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The role of strain hardening in the transition from dislocation-mediated to frictional deformation of marbles within the Karakoram Fault Zone, NW India

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ABSTRACT

The onset of frictional failure and potentially seismogenic deformation in carbonate rocks undergoing exhumation within fault zones depends on hardening processes that reduce the efficiency of aseismic dislocation-mediated deformation as temperature decreases. However, few techniques are available for quantitative analysis of dislocation slip system activity and hardening in natural tectonites. Electron backscatter diffraction maps of crystal orientations offer one such approach *via* determination of Schmid factors, if the palaeostress conditions can be inferred and the critical resolved shear stresses of slip systems are constrained. We analyse calcite marbles deformed in simple shear within the Karakoram Fault Zone, NW India, to quantify changes in slip system activity as the rocks cooled during exhumation. Microstructural evidence demonstrates that between ~300 °C and 200–250 °C the dominant deformation mechanisms transitioned from dislocation-mediated flow to twinning and frictional failure. However, Schmid factor analysis, considering critical resolved shear stresses for yield of undeformed single crystals, indicates that the fraction of grains with sufficient resolved shear stress for glide apparently increased with decreasing temperature. Misorientation analysis and previous experimental data indicate that strain-dependent work hardening is responsible for this apparent inconsistency and promoted the transition from dislocation-mediated flow to frictional, and potentially seismogenic, deformation.

1. Introduction

Calcite exhibits marked velocity-weakening behaviour, which may promote nucleation of unstable earthquake ruptures (Han et al., 2010; Verberne et al., 2015; Cowie et al., 2017). Faults hosted in calcite-rich lithologies are therefore major sources of seismic hazard in zones of active continental deformation (Smith et al., 2011). The depth extent of earthquake nucleation in such faults broadly corresponds to the depth at which the activity of temperature-dependent aseismic creep processes can prevent unstable frictional failure under interseismic strain rate conditions (Scholz, 1988; Verberne et al., 2015). Dislocation-mediated deformation mechanisms (potentially including contributions from dislocation creep, low-temperature plasticity, and/or dislocation-accommodated grain boundary sliding) are commonly inferred to have operated in calcite-rich shear zones exhumed from mid-crustal depths and in which the grain size and/or conditions were unfavourable for efficient diffusion creep (e.g. Bestmann et al., 2006; Rutter et al., 2007; Wallis et al., 2013; Parsons et al., 2016). Therefore, competition between dislocation-mediated flow and frictional failure may exert an important control on the depth limit of earthquake nucleation. However, the precise microphysical processes that control this transition in natural fault zones remain poorly constrained, particularly in situations where rocks are progressively exhumed during deformation, resulting in a transition from aseismic flow to potentially seismogenic frictional failure within the exhuming rock mass (Handy et al., 2007). The strength of rocks undergoing dislocation-mediated deformation is a function of the stresses required to activate dislocation glide on particular crystallographic slip systems, which may depend on both environmental conditions (e.g. temperature, pressure, and strain rate) and other state variables (e.g. composition, dislocation density and distribution) (e.g., Hobbs et al., 1972; De Bresser and Spiers, 1997). However, it is challenging to determine the strength and activity of slip systems during dislocation-mediated deformation in natural tectonites, and relatively few techniques are available to do so. As a result, the precise controls on the transition from aseismic creep to frictional failure and potentially seismogenic behaviour in natural fault zones

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remain poorly constrained.

The most common approach to assess the relative activity of different slip systems in natural tectonites is to interpret the slip system(s) most likely to have generated an observed crystallographic preferred orientation (CPO); for example, by determining the slip system inferred to have most readily rotated into orientations with high resolved shear stress (e.g., Toy et al., 2008). However, such analysis is often limited to qualitative interpretations and comparisons. More quantitative information can be gleaned by comparing natural and experimental CPOs to results from simulations of polycrystal plasticity (e.g. Wenk et al., 1987). However, this approach tends to place relatively loose constraints on slip system activity due to the large parameter space that needs to be searched (i.e., typically many combinations of slip system strengths and deformation geometries have to be tested) and challenges in comparing natural and simulated CPO geometries quantitatively.

Another approach is to analyse crystallographic misorientations resulting from the presence of dislocations within grains (Lloyd et al., 1997; Bestmann and Prior, 2003; Wheeler et al., 2009). However, due to the limited angular resolution of commonly available measurement techniques (e.g. ~0.2° for misorientation angles from conventional electron backscatter diffraction, EBSD) such analysis can only sample the fraction of the dislocation population that is arranged into relatively high misorientation substructures such as subgrain boundaries (Prior, 1999). As such, 'free' dislocations that are not in subgrain boundaries can be difficult to detect and generally require higher precision and more computationally expensive techniques such as high-angular resolution electron backscatter diffraction (Wallis et al., 2016a, 2017). Moreover, it is unclear to what extent the measured dislocation content was glissile or sessile during deformation. This ambiguity also often applies to direct observation of dislocations, by transmission-electron imaging, chemical etching, or decoration by oxidation.

