Accessory priderite and burbankite in multiphase solid inclusions in the orogenic garnet peridotite from the Bohemian Massif, Czech Republic

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This paper reports on priderite (potassium titanate) and burbankite (alkali Sr–Ca–REE–Ba carbonate) from an orogenic garnet peridotite body enclosed in high-pressure garnet-kyanite-bearing quartzo-feldspathic Göhl granulite in the Bohemian Massif of the Variscan belt. The garnet peridotite contains ubiquitous phlogopite and was interpreted to be derived from the mantle wedge formed at the convergent plate margin. The earliest generation of chromian spinel, surrounded by kelyphitized garnet, ubiquitously contains multiphase solid inclusions (MSIs), which are mainly composed of phlogopite, dolomite, calcite, apatite, graphite, monazite, thorite, and sulfides, and priderite and burbankite are newly identified as rare accessory minerals in such MSIs. Most of these MSIs contained significant amounts of carbonates. The presence of peculiar accessory minerals in MSIs characterizes the nature of parental melts. The formation of priderite requires an ultrapotassic condition, which is usually defined by K<sub>2</sub>O > 3 wt% and K<sub>2</sub>O/Na<sub>2</sub>O > 2 in bulk composition, and high Cr<sub>2</sub>O<sub>3</sub> content in priderite (15–18 wt%) suggests that it was formed as a reaction product between a melt inclusion and a host chromite. Burbankite contains significant amounts of Na<sub>2</sub>O and K<sub>2</sub>O (~ 3 wt%) and REE concentration (>31 wt%), and requires more sodic composition. The presence of priderite and burbankite in MSIs suggests that some of them crystallized from ultrapotassic melts, whereas others crystallized from sodic peralkaline melts. Such alkali-carbonate melts could be present in the mantle wedge peridotite before its incorporation into the granulite.

Keywords: Garnet peridotite, Variscan orogeny, Multiphase solid inclusion, Priderite, Burbankite

INTRODUCTION

Recently, multiphase solid inclusions, consisting of aggregates of solid phases with subordinate fluid or cavi- ties, have been found in ultrahigh-pressure (UHP) metamorphic rocks (e.g., Ferrando et al., 2005; Malaspina et al., 2006; Frezzotti and Ferrando, in press). These multiphase solid inclusions (MSIs) are considered to have been crystallized from supercritical fluids (i.e., dense fluids that are stable deeper than the second critical point in the fluid-rock system), ranging from hydrous silicate melt to carbonatite (Ferrando et al., 2005; Korsakov and Hermann, 2006). These dense, supercritical fluids serve candidates for deep subduction–zone fluids released from subducting plates, and they are responsible for initiating arc magmatism (Malaspina et al., 2006; Frezzotti and Ferrando, in press).

In this study, we report on peculiar accessory minerals in MSIs found in the metasomatized orogenic garnet peridotite from the southern part of the Bohemian Massif (Naemura et al., 2009). The purpose of this study is to characterize MSIs by identification of accessory minerals that can be stable in particular chemical environments. This paper is the first to identify priderites—ideally K<sub>2</sub>Al<sub>2</sub>Ti<sub>16</sub>O<sub>16</sub>—and burbankite—ideally (Na,Ca)<sub>3</sub>(Sr,REE,...
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Ba$_3$(CO$_3$)$_5$—from orogenic garnet peridotite. The Ti-rich accessory minerals in ultramafic rocks are commonly ilmenite, rutile, armalcolite, Ti-clinohumite, and Ti-chondrodite, and the presence of priderite has been recognized only in highly metasomatized mantle xenoliths such as Mica–Amphibole–Rutile–Ilmenite–Diopside rock (MARID) and phlogopite–K–richterite peridotite (PKP) (Haggerty et al., 1983; Konzett et al., 2013). Burbankite had only been reported at a few localities, mainly from highly alkaline volcanic rocks, carbonatites, and lacustrine sediments (Bühn et al., 1999), and it has never been reported from the mantle peridotite to the best of our knowledge. These accessory minerals can store high amounts of potassium, Ba, Sr, and REE in their crystal structures, and thus they can serve as important carriers of these elements in the upper mantle.

