Journal of Structural Geology 48 (2013) 95–112

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Transition from fracturing to viscous flow in granulite facies perthitic feldspar (Lofoten, Norway)

Luca Menegon [a,*], Holger Stünitz [a], Pritam Nasipuri [a], Renee Heilbronner [b], Henrik Svahnberg [c]

[a] Department of Geology, University of Tromsø, Dramsveien 201, N-9037 Tromsø, Norway
[b] Geological Institute, Department of Environmental Sciences, Basel University, Bernoullistrasse 32, CH-4056 Basel, Switzerland
[c] Department of Geological Sciences, Stockholm University, SE-10691 Stockholm, Sweden

ARTICLE INFO

Article history:
Received 10 April 2012
Received in revised form
7 November 2012
Accepted 11 December 2012
Available online 27 December 2012

Keywords:
Fracturing
Recrystallization
Perthites
Diffusion creep
Spatial distribution of phases
Electron backscatter diffraction (EBSD)
Deformation of the lower crust

ABSTRACT

Recrystallization of perthites in granulite facies (T = 700–730 °C, P = 0.65–0.8 GPa) shear zones in mangerite-charnockite rocks from Lofoten (Norway) is localized along intracrystalline bands parallel to fractures. Fracturing preferentially occurred along the cleavage planes (010) and (001). EBSD analysis of perthite porphyroclasts indicates a very low degree of internal misorientation (within 5°) and the lack of recovery features. Recrystallized grains show coarsening with increasing width of the bands, and chemical changes with respect to the host grains. Crystallographic orientation of the new grains does not show a host-control relation to the parent perthite grains. In summary, the microstructure and CPO data consistently indicate intragranular recrystallization by nucleation and growth from fractured grains. Perthite porphyroclasts are surrounded by a matrix of recrystallized plagioclase + K-feldspar ± amphibole ± biotite. There is extensive evidence of syndeformational nucleation of new phases and of phase boundary migration in the matrix, with plagioclase grains forming bulges and protrusions towards K-feldspar. The spatial distribution of K-feldspar and plagioclase in the recrystallized matrix is characterized by the predominance of phase boundaries over grain boundaries. All these observations are consistent with diffusion creep as the dominant deformation mechanism in the matrix, associated with grain boundary sliding. Accordingly, recrystallized plagioclase and K-feldspar show a very weak crystallographic preferred orientation, which is interpreted in terms of oriented growth during diffusion creep. Fracturing of perthites promoted extensive grain size reduction, recrystallization, fluid infiltration, and operation of grain-size sensitive creep, resulting in strain localization.

1. Introduction

The strength and mechanical behaviour of the lower continental crust frequently are modelled using feldspar as a dominant mineral constituent (e.g. Bürgmann and Dresen, 2008). In addition, the dominant deformation mechanism needs to be identified, so that investigating the deformation mechanisms of major mineral constituents of the lower crust and the progressive development of their microstructures in high strain zones are major tasks in structural geology, the results will provide the basis for rheological modelling of the lithosphere.

K-feldspar is a major constituent of granulites and the knowledge of its deformation processes is important to our understanding of the rheology of the lower crust. Many K-feldspars occur as perthites. Under granulite facies conditions, perthites have been reported to deform dominantly by dislocation creep and to undergo extensive subgrain rotation recrystallization associated with shape change and growth of the exsolution features (White and Mawer, 1986, 1988; Martelat et al., 1999; Franek et al., 2011).

One interesting aspect, which has not been explored in detail so far, is the recrystallization of perthites and the development of a two-phase mixture of recrystallized orthoclase and Na-plagioclase grains. In such a two-phase mixture grain growth is likely to be inhibited by pinning with second phase particles, and the grains may be maintained at a sufficiently small size to activate diffusion creep as the main deformation mechanism (e.g. Fliervoet et al., 1997; Kruse and Stünitz, 1999; Mehl and Hirth, 2008; Kanagawa et al., 2008).

