₂/HfO₂ ratios in cores and rims (39 and 26, respectively) is a result of evolved magmatic differentiation.

U–Pb geochronology

The zircon population of the granite sample MF-DS contains clear or rarely pale brown, mostly euhedral, both short- and long-prismatic crystals or their fragments 150–350 µm long. Internal zircon structures studied by cathodoluminescence images (CL) displaying symmetrical, oscillatory growth zoning preserved in nearly all imaged crystals and all grains

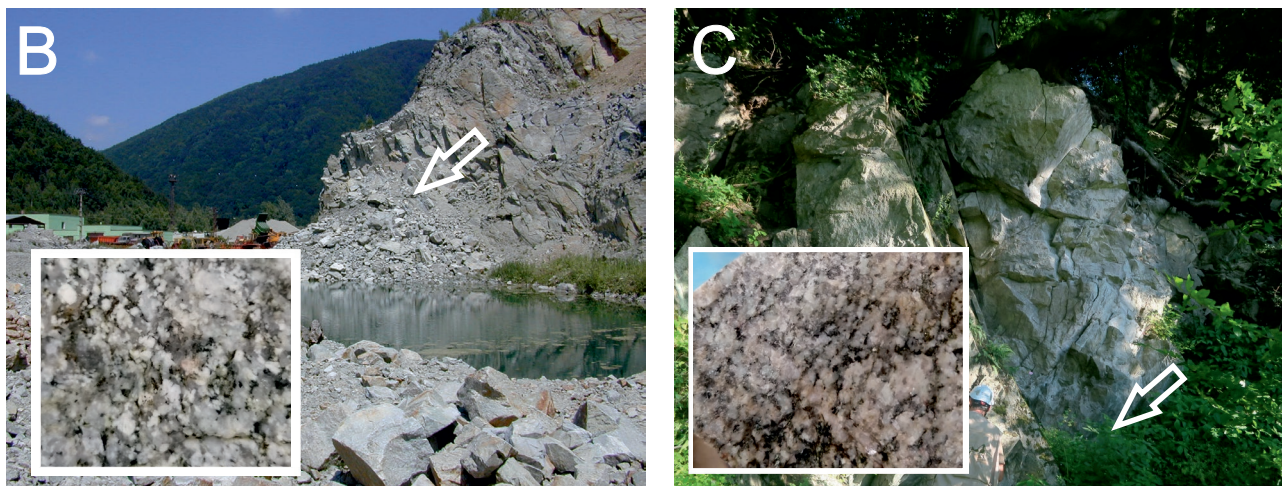
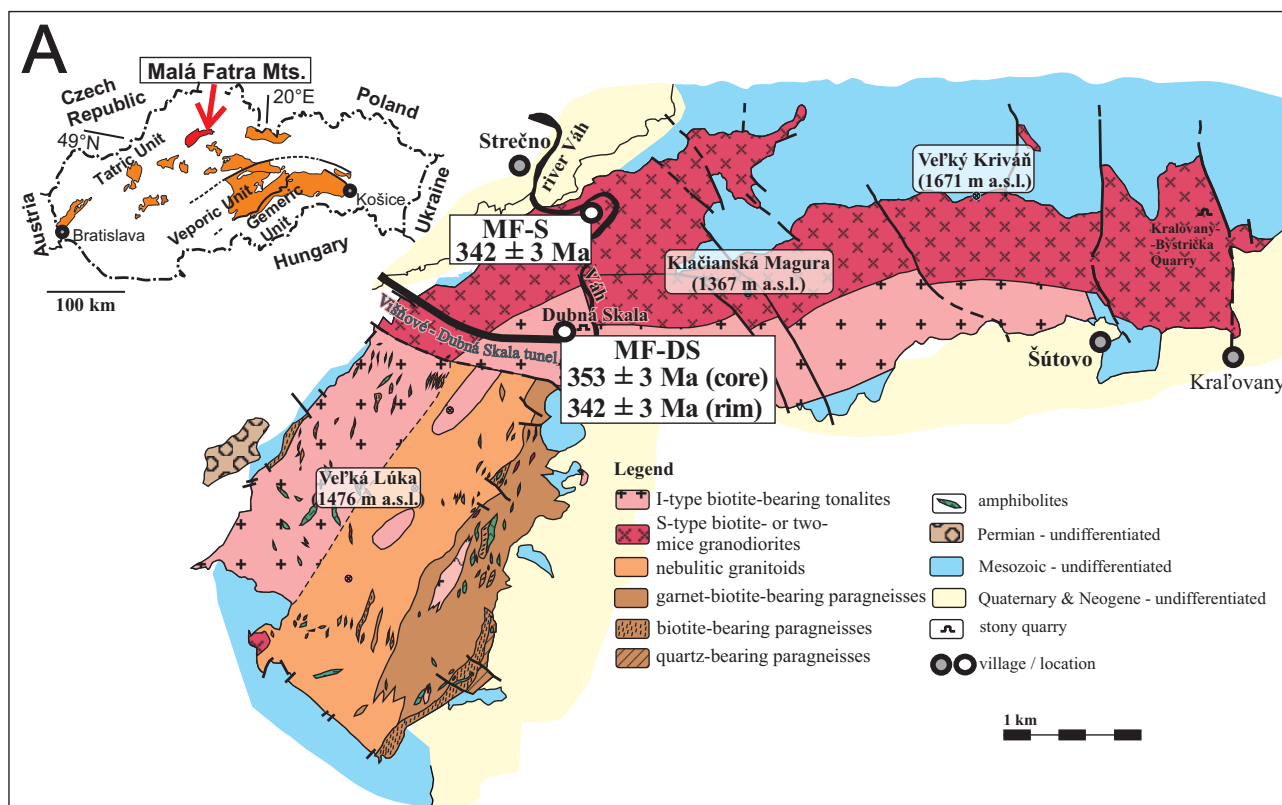


