RESEARCH LETTER

10.1002/2015GL063507

Key Points:

- Strengthening at intermediate velocities in room-humidity Tohoku-oki gouge
- Lack of strengthening in water-dampened gouges facilitated rupture to the trench
- Amorphization of clays in room-humidity gouge at all tested slip velocities

Supporting Information:

- Text S1, Figures S1–S4, and Table S1

Correspondence to:

F. Remitti,
francesca.remitti@unimore.it

Citation:

Remitti, F., S. A. F. Smith, S. Mitterpergher, A. F. Gualtieri, and G. Di Toro (2015), Frictional properties of fault zone gouges from the J-FAST drilling project (M_w 9.0 2011 Tohoku-Oki earthquake), *Geophys. Res. Lett.*, 42, doi:10.1002/2015GL063507.

Received 16 FEB 2015

Accepted 26 MAR 2015

Accepted article online 31 MAR 2015

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

F. Remitti¹, S. A. F. Smith², S. Mitterpergher¹, A. F. Gualtieri¹, and G. Di Toro^{3,4,5}
¹Dipartimento di Scienze Chimiche e Geologiche, Università di Modena e Reggio Emilia, Modena, Italy, ²Department of Geology, University of Otago, Dunedin, New Zealand, ³School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Manchester, UK, ⁴Dipartimento di Geoscienze, Università degli Studi di Padova, Padua, Italy, ⁵Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

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 M_w 9.0 Tohoku-Oki earthquake were deformed at slip velocities of $10 \mu\text{m s}^{-1}$ to 3.5 m s^{-1} and normal stresses up to 12 MPa. Water-dampened gouges (1) are weaker (apparent friction coefficient, $\mu^* < 0.1$) than room-humidity gouges (apparent friction coefficient, $\mu^* \sim 0.1$ – 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 ($V > 0.1 \text{ m s}^{-1}$). 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 M_w 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 ($> 50 \text{ m}$) 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 $< 5 \text{ m}$) 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 $\sim 820 \text{ mbsf}$ 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 in to 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 $< 1 \text{ mm}$ in size. The single particles forming the aggregates do not exceed $50 \mu\text{m}$ in diameter. Gouges were poured

Table 1. Summary of Friction Experiments and Results^a

Experiment	Conditions	Slip Velocity V (m/s)	σ_n (MPa)	Slip (m)	Peak τ (MPa)	Average Steady State τ (MPa)	Average Steady State μ^* (MPa)	Range in Steady State μ^* (MPa)
<i>Single-Velocity Experiments</i>								
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
<i>Velocity-Stepping Experiments</i>								
s725								
Step 1	Room humidity	0.0001	8.35	0.03	2.14	1.56	0.19	0.01
Step 2	Room humidity	0.01	8.31	0.08	-	2.22	0.27	0.01
Step 3	Room humidity	0.001	8.33	0.05	-	1.91	0.23	0.02
s726								
Step 1	Room humidity	0.00001	8.29	0.01	2.21	1.97	0.24	0.01
Step 2	Room humidity	0.0001	8.26	0.02	2.06	1.67	0.20	0.01
Step 3	Room humidity	0.001	8.25	0.04	1.88	1.64	0.20	0.03
Step 4	Room humidity	0.01	8.30	0.11	-	2.42	0.29	0.01
Step 5	Room humidity	0.001	8.37	0.05	-	2.00	0.24	0.02
Step 6	Room humidity	0.0001	8.48	0.02	-	1.90	0.22	0.03
Step 7	Room humidity	0.00001	8.56	0.01	-	1.85	0.22	0.01
s737								
Step 1	Room humidity	0.05	8.44	0.19	-	2.66	0.32	0.04
Step 2	Room humidity	0.1	8.39	0.20	-	2.82	0.34	0.03
s741								
Step 1	Water damped	0.00001	3.49	0.01	0.37	0.32	0.09	0.01
Step 2	Water damped	0.0001	3.44	0.02	0.33	0.27	0.08	0.02
Step 3	Water damped	0.001	3.44	0.04	0.28	0.22	0.07	0.02
Step 4	Water damped	0.01	3.48	0.11	0.30	0.21	0.06	0.04
Step 5	Water damped	0.001	3.57	0.05	-	0.18	0.05	0.02
Step 6	Water damped	0.0001	3.44	0.01	-	0.21	0.06	0.00
Step 7	Water damped	0.00001	3.42	0.02	-	0.25	0.07	0.01
s750								
Step 1	Room humidity	0.2	8.48	0.20	3.15	1.80	0.21	0.06
Step 2	Room humidity	0.5	8.62	0.20	2.18	1.56	0.18	0.07

