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High-pressure partial melting and melt loss in felsic granulites in the Kutná Hora complex, Bohemian Massif (Czech Republic)

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A B S T R A C T

Felsic granulites from the Kutná Hora complex in the Moldanubian zone of central Europe preserve mineral assemblage that records transition from early eclogite to granulite facies conditions, and exhibits leucocratic banding, which is interpreted as an evidence for melt loss during the decompression path. The granulites are layered and consist of variable proportions of quartz, ternary feldspar, garnet, biotite, kyanite, and rutile. In the mesocratic layers, garnet grains show relatively high Ca contents corresponding to 28–41 mol% grossular end member. They have remarkably flat compositional profiles in their cores but their rims exhibit an increase in pyrope and a decrease in grossular and almandine components. In contrast, garnets from the leucocratic layers have relatively low Ca contents (15–26 mol% grossular) that further decrease towards the rims. In addition to modeling of pressure–temperature pseudosections, compositions of garnet core composition, garnet rim-ternary feldspar–kyanite–quartz equilibrium, ternary feldspar composition, and the garnet–biotite equilibrium provide five constraints that were used to reconstruct the pressure–temperature path from eclogite through the granulite and amphibolite facies. In both layers, garnet cores grew during omphacite breakdown and phengite dehydration melting at 940 °C and 2.6 GPa. Subsequent decompression heating to 1020 °C and 2.1 GPa produced Ca- and Fe-poor garnet rims due to the formation of Ca-bearing ternary feldspar and partial melt. In both the mesocratic and leucocratic layer, the maximum melt productivity was 26 and 18 vol.%, respectively, at peak temperature constrained by the maximum whole-rock H_2O budget, ~1.05–0.75 wt.%, prior to the melting. The preservation of prograde garnet-rich assemblages required nearly complete melt loss (15–25 vol.%), interpreted to have occurred at 1000–1020 °C and 2.2–2.4 GPa by garnet mode isopleths, followed by crystallization of small amounts of residual melt at 760 °C and 1.0 GPa. Phase formation and melt productivity were independently determined by experiments in the piston-cylinder apparatus at 850–1100 °C and 1.7–2.1 GPa. Both the thermodynamic calculations and phase equilibrium experiments suggest that the partial melt was produced by the dehydration melting: muscovite + quartz = melt + K-feldspar + kyanite. The presence of partial melt facilitated attainment of mineral equilibria at peak temperature thus eliminating any potential relics of early high-pressure phases such as phengite or omphacite. By contrast, adjacent mafic granulites and eclogites, which apparently share the same metamorphic path but have not undergone partial melting commonly preserve relics or inclusions of eclogite-facies mineral assemblages.

1. Introduction

High-pressure (HP) metamorphic rocks, and eclogite-facies rocks in particular, are frequently considered as key evidence for fossil subduction zone settings (Möller et al., 1995; Newton and Anderson, 1986). However, later episodes of the orogenic cycle during continental collision and subsequent collapse may lead to transformation of eclogite-facies HP rocks into granulites (Carswell and O'Brien, 1993; Faryad et al., 2010; Kryza et al., 1996). Many orogenic belts assumed to have been formed by subduction-to-collision convergence preserve no or only a small portion of pristine HP-metamorphic rocks that have escaped subsequent thermal equilibration and can thus be used to reconstruct the complete geodynamic scenario. Frequently, felsic granulites and migmatites from pelitic or quartzofeldspathic precursors have re-equilibrated at low pressures (Bhattacharya and Kar, 2002; Brown, 2006; Nair and Chacko, 2002; Waters, 1988). In contrast, several recent studies of ultra-high pressure (UHP) metamorphic rocks proposed that crustal rocks can be buried to depths exceeding 100 km (Liou et al., 2005; Massonne, 2001; Sobolev et al., 2003; Zhang et al.,

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2003) provided that mineral equilibria were sufficiently preserved through their exhumation and granulite facies overprint.

