Frictional properties of fault zone gouges from the J-FAST drilling project (Mw 9.0 2011 Tohoku-Oki earthquake)

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Abstract
Smectite-rich fault gouges recovered during Integrated Ocean Drilling Program Expedition 343 (Japan Trench Fast Drilling Project (J-FAST)) from the plate boundary slip zone of the 2011 Mw 9.0 Tohoku-Oki earthquake were deformed at slip velocities of 10 μm s⁻¹ to 3.5 m s⁻¹ and normal stresses up to 12 MPa. Water-dampened gouges (1) are weaker (apparent friction coefficient, μ* < 0.1) than room-humidity gouges (apparent friction coefficient, μ* ~ 0.1–0.35) at all slip velocities, (2) are velocity insensitive to velocity weakening at all slip velocities, unlike room-humidity gouges that are velocity strengthening at intermediate velocities (V = 0.001–0.1 m s⁻¹), and (3) have negligible peak μ* at high slip velocities (V > 0.1 m s⁻¹). A significant amount of amorphous material formed in room-humidity experiments at low- and high-slip velocities, likely by comminution and disordering of smectite. Our results indicate that the frictional properties of water-dampened gouges could have facilitated propagation of the Tohoku-oki rupture to the trench and large coseismic slip at shallow depths.

1. Introduction

Two unexpected seismological characteristics of the 2011 Mw 9.0 Tohoku-Oki earthquake were the propagation of the rupture to the trench [Chu et al., 2011; Fujiwara et al., 2011; Kodaira et al., 2012] and the extremely large coseismic slip (>50 m) at shallow depths [Ide et al., 2011; Lay et al., 2011; Ozawa et al., 2011]. These characteristics have been related to the frictional properties of clay-rich gouge present along the shallow part of the fault zone [Chester et al., 2013; Ujiie et al., 2013]. Integrated Ocean Drilling Program (IODP) Expedition 343/343T (Japan Trench Fast Drilling Project (J-FAST)) successfully penetrated and sampled the shallowest part of the megathrust [Chester et al., 2013], providing a unique opportunity to study the physical properties of fault-related rocks in the region of largest coseismic slip. About 1 m of clay-rich fault rock (from a maximum fault thickness of <5 m) was recovered in core 17R from 821.5 to 822.65 m below seafloor (mbsf) and is considered representative of the material that slipped during the Tohoku-Oki earthquake [Chester et al., 2013; Kirkpatrick et al., 2015]. Temperature data obtained from borehole instrumentation [Fulton et al., 2013] confirmed that the fault zone centered at ~820 mbsf slipped during shallow rupture. Friction experiments on clay-rich fault gouge materials (Figure S1 in the supporting information) performed at a slip velocity of 1.3 m s⁻¹ and normal stress of 2 MPa indicated that the gouges are frictionally weak at seismic slip velocities [Ujiie et al., 2013]. In this paper, we present the results of experiments performed on similar gouge materials (taken from an adjoining core section; Figure S1) over a wide range of subseismic to seismic slip velocities, and we extend the results of Ujiie et al. [2013] to higher normal stresses, closer to the estimated in situ effective normal stress at the J-FAST site (7 MPa [Fulton et al., 2013]). Microstructural and quantitative mineralogical phase analyses were performed on the gouges to provide insights into possible deformation processes active during coseismic slip.

2. Methods

2.1. Friction Experiments

The sample is a 9 cm long interval of core from section 17R (Figure S1). Gouges were prepared by disaggregating small pieces of the sample, followed by sieving to obtain particle aggregates <1 mm in size. The single particles forming the aggregates do not exceed 50 μm in diameter. Gouges were poured
into a ring-shaped (35/55 mm internal/external diameter) impermeable metal sample holder with rotary and stationary parts (details and calibration tests in Smith et al. [2013]). For each experiment 3.5 g of gouge was used, resulting in an initial layer thickness of ~2 mm.

