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Microstructural evidence for the transition from dislocation creep to dislocation-accommodated grain boundary sliding in naturally deformed plagioclase

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ABSTRACT

We use quantitative microstructural analysis including misorientation analysis based on electron backscatter diffraction (EBSD) data to investigate deformation mechanisms of naturally deformed plagioclase in an amphibolite gabbro mylonite. The sample is from lower oceanic crust exposed near the Southwest Indian Ridge, and it has a high ratio of recrystallized matrix grains to porphyroclasts. Microstructures preserved in porphyroclasts suggest that early deformation was achieved principally by dislocation creep with subgrain rotation recrystallization; recrystallized grain (average diameter ~8 μm) microstructures indicate that subsequent grain boundary sliding (GBS) was active in the continued deformation of the recrystallized matrix. The recrystallized matrix shows four-grain junctions, randomized misorientation axes, and a shift towards higher angles for neighbor-pair misorientations, all indicative of GBS. The matrix grains also exhibit a shape preferred orientation, a weak lattice preferred orientation consistent with slip on multiple slip systems, and intragrain microstructures indicative of dislocation movement. The combination of these microstructures suggest deformation by dislocation-accommodated GBS (DisGBS). Strain localization within the recrystallized matrix was promoted by a transition from grain size insensitive dislocation creep to grain size sensitive GBS, and sustained by the maintenance of a small grain size during superplasticity.

1. Introduction

Plagioclase feldspar is an abundant mineral in both the lower continental and oceanic crust; its behavior therefore strongly influences the rheology of the lower crust. High-temperature (>700 °C) deformation of plagioclase has been studied both in the laboratory and in naturally deformed samples to investigate deformation mechanisms and how they may influence strain localization in the crust (e.g., Olsen and Kohlstedt, 1984; Montardi and Mainprice, 1987; Cannat, 1991; Kruse et al., 2001; Stünitz et al., 2003; Mehl and Hirth, 2008; Raimbourg et al., 2008; Hansen et al., 2013). Though many of these studies explore the behavior of plagioclase during grain size insensitive dislocation creep (e.g., Cannat, 1991; Kruse et al., 2001; Stünitz et al., 2003), relatively few address how plagioclase deforms during a transition from grain size insensitive to grain size sensitive creep (Jiang et al., 2000; Kanagawa et al., 2008; Mehl and Hirth, 2008; Raimbourg et al., 2008; Svahnberg and Piazolo, 2010; Pearce et al., 2011). This is an important but relatively unexplored aspect of plagioclase deformation, and it has timely relevance as grain size sensitive mechanisms such as grain boundary sliding (GBS) are being recognized more commonly as key deformation mechanisms in the crust and mantle (e.g., Getsinger et al., 2013; Hansen et al., 2011), with some workers even suggesting GBS may be the dominant mechanism promoting mantle flow (Miyazaki et al., 2013).

Experimental studies show that several processes can accommodate GBS (Paterson, 1990; Zelin and Mukherjee, 1996; Nieh et al., 1997; Wakai et al., 1999), and recent work confirms that specific intracrystalline characteristics may be used to differentiate between them. (e.g., Hansen et al., 2011; Cordier et al., 2014; Linckens et al., 2014). GBS can be accommodated by dislocation motion

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(DisGBS) or diffusion (i.e. diffusion creep). However, none of the aforementioned studies were carried out on plagioclase, and the identification of DisGBS in plagioclase may have been overlooked, since some microstructures indicative of dislocation creep, including subgrain development, lattice preferred orientation (LPO), and recrystallized grains are also produced during DisGBS (e.g., Rutter et al., 1994; Warren and Hirth, 2006; Hansen et al., 2012).

In studies where GBS has been interpreted as a deformation mechanism in plagioclase, phase mixing combined with diffusion creep is most commonly identified as the process contributing to the enhancement of GBS over dislocation creep (e.g., Mehl and Hirth, 2008; Raimbourg et al., 2008; Pearce et al., 2011). In these studies, a small recrystallized grain size (relative to single phase domains) and the absence of LPO are cited as microstructural evidence of diffusion creep (i.e. diffusion accommodated GBS). Svahnberg and Piazolo (2010) inferred deformation accommodated by DisGBS in dynamically recrystallized plagioclase from naturally deformed gabbro based on textural evidence for strain localization in the fine-grained matrix, weak to moderate LPO, and significant shape preferred orientation (SPO).

In this study, we investigate how dynamic recrystallization in naturally deformed plagioclase promotes a transition from dislocation creep to grain size sensitive creep, and we evaluate the role of DisGBS. We build on the work of Svahnberg and Piazolo (2010) by evaluating how DisGBS contributes to plagioclase microstructures in a gabbro mylonite from an oceanic fault system. We use criteria developed by other workers (Hirth and Kohlstedt, 2003; Warren and Hirth, 2006; Hansen et al., 2012) to identify the activity of DisGBS in our naturally deformed sample, and discuss how DisGBS may promote strain localization.

