Crystal chemistry and origin of grandidierite, ominelite, boralsilite, and werdingite from the Bory Granulite Massif, Czech Republic

JAN CEMPÍREK,^{1,*} MILAN NOVÁK,² ZDENĚK DOLNÍČEK,³ JANA KOTKOVÁ,^{2,4} AND RADEK ŠKODA²

¹Department of Mineralogy and Petrography, Moravian Museum, Zelný trh 6, 65937 Brno, Czech Republic
 ²Department of Geological Sciences, Masaryk University, Kotlářská 2, 61137 Brno, Czech Republic
 ³Department of Geology, Palacký University, třída 17. listopadu 12, 77146 Olomouc, Czech Republic
 ⁴Czech Geological Survey, Klárov 3, 118 21 Prague 1, Czech Republic

ABSTRACT

A mineral assemblage involving grandidierite, ominelite, boralsilite, werdingite, dumortierite (locally Sb,Ti-rich), tourmaline, and corundum, along with the matrix minerals K-feldspar, quartz, and plagioclase, was found in a veinlet cutting leucocratic granulite at Horní Bory, Bory Granulite Massif, Moldanubian Zone of the Bohemian Massif. Zoned crystals of primary grandidierite to ominelite enclosed in quartz are locally overgrown by prismatic crystals of boralsilite and Fe-rich werdingite. Boralsilite also occurs as separate cross-shaped plumose aggregates with Fe-rich werdingite in quartz. Grandidierite is commonly rimmed by a narrow zone of secondary tourmaline or is partially replaced by the assemblage tournaline + corundum \pm herevnite. Grandidierite ($X_{\text{Fe}} = 0.34-0.71$) exhibits dominant FeMg₋₁ substitution and elevated contents of Li (120–1890 ppm). Boralsilite formula ranges from Al_{15.97}B_{6.20}Si_{1.80}O₃₇ to Al_{15.65}B_{5.29}Si_{2.71}O₃₇ and the formula of werdingite ranges from (Fe,Mg)₁₄₄Al₁₄₆₁B₄₀₀Si_{3.80}O₃₇ to (Fe,Mg)₁₂₂Al₁₄₈₆B_{4.25}Si_{3.55}O₃₇. Dumortierite and Sb,Ti-rich dumortierite occur as zoned crystals with zones poor in minor elements (≤0.12 apfu Fe+Mg) and zones enriched in Sb (≤ 0.46 apfu) and Ti (≤ 0.25 apfu). Secondary tournaline ($X_{Fe} = 0.44-0.75$) of the schorlmagnesiofotite-foitite-olenite solid solution occurs as a replacement product of grandidierite, rarely boralsilite. Other accessory minerals in the veinlet include monazite-(Ce), ilmenite, rutile, ferberite, srilankite, löllingite, arsenopyrite, and apatite. Formation of the borosilicate-bearing veinlet post-dates the development of foliation in the host granulite and is related to the decompressional process. The assemblage most probably originated from a H₂O-poor system at $T \sim 750$ °C and $P \sim 6-8$ kbar. Textural relations as well as geological position of the borosilicate veinlet suggest that it represents the earliest intrusion related to pegmatites in the Bory Granulite Massif. Younger granitic pegmatites in the area are characterized by high contents of B, Al, P, Fe, and minor concentrations of W, Ti, Zr, Sc, and Sb. All pegmatite types probably formed within a short time period of ~5 Ma.

Keywords: Boron, grandidierite, ominelite, werdingite, boralsilite, granulite, partial melting, Moldanubicum, Bohemian Massif

INTRODUCTION

Anhydrous borosilicates with mullite-type structure represent an uncommon but very distinct group of minerals associated with rocks of a specific peraluminous composition, in most cases metamorphosed under high-temperature and low- to medium-pressure conditions (Grew 1996). Grandidierite is the most common, as it is known from more than 40 occurrences worldwide in peraluminous metamorphic rocks (rarely in calcsilicate rocks) as well as in abyssal (metamorphogenic) pegmatites, commonly in Precambrian terrains [e.g., Madagascar, Antarctica, Norway, Canada; see review in Grew (1996)]. On the other hand, ominelite—the Fe-analog of grandidierite—is rare, as it has been known only from five localities so far (Hiroi et al. 2001; Dzikowski et al. 2007; Buick et al. 2008). Other rare anhydrous borosilicates include werdingite, boralsilite, and

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boromullite. Werdingite occurs in granulite-facies metamorphic rocks in South Africa, Zimbabwe, and Australia (Moore et al. 1990; Grew et al. 1997; Buick et al. 2008) and in abyssal pegmatites in Madagascar, Norway, and Antarctica (Grew et al. 1998b, 2008). Boralsilite has been found in two localities so far, in Antarctica and Norway (Grew et al. 1998a, 2008), whereas boromullite is known only from a single locality in granulitic rock in Australia (Buick et al. 2008). The anhydrous borosilicates are commonly associated with or replaced by hydrous borosilicates, e.g., minerals of kornerupine-prismatine series, tourmaline or dumortierite (e.g., Huijsmans et al. 1982; Grew 1996; Grew et al. 1998a, 1998b).

Borosilicate occurrences are also important for petrological and geochemical considerations, as borosilicates commonly store light elements under high-grade conditions. For this reason, stability fields of the most common borosilicates (e.g., tourmaline, dumortierite, kornerupine, grandidierite, werdingite) were experimentally studied (e.g., Schreyer and Werding 1997).

^{*} E-mail: jcempirek@mzm.cz

We report here the first occurrence of grandidierite, ominelite, werdingite, and boralsilite from the Bohemian Massif, as well as from the Variscan orogene. The minerals were found in a veinlet cutting leucocratic granulite of the Variscan age. We discuss crystal chemistry of the individual minerals based on electron microprobe analyses (EMPA) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), origin of the paragenesis of the borosilicates in the veinlet, and the relationship to spatially associated peraluminous, low-pressure granitic pegmatites of the Bory Granulite Massif.

GEOLOGICAL BACKGROUND

The Bory Granulite Massif is located in the Strážek Moldanubicum, the easternmost part of the Moldanubian Zone of the Bohemian Massif, where the lens-shaped ENE-WSW trending granulite body (10×3.5 km in diameter) occurs in the SW flank of a large-scale brachysynform (Fig. 1). It is a member of Gföhl Unit, a rock suite metamorphosed under high-pressure conditions (e.g., O'Brien and Rötzler 2003) and typical by occurrences of boron-enriched lithologies, e.g., tourmaline- and dumortierite-rich migmatites, migmatitic gneisses, and related abyssal (metamorphogenic) pegmatites (Fig. 1b; e.g., Fuchs et al. 2005; Cempírek and Novák 2006; Vrána et al. 2009).

The granulite body is constituted predominantly by: (1) leucocratic fine-grained felsic granulites (quartz + alkali-feldspar + plagioclase + garnet + kyanite and/or sillimanite ± biotite), alternating with (2) melanocratic garnet + biotite ± cordierite-rich granulites to (3) granulite gneisses in layers, several centimeters to first meters thick. The granulite gneisses (quartz + K-feldspar + plagioclase + garnet + cordierite + kyanite and/or sillimanite) are massive to strongly foliated. The accessory minerals in granulitic rocks include rutile, hercynite, apatite, ilmenite, zircon, and monazite (Kotková and Melichar 2003). The cordierite-bearing, K-feldspar-rich leucosome with diffusive contacts and pegmatitic textures (graphic intergrowths, blocky K-feldspar) is another typical rock closely associated with the melanocratic granulite (Povondra et al. 1992; Kotková et al. 2003). The granulites are weakly to strongly peraluminous (A/CNK 1.17-1.8) and they correspond to leucogranite-granite-quartz diorite in the TAS classification (Cox et al. 1979; Kotková and Melichar 2003), similar to the other high-pressure granulites of the Bohemian Massif. These granulites were exhumed along a steep P-T path from a deeper level of the orogenic crust, which is suggested also by their association with mantle rocks and by P-T estimates corresponding to ~16 kbar and ~1000 °C (O'Brien and Rötzler 2003; Kotková 2007). The only remnant of the initial high-pressure conditions of the Bory granulite is the elevated grossular content in garnet cores (which depends on the bulk rock composition), as it has been extensively overprinted at medium- and low-pressure conditions. Thermodynamic modeling for Bory granulite yielded the "peak" *P-T* conditions of 16 kbar for 850–900 °C (X_{Grs} = 0.11; Hrouda et al. 2009). Extensively developed disequilibrium reaction textures, i.e., transformation of kyanite into sillimanite, hercynite coronas around kyanite or sillimanite, orthopyroxene



FIGURE 1. Schematic geological maps of the eastern part of the Variscan orogene (**a**), eastern part of the Moldanubian Zone (**b**), and of the Bory Granulite Massif (**c**). In **b**, dumortierite occurrences in the Gföhl Unit are marked by symbols. In **c**, only the largest pegmatite dikes of the Bory pegmatite district are shown. The studied locality is marked by a four-pointed star. [Figures modified from Duda (1986), Fiala et al. (1995), Kachlík (1999), Fuchs et al. (2005), and Cempírek and Novák (2006)]. Symbols: 1 = major occurrences of dumortierite in boron-bearing granulites and migmatites; 2 = rare occurrences in granulites, migmatites, and gneisses; 3 = occurrences in abyssal pegmatites.

+ plagioclase and cordierite + quartz symplectites consuming garnet, suggest a significant decompression to the spinel or cordierite stability fields (Kotková and Melichar 2003). Such *P-T* evolution is comparable with the trend of the *P-T* path derived for the eastern part of the Strážek Moldanubicum (Tajčmanová et al. 2006, 2007) rather than that of Hrouda et al. (2009) (based only on the correlation with another terrane). Decompressionrelated reaction textures also have been extensively developed in peridotites, pyroxenites, and eclogites, which occur in spectacular boudins in the Horní Bory quarry, where the borosilicate-bearing veinlet was found. The peak *P-T* conditions calculated for these rocks correspond to 3.8–4.8 GPa and 900–1000 °C (Medaris et al. 2005; Ackerman et al. 2009; Naemura et al. 2009).

