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Investigation of Accessory Minerals from the Blatná Granodiorite Suite, Bohemian Massif, Czech Republic

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Abstract

The Central Bohemian magmatic complex belongs to the Central European Variscan belt. The granitic rocks of this plutonic complex are formed by several suites of granites, granodiorites, and tonalites, together with small bodies of gabbros, gabbro diorites, and diorites. The granodiorites of the Blatná suite are high-K, calc-alkaline to shoshonitic, and metaluminous to slightly peraluminous granitic rocks. Compared to the common I-type granites, granodiorites of the Blatná suite are enriched in Mg (1.0–3.4 wt.% MgO), Ba (838–2560 ppm), Sr. (257–506 ppm), and Zr (81–236 ppm). For granodiorites of the Blatná suite is assemblage of apatite, zircon, titanite, and allanite significant. Zircon contains low Hf concentrations (1.1–1.7 wt.% HfO₂). The composition of titanite ranges from 83 to 92 mol.% titanite end-member. Allanite is relatively Al-poor and displays Fe_{ox} ratio 0.2–0.5.

Keywords: granodiorite, I-type granite, accessory minerals, apatite, zircon, titanite, allanite, Bohemian Massif, Central European Variscides

1. Introduction

The main carriers of rare-earth elements (REE), uranium, thorium, and zirconium in granitic rocks are usually different accessory minerals, including apatite, zircon, monazite, xenotime, and allanite. However, more detailed information about the assemblage and composition of these accessories is often missing. The granitic rocks of the Blatná suite are part of relatively bigger the Central Bohemian magmatic complex. This magmatic complex represents one of the biggest Variscan magmatic bodies in the Central European Variscides. This magmatic complex is formed by several suites of granodiorites, tonalites, and granites. The Blatná suite is represented by the Blatná hornblende-bearing biotite granodiorites and the Červená hornblende-biotite granodiorites. The accessory minerals assemblage is in a both granodiorites represented by apatite, zircon, titanite and allanite. The presented study is concentrated on comprehensive petrological and geochemical description of the Blatná suite and detailed investigation of accessory minerals assemblage that occurred in this magmatic suite, which is represented by the occurrence of apatite, zircon, titanite, and allanite.

2. Geological setting

The Central Bohemian plutonic complex is a large composite magmatic body that occurred in the central part of the Bohemian Massif between Prague and Klatovy. This plutonic complex represents according to its mineralogical and geochemical compositions the most fractionated Variscan magmatic body in the Bohemian Massif (**Figure 1**). The most widespread rock types that occurred in this complex are amphibole-biotite granodiorites accompanied by biotite granites, tonalites, and melagranites (durbachites) [1–3]. The Blatná suite occurred in the south-west part of magmatic complex is formed by the Blatná hornblende-bearing biotite granodiorites and the Červená hornblende-biotite granodiorites. Other petrographic varieties of the Blatná suite are the Klatovy and Kozárovce granodiorites and tonalites occurring in the southwestern part of the Central Bohemian magmatic complex (**Figure 1**). The Blatná granodiorites intruded during the Variscan magmatic event (346.7 ± 1.6 Ma, U/Pb TIMS analyses on zircon) [2].

Figure 1.
Geologic map of the Central Bohemian Plutonic complex, modified from [1].

3. Materials and methods

Detailed mineralogical and geochemical investigations of the Blatná and Červená granodiorites were carried out on a representative suite of the 37 rock samples which were taken predominantly from boreholes performed by the Czechoslovak Uranium industry (ČSUP, recently DIAMO) during their exploration activities (1978–1989) in this area [4, 5]. The contents of major elements were determined by a standard XRF method, using the Philips PW 1410 spectrometer at the Geochemical laboratories of the Czechoslovak Uranium Industry (Stráž under Ralsko, Northern Bohemia). The FeO content was measured via titration, whereas the H₂O content was determined gravimetrically. The contents of selected trace elements were determined also by a standard XRF method, using the Philips PW 1410 spectrometer at the chemical laboratory of the Unigeo Brno Ltd. in Brno, Moravia. The content of U and Th was determined by gamma spectrometry using a multichannel spectrometer at Geophysics Brno Ltd., also in Brno, Moravia. The content of REE was quantified by inductively coupled plasma mass spectrometry (ICP MS) at Activation Laboratories Ltd., Ancaster, Canada, using a Perkin Elmer Sciex ELAN 6100 ICP mass spectrometer, following standard sample preparation procedures involving lithium metaborate/tetraborate fusion and acid decomposition. All chemical analyses were calibrated against international reference materials.

