ELSEVIER

Journal of Structural Geology 29 (2007) 1049–1069

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Creep and strain-dependent microstructures of synthetic anorthite–diopside aggregates

A. Dimanov [a,*], E. Rybacki [b], R. Wirth [b], G. Dresen [b]

[a] *Laboratoire de Mécanique des Solides, UMR 7649, Ecole Polytechnique, Bat 65, Route de Saclay, 91128 Palaiseau, France*
[b] *GeoForschungsZentrum Potsdam, Telegrafenberg, 14473 Potsdam, Germany*

Received 4 May 2006; received in revised form 15 February 2007; accepted 18 February 2007

Abstract

We investigated plastic deformation of fine-grained synthetic diopside and two-phase anorthite–diopside aggregates in triaxial compression and torsion (up to $\gamma \sim 5$). Temperature, confining pressure and stress ranged between 950–1180°C, 200–400 MPa and 5–500 MPa, respectively. Water content of samples ranged between $\sim 0.005 \pm 0.002$ and 0.075 ± 0.025 wt% H_2O. All samples deformed in linear-viscous creep with a stress exponent of 1.0 ± 0.2. The activation energy ranged between 571 ± 53 and 290 ± 28 kJ/mol, depending on mineralogy and water content. Sample strength depended on water fugacity with an exponent of 1.55 ± 0.25. Samples deformed in torsion and coaxial compression gave similar flow laws, in spite of significant differences in the corresponding microstructures. Scanning and transmission electron microscopy of two-phase samples deformed in torsion showed phase mixing, cavitation and dislocation processes. We suggest that linear-viscous creep of fine-grained two-phase aggregates involved grain boundary sliding accommodated by grain boundary diffusion and significant dislocation accommodation at high strains. We also observed that cavity coalescence and microcracking led to sample failure. Hence, dynamic instabilities may exist in high-strain shear zones accommodating viscous deformation in the lower continental crust.

Keywords: Lower crust; Shear zones; Two-phase rocks; Diffusion creep; High strain; Ductile failure

1. Introduction

Earthquake activity, structure and kinematics of large-scale faults transecting the brittle upper crust are strongly controlled by temperature- and pressure-varying viscosities of rocks at mid- to lower-crustal depth. Recent results from mechanical modelling suggest that the structural complexity of strike-slip fault systems and seismic recurrence intervals are significantly affected by viscous flow in the lower crust (Bourne, 2003; Rolandone et al., 2004; Savage, 2000). The time-averaged depths of seismic activity at major strike-slip faults transecting the continental crust such as the San Andreas Fault and the North Anatolian Fault Zone indicate a broad transition from brittle and/or friction-controlled deformation to aseismic creep at about 20 ± 5 km depth depending on local heat flow, shear strain rates and petrological composition (Hauksson, 2000; Magistrale and Zhou, 1996; Özalaybay et al., 2002; Tibi et al., 2001). However, slip-rate distribution and deformation mechanisms operating in fault zones at mid- to lower-crustal depth are complex and may vary considerably in space and time (Bürgmann et al., 2002; Tse and Rice, 1986). For example, time-dependent shallowing of aftershock activity as observed for the 1992 Landers earthquake is attributed to increasing contribution of viscous creep at the expense of brittle deformation (Rolandone et al., 2004). Recently, studies of mylonite shear zones exhumed from the base of the seismogenic upper crust reveal microstructures associated with high-stress episodes during coseismic loading overprinted by microstructures due to low-stress plastic flow that reflect post-seismic stress relaxation (Ellis and Stöckhert, 2004; Trepmann and Stöckhert, 2003). Analytical modelling indicates that

---

* Corresponding author. Fax: +33 1 96 33 30 28.
E-mail address: dimanov@lms.polytechnique.fr (A. Dimanov).

0191-8141/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2007.02.010

coseismic stress pulses likely scale with stress drops and decay rapidly with distance from earthquake hypocenters (Montési, 2004).

The complex spatio-temporal variation of stress and slip-rate at crustal depth is still inaccessible to direct observations but may be constrained by a combination of laboratory studies of rheology, field observations and modelling of active deformation. Geodetic records of postseismic surface deformation at strike-slip faults span just a few years to decades, but existing data generally indicate that earthquake-induced perturbations of strain rates and stresses decay on timescales of <1 to 100 years (Hearn et al., 2002; Kenner and Segall, 2000, 2003; Savage and Svarc, 1997; Savage et al., 2003). Estimates of "long-term" relaxation times are on the order of a few decades, suggesting that creep viscosities in the lower crust and upper mantle are of the order of 10^{18}–10^{20} Pa.s (Hetland and Hager, 2003; Kenner and Segall, 2000; Li and Rice, 1987; Thatcher, 1983).