Radiometric dating of the Bory Granulite Massif [349+9/–10 Ma, U-Pb zircon; Kröner et al. (1988)] is consistent with other data from granulites in the Bohemian Massif (~340 Ma). This age is commonly attributed to the peak pressure stage of the granulite evolution [see Kotková (2007) for review].

Granitic pegmatites showing a wide range of geochemical evolution are common in the Bory Granulite Massif and its close vicinity (Novák 2005). The pegmatites are represented, in order from the most primitive to the most evolved by (1) nearly homogeneous, coarse-grained, cordierite-rich leucosome {K-feldspar + quartz + plagioclase + cordierite $[X_{Fe} = 0.44 - 0.50; X_{Fe} = Fe_{tot})$ $(Fe_{tot}+Mg)$] + biotite}, locally with pegmatitic texture (graphic intergrowths of Qtz+Kfs, blocky Kfs); (2) simply zoned, primitive pegmatites (K-feldspar + quartz + plagioclase + muscovite + tourmaline + andalusite + pinitized cordierite + biotite + apatite) with diffusive contacts and locally large crystals of smoky quartz in pockets; (3) cross-cutting, symmetrically zoned pegmatites [K-feldspar + quartz + albite + muscovite + tourmaline + andalusite + sekaninaite ($X_{\text{Fe}} = 0.74 - 0.97$) + biotite + apatite] with sharp contacts and locally containing primary Fe,Mn-phosphates (triplite, zwieselite, triphylite, graftonite), pyrite, löllingite, and numerous accessory minerals; (4) discordant, highly evolved, symmetrically zoned, complex lepidolite pegmatites with sharp contacts to the host rock (Duda 1986; Staněk 1991; Novák et al. 1992; Novák 2005).

Tourmaline is widespread and ranges from dravite-schorlfoitite solid solution in the primitive pegmatites (Pegmatite types 1, 2, and 3) to schorl-foitite and elbaite-rossmanite in the highly evolved pegmatites (Pegmatite type 4). Dumortierite is also present as a rare accessory mineral in all pegmatite types (Selway et al. 1999; Novák et al. 2004b; Novák and Taylor 2000; Cempírek and Novák 2006). At the studied locality, primitive pegmatites (Pegmatite types 1 and 2) are enclosed in the granulite and granulite gneisses ca. 20 m from the studied borosilicate occurrence.

The U-Pb radiometric data (conventional method) on two individual grains of monazite-(Ce) from the discordant (Pegmatite type 3) pegmatite dike Oldřich, Dolní Bory-Hatě provided ages of 335.8 ± 2 and 337.2 ± 2 Ma (Novák et al. 1998).

EXPERIMENTAL METHODS

Chemical composition of all minerals was studied using an electron microprobe Cameca SX-100 (Laboratory of Electron Microscopy and Microanalysis, the joint facility of the Masaryk University and Czech Geological Survey in Brno; operator R. Škoda). The following analytical conditions were applied: accelerating voltage 15 kV, beam diameter 1–5 μ m, beam current 10–20 nA. The following standards were used for tourmaline, grandidierite, ominelite, boralsilite, and werdingite ($K\alpha$ lines if not specified): sanidine (Si,Al,K), hornblende (Ti), andradite (Ca,Fe), rhodonite (Mn), albite (Na), olivine (Mg), chromite (Cr), topaz (F), vanadinite (Cl), fluorapatite (P), ZnS (Zn), metallic Cu (Cu), and metallic V (VK β). For other minerals, some standards were modified or added, i.e., for hercynite: MgAl₂O₄ (Al,Mg) and gahnite (ZnL α); for garnet: spessartine (Si,Mn), sanidine (Al,K), MgAl₂O₄ (Mg), almandine (Fe), metallic Ni (Ni), andradite (Ca), and YAG (YL α); for dumortierite: InAs (AsL α), metallic W (WL α), and Sb (SbL β); for feldspars: barite (BaL α) and SrSO₄ (SrL α). Raw data were reduced using the PAP correction (Pouchou and Pichoir 1985).

Boron in grandidierite and werdingite was analyzed on BK α in peak-area mode using a slightly modified approach described in Grew et al. (2008). We used a Ni/C multilayered monochromator 2d = 95 Å (PC2). Peak integration was carried out over 2000 steps in wavelengths range 61–74 Å and the peak integration time was 240 s. The first and last 150 steps were used for background. The accelerating voltage was 5 kV, beam current 60 nA, and beam size 8 µm. Buergerite (San Luis Potosi, Mexico) was used as a standard. Reliability of the method was confirmed on ideal stichiometry of analyzed grandidierite. Only two analytical spots were done for werdingite due to its small grain size (usually less than 10 µm).

Trace elements in grandidierite and garnet were studied using LA-ICP-MS. The instrumentation for LA-ICP-MS (Masaryk University, Institute of Chemistry) consists of a laser ablation system UP 213 (New Wave, U.S.A.), an ICP-MS spectrometer Agilent 7500 CE (Agilent, Japan) and a commercial Q-switched Nd: YAG laser with the wavelength of 213 nm. Optimization of LA-ICP-MS conditions (gas flow rates, sampling depth, electrostatic lenses voltages of the MS) was performed with the glass reference material NIST SRM 612 in respect to maximum S/N ratio and minimum oxide formation (ThO⁺/Th⁺ counts ratio 0.2%, U⁺/Th⁺ counts ratio 1.1%). Laser ablation was performed with laser spot diameter 80 µm, laser fluency 4.5 J/cm², and repetition rate 10 Hz. The detected elements include: Li, Be, B, Na, Mg, Al, Si, P, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Rb, Sr, Y, Zr, Nb, Sn, Sb, Cs, Ba, REE, Hf, Ta, W, Pb, Bi, Th, and U.

Whole-rock chemical analyses were performed at the ACME Analytical Laboratories Ltd, Vancouver, Canada, using ICP-ES (major oxides, Ba, Ni, Sc, Mo, Cu, Pb, Zn, As, Cd, Sb, Bi, and Ag) and ICP-MS (Co, Cs, Ga, Hf, Nb, Rb, Sn, Sr, Ta, Th, Tl, U, V, W, Zr, Y, and REE).

Fluid inclusions (FI) were studied by means of optical microthermometry. Microthermometric parameters (Tm-CO₂ = melting temperature of solid CO₂; Th-CO₂ = homogenization temperature of CO₂ phase; Tm-cla = melting temperature of clathrate; Tm-ice = melting temperature of ice; Th-tot = temperature of final homogenization; Te = eutectic temperature) were measured using Linkam THMSG 600 stage mounted on Olympus BX-51 microscope (Palacký University, Olomouc). The stage was calibrated between -56.6 and 374.1 °C with inorganic standards and synthetic FI. The fluid composition, densities, and isochores were calculated using Flincor software (Brown 1989) with calibration by Bowers and Helgeson (1983), Holloway (1981), and Zhang and Frantz (1987) for CO₂-H₂O-NaCl, CH₄, and H₂O-NaCl fluids, respectively. Most of the abbreviations of mineral names used in the text are after Kretz (1983) and Whitney and Evans (2010).

HOST ROCK PETROGRAPHY AND GEOCHEMISTRY

Fine- to medium-grained host leucocratic granulite cut by the veinlet exhibits distinct foliated fabric (Fig. 2) with typical quartz ribbons, featuring asymmetric deformation structures such as σ -type porphyroclasts of feldspar, kyanite, or sillimanite with asymmetric pressure shadows. The granulite exhibits a simple mineral assemblage: quartz + alkali feldspar $(Or_{91}Ab_9 - Or_{83}Ab_{16}An_1) + plagioclase (Ab_{86}An_{12}Or_2 - Ab_{84}An_{14})$ Or_2 + garnet (Alm₇₄Sps₈Prp₁₄Grs₄-Alm₇₉Sps₁₂Prp₈Grs₁) + kyanite + sillimanite; biotite was not found in the samples of granulite with the borosilicate veinlet. K-feldspar is commonly perthitic, and large grains of plagioclase are also antiperthitic. Prismatic kyanite, sillimanite, and anhedral garnet are usually rimmed by plagioclase, and aluminosilicate is commonly consumed by plagioclase + hercynite ($Hc_{89}Spl_{10}Gx_1$) symplectite or locally transformed into kaolinite-like mineral. Accessory minerals include rare rutile, ilmenite, sphalerite, apatite, and monazite.

Whole-rock analysis (Table 1) features a very high SiO₂



FIGURE 2. Photograph of the grandidierite-bearing veinlet. Granulite foliation is marked.

content, strongly peraluminous character (A/CNK = 1.27), and granitic composition of the leucogranulite (TAS diagram; Cox et al. 1979). Contents of all trace elements, except for Sr, are lower compared to the other Moldanubian granulites (cf. Janoušek et al. 2004), and the most pronounced depletion is observed especially in HREE and HFSE. The rock exhibits elevated K/Rb = 300, very low Rb/Sr = 0.662, K/Ba = 161, fractionated LREE/HREE patterns with $La_N/Yb_N = 6.74$, low $Gd_N/Yb_N = 0.25$ (cf. patterns of garnet) and a positive Eu anomaly (Eu/Eu* = 2.7) in the chondrite-normalized data (Fig. 3). The high ASI of the leucogranulite and trace element composition suggest that it most probably originated during water-undersaturated melting producing Kfs-bearing melts with high LILE (K, Rb), low HFSE, and low REE contents indicating that the accessories were not dissolved during the disequilibrium melting (Watt and Harley 1993).