Approximately 140 quantitative electron microprobe analyses of apatite, zircon, allanite, titanite, and selected rock-forming minerals (plagioclase, K-feldspar, and biotite) were collected from representative samples of the Blatná suite. All these minerals were analyzed in polished thin sections. The back-scattered electron (BSE) images were acquired to study the internal structure of mineral aggregates and individual mineral grains. The abundances of all chemical elements were determined using a CAMECA SX 100 electron probe micro-analyzer (EPMA) operated in wavelength-dispersive mode at the Department of Geological Sciences, Masaryk University in Brno. The accelerating voltage and beam currents were 15 kV and 20 or 40 nA, respectively, and the beam diameter was 1–5 µm. The peak count time was 20 s, and the background time was 10 s for major elements. For the trace elements, the times were 40–60 s on the peaks, and 20–40 s on the background positions. The following standards, X-ray lines and crystals (in parentheses), were used: AlK_α, sanidine (TAP); CaK_α, fluorapatite (PET); CeL_α, CePO₄ (PET); ClK_α, vanadinite (LPET); DyL_α, DyPO₄ (LLIF); ErL_α, ErPO₄ (PET); EuL_β, (LLIF); FK_α, topaz (PC1); FeK_α, almandine (LLIF); GdL_β, GdPO₄ (LLIF); HfM_α, Hf (TAP); KK_α, sanidine (TAP); LaL_α, LaPO₄ (PET); MgK_α, Mg₂SiO₄ (TAP); MnK_α, spessartine (LLIF); NaK_α, albite (PET); NbL_α, columbite, Ivigtut (LPET); NdL_β, NdPO₄ (LLIF); PK_α, fluorapatite (PET); PbM_α, vanadinite (PET); PrL_β, PrPO₄ (LLIF); RbL_α, RbCl (LTAP); SK_α, SrSO₄ (LPET); ScK_α, ScP₅O₁₄ (PET); SiK_α, sanidine (TAP); SmL_β, SmPO₄ (LLIF); SrL_α, SrSO₄ (TAP); TaM_α, CrTa₂O₆ (TAP); TbL_α, TbPO₄ (LLIF); ThM_α, CaTh(PO₄)₂ (PET); TiK_α, anatase (PET); UM_β, metallic U (PET); VK_β, vanadinite (LPET); YL_α, YPO₄ (PET); YbL_α, YbPO₄ (LLIF); and ZrL_α, zircon (TAP). The raw data were corrected using the PAP matrix corrections [6]. The detection limits were approximately 400–500 ppm for Y, 600 ppm for Zr, 500–800 ppm for REE, and 600–700 ppm for U and Th.

Apatite structural formula was calculated on the basis of 13 oxygen. The calculation of mineral formulas for end-member F-, Cl, and OH-apatites was performed according to Piccoli and Candela [7]. The formula of titanite was calculated on the basis of 1 Si as suggested by Harlov et al. [8]. Allanite formula was calculated on the basis of 12.5 oxygen and eight cations per formula using WinEpclas software developed by Yavuz and Yildirim [9].

4. Results

4.1 Petrology of the Blatná suite

Granitic rocks of the Blatná suite are formed by the Blatná hornblende-bearing biotite granodiorites and the Červená hornblende-biotite granodiorites. The Blatná granodiorites are medium-grained, usually equigranular rocks. Major components of these granodiorites are biotite (12–18 vol.%) formed by phlogopite-eastonite (Fe/Fe + Mg 0.48–0.51, Al^{4+} 2.4–2.6 apfu (atoms per formula unit), Ti 0.20–0.43 apfu), plagioclase (An_{23–31}) (40–42 vol.%), quartz (25–28 vol.%), K-feldspar (10–17 vol.%), and magnesiohornblende (0.2–0.7 vol.%) (**Figure 2**). The relatively rarely occurring porphyric variety contains K-feldspar phenocrysts, up to 1–2 cm big. Accessory minerals are represented by apatite, zircon, magnetite, titanite, and rare allanite.