We applied confocal laser Raman spectroscopy, field–emission-type electron probe micro-analyzer (FE–EPMA), and electron–backscattered diffraction (EBSD) pattern techniques for comprehensive identifications of minute minerals in MSIs. The primary goal of this study was to identify minute crystals of priderite and burbankite in the MSIs, and secondarily we wanted to establish some constraints on the chemical compositions of MSIs in the light of these accessory minerals.

GEOLOGICAL BACKGROUND

The Bohemian Massif is located at the eastern end of the Variscan orogenic belt, which was formed during the continent–continent collision between northern Laurussia and southern Gondwana. The Variscan orogenic belt was subdivided into the Moldanubian Zone, the Saxothuringian Zone and the Rheno–Hercynian Zone, with the Moldanubian Zone being well exposed in the Bohemian Massif (Fig. 1a). The studied spinel–garnet peridotite occurs at the Plešovice quarry in the Blanský les granulite massif, which constitutes one of the south Bohemian granulite massifs (Svojtka et al., 2002; Naemura et al., 2009). In the quarry, priderite occurs as a small, lenticular body (~10 m width; Fig. 1b) enclosed in the felsic Gfohl granulite of calc–alkaline granitic compositions with high-pressure assemblage of garnet + kyanite + ternary feldspar + quartz equilibrated at 1.6 GPa and 1000 °C (Carswell and O’Brien, 1993). In the Plešovice quarry, a garnetiferous peridotite assemblage, consisting of pyrope–rich garnet, ternary feldspar, and quartz, occurs as lenses/layers in the Gfohl granulite. The pressure–temperature path of the peridotite was identified by Naemura et al. (2009, 2011), who proposed that the phlogopite-bearing spinel–garnet peridotite experienced a multiple exhumation history, including the initial garnet peridotite assemblage in the diamond–stability field (Stage 1, P >4 GPa), exhumation to the chlorite peridotite field (Stage 2, T ~700 °C, P ~2 GPa), subduction to the garnet lherzolite field (Stage 3) at ~2.9 GPa at 950 °C, followed by exhumation to the spinel lherzolite field (Stage 4) at ~750 °C. Naemura et al. (2009) envisaged that such a multiple exhumation path could be realized in the corner flow motion in the mantle wedge, with the mantle–wedge peridotite being entrained into the subducted continental crust (Gfohl granulite) by the sinking intrusion mechanism (Brueckner, 1998).

ANALYTICAL METHODS

All thin sections were made by use of silicon carbide with water, which might dissolved Na$_2$CO$_3$/K$_2$CO$_3$ into water if they were present in MSIs. In order to avoid further reaction with water, we used diamond paste (3 µm diameter) and ethanol-based lubricant during the final stage of polishing. Phase identifications of minerals in MSIs were carried out using a scanning electron microscope (JEOL JSM–6010LA, the University of Tokyo) with an energy-dispersive X-ray detector and a backscattered electron detector attached. Operating conditions for the SEM were 15 kV, 12 mm working distance, and filament current = 50 µA. Raman spectra of priderite and carbonates were obtained using a Raman spectroscope with a YAG laser source (wave-length = 532 nm) (Nano-Photon Co. Raman–11, the University of Tokyo). Operating conditions were ×100 objective lens, 1200 grating, exposure time = 30 s for priderite and 250 s for carbonates, laser intensities on the sample = 1.4 mW for priderite and 10 mW for carbonates, respectively.

Quantitative analyses of priderite and burbankite were carried out using the FE–EPMA (JEOL JSM–8350F, the University of Tokyo). Analytical conditions were 15 kV, beam current on the surface was 6 nA (3–µm beam diameter) for priderite and 25 kV, 20 nA (10–µm diameter) for burbankite, respectively. Oxides, silicate minerals and synthetic monazites were used as analytical standards, and the electron backscattered diffraction pattern of burbankite was investigated using the Thermo Noran Phase ID EBSD system installed on the Hitachi S–4500 field–emission (FE)–SEM system at the University of Tokyo. The accelerating voltage of the incident beam was 20 kV, and the emission current was 15 µA. Calculations of Kikuchi patterns and analyses of the observed patterns were performed using a program by Kogure (2003).