Fig. 1. A — Simplified geological map of the Malá Fatra Mts. acc. to Polák et al. (2008) and location of dated granitoids (Dubná Skala quarry; MF-DS) and (Strečno site; MF-S). Inset top left showing location of the Malá Fatra Mts. within the West-Carpathians Alpine structure. B — View on the Dubná Skala quarry with structure of tonalite sample; C — View of the Strečno roadcut with structure of granodiorite sample with visible ocelli formed during late-stage of the magma mixing and crystallization. Arrows show places of sampling.

show uniform overgrown rims ca. 10–30 μm wide. Only a few crystals show growth zoning with patchy xenocrystic cores (Fig. 3A). U–Pb zircon analyses of inherited cores revealed three age peaks at ca. 466–475 and 593 Ma, but most of the crystals yielded Carboniferous scattered ages between ca. 335 Ma and 360 Ma. Datings placed in the cores are interpreted as magmatic crystallization yielded Concordia age peak of ca. 353 $\pm$ 3 Ma (MSWD=1.4; probability of concordance 0.98; 15 analyses), while dating of rims shows spread of

analyses that constitute a weighted mean of ca. 342 $\pm$ 3 Ma (MSWD=4.4; probability of fit=0.0000000015; 19 analyses; Fig. 3B). Th/U ratio for all analyses from the cores varies from 0.1 to 3.1 with median 1.01 typical for magmatic origin, from rims the ratio is only 0.2 in average (Table 2).

The zircons from the second granitoid sample MF-S are predominantly clear and generally have prismatic and stubby shapes or their fragments with a length of 150–350 μm . In CL images (Fig. 4A), most zircons have oscillatory zonation with

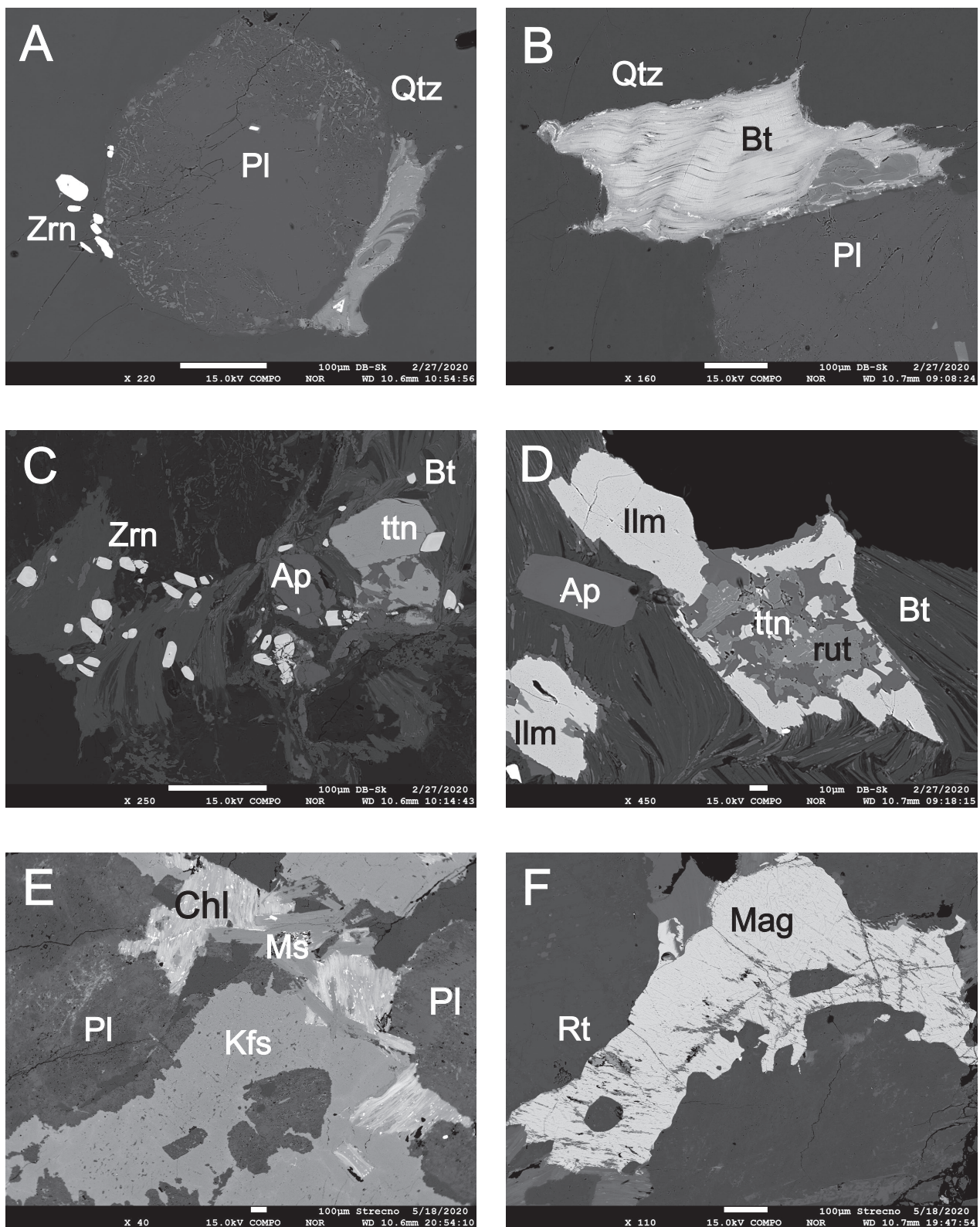


Fig. 2. BSE images of rock-forming and accessory minerals from Dubná Skala quarry (sample MF-DS: A–D) and from the former roadcut towards Strečno village (sample MF-S: E, F): **A** — Relic of resorbed plagioclase by quartz and early-magmatic zircon (ocelli indicates mixing); **B** — Deformed biotite in the shear zone; **C** — Second generation of zircon with higher Zr/Hf_{wt} ratio is locally abundant; **D** — Titanite fluid breakdown to ilmenite and rutile; **E** — Secondary chlorite and muscovite and feldspars distribution in the S-type granite (Strečno); **F** — Secondary Ti-magnetite with typical exsolutions during cooling (Strečno).

