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Recrystallization of quartz after low-temperature plasticity – The record of stress relaxation below the seismogenic zone

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Quartz microfabrics in rocks from the Silvretta basal thrust and the Defereggen-Antholz-Vals (DAV) shear zone in the Eastern Alps, are analysed by polarized light and electron microscopy. The microfabrics from both shear zones record a switch from low-temperature plasticity at transient high stress to recrystallization at relaxing stresses at greenschist facies conditions. The development of new grains is dominantly by subgrain rotation and subsequent strain-induced grain-boundary migration in areas of localized high strain developed during initial low-temperature plasticity. The findings suggest that new grains develop at almost random crystallographic orientations at fast rates of stress relaxation (i.e. at low stress), as indicated by recrystallized quartz zones in the Silvretta fault rocks. In contrast, at slow rates of stress relaxation, new grains develop at moderately high stresses with crystallographic preferred orientation characterized by high Schmid factor for basal <a> glide, as indicated by vein quartz samples from the DAV shear zone. Both recorded histories with transient peak stresses and different rates of stress relaxation are interpreted to be related to seismic activity of the fault systems. This study demonstrates that characteristic microfabrics provide important information about the deformation history of natural shear zones developed in different tectonic regimes.

1. Introduction

Dynamic recrystallization of quartz is known to largely influence the physical properties of crustal rocks (e.g., strength, anisotropy) and the rheology of the upper lithosphere (e.g., Evans and Kohlstedt, 1995; Kohlstedt et al., 1995). Although dynamic recrystallization has been the focus of a vast number of observational, experimental and numerical studies, many details about the development of microstructural anisotropy, especially crystallographic preferred orientation (CPO) and shape preferred orientation (SPO), during recrystallization remain equivocal (e.g., Hobbs, 1968; Hirth and Tullis, 1992, 1994; Skrotzki, 1994; Lloyd and Freeman, 1994; Piazolo et al., 2002; Passchier and Trouw, 2005; Derez et al., 2015; Kjøll et al., 2015). This uncertainty is especially true for complex stress and strain rate histories. Transient high-stress deformation of quartz can be followed by recrystallization at relaxing stresses during the seismic cycle at depths below the seismogenic zone (Trepmann and Stöckhert, 2003, 2013; Trepmann et al., 2007; Bestmann et al., 2012). The resulting microfabrics may be difficult to distinguish from those that develop during dislocation creep with dynamic recrystallization at rather constant stresses (Stipp and Tullis, 2003; Austin and Evans, 2007; Platt and Behr, 2011a,b). Yet, this distinction is important for deciphering and understanding the deformation record of natural shear zones.

In natural shear zones, a complex history of deformation and recrystallization at varying conditions influences the texture (i.e., the crystallographic orientation relationship of grains) of the evolving quartz recrystallization microfabric. It is generally assumed that deformation by dislocation glide can cause a CPO, where crystal orientations rotate towards an orientation that promotes glide on the active glide system(s) (Hobbs, 1968; Schmid and Casey, 1986; Schmid, 1994; Skrotzki, 1994). Which glide system will be active during dislocation glide depends on the critical resolved shear stress (CRSS). More than one glide system can be active, especially at large differential stresses. The CPO resulting from deformation by dislocation glide is dependent on deformation

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conditions, as temperature, water content, pressure, stress and strain rate (e.g., Lister and Hobbs, 1980; Hobbs, 1985; Schmid, 1994; Skrotzki, 1994; Passchier and Trouw, 2005; Hobbs and Ord, 2015; Law, 2014). During ongoing deformation, grains in specific crystallographic orientations may develop a systematically higher dislocation density than others, such that strain-induced grain-boundary migration (SIGBM) may lead to a preferred growth of those with the lower dislocation density (Jessell, 1987; Ree, 1990; Gleason and Tullis, 1993), influencing the evolution of a CPO. A CPO, however, may as well develop by dissolution-precipitation creep (Bons and den Brok, 2000) or preferred precipitation from a fluid, where the growth rate of quartz is dependent on crystallographic orientation (e.g., Shelley, 1979, 1989, 1994).

To be able to interpret a texture in the context of the deformation conditions and history, the deformation mechanisms as well as the recrystallization processes must be understood. From microstructural observations of deformed metamorphic rocks, it can be difficult to unravel the associated processes during recrystallization, owing to similar microstructures that can be formed by a sequence of different deformation and recrystallization stages. Experiments allow the investigation of microstructural evolution through a sequence of specific stages at different stress conditions. A sequence of high-stress deformation of quartz, followed by deformation at relaxing stresses was performed to simulate deformation during the seismic cycle just below the seismogenic zone in the continental lithosphere by Trepmann et al. (2007) and Trepmann and Stöckhert (2013). The deformation experiments were performed in a Griggs-type deformation apparatus at 400 °C and 2 GPa confining pressure. Maximum differential stresses reached 2–3 GPa during the experiments. The high-stress deformation stage was followed by a stage of creep at low stresses, 900 °C and 2.5 GPa confining pressure. Low-temperature plasticity (i.e., dislocation glide-controlled deformation commonly associated with microcracking due to strain-hardening) of quartz involved the formation of localized highly-damaged zones (Fig. 1) characterized by large dislocation densities and microcracks. During creep, two different stress histories were chosen: fast rates of relaxing differential stresses (to < 125 MPa) and slow rates of stress relaxation, where moderate differential stress were kept constant at about 250 MPa. These experiments revealed characteristically different recrystallization microfabrics: creep at low stress after low-temperature plasticity resulted in a random texture of new grains (Fig. 1a); When the subsequent creep-stage was performed at moderately high stresses, in contrast, a marked CPO and SPO developed (Fig. 1b; Trepmann et al., 2007; Trepmann and Stöckhert, 2013). Whereas the high-stress deformation stage was performed close to the conditions at the base of the seismogenic zone, the creep stage was performed at higher temperatures to accelerate thermally activated dislocation climb and strain-induced grain-boundary migration. Whether indeed the same processes are activated at isothermal conditions in nature can only be evaluated by a comparison to natural microstructures. For this comparison, we present quartz microfabrics analysed by polarized light microscopy, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) from two selected shear zones in the Eastern Alps: the Defereggen-Antholz-Vals (DAV) shear zone and the basal thrust of the Silvretta nappe (Fig. 2). We analysed the deformation mechanisms and formation of new grains recorded by characteristically different recrystallization microfabrics of the two shear zones to obtain information about their stress histories. Finally, we discuss geological implications of the different recorded stress histories.