Garnet grains are rather homogeneous with slightly elevated contents of grossularite component (CaO < 1.43 wt%; 0.122 apfu), Na₂O (<0.07 wt%; 0.011 apfu), and P₂O₅ (<1.16 wt%; 0.081 apfu) in grain centers (Table 2). Elevated contents of the grossularite component in grain centers along with the higher

TABLE 1. Whole-rock analysis of leucogranulite hosting the borosilicate-bearing veinlet

| | cute beu | ing venie | | | | | |
|--------------------|----------|-----------|-------|----|-------|----|------|
| P_2O_5 | 0.07 | Ba | 246.0 | Sb | 0.2 | La | 5.8 |
| TiO₂ | 0.05 | Co | 0.9 | Sc | 12.0 | Ce | 9.2 |
| SiO ₂ | 74.44 | Cs | 0.6 | Sn | 3.0 | Pr | 0.87 |
| AI_2O_3 | 14.77 | Cu | 4.9 | Sr | 199.9 | Nd | 3.0 |
| FeO _{tot} | 1.38 | Ga | 19.5 | Та | 0.3 | Sm | 0.41 |
| MnO | 0.06 | Hf | 0.3 | Th | 1.4 | Eu | 0.24 |
| MgO | 0.16 | Мо | 0.3 | U | 0.3 | Gd | 0.18 |
| CaO | 0.65 | Nb | 2.8 | W | 1.0 | Tb | 0.05 |
| Na₂O | 3.74 | Ni | 2.0 | Y | 2.5 | Dy | 0.39 |
| K₂O | 3.97 | Pb | 1.5 | Zn | 6.0 | Ho | 0.08 |
| Total | 99.29 | Rb | 132.4 | Zr | 7.4 | Er | 0.26 |
| | | | | | | Tm | 0.05 |
| | | | | | | Yb | 0.58 |
| | | | | | | Lu | 0.1 |





FIGURE 3. Chondrite-normalized (Boynton 1984) bulk REE contents in the leucogranulite that hosts the borosilicate-bearing veinlet and REE-contents in garnet from the leucogranulite.

Na2O and P2O5 contents represent a record of the original highpressure metamorphic conditions (e.g., Haggerty et al. 1994) experienced by the granulites of the Bohemian Massif (e.g., Kotková and Harley 1999). Garnet exhibits elevated contents of Ni (≤ 680 ppm), Y (≤ 460 ppm), HREE (≤ 380 ppm of Σ HREE), Sc (≤1200 ppm), Ga (≤46 ppm), Na (≤600 ppm), and Li (≤1113 ppm). The trace element contents are highly variable among the individual garnet grains (e.g., REE, Fig. 3). Generally, the highest contents of Na and Li are commonly (but not always) in the grain centers, Li decreases toward the grain rim (200-800 ppm). Both Na and Li could enter the garnet structure by a substitution (Na,Li)P[(Fe,Mg)Si]-1 (cf. Brunet et al. 2006) or by more complex substitutions [e.g., alluaudite-type, Breiter et al. (2005)]. However, the mechanism for Li corporation could differ from that for Na incorporation, e.g., Li could occupy the dodecahedral site as reported in a majoritic garnet synthesized at ultrahigh pressure (Yang et al. 2009) or the tetrahedral site plus octahedral and tetrahedral sites normally vacant in garnet as reported in synthetic Li₅La₃Ta₂O₁₂ (Cussen 2006). Chondrite-normalized garnet REE patterns (Fig. 3) are strongly fractionated, showing LREE depletion and HREE enrichment, as typical of garnets. One garnet pattern shows a level trend from La to Sm, which could be due to the beam hitting an apatite inclusion. The negative Eu anomaly, however, is characteristic only of garnets formed in granulite-facies migmatites and leucogranites. A similar feature observed in the South Bohemian leucogranulites was interpreted by Kotková and Harley (1999) as evidence of separation of the

TABLE 2. Selected analyses of major and trace elements in garnet

| | | | | - | | | | - | |
|-------------------|----------|---------|-----------|-----------|--------------|---------|------|------|------|
| Grain n | io. 1 | 1 | 2 | 2 | | 4 | 4 | 5 | 5 |
| | core | rim | core | rim | | core | rim | core | rim |
| SiO₂ | 35.67 | 36.59 | 36.47 | 36.93 | Li | 769 | 407 | 1113 | 396 |
| TiO ₂ | 0.00 | 0.00 | 0.00 | 0.02 | Na | 353 | 160 | 550 | 145 |
| AI_2O_3 | 20.58 | 20.59 | 20.98 | 21.36 | Sc | 1263 | 1081 | 513 | 532 |
| Cr_2O_3 | 0.00 | 0.00 | 0.01 | 0.01 | V | 54 | 37 | 25 | 32 |
| MgO | 2.25 | 2.05 | 3.41 | 3.48 | Ni | 670 | 605 | 681 | 562 |
| FeO | 34.51 | 34.99 | 33.61 | 33.98 | Zn | 15 | 16 | 21 | 21 |
| MnO | 5.19 | 5.29 | 3.65 | 3.70 | Ga | 46 | 31 | 46 | 33 |
| CaO | 0.56 | 0.46 | 1.21 | 1.43 | Ge | 49 | 39 | 38 | 42 |
| Na ₂ O | 0.07 | 0.03 | 0.06 | 0.01 | Y | 159 | 174 | 181 | 156 |
| P_2O_5 | 1.17 | 0.06 | 0.64 | 0.06 | | | | | |
| Total | 100.00 | 100.06 | 100.04 | 100.98 | | | | | |
| Si ⁴⁺ | 2.904 | 2.979 | 2.934 | 2.941 | Gd | 3.3 | 1.4 | 2.8 | 2.2 |
| Ti ⁴⁺ | 0.000 | 0.000 | 0.000 | 0.001 | Tb | 0.5 | 1.7 | 3.5 | 1.1 |
| Al ³⁺ | 1.975 | 1.976 | 1.989 | 2.005 | Dy | 25.9 | 22.9 | 20.6 | 19.9 |
| Cr ³⁺ | 0.000 | 0.000 | 0.001 | 0.000 | Ho | 5.4 | 5.7 | 4.9 | 4.5 |
| Mg ²⁺ | 0.273 | 0.248 | 0.408 | 0.413 | Er | 19.4 | 20.6 | 18.6 | 18.3 |
| Fe ²⁺ | 2.350 | 2.382 | 2.261 | 2.263 | Tm | 4.3 | 4.8 | 4.3 | 4.1 |
| Mn ²⁺ | 0.358 | 0.365 | 0.248 | 0.250 | Yb | 37.3 | 43.2 | 40.6 | 40.5 |
| Ca ²⁺ | 0.048 | 0.040 | 0.104 | 0.122 | Lu | 6.4 | 6.9 | 6.4 | 6.5 |
| Na+ | 0.011 | 0.005 | 0.010 | 0.001 | | | | | |
| P ⁵⁺ | 0.080 | 0.004 | 0.044 | 0.004 | | | | | |
| Σ | 8 | 8 | 8 | 8 | | | | | |
| Note: C | arnet fo | rmula w | as calcul | ated on t | the basis of | 8 catio | ns. | | |

(high-pressure) leucogranulitic melt from peritectic and residual K-feldspar (ternary feldspar).

MINERALS IN THE BOROSILICATE-BEARING VEINLET

Borosilicates occur in a thin veinlet, up to 10 mm thick, cutting exclusively the leucocratic granulite (Fig. 2), discordant to the planar fabric indicated by quartz ribbons, elongation of kyanite and sillimanite prisms, and arrangement of garnet grains. In general, we found the following primary (1-2) and secondary (3-5) mineral assemblages:

(1) K-feldspar + quartz ± plagioclase + grandidieriteominelite ± boralsilite

(2) K-feldspar \pm plagioclase + quartz + boralsilite \pm werdingite

(3) tourmaline + corundum \pm dumortierite \pm hercynite (after grandidierite and boralsilite)

(4) Al-rich tourmaline (after boralsilite + werdingite)

(5) clay minerals – kaolinite, illite (after grandidierite, boralsilite, werdingite).



FIGURE 4. BSE-images of primary minerals: (**a**) crystals of grandidierite and boralsilite in K-feldspar and quartz; (**b**) skeletal zoned crystal of grandidierite-ominelite overgrown by plumose aggregates of intergrown werdingite and boralsilite prisms; (**c**) zoned crystal of grandidierite-ominelite overgrown by plumose aggregate of boralsilite mixed with rare werdingite; (**d**) cross-shaped plumose aggregates of intergrown werdingite and boralsilite prisms.



FIGURE 5. Replacement of primary phases (BSE-images): (a) grandidierite replaced by assemblage tourmaline + corundum; (b) boralsilite and werdingite replaced by Al-rich tourmaline and foitite-olenite, while boralsilite is decomposed into fine-grained phyllosilicates (dark gray); (c) aggregate of grandidierite and boralsilite replaced by tourmaline + corundum and fine-grained phyllosilicates, respectively. Small crystals of dumortierite (dark gray) and Sb-rich dumortierite (light gray) are enclosed in tourmaline; inset shows enlargement of zoned dumortierite; (d) aggregate of grandidierite crystals replaced by assemblage tourmaline + corundum + hercynite.

The primary assemblage 1 occurs close to the veinlet contact with the host granulite. Toward the veinlet center, the quartz content and grain size increases, as well as the size of grandidierite crystals. The assemblage 2 was irregularly observed in grandidierite-free portions in the central part of the veinlet.

K-feldspar ($Or_{94}Ab_6-Or_{85}Ab_{14}An_1$) forms slightly deformed and brecciated grains in a quartz matrix. It is almost always perthitic (Fig. 4); the composition of exsolution lamellae ranges from $Ab_{94}An_5Or_1$ to $Ab_{97}An_2Or_1$. K-feldspars are locally replaced by veinlets of fine-grained muscovite and quartz. The associated anhydrous borosilicates (grandidierite, boralsilite, werdingite), where present, have been also transformed into a mixture of clay minerals. Composition and appearance of Kfeldspar in thin section is very similar to that of K-feldspar in the host leucogranulite.

