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An experimental study on creep of partially molten granulite under high temperature and wet conditions

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ABSTRACT

Samples of natural granulite were deformed in a gas medium apparatus to evaluate the flow strength of the lower crust. The sample consists of ~52 vol% plagioclase, ~40 vol% pyroxene, ~3 vol% quartz, ~5 vol% magnetite and ilmenite. Water content was ~0.17 ± 0.05 wt% in the deformed samples. 40 creep tests were performed on 13 samples at 300 MPa confining pressure, temperatures of 900–1200 °C, and strain rates between 3.13×10^{-6} and 5×10^{-5}/s, resulting in axial stresses of 12–764 MPa and the total strain up to 7.8–20.5%.

At low temperatures of 900–1000 °C, the microstructural observations show that the granulite samples were deformed in semi-brittle deformation regime, mainly by dislocation glide and intragranular microcracking. At medium temperatures (MT) of 1050–1100 °C, deformation was observed to be dominated by grain boundary migration recrystallization, corresponding to stress exponent n_{MT} of 5.7 ± 0.1, activation energies Q_{MT} of 525 ± 34 kJ/mol, $\log A_{MT}$ of 1.3. At high temperatures (HT) of 1125–1150 °C, the samples was deformed mainly by grain boundary migration recrystallization accommodated by partial melting and metamorphic reactions characterized by neo-crystallization of fine-grained olivine, with n_{HT} of 4.8 ± 0.1, Q_{HT} of 1392 ± 63 kJ/mol, and $\log A_{HT}$ of 37.5. Partial melting at high temperatures of 1125–1200 °C, which induces grain boundaries slip and enhances diffusion, has a significant weakening effect on the rheology of granulite, with an estimated strain rate enhancement by 5 times at melt fraction of ~2 vol%. Reaction from pyroxene to olivine may affect the flow law parameters and deformation mechanism. Based on our data, a wet and cool continental lower crust may still be in brittle deformation regime, whereas a hot lower crust may likely have a weak layer with plastic deformation.

1. Introduction

Laboratory-derived flow laws provide important constraints on rheological behavior in the continental lower crust (e.g., Brace and Kohlstedt, 1980; Jackson, 2002; Bürgmann and Dresen, 2008). Earthquake focal depth distribution has suggested a strong lower crust (Maggi and Jackson, 2000a, 2000b; Jackson, 2002) or conversely a weak lower crust with a strong upper mantle (Chen and Molnar, 1983; Kohlstedt et al., 1995), which needs to be examined by laboratory-derived mechanical properties of typical rocks in the lower crust. In addition to mineral composition and water content, partial melting and mineral reactions are also important factors that affect lower crustal deformation.

In the continental lower crust, feldspar and pyroxene are the most abundant minerals. These minerals generally contain traces of water, with contents varying significantly in different regions (Beran, 1986, 1987; Skogby et al., 1990; Skogby, 2006; Johnson, 2006; Xia et al., 2006; Yang et al., 2008). Despite its important effect on rock deformation, water content was not specified in most of early experimental studies on the creep strength of mafic rocks. Of those, Wilks and Carter (1990) and Ross and Wilks (1995, 1996) reported flow laws for oven-dried granulite without measuring the water content; He et al. (2003) examined semi-brittle to plastic deformation on oven-dried gabbro in a similar way.

More recent experimental studies on mineral aggregates with known water content focused on single- or two-phase samples of plagioclase and pyroxene. These studies include investigations on diffusion and dislocation creep of synthetic anorthite aggregates (Dimanov et al., 1998, 1999, 2003; Rybacki and Dresen, 2000, 2004; Rybacki et al., 2006, 2008, 2010), diopside (Dimanov et al., 2003, 2007), clinopyroxenite (Hier-Majumder et al., 2005; Chen et al., 2006), orthopyroxene (Ohuchi et al., 2011), and two-phase

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anorthite-diopside mixtures (Dimanov and Dresen, 2005; Dimanov et al., 2007, 2011). In a recent experimental study on crushed and hot-pressed natural granulite containing ≈0.2 wt% H_2O, Wang et al. (2012) measured a very low creep strength, favoring the weak lower crust ('jelly sandwich') model (Bürgmann and Dresen, 2008). All of these studies show that the strength of fine-grained feldspar and pyroxene aggregates is strongly reduced when trace amounts of water in the minerals are above a level of ~0.07 wt% (Rybacki and Dresen, 2000, 2004), implying that the lower crust can be weak if the nominally dry constituents contain traces of water above a level of ~0.07 wt% (Jackson, 2002; Bürgmann and Dresen, 2008).

Compared to the synthetic, hot-pressed single- and two-phase aggregates used in these experiments, natural rocks of the lower crust have a more complex mineral assemblage with different plagioclase and pyroxene compositions and various amounts of accessory olivine and opaque minerals. Metamorphic reactions from multi-phase mineral aggregates often involve grain size reduction which may cause weakening and strain localization in natural shear zones (Rubie, 1983; Brodie and Rutter, 1985, 1987; Rutter and Brodie, 1988, 1995; Stünitz, 1998; Stünitz and Tullis, 2001; Kenkmann and Dresen, 2002). An example of these can be seen in natural mantle xenoliths, where olivine forms reaction rims around large orthopyroxene crystals (Shaw et al., 2006). Experimental investigations also reveal that solid-solid reactions from plagioclase-olivine to pyroxene (Liu et al., 1997; de Ronde et al., 2004) and from forsterite-quartz to enstatite (Yund, 1997; Shaw, 2004) are controlled by grain boundary diffusion under static conditions. Shear deformation experiments on olivine-feldspar aggregates resulted in fine-grained pyroxene and spinel as reaction products occurring in a core-rim structure. The reaction-induced grain size reduction resulted in a switch from dislocation creep to grain-size-sensitive diffusion creep (de Kloe et al., 2000; de Ronde et al., 2004, 2005). In contrast to the experiments mentioned above, syn-deformation reaction from pyroxene to olivine in creep experiment of wet gabbro leads to strength hardening (Zhou et al., in preparation). Although they are in different situations, all these experiments indicate that mineral reactions have a significant effect to the lower crust deformation.

