Potential role of volcanic glass-smectite mixtures in slow earthquakes in shallow subduction zones: Insights from low- to high-velocity friction experiments

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Abstract

Volcanic glass and its mixture with smectite are commonly observed in shallow parts of subduction zones. As volcanic glass layers often act as a glide plane to induce mass transportation such as submarine landslides, and because its alteration product, smectite, is one of the frictionally weakest geological materials, the frictional characteristics of volcanic glass-smectite mixtures are important for fault slip behavior in shallow parts of subduction zones. We performed a series of friction experiments on volcanic glass-smectite mixtures with different smectite contents at various velocity conditions from 10 µm/s to 1 m/s under an effective normal stress of 5 MPa and pore pressure of 10 MPa. In general, friction coefficients negatively depend on the smectite content at any velocity tested. We found that samples with smectite contents of 15-30 % showed a drastic slip-weakening behavior at intermediate velocities of 1-3 mm/s with a characteristic slip displacement of ~0.1 m. Finite element method modeling shows that thermal pressurization does not contribute to the observed weakening behavior. We propose that gouge fluidization or compaction-induced pore pressure increase may be the cause of the weakening. The slip-weakening behavior at intermediate velocities enlarges a critical nucleation length for frictional instability to 1-30 km, or prevent acceleration to seismic slip velocities. Therefore, gouges with minor amount of clay, such as subducting volcanic ash layers, may contribute to the occurrence of the at shallow depths in subduction zones.

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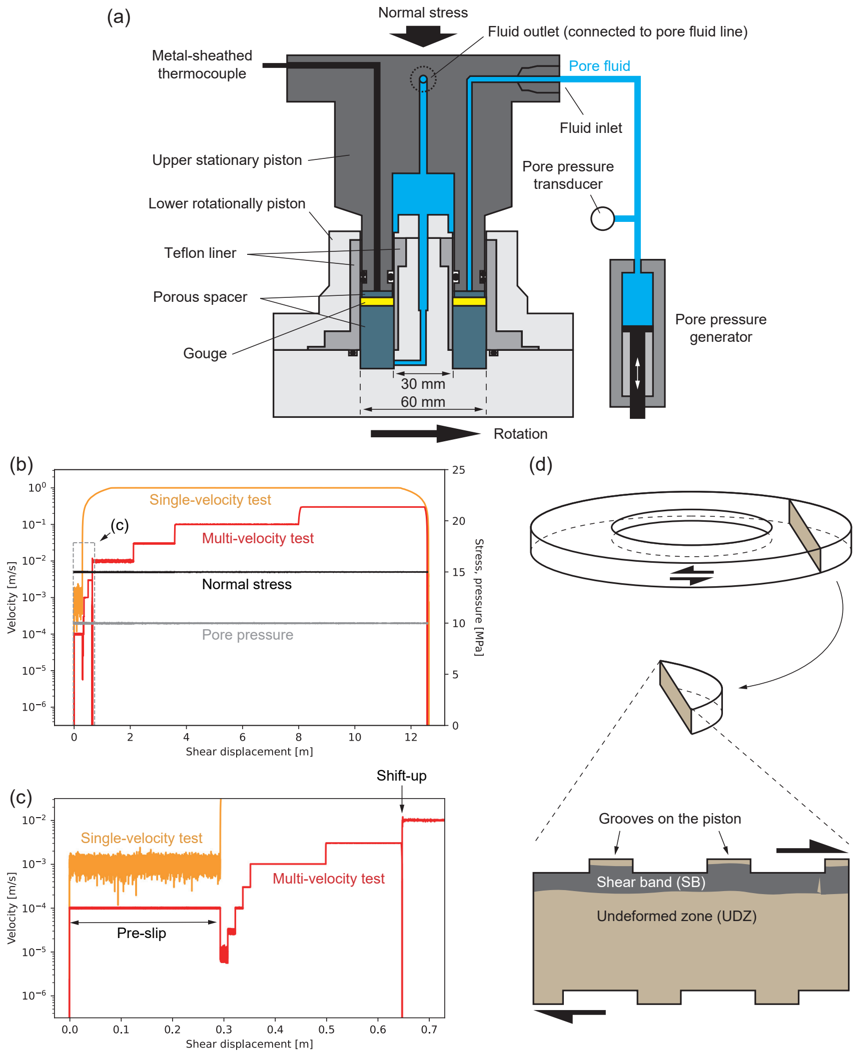
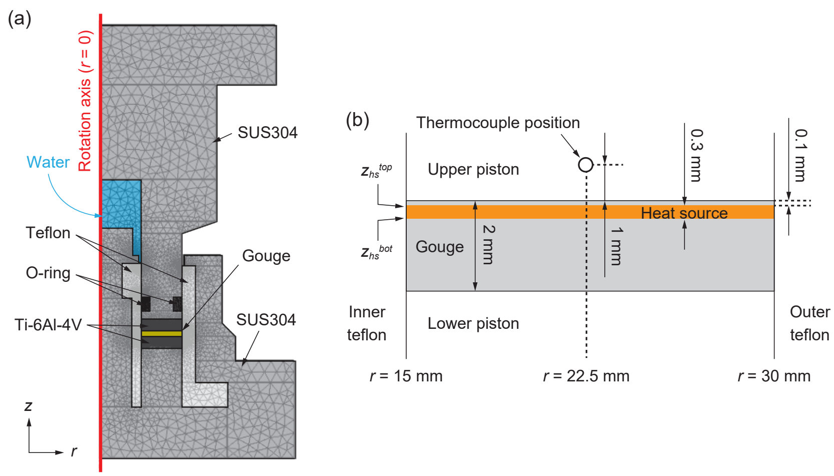