Plagioclase (Ab₉₂An₇Or₁-Ab₉₇An₂Or₁) is rather rare in boralsilite- and grandidierite-bearing assemblages. It forms irregular grains to small spots, and rims overgrowing K-feldspar; they most probably represent an exsolved phase from primary K-feldspar. Larger anhedral plagioclase grains with twinning lamellae occur only locally; they are younger than K-feldspar and seem to be older than quartz. On the contacts of plagioclase and grandidierite, the latter is typically replaced by tourmaline + corundum; however, the replacement also occurs apart from plagioclase grains.

Quartz forms larger rounded grains with lobate offshoots. Locally it forms vermicular grains in K-feldspar. It contains abundant fluid inclusions. Quartz usually encloses grandidierite and other anhydrous borosilicates.

Grandidierite to ominelite forms lenticular to needle-like crystals (further referred as grandidierite only) enclosed in K-feldspar and quartz. In sections perpendicular to the prismatic zone, the crystals feature rhombic, locally skeletal shape (Figs. 4a–4b). Content of ominelite component increases toward rims of grandidierite crystals: X_{Fe} varies between 0.34 and 0.47 in their cores, and it reaches up to 0.71 in rims. Ominelite is commonly rimmed by a narrow zone of secondary tourmaline or it is completely replaced by the assemblage tourmaline + corundum

 \pm hercynite. Tourmaline has irregular rims enriched in Fe that suggest retention of the zoning in the grandidierite that it had replaced (Fig. 5a). Corundum always forms anhedral grains (~50 μ m) enclosed in tourmaline (Figs. 5a, 5c, and 5d).

Grandidierite grains are locally overgrown by plumose aggregates formed by intergrowths of boralsilite and Fe-rich werdingite (Figs. 4b-4c). Boralsilite and its intergrowths with werdingite also occur in cross-shaped plumose aggregates enclosed in quartz and K-feldspar (Fig. 4d). The individual prisms are composed of alternating crystals of boralsilite and werdingite, giving the aggregates a brick-wall texture on a scale of tens of micrometers (Fig. 4d). When inspected in detail, boralsilite and werdingite also form ladder-like intergrowths on a micrometer scale, identical with those reported by Grew et al. (1998a). The relative proportion of boralsilite in these intergrowths ranges from less than 50% to nearly 100%. Rarely, the aggregates are replaced by Al-rich tourmaline of the foitite-olenite series (Fig. 5b). In tourmaline-bearing assemblages, boralsilite is frequently altered to clay minerals, whereas werdingite is more resistant to alteration. Similar plumose boralsilite (± werdingite) aggregates overgrowing sillimanite and grandidierite were earlier reported from other localities (Grew et al. 1998b, 2008); also the crossshaped intergrowths are characteristic for the Larsemann Hills occurrence (E.S. Grew, personal communication).

Zoned grains and prismatic crystals of dumortierite and Sb,Tirich dumortierite were found embedded in secondary tourmaline along with decomposition products of boralsilite or grandidierite (Fig. 5c). From the textural relations, it is not clear whether dumortierite is a primary phase or if it formed together with tourmaline during breakdown of some of the primary phases.

Hercynite ($Hc_{87}Spl_{10}Gx_3$) rarely occurs as very small (~20 µm) anhedral grains in the grandidierite-bearing assemblages, enclosed in secondary tournaline together with corundum (Fig. 5d).

Borosilicate-bearing veinlet contains several accessory minerals commonly enclosed in quartz or on its fractures. Only monazite, ilmenite, löllingite, arsenopyrite, and apatite are of primary origin, the others represent inclusions of various origin or products of breakdown. Monazite-(Ce) in grains up to 200 μ m in diameter irregularly overgrows grandidierite and boralsilite prisms in quartz. Ilmenite forms irregular or rounded grains, up to 200 μ m in diameter (Fig. 6) that are commonly broken down to secondary rutile and hydrous Fe-oxides. Rare exsolution products from ilmenite include Nb-rich rutile, ferberite (locally Nb,Sc-rich), and a mineral compositionally close to srilankite; they were usually found in very small grains of ~5–20 μ m in ilmenite. Very rare löllingite, arsenopyrite, and apatite were found in tiny grains of a few micrometers in diameter, enclosed in quartz close to ilmenite.

CRYSTAL CHEMISTRY OF MINERALS

Grandidierite with $X_{\text{Fe}} = 0.34-0.71$ is chemically rather simple. Only subordinate amounts of MnO (≤ 0.45 wt%) and traces of P_2O_5 (≤ 0.1 wt%) and ZnO (≤ 0.09 wt%) were detected in addition to the major oxides, and the analyzed boron content is very close to ideal stoichiometry (Table 3). Substitution is primarily FeMg_1, and variation in P⁵⁺ seems to be independent of content of other cations. LA-ICP-MS analyses of three grandidierite crystals revealed high Li content (120, 210, and 1890 ppm), Ni (450, 412, and 390 ppm), Zn (109, 140, and 140 ppm), Ga (102, 98, and 86 ppm), and V (1432, 419, and 635 ppm). Contamination of some LA-ICP-MS analytical spots by clay minerals replacing grandidierite cannot be ruled out (e.g., in case of highest Li content).

The observed compositions are very similar to the published data for grandidierite from pegmatites and metamorphic rocks (see e.g., Grew 1996). Slightly elevated Mn contents show positive correlation with Fe (Fig. 7), which may be explained by the fractionation of (Fe+Mn) from Mg as well as by crystal structure constraints. Hiroi et al. (2001) reported up to 0.73 wt% of MnO in ominelite, however, in their samples, Mn content varies independently of the Fe content. Slightly non-stoichiometric contents of Si and Al are more likely an analytical artifact than the result of vacancies or Fe³⁺Al₋₁ substitution, which is considered to be very low in the grandidierite-ominelite series (Grew



FIGURE 6. BSE-images of ilmenite and its exsolution products: (a) ilmenite overgrowing and cross-cutting a plumose aggregate of boralsilite + werdingite; (b) exsolution products (white Nb,Sc-rich ferberite; dark gray Nb-rutile) in ilmenite (light gray). Numbers refer to the analyses in Table 6.

TABLE 3. Representative electron-microprobe analyses of grandidierite (Gdd), ominelite (Oml), werdingite (Wrd), and boralsilite (Brs)

| | • | | | | • | | | | | | | - | | | | | |
|------------------|--------|--------|--------|--------|--------|---------|---------|--------|---------|---------|--------|--------|--------|--------|--------|--------|--------|
| | Gdd * | Gdd† | Oml | Oml | Wrd‡ | Wrd | Wrd | Wrd | Wrd | Wrd* | Wrd* | Brs§ | Brs | Brs | Brs | Brs | Brs |
| P_2O_5 | n.a. | 0.01 | 0.01 | 0.07 | 0.02 | 0.10 | 0.04 | 0.00 | 0.05 | n.a. | n.a. | 0.00 | 0.00 | 0.02 | 0.01 | 0.02 | 0.08 |
| SiO ₂ | 19.97 | 20.76 | 19.51 | 19.85 | 19.00 | 18.28 | 18.70 | 18.03 | 17.28 | 18.00 | 18.47 | 9.44 | 10.74 | 10.82 | 11.51 | 11.54 | 13.97 |
| B_2O_3 | 11.92 | 11.63 | 11.27 | 11.23 | 11.59 | 11.89 | 12.14 | 12.51 | 12.42 | 12.18 | 11.64 | 18.89 | 18.18 | 18.03 | 17.33 | 17.27 | 15.79 |
| AI_2O_3 | 51.21 | 50.36 | 49.35 | 48.94 | 61.99 | 62.08 | 63.56 | 64.05 | 64.17 | 63.86 | 63.27 | 71.24 | 70.98 | 70.77 | 69.55 | 69.28 | 68.43 |
| MgO | 9.09 | 8.57 | 4.14 | 3.70 | 1.12 | 1.42 | 0.94 | 1.02 | 0.52 | 0.88 | 1.15 | 0.07 | 0.11 | 0.03 | 0.09 | 0.16 | 0.14 |
| FeO | 8.28 | 8.75 | 15.58 | 16.12 | 6.56 | 5.28 | 6.28 | 5.53 | 2.91 | 4.01 | 5.52 | 0.60 | 0.55 | 0.30 | 0.59 | 0.70 | 0.51 |
| MnO | 0.13 | 0.14 | 0.38 | 0.45 | 0.09 | 0.05 | 0.07 | 0.06 | 0.02 | 0.05 | 0.07 | 0.00 | 0.02 | 0.02 | 0.01 | 0.00 | 0.00 |
| ZnO | 0.03 | 0.06 | 0.06 | 0.02 | 0.07 | 0.10 | 0.06 | 0.04 | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| F | 0.07 | 0.00 | 0.00 | 0.00 | 0.04 | 0.00 | 0.00 | 0.02 | 0.07 | 0.08 | 0.04 | 0.06 | 0.05 | 0.06 | 0.05 | 0.05 | 0.03 |
| Total | 100.74 | 100.28 | 100.29 | 100.38 | 100.48 | 99.20 | 101.79 | 101.26 | 97.44 | 99.06 | 100.19 | 100.30 | 100.63 | 100.05 | 99.14 | 99.02 | 98.96 |
| P5+ | _ | 0.000 | 0.001 | 0.003 | 0.003 | 0.017 | 0.006 | 0.001 | 0 009 | _ | _ | 0.001 | 0.000 | 0 004 | 0.002 | 0.003 | 0.013 |
| Si ⁴⁺ | 0.987 | 1.035 | 1.003 | 1.024 | 3,798 | 3.674 | 3 679 | 3,549 | 3 482 | 3 592 | 3,686 | 1.796 | 2.040 | 2.065 | 2,223 | 2,232 | 2,711 |
| B ³⁺ | 1 017 | 1 | 1 | 1 | 4 002 | 4 1 2 6 | 4 1 2 1 | 4 251 | 4 3 1 8 | 4 1 9 4 | 4 009 | 6 204 | 5 960 | 5 935 | 5 777 | 5 768 | 5 289 |
| Al ³⁺ | 2.983 | 2.957 | 2,990 | 2.976 | 14.611 | 14,709 | 14,736 | 14 860 | 15,236 | 15 019 | 14 879 | 15.972 | 15 890 | 15 911 | 15,830 | 15 801 | 15.649 |
| Ma ²⁺ | 0.670 | 0.637 | 0.317 | 0.285 | 0.333 | 0.426 | 0.275 | 0 299 | 0.156 | 0.261 | 0.341 | 0.018 | 0.031 | 0.009 | 0.027 | 0.046 | 0.040 |
| Fe ²⁺ | 0.342 | 0.365 | 0.670 | 0.696 | 1.097 | 0.888 | 1.033 | 0.911 | 0.491 | 0.668 | 0.922 | 0.095 | 0.088 | 0.048 | 0.095 | 0.113 | 0.082 |
| Mn ²⁺ | 0.005 | 0.006 | 0.016 | 0.020 | 0.015 | 0.008 | 0.011 | 0.009 | 0.004 | 0.009 | 0.011 | 0.000 | 0.004 | 0.003 | 0.001 | 0.000 | 0.000 |
| Zn ²⁺ | 0.001 | 0.002 | 0.002 | 0.001 | 0.010 | 0.014 | 0.009 | 0.005 | 0.000 | 0.000 | 0.004 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.002 |
| F- | 0.011 | 0.000 | 0.000 | 0.000 | 0.027 | 0.000 | 0.000 | 0.014 | 0.043 | 0.052 | 0.023 | 0.039 | 0.032 | 0.034 | 0.029 | 0.029 | 0.020 |
| 0 ²⁻ | 8.989 | 9.019 | 9.002 | 9.023 | 36.973 | 37.000 | 37.000 | 36.986 | 36.957 | 36.948 | 36.977 | 36.961 | 36.968 | 36.966 | 36.971 | 36.971 | 36.980 |
| X_{Fe} | 0.34 | 0.36 | 0.68 | 0.71 | 0.77 | 0.68 | 0.79 | 0.75 | 0.76 | 0.72 | 0.73 | 0.84 | 0.74 | 0.84 | 0.78 | 0.71 | 0.67 |