Table 1: Representative zircon compositions from dated granitoids (in wt. %).

Locality	MF-DS	MF-DS	MF-DS	MF-DS	MF-S	MF-S	MF-S	MF-S	MF-S	MF-S
Grain pos.	1.1	1.2	2.1	2.1	1.1	1.2	1.3	2.1	2.2	2.3
Spot	core	rim	core	rim	core	middle	rim	core	middle	rim
P ₂ O ₅	0.13	0.12	0.13	0.28	0.11	0.11	0.24	0.10	0.07	0.21
As ₂ O ₅	0.13	0.13	0.14	0.10	0.14	0.12	0.15	0.13	0.14	0.16
SiO ₂	32.39	32.07	32.12	31.89	32.19	32.38	31.83	32.33	31.40	31.11
ZrO ₂	64.88	64.69	64.86	64.42	65.02	64.59	64.43	64.94	64.41	63.26
HfO ₂	1.61	1.94	1.64	1.87	1.69	1.80	2.34	1.64	1.89	2.44
UO ₂	0.10	0.08	0.09	0.10	0.06	0.04	0.15	0.04	0.03	0.45
ThO ₂	0.06	0.02	0.11	0.05	0.01	0.02	0.01	0.00	0.00	0.01
La ₂ O ₃	0.00	0.02	0.10	0.02	0.00	0.08	0.00	0.01	0.07	0.00
Ce ₂ O ₃	0.07	0.04	0.09	0.04	0.04	0.07	0.03	0.05	0.02	0.08
Gd ₂ O ₃	0.09	0.08	0.09	0.16	0.07	0.06	0.06	0.09	0.05	0.11
Dy ₂ O ₃	0.00	0.00	0.05	0.00	0.00	0.00	0.01	0.00	0.01	0.02
Er ₂ O ₃	0.30	0.32	0.23	0.36	0.36	0.31	0.31	0.24	0.27	0.26
Yb ₂ O ₃	0.12	0.13	0.12	0.21	0.09	0.11	0.19	0.14	0.13	0.18
Y ₂ O ₃	0.10	0.34	0.20	0.41	0.09	0.12	0.13	0.13	1.16	0.56
FeO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17
CaO	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.02	0.02	0.04
Total	99.97	99.97	99.97	99.91	99.78	99.82	99.89	99.88	99.67	99.06
P	0.004	0.004	0.004	0.009	0.003	0.004	0.008	0.003	0.002	0.007
As	0.005	0.005	0.005	0.004	0.005	0.005	0.006	0.005	0.005	0.006
Si	1.948	1.929	1.932	1.918	1.937	1.948	1.915	1.945	1.889	1.872
Tsum	1.957	1.938	1.941	1.931	1.945	1.956	1.928	1.953	1.897	1.885
Zr	1.903	1.897	1.902	1.889	1.907	1.894	1.890	1.905	1.889	1.856
Hf	0.028	0.034	0.029	0.033	0.030	0.032	0.041	0.029	0.033	0.043
U	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.002
Th	0.001	0.000	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000
La	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.000
Ce	0.001	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.001
Gd	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.001	0.000	0.001
Dy	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Er	0.002	0.002	0.002	0.003	0.003	0.002	0.002	0.002	0.002	0.002
Yb	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Y	0.001	0.004	0.002	0.005	0.001	0.001	0.002	0.002	0.014	0.007
Fe	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.001
Asum	1.938	1.941	1.941	1.934	1.943	1.933	1.938	1.940	1.941	1.918
Zr/Hfw	40.4	33.3	39.6	34.4	38.5	35.9	27.6	39.6	34.1	25.9

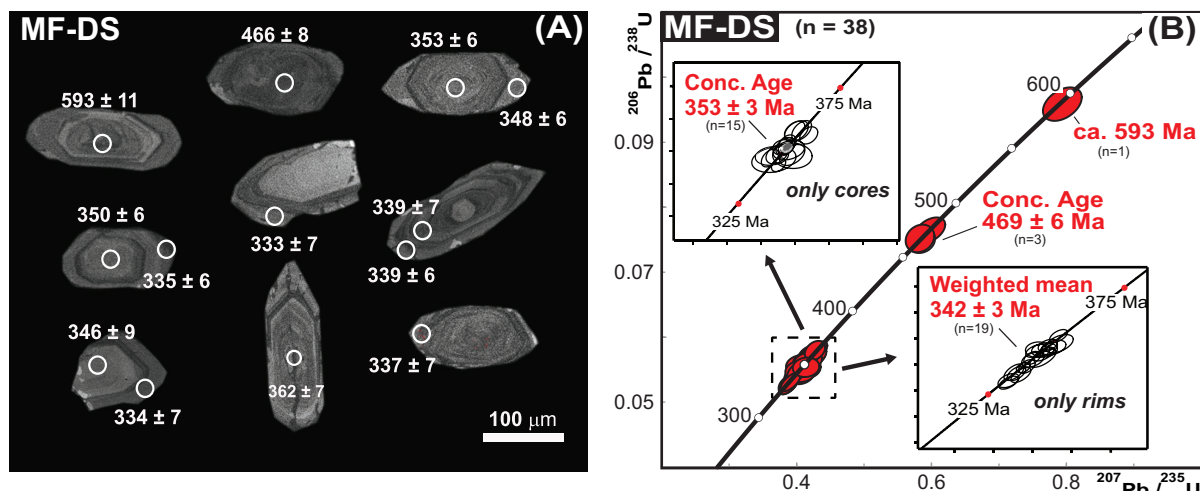


Fig. 3. A — Representative cathodoluminescence images of the zircons from the studied MF-DS sample. Laser-ablation ICP-MS analysis spots (25 μm) marked with Concordant $^{206}\text{Pb}/^{238}\text{U}$ ages $\pm 2\sigma$ uncertainties; **B** — Concordia age plot and the $^{206}\text{Pb}/^{238}\text{U}$ weighted mean age of laser ablation ICP-MS U–Pb analyses of studied zircons from granite sample MF-DS. Data-point error ellipses are 2σ .

