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Reduction in BET surface area of Nojima fault gouge with seismic slip and its implication for the fracture energy of earthquakes

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ABSTRACT

A common view concerning the energetics of seismogenic fault motion is that at least part of the fracture energy is consumed in grain crushing in the fault zone, and that this part may be estimated by grain-size analysis of fault rocks. We address this problem by conducting room-dry friction experiments on Nojima fault gouge at subseismic to seismic slip rates (0.009–1.31 m/s) and at normal stresses up to 3.64 MPa, and by measuring the BET surface area of the gouge before and after the experiments. Where it cuts granite, the Nojima fault zone has BET surface area of about 65×10^6 m^2 per unit fault area (1 m^2). Clayey and granular fault gouges, composed mainly of quartz, plagioclase, kaolinite and smectite, were collected from a granitic fault zone at a new outcrop in Funaki, Awaji Island, southwest Japan. Both clayey and granular gouges exhibit dramatic weakening at high slip rates. Specific BET surface areas of clayey and granular gouges decreased with increasing slip rate from 46.0 and 15.4 m^2/g before deformation to about 20 and 5 m^2/g after deformation (55–70% reduction), respectively. Microstructural observations revealed that grain welding within the slip zones at high slip rates reduced grain surface area. The energetics of seismic fault motion should be examined with broader views taking into account grain crushing, grain welding, decomposition and frictional melting.

1. Introduction

The energy budget during seismic fault motion is a well established but controversial topic. Olgaard and Brace (1983) clearly state that the released energy during an earthquake goes to “heat, seismic waves and microstructural defects formed during crushing”. They measured Brunauer–Emmett–Teller (BET) surface areas (e.g., Gregg and Sing, 1982) of gouge in fault zones in South African gold mines and estimated 1–10% of the total energy released during earthquakes was consumed in grain crushing. Chester et al. (2005) and Ma et al. (2006) report very detailed grain-size analyses of fault gouge from the cores of the Punchbowl fault in California, USA and the Chelungpu fault in Taiwan, respectively. They provide excellent reviews of previous work and the current status of this issue and we will not repeat those here. Primarily those two papers estimated surface areas of grains constituting fault gouge through detailed grain-size analyses under optical and electron microscopes. Chester et al. (2005) tried to define the energy used in grain crushing for the entire history of fault motion and point out difficulties and uncertainty arising from repeated fault motion, interseismic and long-term changes such as alteration and weathering, imperfectly determined fracture energy and poorly known frictional work. Ma et al. (2006) focused on the slip zone that is likely to have moved during the 1999 Chi-Chi earthquake and compared surface-area estimates with the fracture energy estimated for this earthquake. Their conclusion was that about 6% of the fracture energy of this earthquake was consumed in grain comminution, although it is not easy to exclude the effects from previous earthquakes.

To avoid complexities arising from repeated fault motion, Pittarello et al. (2008) carefully selected pseudotachylite that formed in a single event in the Gole Larghe fault zone, northern Italy, which is estimated to have formed at a depth of about 10 km. They estimated the energy used for grain crushing from grain-size analysis of clasts contained in pseudotachylite and the amount of frictional heat per unit fault area from the average thickness of pseudotachylite. They concluded that 3% or less of the total work was consumed in creating surface area associated with the formation of clasts. This is probably the only estimate of energy partitioning during a single earthquake event at typical focal depths. For most natural faults, however, such delineation of

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a single event is extremely difficult. Thus the complexity of natural faults warrants conducting friction experiments under simplified and known conditions to address the issue of earthquake energy partitioning (e.g., Kanamori and Rivera, 2006).

Yoshioka (1986) conducted direct shear experiments on sandstone and granite and estimated from the grain-size distribution of the generated gouge that only 0.01–0.1% of frictional work was consumed in gouge generation. Fulton and Rathbun (2011) recently estimated that about 1% of the total work (sum of work due to shear and work due volume change) is consumed in generating new surfaces associated with grain crushing, based on their biaxial friction experiments using Ottawa sands and glass beads as fault gouge. Those experiments were conducted at low slip rates and it is desirable to conduct high-velocity friction experiments in order to estimate energy partitioning during earthquakes. We have thus attempted to evaluate the energy consumed in grain crushing or in surface-area increase (1) by conducting friction experiments at subseismic to seismic slip rates and (2) by measuring BET surface area of gouge before and after experiments (Togo and Shimamoto, 2009, 2012; Sawai et al., 2009; Togo et al., 2011,b). This experimental approach has great merit in studying the problem in an idealized situation where complex interseismic processes are excluded and fracture energy and frictional work can be measured. We reproduced subseismic to seismic fault motion using a low to high-velocity friction apparatus that is capable of plate to seismic slip rates (3 mm/year to almost 10 m/s; Shimamoto and Hirose, 2006; Togo and Shimamoto, 2012).

The surface area of fault rocks has been estimated mostly by grain-size analysis (e.g., Chester et al., 2005; Ma et al., 2006; Wilson et al., 2005; Heilbronner and Keulen, 2006; Keulen et al., 2007). Grain-size analysis is often time-consuming and sometimes produces controversial results (cf. Wilson et al., 2005; Rockwell et al., 2009). Recent elaborate work by Storti and Balsamo (2010) demonstrated that grain-size distributions determined from different analytical methods are not the same. The typical amount of gouge in our rotary-shear experiments is 1 g, not enough for attempting different methods of grain-size analysis. Moreover, grain shapes have to be assumed to infer surface area from grain-size distribution. We thus employed BET surface-area measurements (e.g., Gregg and Sing, 1982) using BELSORP-mini of Bell Japan, Inc. because this method provides a more simple and straight-forward measurement of surface area than grain-size analysis.