The dominance of diffusion creep has great consequences for the rheological behaviour of the lower crust, because it potentially leads to a marked weakening and to strain localization. Generally, the operation of diffusion creep is promoted by intense grain size reduction and phase mixing. Dynamic recrystallization (Raimbourg

* Corresponding author. Present address: School of Geography, Earth and Environmental Sciences, Plymouth University, Drake Circus, Plymouth PL4 8AA, United Kingdom.
E-mail address: luca.menegon@uit.no (L. Menegon).

0191-8141/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jsg.2012.12.004

et al., 2008), mineral reactions (Brodie and Rutter, 1985, 1987; Rutter and Brodie, 1992; De Ronde et al., 2005; Pearce et al., 2011) and nucleation of fine-grained new phases (Kruse and Stünitz, 1999; Kenkmann and Dresen, 2002) are common processes involved in the grain size reduction and in the development of a phase mixture in lower crustal shear zones.

Cataclasis and grain crushing have been inferred to occur even under the high P, T conditions typical of the plastic field of deformation (e.g. Tullis and Yund, 1987; Kenkmann, 2000; Handy and Stünitz, 2002), and to contribute strongly to the grain size reduction, potentially leading to the operation of diffusion creep. However, microstructural evidence of brittle deformation in the lower crust can be obliterated due to healing of the (micro)fractures, grain growth and sintering, and subsequent deformation history. Recent experiments carried out under high P, T and differential stress conditions (McLaren and Pryer, 2001; Stünitz et al., 2003; Trepmann et al., 2007) have provided many useful microstructural criteria to identify the interdependence between fracturing, plastic deformation and recrystallization.

Feldspars are well suited to investigate the interplay between fracturing and high temperature deformation in natural rocks, because feldspars contain two sets of excellent cleavage planes ((001) and (010)), which make fracturing very likely under a wide range of P, T conditions (Tullis, 1983; Tullis and Yund, 1987). Although the progressive predominance of dislocation activity and crystal plasticity over fracturing during deformation of feldspars with increasing temperature is well documented (e.g. White and Mawer, 1986; Kruse et al., 2001; Kenkmann and Dresen, 2002; Kanagawa et al., 2008; Mehl and Hirth, 2008), fracturing has been reported also at high temperatures where the deformation takes place dominantly by crystal plasticity (e.g. Vernon, 1975; Tullis and Yund, 1987; Fitz Gerald and Stünitz, 1993; McLaren and Pryer, 2001; Stünitz et al., 2003; Menegon et al., 2008).

In this contribution we report a detailed microstructural analysis of perthites from shear zones developed under granulite facies conditions on the Lofoten islands (northern Norway). The main feature of the shear zones is that they display an Augen-structure where perthite porphyroclasts are surrounded by a recrystallized matrix. The porphyroclasts show extensive intragranular recrystallization features, so that the incipient stages of recrystallization and the deformation mechanism in the matrix can be accurately investigated. For this purpose, we made use of quantitative microstructural analysis and of electron backscatter diffraction (EBSD) of perthite porphyroclasts and recrystallized matrix. Our analyses indicate that, in spite of the high grade metamorphic conditions of deformation, fracturing played a primary role in the microstructural evolution of perthites, whereas the contribution from crystal plasticity was negligible. Recrystallization was invariably associated with a preliminary stage of fracturing, and occurred by nucleation and growth processes along cracks.

