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Grain size reduction due to fracturing and subsequent grain-size-sensitive creep in a lower crustal shear zone in the presence of a CO_2-bearing fluid

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ABSTRACT

To understand rheological weakening in the lower continental crust, we studied mylonites in the Paleoproterozoic Eidsfjord anorthosite, northern Norway. The zones of anorthositic mylonites range from a few millimeters to several meters thick, and include ultramylonites and protomylonites. They contain syn-kinematic metamorphic minerals, including Cl-bearing amphibole and scapolite. Thermodynamic analysis reveals that syn-deformational hydration reactions occurred at ~600 °C and ~700 MPa under CO_2-bearing conditions. The protomylonites contain many fragmented plagioclase porphyroclasts. The fractures in porphyroclasts are filled with fine-grained plagioclase, suggesting that fracturing is a common mechanism of grain size reduction. The anorthite contents of fine-grained polygonal matrix plagioclase are different from those of porphyroclastic plagioclase, suggesting that the matrix grains nucleated and grew during syn-kinematic metamorphism. Plagioclase aggregates in the matrices of mylonites do not exhibit a distinct crystallographic preferred orientation, which implies that the dominant deformation mechanism was grain-size-sensitive creep. Consequently, in the lower crustal anorthositic mylonites, grain size reduction occurred via fracturing, rather than through dynamic recrystallization, leading to grain-size-sensitive creep. The syn-kinematic recrystallization of minor phases at plagioclase grain boundaries may suppress the growth of plagioclase and contribute to the development of grain-size-sensitive creep.

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1. Introduction

Plagioclase-rich rocks (i.e., anorthosite, gabbro, and gabbronorite) are major constituents of the lower crust. Thus, understanding the rheological properties and deformation processes of plagioclase-rich rocks is key to evaluating the strength and mechanical behavior of the lower crust. Investigating grain size reduction and possible subsequent grain-size-sensitive (GSS) deformation in plagioclase-rich rocks is particularly important because a transition to GSS creep would result in significant rheological weakening, with flow stresses (or strain rates) potentially decreasing (or increasing) more than an order of magnitude at a constant strain rate (or stress).

Dynamic recrystallization is a common grain-size reduction mechanism in plagioclase aggregates deformed by grain-size-insensitive (GSI) dislocation creep under conditions of the greenschist to granulite facies (e.g., Olsen and Kohlstedt, 1985; Tullis and Yund, 1985; Ji and Mainprice, 1990; Yund and Tullis, 1991; Shigematsu, 1999; Kruse et al., 2001; Kanagawa et al., 2008; Raimbourg et al., 2008; Svahnberg and Piazolo, 2010). Empirical relationships between stress and recrystallized grain size have been proposed for plagioclase aggregates (Twiss, 1977; Post and Tullis, 1999). If such stress and grain size relations transect the boundary between GSI and GSS creep fields, grain size reduction by dynamic recrystallization can lead to a transition from GSI dislocation creep to GSS creep. However, in the GSS creep field the applicability of the empirical piezometer is problematic owing to a potential lack of driving force for recrystallization. Dynamic recrystallization may represent a balance between grain size reduction and crystal growth processes set up in the boundary region between the GSI

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and GSS creep fields (De Bresser et al., 2001; Shimizu, 2008), and then recrystallized grain size and stress balance near the GSI–GSS field boundary. Thus, major weakening in localized natural deformation zones is unlikely to be caused by dynamic recrystallization.

Fracturing and/or comminution are dominant grain-size reduction mechanisms at low temperatures because the critical resolved shear stress may not be reached in plagioclase, and recovery and recrystallization are limited. However, even under high-temperature conditions where plagioclase undergoes plastic deformation, fracturing and nucleation of new grains as small fragments has been identified in naturally and experimentally deformed rocks (e.g., Tullis and Yund, 1987; Hadizadeh and Tullis, 1992; Kruse et al., 2001; Stünitz et al., 2003; Brander et al., 2012; Menegon et al., 2013; Okudaira et al., 2015). Zones of very fine grains that result from fracturing and/or comminution would deform by GSS creep. However, without a mechanism to limit grain growth, the size of recrystallized grains increases to the maximum size allowed by the dynamic balance between crystal growth and dynamic recrystallization, which may not promote a transition to GSS creep.

Fracturing facilitates fluid flow due to the increased dilatancy and connectivity of pore spaces (e.g., Gratier and Gueydan, 2007; Samuelson et al., 2009). An influx of fluid enhances hydration reactions, which form small, strain-free recrystallized grains (e.g., Stünitz and Tullis, 2001). The metamorphic evolution of shear zones depends on the fluid composition that is approximated by the system H_2O–salt (NaCl and KCl)–CO_2 (Newton and Manning, 2010; Yardley and Bodnar, 2014). For example, zoisite and scapolite are formed by metamorphic reactions of plagioclase with H_2O-rich and CO_2-rich fluids, respectively (e.g., Moecher and Essene, 1990), and they precipitate at plagioclase grain boundaries, possibly inhibiting the growth of plagioclase to promote GSS creep. Infiltration of a CO_2-bearing fluid into the lower crust has been reported from many lower crustal shear zones and granulite facies terrains (e.g., Newton et al., 1980b; Moecher and Essene, 1991; Lamb and Moecher, 1992; Kullerud and Erambert, 1999). Consequently, it is important to investigate the interaction between CO_2-bearing fluid and lower crustal rocks.