Eleven single-velocity and velocity-stepping rotary shear friction experiments (Table 1) were performed on gouges using the SHIVA (Slow to High-Velocity) Apparatus at Istituto Nazionale di Geofisica e Vulcanologia, Rome [Di Toro et al., 2010], following experimental procedures described in Smith et al. [2013]. Eight experiments used gouges at room humidity (ambient humidity 50–80%) and three experiments used water-dampened gouges. For the water-dampened experiments, 0.5 mL of distilled H$_2$O was added to the gouge layer. Experiments with room-humidity gouges were performed at constant normal stresses ($\sigma_n$) of 8.2–12.4 MPa and experiments with water-dampened gouges at a constant $\sigma_n$ of ~3.5 MPa (higher $\sigma_n$ was not applied because of gouge extrusion). Gouges were sheared at slip velocities ($V$) ranging from $10 \mu m s^{-1}$ to $3.5 m s^{-1}$ for total displacements of <1 m (Table 1). The pore pressure inside the gouge layers could not be monitored during the experiments; therefore, results below are reported in terms of the “apparent” friction coefficient, $\mu^*$, defined as measured shear stress/applied normal stress ($\mu^* = \tau/\sigma_n$).

### 2.2. Mineralogical and Microstructural Analysis

Qualitative X-ray powder diffraction (XRPD) analysis was carried out on oriented samples of the starting material to identify the major clay minerals (see Text S1 and Figure S2). Qualitative chemical analysis was

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**Table 1. Summary of Friction Experiments and Results**

| Experiment | Conditions   | Slip Velocity $V$ (m/s) | $\sigma_n$ (MPa) | Slip (m) | Peak $\tau$ (MPa) | Average Steady State $\tau$ (MPa) | Average Steady State $\mu^*$ (MPa) | Range in Steady State $\mu^*$ (MPa) |
|------------|--------------|-------------------------|-----------------|----------|------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| s722       | Room humidity | 1.120                   | 8.39            | 1.00     | 2.71             | 1.37                              | 0.16                              | 0.05                              |
| s723       | Room humidity | 2.295                   | 8.20            | 0.50     | 3.14             | 1.01                              | 0.12                              | 0.03                              |
| s724       | Room humidity | 3.500                   | 12.37           | 0.50     | 4.16             | 1.21                              | 0.10                              | 0.02                              |
| s756       | Room humidity | -                       | 8.32            | 0.49     | 2.77             | 2.34                              | 0.28                              | 0.03                              |
| s740       | Water damped  | 0.055                   | 3.51            | 0.19     | 0.43             | 0.13                              | 0.04                              | 0.02                              |
| s751       | Water damped  | 1.130                   | 3.53            | 0.50     | 0.41             | 0.24                              | 0.07                              | 0.02                              |

**Single-Velocity Experiments**

**Velocity-Stepping Experiments**

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*aSummary of eleven friction experiments performed with SHIVA on sample C0019E-17R-1W 76–85 cm; $\tau$ = shear stress, $\sigma_n$ = normal stress, $\mu^*$ = apparent friction coefficient ($\tau/\sigma_n$).
Quantitative Phase Analysis (QPA) using the Rietveld method and following procedures outlined in Gualtieri [2000] was performed on five separate specimens of the starting material and six deformed gouges (Table S1) to discriminate natural variability in the starting material from variations induced by gouge deformation. Structural refinement of the major clay species in the starting material was conducted using the Rietveld method on a separated clay fraction (<2 μm) (see Text S1 and Figure S2).

Microstructural analysis of deformed gouges was performed by SEM (ESEM Quanta-200 SEM; working distance 9–12 mm, accelerating voltage of 20–25 kV; SEM Nova NanoSEM 450, working distance 5–6 mm, accelerating voltage 20 kV) on thin sections cut approximately parallel to the slip direction and perpendicular to gouge layer boundaries, polished with oil-based diamond pastes and coated with 5 nm of gold. Powders derived from two samples (s724 and s725) were investigated by transmission electron microscopy (TEM) using a JEOL JEM 2010 working at 200 kV and equipped with an Oxford INCA 350 X-EDS for microanalysis (spot size 10 nm). Powders for TEM were prepared by gentle disaggregation of the deformed gouges in a mortar, followed by ultrasonic dispersion in acetone for ~15 min.