2. Geological overview and sample selection

For this study, we chose the Silvretta basal thrust at the southwestern border of the Engadine window (Jamtal, Austria) and the DAV shear zone to the south of the western Tauern window (Southern Tyrol, Italy) in the Eastern Alps (Fig. 2), because: (1) The associated fault rocks were deformed at lower greenschist facies conditions (DAV: e.g., Kleinschrodt, 1987; Stöckhert et al., 1999; Silvretta: e.g., Koch and Masch, 1992). These conditions correspond to the base of the seismogenic zone in the continental lithosphere (e.g., Scholz, 2002) as well as to the so-called brittle-viscous transition of quartz, depending on the stress-loading rates (e.g., Voll, 1976; Hirth and Tullis, 1994; Hirth et al., 2001; Stöckhert et al., 1999). Just below the base of the seismogenic zone, systematically varying stresses during the seismic cycle can be expected to leave a marked imprint in the quartz microfabrics of the deformed rocks (Trepmann and Stöckhert, 2003, 2013; Trepmann et al., 2007). (2) Both, the thrust and the shear zone contain pseudotachylytes indicating seismic activity during their development (DAV: e.g. Mancktelow et al., 2001; Silvretta: e.g., Koch and Masch, 1992). (3) Given the generally different tectonic settings for the

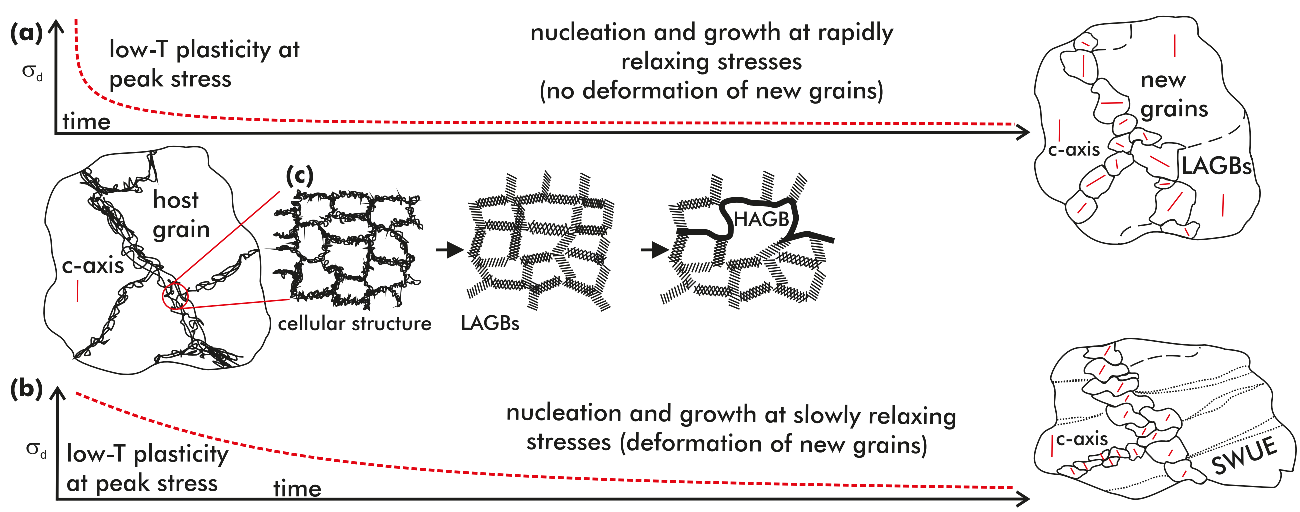

Fig. 1. Schematic sketch depicting formation of new grains from localized highly-damaged zones after low temperature plasticity at transient peak stresses during **(a)** fast stress relaxation, i.e. nucleation and growth at low stress (below 125 MPa), leading to isometric grains with no CPO, and **(b)** slow stress relaxation, i.e. nucleation growth at moderately high stresses (on the order of a few hundred MPa, see text for discussion) resulting in elongate new grains with SPO and CPO. **(c)** Possible mechanism of "nucleation" from a cellular structure characterized by zones of a high density of tangled dislocations, modified after Humphreys (2004, see text for discussion).