The Červená granodiorites are medium-grained, equigranular to slightly porphyritic rocks, containing biotite (15–17 vol.%) formed by eastonite (Fe/Fe + Mg 0.44–0.47, Al^{4+} 2.5–2.6 apfu, and Ti 0.28–0.38 apfu), plagioclase (An_{22–40}) (28–41 vol.%), quartz (22–23 vol.%), K-feldspar (9–19 vol.%), and 1–2 vol.% hornblende (magnesiohornblende, actinolite) (**Figure 3**). Accessory minerals are represented by apatite, zircon, titanite, magnetite, and allanite. The Červená granodiorites display, in some cases, a strong planar fabric.

4.2 Chemical composition of the Blatná suite

The representative chemical analyses of the Blatná suite are presented in **Table 1**. These granodiorites are high-K, calc-alkaline to shoshonitic, and metaluminous to slightly peraluminous rocks ($A/CNK = \text{mol. } Al_2O_3 / (CaO + Na_2O + K_2O) = 0.8–1.2$). Compared to the common I-type granites [10, 11], these granodiorites are enriched in

Figure 2. Microphotograph of the Blatná granodiorite (Bt, biotite; Kfs, K-feldspar; Pl, plagioclase; Qz, quartz). Crossed polarizers.

Figure 3.
 Microphotograph of the Červená granodiorite (Bt, biotite; Kfs, K-feldspar; Pl, plagioclase; Qz, quartz). Crossed polarizers.

Mg (1.0–3.4 wt.% MgO), Ba (838–2560 ppm), Sr. (257–506 ppm), Zr (81–236 ppm), Th (2–32 ppm), and U (2–15 ppm).

4.3 Accessory minerals association and textures

The REE-, Zr-, and Y-bearing accessories in granodiorites of the Blatná suite are represented by apatite, zircon, and relatively rare occurred titanite and allanite. Apatite occurs usually in form of euhedral and subhedral grains (20–50 μm , rarely up to 100–120 μm) (**Figure 4**). Zircon usually occurs as small euhedral and subhedral grains (10–15 μm , rarely 50–70 μm). Both minerals are usually enclosed in biotite flakes. Apatite and zircon are sometimes zoned (**Figures 5 and 6**). Titanite occurs in relatively bigger, 100–200 μm , subhedral to euhedral grains (**Figure 7**). Allanite grains are 200–600 μm large, usually euhedral, interstitially grown between major mineral phases in the granodiorite groundmass (**Figure 8**). Its grains sometimes exhibit complex growth/alteration textures (**Figure 9**).

4.4 Apatite composition

All analyzed apatites contain more F (3.0–4.5 wt.%) and less Cl (0.0–0.2 wt.%) (**Table 2**). Their content of Fe (0.02–0.27 wt.% FeO) and Mn (0.02–0.12 wt.% MnO) are low. Their contents of sulfur and sodium are also low (0.01–0.28 wt.% SO_3 , 0.01–0.09 wt.% Na_2O). The concentrations of U and Th in analyzed apatite are low (0.01–0.09 wt.% UO_2 , 0.01–0.05 wt.% ThO_2). The concentrations of REE and Y are usually under microprobe detection limits. In analyzed apatite, grains were found La/Y ratios from 0.0 to 0.4. Zonation of analyzed apatites, that could be observed in the backscattered images (BSE) is very rare and is coupled with different concentrations of Y and REE. Light parties of analyzed apatite grain are enriched in Y (0.31 wt.% Y_2O_3) and REE (0.13 wt.% Ce_2O_3) (**Figure 5**).

Sample	R-704	R-708	R-782	R-794
Locality	Nahošín	Nahošín	Mečichov	Mečichov
Rock wt %	Biotite granodiorite	Biotite granodiorite	Amphibole-biotite granodiorite	Amphibole-biotite granodiorite
SiO ₂	69.52	68.50	63.38	63.26
TiO ₂	0.60	0.64	0.71	0.67
Al ₂ O ₃	15.66	15.59	16.02	16.28
Fe ₂ O ₃	0.01	0.26	0.80	0.83
FeO	2.08	2.45	3.55	3.46
MnO	0.04	0.05	0.07	0.07
MgO	1.27	1.47	2.65	2.65
CaO	1.98	2.40	3.25	3.45
Na ₂ O	3.26	3.12	3.06	3.25
K ₂ O	4.20	3.86	4.11	3.89
P ₂ O ₅	0.30	0.30	0.26	0.22
H ₂ O ⁺	0.83	0.72	0.86	0.64
H ₂ O ⁻	0.00	0.02	0.20	0.00
CO ₂	0.14	0.19	0.14	0.00
Total	99.89	99.57	99.06	98.67
A/CNK	1.26	1.14	1.04	1.03
ppm				
Ba	1165	1167	1562	1284
Rb	161	160	101	105
Sr	410	421	466	261
Nb	11	9	11	14
Zr	150	170	223	195
Y	23	21	29	29
U	9	9	8	8
Th	18	21	15	13