Table 2: Results of laser ablation ICP-MS zircon dating from sample MF-DS (Dubná Skala quarry).

No.	Corrected isotope ratios					Apparent ages (Ma)				U, Th and Pb content (ppm)						disc.	
	²⁰⁷ Pb/ ²³⁵ U	±2s	²⁰⁶ Pb/ ²³⁸ U	±2s	error corr.	²⁰⁷ Pb/ ²³⁵ U	±2s	²⁰⁶ Pb/ ²³⁸ U	±2s	Approx U	±2s	Approx Th	±2s	Approx Pb	±2s	Th/U	%
Sample MF-DS cores																	
1	0.4093	0.0110	0.0558	0.0010	0.3533	347.9	7.6	350.1	6.2	299.7	2.6	38.51	0.71	18.5	0.62	0.1	−0.6
2	0.7940	0.0190	0.0959	0.0017	0.4063	593	11	590.1	9.8	449.7	6	684.2	8.7	608.6	7.9	1.5	0.5
3	0.4103	0.0094	0.0552	0.0009	0.3879	348.8	6.8	346.2	5.6	1520	21	638	6.6	286.6	3	0.4	0.7
4	0.4080	0.0160	0.0555	0.0011	0.1299	346.8	11	348.1	7	98.3	1.4	47.3	1.1	20.86	0.83	0.5	−0.4
5	0.4143	0.0100	0.0563	0.0010	0.3774	351.5	7.3	353	6.1	433.5	6.9	494.6	8.9	231.9	4	1.1	−0.4
6	0.4180	0.0140	0.0557	0.0011	−0.0446	354.6	10	349.6	7	92.5	1.9	109.4	2.2	49.7	1.3	1.2	1.4
7	0.4198	0.0110	0.0573	0.0010	0.4650	355.6	7.5	359.1	6.2	456	12	338.9	8.2	184.9	3.9	0.7	−1.0
8	0.4239	0.0100	0.0573	0.0010	0.4988	359.4	7.3	359.1	6.4	569	16	400	12	231.3	8.5	0.7	0.1
9	0.5976	0.0150	0.0765	0.0013	0.4396	475.6	9.2	474.9	8.1	240.1	3.3	42.73	0.62	32.33	0.85	0.2	0.1
10	0.4064	0.0130	0.0557	0.0010	0.1690	346.1	9.3	349.5	6.2	101.8	1.8	85.7	2.8	63.3	1.7	0.8	−1.0
11	0.4129	0.0100	0.0562	0.0010	0.1695	350.9	7.6	352.7	5.9	179.8	7.1	124.4	7.2	120.1	6.2	0.7	−0.5
12	0.4281	0.0100	0.0570	0.0010	0.3582	361.5	7.3	357.2	6.1	371.1	9.3	128.8	4.7	135.4	5	0.3	1.2
13	0.4184	0.0110	0.0558	0.0011	0.4516	354.4	8.1	349.8	6.4	278	16	214	24	189	20	0.8	1.3
14	0.4153	0.0100	0.0564	0.0010	0.3879	352.4	7.2	353.8	6.3	503	26	45.1	2.8	37.7	2.5	0.1	−0.4
15	0.5840	0.0140	0.0749	0.0013	0.1214	466.6	9	465.7	7.8	698.9	8.6	2175	61	242.1	3.7	3.1	0.2
16	0.5829	0.0140	0.0752	0.0014	0.1804	466.2	8.8	467.3	8.1	320.7	3.5	734.2	7.5	414.2	4.7	2.3	−0.2
17	0.4052	0.0098	0.0556	0.0010	0.4421	345.2	7	348.7	6.1	794	11	1496	21	449.9	6.6	1.9	−1.0
18	0.4208	0.0110	0.0572	0.0011	0.4266	356.4	7.9	358.8	6.5	443.6	7.6	1061	24	370.2	7.9	2.4	−0.7
19	0.4164	0.0130	0.0561	0.0010	0.3057	353.8	8.9	351.6	6.3	131	3.4	25.83	0.72	13.8	0.64	0.2	0.6
Sample MF-DS rims																	
20	0.3917	0.0093	0.0533	0.0010	0.5565	335.7	6.7	334.8	5.9	1038	15	53.8	1.5	29.2	1.7	0.1	0.3
21	0.4136	0.0110	0.0556	0.0011	0.4691	351.3	7.9	348.8	6.6	330.4	5.7	54.4	1.5	26.03	0.9	0.2	0.7
22	0.4053	0.0110	0.0545	0.0011	0.6659	345.2	7.7	342.1	6.6	724	15	22.31	0.33	13.38	0.63	0.0	0.9
23	0.3876	0.0096	0.0528	0.0010	0.4518	332.7	7	331.5	5.8	593	10	173.1	2.2	87	1.4	0.3	0.4
24	0.4000	0.0100	0.0544	0.0010	0.3838	342.5	7.2	341.3	6	383.3	3.3	67.22	0.75	32.14	0.68	0.2	0.4
25	0.4061	0.0110	0.0551	0.0010	0.1559	345.6	7.7	345.8	6	425	10	23.73	0.64	11.53	0.42	0.1	−0.1
26	0.4077	0.0097	0.0555	0.0010	0.4185	347.1	7	348	5.8	387.9	4.9	28.09	0.46	14.5	0.67	0.1	−0.3
27	0.3876	0.0093	0.0526	0.0009	0.5716	333.1	7	330.8	5.8	989	13	87.1	1.2	40.49	0.91	0.1	0.7
28	0.4106	0.0110	0.0553	0.0010	0.3702	349.3	7.7	347.3	6.2	294.6	6.4	38.38	0.88	18.16	0.55	0.1	0.6
29	0.3970	0.0092	0.0539	0.0010	0.4561	339.3	6.7	338.1	5.9	638	18	87.6	1.5	43.2	1.1	0.1	0.4
30	0.3951	0.0088	0.0538	0.0009	0.3721	338.6	6.4	337.6	5.5	981	21	147.4	3.4	70.9	1.6	0.2	0.3
31	0.4017	0.0098	0.0551	0.0010	0.5035	342.8	7.1	345.7	5.9	602	12	334.7	5.1	173.3	2.5	0.6	−0.8
32	0.4058	0.0098	0.0548	0.0010	0.6053	346.2	7.1	343.9	5.9	548.2	5.9	84.6	2	54.4	2	0.2	0.7
33	0.4081	0.0096	0.0552	0.0010	0.6272	347.5	6.8	346.5	6	686	12	20.22	0.58	12.86	0.38	0.0	0.3
34	0.4132	0.0096	0.0562	0.0010	0.5530	350.9	6.9	352.4	5.9	639.3	8.2	98.1	0.89	50.63	0.96	0.2	−0.4
35	0.3904	0.0095	0.0534	0.0010	0.5879	334.4	7	335.4	6.2	763	11	43.49	0.58	40.8	1.1	0.1	−0.3
36	0.4026	0.0100	0.0551	0.0010	0.0851	343.1	7.5	346	6.2	425.2	6	143.4	1.4	29.61	0.63	0.3	−0.8
37	0.3997	0.0093	0.0545	0.0010	0.4525	341.2	6.7	342.1	5.8	732	13	789	22	124	2.3	1.1	−0.3
38	0.3940	0.0096	0.0532	0.0010	0.6248	337	7	334.1	6	741.4	9.2	174.5	31	269.7	4.6	0.2	0.9