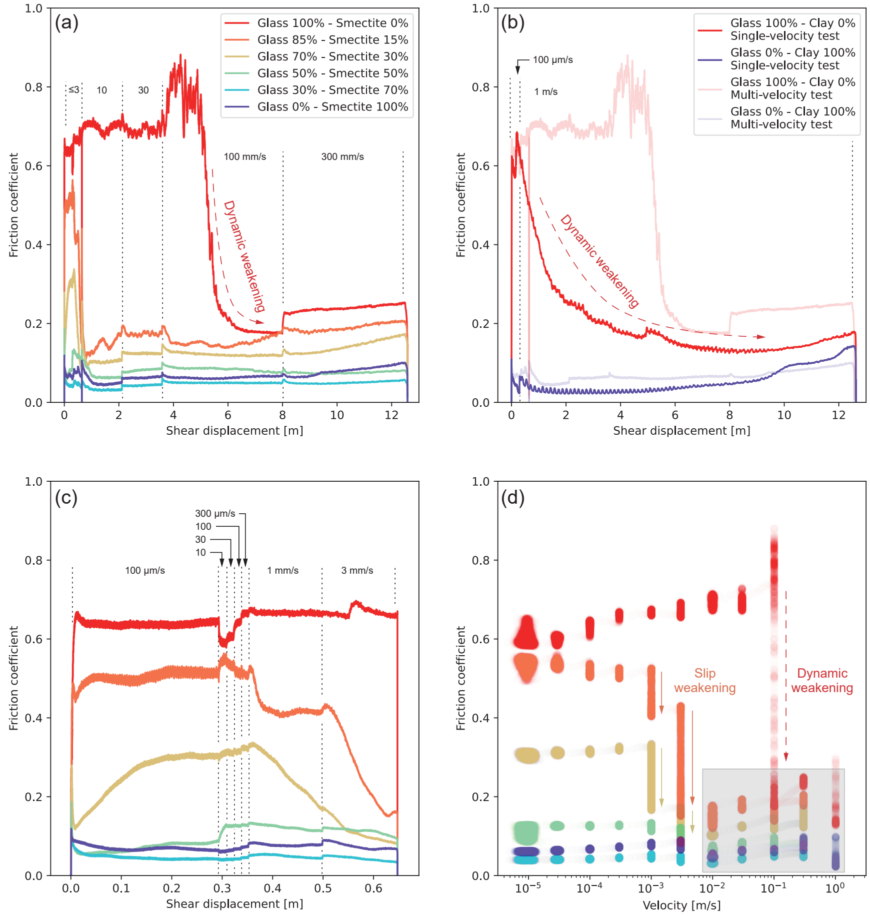
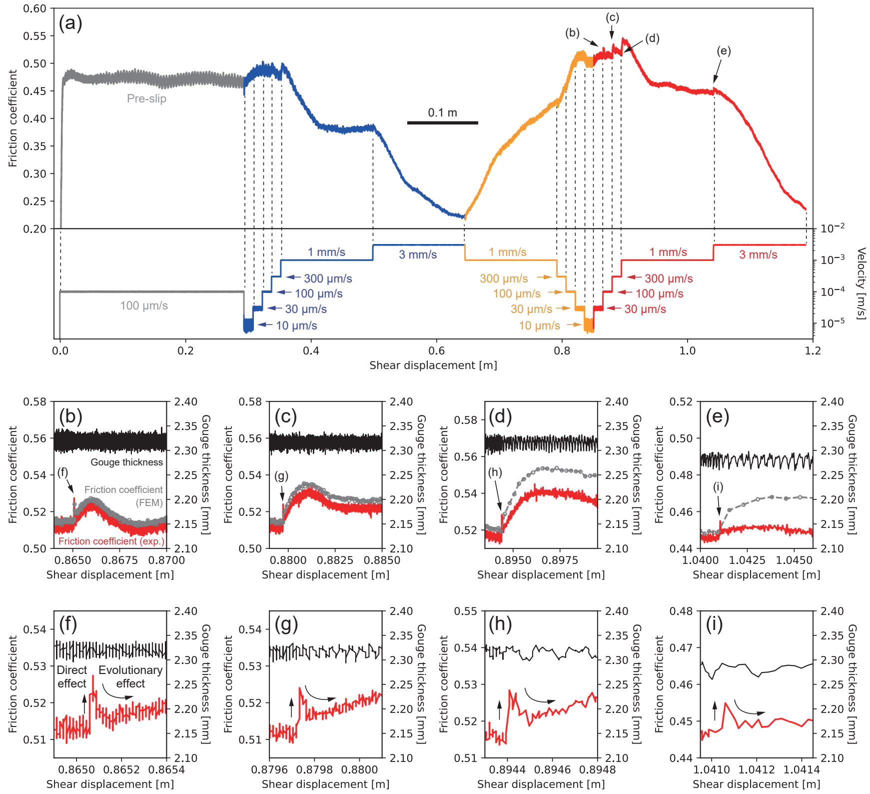
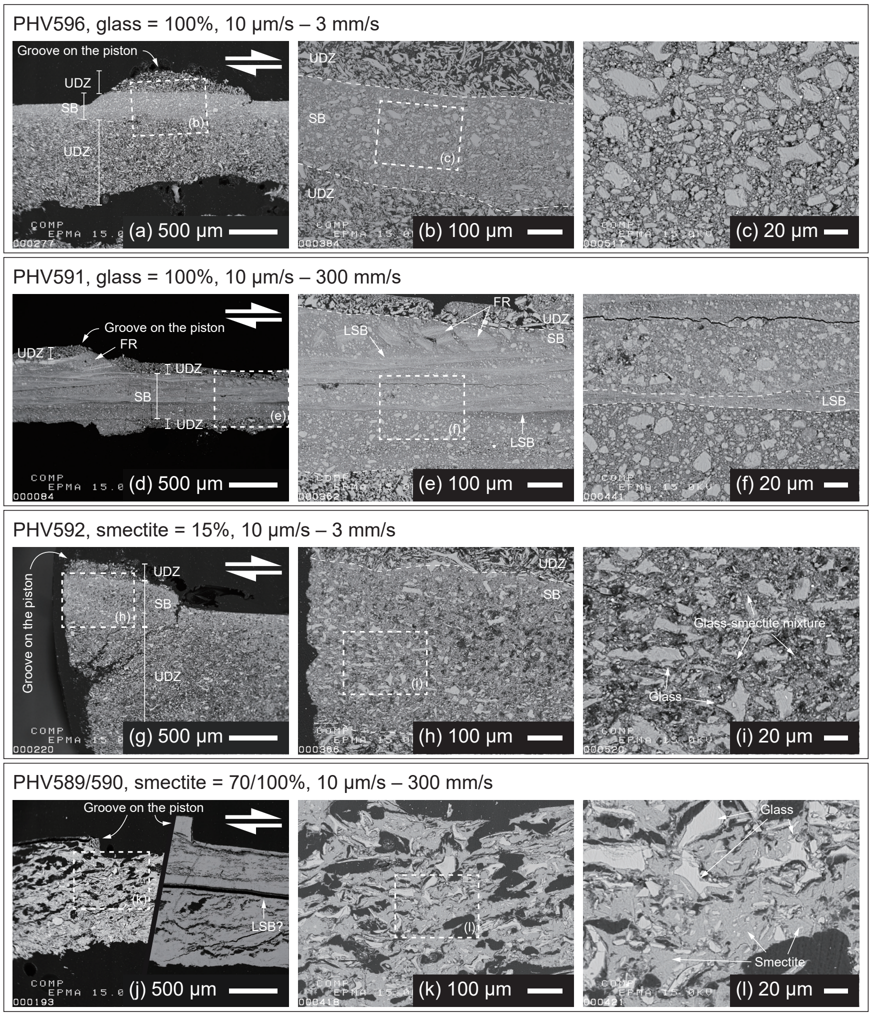

(a)
Normal stress
Fluid outlet (connected to pore fluid line)
Metal-sheathed thermocouple
Pore fluid
Fluid inlet
Upper stationary piston
Lower rotationally piston
Pore pressure transducer
Teflon liner
Porous spacer
Pore pressure generator
Gouge
30 mm
60 mm
Rotation
(b)
Single-velocity test
Multi-velocity test
Normal stress
Pore pressure
Velocity [m/s]
Stress, pressure [MPa]
Shear displacement [m]
(c)
Shift-up
Pre-slip
(d)
Grooves on the piston
Shear band (SB)
Undeformed zone (UDZ)

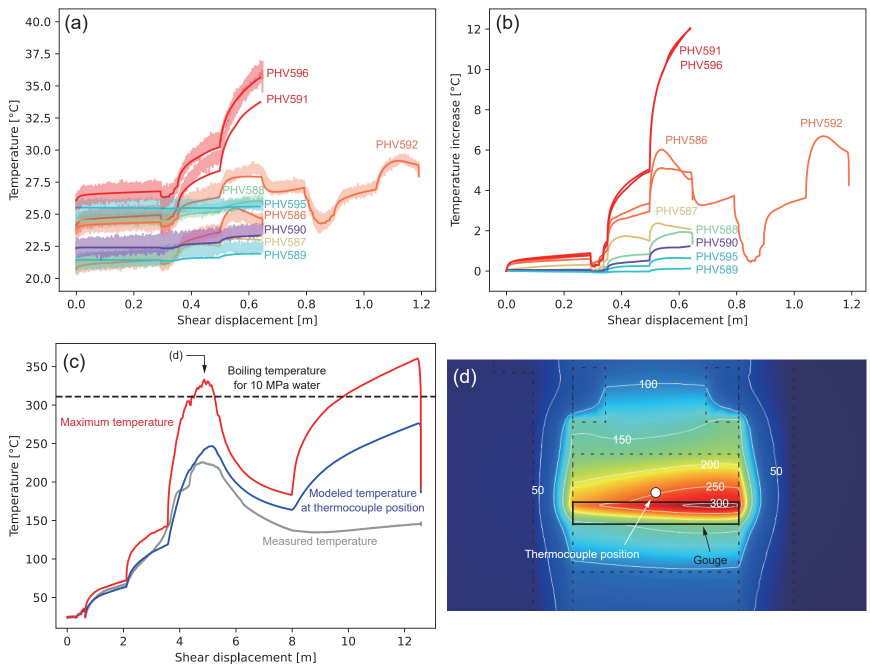