^aSummary of eleven friction experiments performed with SHIVA on sample C0019E-17R-1W 76–85 cm; τ = shear stress, σ_n = normal stress, μ^* = apparent friction coefficient (τ/σ_n).

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 H₂O was added to the gouge layer. Experiments with room-humidity gouges were performed at constant normal stresses (σ_n) of 8.2–12.4 MPa and experiments with water-dampened gouges at a constant σ_n of ~ 3.5 MPa (higher σ_n was not applied because of gouge extrusion). Gouges were sheared at slip velocities (V) ranging from $10 \mu\text{m s}^{-1}$ 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, μ^* , 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

performed on clay particles using energy-dispersive X-ray spectroscopy (X-EDS, Oxford INCA-350) in a ESEM Quanta-200 scanning electron microscope (SEM).

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 ($<2\ \mu\text{m}$) (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 ($<2\ \mu\text{m}$) 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 $(\text{Na,K})_{0.5}(\text{Al,Mg,Fe})_2[\text{Si}_{3.5}\text{Al}_{0.5}\text{O}_{10}(\text{OH})_2 \cdot n(\text{H}_2\text{O})$. 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 ($V < 0.01\ \text{m s}^{-1}$, Figures 1a and 1b) and high ($V \geq 0.1\ \text{m s}^{-1}$, Figures 1c and 1d) slip velocities. Figure 2 plots the average steady state μ^* across the range of investigated V . In velocity-stepping tests ($V < 0.01$, Figures 1a and 1b) μ^* did not achieve “steady state” values. To take this into account, the average μ^* in each velocity step is plotted in Figure 2 and the error bars represent the total range in μ^* during the velocity step. In high-velocity tests ($V \geq 0.1\ \text{m s}^{-1}$) the average steady state μ^* 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 μ^* within this slip interval.

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

Figure 1. Representative friction experiments performed at low (Figures 1a and 1b) and high (Figures 1c and 1d) slip velocities in room humidity (Figures 1a and 1c) and water-dampened (Figures 1b and 1d) conditions. (a) Apparent friction coefficient (μ^*) and axial displacement versus slip for velocity-stepping experiments s726 (room humidity; 8.5 MPa normal stress) and (b) s741 (water dampened; 3.5 MPa normal stress). The experiments included seven velocity steps between $10 \mu\text{m s}^{-1}$ and 0.01 m s^{-1} . (c) Apparent friction coefficient (μ^*) and axial displacement versus slip for single-velocity experiments s723 (room humidity; 8.2 MPa normal stress) and (d) s751 (water dampened; 3.5 MPa normal stress). Positive and negative axial displacements indicate dilation and shortening, respectively. Dashed boxes show the intervals used to calculate the average steady state friction coefficient.

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 $\sim 200 \mu\text{m}$ 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 $<5 \text{ wt %}$ in undeformed samples; Table S1). The crystalline phases are present in similar quantities to the starting material (Table S1).

Figure 2. Steady state apparent friction coefficient and peak apparent friction coefficient versus slip velocity. Error bars represent the range in steady state apparent friction coefficient measured at each slip velocity. For comparison, steady state friction coefficients of Pacific pelagic clay tested by Sawai *et al.* [2014] are displayed; see discussion in the text.

