Frictional melting of gabbro under extreme experimental conditions of normal stress, acceleration and sliding velocity

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Abstract

Understanding the physics of earthquake slip helps to improve seismic hazard predictions. The occurrence of quenched frictional melts along exhumed fault zones (pseudotachylytes) provides unequivocal evidence of ancient seismic slip along these faults [Sibson, 1975]. In order to better understand the evolution of friction (the ratio of shear stress over normal stress) during melt-generating slip events and with the advent of high velocity shear apparatuses, several experimental studies have been done in recent years. However, these studies were conducted at relatively low normal stress (< 20 MPa) and/or using solid cylindrical samples (usually < 25 mm in diameter) where there is a large gradient in slip velocity across the sliding surface. Here we present results from an experimental study on gabbroic rocks using a newly developed Slow to HIgh Velocity shear Apparatus (SHIVA, installed at INGV, Rome), capable of obtaining higher normal stress (up to 50 MPa), allowing precise control on the imposed slip velocity and using rings of 30/50 mm inner/outer diameter rather than solid cylinders. In this manner, we are able to systematically vary normal stress, acceleration and deceleration and slip velocity.

Each experiment consists at least of three steps: (1) loading of the sample to the target normal stress; (2) acceleration to the imposed slip rate; (3) deceleration at the prescribed displacement to end the experiment. Typical results for the evolution of friction and shortening as well as the slip velocity function applied are reported in Figure 1. As observed in previous experiments performed at lower normal stresses [Hirose and Shimamoto, 2005; Tsutsumi and Shimamoto, 1997], friction has a quasi-instantaneous (less than 10 ms in this example) sharp initial peak at (a), followed by short-duration (< 20 ms) weakening curving over into strengthening at (b) until another maximum in friction is reached at (c), after which friction drops dramatically in an exponential fashion reaching a steady-state value after roughly 500 ms at (d). At the end of the experiment, when velocity is reduced at (e), friction increases reaching a final maximum when the velocity approaches zero at (f). Observations with a high speed camera (recording at rates of 1 to 5 kHz) sensitive to infrared light shows bright spots along the sliding surface from (b) to (c) and a through-going bright layer from point (c) onwards. At the end of the experiment, we observe that the sample pairs are welded together by a quenched melt layer.

The results show that steady-state shear stress during the melt-lubricated phase depends on normal stress in the form of an equation with a power of 0.25, in agreement with theoretical models for melt lubrication [Nielsen et al., 2008]. Moreover, the maximum shear stress in the presence of a through-going layer of melt (point c) varies with normal stress following a very similar trend as the steady-state values (Figure 2). Also, the displacement at which this maximum occurs (point c) decreases systematically with increasing normal stress. Taken together, these observations imply that crustal faults under high normal stress are more likely to generate melt-lubricated seismic slip events than faults under low normal stress, since the maximum stress that needs to be overcome (point c) to result in slip weakening will be relatively lower and the slip needed to reach this point will be shorter [Fialko and Khazan, 2005].

Furthermore, we observe no systematic dependence of steady-state shear stress on acceleration, but find a decrease in final shear stress with increasing deceleration (Figure 3). This might have profound implications in the velocity functions applied in seismic source models since too
slow deceleration could result in a negative static stress drop. Additionally, we find that the slip weakening or break down distance (\(d_w\)) decreases inversely with increasing normal stress, also in agreement with theoretical considerations [Figure 4, Nielsen et al., in press]. Estimates of coseismic shear stress from measurements of the thickness and offset of pseudotachylytes-bearing faults (Outer Hebrides Thrust) indicate a slip weakening distance between 0.15 – 0.4 m [Di Toro et al., 2006]. Since these rocks were exhumed from 4-10 km depth [Sibson, 1975], we use our experimentally determined relation between \(d_w\) and normal stress and slip velocity and calculate a possible slip velocity during the seismic events that produced the OHT pseudotachylytes between 0.3 and 1 m/s (Figure 5), which seems a reasonable estimate.

**Figure 1:** Evolution of friction coefficient and sample length during a typical experiment (s049) at 20 MPa normal stress. Also shown is the slip velocity function applied.

**Figure 2:** Shear stress as a function of normal stress applied for the maximum when melt forms a through-going layer at point (c) in Figure 1 (\(\tau_{melt}\)) and for the steady state, i.e. right before point (e) in Figure 1 at a displacement of ~5.5 meters and a slip velocity of 3 m/s (\(\tau_0\)).
Figure 3: Maximum shear stress (between (b) and (c)) and final shear stress (point (f)) as a function of acceleration/deceleration with a slip velocity of 3 m/s and 20 MPa normal stress.

Figure 4: Slip weakening distance as a function of applied normal stress at a constant velocity of 3 m/s. The distances were determined by an exponential fit to the data (blue) and by graphical inspection (red).
Figure 5: Depth profile of the inferred slip weakening distance from the experimental fits and location of Outer Hebrides Thrust pseudotachylites.

References


