



Friction properties and deformation mechanisms of halite(-mica) gouges from low to high sliding velocities



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ABSTRACT

The evolution of friction as a function of slip rate is important in understanding earthquake nucleation and propagation. Many laboratory experiments investigating friction of fault rocks are either conducted in the low velocity regime (10^{-8} – 10^{-4} ms^{-1}) or in the high velocity regime (0.01 – 1 ms^{-1}). Here, we report on the evolution of friction and corresponding operating deformation mechanisms in analog gouges deformed from low to high slip rates, bridging the gap between these low and high velocity regimes. We used halite and halite-muscovite gouges to simulate processes, governing friction, active in upper crustal quartzitic fault rocks, at conditions accessible in the laboratory. The gouges were deformed over a 7 orders of magnitude range of slip rate (10^{-7} – 1 ms^{-1}) using a low-to-high velocity rotary shear apparatus, using a normal stress of 5 MPa and room-dry humidity. Microstructural analysis was conducted to study the deformation mechanisms. Four frictional regimes as a function of slip rate could be recognized from the mechanical data, showing a transitional regime and stable sliding (10^{-7} – 10^{-6} ms^{-1}), unstable sliding and weakening (10^{-6} – 10^{-3} ms^{-1}), hardening (10^{-2} – 10^{-1} ms^{-1}) and strong weakening (10^{-1} – 1 ms^{-1}). Each of the four regimes can be associated with a distinct microstructure, reflecting a transition from mainly brittle deformation accompanied by pressure solution healing to temperature activated deformation mechanisms. Additionally, the frictional response of a sliding gouge to a sudden acceleration of slip rate to seismic velocities was investigated. These showed an initial strengthening, the amount of which depended on the friction level at which the step was made, followed by strong slip weakening.

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1. Introduction

Variations in fault friction are key in understanding and modeling of the seismic cycle. Friction on a sliding surface or within a gouge can be described by the empirical laboratory-derived rate-and-state friction laws (Dieterich, 1979; Ruina, 1983). Frictional strength may increase with increasing velocity ($a - b > 0$, stable

sliding), or decrease with increasing velocity ($a - b < 0$), which is a requirement for an earthquake instability to develop (Ruina, 1983). Implementation of these rate-and-state friction models in (quasi-) dynamic fault modeling of crustal-scale faults has reproduced many phenomena observed in the seismic cycle, such as preseismic slip, the nucleation and propagation of instabilities, coseismic, interseismic fault healing and seismic transients (e.g. Lapusta et al., 2000; Ben-Zion and Rice, 1997). Including an ($a - b$) value which varies with velocity in sign (e.g. Shibasaki and Shimamoto, 2007; Hawthorne and Rubin, 2013) can have large effects on the rupture characteristics. For our understanding of the mechanisms of seismicity, it is thus important to investigate how friction and its velocity dependence, ($a - b$), evolve over the entire range of slip rates relevant to the seismic cycle, and to understand the controlling processes to allow for more reliable extrapolation of laboratory data to nature.

Laboratory experiments at slow slip velocities (< 100 μms^{-1}) and mostly small displacements (10^{-3} – 10^{-2} ms^{-1}) formed the

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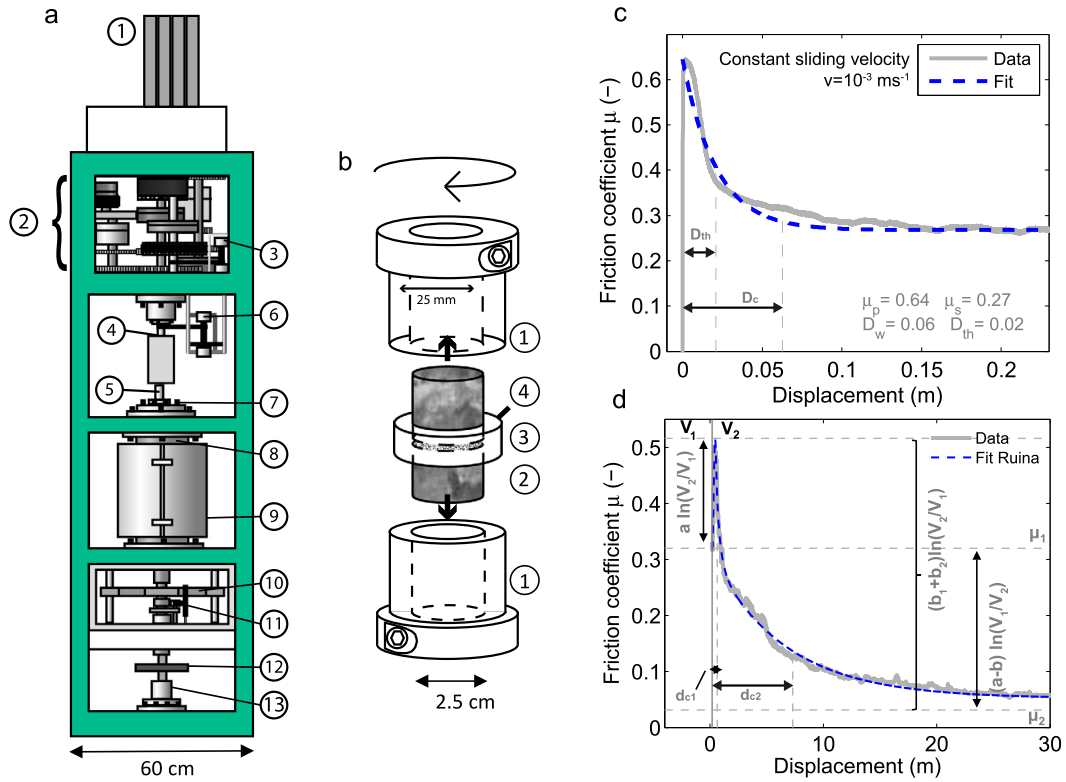