*disc. — discordance was calculated as $(1 - ((^{206}\text{Pb}/^{238}\text{U}) / (^{207}\text{Pb}/^{235}\text{U}))) * 100$

weakly or irregular patchy zoned cores. Zircon dating from sample MF-S revealed a Cambrian inherited age of ca. 490 Ma in one case but the dominant age span is Carboniferous between ca. 330 and 350 Ma which do not constitute a single Concordia age peak. Both cores and rims yielded identical weighted mean peak of ca. 342 ± 3 Ma (for both cores and rims MSWD=5.18; 49 analyses; Fig. 4B; statistical values for cores and rims are in Table 3). Th/U ratio is rather uniform in range 0.1–0.8 with an average of 0.4 for both core and rims interpreted as magmatic (Table 3).

Discussion

The ICP-MS zircon age of the cores 353 ± 3 Ma in the tonalite from Dubná Skala quarry corresponds to the first U–Th–Pb conventional dating from zircon multigrain concentrates 353 ± 5 (−11) Ma published by Shcherbak et al. (1990). But the ICP-MS zircon dating on single crystals presented here allowed us to identify zircon age zonality (ca. 353 vs. 342 Ma). Datings of zircon rims from Dubná Skala (MF-DS) show a Concordia age of ca. 342 ± 3 Ma which is equal to the dates

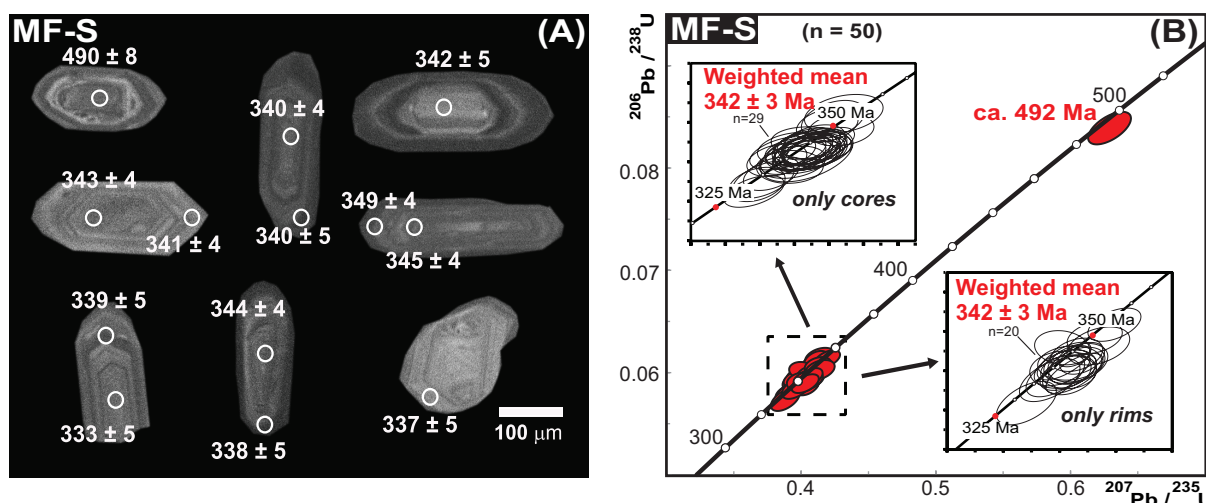


Fig. 4. A — Representative cathodoluminescence images of the magmatic zircons from the studied MF-S sample. Laser ablation ICP-MS analysis spots (25 μm) marked with Concordant $^{206}\text{Pb}/^{238}\text{U}$ ages $\pm 2\sigma$ uncertainties; **B** — Concordia age plot and the $^{206}\text{Pb}/^{238}\text{U}$ weighted mean age of laser ablation ICP-MS U–Pb analyses of studied zircons from granite sample MF-S. Data-point error ellipses are 2σ .