Note: n.a. = not analyzed.

* Boron contents were analyzed using EMPA. Formula calculated on ideal stoichometric number of anions.

+ Grandidierite and ominelite formulae were calculated on the basis of 5 cations and B = 1 apfu.

‡ Werdingite formulae were calculated iteratively on the basis of (B+Si) = 7.8 apfu and (O+F) = 37 apfu.

§ Boralsilite formulae were calculated iteratively on the basis of (B+Si) = 8 apfu and (O+F) = 37 apfu.



FIGURE 7. Variation of Mn vs. Fe/(Mg+Fe) in grandidierite and ominelite.

1996; Hiroi et al. 2001; Dzikowski et al. 2007). The Li content in grandidierite was never reported before; lithium can chargebalance the entrance of phosphorus into grandidierite structure, e.g., via substitution LiP(MgSi)_1.

Boralsilite and werdingite exhibit large variations in chemical composition (Table 3; Fig. 8). Boralsilite varies strongly in Al/Si ratio, with simplified formula ranging from Al_{15.97}B_{6.20}Si_{1.80}O₃₇ to Al_{15.65}B_{5.29}Si_{2.71}O₃₇. Low amounts of Fe and Mg (0.06–0.16 apfu Fe+Mg; $X_{Fe} = 0.67-0.84$) and F (up to 0.08 wt% F, ~0.05 apfu F) were also detected. Werdingite formulae range mostly from (Fe,Mg)_{1.44}Al_{14.61}B_{4.00}Si_{3.80}O₃₇ to (Fe,Mg)_{1.22}Al_{14.86}B_{4.25}Si_{3.55}O₃₇ (Fig. 8) with low variation of the X_{Fe} (0.68–0.79). The analyzed boron contents (two analytical spots only) confirm the validity of the formula calculation method used [B+Si = 7.8 per formula unit of 37 (O+F)], which is based on Grew at al. (2010) and E.S. Grew (personal communication). Despite the prevalence of Fe

over Mg in the examined werdingite, the mineral cannot be treated as the Fe-analog of werdingite since the new structural study of Grew et al. (2010) on Fe-rich ($X_{Fe} \sim 0.75$) werdingite from Almgjotheii showed that Fe is present at four structural sites and dominant at none of them. Also, the valence state of Fe is not known. Amounts of Fe+Mg lower than ideal two atoms per formula unit are rather common in the published data on werdingite (e.g., Grew et al. 1998b, 2008, 2010).

Both boralsilite and werdingite exhibit a variable Al/Si ratio and werdingite also shows rather low Fe+Mg (Fig. 8). The chemical variations in boralsilite can be explained by a substitution $(Si+\Box_{0.33})(B+Al_{0.33})_{-1}$ producing vacancies in octahedral sites (Fig. 8). This suggests a solid solution (or sub-microscopic intergrowths) of boralsilite with sillimanite. Boralsilite also contains low but stable amount of the werdingite component (~8 mol%; Fig. 8). Their solid solution was earlier suggested by Grew et al. (1998a, 1998b), and up to 30 mol% of werdingite component in boralsilite were reported by Grew et al. (2008). The chemical data for werdingite do not allow simple generalization; variation of part of the data can be expressed by a Tschermak's-like substitution $(B+Al_{0.66}+\Box_{0.33})(Si+Fe)_{-1}$ (see Fig. 8) that can be explained by a solid solution with boralsilite. Three analytical spots of werdingite (two with analyzed and one with calculated boron content) seem to fit better to a substitution (B+Al_{1.75}+ \Box _{1.25}) $(Si+Fe_3)_{-1}$ suggesting presence of a fine-scale intergrowths with both boralsilite and boromullite (or contamination of the analytical spot by boromullite or corundum), which were not visible in the BSE image during analysis.

The occurrence at Horní Bory of boralsilite and werdingite in cross-shaped plumose aggregates of prismatic crystals (Fig. 4d) suggests that these two minerals formed a more extensive solid solution at high temperature; i.e., the intergrowths resulted from exsolution of an earlier high-temperature mineral. Grew et al. (1998a) do not exclude the simultaneous growth of both phases; in the case of Horní Bory occurrence, however, we favor



FIGURE 8. Compositional variation of boralsilite (open symbols) and werdingite (filled and cross-filled symbols) in terms of Al, Si, and (Fe+Mg+Mn). White cross-filled symbols represent werdingite analyses where boron was analyzed using EMPA. Gray symbols represent composition of boralsilite, boromullite, and werdingite end-members.

the explanation of the aggregates origin owing to the exsolution process, due to the textures reported above.

Dumortierite occurs in zoned crystals (Fig. 5c), with zones poor in trace elements (≤ 0.12 apfu Fe+Mg+Ti) and zones enriched particularly in Sb (≤ 0.46 apfu) and Ti (≤ 0.25 apfu). Formulae of both dumortierite types show a good agreement with the ideal stoichiometry when calculated according to Moore and Araki (1978), i.e., with 0.25 apfu vacancy in M1-site; they exhibit only low amounts of ^TA1 (Table 4). The dumortierite poor in minor elements, is compositionally similar to the rare green variety of dumortierite reported by Cempírek and Novák (2005). The Sb-rich dumortierite (Fig. 5c; Table 4) features contents of Sb between 0.3 and 0.46 apfu, accompanied by elevated contents of Ti (0.05–0.25 apfu). As for the other elements detected, only elevated contents of P (0.035–0.040 apfu) were observed (Table 4).

The ratio (Sb+As)/(Sb+As+Si+P) between 0.1 and 0.16 in Sb,Ti-rich dumortierite approaches closely the definition of "holtite I" of Kazantsev et al. (2005), except that it contains Ti instead of Ta. Lack of structural data and the problematic definition of holtite end-member (e.g., Groat et al. 2009) do not allow more detailed classification of the Sb,Ti-rich dumortierite from Horní Bory. Regarding the elevated Ti in Sb,Ti-rich dumortierite,

 TABLE 4. Representative electron-microprobe analyses of Sb-rich dumortierite and dumortierite