In this contribution, we exploit advances in EBSD (Prior et al., 1999, 2009; Bachmann et al., 2010; Mainprice et al., 2011) to develop a method of slip system analysis based on determination of Schmid factors (Schmid, 1928; Schmid and Boas, 1950; Farla et al., 2011; Hansen et al., 2011). The Schmid factor of a slip system quantitatively describes the relation between resolved shear stress and applied stress state (the higher the Schmid factor, the greater the resolved shear stress on the slip system). This orientation relationship is typically qualitatively inferred when interpreting slip systems that contribute to CPO development (e.g. Toy et al., 2008). However, the Schmid factor not only quantifies this relationship, but also allows for calculation of resolved shear stresses on each slip system, and enables mapping of grains that are (un)favourably oriented for dislocation glide. Relatively few geological studies have utilised detailed Schmid factor analysis. Most of these focussed on stress states associated with radially-symmetric shortening or extension (e.g. Ralser et al., 1991; Farla et al., 2011; Hansen et al., 2011), and to our knowledge, only two have considered simple shear, both focussed on quartz (Law et al., 1990; Toy et al., 2008).

To explore the capabilities of this approach, we conduct a detailed Schmid factor analysis of calcite in marbles deformed within a shear zone of the Karakoram Fault Zone (KFZ), NW India (Fig. 1). Calcite is particularly well suited for Schmid factor analysis because: (1) techniques are well established to infer palaeostress magnitudes and orientations (Turner, 1953; Rowe and Rutter, 1990) as well as metamorphic and deformation temperatures (Covey-Crump and Rutter, 1989; Burkhard, 1993) from calcite microstructures; (2) the critical resolved shear stresses (CRSSs) of calcite slip systems are experimentally constrained (De Bresser and Spiers, 1997); and (3) these CRSSs and the post-yield behaviour exhibit low strain rate sensitivity (stress exponents in the ranges 5.3–42.6 and 9.3–15.5, respectively) indicating near plastic (as opposed to strain rate-sensitive viscous) behaviour when deformed at differential stresses greater than approximately 30 MPa (Wang et al., 1996; De Bresser and Spiers, 1997). The marbles that we investigate have undergone a protracted deformation history during exhumation and cooling from upper amphibolite-grade conditions to near surface depths and occur in a fault zone that exhibits geomorphological evidence for M_w 7+ earthquakes during the Quaternary (Brown et al., 2002; Rutter et al., 2007; Wallis et al., 2013). We investigate the latter part of this history as the rocks were exhumed and cooled through the frictional-viscous transition zone (Wallis et al., 2013, 2015) and underwent a transition from aseismic flow to potentially seismogenic frictional failure (Rutter et al., 2007). In particular, we use Schmid factor analysis combined with other microstructural observations to test: (1) the manner in which slip system activity potentially varied under evolving temperature and stress conditions during exhumation, (2) the impact of strain hardening on slip system activity, and (3) how these factors affected the transition from crystal plastic to frictional and potentially seismogenic styles of deformation.

2. Geological setting

The KFZ is a > 800 km long fault zone that strikes NW-SE and delineates the western margin of the Tibetan plateau, accommodating dextral displacement resulting from the India-Asia collision (Fig. 1). Along the central KFZ in NW India structures formed at and below lower amphibolite grade are unequivocally attributable to deformation within the KFZ, and record a sequence of fault rocks formed at progressively lower temperature due to ongoing deformation during exhumation (Phillips and Searle, 2007; Wallis et al., 2013, 2015). We investigate marbles deformed within the Pangong strand of the KFZ, adjacent to the Pangong Transpressional Zone (PTZ) (Fig. 1).

Between Muglib and Pangong Tso, the Pangong strand deforms rocks of the Pangong Metamorphic Complex (PMC) and juxtaposes them with the PTZ (Fig. 1). The PMC consists of banded marbles, amphibolites, and pelites that underwent regional metamorphism under kyanite grade (up to 736 ± 47 °C and 1059 ± 219 MPa, Wallis et al., 2014) and sillimanite grade conditions (Streule et al., 2009), followed by retrograde metamorphism and KFZ deformation under lower amphibolite to sub-greenschist conditions (Rutter et al., 2007; Streule et al., 2009; Wallis et al., 2014; Van Buer et al., 2015).

Rutter et al. (2007) studied in detail an outcrop of deformed marble near Muglib (N34°00′55″ E078°17′03″), providing the context for this study (Fig. 1). Here we summarise the most relevant findings of their study. Grain-shape foliation at this locality dips moderately SW and mineral stretching lineations plunge gently both NW and SE, consistent with the wider KFZ kinematics. Rutter et al. (2007) investigated seven marble samples exhibiting microstructures that record mylonitic fabrics evident as varying degrees of dynamic recrystallisation. From the reconstructed grain size of weakly recrystallised host grains, they estimated metamorphic temperatures in the range 300 ± 20 °C to 480 + 130/-30 °C, using the grain size-temperature relationship of Covey-Crump and Rutter (1989). These data place an upper limit on the temperature of overprinting deformation in each sample. The grain size of dynamically recrystallised neoblasts indicates flow stresses in the range of 40 ± 20 MPa to 110 ± 40 MPa according to the calibration of Rutter (1995) based on dynamic recrystallisation by grain boundary migration. The choice of this calibration, rather than an alternative based on dynamic recrystallisation by subgrain rotation (Rutter, 1995), is supported by our microstructural analysis in the following sections, which reveals irregular grain boundary morphologies but limited subgrain development, consistent with microstructures reported by Rutter et al. (2007). Twin incidence (the percentage of grains, in a given grain size class interval, that contain optically visible twin lamellae) indicates differential stresses in the range of 160 ± 30 MPa to 250 ± 30 MPa according to the calibration of Rowe and Rutter (1990). Thick twins exhibit straight, or curved and tapered boundaries indicating temperatures of 200–250 °C (Burkhard, 1993). These constraints, along with observations that the mylonitic fabric is cross-cut by calcite veins that are twinned but not mylonitised, suggest that twinning postdates dynamic recrystallisation (Rutter et al., 2007). Dynamic analysis of