3. Results

3.1. Composition of the Starting Material

Variations of peak positions in the XRPD patterns of oriented samples after thermal and ethylene glycol treatments indicate that (1) the main clay phase is a smectite and (2) illite and kaolinite are present. Rietveld refinement of XRPD data collected from the clay fraction (<2 μm) indicates that the best fitting structure model is that of beidellite, a dioctahedral species of the smectite group. Qualitative EDS chemical analysis reveals that the major clay species bears Na and K, with ideal chemical formula \((\text{Na},\text{K})_0.5(\text{Al,}\text{Mg,Fe})_2\) \((\text{Si}_3.5\text{Al}_{0.5})\text{O}_{10}(\text{OH})_2\cdot n(\text{H}_2\text{O})\). QPA indicates that the starting material has a composition of (average values of five analyses; Table S1): smectite (beidellite) 55.2 wt %, illite 17.0 wt %, quartz 8.4 wt %, K-feldspar 7.0 wt %, plagioclase 7.3 wt %, and kaolinite 5.1 wt % (Figure S2). The average content of amorphous material is below the detection limit, with a total variability of ±5 wt %. Accessory apatite and Fe, Ti, Mn oxides (<1 wt %) were identified by SEM-EDS and TEM-EDS analysis. Our results are comparable with those reported for the fault gouge material by Kameda et al. [2015] who measured 60–80 wt % smectite.

3.2. Frictional Behavior

Figure 1 shows the results of representative experiments at low \((V<0.01 \text{ m s}^{-1}, \text{Figures 1a and 1b})\) and high \((V \geq 0.1 \text{ m s}^{-1}, \text{Figures 1c and 1d})\) slip velocities. Figure 2 plots the average steady state \(\mu*\) across the range of investigated \(V\). In velocity-stepping tests \((V<0.01, \text{Figures 1a and 1b})\) \(\mu*\) did not achieve “steady state” values. To take this into account, the average \(\mu*\) in each velocity step is plotted in Figure 2 and the error bars represent the total range in \(\mu*\) during the velocity step. In high-velocity tests \((V \geq 0.1 \text{ m s}^{-1})\) the average steady state \(\mu*\) was calculated for an interval of data during the constant-velocity portion of the experiments (e.g., dashed box in Figures 1c and 1d) and the error bars in Figure 2 represent the range in \(\mu*\) within this slip interval.

At all investigated \(V\), water-dampened gouges are much weaker than room-humidity gouges. At subseismic \(V\) (<0.001 m s\(^{-1}\)), room-humidity gouges have \(\mu*\) between 0.2 and 0.25, while \(\mu*\) for water-dampened gouges is 0.06–0.1 (Figures 1a, 1b, and 2). At intermediate \(V\) (0.001–0.1 m s\(^{-1}\)), water-dampened gouges remain extremely weak with \(\mu*\) around 0.05 (Figure 2). In contrast, room-humidity gouges exhibit velocity-strengthening behavior over this range of \(V\), with \(\mu*\) increasing to 0.3–0.35 at \(V\) approaching 0.1 m s\(^{-1}\) (Figure 2). At low to intermediate \(V\) (<0.1 m s\(^{-1}\)), room-humidity and water-dampened gouge experiments display initial rapid axial shortening of about 0.1 mm within the first centimeter of slip, after which axial shortening slows and stabilizes (Figures 1a and 1b). At seismic \(V\) (>0.1 m s\(^{-1}\)), room-humidity gouges exhibit pronounced peak friction, followed by dynamic weakening (in <0.1 m of slip) to reach a lower steady state \(\mu*\) approaching 0.1 at \(V > 1 \text{ m s}^{-1}\) (Figures 1c and 2). Water-dampened gouges deformed at seismic \(V\) have low peak \(\mu*\)(~0.1) and low steady state \(\mu*\) (~0.06), as well as much less axial shortening compared to the other experimental conditions (Figure 1d).
3.3. Microstructure of Deformed Gouges