In TEM bright field images, the submicron fraction of samples s725 (Figure 3i; $V=0.01 \text{ m s}^{-1}$) and s724 (Figures 3j and 3k; $V=3.5 \text{ m s}^{-1}$) appears as a light grey, homogeneous matrix embedding tiny lamellae of Fe, Mn, and Ti oxides, and rare fragments of quartz, plagioclase, and K-feldspar (Figures 3i–3k and Figure S3). From TEM-EDS analysis, the matrix consists of Si, Al, Mg, Fe, K, $\pm \text{Na}$, $\pm \text{Ca}$, $\pm \text{Mn}$, and $\pm \text{Ti}$ (Figure S4). Selected area electron diffraction (SAED) patterns collected from different spots in the matrix show diffuse haloes (Figures 3i and 3j) or ring patterns with smectite spacing and sparse diffraction spots (Figure 3k). These indicate that the light grey matrix is amorphous in some areas (diffuse haloes) or contains aggregates of disordered smectite crystallites (ring patterns). In all of the analyzed spots, the chemical composition of the amorphous matrix is compatible with illite, smectite, and/or kaolinite, mixed with oxides of Fe, Mn, and Ti (Figure S4).

4. Discussion

4.1. Frictional Properties and Processes in Room-Humidity Gouges

At $V < 0.001 \text{ m s}^{-1}$, μ^* at room humidity is between 0.2 and 0.25 (Figure 2). Many experimental studies at low V (10^{-3} – $10^2 \mu \text{m s}^{-1}$) and different conditions of σ_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} , μ^* 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 μ^* (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; Ujiie *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 ($T=150$ – 250°C) or dehydroxylation and melting ($T=480$ – 590°C), both leading to thermochemical pressurization [Brantut *et al.*, 2008; Ferri *et al.*, 2011]. In gouges deformed at $V \sim 2.3 \text{ m s}^{-1}$, we observed slip localization along a discrete, thoroughgoing $100 \mu\text{m}$ 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 $<150^\circ\text{C}$). However, given the relatively small total displacements ($<1 \text{ m}$) in the experiments, and the localized

Figure 3. Microstructures and mineralogy of deformed gouge layers. Figures 3a to 3h are backscatter SEM images (Figures 3a–3d: room-humidity gouges, Figures 3e–3h: water-dampened gouges), Figures 3i–3k are TEM bright field images and SAED images. (a) Gouge layer s725 (deformed up to 0.01 m s^{-1}). Fractures exploit Y shears and wavy P foliation planes. (b) The matrix of s725 shows a pervasive P foliation defined by a preferred alignment of clasts and clay lamellae. (c) Gouge layer s724 (deformed at 3.5 m s^{-1}). Deformation is localized to a continuous, thoroughgoing Y shear close to the stationary side of the gouge layer. The inset shows the location of Figure 3d. (d) Detail of s724, showing the transition to brighter, compacted, and comminuted material along the Y shear. (e) Gouge layer s741 (deformed up to 0.001 m s^{-1}) shows a relatively homogenous internal fabric. Cracks are interpreted as desiccation cracks formed during sample preservation. (f) Detail of gouge layer s741. The orientation of clasts and clay lamellae is scattered. (g) Gouge layer s751 (deformed at 1.13 m s^{-1}) has a microstructure similar to samples deformed at lower slip velocities and cracks subvertical to layer boundaries. (h) Detail of gouge layer s751. Clay lamellae tend to rotate to a direction parallel to the layer boundary toward the rotary side. (i) TEM bright field image of powder from room-humidity sample s725 deformed at $V < 0.01 \text{ m s}^{-1}$. The selected area electron diffraction (SAED) pattern collected in the area outlined by the white circle shows a halo around the central bright spot, indicating that electrons are diffracted randomly by material with amorphous structure. (j) TEM bright field image of powder from room-humidity sample s724 deformed at 3.5 m s^{-1} . The SAED pattern corresponds to an amorphous material. The elongate dark lamella is rich in Fe and Mn, likely an oxide phase (Figure S4). (k) TEM bright field image of powder from room-humidity sample s724 deformed at 3.5 m s^{-1} . The ring patterns and sparse diffraction spots in the SAED pattern indicate a mixture of amorphous material and disordered crystallites of smectite.