In addition to minerals reactions, partial melting is also considered to strongly influence the mechanical behavior of the crust and upper mantle (e.g., Vanderhaeghe, 2009; Yoshino et al., 2009). However, experimental studies investigating the effect of partial melt on the high temperature rheology of lower crustal rocks are still quite limited. Previous studies (Tullis et al., 1996; Dimanov et al., 1998, 2000; Kohlstedt and Holtzman, 2009; Kohlstedt et al., 2010) have shown that melt distribution has a significant effect on strain rate enhancement for feldspar-bearing rocks. In the case for feldspars, melt films between grain boundaries were found in hot-pressed samples annealed at high temperature, resulting in significant weakening of the aggregates even at melt content of 2–3% (Tullis et al., 1996; Dimanov et al., 2000) in contrast to effect of partial melt predominantly residing in triple junctions, which enhance the strain rate only moderately with increasing melt content (Cooper and Kohlstedt, 1986). Similarly, partial melt in creep experiments of dry gabbro (Zhou et al., 2012) show that melt films between grain boundaries has a strong weakening to creep strength of gabbro.

In this study, we investigate deformation of a natural granulite with partial melt and accompanying reaction at high temperatures using a gas-medium deformation apparatus, to acquire rheological parameters of a complicated aggregate typical in the continental lower crust as represented by the natural granulite sample. We present mechanical data and microstructures including partial melt and syn-deformational formation of olivine.

2. Starting material and experimental methods

2.1. Chemical composition and microstructure

The samples were prepared from a natural fine-grained granulite, collected at Wayaokou village, Huai'an, Hebei province, China. Microstructures of the starting material were examined on polished thin sections with a polarizing optical microscope and a scanning electron microscope (Zeiss SIGMA) at State Key Laboratory of Earthquake Dynamics. The grain shapes of plagioclase are elongated and those of pyroxene, magnetite and ilmenite are mostly equant. The grain fabric of the samples is considered isotropic (Fig. 1).

The granulite sample is composed of ~52 vol% plagioclase, ~40 vol% pyroxene, ~3 vol% quartz and ~5 vol% magnetite and ilmenite. The composition of starting samples is heterogeneous at the grain scale. Microprobe (JXA-8100) analyses were performed at Beijing Research Institute of Uranium Geology (BRIUG), indicating a chemical composition of $An_{45-47}Ab_{45-48}Or_{1-2}$ for plagioclase grains, $En_{29-33}Fs_{17-19}Wo_{42-45}$ for clinopyroxene grains, and En_{49-50}-$Fs_{47}Wo_{0-1}$ for orthopyoxene grains. The result of bulk chemical composition was measured with X-ray fluorescence (XRF) spectroscopy (AxiosmAX) at the same institute, yielding main oxides of SiO_2 (49.0 wt%), Al_2O_3 (13.5 wt%), CaO (10.2 wt%), FeO (16.0 wt %), MgO (6.3 wt%), Na_2O (2.6 wt%), TiO_2 (1.4 wt%), K_2O (0.3 wt%), MnO (0.2 wt%) and P_2O_5 (0.1 wt%).

To measure the grain size distribution we used the line intercept method (Underwood, 1970). The intercept length L was determined along 12 lines across each section oriented in 15° intervals and converted to grain size using a correction factor of 1.9 for plagioclase assuming an average aspect ratio of 2.6 and a rectangular prism grain shape (Dimanov et al., 1998) and 1.78 for pyroxene and magnetite assuming equant grains (Underwood, 1970). Calculated mean grain sizes are 294 μm, 282 μm, 97 μm and 109 μm for plagioclase, pyroxene, quartz, magnetite and ilmenite, respectively (Fig. 2).

Cylindrical cores were drilled from natural samples and ground and polished to 20 mm height and 10 mm diameter. All samples were dried in a 1 atm furnace at 100 °C for 24 h.

2.2. Water content

To determine the water content, a Fourier-transform infrared spectrometer (FTIR, Bruker VERTEX 70V, Hyperion 1000Z) was used to measure absorbance spectra on double-polished 150 μm thick sections of pre-dried samples before and after deformation at State Key Laboratory of Earthquake Dynamics. The spectra were recorded at 20 °C and averaged from >128 scans between wave numbers of 2500 and 4000 cm^{-1} with a resolution of 2 cm^{-1}. We measured both the water content of bulk rock and the water content of individual mineral grains using a spectrometer microscope with a spot size of about 50 μm. The shape of measured spectra for individual mineral grains is generally broad without distinct sharp peaks, characteristic of molecular water or O—H bonds (Aines and Rossman, 1984; Rybacki and Dresen, 2000). For quantitative estimates of water content the method given by Paterson (1982) was applied. The average water content of samples is ~0.17 ± 0.05 wt% H_2O, with 0.12 wt% for feldspar, and 0.22 wt% for pyroxene (Table 1). No significant difference in water content was found before and after deformation.

2.3. Experimental procedure and data processing

Constant strain rate deformation tests were performed on 13 samples in a gas deformation apparatus at 300 MPa confining pressure and temperatures ranging from 900 °C to 1200 °C with strain rates from 5×10^{-5} to 3.125×10^{-6} s^{-1}. Samples were jack-

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