



Frictional behavior of simulated biotite fault gouge under hydrothermal conditions

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ARTICLE INFO

Article history:

Received 20 October 2013

Received in revised form 22 February 2014

Accepted 2 March 2014

Available online 11 March 2014

Keywords:

Biotite

Friction coefficient

Around-neutral velocity weakening

Submicron characteristic slip distance

Hydrothermal conditions

Weak faults

ABSTRACT

We investigated frictional properties of biotite under hydrothermal conditions by shearing simulated biotite gouge sandwiched between saw-cut driving blocks, using a testing system with argon as confining medium. Experiments were conducted under an effective normal stress of 200 MPa, with pore pressure of 30 MPa. Temperatures were varied from room temperature to 600 °C, with shear displacement rate stepped at standard velocities (1.22–0.122 μm/s) and slow velocities (0.244–0.0488 μm/s) to acquire rate dependence of friction.

Our results show that the friction coefficient of biotite ranges from 0.25 to 0.44, significantly lower than that of muscovite documented in previous studies. The steady-state rate dependence shows velocity strengthening at temperatures of 25 °C to 200 °C, and transitions to velocity weakening at temperatures above 300 °C. The velocity weakening is quite minor with $(a - b)$ ranging from -4×10^{-4} to -9×10^{-4} , and stick-slip motions at temperatures from 400 °C to 600 °C are found to be related to submicron d_c values corresponding to critical stiffness higher than the actual stiffness surrounding the fault, thus leading to unstable slips. Microstructures of deformed samples show three types corresponding respectively to three different temperature ranges. While brittle structures are dominantly associated with deformation at 100 °C, significant plastic deformation occurred at higher temperatures. Deformation at temperatures of 200 °C to 400 °C are characterized with shear fracture zones accompanied with plastic deformation mostly associated with basal glide. Intensively deformed zones are the characteristic structures for samples deformed at 500 °C to 600 °C, accompanied with shear fracture zones and moderately deformed zones. It is evident that biotite alone is not weak enough to explain a weak fault like the San Andreas Fault, thus overpressured pore fluid or another weaker mineral is needed to produce a weak fault with apparent friction coefficient of 0.1–0.2. The around-neutral velocity weakening found for biotite may be appropriate in modeling fault creep transients in the mid crust.

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1. Introduction

Deformation of continental crust is generally heterogeneous and the presence of weak phases may significantly influence the localized deformation in faults and shear zones. Related to this aspect, the creeping sections of San Andreas Fault system (Lachenbruch and Sass, 1980; Mount and Suppe, 1987) and some other faults (Balfour et al., 2005; Collettini et al., 2009b; Imber et al., 1997, 2001) have attracted special attention for their possible weak mechanical property. As a common class of constituents of crustal rocks, phyllosilicates are weaker than typical framework minerals such as quartz and feldspar (Imber et al., 1997). Hence investigation of their mechanical properties through laboratory experiments offers a way to probe the weak domains.

Studies on properties of frictional sliding have been performed extensively on phyllosilicates such as montmorillonite, smectite

(Carpenter et al., 2011; Moore and Lockner, 2007; Morrow et al., 2000; Takahashi et al., 2007; Tembe et al., 2010), illite (Morrow et al., 1992; Tembe et al., 2009, 2010), saponite (Carpenter et al., 2012; Lockner et al., 2011), talc (Hirauchi et al., 2013; Moore and Lockner, 2007, 2008; Moore and Rymer, 2007) and chlorite (Ikari et al., 2009; Shimamoto and Logan, 1981). One of the most important results of these studies is the confirmation of the low frictional strength of clays. However, most such minerals are chemically unstable in the deep crust (Velde, 1993), thus the results on these minerals are not justified to be used as representative of the property of mechanically weak fault zones in the whole depth range of interest except for illite and talc, which are stable at high temperature (at least above ~400 °C). The friction coefficient of illite increases with temperature, with coefficient of friction of ~0.4 at temperatures lower than 200 °C and a much higher value of ~0.7 at 400 °C (Tembe et al., 2009), thus it is not plausible to explain the mechanical weakness with this temperature dependence. Talc has low strength and is chemically stable at high temperature, thus it is consistent with the weakness of San Andreas Fault (Moore and Rymer,

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2007). On the other hand, talc may hardly be a significant constituent of weak fault zones in general, especially in the continental crust, because it is often seen as an altered phase of serpentine and is usually of plate boundary origin (Hirauchi et al., 2013; Moore and Lockner, 2008; Peacock and Hyndman, 1999).

Mica minerals came into focus as weak phases in the mid to upper crust because of the wide range of environments where they are chemically stable (Brown and Fyfe, 1970). The significantly low frictional strength (Scruggs and Tullis, 1998) and the sheet structure may facilitate the anisotropic deformation and foliations (Gottschalk et al., 1990; Johnson et al., 2004; Kronenberg et al., 1990; Shea and Kronenberg, 1992).