The Bohemian Massif provides a unique opportunity for the investigation of the petrological record of the early convergence history because felsic granulites are closely associated in space and time with high-temperature (HT) eclogites and garnet peridotites in the Moldanubian and Saxothuringian zones. The UHP conditions, above 3.5 GPa, of mafic and ultramafic rocks were already documented by HP mineral inclusions and conventional thermobarometric calculations in the Saxothuringian zone (Massonne and Bautsch, 2004; Schmädicke and Evans, 1997) and in the Moldanubian zone (Kotková et al., 1997; Medaris et al., 2006; Nakamura et al., 2004). The presence of microdiamond in gneisses from the Saxothuringian zone (Massonne, 1999; Massonne and Nasdala, 2003) proved that crustal rocks were subducted to a depth exceeding 140 km. However, the associated felsic and intermediate granulites yield peak pressures of 2.3 GPa at 1000–1020 °C in the Saxothuringian zone (Rötzler et al., 2004) or 1.6–1.8 GPa at 850–1000 °C in the Moldanubian zone (Cooke and O'Brien, 2001; Kotková and Harley, 1999, 2010; O'Brien, 2006, 2008; Štípská and Powell, 2005; Tajčmanová et al., 2006), respectively. The interpretation of granulite protoliths and their possible prograde history, if attempted, have remained controversial: they were interpreted to represent H_2O-poor magmas crystallized at the base of the orogenic root, up to 1170 °C and 2.3 GPa (Janoušek et al., 2004; Janoušek and Holub, 2007; Kotková, 2007; Kotková and Harley, 1999, 2010; Vrána, 1989; Vrána and Jakeš, 1982) or products of prograde metamorphism of granitic, rhyolitic or sedimentary precursors (Fiala et al., 1987; Vrána et al., 2005) that have experienced limited fluid-absent melting (Roberts and Finger, 1997; Tropper et al., 2005; Vrána et al., 2009). Thus, the prograde metamorphic path of central European granulites remains unresolved but its understanding is essential for the geodynamic reconstruction of the Variscan collisional convergence.

To better constrain the metamorphic conditions of the high-pressure granulites we have chosen sample of felsic granulite with leucocratic and mesocratic layering for a detailed petrological and experimental study. The modal and compositional variability allows us to apply a larger number of phase equilibria and compare their consistency. The pressure–temperature paths were reconstructed from the garnet zoning and several equilibria between inclusions, porphyroblast core and rims, and matrix phases. In addition, the reaction progress and melt productivity at peak conditions were simulated by dehydration melting experiments in a piston cylinder apparatus at 900–1100 °C and 1.7–2.1 GPa.

2. Geological setting

Numerous occurrences of garnet- and kyanite-bearing felsic granulites are associated with metasedimentary gneisses and migmatites in the Variscan orogen of Europe (*e.g.*, O'Brien and Rötzler 2003; Pin and Vielzeuf, 1983). In the Moldanubian zone, most granulites and migmatites are situated along its eastern border (the Gföhl unit), in its southern (South Bohemian granulite massifs) and central parts (the Kutná Hora complex; Fig. 1). The granulites are commonly associated and intimately imbricated with high-temperature eclogites and garnet- or spinel-bearing peridotites. In the interpretation of Schulmann et al. (2005), the Gföhl unit has been formed by extrusion of lower crustal rocks from the continental collision root, and has been sandwiched within and/or between the Monotonous series and Varied group (*cf.* Finger and Steyer, 1995; Franke, 1989; Matte, 1986).

The Kutná Hora complex (KHC) forms a 50 km long NW–SE oriented belt in the northern part of the Moldanubian zone and predominantly consists of high-grade metasediments that were migmatized to a variable degree. Based on its lithology and high-grade metamorphism, the complex has been correlated with the Gföhl unit in the eastern part of the Moldanubian zone (Synek and Oliveriová, 1993). From top to bottom, the KHC is represented by felsic and intermediate granulites (Běstvina and Miškovice granulite body) and migmatites (Malín unit), the Kouřim nappe, and by two, inner and outer, Micaschist zones. The Kouřim nappe is built up of a sequence of fine-grained leucocratic migmatites and gneisses that were strongly mylonitized. The inner Micaschist zone consists of mica schists to migmatites with mafic and ultramafic rocks and skarns that were affected by amphibolization and serpentinization. The outer Micaschist zone is represented by mica schists with lenses of amphibolites; this unit is underlain by the Monotonous and Varied groups of the Moldanubian zone.