Table 1.
Representative chemical analyses of granodiorites.

4.5 Zircon composition

The analyzed zircons contain low Hf concentrations (1.1–1.7 wt.% HfO₂) (Table 3). The proportion of the hafnium end member indicated by atomic ratio Hf/(Zr + Hf) varies from 0.010 to 0.015 (Figure 10). The concentration of Y in analyzed zircon is partly variable and varies from 0.01 to 0.43 wt.% Y₂O₃. All analyzed zircons display lower concentrations of U (0.03–0.49 wt.% UO₂) and Th (0.01–0.19 wt.% ThO₂).

Figure 4.
Back-scattered electron (BSE) image of allanite from the Blatná granodiorite (Aln, allanite; Ap, apatite; Bt, biotite; Kfs, K-feldspar; Pl, plagioclase; Qz, quartz).

Figure 5.
BSE image of zoned apatite from the Červená granodiorite.

4.6 Titanite composition

The composition of titanite ranges from 83 to 92 mol.% titanite end-member (Table 4). The Al and Fe³⁺ contents range from 0.06 to 0.16 apfu and from 0.01 to

Figure 6.
BSE image of zoned zircon from the Červená granodiorite.

Figure 7.
BSE image of titanite (Ttn) from the Červená granodiorite.

0.04 apfu, respectively. Analyzed titanites show Al + Fe³⁺ excess over F. This excess indicates the occurrence of the coupled substitution of Al + Fe³⁺ (**Figure 11**). The content of (Al + Fe³⁺)-F component ranges from 6 to 13 mol.%. The content of (Al + Fe³⁺)-OH component is lower and ranges from 0 to 5 mol.%. The content of REE in analyzed titanites is usually low, however the content of Ce₂O₃ ranges from 0.11 to 0.33 wt.% and content of Nd₂ O₃ ranges from 0.02 to 0.30 wt.%.

Figure 8.
BSE image of allanite from the Blatná granodiorite (Aln, allanite; Bt, biotite; Kfs, K-feldspar; Qz, quartz).

Figure 9.
BSE image of altered allanite from the Blatná granodiorite (Aln, allanite; Bt, biotite; Py, pyrite).

4.7 Allanite composition

The originally magmatic allanite contains 31.4–32.4 wt.% SiO₂, 10.3–13.3 wt.% CaO, 9.8–15.1 wt.% FeO, 0.1–2.7 wt.% ThO₂, and 17.5–23.2 wt.% REE₂O₃ (**Table 5**). Analyzed allanites are relatively enriched by Mn, containing 0.23–0.65 wt.% MnO. All analyzed allanites display variable distribution of REE, with the preference of Ce over