2. Geological setting and sampling site

The Lofoten–Vesterålen islands of northern Norway consist of a pre-Caledonian basement horst, which trends NNE–SSW. Tectonically, the islands are considered to be part of the Baltic Shield, whose main part is separated from the western coast of Norway by the NNE–SSW trending Caledonian orogen (Corfu, 2004, and references therein). The Lofoten–Vesterålen basement is composed mainly of an Archean- to Paleoproterozoic metamorphic complex of para- and orthogneisses intruded at 1870–1770 Ma by a large Anorthosite–Mangerite–Charnockite–Granite (AMCG) suite (Griffin et al., 1978; Corfu, 2004). The intrusive suite forms about 50% of the islands and consists of several plutons of dominantly mangerite and charnockite composition (i.e. orthopyroxene- and olivine-bearing granitic melts, respectively; Griffin et al., 1978; Markl et al., 1998; Corfu, 2004). The AMCG suite was emplaced into the granulitic crust at ambient conditions estimated to be 750–800 °C and 0.4 GPa (Markl and Bucher, 1997), or 1.0–1.2 GPa (Ormaasen, 1977) (see Markl et al. (1998) for a discussion about this discrepancy in P estimate). Geochronology data indicate that the granulite facies metamorphism was initiated at least 10 Ma before the emplacement of the first intrusives, and it accompanied the main intrusive activity at 1800–1790 Ma. The most likely cause of the granulite facies metamorphism is magmatic underplating and related contact metamorphism (Corfu, 2007). The dry rocks of the AMCG were only locally hydrated during the infiltration of late-magmatic pegmatitic melts at 1770 Ma (Corfu, 2004). The granulite facies mineral assemblages are generally well preserved throughout the central-western portion of the Lofoten–Vesterålen islands.

Ductile shear zones are common in the AMCG suite and typically consist of narrow structures (1 cm–1 m in thickness) showing a mylonite-to ultramylonite transition (characterized by the complete consumption of porphyroclasts, an extreme grain size reduction, and the development of a polymineralic matrix with a high degree of phase mixing) from the shear zone boundary to the shear zone centre or to one side of the shear zones. In this contribution we examine the grain size reduction and deformation processes of perthitic feldspars in shear zones developed from the Raftsund mangerite in Austvågøya (western Lofoten) (Fig. 1), which is the largest intrusion in the Lofoten–Vesterålen region (Griffin et al., 1978). Discrete shear zones are recognizable in the field by their typical pinkish colour, which contrasts with the dark brown to black appearance of undeformed and massive mangerites.

The studied samples (shear zone LST29: Figs. 1b and 2) were collected from mylonite outcrops along the north-eastern coast of Austvågøya (Fig. 1a; UTM coordinates relative to WGS84: zone 33W, 0505656 East, 7594514 North). The mylonite occurs within a 0.5 m thick shear zone oriented 350/80 (dip direction/dip) and flanking a mafic dyke in the mangerite. The mylonitic foliation contains a stretching lineation plunging steeply to the NW (305/60) and marked by the rodding of feldspars and by elongated amphibole-rich polymineralic aggregates. Asymmetric fabrics on the field (SC and SC′ fabric, σ-porphyroclasts, sigmoidal foliation) consistently indicate a N-block-down-to-the-NW sense of movement.

3. Methods of study

3.1. Petrography and quantitative microstructural analysis

The petrography and microstructure of the shear zone have been investigated with polarized light- and scanning electron microscopy on polished thin sections cut perpendicular to the foliation and parallel to the stretching lineation. SEM backscatter electron images were collected with a Jeol-840 SEM at the Department of Medical Biology, Tromsø University, and a Philips XL-30 FEG-ESEM at the Department of Geological Sciences, Stockholm University. The same thin sections were used for electron backscattered diffraction (EBSD) and electron microprobe (EMP) analysis.

Grain size analysis of recrystallized feldspar was performed on grain boundary maps produced by manually digitizing grains on SEM backscattered images. The 2D size of the grains was calculated as the diameter of the circle with an area equivalent to that of the grain using the freeware Image SXM software (http://www.ImageSXM.org.uk). The grain boundary maps were used to quantify the particle (grain long axis) and the surface (grain boundary) fabric using the SPAROR (Panozzo, 1983) and the SURFOR (Panozzo, 1984) method, respectively (software available at http://pages.unibas.ch/earth/micro/). These two methods describe the bulk fabric of a crystalline aggregate as a whole by generating projection