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Effect of pre-existing crystallographic preferred orientation on the rheology of Carrara marble

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Localized deformation during high temperature plastic flow is frequently attributed to mechanical weakening caused by grain size reduction and, in some cases, by the development of a crystallographic preferred orientation (CPO). This study aims to investigate experimentally the contribution of CPO development to the strain weakening seen in Carrara marble samples during large strain torsion experiments at temperatures in the range 600–800 °C at constant strain rate and confining pressure. The starting material shows little or no CPO. Samples were treated in three steps. First, they were deformed to achieve a well-developed CPO and recrystallized to a finer grain size. Second, the samples were annealed at 727 °C for 5 h to grow the grains to approximately their original size and shape while maintaining a reasonably strong CPO. Finally, the samples were deformed again, under the same conditions as the first step. Re-deformed samples showed a strain weakening lower than during the first step. We infer that this strength difference is caused primarily by the CPO developed during the first deformation event. This implies that CPO development is an important process that contributes to strain weakening during flow of Carrara marble and likely of other rock types as well.

1. Introduction

Weakening of rocks and strain localization into shear zones during plastic flow is a key rheological and structural process in natural deformation in both the crust and the upper mantle (Rutter and Brodie, 1988; Karato and Wu, 1993; Ter Heege, 2002; Precigout et al., 2007; Karato, 2008; Hunt et al., 2009). Weakening attributes to factors such as texture development (the development of a crystallographic preferred orientation (CPO)) and the reduction of grain size due to dynamic recrystallization (Poirier, 1980; Franssen and Spiers, 1990; Rutter, 1998; Pieri et al., 2001a; Barnhoorn et al., 2004; Delle Piane and Burlini, 2008; Skemer et al., 2013). However, little is known about the relative contributions of these processes to the amount of weakening.

Carrara marble is a well-investigated rock material, suitable for studying deformation mechanisms and related microstructural features during ductile flow at elevated pressures and temperatures (Covey-Crump, 1997; Pieri et al., 2001a; Ter Heege, 2002; Barnhoorn et al., 2004, 2005; Valcke et al., 2006; Delle Piane and Burlini, 2008). Investigations of the high strain rheology of Carrara marble, at high pressure (300 MPa) and high temperature (500–927 °C), have revealed a characteristic stress vs. strain curve (Fig. 1) (Pieri et al., 2001a; Ter Heege, 2002; Barnhoorn et al., 2004), showing an initial quasi-elastic response until yielding, followed by hardening until a peak stress is reached, and then gradual weakening. Flow at constant shear stress was reached for higher temperatures (727 °C or higher) for a shear strain of 8 and higher.

Microstructural observations in the hardening stage seen in high strain compression and torsion tests on Carrara marble have revealed that the stress increase is accompanied by intense twinning and is assumed to involve glide and climb of dislocations (Ter Heege, 2002; Barnhoorn et al., 2004). Usually the peak stress is reached between a finite shear strain of 1 and 2 (for $\dot{\gamma} = 1 \times 10^{-3}\ s^{-1} - 1 \times 10^{-5}\ s^{-1}$), depending on the temperature, and lasts almost one unit of shear strain. Subsequent weakening is associated with grain size reduction by dynamic recrystallization,

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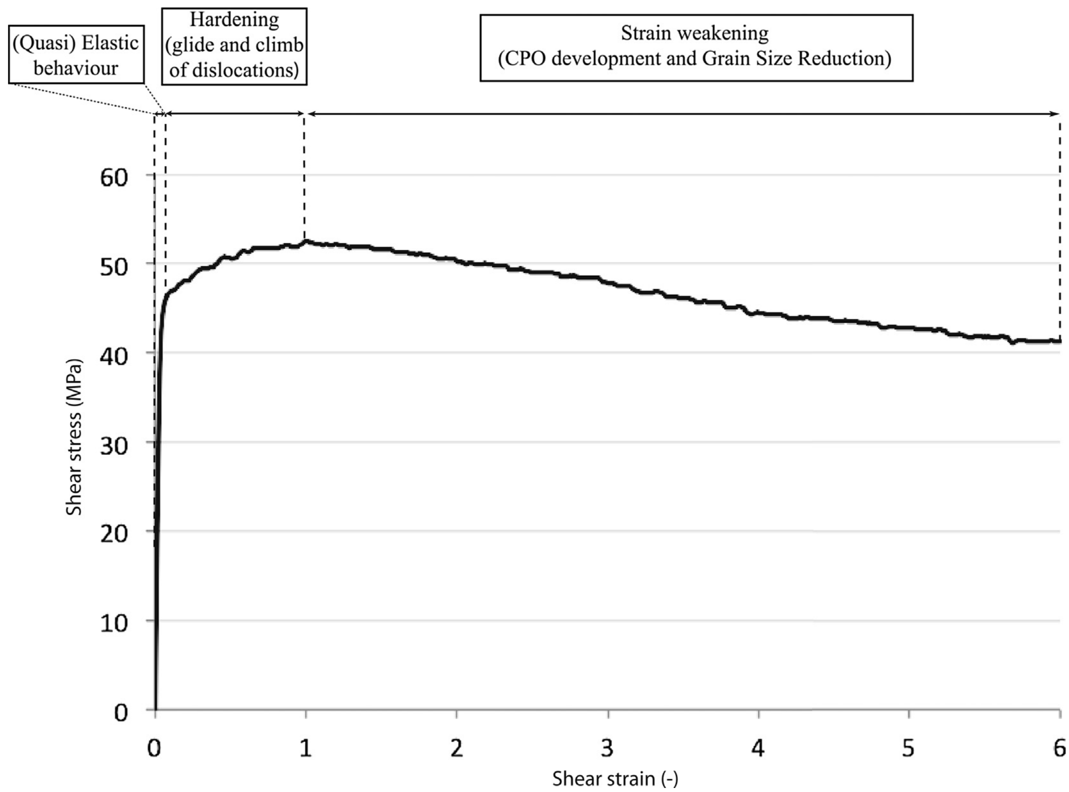

