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Rheology of talc sheared at high pressure and temperature: a case study for hot subduction zones

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ABSTRACT

Talc is a common fault-coating mineral occurring in a variety of tectonic settings from the immediate subsurface down to more than 100 km depth along subducting plate interfaces. It is considered to stabilize slip at seismogenic depth. To gain insight into the rheological behavior of talc and related deformation processes along the subduction interface of hot oceanic slabs, we conducted torsion experiments on intact synthetic talc samples at 200–600 °C under 100–300 MPa confining pressure at intermediate strain rates (3×10^{-4} and 2.45×10^{-3} s^{-1}) for bulk shear strains up to 12.6.We also conducted stepping strain rate experiments to investigate rate and temperature dependence on sliding velocity and slide–hold–slide experiments to explore the re-strengthening and frictional healing of the sliding zones. The experimental results reveal 1) post-yield strain hardening followed by brief weakening episodes and then again strain hardening with increasing deformation and 2) a gradual transition of friction evolution from velocity-strengthening to velocity-neutral. Microstructural observations coupled with mechanical data suggest that talc rheology combines localized and distributed deformation, in a state called the brittle–ductile transition, with a predominance of crystal-plastic over cataclastic (brittle to semi-brittle) processes at 600 °C and 300 MPa confining pressure. These data suggest that talc cannot accumulate the tectonic stress necessary for earthquake-generating rupture along the subduction interface. This result concurs with the concept that in weak heterogeneous talc-rich material, strong asperities that can resist the tectonic stress to a greater extent are responsible for the consequential earthquake occurrence.

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1. Introduction

Talc is a product of long-term hydrothermal alteration of mafic and ultramafic rocks of the oceanic lithosphere by Si-saturated seawater circulation (Boschi et al., 2006; Escartin et al., 2003). This mineral is primarily found in the upper oceanic crust of slow-spreading ridges (e.g., the mid-Atlantic ridge). Tectono-stratigraphic maps of the seafloor show that the oceanic lithosphere of the West Pacific is fast-spreading (Lallemand and Funiciello, 2009). In this situation, the formation of a continuous layer of talc in the upper oceanic crust of the Cascadia subduction zone or the southern Chile subduction zone appears to be unlikely due to the lack of ultramafic components. However, oceanic crusts exhibit transform faults, extensive fracture networks and active faults along both slow- and fast-spreading ridges (Faccenda et al., 2008; Lallemand and Funiciello, 2009). As for subduction zones, a wide range of geophysical and geological data shows the occurrence of trenchward-dipping faults and seaward-dipping faults (e.g., Ranero et al., 2003). These faults provide pathways for seawater into the crust and the mantle (Ranero et al., 2005), hence for hydrothermal alteration of peridotites leading eventually to the crystallization of talc (Mével and Stamoudi, 1996). Moreover, talc occurrence is not limited to peridotites. Between 400 °C and 700 °C, the hydrothermal alteration product of orthopyroxene is talc. The chemical reaction is controlled by the low amount of magnesium available from olivine degradation over 350 °C (Manning, 1995; Martin and Fyfe, 1970). These data demonstrate that talc has a widespread occurrence from the seafloor surface to more than 100 km depth, where it remains one of the last minerals containing structural water (Chollet et al., 2009; Pawley, 1998). Its occurrence along the Cascadia or the southern Chile slip-partitioning zones at 8–15 km depth can be considered either as an inheritance from spreading ridges or having formed during subduction.