OCCURRENCE OF PRIDERITE AND BURBANKITE IN MULTIPHASE SOLID INCLUSIONS

Most of the spinel–garnet peridotites in the Blanský les
granulite massif show in-equi-granular texture, in which large spheroidal garnet grains (~ 1 cm in diameter) are surrounded by a fine-grained matrix (generally less than 1 mm in diameter) of olivine, orthopyroxene, clinopyroxene with accessory chromian spinel, Ba-rich phlogopite, and Sr-rich apatite. Garnet and matrix minerals were equilibrated at ~ 2.9 GPa and ca. 950 °C (cf., Stage 3; Naemura et al., 2009). The earliest Stage 1 is evidenced by chromian spinel enclosed in garnet/kelyphite (Figs. 1c and 1d). This type of chromian spinel contains exsolution lamellae of diopside and clino-enstatite, suggesting the presence of high-pressure polymorph of chromian spinel with a substantial amount of pyroxene components, possibly with a calcium-ferrite-type crystal structure (Yamamoto et al., 2009). Hereinafter, we refer to such a chromian spinel as ultrahigh-pressure (UHP) chromite. Naemura et al. (2011) suggested that UHP chromite was present in the stability field of diamond (cf., Stage 1 mentioned above), based on the finding of diamond in the peridotite. Such UHP chromites ubiquitously contain MSIs (Figs. 2a–2f), which are usually enclosed as the euhedral shape outline in chromian spinel. We selected 37 thin sections from 10 samples, and among these thin sections we found 282 solid inclusions in UHP chromites, which mainly consisted of (1) phlogopite-rich (>$90$ vol%) inclusions (58 of 282); (2) phlogopite-free, carbonate-rich MSIs (34 of 282), mainly consisting of dolomite + calcite + apatite with subordinate amounts of graphite, monazite, and chlorite; and (3) phlogopite-carbonate-rich MSIs (165 of 282) with subordinate amounts of apatite, graphite, monazite, thorianite, and sulfides (Figs. 2a–2f). In addition, we found (4) three carbonate-free, phlogopite-apatite-rich MSIs. Finally, although the above four types do not contain calcic amphibole,
there are (5) four amphibole-bearing inclusions, which consist of calcic amphibole and chlorite with subordinate amounts of Al-poor clinopyroxene and olivine (Naemura et al., 2009). The remainder of the inclusions are single-grained olivine, pyroxenes, garnet (some are kelyphitized/symplectite), serpentine, and thorianite. The diver-
sity of the observed mineral inclusions could be produced by temporal heterogeneity of melts during entrapments and subsequent subsolidus reactions (Giuliani et al., 2012, 2013, 2014). We are now trying to understand how these mineral inclusions were formed during the complex metamorphic history. Based on the similarity with melt inclusions reported from carbonatite (e.g., Guzmics et al., 2011), these MSIs seem to have crystallized from carbonate–rich melts. This view was supported by the recently published review paper by Frezzotti and Ferrando (in press) who classify MSIs found in the Plešovice peridotite as typical examples of what they call ‘melt inclusions’. The reconstruction of the melt compositions for these MSIs will be published elsewhere because in this paper we want to focus on peculiar accessory minerals found in these mineral inclusions. Among 282 mineral inclusions examined, we found 6 grains of priderite (5 were found in phlogopite–carbonate–rich MSIs and one in a phlogopite–rich inclusion) and 2 grains of alkali–REE carbonate grains in phlogopite–carbonate–rich inclusions.

Priderite usually occurs as euhedral and subhedral crystals, with sizes up to 10 µm in the vicinity of the wall of chromite (Figs. 2b–2d). Priderite was first analyzed using Raman spectroscopy, which yielded a spectrum with peaks at 150, 350, and 685 cm$^{-1}$ (Fig. 3a); this was consistent with those of chromian priderite reported by Konzett et al. (2013). In Table 1, chemical compositions of priderite are shown. Priderite belongs to the hollandite group of minerals, which have cation sites of A (Ba, K, Na) and B (Fe, V, Cr, Nb, Zr) and have TiO$_4$ tetrahedrons. A–site is mostly occupied by K and Ba priderites, which form solid solutions of Ba$_2$Ti$_7$O$_{16}$–BaB$_2$Ti$_6$O$_{16}$, and K$_2$BTi$_7$O$_{16}$–K$_2$B$_2$Ti$_6$O$_{16}$, respectively. Priderite in the spinel–garnet peridotite has $\Sigma A = 1.1–1.7$ and $\Sigma B = 1.9–2.1$, with K/(K + Ba) = 0.5–1.0 and Cr/(Cr + Fe$^{3+}$) = 0.89–0.98 (see Table 1). The concentration of V$_2$O$_5$ is quite low (0.7–1.3 wt%), and MgO and PbO are scarce (<0.1 wt%). Titanium is fairly constant (5.9–6.2 apfu). Therefore, the priderite in the peridotite forms a solid solution between BaCr$_2$Ti$_6$O$_{16}$ and K$_2$Cr$_2$Ti$_6$O$_{16}$. The occurrence of priderite in a terrestrial rock is quite uncommon and is almost restricted to ultrapotassic rocks such as lamproite, orpiment, and glimmerite veins in carbonatite (Foley and Wheller, 1990). High Cr$_2$O$_3$ content in the priderite suggests that the priderite grain was not directly precipitated from a melt but rather was formed by interaction between a melt inclusion and a host chromite (i.e., a step–daughter mineral; Frezzotti and Ferrando, in press).