of zircon cores and rims from Strečno granodiorite (MF-S). This age is close to the ICP-MS zircon dating of 346 ± 10 Ma of the Magura S-type granodiorite taken close to the chalet below the Kľačianska Magura hill (Hrdlička et al. 2005; Hrdlička 2006). The Visean $^{39}\text{Ar}/^{40}\text{Ar}$ muscovite plateau age of 345 ± 2 Ma for the S-type granite is also reported from the southern part of the Malá Fatra Mts. (Hók et al. 2000). Dubná Skala granitoid contains common hypidiomorphic titanite, which is probably Visean in age like dated titanites from the nearby Nízke Tatry Mts. granitoids (ca. 343 Ma; Uher et al. 2019). The identical zircon age from the Strečno area (MF-S) and from zircon rims in Dubná Skala (MF-DS) along with deformation of the Dubná Skala granitoids (Fig. 2B) is an argument for the existence of stress and thermal influence of emplaced Magura granodiorite (MF-S) on older tonalite (MF-DS). Precipitation of late zircons along the shearing (Fig. 2C) indicates their identical composition like zircons from the northern Strečno sample MF-S (see Table 1). Anyway, both granitoid types in the Malá Fatra Mts. were later overprinted and the formation of pummpelite, chlorite and epidote probably resulted from the Alpine metamorphism (Faryad & Dianiška 2003).

Bagdasaryan et al. (1992) reported almost identical $^{87}\text{Sr}/^{86}\text{Sr}$ ratios 0.70876 vs 0.70848 and low initial Sr isotopes ($^{87}\text{Sr}/^{86}\text{Sr}_i = 0.70627 \pm 0.00022$ for granitoids from Dubná Skala quarry and Strečno. These initial Sr ratios in the Malá Fatra granites imply a Rb-poor crustal source (Kráľ 1992, 1994). Kohút et al. (1999) described similar $^{87}\text{Sr}/^{86}\text{Sr} = 0.7063$ ratio and negative $\varepsilon\text{Nd}_{(\text{CHUR})} = -2.75$ in the granitoid from Kľačovany-Bystrička quarry, which is genetically identical to granodiorite sample MF-S. Thus the data indicates derivation of Malá Fatra granitoids from metasomatized mantle component mixed with a crustal source. In this sense, they could be referred to hybrid

according to the classification of Castro et al. (1991) but not according to the old view in which the granites rich in inhomogeneities mainly from included metasedimentary xenoliths were considered hybrid.

Burda et al. (2013) reports by LA-ICP-MS dating two distinct age groups in the High Tatra granites where the zircon cores yielded an age of 350 ± 5 Ma but for rims 337 ± 6 Ma. The S-type granite from the northern part of the High Tatra Mts. is older in age ca 356 Ma (Burda & Klötzli 2007) and the oldest magma formation is dated 368 ± 8 Ma (Burda et al. 2011). Generally, High Tatra polygenic plutonism is formed by repeated magma injections from ca. 370 to ca. 340 Ma with cooling ages at ca. 330 Ma (Gawęda et al. 2016). The ages from the nearby I-type granitoids in the Nízke Tatry massif show ages of ca. 356 for Ďumbier tonalite and ca. 353 Ma for Prašivá tonalite/granodiorite (Broska et al. 2013), which is similar to ages obtained from the zircon cores in the Dubná Skala quarry in the Malá Fatra Mts. The zircon metasomatic age of ca. 353 Ma records a thermal imprint from Ďumbier granitoid on Chopok granite (Burda et al. 2020). The close Tournaisian age ca. 356 Ma was also obtained from the Čierna Hora Mts. granitoid and from the Sihla granitoid located in the Veporic Unit (Broska et al. 2013). In the Malé Karpaty Core mountain the S-type granodiorite 355 ± 5 Ma are coeval or slightly older than the I-type tonalite 347 ± 4 Ma (Kohút et al. 2009).

The closest archetypal Variscan domain is the Bohemian Massif which comprises the following principal granite suites: (1) normal K-calc alkaline in age range 375–355 Ma as an initial stage of arc-related magmatism (2), high K-calc-alkaline Visean collisional S-type granite ca. 345 Ma with evidence of interaction of moderately enriched mantle melt with $\varepsilon\text{Nd} \approx -3$ and (3) ultra-K post-tectonic suite connected with extensional

Table 3: Results of laser ablation ICP-MS zircon dating from sample MF-S (Strečno).

