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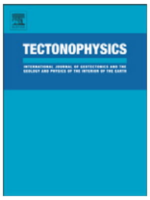

Influence of subduction zone conditions and gouge composition on frictional slip stability of megathrust faults

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ABSTRACT

To understand the temperature/depth distribution of destructive earthquakes in subduction megathrusts, and the mechanisms of nucleation of these events, data on the frictional behaviour of phyllosilicate/quartz-rich megathrust fault gouges under in-situ conditions are needed. We performed rotary shear friction experiments at effective normal stresses of 25–200 MPa, pore fluid pressures of 50–200 MPa, at 140–600 °C and sliding velocities of 1–100 μm/s, using gouge mixtures with an illite:quartz ratio between 65:35 and zero. Experiments on 65:35 mixtures, deformed at an effective normal stress (σ_n^{eff}) of 170 MPa, a pore fluid pressure (P_f) of 100 MPa and 150–500 °C provided a reference dataset. This showed three temperature-dependent slip stability regimes with potentially unstable, velocity-weakening behaviour at 250–400 °C and velocity-strengthening at lower and higher temperatures. The velocity-weakening regime was found to shift towards higher temperatures with decreasing σ_n^{eff}, being located at ~350–600 °C at 50 MPa. Increasing quartz content and decreasing sliding velocity also displaced the velocity-weakening regime towards lower temperatures. Increasing P_f increased $(a–b)$ at all temperatures, narrowing the temperature extent of the velocity-weakening regime. We explain our results qualitatively in terms of a microphysical model in which changes in friction coefficient and $(a–b)$ with velocity and temperature are brought about by changes in the relative importance of deformation of the clast phase, by thermally activated stress corrosion cracking and pressure solution, versus athermal granular flow of the mixture accompanied by dilatation. Our results imply that the depth extent of the seismogenic zone on subduction megathrusts depends not only on temperature and that to predict its location, it is essential to have well-constrained depth profiles for pore fluid pressure and effective normal stress.

1. Introduction

It is widely believed that the depth range of the seismogenic portion of subduction megathrusts is thermally controlled, with the up- and down-dip limits being located at ~150 and ~350 °C, respectively (Hyndman et al., 1997). This view is based on focal depth distribution data (cf. Oleskevich et al., 1999; Tichelaar and Ruff, 1993), on experiments showing dehydration of smectite-rich sediments to form illite-rich rock at around 150 °C (Hower et al., 1976; Jennings and Thompson, 1986), and on experiments showing a transition from unstable to stable sliding in simulated granitic fault gouge at ~350 °C (Blanpied et al., 1991, 1995, 1998). However, the seismogenic zone does not coincide with the temperature range of 150–350 °C in all subduction zones (e.g. McCaffrey et al., 2008). Moreover, illite gouge does not seem to be capable of supporting unstable slip, at least in experiments at room temperature (e.g. Saffer and Marone, 2003), and granitic gouge is unlikely to be representative for the behaviour of the metapelitic fault rocks believed to be present in many subduction megathrusts (e.g. Underwood, 2007). The basis for our understanding of the extent of the seismogenic zone is therefore open to question.

To understand the depth/temperature range of destructive earthquakes in subduction zones, and the mechanisms of nucleation of these events, data are needed on the frictional behaviour of realistic, metapelitic (i.e. phyllosilicate/quartz-rich) megathrust fault gouges under in-situ pressure, temperature and velocity conditions. However, only a few experimental studies have been performed using appropriate materials and conditions. Recently, Den Hartog et al. (2012a) presented the results of ring shear experiments performed on simulated illite–quartz fault gouge at pressure conditions corresponding to ~10 km depth on a subduction megathrust (effective normal stress of 170 MPa, pore fluid pressure of 100 MPa), at sliding velocities of 1–100 μm/s and covering temperatures in the range 150–500 °C. These confirmed the importance of temperature in controlling subduction zone seismogenesis, showing a switch from predominantly stable ("velocity-strengthening") sliding behaviour to potentially unstable ("velocity-weakening") behaviour at ~255 °C, as well as a reverse transition at ~370 °C (Fig. 1). At the same time, however, the temperature of these transitions was observed to depend on sliding velocity, being displaced towards lower temperatures with decreasing velocity. In-situ nucleation velocities are believed