An alkali–REE mineral in MSI shows a rectangular shape (Fig. 2e), and it appears to be carbonate based on the low total wt% (Table 2), which is supported by the presence of a significant C peak in the energy–dispersive X–ray spectrum with gold coating. The Raman spectroscopy provided conclusive evidence of the presence of CO$_2$ in the alkali–REE mineral because it gave a band at around 1078 cm$^{-1}$ (Fig. 3b). The band position is much lower than those of other carbonates such as dolomite, norsethite, and calcite (~ 1086 cm$^{-1}$), and the width of the band (~ 20 cm$^{-1}$ in full width at half maximum) is broader than those of other species of carbonate (<10 cm$^{-1}$). All of these features for the band coincide with that reported for burbankite by Bühn et al. (1999). There are various species of alkali–REE carbonates, namely burbankite, calcio–burbankite, carbocernaite, domayite–(Y), ewalite, khanneshite, lukechangite–(Ce), mckelveyite–(Y), petersenite–(Ce), and remondite–(Ce). The low

![Figure 3. Raman spectra of (a) priderite and (b) various carbonates in multiphase solid inclusions in the Plešovice peridotite.](image-url)
Yttrium content of the alkali–REE carbonate makes it unlikely donnayite–(Y), ewaldite, and mckelveyite–(Y). High Ba and relatively low REE contents negate a possibility for lukechangite–(Ce), petersenite–(Ce), and remondite–(Ce), which contain >40 wt% LREE. Therefore, the alkali–REE mineral identified by this study is either (1) a burbankite–group mineral (burbankite, calcio–burbankite, khanneshite) with hexagonal structure, or (2) carbocernaite with orthorhombic structure.

In order to discriminate between these two groups, we analyzed an EBSD pattern for the alkali–REE carbonate (Fig. 4a), and it turned out that the core of the alkali-

| Sample | PQ101a-21 Priderite | PQ101a-21 Priderite | PQ210-4 Priderite | PQ101q-4 Priderite |
|--------|----------------------|----------------------|------------------|---------------------|
| TiO₂   | 60.3                 | 58.1                 | 63.3             | 65.8                |
| Cr₂O₃  | 17.8                 | 18.2                 | 15.5             | 18.3                |
| Fe₂O₃  | 1.5                  | 1.5                  | 2.1              | 0.5                 |
| MnO    | 0.24                 | 0.26                 | 0.29             | 0.03                |
| MgO    | 0.63                 | 0.16                 | 0.18             | 0.16                |
| CaO    | 0.16                 | 0.16                 | 0.18             | 0.19                |
| Na₂O   | 0.00                 | 0.05                 | 0.25             | 0.21                |
| K₂O    | 4.9                  | 4.5                  | 4.7              | 10.5                |
| NiO    | 0.49                 | 0.52                 | 0.48             | 0.38                |
| BaO    | 9.8                  | 15.2                 | 9.4              | 1.4                 |
| V₂O₅   | 0.6                  | 0.9                  | 1.1              | 0.9                 |
| PbO    | 0.41                 | 0.00                 | 0.02             | 0.00                |
| Nb₂O₅  | 0.00                 | 0.31                 | 0.27             | 1.45                |
| ZrO₂   | 0.02                 | 0.00                 | 0.51             | 0.11                |
| Total  | 96.7                 | 99.8                 | 97.9             | 99.7                |

