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Permeability control on transient slip weakening during gypsum dehydration: Implications for earthquakes in subduction zones

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ABSTRACT

A conflict has emerged from recent laboratory experiments regarding the question of whether or not dehydration reactions can promote unstable slip in subduction zones leading to earthquakes. Although reactions produce mechanical weakening due to pore-fluid pressure increase, this weakening has been associated with both stable and unstable slip. Here, new results monitoring strength, permeability, pore-fluid pressure, reaction progress and microstructural evolution during dehydration reactions are presented to identify the conditions necessary for mechanical instability. Triaxial experiments are conducted using gypsum and a direct shear sample assembly with constant normal stress that allows the measurement of permeability during sliding. Tests are conducted with temperature ramp from 70 to 150 °C and with different effective confining pressures (50, 100 and 150 MPa) and velocities (0.1 and 0.4 μm s^{-1}). Results show that gypsum dehydration to bassanite induces transient stable-slip weakening that is controlled by pore-fluid pressure and permeability evolution. At the onset of dehydration, the low permeability promoted by pore compaction induces pore-fluid pressure build-up and stable slip weakening. The increase of bassanite content during the reaction shows clear evidence of dehydration related with the development of R_1 Riedel shears and P foliation planes where bassanite is preferentially localized along these structures. The continued production of bassanite, which is stronger than gypsum, provides a supporting framework for newly formed pores, thus resulting in permeability increase, pore-fluid pressure drop and fault strength increase. After dehydration reaction, deformation is characterized by unstable slip on the fully dehydrated reaction product, controlled by the transition from velocity-strengthening to velocity-weakening behaviour of bassanite at temperature above ∼140 °C and the localization of deformation along narrow Y-shear planes. This study highlights the generic conditions required to trigger instabilities during dehydration reactions. It shows that pore-fluid pressure build-up during dehydration reactions associated with the localization of a velocity-weakening reacting or dehydrated phase along shear planes is necessary for earthquake triggering.

1. Introduction

The understanding of fault mechanics is of first order importance to unravel earthquake triggering. Among the parameters promoting fault reactivation and earthquake triggering, the influence of pore-fluid pressure and friction on stability of fault zones has been a focus of recent work based on geological, geophysical and experimental analyses. Many authors have dealt with mechanisms promoting fault reactivation such as the reduction of friction coefficient due to mineralogical and/or microstructural transformations (Collettini et al., 2009) or the increase of pore-fluid pressure in fault zones by fault compaction or devolatilization (Sleep and Blanpied, 1992; Ko et al., 1997; Wong et al., 1997; Leclère et al., 2015). Dehydration reactions combine these two mechanisms due to mineral phase changes and free-water release during reaction. The interest in how mechanical behaviour is affected by dehydration reactions is fuelled by the desire to understand and explain the strong correlation between the location of dehydration reactions along subduction zones and intermediate depth earthquakes (50 to 200 km) (Peacock, 2001; Hacker et al., 2003; Nakajima et al., 2009; Abers et al., 2013). However, key questions still remain, such as recent work that has highlighted a conflict surrounding whether or not dehydration reactions can promote instability in subduction zones where dehydration occurs (Proctor and Hirth, 2015).

Many studies conducted in the laboratory have focused on the modifications of hydro-mechanical properties during dehydration reactions. The concept of dehydration embrittlement was intro-

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duced by Raleigh and Paterson (1965) and was proposed as a mechanism to explain the triggering of earthquakes during dehydration reactions in subduction zones. A key issue is that, at the very high pressures in the intermediate depth range (50–200 km), pressure-sensitive brittle behaviour would be inhibited and brittle instability would be suppressed (Hilairet et al., 2007). Dehydration embrittlement can circumvent this problem by the build up of pore-fluid pressure during the release of free-water, reducing the effective stress and allowing brittle behaviour to occur (Raleigh and Paterson, 1965; Dobson et al., 2002; Jung et al., 2004). However, recent laboratory dehydration experiments have led to conflicting views on whether the brittle behaviour promoted by dehydration embrittlement can result in earthquake triggering. These studies can be broadly divided in two categories: (1) studies documenting brittle instability and stick–slip events during dehydration reactions (Shimamoto, 1986; Milsch and Scholz, 2005; Takahashi et al., 2011; Okazaki and Katayama, 2015) and (2) studies documenting stable slip during dehydration reactions (Chernak and Hirth, 2011; Proctor and Hirth, 2015).

Dehydration embrittlement has been observed from thin sections or recorded using acoustic emissions sensors during experiments (Raleigh and Paterson, 1965; Dobson et al., 2002; Jung et al., 2004; Burlini et al., 2009; Brantut et al., 2012). Dramatic stick–slip events have been also recorded during dehydration reactions using a saw cut geometry with serpentine and gypsum leading to the conclusion that dehydration reactions can trigger earthquakes (Shimamoto, 1986; Milsch and Scholz, 2005; Takahashi et al., 2011; Okazaki and Katayama, 2015). Takahashi et al. (2011) explained stick–slip events recorded during their triaxial experiments at constant pore pressure ($PP = 30$ MPa) and confining pressure ($PC = 100$ MPa) by the preferential localization of dehydrated products (*i.e.* olivine) along frictional shear planes. Conversely, Chernak and Hirth (2011) and Proctor and Hirth (2015), using a Griggs type-apparatus, recorded stable sliding during serpentine dehydration associated with distributed semi-brittle deformation at antigorite dehydration conditions. From the studies above it is clear that the understanding of strain localization during metamorphism and the conditions leading to unstable frictional sliding along localized zones is of primary importance (Proctor and Hirth, 2015).