Fig. 1. Characteristic stress/strain curve for Carrara marble deformed by torsion experiments at a temperature of 727 °C and a shear strain of 1 × 10^{-3} s^{-1} (experiment P1168, Table 1). Elastic behaviour is followed by yielding with work hardening, caused by glide and climb of dislocations. After a peak in strength, weakening occurs, associated with the development of a CPO and grain size reduction due to recrystallization processes (Barnhoorn et al., 2004).

until at high shear strains (5–8, depending on the temperature) the bulk of the material has recrystallized (Barnhoorn et al., 2004). A shape preferred orientation (SPO) of non-recrystallized grains and a CPO develop during the deformation process. The type and intensity of this CPO depends on the deformation temperature (Barnhoorn et al., 2004).

Recrystallization and CPO development are accordingly assumed to be the main processes that cause weakening during the plastic deformation of Carrara marble at elevated pressures and temperatures (e.g. Pieri et al., 2001a), though they do not lead to strain localization, i.e. are insufficiently effective to cause localization at experimentally achievable strains. The absence of localization in single-phase materials is in agreement with Fressengas and Molinari (1987), as long as tests are carried out under displacement rate boundary conditions, as has been discussed by Paterson (2007). Hansen et al. (2012) performed torsion experiments on olivine-rich materials and concluded that localization in torsion experiments at constant strain rates were not observed because variations in strength were not large enough to initiate localization.

Delle Piane and Burlini (2008) investigated the contribution of CPO to the weakening of Carrara marble by performing a torsion experiment involving deformation followed by annealing and repeated deformation at a shear strain rate of 3 × 10^{-4} s^{-1} and a temperature of 727 °C. Strain weakening during the repeated deformation, of a sample with a pre-existing CPO, had reduced by one third with respect to the initial deformation, which resulted in the conclusion that roughly one third of the weakening of the sample studied was caused by CPO development, while the other two thirds were due to grain size reduction by recrystallization processes. However, because only one experiment was performed, further investigation on the subject is needed in order to draw convincing conclusions about the contribution of CPO and recrystallization to the weakening processes in Carrara marble.

The microstructural effect of the annealing of Carrara marble after a period of shear deformation has been investigated by Barnhoorn et al. (2005), who describe widespread grain growth and subtle changes in CPO during the annealing process. Barnhoorn et al. (2005) and Delle Piane and Burlini (2008) concluded that a sample deformed to a shear strain of 5 at 727 °C, and then annealed for 5 h at the same temperature, was similar to the original Carrara marble in grain size, but possessed a strong CPO (J index ~10), with a pattern similar but not equal to that reached after pre-annealing deformation. The J-index is defined as the second moment of an orientation distribution function (ODF) (Bunge, 1982). However, in the above experimental studies, the pressure-temperature conditions during the various deformation and annealing stages were the same (T = 727 °C, confining P = 300 MPa and shear strain rate = 3 × 10^{-4} s^{-1}). There is no experimental data on high-strain and high temperature torsion experiments yet where the experimental conditions during deformation are different from those of the annealing conditions. Therefore, no conclusions can be drawn about the (microstructural) effect of annealing on samples deformed at different temperatures and strain rates and possible implications on strengths of rocks, both during experiments and in nature.

The present study investigated the contribution of CPO to the weakening of Carrara marble at different shear strains and temperatures to explore the role of pre-existing CPO on the rheology. Deformation experiments in torsion were performed at different temperatures (600 °C, 727 °C and 800 °C) and strain rates (3 × 10^{-4} s^{-1} and 1 × 10^{-3} s^{-1}) at a confining pressure of 300 MPa, keeping the annealing conditions constant at 727 °C and 300 MPa.