Togo and Shimamoto (2009, 2012) conducted friction experiments on quartz gouge and found that only a very small fraction of frictional work (on the order of 0.1% or less) is used in grain crushing of quartz gouge. This paper attempts to evaluate the same energy budget for a natural fault zone using the Nojima fault as an example. We selected the Nojima fault because this fault is one of the faults that caused the 1995 Kobe earthquake and very detailed work has been conducted on this fault since then (e.g., Lin et al., 2001; Ohtani et al., 2001; Fujimoto et al., 2001; Kobayashi et al., 2001). We report here that the surface area of Nojima fault gouge deformed experimentally decreases, rather than increases, during seismogenic fault motion. This rather unexpected result demonstrates that intrafault processes are more complex than treated in previous studies. In particular, recent experimental studies have demonstrated that decomposition of minerals such as calcite, dolomite, siderite, serpentinite, kaolinite and gypsum can take place during seismogenic fault motion due to frictional heating (Han et al., 2007a,b; Hirose and Bystricky, 2007; Brantut et al., 2008, 2011a; De Paola et al., 2011; Di Toro et al., 2011). Thus intrafault processes during seismic fault motion can be far more complex than a simple scenario of "grain crushing and surface-area increase" even without frictional melting (e.g., Sibson, 1975; Hirose and Shimamoto, 2005) and we suggest an updated research plan for the future.

2. Internal structures of Nojima fault zone at Funaki outcrop

The Nojima fault runs along the northwestern coast of Awaji Island in Hyogo Prefecture, Southwest Japan in the northeast–southwest direction, dipping steeply to the southeast (Fig. 1). It forms part of a 60-km-long belt of active faults known as the Rokko-Awaji fault system (e.g., Huzita, 1967) that caused the 1995 Kobe earthquake (Hyogo-ken-nanbu earthquake, M_w6.9). The Nojima fault system consists of a main fault that extends fairly straight from A to B in Fig. 1 and the Nojima branch fault that offsets from a point near D to C in the same figure. Clear surface ruptures, about 9 km long, formed along the Nojima fault (both main and branch faults) during this earthquake with the maximum horizontal and vertical displacements of 2.0 m and 1.2 m, respectively, at Hirabayashi (Nakata and Okada, 1999). The sense of movement was dextral with the southeast side (i.e., inner side of the island) uplifted. The Northern area of Awaji Island consists of Cretaceous granite and granodiorite overlain by the Miocene Kobe Group and the Plio-Pleistocene Osaka Group (Fig. 1; Awata and Mizuno, 1998). The Kobe Group is mainly composed of sandstone, conglomerate, sandy mudstone, and thin intercalated lignite beds, and the Osaka Group consists mainly of silt-clay, sand and conglomerate. The total Quaternary vertical displacement along the Nojima fault is estimated to be about 500 m (Murata et al., 2001). The Nojima branch fault was mapped as the Nojima fault before the Kobe earthquake in geological maps because it was a boundary fault between granite and the Osaka group. But clear surface rupture formed along the solid line between A and D and the displacement along this segment was greater than that along the boundary fault (Nakata and Okada, 1999). Geologists began to call the fault that runs from A to B the Nojima fault and the boundary fault the Nojima branch fault after the earthquake. Drilling ranging in depth from about 500 m to 1800 m was conducted at 5 sites (2 in Hirabayashi and 3 in Funaki) for geological and geophysical studies of the Nojima fault zone (see Oshiman et al., 2001, a special issue on "Nojima Fault Probe" project).

We studied a new outcrop of the Nojima Branch fault at Funaki (open circle in Fig. 1), located about 100 m southwest of the outcrop reported by Mizoguchi et al. (2008). The outcrop is located near the southwestern end of surface ruptures and the coseismic horizontal and vertical displacements near the outcrop were 0.35 m and 0.45 m, respectively, with the same sense of movement as that in Hirabayashi (Nakata and Okada, 1999). A small drainage canal was constructed to form an outcrop of the Nojima Branch fault, shown in Fig. 2. The fault zone consists of the main dark-gray clayey fault gouge (0.05–0.2 m in width), fault breccia of the Cretaceous granite (3–3.5 m wide) and fault breccia of Plio-Pleistocene Osaka Group (a few meters wide). The main gouge has strike and dip of N20°E and 82°NW, respectively. This inclination is opposite to that of the Nojima fault itself, which dips to about 80°NE (Murata et al., 2001). On the northwest side of the fault zone, a clayey fault breccia zone is developed in weakly deformed fault breccia zones (Fig. 2a). We conventionally classified fault breccia zones on the granite side into seven types based mainly on their colors and occurrence as shown in Fig. 2a and b. All of the breccia zones on both sides of the main clayey fault gouge zone are separated by thin gouge zones, typically several millimeters thick, and clear cross-cutting relationships are recognized among some of these (Fig. 2b). Thus the breccia zones do not represent a simple sequence of deformation, but were rearranged by internal shear surfaces. Granitic coarse fault breccia changes gradually to fractured granite just outside the photograph in Fig. 2a.