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 ($10 \mu\text{m s}^{-1}$ 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 $V < 0.01 \text{ m s}^{-1}$, 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 crystallites, 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 ($\sim 12 \text{ wt } \%$,

Table S1) was produced in experiments (samples s724 and s726) where μ^* remained above 0.2 in each velocity step. Comparable amounts (~ 15 wt %, Table S1) of amorphous material were produced in sample s725 with $\mu^* \sim 0.1$. 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-Dampened Gouges

Water-dampened gouges are velocity weakening or velocity insensitive, with μ^* 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 μ^* 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 μ^* , (2) low steady state μ^* , (3) velocity-weakening or velocity-independent μ^* (Figure 2), and (4) short slip weakening distance at seismic V (Figure 1d). In contrast, room-humidity gouges show an increase in μ^* 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 μ^* under water-dampened conditions at all tested V ($\mu^* = 0.05$ – 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 M_w 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.

Acknowledgments

Mineralogical data are available in the supporting information Table S1. This study used samples and/or data provided by the Integrated Ocean Drilling Program (IODP). Funding from PRIN 2010/2011 project 2010AZR98L_009, the European Research Council grants USEMS (205175) and NOFEAR (614705) (to G.D.T.), ASTARTE (603839) and a University of Otago Research grant (to S.A.F.S.) is gratefully acknowledged. F.R. thanks all the IODP expedition 343 scientific party. We are grateful for the assistance of the scientific and drilling staff on Drilling Vessel Chikyu. We thank M. Ikari, N. Brantut, and two anonymous reviewers for their thoughtful and careful revisions of the manuscript. S.A.F.S. performed the experiments and wrote a first version of the manuscript. All authors contributed to scientific discussion and wrote the manuscript.

The Editor thanks Matt Ikari for his assistance in evaluating this paper.