| Sample | Priderite | PQ101a-21 | PQ210-4 | PQ101q-4 |
|--------|-----------|-----------|---------|-----------|
| Ti      | 5.91      | 5.74      | 6.05    | 6.00      |
| Cr      | 1.83      | 1.89      | 1.56    | 1.76      |
| Fe³⁺    | 0.14      | 0.14      | 0.20    | 0.04      |
| Mn      | 0.03      | 0.03      | 0.03    | 0.00      |
| Mg      | 0.12      | 0.03      | 0.03    | 0.03      |
| Ca      | 0.02      | 0.02      | 0.02    | 0.02      |
| Na      | 0.00      | 0.01      | 0.06    | 0.05      |
| K       | 0.81      | 0.75      | 0.76    | 1.62      |
| Ni      | 0.05      | 0.05      | 0.05    | 0.04      |
| Ba      | 0.50      | 0.78      | 0.47    | 0.07      |
| V       | 0.05      | 0.08      | 0.09    | 0.07      |
| Pb      | 0.01      | 0.00      | 0.00    | 0.00      |
| Nb      | 0.00      | 0.02      | 0.02    | 0.08      |
| Zr      | 0.00      | 0.00      | 0.03    | 0.01      |
| Cation  | 9.49      | 9.55      | 9.38    | 9.78      |

| Sample | PQ101-1 |
|--------|---------|
| FeO    | 1.1     |
| MnO    | 0       |
| MgO    | 0       |
| CaO    | 6.3     |
| Na₂O   | 3.1     |
| K₂O    | 3.3     |
| BaO    | 13.0    |
| SrO    | 9.8     |
| PbO    | 0.04    |
| La₂O₃  | 8.4     |
| Ce₂O₃  | 16.9    |
| Nd₂O₃  | 4.1     |
| Pr₂O₃  | 0.9     |
| Sm₂O₃  | 0.08    |
| UO₂    | 1.6     |
| ThO₂   | 0.5     |
| P₂O₅   | 0.12    |
| Cl     | 0.08    |
| F      | 0.7     |
| CO₂*   | 27.1    |
| Total  | 97.2    |
| Fe     | 0.05    |
| Mn     | 0.00    |
| Mg     | 0.00    |
| Ca     | 0.34    |
| Na     | 0.31    |
| K      | 0.21    |
| Ba     | 0.26    |
| Sr     | 0.29    |
| Pb     | 0.0005  |
| La     | 0.16    |
| Ce     | 0.31    |
| Nd     | 0.02    |
| Pr     | 0.02    |
| Sm     | 0.001   |
| U      | 0.02    |
| Th     | 0.01    |
| P      | 0.01    |
| Cl     | 0.01    |
| F      | 0.12    |
| CO₃    | 1.88    |

* Calculated based on stoichiometry assuming 6 oxygens.

Table 1. Chemical Composition of Priderite from Plešovice Peridotite

| Mineral | PQ101a-21 Priderite | PQ101a-21 Priderite | PQ210-4 Priderite | PQ101q-4 Priderite |
|---------|----------------------|----------------------|------------------|---------------------|
| TiO₂   | 60.3                 | 58.1                 | 63.3             | 65.8                |
| Cr₂O₃  | 17.8                 | 18.2                 | 15.5             | 18.3                |
| Fe₂O₃  | 1.5                  | 1.5                  | 2.1              | 0.5                 |
| MnO    | 0.24                 | 0.26                 | 0.29             | 0.03                |
| MgO    | 0.63                 | 0.16                 | 0.18             | 0.16                |
| CaO    | 0.16                 | 0.16                 | 0.18             | 0.19                |
| Na₂O   | 0.00                 | 0.05                 | 0.25             | 0.21                |
| K₂O    | 4.9                  | 4.5                  | 4.7              | 10.5                |
| NiO    | 0.49                 | 0.52                 | 0.48             | 0.38                |
| BaO    | 9.8                  | 15.2                 | 9.4              | 1.4                 |
| V₂O₅   | 0.6                  | 0.9                  | 1.1              | 0.9                 |
| PbO    | 0.41                 | 0.00                 | 0.02             | 0.00                |
| Nb₂O₅  | 0.00                 | 0.31                 | 0.27             | 1.45                |
| ZrO₂   | 0.02                 | 0.00                 | 0.51             | 0.11                |
| Total  | 96.7                 | 99.8                 | 97.9             | 99.7                |