| | | Sb-rich Dum | | Dum | | | | |
|---------------------------------|--------|-------------|--------|--------|----------|--|--|--|
| Anal. no. | 1 | 2 | 3 | 4 | 5 | | | |
| P ₂ O ₅ | 0.40 | 0.46 | 0.43 | 0.31 | 0.09 | | | |
| SiO2 | 23.19 | 22.80 | 25.65 | 29.49 | 29.09 | | | |
| As_2O_3 | 0.44 | 0.45 | 0.31 | n.d. | n.d. | | | |
| b_2O_3 | 10.76 | 10.97 | 7.13 | n.d. | n.d. | | | |
| 3 ₂ O ₃ * | 5.64 | 5.64 | 5.77 | 5.98 | 6.02 | | | |
| NO₃ | 0.08 | 0.29 | 0.19 | n.d. | n.d. | | | |
| ΓiO ₂ | 3.24 | 3.09 | 0.61 | 0.00 | 0.09 | | | |
| Al ₂ O ₃ | 53.88 | 53.91 | 56.54 | 59.19 | 60.45 | | | |
| / ₂ O ₃ | 0.13 | 0.12 | 0.00 | 0.00 | 0.03 | | | |
| eO | 0.42 | 0.61 | 0.59 | 0.56 | 0.56 | | | |
| ИnО | 0.02 | 0.01 | 0.03 | 0.00 | 0.00 | | | |
| ИgO | 0.15 | 0.18 | 0.23 | 0.39 | 0.20 | | | |
| la₂O | 0.01 | 0.05 | 0.01 | 0.00 | 0.03 | | | |
| - | 0.12 | 0.10 | 0.10 | 0.07 | 0.07 | | | |
| H₂O* | 1.55 | 1.63 | 1.63 | 1.41 | 1.53 | | | |
| -O=F | -0.01 | -0.01 | -0.01 | 0.00 | 0.00 | | | |
| Total | 100.02 | 100.30 | 99.21 | 97.40 | 98.16 | | | |
| | | | | | | | | |
| 5i ⁴⁺ | 2.382 | 2.343 | 2.574 | 2.860 | 2.799 | | | |
| \s ³⁺ | 0.028 | 0.028 | 0.019 | - | - | | | |
| 5b3+ | 0.456 | 0.464 | 0.295 | _ | | | | |
| 3 5+ | 0.035 | 0.040 | 0.037 | 0.025 | 0.007 | | | |
| 4l ³⁺ | 0.099 | 0.125 | 0.075 | 0.115 | 0.194 | | | |
| E T-site | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | | | |
| 33+ | 1 | 1 | 1 | 1 | 1 | | | |
| N ₀₊ | 0.002 | 0.008 | 0.005 | | | | | |
| 1 ⁴⁺ | 0.251 | 0.239 | 0.046 | 0.000 | 0.006 | | | |
| AI3+ | 6.425 | 6.403 | 6.611 | 6.649 | 6.663 | | | |
| /3+ | 0.011 | 0.010 | 0.000 | 0.000 | 0.002 | | | |
| e ²⁺ | 0.036 | 0.052 | 0.050 | 0.045 | 0.045 | | | |
| VIn ²⁺ | 0.001 | 0.001 | 0.003 | 0.000 | 0.000 | | | |
| //g²⁺ | 0.022 | 0.027 | 0.035 | 0.056 | 0.029 | | | |
| Va ⁺ | 0.003 | 0.010 | 0.002 | 0.000 | 0.005 | | | |
| E M-sites | 6.750 | 6.750 | 6.750 | 6.750 | 6.750 | | | |
| - | 0.038 | 0.032 | 0.033 | 0.021 | 0.023 | | | |
| DH- | 1.064 | 1.118 | 1.089 | 0.913 | 0.984 | | | |
|) ²⁻ | 16.897 | 16.847 | 16.876 | 17.066 | 16.993 | | | |
| Sb+As)/ΣT | 0.161 | 0.164 | 0.104 | - | - | | | |
| | | | | (| 1 /0 011 | | | |

* Formula was calculated assuming B = 1 apfu, (T+M) = 9.75 apfu, and (O, OH, F) = 18 apfu. Contents of Nb, Ta, Bi, Cr, Ca, Zn, Cu, and K were below detection limit.

there are too few analyses to confirm a positive correlation of Sb and Ti and their coupled substitution $(TiSb)(AlSi)_{-1}$ in the dumortierite structure. Although introduction of charge-compensating hydroxyl groups is likely, the calculated amount of OH in both types of dumortierite (Table 4) depends on what is assumed in calculating the formulae (M+T = 9.75; O+OH+F = 18) and thus should be considered conjectural in the absence of crystal structure and spectroscopic data.

Tourmaline occurs as a replacement product of grandidierite, rarely boralsilite. All tourmaline compositions are Al-rich, F-free, Ca-poor and with high vacancy in the X-site, varying from Mgrich schorl with high foitite component to Fe-rich magnesiofoitite and foitite-olenite solid solution (up to 1.6 apfu ^YAl, 0.2 apfu ^TAl, and only 0.28 apfu Na; Fig. 9). Tourmaline X_{Fe} (=0.44–0.75) overlaps that of its grandidierite precursor (Fig. 10). The rare secondary tourmaline after boralsilite compositionally represents a solid solution between foitite and olenite with elevated content of ^TAl and high vacancy in the X-site (Fig. 10; Table 5). The high Al and vacancy in X-site could also suggest a solid solution with X-site vacant Al-tourmaline end-member, possibly also with excess boron (e.g., Schreyer et al. 2000), or solid solution with rossmanite (due to unknown content of Li). Similar X-site vacant, Al-rich tourmaline was found adjacent to boralsilite in Larsemann Hills (Grew et al. 1998a). Al-rich, F-poor tourmaline is a typical accessory of abyssal pegmatites in the Gföhl Unit (Cempírek and Novák 2006; Cempírek et al. 2006).

Monazite-(Ce) is characterized by Ce > Nd > La and elevated contents of Th (0.35–0.40 apfu), Si (\leq 0.24 apfu), and Ca (\leq 0.20 apfu) reflecting moderate participation of both huttonite (11–13 mol%) and cheralite (8–9 mol%) substitutions. Ilmenite with elevated Nb₂O₅ (\leq 0.37 wt%), WO₃ (\leq 0.1 wt%), Ta₂O₅ (\leq 0.09 wt%), and Sc₂O₃ (\leq 0.07 wt%), is probably the main primary carrier of W, Nb, Ta, and Sc in the veinlet (Table 6). Inclusions and exsolutions of Nb₅Sc, W-enriched minerals in ilmenite comprise Nb-rich rutile with up to 9.85 wt% Nb₂O₅ (0.063 apfu), Nb₅Scrich ferberite with up to 12.48 wt% Nb₂O₅ (7.40 wt% Sc₂O₃, X_{Nb} = 0.88–0.91, and X_{Fe} = 0.89–0.90 and trace amounts of Nb₂O₅ (0.28–1.01 wt%), Sc₂O₃ (0.40–0.63 wt%), and TiO₂ (0.18–0.62 wt%). Primary rutile to Nb-enriched rutile is compositionally



FIGURE 9. Compositional variation of tourmaline from the borosilicate-bearing veinlet and from spatially associated primitive (Horní Bory) and fractionated (Dolní Bory, Cyrilov) granitic pegmatites in the Bory pegmatite district. (**a**) X-site; (**b**) W-site; (**c**) Z+Y sites.



FIGURE 10. Composition of garnet and hercynite from the host leucogranulite and of the veinlet accessory minerals.

TABLE 5. Representative electron-microprobe analyses of tourmaline (Tur) and foitite-rich tourmaline (Foi)

| Anal. no. 1 2 3 4 5 6 P_2O_5 0.09 0.08 0.05 0.25 0.08 0.0 SIO_ 35.89 35.82 36.12 35.45 35.66 35.6 |)4 92 77 |
|---|----------------|
| P ₂ O ₅ 0.09 0.08 0.05 0.25 0.08 0.0 SiO ₂ 35.89 35.82 36.12 35.45 35.66 35.9 | 92 77 |
| SiO ₂ 35.89 35.82 36.12 35.45 35.66 35.9 | 92 77 |
| 5102 55.05 55.02 50.12 55.15 55.00 55. | 77 |
| $B_2O_3^*$ 10.52 10.47 10.68 10.62 10.57 10.7 | 0 |
| TiO ₂ 0.03 0.01 0.01 0.01 0.00 0.0 | 0 |
| Al ₂ O ₃ 34.99 35.19 36.82 37.49 37.44 41.0 | 04 |
| V ₂ O ₃ 0.00 0.00 0.02 0.00 0.02 0.0 | 0 |
| Cr ₂ O ₃ 0.00 0.03 0.01 0.01 0.00 0.0 | 0 |
| MgO 3.90 3.30 4.78 3.65 3.33 0.3 | 9 |
| FeO 9.28 9.58 6.63 7.75 7.70 7.4 | 5 |
| MnO 0.07 0.07 0.02 0.06 0.05 0.0 | 12 |
| ZnO 0.02 0.02 0.02 0.05 0.00 0.0 | 1 |
| CuO 0.00 0.00 0.06 0.06 0.01 0.0 | 1 |
| CaO 0.14 0.08 0.04 0.10 0.26 0.1 | 0 |
| Na ₂ O 1.80 1.62 1.32 1.85 1.51 0.9 | 0 |
| K ₂ O 0.01 0.03 0.01 0.03 0.02 0.0 | 12 |
| F 0.05 0.02 0.00 0.03 0.00 0.0 | 13 |
| Cl 0.01 0.01 0.01 0.02 0.01 0.0 | 0 |
| H ₂ O* 3.26 3.23 3.39 3.02 3.08 3.5 | 8 |
| Total 100.06 99.56 99.99 100.45 99.74 100. | .28 |
| P ⁵⁺ 0.012 0.011 0.007 0.035 0.011 0.00 | 05 |
| Si ⁴⁺ 5.930 5.948 5.876 5.803 5.863 5.79 | 95 |
| ^T AI 0.058 0.041 0.117 0.162 0.126 0.20 | 00 |
| B ³⁺ 3 3 3 3 3 3 | |
| ^z Al 6 6 6 6 6 | |
| Ti ⁴⁺ 0.003 0.002 0.001 0.002 0.000 0.00 | 00 |
| ^Y AI 0.757 0.847 0.943 1.072 1.129 1.60 | 02 |
| V ³⁺ 0.000 0.000 0.003 0.000 0.002 0.00 | 00 |
| Cr ³⁺ 0.000 0.004 0.001 0.002 0.000 0.00 | 00 |
| Mg ²⁺ 0.960 0.817 1.158 0.892 0.816 0.09 | 93 |
| Fe ²⁺ 1.283 1.331 0.901 1.060 1.059 1.00 | 05 |
| Mn ²⁺ 0.009 0.010 0.003 0.008 0.007 0.00 | 03 |
| Zn ²⁺ 0.003 0.002 0.002 0.006 0.000 0.00 | 01 |
| Cu ²⁺ 0.000 0.000 0.007 0.007 0.001 0.00 | 01 |
| Ca ²⁺ 0.025 0.015 0.008 0.018 0.047 0.07 | 16 |
| Na ⁺ 0.577 0.523 0.417 0.588 0.481 0.28 | 33 |
| K ⁺ 0.002 0.006 0.003 0.007 0.005 0.00 | 03 |
| [×] □ 0.396 0.456 0.572 0.387 0.467 0.69 | 98 |
| F 0.025 0.012 0.000 0.014 0.000 0.01 | 13 |
| CI- 0.004 0.003 0.001 0.004 0.003 0.00 | 00 |
| OH- 3.589 3.573 3.684 3.298 3.373 3.84 | 48 |
| O ²⁻ 27.382 27.413 27.315 27.683 27.624 27.1 | 38 |
| * Formulae were calculated assuming $(T+Z+Y) = 15$ apfu, B = 3 apt | fu, |

variable and typical trace to minor oxides include Nb₂O₅ (\leq 3.89 wt%), FeO_{tot} (\leq 2.35 wt%), WO₃ (\leq 2.72 wt%), Ta₂O₅ (\leq 0.54 wt%), Sc₂O₃ (\leq 0.54 wt%), and Al₂O₃ (\leq 0.33 wt%). A mineral compositionally close to srilankite with the empirical formula (Ti_{0.63}Zr_{0.28}Nb_{0.02}U_{0.02}Hf_{0.02}Fe³⁺_{0.01}Si_{0.01})_{1.00}O₂ also occurs in ilmenite. Although the primary ilmenite is calculated to contain little Fe³⁺ (Table 6), its exsolution products feature elevated Fe³⁺/Fe_{tot} ratio (0.23–0.84).