No.	Corrected isotope ratios					Apparent ages (Ma)				U, Th and Pb content (ppm)						disc.	
	²⁰⁷ Pb/ ²³⁵ U	±2s	²⁰⁶ Pb/ ²³⁸ U	±2s	error corr.	²⁰⁷ Pb/ ²³⁵ U	±2s	²⁰⁶ Pb/ ²³⁸ U	±2s	Approx U	±2s	Approx Th	±2s	Approx Pb	±2s	Th/U	%
Sample MF-S core (weighted mean – 342 Ma with one sample rejected – 492 Ma; MSWD=5.63, probability of fit=0)																	
1	0.4020	0.0069	0.0546	0.0007	0.3091	342.9	5	342.8	4.2	683	14	256.3	4.3	127.9	2.2	0.4	0.03
2	0.4019	0.0085	0.0544	0.0007	0.1067	342.5	6.2	341.4	4	288	4.7	178.4	5.1	84.5	2.6	0.6	0.3
3	0.3891	0.0067	0.0529	0.0007	0.3548	333.5	4.9	332	4.4	2013	36	52.5	2.4	25.7	1.5	0.0	0.4
4	0.4035	0.0110	0.0543	0.0011	0.4583	343.9	7.3	341	6.7	621	14	364.1	9.5	172.8	5	0.6	0.8
5	0.4049	0.0081	0.0549	0.0007	0.3402	345.3	5.8	344.5	4.1	328	7.3	250	5	123.2	2.4	0.8	0.2
6	0.4026	0.0070	0.0546	0.0007	0.5847	343.3	5.1	342.7	4.2	1136	17	901	15	459	10	0.8	0.2
7	0.4135	0.0078	0.0556	0.0007	0.1848	351	5.6	349	4.1	522.7	6.7	239.6	3.6	128.5	2	0.5	0.6
8	0.4047	0.0072	0.0546	0.0007	0.3064	344.8	5.2	342.7	4	563.3	6.2	270.1	4.4	135.8	2.1	0.5	0.6
9	0.3992	0.0081	0.0547	0.0007	0.2778	340.7	5.9	343.1	4.1	516	12	336.6	7.7	169.9	3.3	0.7	-0.7
10	0.3987	0.0079	0.0537	0.0007	0.0642	340.3	5.8	337.4	4.2	438.3	4.3	63.49	0.82	32.03	0.84	0.1	0.9
11	0.4025	0.0088	0.0544	0.0007	0.3007	343.4	6.4	341.4	4.2	267.2	4.2	48	1	23.43	0.76	0.2	0.6
12	0.4095	0.0073	0.0559	0.0007	0.3170	348.2	5.2	350.4	4.3	616.1	8	281.1	4.9	145.8	2.3	0.5	-0.6
13	0.3949	0.0071	0.0541	0.0007	0.3395	338	5.1	339.6	4.2	489	7.8	247.5	3.4	126.2	2.2	0.5	-0.5
14	0.4056	0.0074	0.0545	0.0007	0.3970	345.7	5.3	342	4.2	476	13	285	11	142.4	4.9	0.6	1.1
15	0.4067	0.0080	0.0547	0.0007	0.2926	346.1	5.8	343	4.5	578	14	208.8	4.7	101.2	2.2	0.4	0.9
16	0.6290	0.0130	0.0789	0.0013	0.5989	494.9	8.4	489.2	7.6	527.8	8.7	384.3	5.7	255.1	4.5	0.7	1.2
17	0.3883	0.0071	0.0525	0.0007	0.5088	332.8	5.2	329.8	4	816	15	496	13	239.1	5.4	0.6	0.9
18	0.3994	0.0079	0.0540	0.0007	0.2719	340.8	5.7	338.9	4.1	461.1	9.7	251.9	4.8	128.8	2.3	0.5	0.6
19	0.4056	0.0074	0.0550	0.0007	0.3896	346.4	5.4	345.3	4.3	491	11	270.5	5.9	137	2.7	0.6	0.3
20	0.4075	0.0081	0.0548	0.0008	0.6299	347.5	5.8	343.8	4.8	570	33	296	21	146.8	9.2	0.5	1.1
21	0.4058	0.0077	0.0547	0.0007	0.4220	345.8	5.5	343.5	4.2	467.6	7.9	160.8	1.4	81.7	1.3	0.3	0.7
22	0.3933	0.0066	0.0534	0.0007	0.4309	336.5	4.8	335.3	4.3	1089	22	130.5	2.8	62.5	1.9	0.1	0.4
23	0.4033	0.0075	0.0547	0.0007	0.2663	344.3	5.3	343.3	4.3	500	19	239.5	5	122.5	2.6	0.5	0.3
24	0.4038	0.0083	0.0542	0.0007	0.5042	344.4	6	340.4	4.2	489	11	153	2.6	74.3	1.5	0.3	1.2
25	0.3966	0.0078	0.0544	0.0007	0.4497	339.4	5.6	341.6	4.2	597	18	324.6	7.6	161.2	3.5	0.5	-0.6
26	0.4143	0.0093	0.0564	0.0008	0.3116	352.2	6.8	353.9	4.9	566.2	9.4	371.9	6.9	209.2	4.9	0.7	-0.5
27	0.4051	0.0067	0.0547	0.0007	0.6939	345.6	4.7	343.2	4.2	2975	57	227.4	6.9	121.4	4.1	0.1	0.7
28	0.4048	0.0086	0.0545	0.0008	0.3527	345	6.1	342.1	4.6	371.3	7.7	58.2	2	30.1	1.4	0.2	0.8
29	0.4112	0.0075	0.0562	0.0008	0.3849	349.9	5.5	352.1	4.8	642	11	277.5	5.1	152.1	2.7	0.4	-0.6
30	0.3910	0.0073	0.0531	0.0008	0.5060	335.2	5.4	333.4	4.7	539	11	134.3	5.5	71.2	3	0.2	0.5
Sample MF-S rims (weighted mean – 342 Ma; MSWD=4.79, probability of fit=0.000000000022)																	
31	0.4036	0.0093	0.0544	0.0007	0.1220	343.8	6.7	341.4	4.3	478.1	7.2	167.4	1.7	86.2	1.6	0.4	0.7
32	0.4195	0.0077	0.0563	0.0007	0.4869	355.6	5.6	353.3	4.2	625	23	196	4.9	97.1	2.5	0.3	0.6
33	0.4009	0.0080	0.0552	0.0007	-0.1416	342	5.8	346.2	4.3	583.9	4.3	318.8	2.9	161.8	2.3	0.5	-1.2
34	0.4016	0.0078	0.0545	0.0008	0.6592	342.5	5.7	342	4.8	696.2	8.6	269	2.5	138.9	2.1	0.4	0.1
35	0.4060	0.0076	0.0548	0.0007	0.3199	345.9	5.4	344	4.2	602	47	259	24	128	12	0.4	0.5
36	0.4009	0.0081	0.0542	0.0008	0.4879	342.5	5.8	339.9	4.6	694.2	7.6	284.2	3	145.2	2.6	0.4	0.8
37	0.4053	0.0083	0.0539	0.0008	0.6805	345.7	6.1	338.1	5.1	854	32	161.4	2	80.5	1.8	0.2	2.2
38	0.3985	0.0085	0.0537	0.0009	0.5563	340.2	6.2	337.4	5.3	785	19	319	5.1	154.8	2.9	0.4	0.8
39	0.3882	0.0087	0.0524	0.0009	0.5346	332.7	6.3	328.9	5.5	838	13	315.9	4.7	146.5	2.5	0.4	1.1
40	0.4032	0.0081	0.0539	0.0007	0.0842	343.6	5.8	338.6	4.2	516.8	8.2	176.1	2	85	2	0.3	1.5
41	0.4125	0.0080	0.0557	0.0007	0.3008	350.2	5.8	349.3	4.1	507	14	162.3	2.8	80.7	1.6	0.3	0.3
42	0.4138	0.0091	0.0553	0.0008	0.3653	351.7	6.5	346.7	4.8	466.1	6.9	178.4	2.4	90.8	1.7	0.4	1.4
43	0.4035	0.0078	0.0538	0.0008	0.3200	344.2	5.6	337.6	4.9	626	14	274.2	9	136.6	4.8	0.4	1.9
44	0.3965	0.0088	0.0535	0.0009	0.5375	338.8	6.4	336.1	5.4	699	10	368.1	3.7	185.4	3	0.5	0.8
45	0.4003	0.0089	0.0541	0.0008	0.1268	341.5	6.5	339.3	4.7	581	9.9	236.3	4.2	118.1	2.2	0.4	0.6
46	0.4061	0.0082	0.0543	0.0008	0.4079	345.7	5.9	340.5	4.7	558.7	5.5	270.1	2.8	131.9	2.5	0.5	1.5
47	0.4052	0.0047	0.0547	0.0004	0.4484	345.4	6.4	343.8	5.4	522.9	6.4	239.8	2.1	121.1	1.9	0.5	0.5
48	0.4037	0.0076	0.0542	0.0007	0.2064	343.9	5.5	340.3	4.3	716	14	276.7	5.6	132.2	2.8	0.4	1.0
49	0.4080	0.0065	0.0546	0.0007	0.4035	347.1	5.5	342.8	4.7	731.7	9.7	334.2	4.8	178	4.2	0.5	1.2
50	0.4031	0.0082	0.0539	0.0008	0.5327	343.6	5.9	338.5	4.6	1001	23	234.3	4.2	110.1	2.8	0.2	1.5