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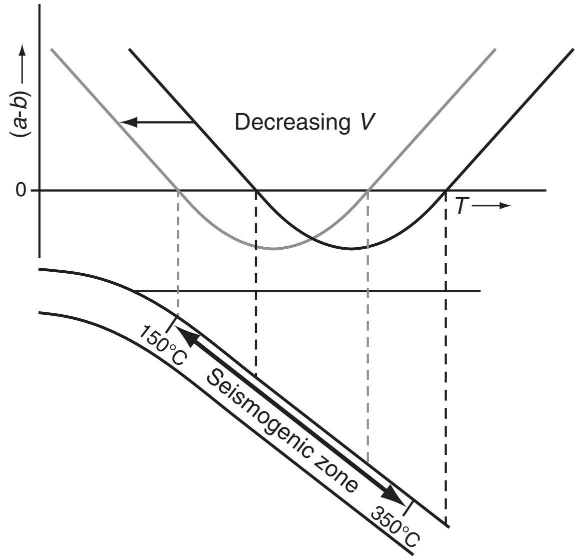

Fig. 1. Schematic figure of the rate and state friction parameter $(a-b)$ versus temperature curve reported by Den Hartog et al. (2012a) in experiments on illite-rich fault gouge, showing three slip stability regimes as a function of temperature and the experimentally observed effect of decreasing the slip velocity. The experiments were performed at an effective normal stress of 170 MPa, a pore fluid pressure of 100 MPa and slip velocities of 1–100 μm/s. A positive $(a-b)$ value indicates inherently stable velocity-strengthening slip behaviour, whereas a negative $(a-b)$ value indicates velocity-weakening behaviour, which is potentially unstable. The schematic cross section of the subduction zone shows the discrepancy between the temperature-range of velocity-weakening found in the experiments (black curve) versus the generally accepted temperature-range of the seismogenic zone on subduction zone megathrusts. Den Hartog et al. (2012a) proposed that extrapolating the $(a-b)$ data to in-situ velocities would move the velocity-weakening region into correspondence with the seismogenic zone.

to be close to plate velocities of ~10^{-9} m/s (e.g. Segall and Rice, 2006). On this basis, it was proposed that the observed velocity effect might explain the discrepancy between the onset of velocity-weakening behaviour observed at 255 °C and the temperature of 150 °C typically associated with the up-dip seismogenic limit (Fig. 1).

The role of temperature in determining the occurrence of velocity-strengthening versus velocity-weakening slip has also been observed in experiments on other materials besides illite-rich gouge. Specifically, wet quartz (Chester and Higgs, 1992; cf. Kanagawa et al., 2000; cf. Niemeijer et al., 2008), granite (Blanpied et al., 1991, 1995, 1998), gabbro (He et al., 2007) and San Andreas Fault (SAF; Tembe et al., 2009) gouges all show three frictional “slip stability” regimes. These are characterized by velocity-weakening behaviour at respectively 300 °C, 100–350 °C, 170–310 °C and 266–283 °C, with velocity-strengthening occurring at lower and higher temperatures. The broad similarity of these temperature ranges with each other, and with that observed for velocity-weakening in illite-rich fault gouge is surprising, not only because of the differences in materials studied, but also because significantly different sliding velocities, effective normal stresses and pore fluid pressures were often used.

