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The brittle-to-viscous transition in polycrystalline quartz: An experimental study

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ABSTRACT

Shear experiments on quartz gouge were performed at elevated confining pressures (predominantly 1.5 GPa) and temperatures (500 °C - 1000 °C) at shear strain rates of $3.5 \cdot 10^{-6}\ s^{-1}$ to $2 \cdot 10^{-3}\ s^{-1}$ to study the brittle-to-viscous transition. An unsystematic temperature dependence of strength at low temperatures changes towards a clear temperature weakening dependence above 650 °C. The transition from a pressure strengthening to a pressure weakening relationship takes place continuously between 650 °C and 800 °C. Strain rate stepping experiments reveal power-law breakdown at low temperatures (~650 °C). Between 800 °C and 1000 °C, a stress exponent of $n = 1.9 \pm 0.6$ and an activation energy of $Q = 170 \pm 72$ kJ/mol indicate a combination of diffusion and dislocation creep. The Goetze criterion is confirmed as the upper stress limit for viscous deformation mechanisms. Localised deformation in the form of semibrittle shear bands with Riedel geometry at low temperatures changes to homogeneous deformation with a pervasive foliation accompanied by a continuous texture evolution between 700 °C and 1000 °C. Fracturing dominates at low temperatures accompanied by increasing amounts of dissolution and precipitation in fine-grained zones with increasing temperature. Above 650 °C, dislocation and diffusion creep are the dominating deformation processes, with dislocation creep being favoured in larger grains while dissolution-precipitation is active in the fine-grained fraction.

1. Introduction

The transition from fully brittle to fully viscous deformation in rocks (semi-brittle field) occurs over a broad range of conditions in pressure, temperature, strain rate, and H_2O-content with several changes in deformation mechanisms (e.g., Kohlstedt et al., 1995; Scholz, 2007; Hirth and Tullis, 1994). Viscous denotes temperature- and strain-rate dependent deformation here. In the lithosphere, the transition commonly takes place within the middle crust (continents) (e.g., Brace and Kohlstedt, 1980; Handy, 1989; Sibson, 1989) but it may extend into the upper mantle for some rocks, e.g., below the oceanic crust (e.g., Kohlstedt et al., 1995). The transition region coincides with the greatest strength of rocks, and many large earthquakes nucleate in this region (e.g., Sibson, 1989; Scholz, 2007).

Under conditions of brittle deformation (e.g., low temperatures, high strain rates, typically shallow crustal levels), the strength of rocks primarily depends on normal stress and pore pressure (Byerlee, 1978). Fracture strength and/or friction control the rock deformation, leading to cataclastic processes (e.g., fracturing, frictional sliding) with characteristic microstructures at greater strain. The intersection of Byerlee's law (Byerlee, 1978) with the Mohr-Coulomb fracture criterion marks the onset of semi-brittle deformation in most lithologies (e.g., Kohlstedt et al., 1995). This intersection is termed “brittle-ductile transition” and is temperature independent. Viscous deformation at higher temperature, typically at deeper crustal levels, depends on strain rates and temperatures, and is caused by diffusion and/or dislocation creep involving recovery processes like dynamic recrystallisation (e.g., Poirier and Guillope, 1979; Tullis and Yund, 1977; Yund and Tullis, 1991; Hirth and Tullis, 1994; Tullis, 2002). The transition from semibrittle to viscous deformation is marked by the brittle-to-viscous-transition (Kohlstedt et al., 1995) (BVT). The Goetze criterion has been introduced as an ad hoc approximation by Kohlstedt et al. (1995) to delineate this transition. It is formulated as $\Delta\sigma = Pc$, i.e. the differential stress to drive viscous flow is equal to the confining pressure.

In the transitional semi-brittle zone, stresses required to create new fractures are lower than those for sliding on pre-existing faults (e.g., Byerlee, 1968; Kohlstedt et al., 1995) causing pervasive fracturing and grain-size reduction (cataclasis). Dislocations may be generated by cracking and healing processes (e.g., FitzGerald et al., 1991; Tarantola et al., 2012; Trepmann and Stöckhert, 2013; Stünitz et al., 2017), but