The frictional strength of talc has been reported to be extremely low (i.e., $\mu < 0.35$), independent of the experimental setting (i.e., biaxial or triaxial deformation), applied confining pressures, temperatures, shear velocities and water conditions (Boutareaud et al., 2012; Edmond and Paterson, 1971a, 1971b; Escartin et al., 2008; Moore and Lockner, 2004, 2007, 2008; Morrow et al., 2000; Summer and Byerlee, 1977). Based on these laboratory measurements and the petrological stability field of talc (Melekhova et al., 2006; Pawley, 1998; Ulmer and Trommsdorf, 1999; Wunder and Schreyer, 1997), it has been stated that talc facilitates stable (i.e. aseismic) frictional sliding of

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oceanic detachments under low resolved shear stress (Boschi et al., 2006; Escartin et al., 2003; Floyd et al., 2001), continental detachments (Collettini et al., 2009a), as well as continental strike-slip faults (Moore and Rymer, 2007). It has also been proposed that talc limits the depth of subduction-thrust earthquakes (Peacock and Hyndman, 1999), and that its participation in dehydration embrittlement causes the deepest level of the double seismic zone (Chollet et al., 2009). However, the mechanical effect of talc on the degree of plate coupling (i.e. potential for nucleation of seismogenic rupture) from the slip-partitioning zone (the transition zone between aseismic and locked zones) to the down-dip seismogenic zone (schematic cross section in Park et al., 2002) remains poorly investigated. In addition, efficiency of post-earthquake displacement transfer from the seismogenic zone to the near surface remains a matter of debate (Faulkner et al., 2011; Lallemand and Funiciello, 2009). It is important to note that, existing studies, mentioned above, are mostly conducted in biaxial and/or triaxial experimental settings. The data obtained from these experiments represent the coaxial nature of deformation and are limited to low magnitude of deformation, whereas talc and talc rich rocks experience a greater magnitude of non-coaxial shear strain in the natural setting. The rheology and frictional properties of talc will be better understood if rheological data is obtained from larger strain shear experiments and the data is explained in conjunction with the evolution of microstructures in response to the deformation.

In this paper talc rheology along slip-partitioning zones in hot subducting slabs is modeled using deformation experiments of talc in torsion at variable strain rates, temperatures and confining pressures. Experiments were conducted to investigate rate and temperature dependence on sliding velocity and the re-strengthening and frictional healing of the sliding zones. The experimental data coupled with microstructural observations suggest that deformation is accommodated by semi-brittle mechanisms with crystal-plastic processes predominating cataclastic processes. The friction evolution of talc aggregate from velocity-strengthening to velocity-neutral has implications for earthquake occurrence along the subduction interface of hot subducting oceanic slabs.

2. Experimental methods and sample preparation

2.1. Sample preparation and characterization

Solid polycrystalline talc samples were prepared from an initial quasi-pure (99.99 wt.%) natural talc powder with grain size ranging from 1 to 100 μm (mean = 25 μm) acquired from VWR Corporation (https://www.vwrsp.com). Pyroxene is the main accessory mineral. The powder was uniaxially cold-pressed (UCP) at 115 MPa in a steel canister, and then hot isostatically pressed (HIP) at 160 MPa and 590 °C for 24 h (e.g., Misra et al., 2009b). The resulting polycrystalline samples were drilled, keeping the drill axis parallel to the UCP direction, as 3–7 mm long and 10 ± 0.2 mm diameter cores for deformation experiments. The microstructure of the synthetic talc aggregate observed in back scattered electron mode in an SEM revealed a crude planer fabric developed perpendicular to the UCP direction (Fig. 1a, b). The planer fabric is defined by the preferred orientation of the basal planes (001) of flaky talc grains. XRD analysis did not reveal any mineral reaction or phase changes in these samples. Helium gas pycnometer measurements showed that the sample has residual connected porosity 0.37 ± 0.22 vol.% and the average density $2.731 \pm 0.005\ \text{g}\cdot\text{cm}^{-3}$. Karl-Fischer-titration (KFT) conducted on initial and post-static run samples P1423 (4 h at 300 MPa and 600 °C) indicated similar structural water content (4.063 ± 0.009 wt.%) for non-drained experimental conditions. Escartin et al. (2008) indicated release of structural water from talc mineral at 750 °C and 300 MPa confining pressure with formation of enstatite as the reaction product. Our preparation procedure did not reach that reaction condition.

