Earth and Planetary Science Letters 466 (2017) 91–102

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Computational study of deformation mechanisms and grain size evolution in granulites – Implications for the rheology of the lower crust

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ARTICLE INFO

Article history:
Received 19 October 2016
Received in revised form 3 March 2017
Accepted 6 March 2017
Available online xxxx
Editor: J. Brodholt

Keywords:
grain size
granulites
Zener pinning
deformation mechanisms
Bohemian Massif

ABSTRACT

Most of granulite terrains worldwide are characterized by large mean grain sizes of 1 mm or more. An important exception are the high-pressure felsic granulites in the Bohemian Massif, the European Variscan belt. There, recrystallization of original coarse-grained ternary feldspar led to formation of a fine-grained (∼100 μm) mixed matrix dominated by plagioclase and K-feldspar. This change occurred at temperatures of ∼850 °C and was probably caused by chemically induced decomposition related to slight cooling and enhanced by deformation during continental collision. The resulting microstructure shows indications of diffusion creep assisted by melt-enhanced grain-boundary sliding. Further on, minor coarsening occurred associated with deformation by dislocation creep and aggregation of mineral phases. Using a thermodynamics-based model of grain size evolution we show that stability of the fine-grained microstructure crucially depends on Zener pinning in the two-phase mineral matrix. Pinning efficiently hinders grain growth, and the small grain size that resulted from the ternary feldspar decomposition can be stable even at high temperatures. The late switch from the grain-size-sensitive creep to dislocation creep is rather difficult to explain by temperature and strain rate (or stress) changes only. However, a simple incorporation of melt solidification can successfully simulate this behavior. Alternatively, the switch and the associated grain size growth can be related to mineral phase aggregation at lower pressure–temperature conditions resulting into a decrease of pinning efficiency. This study suggests that the fine grain size of the Bohemian granulites, in contrast to the common coarse-grained type, stems from abrupt recrystallization during the high-pressure high-temperature conditions, and pinning in the fine-grained matrix. Such a process may in some cases significantly and suddenly reduce the strength of the lower continental crust and allow for its efficient redistribution.

1. Introduction

Granulite-facies metamorphic rocks formed over the entire Earth history ranging from the late Archean to recent (Brown, 2007). These rocks can be classified into two major metamorphic-facies series: ultrahigh temperature (UHT) series (750–1100 °C and 5–10 kbars) and eclogite-high pressure (HP) granulite series (700–1000 °C and 10–20 kbar). The formation of UHT granulites is generally attributed to the elevated thermal state of the pre-Cambrian lithosphere or to lithospheric thinning in the Phanerozoic era (Brown, 2006). In contrast, the HP granulites are considered to reflect either distributed crustal thickening characteristic to hot and ultra-hot orogens in the pre-Cambrian, or collisional environments in Phanerozoic orogens (e.g. O'Brien and Rötzler, 2003; Chardon et al., 2009), where granulites are accompanied by other HP to UHP metamorphic rocks reflecting the early subduction processes.

While the pressure–temperature conditions of granulite-facies rocks were subject of numerous studies (see overview by Brown, 2007), the microstructure of granulites was described in detail only rarely (e.g. Behr, 1964; Martelat et al., 1999; Franěk et al., 2011b). This lack of interest prevails despite the recognition that min-

Abbreviations: HP, high-pressure; HT, high-temperature; UHP, ultra-high-pressure; UHT, ultra-high-temperature; TH, thermodynamics-based model; THZ, thermodynamics-based model with Zener pinning; GSS, grain-size-sensitive; GSI, grain-size-insensitive.

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http://dx.doi.org/10.1016/j.epsl.2017.03.010
0012-821X/

eral fabrics can be used as a proxy to the rheology of hot lower crust (Brown et al., 2011). Several recent studies show that the microstructural parameters such as grain size distribution, grain contact frequencies, shapes of grains and their crystallographic orientation are sensitive to various environmental conditions (e.g. Lexa et al., 2005). In particular, the mean grain size of most silicate minerals can be used as a paleopiezometer due to its strong dependence on the deviatoric stress during dislocation creep associated with dynamic recrystallization (Shimizu, 2008).

Inspection of micrographs reported in literature shows that most of the UHT and HP granulites have large mean grain sizes of 500–1500 μm (e.g. Cagnard et al., 2011). In contrast, the HP granulites in the Variscan Bohemian Massif reveal a fine-grained mylonitic microstructure with the grain size of ∼80–150 μm (Behr, 1964; Franěk et al., 2011b; Kusbach et al., 2012). Formation of these granulites was attributed to a polyphase deformation of continental crust in a subduction wedge, its transformation to HP/UHP granulites and final exhumation to the mid-crustal level (Schulmann et al., 2014). Another known example of such a mylonitic microstructure is the early Proterozoic Athabasca granulite (Dumond et al., 2010).

Here we study how the fine grain size of the Bohemian granulites could be formed and preserved during polyphase deformation. To tackle this problem we adopt a physical model in which microstructure, in particular distribution of different mineral phases, significantly affects the grain size and consequently also the strength of the granulites. We show that the fine grain size can be maintained over a wide range of temperatures due to the pinning effect: the presence of two immiscible mineral phases prevents the motion of grain boundaries and therefore hinders grain growth. This mechanism may have fundamental implications for lower crust rheology in collisional orogens.