Sample	R-704-5	R-712-44-	R-782-6	R-782-7	R-981-10
Locality	Nahošín	Nahošín	Mečichov	Mečichov	Mečichov
Rock wt. %	Blatná	Blatná	Červená	Červená	Červená
SO ₃	0.03	0.01	0.02	b.d.l.	b.d.l.
P ₂ O ₅	40.95	41.40	40.54	40.89	40.67
SiO ₂	0.81	0.48	0.07	0.45	0.12
La ₂ O ₃	b.d.l.	0.08	b.d.l.	0.02	0.04
Ce ₂ O ₃	0.18	0.26	0.02	0.13	0.04
Pr ₂ O ₃	0.14	0.13	b.d.l.	b.d.l.	b.d.l.
Nd ₂ O ₃	0.16	0.27	0.03	0.12	0.08
Sm ₂ O ₃	0.17	0.11	0.03	0.06	b.d.l.
Gd ₂ O ₃	0.15	0.07	0.04	0.13	b.d.l.
Dy ₂ O ₃	0.07	0.08	0.02	0.01	b.d.l.
Er ₂ O ₃	0.05	0.05	0.05	0.06	b.d.l.
Y ₂ O ₃	0.63	0.38	0.05	0.31	0.08
ThO ₂	0.01	0.03	0.04	b.d.l.	b.d.l.
UO ₂	0.04	0.07	b.d.l.	b.d.l.	b.d.l.
CaO	53.74	53.82	55.55	54.50	56.06
FeO	0.13	0.13	0.12	0.19	0.01
MnO	0.02	0.08	0.04	0.07	0.03
SrO	b.d.l.	b.d.l.	0.02	0.04	b.d.l.
Na ₂ O	0.05	0.02	b.d.l.	b.d.l.	0.08
SO ₃	0.03	0.01	0.02	b.d.l.	b.d.l.
F	3.71	3.57	3.14	3.09	3.46
Cl	0.02	0.02	0.08	0.05	0.14
O=F,Cl	1.57	1.51	1.34	1.31	1.49
Total					
X _{Fap}	0.985	0.948	0.834	0.820	0.919
X _{Clap}	0.003	0.003	0.012	0.007	0.021
X _{OHap}	0.012	0.049	0.154	0.173	0.060

b.d.l., below detection limit.

Table 2.
Representative microprobe analyses of apatite.

La. Cerium is thus the predominant lanthanide, thus these allanites could be classified as allanite-(Ce). On the plot proposed by Petrík et al. [12], the analyzed allanites are located between allanite and ferriallanite (**Figure 12**). The Al values range between 1.44 and 2.12 apfu. It can be also observed, that the individual points are located between isolines 0.2 and 0.5 $Fe_{ox.} = Fe^{3+}/(Fe^{3+} + Fe^{2+})$. The values of these points calculated by the method Armbruster et al. [13] are partly lower (0.18–0.43).

Sample	R-704-1	R-704-2	R-704-15	R-782-3	R-977-15
Locality	Nahošín	Nahošín	Nahošín	Mečichov	Mečichov
Rock wt. %	Blatná	Blatná	Červená	Červená	Červená
SiO ₂	32.51	32.34	32.63	32.47	32.23
Al ₂ O ₃	0.01	b.d.l.	b.d.l.	b.d.l.	0.01
ZrO ₂	64.92	64.15	64.61	66.36	65.82
HfO ₂	1.22	1.20	1.47	1.23	1.39
CaO	0.04	0.06	0.02	0.03	0.01
FeO	b.d.l.	0.11	0.24	0.05	0.32
P ₂ O ₅	0.11	0.10	0.06	0.01	b.d.l.
Sc ₂ O ₃	0.01	0.03	0.04	0.04	b.d.l.
Y ₂ O ₃	0.23	0.37	0.21	b.d.l.	b.d.l.
La ₂ O ₃	0.04	0.01	b.d.l.	b.d.l.	b.d.l.
Ce ₂ O ₃	0.05	0.05	b.d.l.	0.06	b.d.l.
Dy ₂ O ₃	0.05	0.10	0.05	0.01	0.01
Er ₂ O ₃	0.04	0.10	0.02	0.06	0.06
Yb ₂ O ₃	0.09	0.05	0.01	0.05	0.01
UO ₂	0.20	0.25	0.23	0.19	0.18
ThO ₂	0.02	0.11	0.12	0.07	0.04
Total	99.54	99.03	99.71	100.63	100.08
apfu, O = 4					
Si	1.002	1.003	1.005	0.994	0.993
Al	0.000	0.000	0.000	0.000	0.000
Zr	0.970	0.970	0.970	0.990	0.988
Hf	0.011	0.011	0.013	0.011	0.012
Ca	0.001	0.002	0.001	0.001	0.000
Fe	0.000	0.003	0.006	0.001	0.008
P	0.003	0.003	0.002	0.000	0.000
Sc	0.000	0.001	0.001	0.001	0.000
Y	0.004	0.006	0.003	0.000	0.000
La	0.000	0.000	0.000	0.000	0.000
Ce	0.001	0.001	0.000	0.001	0.000
Dy	0.000	0.001	0.000	0.000	0.000
Er	0.000	0.001	0.000	0.001	0.001
Yb	0.001	0.000	0.000	0.000	0.000
U	0.001	0.002	0.002	0.001	0.001
Th	0.000	0.001	0.001	0.000	0.000

b.d.l., below detection limit.

