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# High-velocity frictional behavior and microstructure evolution of fault gouge obtained from Nojima fault, southwest Japan

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ABSTRACT

High-velocity experiments on fault gouge taken from the Nojima fault that slipped during the 1995 Kobe earthquake were conducted to investigate physical mechanism associated with the slip-weakening behavior. With increasing slip, the friction values of the gouge sheared at 0.62 MPa normal stress and 1.03 m/s slip velocity decrease exponentially from a peak value of more than 0.6 to a steady-state value of 0.2. The textures of the gouge are characterized by grain comminution, oblique and parallel shear planes and localized deformation zone with strongly preferred orientation in the friction weakening stage, and folding and fluttering structures at the steady-state friction stage. Numerical modeling based on the temperature measurements close to the gouge layer shows that the temperature inside the gauge layer did not exceed 400 °C during the experiments. In a slide–hold–slide test, a full strength recovery of the fault gouge was observed only after 12 s slip pause and the slip-weakening curves are the same between the two successive slips. The steady-state coefficient of friction decreased from 0.8 to about 0.2 when the slip velocity increased from 0.006 m/s to 1.03 m/s. This high-velocity weakening feature was observed in a synthetic quartz gouge as well as in the Nojima gouge. Although it is unclear which mechanism causes the weakening among thermal pressurization, silica gel lubrication, flash heating, moisture-draining and so on, the present experimental results suggest that the high-velocity weakening is related to the high heat production rate. Finally, the flow structures observed in the samples deformed up to the final steady-state stages have never been reported in previous slow-rate experiments and could be a key structure characteristic of high-velocity frictional sliding.



## 1. Introduction

Since Brace and Byerlee (1966) suggested that stick–slip behavior of rocks in laboratory friction experiments corresponds to a mechanism of earthquake cycle, many researchers investigated friction of rocks (e.g., Byerlee, 1967; Dieterich, 1972, 1978; Logan, 1978). To understand the overall dynamics of earthquake faulting including inter-, pre-, co-, and post-seismic processes, frictional properties of rocks in a wide range of displacement and slip rate should be investigated.

Frictional properties of rocks at low slip rates (<0.01 m/s) and at small displacements (<1 mm) have been studied in detail in laboratory experiments as reviewed in Marone (1998). The most successful result in slow slip rate friction experiments was the introduction of friction constitutive laws with slip rate and state variables (e.g., Dieterich, 1979; Ruina, 1983). Earthquake modeling using these laws can describe natural seismic and inter-seismic phenomena, such as stable and unstable slip along faults (Scholz, 1998) and generation of aftershocks (Dieterich, 1994).

In spite of this success, there still remain important unsolved problems of seismic fault motion that cannot be explained with the slow slip rate fault properties. One is the frictional strength of natural faults. In-situ heat flow measurements along the San Andreas Fault suggested low strength (i.e., friction coefficient <0.2) of the fault (e.g., Brune et al., 1969; Lachenbruch and Sass, 1980). The low friction is inconsistent with high friction coefficient (0.6–0.85) determined in low slip rate and small slip tests (e.g., Byerlee, 1978). The other problem is the slip-weakening distance of seismic faults during earthquake rupture. Slip-weakening distance of faults inferred from seismic wave analysis ranges between 0.2 and 1 m (Ide and Takeo, 1997; Olsen et al., 1997), whereas laboratory experiments at slow rate and small slip yielded the values typically of the order of 10 μm (e.g., Dieterich, 1978; Ohnaka and Yamashita, 1989). In contrast to the progress in understanding the low velocity friction, frictional properties of rocks at high slip rate (0.01–1 m/s) and at large displacement (~10 m) are not well known.

Recently, rotary-shear apparatuses allow us to conduct laboratory experiments at high slip rate with almost infinite sliding displacement,

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providing a variety of frictional behaviors of rocks during earthquakes. Tsutsumi and Shimamoto (1997) and Hirose and Shimamoto (2005) reported a fault strengthening behavior accompanied with the onset of frictional melting, followed by subsequent fault weakening due to the formation and the growth of a molten layer in the fault. Goldsby and Tullis (2002) and Di Toro et al. (2004) found a friction weakening behavior of a fault resulting from the formation of a thin layer of silica gel on the fault surface. Mizoguchi et al. (2006) found a moisture-drained weakening and moisture-adsorbed strengthening mechanism of wear materials in a fault during high-velocity sliding. In addition, Han et al. (2007) and Hirose and Bystricky (2007) found that thermal decomposition weakens faults dramatically. These high-velocity frictional properties have been filling the gap between the seismic observations and laboratory experiments. We use the term 'high-velocity weakening' for the weakening behavior found in the present high slip velocity friction tests.

Fault gouge zone is composed of granular materials resulting from fracturing and wearing during fault slip. This feature is commonly found in natural active faults (e.g., Chester and Logan, 1987; Wibberley and Shimamoto, 2003). The role of fault gouges on fault strength during high-velocity sliding is of particular interest to clarify earthquake generation processes in natural faults. Several high-velocity friction experiments on clay-bearing gouge samples taken from natural faults (e.g., Fukuchi et al., 2005; Mizoguchi et al., 2007; Tanikawa et al., 2007; Boutareaud et al., 2008; Brantut et al., 2008) and an artificial gouge made of coal (O'Hara et al., 2006) showed dynamic slip-weakening behavior in all samples. Although they showed that strong comminution and abundant frictional heat associated with the sliding resulted in dehydration and amorphization of the clay gouges and devolatilization of the coal gouge, the weakening mechanism is still unclear at present.