These considerations raise the question of to what extent the three-regime behaviour displayed by illite-rich megathrust fault gouge depends on variables such as sliding velocity, composition, effective normal stress and pore fluid pressure. Understanding the effects of these variables on velocity-strengthening versus velocity-weakening behaviour may be crucial for modelling seismogenesis on subduction zone megathrusts and for establishing better constraints on the temperature/depth range of the seismogenic zone. In this paper, we report experiments designed to systematically evaluate the impact of these factors on the frictional strength and slip stability of illite–quartz fault gouge. We add new friction experiments to our previous dataset to cover effective normal stresses in the range 25–200 MPa, pore fluid pressures ranging from 50 to 200 MPa and temperatures in the range 140–600 °C. In addition, we examine the effect of composition by varying the quartz content of the gouge from ~35 to 100%. The lowest temperature investigated was chosen to match our best estimate of the temperature at the source region of the Tohoku-Oki earthquake (140 ± 11 °C), derived using a source depth of 24 km (Japan Meteorological Agency, JMA) and the temperature versus depth profile given by Peacock and Wang (1999). The range of quartz contents investigated was intended to allow for variability in subducted sediment input, including sands (Kitamura and Kimura, 2012; Underwood, 2007), and cherts as in the Tohoku region (Kameda et al., 2012). We show that all variables investigated affect the temperature range at which velocity-weakening behaviour occurs in metapelitic subduction zone gouges, and we consider the implications for the temperature/depth range of the seismogenic zone.

2. Material and methods

2.1. Sample material

The reference material used in this study, and in our previous work (Den Hartog et al., 2012a), consisted of crushed illite-rich Rochester Shale (Folk, 1962), sieved to obtain a grain size below 106 μm (Ikari et al., 2009). Saffer and Marone (2003) reported the same material to contain 59% illite, 23% quartz, 9% kaolinite/dickite and 4% plagioclase. Our own X-ray diffraction (XRD) analysis showed similar results, but with minor chlorite instead of plagioclase and kaolinite/dickite. Varying the illite:quartz content of this material was achieved by adding SIL-CO-SIL 49, obtained from US Silica, to the crushed Rochester Shale. This material has a median grain size of ~11 μm. Ring shaped samples were made by pre-pressing mixtures of ~0.5 g gouge and ~0.04 g distilled water at ~170 MPa for ~20 min in a hydraulic press (see Den Hartog et al., 2012b).

2.2. Experimental apparatus and procedure

Frictional sliding experiments were performed using the hydrothermal ring shear machine (Fig. 2) described by Den Hartog et al. (2012a,b) and Niemeijer et al. (2008). In this machine, a ~1 mm thick, ring-shaped sample is sandwiched between two roughened René 41 Superalloy pistons, and kept in place by inner and outer confining rings of the same material, coated with a graphite powder suspension (Fig. 2c). The sample-piston assembly is located inside an internally heated, 300 MPa pressure vessel, filled with distilled water which forms the pore fluid (Fig. 2a and b). Normal stress is applied via a pressure-compensated upper loading piston (Fig. 2b) and controlled using a 100 kN servo-controlled Instron loading frame. A servo-controlled motor-gearbox system rotates the vessel and lower piston at sliding velocities ranging from ~10 nm/s to ~300 μm/s relative to the non-rotating upper piston, generating rotary shear deformation of the sample. The resulting shear stress and torque are measured externally via the stationary upper piston set.

Note that the use of the pressure-compensated upper loading piston means that normal stress is applied to the sample in excess of the fluid pressure (P_f) measured in the vessel, so that the effective normal stress (σ_n^{eff}) experienced by the sample is equal to the axially applied stress, assuming that the small sample is penetrated by the fluid at pore fluid pressure P_f (Den Hartog et al., 2012a). This implies that the effective normal stress is not affected by changes in the pore fluid pressure. Also note that two experiments were performed in the absence of a (pressurized) pore fluid, but under a vacuum, generated using a vacuum pump with a capacity better than 1 mbar.

The experimental procedure followed is described by Den Hartog et al. (2012b). The experiments were performed under the conditions shown in Table 1, grouped into datasets that each addresses the effect of one specific variable. All experiments performed were velocity stepping tests, employing slip velocities of 1, 10 and 100 μm/s, imposed after initial sliding at 10 μm/s for a displacement of ~5 mm. To enable