In Langøya, Vesterålen, northern Norway, a large anorthosite complex (the Eidsfjord anorthosite complex; Markl, 1998) is in tectonic contact with monzonitic country rocks (monzonite and mangerite) across a detachment fault (Fig. 1). Ductile and brittle deformation of rocks that surround the detachment fault (Markl, 1998; Plattner et al., 2003) has produced a distinct shear zone (the Eidsfjord shear zone; Moecher and Steltenpohl, 2011; Steltenpohl et al., 2011). This area is also part of Heier's pseudotachylyte zone (Løseth and Tveten, 1996). In the Eidsfjord shear zone, Cl-bearing minerals such as amphibole, mica, and scapolite may yield information about the composition of fluid in deep crustal rocks. Therefore, the Eidsfjord shear zone provides an excellent opportunity to study deformation processes in connection with Cl- and CO_2-bearing fluid in the lower crust. To elucidate the mechanisms of grain size reduction and subsequent GSS creep, and the metamorphic evolution of lower crustal rocks under CO_2-bearing conditions, we analyzed the microstructures, mineral chemistry, and crystallographic orientations of anorthositic mylonites along the SE coast of Eidsfjord at Langøya, northern Norway.

2. Geological background

At Langøya, Archean and Proterozoic continental basement rocks (anorthosite, mangerite, monzonite, and granitic migmatite) were metamorphosed under conditions of the upper amphibolite and granulite facies at 1.8–1.7 Ga (e.g., Griffin et al., 1978; Markl, 1998; Plattner et al., 2003; Corfu, 2004; Moecher and Steltenpohl, 2011). Caledonian metamorphism and deformation are strictly limited to shear zones (Klein et al., 1999; Plattner et al., 2003; Steltenpohl et al., 2004; Moecher and Steltenpohl, 2011). Ductile and brittle fault rocks associated with the Eidsfjord shear zone, as examined in this study, are best exposed along the SE coast of Eidsfjord on Langøya, with the main detachment fault exposed at Slåttnes and Grønning (Fig. 1). Mylonites in meta-anorthosite, mangerite, and monzonite gneiss also occur discontinuously at the SW end of Langøya at Skaga. According to Moecher and Steltenpohl (2011), the Eidsfjord shear zone is a 200-m-thick mylonite zone that underwent down-to-the-west normal-slip movement. Mylonitic foliation in the shear zone strikes approximately N50°E and dips 7–35°NW, whereas the detachment fault dips 25–30°NW. The hanging wall consists mainly of massive, coarse-grained, gray, granulite-facies pyroxene anorthosite that gradually transitions into bleached white gneissic–mylonitic meta-anorthosite toward the shear zone (Markl, 1998; Moecher and Steltenpohl, 2011). The footwall consists of coarse-grained, light gray, granulite-facies biotite monzonite and ferrodiorite that grades into mylonitic monzonitic gneiss with meter-sized lenses of amphibolite in the detachment zone. Pseudotachylyte in the Eidsfjord shear zone cuts across the mylonitic foliation and encloses angular clasts of anorthositic mylonite, suggesting the pseudotachylyte post-dates the mylonites (Løseth and Tveten, 1996; Plattner et al., 2003; Moecher and Steltenpohl, 2011). Based on conventional garnet–hornblende–plagioclase–quartz thermobarometry in metamorphosed pseudotachylyte and meta-anorthosite (Moecher and Steltenpohl, 2011), these rocks were metamorphosed under conditions of 650–730 MPa and 640–670 °C. Ar–Ar laser incremental heating analysis of fine-grained, muscovite-bearing anorthosite ultramylonites of the Eidsfjord shear zone yielded plateau ages with a combined mean age of 403.6 ± 1.1 Ma, which is interpreted to represent the age of recrystallization and Ar isotopic re-equilibration in the Eidsfjord detachment (Steltenpohl et al., 2011).

3. Samples

Coarse-grained anorthosite and monzonite are widely exposed in the study area, and anorthosite contains plagioclase laths up to 3 cm long, with variable amounts of interstitial pyroxene and Fe–Ti oxides (Markl, 1998). Some outcrops of anorthosite/monzonite contain mylonites that are a few centimeters to several meters in width and consist mainly of fine-grained feldspar. In this study, mylonite classification is based on the volume proportion of matrix in the rock, regardless of matrix grain size. Rocks with 10–50% matrix are classified as protomylonites, with 50–90% matrix as mylonites, and with >90% matrix as ultramylonites. In the ultramylonites and mylonites, a mylonitic foliation is defined by alternating plagioclase- and mafic-mineral-rich layers (Fig. 2a). The long axes of minerals that define the foliation are aligned parallel to the mylonitic lineation. In the protomylonites, lenses of weakly deformed anorthosite are encapsulated by an anastomosing network of high-strain zones, which consist of fine-grained matrix material that are a few millimeters to several centimeters wide (Fig. 2b). The anastomosing high-strain zones are considered to define the mylonitic foliation in the protomylonites. Gray plagioclase porphyroclasts are fractured and some fractures are filled with fine-grained plagioclase grains. Dark green mafic seams, containing yellow-green cores, are oriented parallel to the mylonitic foliation. The mylonites form several anastomosed, narrow zones across the study area (Fig. 1). Along the northwestern coast, the anastomosing mylonite zones are subhorizontal or dip shallowly to the NNE to N. Each shear zone is up to several meters thick.

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