Field studies of exposed sections from the base of the seismogenic crust often show deformation localized into high-strain shear zones containing fine-grained (<50 μm) ultramylonites. Partly, these zones may represent the downward continuation of seismogenic faults transecting the brittle upper crust (Scholz, 1990; Sibson, 1977). Shear zones cutting through the lower crust often contain fine-grained mixtures of dominantly feldspar, pyroxene and amphibole assumed to deform by linear-viscous flow (Allison et al., 1979; Behrmann and Mainprice, 1987; Egydio-Silva et al., 2002; Kenkmann and Dresen, 1998, 2002; Kruse and Stünitz, 1999; Steffen et al., 2001).

However, to infer bulk mechanical behaviour from local microstructure observations is a daunting task. For example, microstructural criteria commonly used to infer grain size-sensitive, potentially superplastic flow in shear zone mylonites include a small and equant grain size, phase mixing, low dislocation densities and cavitation (Behrmann, 1985; Boullier and Gueguen, 1975). However, even very fine-grained ultramylonite rocks often show evidence for non-linear creep, such as elevated dislocation densities, dynamic recrystallization and crystallographic textures (Behrmann and Mainprice, 1987; Kenkmann and Dresen, 2002). In fact, similar to ceramic materials, grain size-sensitive flow and grain boundary sliding in rocks often involve multiple accommodation mechanisms that are not yet fully understood (Nieh et al., 1997; Paterson, 1990; Wakai et al., 1999; Zelin and Mukherjee, 1996).

Laboratory studies provide independent constraints on viscosities and deformation mechanisms dominating high-temperature creep in the lower crust and mantle. However, available experimental data for rocks typical of the lower crust are still scarce. In particular, there are only a few studies on fine-grained rocks deforming at low stresses (Bystricky and Mackwell, 2001; Dimanov et al., 2003; Mackwell et al., 1998). Robust flow laws now exist for dislocation and diffusion-controlled creep of feldspar rocks (Dimanov et al., 1998; Rybacki and Dresen, 2000, 2004; Rybacki et al., 2004) and clinopyroxene rocks (Dimanov and Dresen, 2005). Recently, Dimanov and Dresen (2005) studied the high-temperature creep strength of anorthite–diopside mixtures exploring the effect of mineralogical composition on the constitutive behaviour.

In this paper we investigate the mechanical behaviour and microstructure evolution of synthetic feldspar–pyroxene aggregates to high strains. We discuss the role of phase mixing and cavitation and present the first experimental results on failure of rocks by cavitation during ductile flow at high temperatures and pressures. The synthetic rocks serve as analogues for fine-grained ultramylonites frequently found in shear zones transecting mafic rock assemblages in the lower crust.

2. Experimental procedures

2.1. Starting materials and sample preparation

We performed deformation experiments on 10 synthetic two-phase plagioclase–clinopyroxene aggregates containing 50 vol% anorthite and 50 vol% diopside and two synthetic single-phase clinopyroxene aggregates. Samples were prepared from glass powders of anorthite and diopside provided by Schott Glasswerk (particle size $d < 40$ μm, <1 wt% impurities). The powders were mechanically mixed in an agate mortar in alcohol. The mixtures were oven dried over a week and then cold-pressed in cylindrical steel cans 2 cm in height and 1 cm or 1.5 cm in diameter for axial and torsion tests, respectively. One cold-pressed two-phase specimen was pre-dried at 850°C and 0.1 MPa in a CO/CO_2 atmosphere for 3 days. As-received or pre-dried cold-pressed specimens were hot-isostatically pressed (HIPed) at 300 MPa and 1100°C for 2–5 h (for details see Wang et al., 1996; Dimanov et al., 1999; Rybacki and Dresen, 2000). During HIP, the fine-grained glass powder crystallized to form dense fine-grained mixtures of anorthite and diopside or pure diopside. For axial compression experiments, samples were deformed directly after HIPing. Sample dimensions of HIPed samples show good reproducibility with 16.5 ± 1.0 mm length and 8.00 ± 0.50 mm diameter (see also Dimanov et al., 2003). The diameter for a single specimen was constant within ± 0.2 mm except very close to the end spacers. Specimens deformed in torsion were precision-ground from the larger size HIPed samples to produce cylinders 10 mm in diameter and 7 mm in length.

2.2. Microstructures and water content of hot-isostatically pressed samples

Microstructures of undeformed and deformed samples were investigated using a scanning electron microscope (SEM; Zeiss DSM 962) and transmission electron microscope (TEM, Phillips CM 200). Appropriate sections were cut parallel and perpendicular to the sample axis. Thick sections prepared for SEM observations were polished and etched thermally to reveal grain boundaries. Thin foils for TEM observations were prepared by ion thinning thin sections from otherwise untreated deformed material.