In this paper, we conducted high-velocity friction experiments on fault gouge samples taken from the Nojima fault, southwest Japan. We obtained microstructure evolution of the fault gouge, temperature change during high-velocity sliding, velocity dependence and material dependence of the frictional weakening, and strength recovery of the weakened fault, which provide useful information about the physical processes associated with the high-velocity friction weakening. We also show that the microstructures observed in experimental fault gouges sheared at high velocities are similar to those observed in natural gouge samples along the Nojima fault.

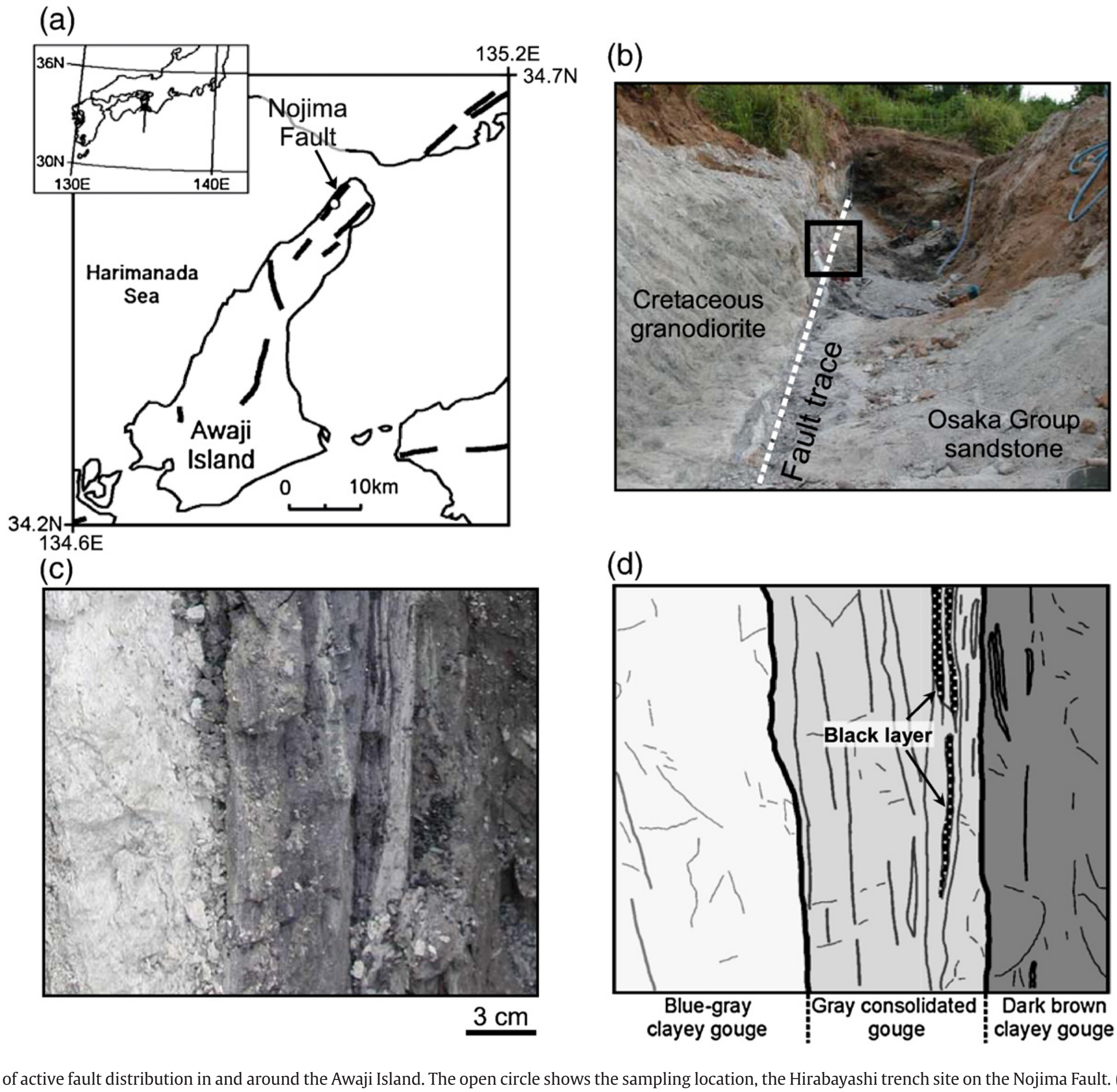


**Fig. 1.** (a) Map of active fault distribution in and around the Awaji Island. The open circle shows the sampling location, the Hirabayashi trench site on the Nojima Fault. (b) Photograph of the trench site viewed toward the southwest. (c, d) Photograph and sketch of the fault gouge zones shown as an open square with solid line in (b). Black layers in the gray consolidated gouge are psudotachylytes reported by Otsuki et al. (2003).