FLUID INCLUSIONS

Only fluid inclusions from quartz in the borosilicate-bearing veinlet assemblage were large enough for a microthermometric analysis. They typically form distinct subparallel trails within quartz grains, precluding an exact determination of their relative age. Three types of fluid inclusions (FI) were recognized.

(1) CO₂ type—very abundant, dark, isometric, one-phase FI (2–12 μ m across) occur mostly in trails cutting the whole grain; rarely they are solitary or in non-continuous trails. Upon cooling, a vapor phase appears. The Tm-CO₂ vary between –58.2 and –59.2 °C, and the Th-CO₂ ranges from +12.9 to +21.9 °C. The Th values differ among individual trails; within a single trail the

| TABLE 6. Electron-microprobe analyses of ilmenite and its exsoluti | ion |
|--|-----|
| products (Nb,Sc-rich ferberite, Nb-rutile) | |

| | Ilmenite | Nb,Sc-1 | Nb,Sc-ferberite | | | | |
|---|--------------------------------------|----------------------------------|-----------------|-------|--|--|--|
| Analysis no. | 19 | 16 | 17 | 18 | | | |
| WO ₃ | 0.10 | 66.32 | 54.60 | 2.27 | | | |
| Nb ₂ O ₅ | 0.37 | 5.01 | 12.48 | 9.85 | | | |
| Ta ₂ O ₅ | 0.09 | 0.75 | 2.89 | 1.17 | | | |
| SnO ₂ | 0.00 | 0.06 | 0.01 | 0.04 | | | |
| TiO ₂ | 51.10 | 0.92 | 2.48 | 79.59 | | | |
| SiO ₂ | 0.02 | 0.08 | 0.12 | 0.06 | | | |
| Sc ₂ O ₃ | 0.07 | 3.25 | 7.40 | 0.68 | | | |
| AI_2O_3 | 0.02 | 0.00 | 0.05 | 0.45 | | | |
| $Fe_2O_3^*$ | 1.02 | 5.31 | 6.62 | 4.58 | | | |
| FeO | 44.49 | 15.40 | 11.75 | 0.76 | | | |
| MnO | 1.79 | 2.34 | 1.99 | 0.02 | | | |
| PbO | n.d | 0.00 | 0.07 | 0.08 | | | |
| MgO | 0.13 | 0.11 | 0.09 | 0.00 | | | |
| CaO | 0.00 | 0.01 | 0.01 | 0.04 | | | |
| Total | 99.20 | 99.56 | 100.56 | 99.59 | | | |
| W ⁶⁺ | 0.001 | 0.812 | 0.619 | 0.008 | | | |
| Nb ⁵⁺ | 0.004 | 0.107 | 0.247 | 0.063 | | | |
| Ta ⁵⁺ | 0.001 | 0.010 | 0.034 | 0.005 | | | |
| Sn ⁴⁺ | 0.000 | 0.001 | 0.000 | 0.000 | | | |
| Ti ⁴⁺ | 0.980 | 0.033 | 0.082 | 0.848 | | | |
| Si ⁴⁺ | 0.001 | 0.004 | 0.005 | 0.001 | | | |
| Sc ³⁺ | 0.002 | 0.134 | 0.282 | 0.008 | | | |
| Al ³⁺ | 0.001 | 0.000 | 0.003 | 0.008 | | | |
| Fe ³⁺ | 0.020 | 0.189 | 0.218 | 0.049 | | | |
| Fe ²⁺ | 0.948 | 0.609 | 0.430 | 0.009 | | | |
| Mn ²⁺ | 0.039 | 0.094 | 0.074 | 0.000 | | | |
| Pb ²⁺ | - | 0.000 | 0.001 | 0.000 | | | |
| Mg ²⁺ | 0.005 | 0.008 | 0.006 | 0.000 | | | |
| Ca ²⁺ | 0.000 | 0.001 | 0.000 | 0.001 | | | |
| Σ cat. | 2 | 2 | 2 | 1 | | | |
| O ²⁻ | 3 | 4 | 4 | 2 | | | |
| Fe ³⁺ /Fe _{tot} | 0.020 | 0.237 | 0.336 | 0.844 | | | |
| $Fe_{tot}/(Fe_{tot}+Mn+Mg)$ | 0.957 | 0.887 | 0.891 | 0.994 | | | |
| Nb/(Nb+Ta) | 0.879 | 0.918 | 0.878 | 0.933 | | | |
| Note: Analysis numb * Formulae were calo | er refers to the culated on the k | Figure 6b. Dasis of ideal sto | ichiometry. | | | | |

variability is minimal (± 0.5 °C). The values of Tm-CO₂ suggest that there is a small amount of methane or nitrogen present in these FI (4–8 mol% CH₄, <15 mol% N₂; Thiéry et al. 1994).

(2) H₂O type—moderately frequent, FI occurs as solitary, in three-dimensional clusters, or in trails cutting the whole grain. Isometric FI (3–8 μ m across) are two-phase FI with limited liquid-vapor ratios (ca. 30–40 vol% of vapor phase). Most FI homogenize to a liquid phase between 287 and 365 °C; two inclusions showed critical homogenization at temperatures of 372 and 375 °C. The Tm-ice are between –4.0 and –2.0 °C. The fluid salinity varies from 3.3 to 6.4 wt% NaCl equivalent (Bodnar 1993) and the bulk density ranges from 0.559 to 0.703 g/cm³.

(3) Random mixtures of vapor phase and aqueous solution. Moderately frequent FI occur along cracks cutting the whole mineral grain. The FI exhibit highly variable phase compositions, from pure vapor (V) to two-phase (V+L and L+V containing down to ca. 5 vol% vapor). FIs richest in aqueous solution showed Th-tot, Te, and Tm-ice in the ranges of 148 to 164 °C, -51 to -54 °C, and -8.0 to -8.4 °C, respectively. The aqueous fluids belong to the system Na-Ca-Cl with a bulk salinity of ca. 12 wt% NaCl equivalent. Within one vapor-rich inclusion with a tiny tip, the condensation of a liquid phase occurred below -150 °C. The liquid did not freeze even at -196 °C. The FI homogenized to vapor at -143 °C. The vapor phase contains methane-dominated low-density (0.006 g/cm³) fluid.

ORIGIN OF THE BOROSILICATE-BEARING VEINLET AND REPLACEMENT REACTIONS

The crystallization sequence of the primary assemblages inferred from the textures present in the borosilicate-bearing veinlet is Kfs \rightarrow Gdd \rightarrow Brs+Wrd intergrowths \rightarrow Qtz. The $X_{\rm Fe}$ in primary borosilicates increases from grandidierite crystals cores to boralsilite and werdingite; this is a result of a continuous Mg-depletion during crystallization of the system. The borosilicate assemblages were subsequently altered by a H2O-enriched fluid, at which time the accessory phases ilmenite, rutile, and monazite crystallized. Very low fluorine content in the newly formed tourmaline indicates low fluorine activity in this fluid. The elevated Fe³⁺/Fe_{tot} ratio in ilmenite exsolution products suggests an increase of f_{02} in the system. Formation of clay minerals and sericite is the last process observed in the veinlet. The presumed precursor of boralsilite + werdingite aggregates crystallized from the melt depleted in Fe and Mg due to the previous crystallization of grandidierite. Textural observations on the secondary borosilicate assemblages indicate that they probably originated via the following reactions:

$$Gdd+Pl+H_2O \rightarrow Tur+Crn\pm Hc$$
(1)
(assemblage no. 3; this work)

$$\begin{array}{ll} Brs+Ab+Qtz+H_2O \rightarrow Olenite & (2) \\ Brs+Sil+Qtz+H_2O \rightarrow Dum & (3) \end{array}$$

 $d_{11} = d_{12} + d$

(assemblage no. 4; Grew et al. 1998a)

The content of Al (or olenite component) in tourmaline is buffered by the amount of newly formed corundum and hercynite. Theoretically, pure olenite tourmaline can form, along with 0.25 mole of Al₂O₃; however, the pure phase was not observed because the chemistry of the newly formed tourmaline and tourmaline/ corundum ratio chiefly reflect the incident *P*-*T* conditions during the reaction. Formation of olenite-rich tourmaline can be expected especially in high-temperature rocks (Ertl et al. 2010).

Alteration of grandidierite to clay minerals took place independently of the immediate environment (i.e., Qtz or Kfs), probably coevally with sericitization of feldspar. Both processes (kaolinization, sericitization) are usually attributed to low temperatures, but it also could take place after grandidierite decomposition into Tur+Crn, as H₂O-bearing fluids were involved in the process. Local activity of alkalis in the reacting fluids could play a significant role in addition to the *P*-*T* conditions.