Table 3.
Representative microprobe analyses of zircon.

Figure 10.
Chemical composition of zircon from granodiorites of the Blatná suite.

The altered allanites are enriched in Si (40.6–42.0 wt.% SiO₂ and Th (3.1–6.4 wt.% ThO₂), depleted in Fe (2.2–4.2 wt.% FeO) and Ca (5.8–8.6 wt.% CaO). The altered allanites display also a lower total analytical sum, which indicate postmagmatic alterations.

5. Discussion

5.1 Fractionation of the Blatná suite

The high-K calc-alkaline to shoshonitic granitic rocks of the Blatná suite could be classified as hybrid H-granites in the sense of granite classification proposed by Castro et al. [14]. According to the primary Rb/Sr. ratio and the Nd-isotope ratios, the origin of this suite could be coupled either by mixing of different magmas with distinct isotopic features and/or by crustal contamination of more basic magmas. According to some other interpretation, granitic rocks of the Blatná suite are products of fractionation mantle-derived magmas and their mixing with relatively heated metamorphic rocks of the Moldanubian Zone [15]. The recently preferred explanation of the Blatná suite origin is coupled with remelting of a heterogeneous earth crust composed of immature greywackes rich in the Cambrian volcanogenic detritus [2]. An additional important process was variable mixing with slightly enriched mantle-derived monzonitic magmas, which also may have supplied the extra heat needed for the crustal anatexis [1].

5.2 Substitution in apatite

There are systematic and distinctive differences in Fe, Mn, REE, F, and Cl contents in apatites from I- and S-type granitic rocks [7, 16]. For I-type, granitic rocks are

Sample	R-704-10	R-704-12	R-712-52	R-782-1	R-782-10
Locality	Nahošín	Nahošín	Nahošín	Mečichov	Mečichov
Rock wt. %	Blatná	Blatná	Blatná	Červená	Červená
SiO ₂	30.38	30.63	30.36	31.09	30.93
TiO ₂	37.42	36.23	36.70	35.60	34.68
Nb ₂ O ₅	0.42	0.24	0.10	0.31	0.05
Ta ₂ O ₅	0.03	b.d.l.	0.11	0.08	0.03
Al ₂ O ₃	1.50	2.07	2.11	2.36	4.30
FeO	0.64	0.87	0.62	0.42	0.52
MnO	0.09	0.07	0.07	0.07	0.02
CaO	28.68	28.77	29.26	28.15	29.05
MgO	b.d.l.	0.01	0.01	b.d.l.	0.03
Na ₂ O	0.02	0.03	0.01	0.02	0.02
K ₂ O	0.02	b.d.l.	b.d.l.	b.d.l.	0.02
La ₂ O ₃	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Ce ₂ O ₃	0.18	0.12	0.16	0.20	0.14
Pr ₂ O ₃	b.d.l.	0.02	0.01	b.d.l.	0.08
Nd ₂ O ₃	0.11	0.03	b.d.l.	0.13	b.d.l.
Y ₂ O ₃	0.09	0.09	0.11	0.28	0.02
ZrO ₂	0.03	0.02	b.d.l.	b.d.l.	b.d.l.
ThO ₂	0.05	b.d.l.	b.d.l.	0.06	b.d.l.
V ₂ O ₃	0.39	0.17	0.24	0.25	0.19
F	0.71	0.84	0.63	0.80	1.33
O=F	0.30	0.35	0.27	0.34	0.56
Total	100.83	100.37	100.57	99.87	101.47
Si	1.000	1.000	1.000	1.000	1.000
Ti	0.926	0.890	0.909	0.861	0.843
Nb	0.006	0.004	0.001	0.005	0.001
Ta	0.000	0.000	0.001	0.001	0.000
Al	0.058	0.080	0.082	0.089	0.164
Fe ³⁺	0.018	0.024	0.017	0.011	0.014
Mn	0.003	0.002	0.002	0.002	0.001
Ca	1.011	1.006	1.033	0.970	1.006
Mg	0.000	0.000	0.000	0.000	0.001
Na	0.001	0.002	0.001	0.001	0.001
K	0.001	0.000	0.000	0.000	0.001
La	0.000	0.000	0.000	0.000	0.000
Ce	0.002	0.002	0.002	0.002	0.002
Pr	0.000	0.000	0.000	0.000	0.001