2. Geological setting

Numerous occurrences of HP granulites represent a characteristic feature of the Variscan orogen in the central Europe (Pin and Vielzeuf, 1983). They typically crop out in the form of isolated bodies in which the prevalent felsic kyanite-bearing granulites are associated with other HP rocks like mafic granulites, garnet peridotites and (mafic) eclogites. Most occurrences are restricted to granulite complexes in the Moldanubian domain (Fig. 1) and are interpreted as portions of orogenic lower crust that has been exhumed during the Variscan orogeny (Franěk et al., 2011a; Schulmann et al., 2014). The typical pressure–temperature conditions of granulite equilibration in the Bohemian Massif are 800–1000 °C and 18–20 kbar (O'Brien and Rötzler, 2003; Štípská and Powell, 2005). The previous UHP stage is recorded by the presence of microdiamonds and coesite (Kotková et al., 2011; Perraki and Faryad, 2014).

In terms of microstructures, all granulite occurrences in the Bohemian Massif reveal striking similarities, namely an exceptionally small grain size typical for mylonitic to ultramylonitic rocks (Fig. 2). The small grain size was stable through the exhumation history characterized by nearly isothermal decompression from 20 to 10–6 kbar in most of the Bohemian granulites (e.g. Štípská et al., 2004; Franěk et al., 2011a). Minor coarsening occurred later in the amphibolite facies conditions when the granulite bodies interfered with mid-crustal rocks and cooled down to 750–700 °C (Franěk et al., 2011a; Kusbach et al., 2012). The microstructural evolution of the Bohemian granulites is exemplified by a well studied case of the Blanský Les granulite complex (Fig. 2a). Here Franěk et al. (2011b) recognized three distinct microstructural types (M1–M3 in Fig. 2b–d) representing the evolutionary stages related to flow of felsic crust at the base of the orogenic root (355–342 Ma), its subsequent diapiric exhumation (342–337 Ma), and short-

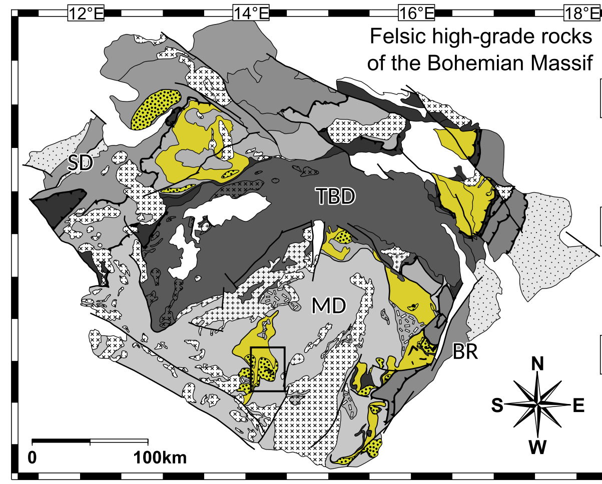

Fig. 1. Map of the main occurrences of the granulite complexes (dotted) within high-grade units (yellow) in the Bohemian Massif, modified after Schulmann et al. (2014). SD – Saxothuringian domain, TBD – Teplá-Barrandian domain, MD – Moldanubian domain, BR – Brunia. The position of the Blanský Les granulite complex (Fig. 2a) is indicated by a rectangle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

lived horizontal flow at mid-crustal levels (Franěk et al., 2011a; Schulmann et al., 2014).

2.1. Granulite microstructures

The rarely observed M1 microstructure (Fig. 2b) is formed by recrystallization of large ternary feldspar grains into a fine-grained mixed matrix of K-feldspar and plagioclase (for details see Franěk et al., 2011b). Relics of the ternary feldspar porphyroclasts (perthite) together with large quartz grains correspond to the earliest nearly obliterated microstructure annotated here as M0. Although the recrystallization process leading to M1 is still not well understood, it represents a critical step in the evolution of the Bohemian granulites. Franěk et al. (2011b) described the recrystallization as a heterogeneous decomposition of alkali feldspars by chemically and strain induced grain boundary migration, resembling discontinuous precipitation well known from material science (e.g. Sennour et al., 2004).

M1 microstructure is restricted to cases where the two-feldspar matrix occurs within or at the contact with the perthite porphyroclasts (M1-a and M1-b, respectively, in Fig. 3a). Further from the contact with the perthite porphyroclasts the microstructure changes to M2 by incorporation of interstitial quartz into the banded feldspar matrix. The bands are separated by platten quartz, i.e. the highly elongated quartz grains or aggregates (Figs. 2c, 3a). Finally it continuously evolves into M3 characterized by an increasing abundance of biotite and sillimanite related to amphibolite facies retrogression (Figs. 2d and 3a). The M1–M2 is associated with diffusion creep-accommodated grain-boundary sliding in feldspars and dislocation creep in quartz. M2 records homogeneous and intense deformation, which is facilitated by the presence of melt distributed along grain boundaries. The melt is documented by interstitial quartz and cuspate feldspar grains as well as predicted by thermodynamic modeling (Franěk et al., 2011b), but most of the melt was transported and solidified elsewhere (Hasalová et al., 2008; Lexa et al., 2011). The change towards M3 reflects a switch to dislocation creep mechanism and corresponds to hardening of the feldspar framework of the retrograde granulite as suggested by Franěk et al. (2011a). In their study they document the switch by a quantitative microstructural analysis, lattice preferred orientation of the main rock-forming minerals and grain boundary geometries,