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Preferred orientation of anorthite deformed experimentally in Newtonian creep

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Abstract

Synthetic anorthite aggregates were deformed in a Paterson gas deformation apparatus at confining pressures up to 400 MPa in torsion and axial compression at temperatures between 950 °C and 1200 °C. Samples deformed in torsion under Newtonian creep display development of texture (or crystallographic preferred orientation) as documented with synchrotron X-ray diffraction measurements. Complex diffraction patterns were deconvoluted with the Rietveld method to obtain quantitative texture information. Torsion samples deformed up to shear strains of 4 and samples deformed in compression at higher stresses to total strains of 0.3 develop clear textures. Texture and shape preferred orientation (SPO) of torsion samples display a monoclinic pattern with an asymmetry inclined against the sense of shear, consistent with polycrystal plasticity simulations that assume the deformation is accomplished by dislocation glide. These results show that a material deforming in linear-viscous creep can develop a strong texture, in striking contrast to the paradigm that the presence of a texture precludes low-stress Newtonian behavior. Our observations show that the presence or absence of crystallographic preferred orientation is not sufficient to uniquely infer the dominant rheological/mechanical regime, as sometimes applied for interpretation of seismic anisotropy in the Earth.

Keywords: anorthite; crystallographic preferred orientation; texture; Newtonian creep; feldspar; torsion; anisotropy; rheology

1. Introduction

Ductile flow of rocks is complex and depends on many parameters, including temperature, strain, strain rate, pressure, grain size, chemical environment, phase transformations and strain history (e.g., Frost and Ashby, 1982; Karato, 1996). In geological systems it is difficult to pinpoint the importance of each variable and deformation experiments proved to be invaluable for understanding the rheology and evolution of microstructure and preferred orientation of crystals. In this paper we use the widely accepted term “texture” synonymous with “crystallographic preferred orientation”.

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Deformation by creep refers to the non-recoverable strain resulting when a rock is subjected to a constant stress during a long period of time. Creep strain is attained by the movement of three types of defects within the polycrystalline material: point defects (vacancies), linear defects (dislocations) and planar defects (grain boundaries). It is recognized that each type of defect has a distinctive contribution to the mechanical response of the aggregate (Langdon, 2000). As a consequence creep mechanisms may be identified from microstructural observations in combination with the values of empirical parameters (e.g. stress exponent n).

The mechanical behavior is described over a wide range of stresses with a power law, relating strain rate $\dot{\varepsilon}$ and stress σ ($\dot{\varepsilon} \sim \sigma^n$). For dislocation creep the stress exponent n is usually observed between 3 and 5. However at low stresses there is a transition to values of n around 1 and 2. Under these conditions and moderately high temperatures three possible mechanisms dominate: diffusion creep, Harper–Dorn creep and grain boundary sliding.

Creep accommodated by dislocation activity results in a preferred orientation of crystals and thus anisotropy of macroscopic physical properties, most notably seismic wave propagation. Grain-size sensitive deformation mechanisms accommodated purely by diffusion have been associated with deformation that does not produce preferred orientation. This latter association is supported by experiments on limestone (Schmid et al., 1977), olivine (Fliervoet et al., 1999) and fine-grained perovskite (Karato et al., 1995). Since a Newtonian (linear) viscous behavior (i.e. $n=1$) is observed for diffusion creep, it has lead to the conclusion that the development of anisotropy in the Earth is a feature restricted to non-Newtonian flow, assuming an isotropic orientation distribution when the behavior is linear-viscous (Karato and Wu, 1993). It also promoted the reverse conclusion that, if anisotropy is observed in the Earth, the mechanical behavior must be non-Newtonian (Savage, 1999; McNamara et al., 2001). We demonstrate that the relationship between mechanical behavior and texture is not unequivocal.

In this paper we investigate fine-grained anorthite aggregates, deformed experimentally in a regime of Newtonian creep, which develop distinct preferred orientation of crystallites, indicating that even in linear-viscous flow anisotropy may develop. Compared to minerals such as quartz, calcite and olivine, relatively little is known about preferred orientation of plagioclase. In naturally deformed anorthosites and some amphibolites it has been attributed to dislocation glide (Jensen and Starkey, 1985; Olsen and Kohlstedt, 1985; Kruhl, 1987; Olesen, 1987; Ji et al., 1988; Siegesmund et al., 1994; Prior and Wheeler, 1999; Jiang et al., 2000; Xie et al., 2003). Several slip systems have been observed to be active in plagioclase (Tullis, 2002). In natural mylonites (010)[001] is an important slip system at medium to high-grade metamorphic conditions (Kruhl, 1987; Ji et al., 1988, 1994; Zhao, 1997). Optical and TEM investigations in experimentally deformed aggregates and single crystals have confirmed this slip system (Olsen and Kohlstedt, 1984; Montardi and Mainprice, 1987; Ji and Mainprice, 1988; Kruse and Stünitz, 1999; Stünitz et al., 2003). Other studies report (010)[100] slip, suggesting that there may be a transition from [001] to [100] slip with increasing temperature (Heidelbach et al., 2000; Ji et al., 1997, 2000, 2004). Other processes for orientation changes are recrystallization (Ji and Mainprice, 1990) and reorientation of non-equiaxed crystals during straining (Shelley, 1979; Ague et al., 1990; Feinberg et al., 2006).

Various techniques have been used to measure texture of plagioclase. Most older reports relied on U-stage methods (Shelley, 1979, 1989; Suwa, 1979; Jensen and Starkey, 1985; Kruhl, 1987; Olesen, 1987; Ji and Mainprice, 1988; Ji et al., 1988, 1994; Siegesmund et al., 1994; Ague et al., 1990; Lafrance et al., 1998; Egydio-Silva and Mainprice, 1999). The resolution of conventional X-ray pole figure measurements is not sufficient to deconvolute the many overlapping diffraction peaks of plagioclase. Electron Back Scatter Diffraction (EBSD) is offering new opportunities for determining texture of plagioclase, both in naturally deformed rocks (Prior and Wheeler, 1999; Jiang et al., 2000; Lapworth et al., 2002; Xie et al., 2003), as well as in experimentally deformed aggregates (Ji et al., 2000, 2004). Synchrotron X-rays and neutron diffraction have recently been applied to feldspars. Both have improved statistics compared to U-stage and EBSD, because volumes, rather than surfaces are analyzed (Siegesmund et al., 1994; Ullemeyer et al., 1994; Xie et al., 2003; Heidelbach et al., 2000; Leiss et al., 2002; Ullemeyer et al., 2006).

The objectives of this study are to explore crystallographic preferred orientation development in experimentally deformed anorthite with synchrotron hard X-rays and time-of-flight (TOF) neutron diffraction. Aggregates were deformed under Newtonian creep in torsion. In addition the transition from Newtonian to non-Newtonian creep was explored in triaxial compression. The experimental data indicate that significant texture develops in both cases.

2. Deformation experiments

A series of deformation experiments was performed in a Paterson-type gas apparatus equipped with an internal