Journal of Structural Geology 38 (2012) 183–199

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Experimental investigation of flash weakening in limestone

Nicola Tisato [a,*], Giulio Di Toro [b,c], Nicola De Rossi [d], Marino Quaresimin [d], Thibault Candela [e]

[a] *Institute of Geology, ETH Zurich, Soneggstrasse 5, Zurich, Switzerland*
[b] *Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy*
[c] *Dipartimento di Geoscienze, Università di Padova, Padova, Italy*
[d] *Dipartimento di Tecnica e Gestione dei Sistemi Industriali, Università di Padova, Vicenza, Italy*
[e] *ISTerre, University Joseph Fourier, Grenoble I, CNRS, OSUG, BP 53, 38041 Grenoble, France*

ARTICLE INFO

Article history:
Received 21 March 2011
Received in revised form
25 November 2011
Accepted 29 November 2011
Available online 8 December 2011

Keywords:
Friction
Limestone
Earthquakes
Powder lubrication
Flash heating and weakening

ABSTRACT

Flash heating and weakening could operate during earthquake nucleation and propagation. We performed 27 friction experiments in a compression-torsion apparatus on ring-shaped limestone samples at sub-seismic to seismic slip rates $\leq$340 mm/s, centimetric displacements and normal stresses of $\leq$8 MPa. Friction decreases dramatically at slip rates of 50–150 mm/s. Flash weakening was contemporaneous with a peripheral temperature rise of $\sim$90 °C measured with an infrared camera. The peripheral temperature yields a lower limit to the slipping zone temperature.

The decrease in friction may result from weakening of the asperity contacts due to decarbonation of calcite induced by (1) flash heating or (2) mechanically-activated reactions. However, X-Ray powder diffraction and Raman Spectroscopy analyses do not reveal the presence of decarbonation products in the slipping zone. Instead, White Light Interferometry and Field Emission Scanning Electron Microscope observations reveal the presence of a smooth sliding surface made of nanometric-particles. The mechanical data can be fit by the rate- and state-dependent friction model or by a quadratic model (the latter proposed for powder lubrication). We conclude that flash heating and weakening and powder lubrication may operate together to decrease dynamic friction in limestone in experiments and, for the conditions investigated here, in nature.

1. Introduction

Earthquakes may nucleate and propagate in limestone ($CaCO_3$) bearing rocks. For instance, the 2009 L'Aquila (Italy) $M_w = 6.3$ earthquake and most of the associated foreshocks and aftershocks nucleated at depths less than 9.5 km (Chiarabba et al., 2009; Cirella et al., 2009) where previous geological and geophysical investigations suggest the presence of limestone (e.g., Parotto and Praturlon, 1975). Slip and slip rate weakening is a necessary condition for earthquake nucleation (Scholz, 2002; Rice, 2006). Experiments with limestone performed at seismic slip rates ($0.3 < V < 1.6$ m/s) and low normal stresses (<15 MPa) triggered extraordinary dynamic weakening ($\mu < 0.2$) at least after some displacement (>1 m) (Han et al., 2007, 2010). The achievement of very low friction was almost concomitant to the thermal decomposition of calcite (Han et al., 2007) which begins at 700 °C (Rodriguez-Navarro et al., 2009) through the decarbonation reaction:

$$CaCO_3 \rightarrow CaO + CO_2 \qquad (1)$$

However, the weakening mechanism in these experiments remained unspecified, probably because different processes operate together. Han et al., 2010, 2011 suggested that nanoparticles of lime (CaO) lubricate the slipping zone. Theoretical work suggests that at seismogenic depths (i.e., normal stresses one order of magnitude larger than those applied in the experiments), thermal decomposition of calcite releases CO_2, which pressurizes the slipping zone resulting in fault lubrication (thermochemical pressurization: Sulem and Famin, 2009; Noda et al., 2009).