Table 2. Chemical Composition of Burbankite from Plešovice Peridotite

| Sample | PQ101-1 |
|--------|---------|
| FeO    | 1.1     |
| MnO    | 0       |
| MgO    | 0       |
| CaO    | 6.3     |
| Na₂O   | 3.1     |
| K₂O    | 3.3     |
| BaO    | 13.0    |
| SrO    | 9.8     |
| PbO    | 0.04    |
| La₂O₃  | 8.4     |
| Ce₂O₃  | 16.9    |
| Nd₂O₃  | 4.1     |
| Pr₂O₃  | 0.9     |
| Sm₂O₃  | 0.08    |
| UO₂    | 1.6     |
| ThO₂   | 0.5     |
| P₂O₅   | 0.12    |
| Cl     | 0.08    |
| F      | 0.7     |
| CO₂*   | 27.1    |
| Total  | 97.2    |

* Calculated based on stoichiometry assuming 6 oxygens.

Figure 4. Electron backscattered diffraction patterns of (a) an alkali–REE carbonate in the multiphase solid inclusion in the Plešovice peridotite, (b) carbocernaite, (c) burbankite, and (d) mckelveyite (Y). Structure parameters of (b), (c) and (d) are from the American Mineralogist Crystal Structure Database (http://rruff.geo.arizona.edu/AMS/amcsd.php).
REE carbonate does not have any diffraction patterns, although its marginal part has a weak diffraction pattern (Fig. 4a). The obtained diffraction pattern for the alkali-REE carbonate is substantially different from that of carbonatite (Fig. 4b), but it is quite similar to those of the burbankite-group minerals (Fig. 4c). Therefore, the alkali-REE carbonate should be classified as a burbankite-group mineral. Unfortunately, the smallness of the grain is too small to be analyzed by FE-EPMA, and thus we analyzed the central part. The Na$_2$O content in the studied alkali-REE carbonate was ~ 3.1 wt%, which is significantly lower than for burbankite in the literature (~8 wt% Na$_2$O). The low Na$_2$O content is partly due to the incorporation of a significant amount of potassium (~3.0 wt%), but the total amount of alkali is still significantly lower (Na + K ~ 0.52 apfu, assuming 2 total cations) than the reported values (Na + K > 0.64 assuming 2 total cations; Bühn et al., 1999). The low alkali content for the central part of the burbankite probably reflects the loss of alkali as it was transformed to the amorphous phase during alteration, and thus only the margin of the grain preserves the original burbankite structure.

**DISCUSSION AND CONCLUSION**

The orogenic garnet peridotite in the south Bohemian granulite contains ubiquitous phlogopite and apatite, and is considered to be formed in the mantle wedge (Naemura et al., 2009). The previously constrained pressure-temperature path demonstrated a convection motion: initial Stage 1 (P >4 GPa), exhumation to Stage 2 (T ~ 700 °C, P ~ 2 GPa), subduction to Stage 3 (~ 2.9 GPa at 950 °C), followed by exhumation to Stage 4 (P ~ 1.5 GPa at ~ 750 °C). Such a metamorphic history could be realized by a corner flow motion in the mantle wedge (Nimis and Morten, 2000). The observed MSIs seem to have crystallized from a melt at Stage 1 when the Plešovice peridotite was in the mantle wedge, and in such MSIs, we report, there are rare occurrences of priderite and burbankite. The extreme rareness of priderite and burbankite in MSIs suggests a significant heterogeneity of constituent minerals and volume proportion of minerals observed for the MSIs.