Room-humidity gouges deformed at subseismic $V (<0.1 \text{ m s}^{-1})$ are cut by a series of shear bands lying either subparallel (Y shears) or at low-angles to the gouge layer boundaries (Figures 3a and 3b). Domains between the shear bands contain a penetrative P foliation (following the terminology of Logan et al. [1979]) (Figure 3b). At high $V (>0.1 \text{ m s}^{-1})$, room-humidity gouges contain a single, prominent Y shear at a distance of ~200 $\mu$m from the stationary side (Figures 3c), characterized by grain size and porosity reduction (Figure 3d).

Water-dampened gouges deformed at low and high $V$ lack a penetrative foliation or systematically organized fracture sets. Irregular tension cracks, mainly subperpendicular to layer boundaries, likely formed during sample preservation due to shrinkage (Figures 3e and 3g). Elongate lithic clasts and clay particles are generally randomly oriented, similar to the undeformed starting materials (Figure S3). Toward the rotary side, clasts and clay lamellae tend to be weakly aligned parallel to the gouge layer boundaries (Figures 3f and 3h).

3.4. Mineralogy of Deformed Gouges

The most noteworthy mineralogical change in the deformed gouges is a significant increase in the amorphous fraction in three samples deformed under room-humidity conditions (s724, 12.7 wt %; s725, 15.8 wt %; s726, 14.6 wt %; compared to <5 wt % in undeformed samples; Table S1). The crystalline phases are present in similar quantities to the starting material (Table S1).
4. Discussion

4.1. Frictional Properties and Processes in Room-Humidity Gouges

At \( V < 0.001 \text{ m s}^{-1} \), \( \mu^* \) at room humidity is between 0.2 and 0.25 (Figure 2). Many experimental studies at low \( V \) (\( 10^{-3} - 10^{-2} \text{ m s}^{-1} \)) and different conditions of \( \sigma_n \), fluid saturation, and fluid chemistry [e.g., Lupini et al., 1981; Logan and Rauenzahn, 1987; Brown et al., 2003; Saffer and Marone, 2003; Ikari et al., 2007, 2009; Moore and Lockner, 2007; Behnsen and Faulkner, 2013] highlighted that the frictional strength of smectite-rich material is strongly controlled by water content and chemistry. Our room-humidity experiments plot in the "partially saturated" smectite field identified in Moore and Lockner [2007]. In such conditions, Moore and Lockner [2007] suggest that the dominant microphysical processes are a combination of (1) shearing in thin films of water adsorbed onto the surfaces of the clay particles and (2) frictional processes such as grain comminution and abrasion. In our experiments, the occurrence of the above processes is testified by (1) strain localization along multiple shear surfaces (Figures 3a and 3b), (2) grain fracturing and formation of amorphous material (discussed below), and (3) foliation development (Figure 3b).

At \( V \) of 0.001–0.1 m s\(^{-1}\), \( \mu^* \) increases to 0.3–0.35 (Figure 2). Similar strengthening in this velocity range was observed in room-humidity experiments performed on smectite-rich gouges from the Vajont landslide [Ferri et al., 2011], although the deformation processes leading to this behavior are still not fully understood.