2. Geologic setting and sample description

The gabbro sample used in this study was collected from lower oceanic crust exposed in the footwall of the Atlantis Bank oceanic core complex (Matsumoto et al., 2002; Miranda and John, 2010), a normal fault system ~90 km south of the present day Southwest Indian Ridge (Fig. 1). Atlantis Bank formed between ~10 and 13 Ma, with its detachment fault accommodating divergent motion between the African and Antarctic plates (Hosford et al., 2003; Baines et al., 2008, 2009). Rapid footwall denudation at the plate boundary, documented by geospeedometry and thermochronologic data, led to rapid cooling rates in excess of 1200°C/my (10^3 to 10^4 °C/my) (Coogan et al., 2007; John et al., 2004; Schwartz et al., 2009). This rapid cooling preserved the high temperature plagioclase deformation microstructures, limiting the effects of annealing, making the sample ideal for the study. The core complex footwall is cut by high-angle normal faults that expose up to ~1200 m of lower oceanic crust beneath the subhorizontal detachment fault surface, enabling detailed sampling (Baines et al., 2003; Matsumoto et al., 2002). Submersible sampling along these fault scarps reveals a ~100 m thick shear zone of granulite and amphibolite mylonites beneath the detachment fault surface (Matsumoto et al., 2002; Miranda and John, 2010); our sample is an amphibolite gabbro mylonite collected from this shear zone (Fig. 1).

The amphibolite mylonite studied exhibits a well-developed foliation, somewhat obscured by a ~3 mm thick layer of manganese oxide common to seafloor samples. The sample was cut as close to perpendicular to foliation and parallel to lineation as possible. In thin section, compositionally banded layers of plagioclase and amphibole define foliation, where the compositional bands are essentially monomineralic interconnected networks. We focus on a monomineralic zone of plagioclase with a high ratio of recrystallized matrix grains to porphyroclasts.

3. Methods

3.1. Mineral chemistry and thermometry

Plagioclase and amphibole mineral compositions were determined using the 5-spectrometer JEOL JXA-8900 electron microprobe at the University of Wyoming. Plagioclase was analyzed for Si, Al, Fe, Ca, Na, and K using a 15 kV accelerating voltage, a 10 nA current, and count times that varied from 10 to 20 s. Amphibole was analyzed for Si, Al, Ti, Cr, Mg, Fe, Mn, Ca, Na, K, F and Cl using a 15 kV accelerating voltage and a 20 nA current; count times varied from 10 to 20 s. Spectral data were corrected with a standard ZAF correction. Analytical errors are estimated at ± 2 wt percent.

Coexisting pairs of metamorphic amphibole and recrystallized plagioclase grains from adjacent amphibole-rich and plagioclase-rich foliation layers were used to estimate temperature during deformation using the plagioclase-amphibole thermometer of Holland and Blundy (1994). This thermometer is based upon the exchange of Al and Na between amphibole and plagioclase. We use this thermometer because it is calibrated for both silica-saturated and -undersaturated rocks in the temperature range of 500–900 °C, with plagioclase compositions between $X_{An} > 0.1$ and < 0.9. Errors associated with the thermometer are in the range of 35–40 °C (Holland and Blundy, 1994).

3.2. Electron backscatter diffraction (EBSD)

EBSD analyses were used to 1) evaluate the distribution of mineral phases, 2) reveal detailed microstructures, and measure 3) grain size and aspect ratio, 4) intragrain distortion to assess dislocation density, and 5) the crystallographic orientation of mineral grains. EBSD data were collected at California State University Northridge using an FEI Quanta 600 SEM equipped with an Oxford Instruments Nordlys EBSD detector and AZtec EBSD acquisition software. Data were collected from an uncoated sample under low vacuum conditions (20 Pa H_2O) to minimize charging. In preparation for EBSD, the thin section was polished down to a 1-μm diamond particle size, and then mechano-chemically polished with colloidal silica solution.

Three EBSD beam maps were collected for the study; a large EBSD map (~600 × 950 μm) with a 2 μm step size to investigate microstructures of porphyroclasts and their adjacent recrystallized grains, and two smaller, high resolution maps (~100 × 130 μm and ~200 × 100 μm) with a 0.5 μm step size to investigate microstructures of a selected porphyroclast and of matrix grains, respectively. The 2 μm step size map was acquired with an accelerating voltage of 25.0 kV and a spot size of 7.0, emission currents ranging from 91 to 98 μA, and a working distance of 14.9 mm. The 0.5 μm step size maps were acquired with an accelerating voltage of 25.0 kV and a spot size of 7.5, an emission current of 103 μA, and working distances of 12.4 mm and 14.2 mm. Raw indexing rates for the large map and two smaller maps were 93%, 94.5%, and 94.5%, respectively.

EBSD map data were minimally processed using the Oxford Instruments Channel 5 software suite. Data were noise reduced, which included removal of pixels different in orientation relative to their surrounding 8 pixels (wild spikes) and iterative extrapolation of zero solutions that were surrounded by at least 7 neighbor-pixels of the same phase. EBSD map data are displayed using the Channel 5 Tango program. We classify grain boundaries as having ≥10° of misorientation between adjacent grains, and we designate low-angle subgrain boundaries as having between 2 and 10° of misorientation between adjacent parts of a grain.

Data are displayed using phase maps to show mineral distribution; Euler maps show the spatial distribution of grain