This study is focused on the links between dehydration reactions, slip weakening and localization of deformation, as well as the question of slip instability, using gypsum as an analogue for dehydrating systems. A direct shear sample assembly allowing constant normal stress and control of the pore-fluid pressure is used during the experiments. This study goes beyond the work conducted by Proctor and Hirth (2015) who showed that slip weakening during serpentine dehydration is qualitatively controlled by how well drained the sample is. In the experiments presented here, the evolution of pore-fluid pressure and permeability, in addition to the shear stress, were measured continuously throughout the experiment until dehydration reaction reached completion. Our study shows that slip weakening is transient and is controlled by permeability and pore-fluid pressure evolution during dehydration reactions. Transient slip weakening is characterized by stable slip weakening followed by fault strength recovery and unstable, stick–slip behaviour on fully dehydrated material. Microstructural analyses conducted on deformed samples show clear evidence of dehydration reactions related to the development of R_1 Riedel shears and P foliation planes. A conceptual model is then proposed to explain transient slip weakening during gypsum dehydration incorporating the key role played by permeability. This model provides a framework to define the conditions required to trigger unstable events during dehydration reactions.

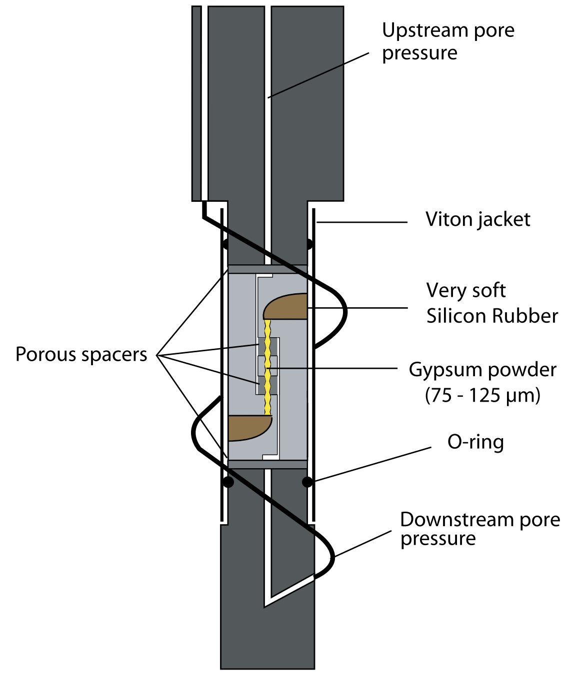

Fig. 1. Schematic diagram of the direct shear sample assembly used in this study.

2. Starting material and experimental setup

2.1. Experimental procedure

Volterra gypsum powder with a grain size ranging from 75 to 125 µm was sheared within a conventional triaxial apparatus using a direct shear sample assembly similar to that used by Verberne et al. (2013) (Fig. 1). Experiments were conducted at one of two controlled slip velocities of 0.1 or 0.4 $\mu m\,s^{-1}$ corresponding respectively to a strain rate of 0.3×10^{-5} s^{-1} and 1.3×10^{-5} s^{-1}, and with a constant temperature ramp of respectively 0.125 and 0.5 $°C\,min^{-1}$ between 70 and 150 °C. The ratio between strain rate and heating rate was kept constant in all experiments and is comparable to those observed in subduction zones (Chernak and Hirth, 2011). Temperature ramps were applied after 1 mm of displacement after the yield point was reached. During the first millimetre of displacement, temperature is kept constant at 70 °C, below the start of dehydration, and the velocity is kept at 0.4 $\mu m\,s^{-1}$ before applying the temperature ramp and changing velocity for experiments conducted at 0.1 $\mu m\,s^{-1}$. The influence of slip velocity (V) and effective confining pressure (PC_{eff}) are analysed for 6 experiments by modifying PC_{eff} (50, 100 and 150 MPa) and V (0.1 and 0.4 $\mu m\,s^{-1}$) (see Table 1). Then, another 4 experiments with conditions equivalent to those of DS20 were run, but halted at different displacements so that microstructural evolution could be determined. Experiments were conducted under semi-undrained conditions where the pore-fluid pressure is only controlled on one side of the sample with a mean pore pressure of 2 MPa. The other side of the shearing layer is connected to a fixed volume reservoir where the pressure is monitored in order to allow permeability measurements. The experimental procedure involves first increasing the confining pressure and then the pore-fluid pressure in order to prevent oil penetrating the pore-fluid system, while ensuring the effective pressure never exceeded the starting conditions. Temperature was then increased up to 70 °C and when pore-fluid pressure was equilibrated, the temperature ramp and constant displacement were applied.