Preceding experiments on calcite-rich rocks (Carrara marble, Han et al., 2007, 2010) were performed with a specifically designed rotary shear apparatus (Shimamoto and Tsutsumi, 1994) in order to achieve seismic slip rates (about 1 m/s) and displacements (several meters for large in magnitude earthquakes) typical of earthquakes (e.g. Cirella et al., 2009). With respect to the rotary shear the use, of a compression-torsion apparatus, which is designed to investigate the mechanical properties of materials of engineering interest,

---

* Corresponding author. Tel.: +41 44 632 24 90.
E-mail addresses: nicola.tisato@erdw.ethz.ch (N. Tisato), giulio.ditoro@unipd.it (G. Di Toro), derossi@gest.unipd.it (N. De Rossi), marino.quaresimin@unipd.it (M. Quaresimin), thibault.candela@ujf-grenoble.fr (T. Candela).

0191-8141/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2011.11.017

permits (1) small but still significant slip (few centimeters) to be imposed, (2) experiments from sub-seismic to seismic slip rates ($0.001 < V < 0.35$ m/s) and (3) large initial accelerations (>10 m/s^2). As a consequence, compression-torsion apparatus provide the opportunity to investigate the initiation of slip during earthquakes (Goldsby and Tullis, 2003, 2011; Kohli et al., 2011). The main limitation of these apparatus is that they can apply only low normal stresses (<10 MPa) on the samples, due to the absence of a confining medium: however, the absence of sample confinement remains a technical challenge also for the so called “high-velocity rock friction experiments” in general (see Di Toro et al., 2006 for discussion).

Flash heating (Bowden and Tabor, 1950; Archard, 1958/59) and weakening are possibly active during seismic slip (Rice, 1999, 2006; Beeler et al., 2008; Rempel, 2006; Rempel and Weaver, 2008; Bizzarri, 2009; Kohli et al., 2011; Goldsby and Tullis, 2011). Rice (2006) assumed that the normal stress σ, between two surfaces in contact, is supported by a number N of asperities with mean diameter D_a. Each asperity is under a critical stress σ_c, which corresponds to the indentation hardness of the material (Beeler et al., 2008); an increase in σ results in an increase of N, but it should only slightly affect the size of D_a (Dieterich and Kilgore, 1994). According to this model, the macroscopic friction (μ) during sliding results from the cumulative contribution of the asperity shear strength (τ_c) and is independent of the normal stress (Bowden and Tabor, 1950):

$$\mu = \tau_c/\sigma_c \tag{2}$$

Since the interaction of the asperities during sliding at a given slip rate V produces heat (Bowden and Tabor, 1950), if the asperities are heated too rapidly for conduction to dissipate the energy released by mechanical work, their temperature increases and the strength of the asperities decreases below τ_c at high temperatures (Rice, 2006; Beeler et al., 2008; Rempel and Weaver, 2008). Simplified models for flash heating and weakening show a satisfactory fit to the experimental data (Goldsby and Tullis, 2011). These constitutive equations assume a threshold temperature T_w (in case of calcite T_w could correspond to the decarbonation temperature) at the asperity contacts upon which τ_c drops to a weakened value τ_w that is treated as a constant (Rice, 2006). In this study, we will keep the above assumptions, though it would be more realistic to consider the evolution of the asperity indentation hardness σ_a and shear strength τ_a both during temperature increase towards T_w (as temperature increases, we expect σ_a and τ_a to decrease, e.g., Evans and Goetze, 1979) and also after T_w has been achieved (τ_a should evolve in the presence of breakdown products or melts: Rempel and Weaver, 2008; Nielsen et al., 2008; Di Toro et al., 2011). According to this scenario, the flash temperature would depend on the competition between increased D_a resulting from a decrease in σ_a (this will increase the flash temperature at a given V), and the decrease in τ_a (this will decrease the flash temperature at a given V) (Goldsby, pers. com). Following the model proposed by Rice, 2006 the critical slip rate V_w at which weakening occurs is given by:

$$V_w = \frac{\pi \cdot \alpha_{\text{th}}}{D_a} \cdot \left(\frac{\rho c \cdot (T_w - T)}{\tau_c} \right)^2 \tag{3}$$

where α_{th} is thermal diffusivity, ρ rock density, c specific heat and T ambient temperature (or the temperature at the initiation of slip). It follows that V_w is related to material properties and to the diameter of the asperity contacts. In fact, given the short duration of these dedicated experiments, the ambient temperature is almost independent of normal stress and, as a consequence, V_w should be also independent of the applied normal stress. In fact, the ambient temperature increases with normal stress in the case of experiments that reproduce larger coseismic displacements (Di Toro et al., 2011).

In this study we investigate the frictional properties of limestone by imposing increasing normal stresses and abrupt accelerations on the samples sliding surface. We observe a dramatic decrease in friction for slip rates above 50 mm/s after few millimeters of slip. Microstructural and mineralogical analysis of post-mortem samples and best fit analysis suggests that weakening could be related to flash heating and weakening and powder lubrication, though the physics of the latter mechanism remains poorly understood.

2. Methods

The experiments were performed at room temperature and humidity conditions by means of a servo hydraulic axial-torsional testing system (MTS 809) installed at the *Department of Management and Engineering* (DTG) of the University of Padova. Fig. 1 shows the machine which has an axial load capacity of 100 kN and a torsional load capacity of 1100 Nm. Experiments on non-cohesive rocks performed as part of the SAFOD Interlab Comparison lead by Chris Marone (http://www.geosc.psu.edu/~cjm/safod/), showed that the MTS 809 apparatus yields mechanical data consistent with those obtained from other conventional biaxial and triaxial rock friction apparatus (i.e., experimental data from MTS 809 are precise and accurate).

In the experiments presented here, sliding occurred during rotary shear of an annular surface perpendicular to the rotation axis and parallel to the floor. Experiments were performed on eight limestone samples (~99% calcite, grain size <5 μm) with 50/60 mm internal/external diameter (samples 003, 005, 011, 013 and 014), and 70/80 mm (samples 004, 006 and 012). The ring-shaped samples were fixed to the upper grip of the apparatus. The ring-shaped sample slides on a cylindrical-shaped sample of 20–25 mm in thickness fixed to the lower grip of the MTS apparatus (Fig. 1A). The maximum slip rate and displacement achieved by 50/60 mm samples were 250 mm/s and 42 mm, respectively,

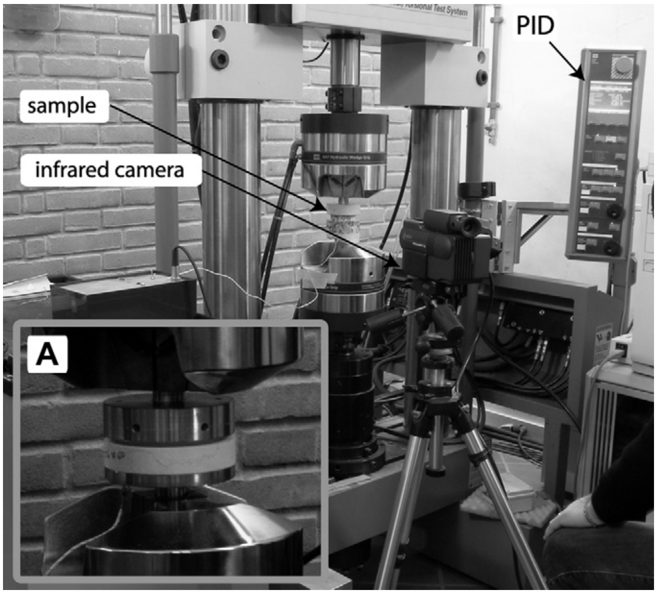

Fig. 1. Experimental set up. General view of the MTS 809 test system used in the experiments; P.I.D. = Proportional Integral Derivative feedback controller. (A) Detail of the sample assembly.