References

- Behnsen, J., and D. R. Faulkner (2013), Permeability and frictional strength of cation-exchanged montmorillonite, *J. Geophys. Res. Solid Earth*, **118**, 2788–2798, doi:10.1002/jgrb.50226.
- Boutareaud, S., A.-M. Boullier, M. Andréani, D.-G. Calugaru, P. Beck, S.-R. Song, and T. Shimamoto (2010), Clay clast aggregates in gouges: New textural evidence for seismic faulting, *J. Geophys. Res.*, **115**, B02408, doi:10.1029/2008JB006254.
- Brantut, N., A. Schubnel, J.-N. Rouzaud, F. Brunet, and T. Shimamoto (2008), High-velocity frictional properties of a clay-bearing fault gouge and implications for earthquake mechanics, *J. Geophys. Res.*, **113**, B10401, doi:10.1029/2007JB005551.
- Brown, K. M., A. Kopf, M. B. Underwood, and J. L. Weinberger (2003), Compositional and fluid pressure controls on the state of stress on the Nankai subduction thrust: A weak plate boundary, *Earth Planet. Sci. Lett.*, **214**, 589–603.
- Chester, F. M., et al. (2013), Structure and composition of the plate-boundary slip zone for the 2011 Tohoku-Oki earthquake, *Science*, **342**(6163), 1208–1211, doi:10.1126/science.1243719.
- Christidis, G. E., F. Dellisanti, G. Valdre, and P. Makri (2005), Structural modifications of smectites mechanically deformed under controlled conditions, *Clay Miner.*, **40**(4), 511–522, doi:10.1180/00098550504040188.
- Chu, R. S., S. J. Wei, D. V. Helmberger, Z. W. Zhan, L. P. Zhu, and H. Kanamori (2011), Initiation of the great M_w 9.0 Tohoku-Oki earthquake, *Earth Planet. Sci. Lett.*, **308**(3–4), 277–283, doi:10.1016/j.epsl.2011.06.031.
- Cocco, M., P. Spudich, and E. Tinti (2006), On the mechanical work absorbed on faults during earthquake ruptures, in *Earthquakes: Radiated Energy and the Physics of Faulting*, *Geophys. Monogr. Ser.*, vol. 170, pp. 237–254, AGU, Washington, D. C., doi:10.1029/170gm24.
- Di Toro, G., et al. (2010), From field geology to earthquake simulation: A new state-of-the-art tool to investigate rock friction during the seismic cycle (SHIVA), *Rend. Lincei Sci. Fis.*, **21**, 95–114, doi:10.1007/s12210-010-0097-x.
- Di Toro, G., R. Han, T. Hirose, N. De Paola, S. Nielsen, K. Mizoguchi, F. Ferri, M. Cocco, and T. Shimamoto (2011), Fault lubrication during earthquakes, *Nature*, **471**(7339), 494–498, doi:10.1038/nature09838.
- Faulkner, D. R., T. M. Mitchell, J. Behnsen, T. Hirose, and T. Shimamoto (2011), Stuck in the mud? Earthquake nucleation and propagation through accretionary forearcs, *Geophys. Res. Lett.*, **38**, L18303, doi:10.1029/2011GL048552.
- Ferri, F., G. Di Toro, T. Hirose, R. Han, H. Noda, T. Shimamoto, M. Quaresimin, and N. de Rossi (2011), Low- to high-velocity frictional properties of the clay-rich gouges from the slipping zone of the 1963 Vaiont slide, northern Italy, *J. Geophys. Res.*, **116**, B09208, doi:10.1029/2011JB008338.
- French, M. E., H. Kitajima, J. S. Chester, F. M. Chester, and T. Hirose (2014), Displacement and dynamic weakening processes in smectite-rich gouge from the Central Deforming Zone of the San Andreas Fault, *J. Geophys. Res. Solid Earth*, **119**, 1777–1802, doi:10.1002/2013JB010757.
- Fujiwara, T., S. Kodaira, T. No, Y. Kaiho, N. Takahashi, and Y. Kaneda (2011), The 2011 Tohoku-Oki earthquake: Displacement reaching the trench axis, *Science*, **334**(6060), 1240, doi:10.1126/science.1211554.
- Fulton, P. M., et al. (2013), Low coseismic friction on the Tohoku-Oki fault determined from temperature measurements, *Science*, **342**(6163), 1214–1217, doi:10.1126/Science.1243641.
- Gualtieri, A. F. (2000), Accuracy of XRPD QPA using the combined Rietveld-RIR method, *J. Appl. Crystallogr.*, **33**, 267–278, doi:10.1107/S002188989901643x.
- Ide, S., A. Batai, and G. C. Beroza (2011), Shallow dynamic overshoot and energetic deep rupture in the 2011 M_w 9.0 Tohoku-Oki earthquake, *Science*, **332**(6036), 1426–1429, doi:10.1126/Science.1207020.
- Ikari, M. J., D. M. Saffer, and C. Marone (2007), Effect of hydration state on the frictional properties of montmorillonite-based fault gouge, *J. Geophys. Res.*, **112**, B06423, doi:10.1029/2006JB004748.
- Ikari, M. J., D. M. Saffer, and C. Marone (2009), Frictional and hydrologic properties of clay-rich fault gouge, *J. Geophys. Res.*, **114**, B05409, doi:10.1029/2008JB006089.
- Ikari, M. J., J. Kameda, D. M. Saffer, and A. J. Kopf (2015), Strength characteristics of Japan Trench borehole samples in the high-slip region of the 2011 Tohoku-Oki earthquake, *Earth Planet. Sci. Lett.*, **412**, 35–41, doi:10.1016/j.epsl.2014.12.014.
- Kameda, J., M. Shimizu, K. Ujiie, T. Hirose, M. Ikari, J. Mori, K. Ohashi, and G. Kimura (2015), Pelagic smectite as an important factor in tsunamigenic slip along the Japan Trench, *Geology*, **43**, 155–158, doi:10.1130/G35948.1.
- Kirkpatrick, J. D., et al. (2015), Structure and lithology of the Japan Trench subduction plate boundary fault, *Tectonics*, **34**, 53–69, doi:10.1002/2014TC003695.
- Kitajima, H., J. S. Chester, F. M. Chester, and T. Shimamoto (2010), High-speed friction of disaggregated ultracataclite in rotary shear: Characterization of frictional heating, mechanical behavior, and microstructure evolution, *J. Geophys. Res.*, **115**, B08408, doi:10.1029/2009JB007038.