The presence of priderite and burbankite will give the following constraints on the bulk compositions for MSIs. Priderite usually occurs in ultrapotassic igneous rocks such as lamproite and orangeite (Foley and Wheller, 1990), and it occurs as xenocryst in kimberlite associated with the linsleyite–mathiasite (LIMA) phase (e.g., Zhou and Lu, 1994). Therefore, the priderite-bearing MSI described here should be ultrapotassic in bulk composition, which is usually defined as K$_2$O >3 wt% and K$_2$O/Na$_2$O >2 in Mg-rich environments (MgO >3 wt%; Foley et al., 1987). The highly potassic nature of MSI was supported by an extremely low concentration of Na$_2$O in phlogopite (<0.01 wt%; Naemura et al., 2009). A high concentration of Cr$_2$O$_3$ in priderite suggests that priderite did not crystallize from a melt but rather was formed as a step-daughter mineral, i.e., as a reaction product between parental melt inclusion and host chromite. On the other hand, the occurrence of burbankite–group minerals is restricted in peralkaline rocks, namely to Na$_2$O + K$_2$O > Al$_2$O$_3$ (molar ratio; Chakhmouradian and Zaitsev, 2012), and it generally occurs in the following three rock types: (1) highly alkaline rocks, (2) carbonatite, and (3) lacustrine sediments (Bühn et al., 1999; Belovitskaya and Pekov, 2004). The presence of significant amounts of carbonate in the studied MSIs suggest an affinity with carbonatite. Burbankites become unstable with a decrease of alkalinity, and they are replaced by alkali-free REE carbonates during the late hydrothermal stage. Therefore, a parental melt for the burbankite-bearing MSIs should be peralkaline. Apart from priderite and burbankite, the most abundant phlogopite–carbonate-rich MSIs seem to have crystallized from potassic-carbonate melts. The presence of priderite and burbankite in them suggests that parental melt compositions sometimes extend to ultrapotassic, and at other times they extend to peralkaline, with a significant amount of sodium.

The sizes, modes of occurrence, and constituent minerals observed in MSIs in the mantle–wedge–derived peridotite described here are similar to those of MSIs found in kimberlite-borne mantle breccia reported by Giuliani et al. (2012, 2013, 2014), who postulated that such an alkali carbonate melt is ubiquitously present in the upper mantle but that its geological record has been overlooked due to its smallness and fragile nature. Here we briefly discuss an origin of this alkali carbonate melt in the context of the high-pressure metamorphism during the Variscan orogeny. The studied garnet peridotite is hosted by the garnet–kyanite–bearing quartzio-feldspathic granulite, which was formed by subduction and exhumation of the upper continental crust (e.g., Carswell and O’Brien, 1993; Štůpská and Powell, 2005). Previous geothermo-barometric studies demonstrated that garnet peridotites in the Bohemian Massif were formed at a much deeper level than the surrounding granulate (e.g., Medaris et al., 1990, 2005; Naemura et al., 2009). However, the recent discoveries of coesite and diamond from the granulate suggest that the granulate also experienced an UHP condition (e.g., Kotková et al., 2011). This suggests the possibility that the granulate was subducted to mantle depth (i.e., an UHP condition) and that it took hold of the surrounding garnet peridotites. In this context, the alkali carbonate melt can be formed by partial melting of
the granulite at UHP condition. In the studied Plešovice quarry, Vrana (1989) described a vein of peridotitic granulite, which were formed by partial melting of the felsic Gfohl granulite at mantle depth (>1.5 GPa). In the Bohemian Massif, Becker et al. (1999) also described gimeritte veins, which was formed by an interaction between granulite–derived ultrapotassic fluid and mantle peridotite. Such granulite-derived melt and fluid should be saturated with SiO2, which is significantly different from the Si-poor nature observed for the phlogopite–carbonate–rich MSIs described here. An alkali carbonate melt can be formed by an immiscible separation from a silicate melt during differentiation in the mantle (Zanetti et al., 1999).

Alternatively, such an alkaline carbonate melt could be present in the mantle wedge. The presence of carbonate–rich melt in the mantle wedge has been suggested by the experimental study of C–O–H–volatile saturated herzolite by Tumiati et al. (2013), who postulated that carbonate and carbonate-bearing peridotite give substance to the ‘cold plume’. This hypothesis proposed that hydration and partial melting along the subducting slab can trigger Rayleigh–Taylor instabilities that evolve into low–temperature, partially molten diapiric structures enriched by volatiles that rise through the hot asthenospheric wedge (Gerya and Yuen, 2003). Such a cold plume could represent an important source of CO2 and H2O, and it is one of a series of processes that ultimately lead to arc magmatism (Tumiati et al., 2013). In this context, the alkali carbonate melt could be present in the mantle wedge peridotite before its incorporation into the subducted continental crust during the Variscan orogeny.

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