Fig. 1. Deformation apparatus, sample assembly and data fits used in this study. a) Schematic drawing of the low-to-high velocity rotary shear apparatus. 1) servo-motor, 2) gear and belt systems that drives the rotary column, 3) rotary encoder, 4) rotary shaft, 5) stationary column, 6) rotary potentiometer, 7) spherical plate for alignment of stationary column, 8) pressure vessel, 9) external furnace, 10) torque gauge, 11) LVDT, 12) axial force gauge and 13) hydraulic jack (buffered by gas pressure) for applying the normal load via the stationary shaft. The place where the sample assembly (b) is located in the machine is indicated by the rectangular area between 4 and 5. b) Sample assembly with 1) shaft lock system to grip the gabbro pistons and connect to the stationary and rotary shaft, 2) gabbro piston, 3) Teflon sleeve, 4) gouge layer. c) Exponential fit of representative experimental data using Equation (1), with μ_p : peak friction coefficient, μ_s : steady state friction coefficient, D_w : slip weakening distance, D_{th} : thermal weakening distance. d) Fit of a representative velocity stepping experiment with a two-state-variable rate-and-state friction law (Equations (2) and (4)), with V_1 : initial sliding velocity (here 10^{-3} ms^{-1}), V_2 : sliding velocity after the step change (here 1 ms^{-1}), a, b ($= b_1 + b_2$): rate-and-state parameters, d_{c1}, d_{c2} : critical slip distances, μ_1 : steady state friction coefficient at V_1 , μ_2 : steady state friction coefficient at V_2 .

basis of the rate-and-state friction model mentioned above. Fault rocks have been deformed under a wide range of conditions (e.g. varying normal stress, temperature, fluid content, grain size, wall-rock roughness) at these velocities (e.g. Marone, 1998). The frictional changes observed in these experiments due to imposed slip or velocity changes are mostly small. On the other hand, high-velocity ($0.1\text{--}1 \text{ ms}^{-1}$) rotary shear experiments with up to 10's of meters of displacement revealed extreme weakening of more than 90% of the friction for various rock types (Tsutsumi and Shimamoto, 1997; Di Toro et al., 2011). Data on friction at intermediate velocities are scarce, although recently a number of studies collected frictional data covering velocities from $100 \mu\text{s}^{-1}$ to 0.1 ms^{-1} (Ferri et al., 2011; Reches and Lockner, 2010; Di Toro et al., 2011; Liao et al., 2014). Here we deformed fault gouges in a rotary shear apparatus at constant velocities ranging from 10^{-7} ms^{-1} to 1 ms^{-1} . Also, we investigate the frictional response to a sudden acceleration (e.g. simulating an advancing rupture front with a short rise time on a fault sliding at slower slip rates) by stepping up the velocity two to three orders of magnitude to velocities of 0.1 to 1 ms^{-1} . We checked whether the frictional response could be modeled with rate-and-state friction theory, as is conventional for slower slip rate stepping experiments.

In the high-velocity apparatus, a (gouge) material cannot be deformed at the in-situ P–T conditions acting on upper crustal faults, due to limitations in normal stress and temperature that can be applied. Hence, the appropriate deformation processes controlling deformation at the in-situ conditions may not be activated. To study a material deforming via processes active in the upper crust, but at conditions accessible in the apparatus, we used halite and

halite–muscovite gouges as a material analog to (phyllosilicate-containing) quartzitic fault rock, following Niemeijer and Spiers (2006). Earlier experiments have shown that these gouges produce microstructures which resemble those found in nature, both at low (Bos et al., 2000a; Niemeijer and Spiers, 2005; Niemeijer et al., 2010; Shimamoto, 1985; Hiraga and Shimamoto, 1987; Chester and Logan, 1990) and high velocities (Kim et al., 2010). Here, we deformed both halite and halite–muscovite gouge at velocities from 10^{-7} ms^{-1} to 1 ms^{-1} , at a normal stress of 5 MPa, and study both the mechanical data and the resulting microstructures to identify the processes controlling the deformation.

2. Experimental procedure methods

2.1. Sample material

In each experiment 1 g of analytical grade halite or mixed halite–muscovite (80:20) was used. The halite was sieved to achieve a halite grain size of $<106 \mu\text{m}$, and the muscovite (mined in Aspang, Austria, Internatio B. V.) had a median grain size of $13 \mu\text{m}$.

2.2. Deformation apparatus, sample assembly and experimental procedure

We performed friction experiments in the low-to-high velocity rotary shear apparatus at Hiroshima University (Togo and Shimamoto, 2012 for detailed machine specifications) (Fig. 1a). The gouge was sandwiched between two solid gabbro cylinders

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