- Kodaira, S., T. No, Y. Nakamura, T. Fujiwara, Y. Kaiho, S. Miura, N. Takahashi, Y. Kaneda, and A. Taira (2012), Coseismic fault rupture at the trench axis during the 2011 Tohoku-oki earthquake, *Nat. Geosci.*, *5*(9), 646–650, doi:10.1038/ngeo1547.
- Lay, T., C. J. Ammon, H. Kanamori, L. Xue, and M. J. Kim (2011), Possible large near-trench slip during the 2011 M_w 9.0 off the Pacific coast of Tohoku Earthquake, *Earth Planets Space*, *63*(7), 687–692, doi:10.5047/Eps.2011.05.033.
- Logan, J. M., and K. A. Rauenzahn (1987), Frictional dependence of gouge mixtures of quartz and montmorillonite on velocity, composition, and fabric, *Tectonophysics*, *144*, 87–108.
- Logan, J. M., M. Friedman, N. Higgs, C. Dengo, and T. Shimamoto (1979), Experimental studies of simulated gouge and their application to studies of natural fault zones, in *Proceedings of Conference VIII, Analysis of Actual Fault Zones in Bedrock, U.S. Geol. Surv. Open File Rep.*, 79-1239, pp. 305–343.
- Lupini, J. F., A. E. Skinner, and P. R. Vaughan (1981), The drained residual strength of cohesive soils, *Geotechnique*, *31*, 181–213.
- Mizoguchi, K., T. Hirose, T. Shimamoto, and E. Fukuyama (2007), Reconstruction of seismic faulting by high-velocity friction experiments: An example of the 1995 Kobe earthquake, *Geophys. Res. Lett.*, *34*, L01308, doi:10.1029/2006GL027931.
- Moore, D. E., and D. A. Lockner (2007), Friction of the smectite clay montmorillonite: A review and interpretation of data, in *The Seismogenic Zone of Subduction Thrust Faults*, edited by T. Dixon and C. Moore, pp. 317–345, Columbia Univ. Press, New York.
- Ozawa, K., and S. Takizawa (2007), Amorphous material formed by the mechanochemical effect in natural pseudotachylyte of crushing origin: A case study of the Iida-Matsukawa Fault, Nagano Prefecture, central Japan, *J. Struct. Geol.*, *29*, 1855–1869, doi:10.1016/j.jsg.2007.08.008.
- Ozawa, S., T. Nishimura, H. Suito, T. Kobayashi, M. Tobita, and T. Imakiire (2011), Coseismic and postseismic slip of the 2011 magnitude-9 Tohoku-Oki earthquake, *Nature*, *475*(7356), 373–376, doi:10.1038/nature10227.
- Pytte, A. M., and R. C. Reynolds (1988), *The Thermal Transformation of Smectite to Illite*, Springer, New York.
- Saffer, D. M., and C. Marone (2003), Comparison of smectite- and illite-rich gouge frictional properties: Application to the updip limit of the seismogenic zone along subduction megathrusts, *Earth Planet. Sci. Lett.*, *215*, 219–235.
- Saffer, D. M., D. A. Lockner, and A. McKiernan (2012), Effects of smectite to illite transformation on the frictional strength and sliding stability of intact marine mudstones, *Geophys. Res. Lett.*, *39*, L11304, doi:10.1029/2012GL051761.
- Sawai, M., T. Hirose, and J. Kameda (2014), Frictional properties of incoming pelagic sediments at the Japan Trench: Implications for large slip at a shallow plate boundary during the 2011 Tohoku earthquake, *Earth Planets Space*, *66*, 65, doi:10.1186/1880-5981-66-65.
- Sibson, R. H. (2013), Stress switching in subduction forearcs: Implications for overpressure containment and strength cycling on megathrusts, *Tectonophysics*, *600*, 142–152, doi:10.1016/j.tecto.2013.02.035.
- Smith, S. A. F., G. Di Toro, S. Kim, J. H. Ree, S. Nielsen, A. Billi, and R. Spiess (2013), Co-seismic recrystallization during shallow earthquake slip, *Geology*, *41*(1), 63–66.
- Ujii, K., et al. (2013), Low coseismic shear stress on the Tohoku-Oki megathrust determined from laboratory experiments, *Science*, *342*(6163), 1211–1214, doi:10.1126/science.1243485.
- Yund, R. A., M. L. Blanpied, T. E. Tullis, and J. D. Weeks (1990), Amorphous material in high strain experimental fault gouges, *J. Geophys. Res.*, *95*(B10), 15,589–15,602, doi:10.1029/JB095iB10p15589.