Sample	R-704-10	R-704-12	R-712-52	R-782-1	R-782-10
Locality	Nahošín	Nahošín	Nahošín	Mečichov	Mečichov
Rock wt. %	Blatná	Blatná	Blatná	Červená	Červená
Nd	0.001	0.000	0.000	0.001	0.000
Y	0.002	0.002	0.002	0.005	0.000
Zr	0.000	0.000	0.000	0.000	0.000
Th	0.000	0.000	0.000	0.000	0.000
V	0.010	0.004	0.006	0.006	0.005
F	0.074	0.087	0.066	0.081	0.136
OH	0.002	0.017	0.033	0.019	0.042
X(Ttn)	0.92415	0.89537	0.90179	0.89594	0.82566
X(Al,Fe ³⁺ -F)	0.07385	0.08753	0.06548	0.08429	0.13320
X(Al,Fe ³⁺ -OH)	0.00200	0.01710	0.03274	0.01977	0.04114

b.d.l., below detection limit.

Table 4.
Representative microprobe analyses of titanite.

Figure 11.
Chemical composition of titanite from granodiorites of the Blatná suite.

significant a lower content of Fe and Mn, higher contents of LREE, and lower content of Y [17]. The content of Fe in analyzed apatites is 0.02–0.27 wt.% FeO and content of Mn in these apatites is 0.03–0.12 wt.% MnO. The increase of Mn content in apatites

Sample	R-704-27	R-704-28	R-704-35	R-977-26
Locality	Nahošín	Nahošín	Nahošín	Mečichov
Rock wt. %	Blatná	Blatná	Blatná	Červená
SiO ₂	31.44	31.43	31.85	32.53
TiO ₂	1.10	1.18	1.64	0.39
Al ₂ O ₃	13.80	13.64	15.19	19.59
FeO	15.14	15.03	12.85	9.77
MnO	0.53	0.41	0.47	0.35
MgO	1.45	1.41	1.15	0.68
CaO	10.74	10.93	11.05	13.83
Na ₂ O	0.06	0.01	0.06	b.d.l.
La ₂ O ₃	6.18	6.39	3.04	3.32
Ce ₂ O ₃	11.49	11.58	9.83	8.65
Pr ₂ O ₃	1.14	1.14	1.46	1.02
Nd ₂ O ₃	3.56	3.66	5.95	4.42
Sm ₂ O ₃	0.31	0.29	0.91	0.62
Gd ₂ O ₃	0.21	0.08	0.53	0.42
Tb ₂ O ₃	b.d.l.	0.05	0.08	0.04
Y ₂ O ₃	0.16	0.13	0.52	0.31
ThO ₂	0.80	0.82	1.93	0.06
UO ₂	0.04	0.04	0.09	0.03
F	0.25	0.21	0.17	0.08
O=F	0.11	0.09	0.07	0.03
Total	98.30	98.34	98.70	96.22
apfu, O = 12.5				
Si	2.992	2.998	3018	2.986
Al(IV)	0.008	0.002	0.,000	0.014
Total-T-site	3.000	3.000	3.018	3.000
Ti	0.079	0.085	0.117	0.027
Al(VI)	1.540	1.531	1.696	2.106
Fe ³⁺	0.482	0.452	0.184	0.216
Fe ²⁺	0.693	0.731	0.834	0.534
Mn ²⁺	0.000	0.000	0.006	0.024
Mg	0.206	0.201	0.162	0.093
Total-M-site	3.000	3.000	3.000	3.000
Mn ²⁺	0.043	0.033	0.032	0.003
Fe ²⁺	0.030	0.016	0.000	0.000
Ca	1.095	1.117	1.122	1.360
Na	0.011	0.002	0.011	0.000

Sample	R-704-27	R-704-28	R-704-35	R-977-26
Locality	Nahošín	Nahošín	Nahošín	Mečichov
Rock wt. %	Blatná	Blatná	Blatná	Červená
REE	0.803	0.814	0.774	0.635
Th	0.017	0.018	0.042	0.001
U	0.001	0.001	0.002	0.001
Total-A-site	2.000	2.000	1.982	2.000
F	0.075	0.063	0.051	0.023
F _{ox.}	0.40	0.38	0.18	0.29

b.d.l., below detection limit.