The borosilicate-bearing veinlet evidently post-dates the formation of the exhumation-related foliation in the host granulite (Kotková and Melichar 2003); its formation can be, therefore, related to decompressional melting processes in the host granulitic rocks, as has been suggested for the cordierite-bearing leucosomes by these authors. The veinlet mineralization could have crystallized either in the H₂O-rich or the H₂O-poor system. In the former case, primary tourmaline would not be stable within the grandidierite stability field at temperatures above the breakdown of dravite. For dravite and Fe-free grandidierite, this would correspond to $T_{min} > 930$ °C and $P_{max} < 12$ kbar (Fig. 11a), whereas for the Fe-rich system present in Horní Bory, we estimate T_{min} > 800 °C and $P_{max} < 10$ kbar. These stability fields are located

B

Ky

And

11



Sil

along the robust "high-temperature" P-T path defined for the Moldanubian granulites of the Lower Austria by Carswell and O'Brien (1993; Fig. 11b). The second, more probable, possibility is crystallization from the H₂O-poor system, where the absence of tourmaline is caused by very low H2O-activity and therefore Fe-rich grandidierite and Fe-rich werdingite could be stable at $\sim T_{\min} \sim 750$ °C and $P_{\max} \sim 8$ kbar. These conditions correspond better to the "lower-temperature" decompressional path for the granulites extensively overprinted under low-pressure conditions (Tajčmanová et al. 2006, 2007; Fig. 11b). Significantly lower pressure is suggested by a medium- to low-pressure reequilibration of the host granulite, e.g., at ~700-750 °C and 4.5-6 kbar (formation of Pl rims around Ky/Sill) documented by Tajčmanová et al. (2007). Late influx of fluids at low pressures in the surrounding gneisses and granulitic rocks, which resulted in retrograde biotite after garnet, might have caused also the partial hydration of the veinlet assemblage and trigger reactions producing water-bearing borosilicates (tourmaline and dumortierite) within their stability fields (Fig. 11).

With regard to the mineral assemblage and mineral composition of the borosilicate-bearing veinlet and the host granulite, we suggest that the primary borosilicate assemblages most probably originated during partial melting of the host granulitic rocks with participation of water-undersaturated B-bearing fluids, at $T \sim$ 750 °C and $P \sim 6-8$ kbar (the intersection with the granulite P-Tpaths). The boron could have been provided by: (1) breakdown of tourmaline in the host leucogranulite; however, relics of tourmaline were not found, and (2) partial melting of adjacent high-grade migmatized gneisses and melanocratic granulites, which contain small amounts of tourmaline and dumortierite, and abundant micas. The latter suggestion is supported by common alternation of leucogranulites with the above-mentioned rocks. High boron content in the rocks of the Gföhl Unit is also documented by numerous occurrences of dumortierite and Al-rich tourmaline along the E and NE border of the Moldanubian Zone in the rocks of the Gföhl Unit (Fig. 1b; e.g., Cempírek and Novák 2006; Cempírek et al. 2006; Vrána et al. 2009; Fuchs et al. 2005).

20

15

5

pressure (kbar

Ι.

Sil

The origin of the borosilicate veinlet, by melting of the host granulitic rocks, is also supported by the chemical composition (EMPA, LA-ICP-MS) of the major ferromagnesian mineralsgarnet from the leucogranulite and grandidierite from the borosilicate veinlet. Both minerals contain high concentrations of Li (up to 1890 ppm in grandidierite; up to 1113 ppm in garnet). Also, elevated contents of Ni (390-450 ppm; 562-681 ppm) but very low concentrations of Co are similar in both minerals. Garnet is also enriched in Sc, which is present in niobian ferberite from the veinlet. Grandidierite accommodates elevated amounts of P and V, which could have been supplied by the breakdown of phases other than garnet in the granulite, e.g., feldspars or apatite. Concerning major elements, grandidierite shows higher variation in $X_{\rm Fe}$ than garnet, but this might be controlled either by grandidierite structure or by fractionation of Fe (and Mn) from Mg during crystallization. However, no garnet-grandidierite relationships have been observed so far. In view of the late character of the borosilicate-bearing veinlet and the geochemical parallels listed above, we assume that grandidierite origin can be related to reaction of garnet with boron-rich fluid. A hypothetical reaction of grandidierite formation at the expense of garnet and sillimanite could be, e.g.:

$$2 \operatorname{Grt} + 7 \operatorname{Sil} + 3 \operatorname{B}_2\operatorname{O}_3 \to 6 \operatorname{Gdd} + 7 \operatorname{Qtz.}$$
(4)
(this work)

Solid-state reactions involving primary tourmaline with garnet/cordierite resulting in grandidierite and plagioclase reported from other localities (see their review in Grew 1996) do not seem



20

15

10

5

And

Ky

pressure (kbar)

to be applicable for the Horní Bory tourmaline-free leucogranulite and plagioclase-poor borosilicate veinlet.

FLUIDS ASSOCIATED WITH BOROSILICATE-BEARING VEINLET

All three types of fluid inclusions should be considered secondary because they occur mostly in subparallel trails. None of isochores constructed for the fluid types found in the veinlet enter the *P*-*T* conditions inferred from the mineral assemblages of primary borosilicate-bearing assemblage (Fig. 11). This can be consistent with: (1) late timing of the (mostly trail-related) inclusions, and/or (2) reequilibration of inclusions, which often occurs in a quartz host during superimposed *P*-*T* events (e.g., Sterner and Bodnar 2007). The high-temperature aqueous (Type 2) fluid inclusions are comparable to those occurring within the Horní Bory cross-cutting primitive subabysal pegmatites (*Z*. Dolníček, unpublished data), whereas the brine + methane mixture (Type 3) is present in primary fluid inclusions within hydrothermal dolomite filling central vugs in a primitive LP pegmatite from Horní Bory (Dolníček et al. 2003).

Analogues of pure carbonic (Type 1) fluid inclusions were previously detected in quartz from Moldanubian granulites by Ďurišová and Dobeš (1997). This anhydrous fluid could potentially represent the fluid phase associated with primary crystallization of the borosilicate-bearing veinlet. However, the low (and within single trail also essentially constant) fluid density, combined with absence of petrographic evidence of reequilibration (Vityk and Bodnar 1995), suggest instead that Type 1 fluid inclusions are most probably related to some stage of superimposed retrograde metamorphism and tectonic processes.

RELATIONS TO THE GRANITIC PEGMATITES OF THE BORY DISTRICT

The abundant granitic pegmatites in the Bory Granulite Massif vary from primitive metamorphogenic abyssal pegmatites (concordant, coarse-grained, pegmatitic leucosome) in granulite, through primitive subabyssal pegmatites (concordant to discordant dikes locally with large pockets) in migmatized gneisses, to primitive or moderately evolved rare-element pegmatites (discordant, symmetrically zoned dikes) in both granulites and gneisses (for pegmatite nomenclature see e.g., Černý and Ercit 2005; Novák 2005). All these pegmatites feature high contents of B, Al, P, and commonly also Fe or high Fe/Mg. Minor to trace concentrations of As, S, W, Ti, Zr, Sc, Sb, and locally Y, REE as well as very low concentrations of Be and Mn are typical (see e.g., Duda 1986; Staněk 1991; Novák et al. 1992, 2004a, 2008; Novák 2005).

As indicated by the presence of cordierite and andalusite, primitive abyssal and subabyssal pegmatites are related to MP-LP migmatization processes, which followed the HP granulite metamorphism. More evolved pegmatites (discordant dikes with tourmaline, sekaninaite and andalusite, and lepidolite pegmatites) belong to a single pegmatite population, which was likely derived from their parental S-type granites and intruded granulite complex at LP conditions of about 2–3 kbar (Novák and Taylor 2005). The estimated *P-T* conditions as well as geological position of the borosilicate veinlet suggest that it represents one of the earliest intrusions related to pegmatites in the Bory Granulite Massif. The geochemical signature of the assemblage (Fe-Al-Brich) and presence of the accessory dumortierite, niobian rutile, monazite-(Ce), srilankite(?), and Sc,Nb-enriched ferberite in the borosilicate-bearing veinlet is very similar to those of highly peraluminous rare-element bearing granitic pegmatites in the Bory district (Pegmatite types 3 and 4). These are characterized by abundant andalusite, sekaninaite, tourmaline, rare primary diaspore, dumortierite, and accessory Sc-enriched ferberitewolframoixiolite, stibiotantalite, and monazite-(Ce) (e.g., Staněk 1991; Novák 2005; Novák et al. 2004a, 2008), and complete absence of beryllium, even in trace amounts (e.g., in sekaninaite; Černý et al. 1997). Remarkable similarities in major and trace chemistry despite the different degree of fractionation of each pegmatite type suggest that all the pegmatite types could have the same melt source.

The U-Pb radiometric dating of monazite from the discordant (Pegmatite type 3) pegmatite dike Oldřich, Dolní Bory-Hatě yielded the ages of 335.8 ± 2 and 337.2 ± 2 Ma (Novák et al. 1998), which overlap with error of the U-Pb zircon data for granulites [349 + 9/-10] for the Bory granulite; ~340 Ma for granulites in the Moldanubian Zone; Kotková (2007)]. Consequently, all pegmatite types from the Bory Granulite Massif, including the examined veinlet with borosilicates, likely originated in a short period of ~5 Ma. This involved formation of: (1) the examined veinlet with borosilicates, which exhibits typical features of abyssal pegmatites (Grew 1998; Černý and Ercit 2005) and formed at the post-peak MP granulite conditions; (2) abyssal to subabyssal pegmatites related to migmatitization with cordierite and andalusite; (3) rare-element pegmatites with sekaninaite, andalusite, and primary diaspore; and (4) complex lepidolite pegmatites. Hence, the decompression process, which was very fast (e.g., Kotková et al. 2007), generated gradually the individual types of pegmatites under rather distinct P-T conditions within a short time span.

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