*disc. — discordance was calculated as $(1 - ((^{206}\text{Pb}/^{238}\text{U}) / (^{207}\text{Pb}/^{235}\text{U}))) * 100$

regime in age span 343–335 Ma (Janoušek et al. 2000; Janoušek & Holub 2007; Schulmann et al. 2009; Janoušek 2019). The Visean collisional processes at ca. 340 Ma are also reported from the External Massifs in the Western Alps (Guillot & Ménot 2009) and in the southern Variscan sector (Rossi et al. 2009). Thus the Visean age identified in the Malá Fatra Mts. can be correlated with Variscan collisional event and older Tournaisian age could probably be related to terminated subduction arc magmatism triggered by previous slab failure (Whalen & Hildebrand 2019).

Th/U zircon ratios confirm two evolutionary stages of zircons in the granitoids from Dubná Skala quarry. The lower limit of magmatic zircons was recommended for values $\text{Th/U} > 0.3$ (Schaltegger et al. 1999; Rubatto 2002), and recently Yakymchuk et al. (2018) recommended Th/U ratios < 0.1 for metamorphic rocks. Th/U zircon ratios in cores from the tonalite show a clearly magmatic value 1 (Kirkland et al. 2014; Yakymchuk et al. 2018), but the much lower ratio from the rims of value 0.2 is probably a result of fluid activity. Th/U zircon ratio 0.4 from granodiorite near Strečno is magmatic and low because of the presence of early Th-rich monazite-(Ce), which decreases the Th content in the melt. On the other hand, the primary REE bearing phase in the tonalite MF-DS was allanite-(Ce) and therefore high Th occurred in the system. The low Th/U ratio 0.2 from zircon rims in the Dubná Skala granitoids probably corresponds to Visean thermal imprint from emanated fluids of the nearby Visean granodiorite intrusion.

Xenocrystic zircons of tonalite in the Dubná Skala quarry display the Ordovician age in the range 466–475 Ma and Ediacaran age 593 Ma. In the sample MF-S among 45 analyses only one inherited Cambrian age 489 Ma has been detected. Anyway, such inherited ages are typical in the West-Carpathian granitoids and Permian depositions from the exhumed Variscan granites (e.g. Vozárová et al. 2018, 2020). The low amount of inherited zircons preserved in the zircon cores indicate the source rocks were derived from the Cadomian and African Craton mixed with mantle components.

Conclusions

Zircon ICP-MS datings on a profile across the Malá Fatra granite massif indicate the existence of two Early Carboniferous successive intrusive phases 353 Ma vs. 342 Ma showing an age difference of ca. 11 Ma. According to the accepted Variscan evolution known in Europe the ages are probably related to: (1) terminated arc-related magmatism and (2) Visean collisional tectonics. The short time span for emplacement of both granite types is a fundamental fact in the architecture of the West-Carpathian crystalline basement, which is in an accordance with the known rapid convergence of Variscan subduction related evolution terminated by emplacement of magmas controlled mainly by collisional and post-collisional tectonics.

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