2.2. Deformation apparatus, experimental methods and observation

Experiments have been conducted in a Paterson type deformation instrument characterized by an internally heated argon-medium pressure vessel and equipped with a torsion actuator for non-coaxial sample deformation (Paterson and Olgaard, 2000). A set of alumina and partially stabilized zirconia (PSZ) pistons was placed at each sample extremity to transfer the torque from the top anvil connected to a motor. A 2 mm wide cylindrical hole along the top piston axis allowed the insertion of a K-type thermocouple to measure the temperature close to (3 mm) the sample (Fig. 1c, d). A 0.25 mm thick annealed Cu tube jacketed the assembly and isolated the sample from the confining argon. Applied confining pressure is controlled to +/− 1.0 MPa. The internal force (to directly measure normal force perpendicular to the sample cylinder axis) and axial position (to monitor axial displacements) of the sample were monitored and recorded during experiments (Fig. 1c). Initial values of these two parameters are set to zero at the beginning of each experiment. Any axial compaction of the sample (labeled *1* in Fig. 1c) induces an increase in axial position (labeled *2* in Fig. 1c), leading to a decrease of the internal force (labeled *3*). It is important to note that the confining pressure configuration in Paterson apparatus is maintained by an axial compensating piston and is independent of the change in axial position and/or internal force.

During experiments, the torque (Γ) was measured in Nm with different pairs of LVDTs (Linear Variable Differential Transformer) placed in the internal load cell (resolution 0.1 Nm; Fig. 1c). An RVDT (Rotary Variable Differential Transformer) was placed at the top of the torsion gear box, which was mechanically connected to the top specimen anvil to measure the angular displacement (θ) in radians for an applied constant angular displacement rate ($\dot{\theta}$ in radians/s). For a given length (l) and radius (r) of the sample, θ with shear strain (γ and $\dot{\theta}$ with shear strain rate ($\dot{\gamma}$) are related to each other by the equations $\theta = \frac{l}{r}\gamma$ and $\dot{\theta} = \frac{l}{r}\dot{\gamma}$, respectively. The measured torque (Γ) was converted to shear stress (τ) using the equation

$$\tau = \frac{\left(3 + \frac{1}{n}\right)\Gamma}{2\pi r^3}$$

where, n is the stress exponent (Paterson and Olgaard, 2000). The radius (r) of the samples and n, corresponding to each experiment at different pressure temperature conditions, are reported in Table 1. The apparent friction coefficient (μ) is calculated as the ratio of shear stress (τ, derived from the measured torque) to normal stress (σ_n, assumed to be equal to the applied confining pressure) i.e., $\mu = \frac{\tau}{\sigma_n}$. This definition is based on the experimental setting of Paterson apparatus which maintains a vertical force equal to the confining pressure by a compensation piston in the load cell assembly (Paterson and Olgaard, 2000). As per the mechanics of torsion, all the rheological and frictional data presented in this work express the mechanical behavior of the outer surface of the cylindrical samples.

We have conducted four series of experiments — Series-1) experiments at constant shear strain rates; Series-2) experiments at variable confining pressure, temperature and strain rate; Series-3) Stepping strain rate (SSR) experiments and Series-4) slide hold slide experiments. All the experiments, experimental conditions and relevant experimental data are listed in Table 1.

The first series (Series-1) of deformation experiments (constant shear strain rate experiments) was conducted at $\dot{\gamma} = 3 \times 10^{-4}$or $2.45 \times 10^{-3}\ \text{s}^{-1}$,reaching bulk shear strains (γ) of up to 6.6. The aims were to relate the mechanical behavior of talc to fabric development and to check the justification for using a torsion apparatus to investigate the dependence of talc's frictional strength on strain rate, pressure and temperature. The second series (Series-2, pressure, temperature and strain rate effect) consisted of varying either the confining pressure (P_c), or the temperature (T) or the strain rate ($\dot{\gamma}$), while keeping the

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