Table 5.
Representative microprobe analyses of allanite.

Figure 12.
The plot of total REE + Y + Th + Mn vs. Al contoured with isolines of the ratio $F_{ox.} = Fe^{3+}/(Fe^{2+} + Fe^{3+})$ illustrating the chemical relationships in the system allanite-ferriallanite-epidote-clinozoisite according Petřík et al. [12].

from S-type granitic rocks is a function of an increase of Mn/Fe and Mn/Ca ratios with fractionation [16]. The La/Y ratio in analyzed apatites is 0.01–0.40. This ratio is partly comparable with the La/Y ratio for I-type granitic rocks (0.2–3.25) according to Sha and Chappell [17].

5.3 Substitution in zircon

The most common trace element in zircon is hafnium. The HfO₂ contents in granitic rocks usually range from 0.5 to 9.9 wt.%, with a median of 1.5 wt.% [18]. In

similar granitic rocks from the Bohemian Massif, their contents usually range between 0.8 and 2.2 wt.% HfO₂ [19, 20]. The content of Y in zircon from granitic rocks is usually 0.2–0.7 wt.% Y₂O₃ [21]. In similar, biotite granites that form the Moldanubian batholith zircon contains 0.1–0.9 wt.% Y₂O₃ [19]. The content of ThO₂ in F-low biotite granites from the Krušné Hory/Erzgebirge batholith is partly higher (up to 1.3 wt.% ThO₂) [20], whereas its content in zircon from two-mica granites of the Moldanubian batholith is similar (0.01–0.2 wt.% ThO₂) [19].

5.4 Substitution in titanite

Titanite is, according to the variability of its chemical composition, suggested as a highly sensitive indicator of oxygen and water fugacity [22–24]. The chemical composition of analyzed titanite shows that the substitution (Al, Fe³⁺) + F = Ti⁴⁺ O²⁻ is the most significant in analyzed titanites. According to their F, Al, and Fe³⁺ concentrations, the analyzed titanites could be considered as low-Al titanites, according to Oberti et al. [25]. Their low F and Al content could be well compared with the contents of both elements in similar magmatic titanites [26].

5.5 Substitution in allanite

For allanite, two main substitutions occur, namely the epidote-allanite and the allanite-ferriallanite substitutions [27, 28]. For analyzed allanites from granodiorites of the Blatná suite, the allanite-ferriallanite substitution is significant. In the other Variscan granitic rocks from the Bohemian Massif allanite was found in some granites and granodiorites of the Moldanubian batholith [29] and from lamprophyres of the Krkonoše-Jizera composite pluton [30]. Allanites from both magmatic bodies display similar chemical compositions and also similar values of Fe_{ox.} = 0.3–0.5.

6. Conclusions

The granodiorites of the Blatná suite contain 12–18 vol.% of biotite, 28–42 vol.% plagioclase, 22–28 vol.% quartz, 9–19 vol.% K-feldspar, and 0.2–1.2 vol.% hornblende. These granodiorites are high-K, calc-alkaline to shoshonitic rocks.

The REE-, Zr-, and Y-bearing accessories in granodiorites of the Blatná suite are represented by apatite, zircon, and relatively rare occurred titanite and allanite. All analyzed apatites contain more F (3.0–4.5 wt.%) and less Cl (0.0–0.2 wt.%). Apatite zonation is very rare and coupled with different concentrations of Y and REE. The analyzed zircons contain low Hf concentrations (1.1–1.7 wt.% HfO₂). The composition of analyzed titanite ranges from 83 to 92 mol.% titanite end-member. The analyzed allanites display variable distribution of REE, with the preference of Ce over La. Allanite is relatively Al-poor and displays Fe_{ox.} ratio 0.2–0.5.

Acknowledgements

This study was carried out thanks to the support of the long-term conceptual development research organization RVO 67985891. I am grateful to R. Škoda, R. Čopjaková, and J. Haifler from the Department of geological sciences of Masaryk

University for technical assistance by electron microprobe analyses of selected minerals (allanite, apatite, titanite, and zircon).

Conflict of interest

The author declares no conflict of interest.

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