The structural record in the Kutná Hora metamorphic complex indicates three stages of deformation (Synek and Oliveriová, 1993): the oldest event (D_1) is contemporaneous with the eclogite-facies metamorphism of metabasic rocks, (re)crystallization of garnet lherzolites and metamorphic crystallization of HP/HT granulites (Brueckner et al., 1991), and it is documented by rare steeply dipping relic planar fabrics S_1 in granulites (Nahodilová et al., 2005). Subsequent deformation event (D_2) reworked the older planar S_1 fabrics into a flat S_2 foliation dipping to NW or NE, facilitated local amphibolite-facies retrogression of mafic rocks, and was accompanied by extensive partial melting and migmatization of quartzofeldspathic rocks that generated kyanite-bearing granitic leucosomes. A late reactivation (D_3) affected the previous structural pattern including migmatitic structures and resulted in a local near-subhorizontal foliation (S_3) associated with low-temperature mylonitization.

A granulite body with well preserved subhorizontal S_2 foliation and metamorphic mineral assemblages is located at the Miškovice village (Fig. 1). It forms a *ca.* 50 × 20 m large exposure along a creek beneath the Cretaceous sedimentary cover. The gray colored felsic granulites contain lenses, approximately 3 by 1 m in size, of dark intermediate granulites, which show continuous gradations to the predominant felsic variety. The felsic granulites are characterized by modal layering where light-colored (leucocratic), 2–5 cm wide layers enriched in quartz and feldspar alternate with darker (mesocratic) layers characterized by higher modal abundance of garnet, locally retrogressed to biotite (Fig. 2). The leucocratic and mesocratic layers are mostly parallel to the weak S_2 foliation of granulites, dipping 20° to NNW.

3. Analytical and experimental methods

We have selected complementary samples of the layered granulites from the Miškovice granulite body for a detailed study: KKF27-l represents an approx. 8 cm thick leucocratic layer and KKF27-p comes from the adjacent gray-colored mesocratic layer. The latter granulite variety was also used as a starting material in our experimental study. The natural samples and experimental run products were analyzed by: (1) CAMECA SX 100 electron microprobe at the Institute of Geological Sciences, Masaryk University in Brno (Czech Republic) using the following standards: pyrope, spinel, olivine (Mg), andradite (Ca, Fe), almandine (Fe), jadeite, albite (Na), sanidine (K, Si), andalusite (Al), rhodonite (Mn), amphibole, TiO_2 (Ti), chromite (Cr), apatite (P), zircon (Zr) and NaCl (Cl). The operating voltage was 15 kV and the beam current was set to 10–30 nA. The beam was focused to a diameter of 1–5 μm; (2) CAMECA SX 100 electron microprobe at the Institute of Mineralogy and Crystal Chemistry, University of Stuttgart (Germany) using the following standards: pyrope (Si, Al, Mg), andradite (Ca and Fe), jadeite (Na), spessartine (Mn), K-silicate glass (K), Ba-silicate glass (Ba), NaCl (Cl) as well as natural rutile (Ti) and topaz (F). The operating voltage was 15 kV and the beam current was set to 10–15 nA. The beam was focused to a diameter of 1–2 μm except for micas for which an 8–10 μm wide beam was used to prevent the loss of alkalis; (3) back-scattered electron (BSE) images were obtained with a scanning electron microscope CamScan at the Institute of Petrology and Structural Geology, Charles University in Prague (Czech Republic). The initial composition of exsolved ternary feldspars was calculated by reintegrating exsolution lamellae and host feldspar compositions using the image analysis system Lucia G, v. 4.82, Laboratory Imaging Ltd. in