At \( V > 0.1 \text{ m s}^{-1} \), peak \( \mu^* \) (0.38) is followed by dynamic weakening to steady state \( \mu^* \sim 0.1 \). Dynamic weakening at seismic \( V \) has been observed in many different rock types [Di Toro et al., 2011], including clay-rich gouges [Mizoguchi et al., 2007; Brantut et al., 2008; Boutareaud et al., 2010; Kitajima et al., 2010; Ferri et al., 2011; Ujije et al., 2013; French et al., 2014], where it is associated with extreme localization of slip and frictional heating. Heating triggers physicochemical processes that cause weakening, which in the case of clay-rich gouges includes dehydration and collapse to an illite-like structure (\( T \approx 150–250 \text{°C} \)) or dehydroxilation and melting (\( T = 480–590 \text{°C} \)), both leading to thermochemical pressurization [Brantut et al., 2008; Ferri et al., 2011]. In gouges deformed at \( V \approx 2.3 \text{ m s}^{-1} \), we observed slip localization along a discrete, thoroughly going 100 \( \mu \text{m} \) thick layer (Figures 3c and 3d). We did not observe significant variations in the illite/smectite ratio in gouges deformed at high velocity (Table S1) (\( T \) of the bulk sample \( < 150 \text{°C} \)). However, given the relatively small total displacements (<1 m) in the experiments, and the localized
nature of the slip zone, an increase in the illite/smectite ratio due to frictional heating [Pytte and Reynolds, 1988; Saffer et al., 2012] probably remains below the resolution of bulk XRPD analysis. In two room-humidity experiments performed at subseismic V (10 μm s⁻¹ to 0.001 m s⁻¹) and one experiment at seismic V (3.5 m s⁻¹), a significant amount of amorphous material formed. The presence of amorphous material in the experiments performed at V < 0.01 m s⁻¹, where the increase in temperature by frictional heating was negligible, excludes a melt origin. Formation of amorphous material in granite gouges sheared at subseismic V and normal stresses of 25 MPa was reported by Yund et al. [1990]; amorphous material was also found in natural fault gouges [Ozawa and Takizawa, 2007]. TEM observations of disordered smectite crystallinites, and partially or completely amorphous material with smectite-like chemical composition (Figure 3), suggest that amorphization in our experiments was likely caused by frictional processes, such as mechanical comminution and disordering of the smectite phase. Amorphization of smectite has been related to breaking of weak hydrogen bonds in the interlayer volume and slip along interlayers, favored by the stacking defects typical of smectites [Christidis et al., 2005]. The production of amorphous material does not correlate with μ*: measurable amorphous material (~12 wt %,
Table S1) was produced in experiments (samples s724 and s726) where \( \mu^* \) remained above 0.2 in each velocity step. Comparable amounts (~15 wt%, Table S1) of amorphous material were produced in sample s725 with \( \mu^* \approx 0.1 \). The experimental observations suggest that the production of amorphous material is not related to dynamic weakening at seismic slip velocities.

### 4.2. Frictional Properties and Processes in Water-Damped Gouges

Water-dampened gouges are velocity weakening or velocity insensitive, with \( \mu^* \) at steady state of 0.05–0.1 (Figure 2). At coseismic \( V (>0.5 \text{ m s}^{-1}) \) our results extend those of Ujiie et al. [2013], performed at normal stress < 1 MPa in wet and impermeable conditions, to higher normal stresses (3.5 MPa) in impermeable conditions (metal holder) and confirm that \( \mu^* \) is low (<0.1) in these materials under water-dampened conditions. Unlike room-humidity gouges, water-dampened gouges display less axial shortening and have negligible apparent peak friction at high velocities (Figures 1d and 2). Very low peak and steady state friction at seismic \( V \) was previously measured in wet clay-rich gouges [Faulkner et al., 2011; Ferri et al., 2011; Ujiie et al., 2013; Sawai et al., 2014] and ascribed to either sliding on pressurized water films expelled by gouge compaction or near-instantaneous thermal pressurization of pore fluids.

Our mechanical data indicate that water-dampened Tohoku-oki gouges are very weak at all \( V \), and the microstructures developed at low and high \( V \) are quite similar. It follows that the mechanisms of weakening are independent of \( V \) and, consequently, frictional heating. For this reason, it is unlikely that thermal pressurization led to weakening in the water-dampened experiments. Additionally, the small amount or absence of newly formed amorphous material in the water-dampened gouges (6.7–7.9 wt%) is close to the primary amorphous content of the sample estimated below 5%; Table S1) indicates that frictional (mechanical and thermal) processes leading to amorphization of smectite were not as important in water-saturated conditions as compared to room-humidity conditions. We suggest that fluid-like gouge behavior and/or disequilibrium fluid (over)pressure contributed to weakening in the case of the water-dampened materials. This is supported by microstructural evidence such as the chaotic gouge fabric and the lack of localized shear surfaces at both subseismic and seismic \( V \) (Figures 3e–3h).