Although both biotite and muscovite are common minerals of the mica group, biotite is chosen in this study for the following reasons: (1) Biotite is chemically more stable than muscovite above temperature of 650 °C and pressure of 200 MPa (Brown and Fyfe, 1970). Results of melting experiments show that biotite is chemically stable in a very wide temperature range, up to 700 °C at least (Brown and Fyfe, 1970; Patiño Douce and Beard, 1995; Singh and Johannes, 1996). (2) Biotite has lower frictional strength than muscovite at room temperature (Scruggs and Tullis, 1998), and the mechanical properties of muscovite have been extensively documented in the literature (Mariani et al., 2006; Van Diggelen et al., 2010). (3) Biotite is a common phyllosilicate mineral in magmatic and metamorphic rocks, and can be formed under a wide range of temperatures and pressure conditions in metamorphic rocks, contact and regionally metamorphosed sediments, and intrusive igneous rocks (Deer et al., 1985), with diverse abundance in these rocks ranging from ~7% to 72% (Dong et al., 2011; Shea and Kronenberg, 1992). Biotite is also well seen in exhumed fault zones, which occurs in cataclases and mylonites and is usually altered to chlorite at shallow depth (Bell and Etheridge, 1973; Holdsworth et al., 2001; Imber et al., 2001; Parry et al., 1988; Stewart et al., 2000). Despite its widespread existence in crustal rocks and in especially fault zones, experimental data on frictional sliding of biotite are quite limited and only available at room temperature conditions (Scruggs and Tullis, 1998), which may be different to faulting behavior under hydrothermal conditions as suggested by previous studies on muscovite (Mariani et al., 2006; Scruggs and Tullis, 1998; Van Diggelen et al., 2010). Thus in this work, we performed a suite of shearing experiments on biotite gouge at temperatures from room temperature to 600 °C, with effective normal stress of 200 MPa, pore pressure of 30 MPa, and shear velocity stepped during the experiments. Major attention is paid to both frictional strength and rate dependence of friction, as functions of temperature, and the mechanism for macroscopic behavior is analyzed via observation on the microstructures of deformed samples. The preliminary results at 300 °C and 400 °C were reported by Lu and He (in press), in which low coefficient of friction and stick–slip behavior was found.

To acquire the properties of both frictional resistance and sliding stability, in this study we try to obtain parameters in the rate and state friction constitutive relation developed by Dieterich (1978, 1979, 1981) and Ruina (1983) which describes the major features of frictional resistance variation of rocks in response to velocity change and stationary contact. Under this framework, the steady state value of friction coefficient μ is described as a function of sliding velocity V , as follows,

$$\mu = \mu_* + (a-b) \ln(V/V_*), \quad (1)$$

where μ_* is the steady-state coefficient of friction at a reference velocity V_* , and a and b are parameters that describe the initial response to the velocity change and the magnitude of the decay to the new steady-state value, respectively. $(a - b)$ is a parameter that is known to be related to the sliding stability, i.e. when $(a - b) > 0$ (velocity strengthening) the sliding is stable under small perturbation, and $(a - b) < 0$ (velocity weakening) leads to occurrence of unstable fault slip when the actual system stiffness falls below the critical stiffness (Rice and Ruina, 1983; Ruina, 1983) and it may result in earthquake nucleation

on actual faults when governed by the same mechanism (Dieterich, 1992; Tse and Rice, 1986).

2. Experimental method

2.1. The sample material

The simulated fault gouge was commercially obtained from Lingshou quarry, Hebei, China, in the form of biotite flakelets. The chemical composition of the biotite sample was obtained through chemical analysis (shown in Table 1), which indicates that the sample belongs to the magnesium-rich biotite class (Xie and Zhang, 1987). The initial biotite flakelets were crushed, ground and sieved through a 200-mesh sieve. The particle size distribution of the resultant biotite gouge was determined with a laser particle size analyzer, with a median size of 47 μm (Fig. 1).

2.2. The apparatus and experimental procedure

A high pressure and high temperature triaxial testing system with argon gas as confining medium was used to perform our shear experiments on the simulated biotite gouge. The machine can apply a confining pressure as high as 420 MPa, pore pressure up to 200 MPa, temperature to 700 °C and axial load to 100 tons. Temperature is controlled with a Yamatake-Honeywell DCP30 industrial controller. The machine can control the confining pressure and pore pressure respectively within 0.5 MPa and 0.3 MPa of the set values. For more details about the apparatus, see He et al. (2006).

A biotite gouge of 1 mm initial thickness was sandwiched between cylindrical driving blocks cut in half along a plane inclined 35° to the sample axis (Fig. 2). The diameter and length of the saw-cut cylinder are respectively 20 mm and 40 mm. The saw-cut surfaces were ground flat and roughened with #300 abrasive. All the driving blocks were soaked in acetone for more than 5 min to remove possible oil contamination on the surfaces during sample preparation and then washed with de-ionized water. High permeability porous ceramic ($\sim 10^{-14} \text{ m}^2$) was used as the upper driving block for lower temperatures (25 °C to 300 °C) to guarantee uniform pore pressure within the gouge. However, for higher temperatures (400 °C to 600 °C), the porous ceramic was found to yield and exhibit viscous behavior during the experiments, thus it could no longer be used as a driving block. So a gabbro block with two holes is used as the upper block for its high strength and enhanced permeability by the two-hole-access for water. For all temperatures, gabbro blocks were used as the bottom driving block to barrier the pore fluid in the lower gouge–rock boundary. Samples were jacketed in an annealed copper tubing with 0.35-mm wall thickness. Boron nitride powder was filled in the space between the furnace and the sample assembly to reduce heat transfer by gas convection. To allow for a symmetric temperature distribution along the sample axis, temperature was applied using an independently controllable two-zone internal furnace, and a power ratio between the two zones can be preset to give a low temperature gradient along the sample. All temperatures in this study were measured at the top of the upper driving

Table 1
Chemical composition of biotite gouge.

Sample							
Biotite							
Major elements (%)							
SiO ₂	TiO ₂	Al ₂ O ₃	TFe ₂ O ₃	FeO	MnO	MgO	
39.91	0.98	16.87	14.98	7.39	0.12	14.14	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LOI	Total		
0.84	0.20	7.99	0.04	3.26	99.33		
Trace elements (ppm)							
Ba	Cr	Ni	Sr	V	Zr		
446	779	282	28	191	58		

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