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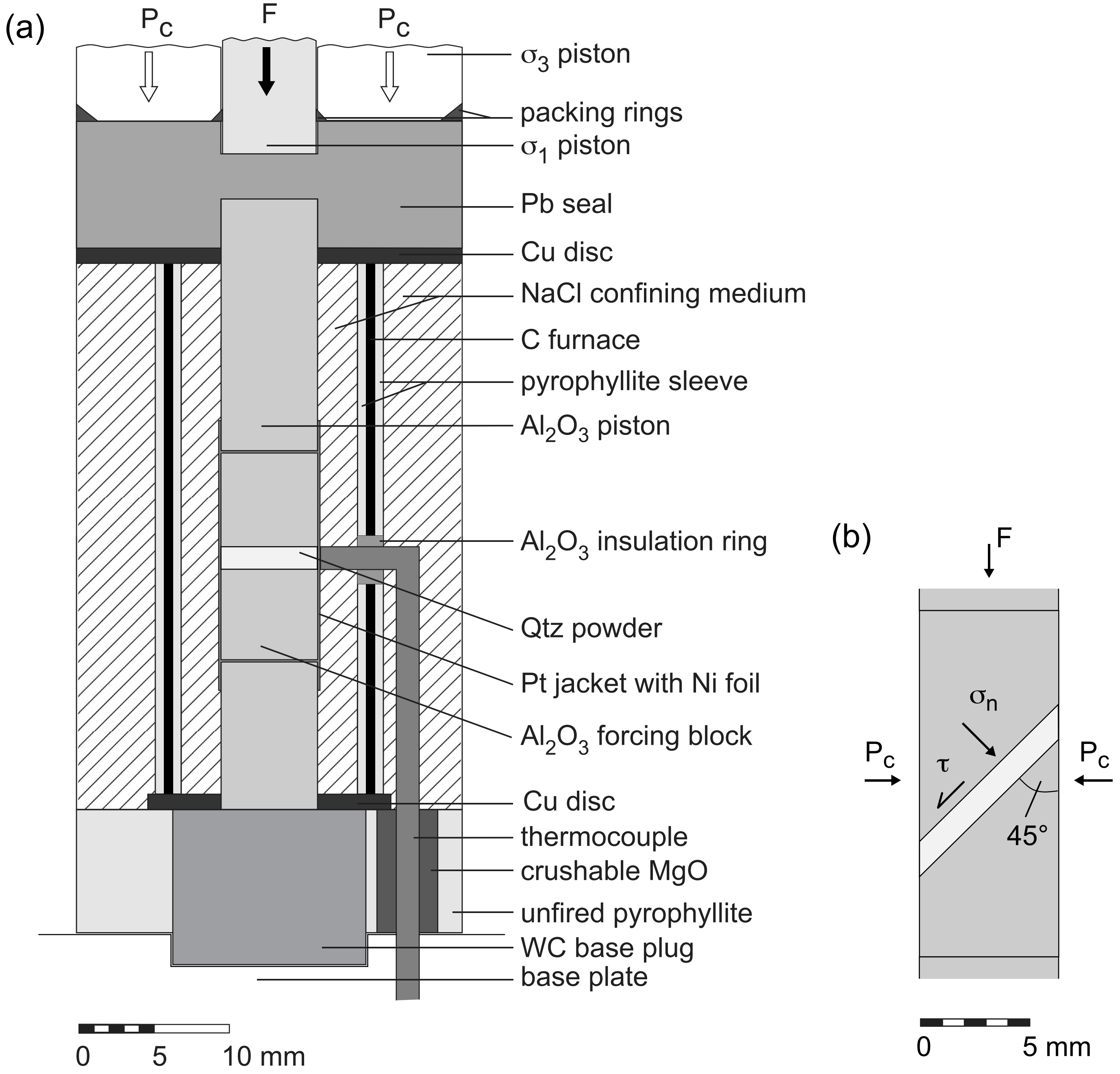

Fig. 1. Sample assembly. (a) Sample (quartz powder) is inserted between 45° pre-cut forcing blocks, in a jacket surrounded by confining medium (NaCl) and a carbon furnace (after Richter et al., 2016). Displacement in the shear zone is at 45° to the plane of drawing. (b) Stresses in the sample: F = load applied to upper forcing block, P_c = confining pressure, σ_n = normal stress, τ = shear stress.

whether these dislocations become important for crystal plasticity (dislocation creep) depends on temperature and the efficiency of the recovery processes. At low temperatures, tangling dislocations and high dislocation densities produce strain hardening and greater stresses (e.g., Barber et al., 2010). Dominant crystal plasticity is achieved at higher temperatures, where dislocation climb and recrystallisation are rate controlling. For quartz, three types of dislocation creep regimes have been identified dependent on the dominance of subgrain-rotation recrystallisation or grain-boundary migration (Hirth and Tullis, 1992).

Grain size reduction by cracking may play an important role for the onset of viscous deformation by increasing the surface area and decreasing the transport distances, leading to accelerated mass-transfer processes (e.g., Pec et al., 2012; Trepmann and Stöckhert, 2003; Menegon et al., 2008; Van Daalen et al., 1999). As a result, deformation by diffusion creep may become the dominant mechanism should such cracking occur (e.g., Paterson, 2013, p. 91–105, and references therein).

It emerges from this brief discussion that in the transition region of brittle-to-viscous deformation, several processes are competing: cracking and frictional sliding, crystal-plastic deformation, and diffusive mass transfer combined with friction-less grain-boundary sliding. This study will try to address their relative importance for deformation in quartz over a range of temperatures and confining pressures.

Quartz as one of the most abundant silicates in the Earth's crust is often used to model and predict the mechanical behaviour of the upper lithosphere (e.g., Brace and Kohlstedt, 1980). In addition, deformation mechanisms in quartz can be studied independently of chemical effects because of its simple chemistry and very limited compositional