### 4.3. Comparison Between Water-Dampened and Room-Humidity Experiments and Implications for Tohoku-Oki Earthquake Mechanics

Our friction experiments show that under water-dampened and impermeable conditions, the Tohoku-oki gouges have (1) negligible peak \( \mu^* \), (2) low steady state \( \mu^* \), (3) velocity-weakening or velocity-independent \( \mu^* \) (Figure 2), and (4) short slip weakening distance at seismic \( V \) (Figure 1d). In contrast, room-humidity gouges show an increase in \( \mu^* \) with \( V \) up to 0.1 m s\(^{-1}\) (Figure 2) and pronounced peak friction, as well as a longer slip weakening distance at seismic \( V \) (Figure 1c). This suggests that in water-dampened gouges, less energy is dissipated as frictional work during slip weakening (fracture energy [Cocco et al., 2006]), favoring the propagation of seismic ruptures [Faulkner et al., 2011].

Sawai et al. [2014] performed rotary shear experiments on pelagic clay-rich gouges (similar in composition to the gouges studied here) collected from the outer rise of the Pacific plate on Leg 56 of the Deep Sea Drilling Project. They used a saline brine as interstitial fluid, permeable “wall rocks” and a velocity range between 250 \( \mu \text{m s}^{-1} \) and 1.3 m s\(^{-1}\) (Figure 2). Their experimental results lie between the water-dampened and room-humidity gouges tested in our study, but with less pronounced intermediate velocity strengthening compared to our room-humidity gouges (Figure 2). This suggests that the “barrier” intensity could be controlled by the water content inside the gouge related to the confining blocks permeability (permeable wall rock in Sawai experiments versus impermeable metal holder in our setting) during the experiments and/or to the chemical composition of the water (brine versus distilled water). Recent work by Ikari et al. [2015] on J-FAST plate boundary material at subseismic velocities confirms that it can exhibit velocity strengthening to velocity weakening behavior depending on the experimental conditions.

Temperature sensors installed in the J-FAST borehole 16 months after the \( M_w \) 9.0 rupture recorded a temperature anomaly up to 0.31°C above the background geothermal gradient centered at the expected stratigraphic level of the seismic slip zone [Fulton et al., 2013]. From the temperature data, Fulton et al. [2013] estimated a coseismic shear resistance of 0.54 MPa and an apparent coefficient of friction of 0.08. This is similar to our estimates of \( \mu^* \) under water-dampened conditions at all tested \( V \) (\( \mu^* \approx 0.05–0.1 \)) and also under room-humidity conditions at seismic \( V \) (steady state \( \mu^* = 0.1 \)). The frontal part of the Japan
Trench megathrust is likely water saturated and with relatively low permeability, although the permeability could increase significantly during seismic rupture propagation [Sibson, 2013]. We suggest that the water-dampened experiments under impermeable conditions are most representative of the deformation conditions in the plate boundary fault during propagation of the Tohoku-oki earthquake rupture. Further studies are needed to investigate more deeply the mechanical and chemical role of water in smectite-rich gouges at different slip velocities.

5. Conclusions

Experimental results indicate that water-dampened smectite-rich fault gouges sampled from the Tohoku-oki earthquake fault zone are weak compared to their room-humidity equivalents. In addition, water-dampened gouges lack peak friction and intermediate-velocity strengthening behavior as shown by room-humidity gouges. The frictional characteristics exhibited by water-dampened gouges (low friction, no peak friction, and no intermediate-velocity barrier) could explain rupture propagation to the trench and very large coseismic slip at shallow depths during the 2011 Mw 9.0 Tohoku-oki earthquake. Amorphous material formed in the experiments at low and high V, likely by comminution and disordering of smectite, but it did not play a role in weakening.

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