(a)
Rotation axis (r = 0)
SUS304
Water
Teflon
O-ring
Ti-6Al-4V
Gouge
SUS304
z
r
(b)
Thermocouple position
Upper piston
0.3 mm
0.1 mm
Heat source
Gouge
2 mm
1 mm
Inner teflon
Lower piston
Outer teflon
r = 15 mm
r = 22.5 mm
r = 30 mm

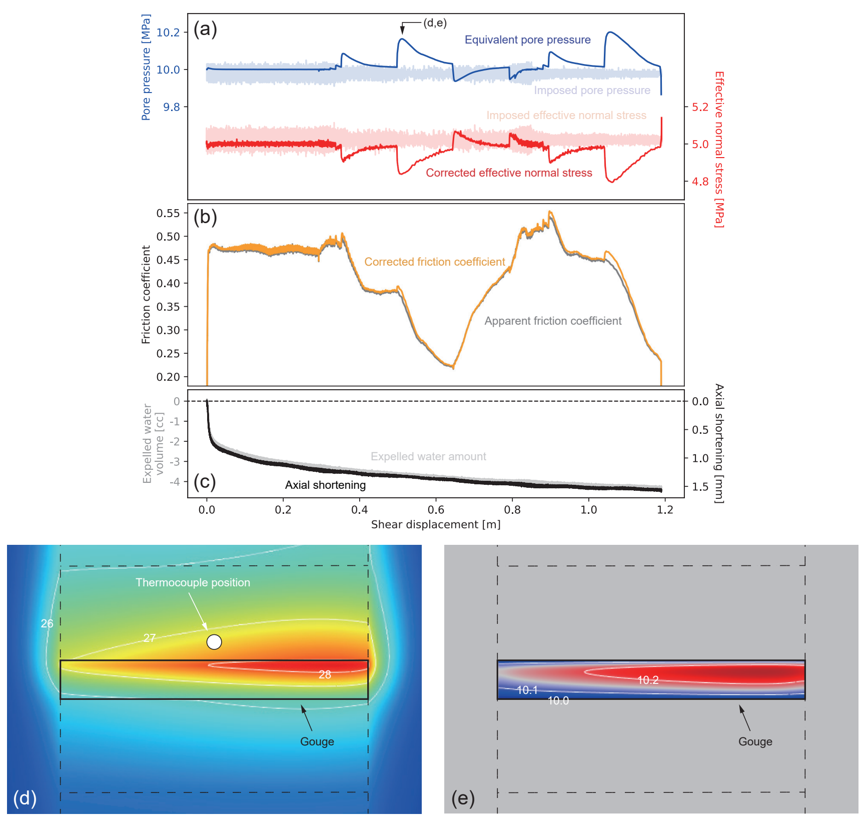


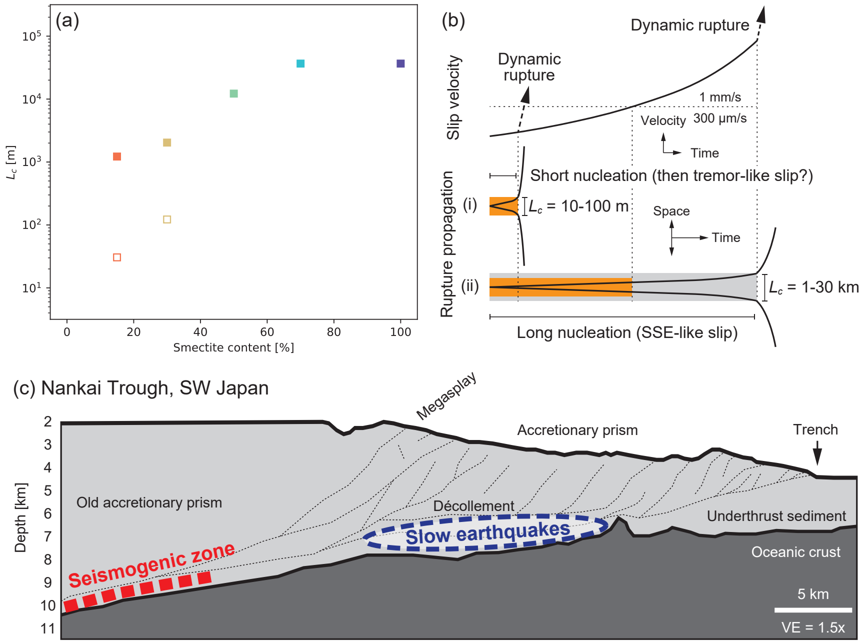
(a)
Glass 100% - Smectite 0%
Glass 85% - Smectite 15%
Glass 70% - Smectite 30%
Glass 50% - Smectite 50%
Glass 30% - Smectite 70%
Glass 0% - Smectite 100%
≤3
10
30
100 mm/s
300 mm/s
Dynamic weakening
Friction coefficient
Shear displacement [m]
(b)
Glass 100% - Clay 0%
Single-velocity test
Glass 0% - Clay 100%
Single-velocity test
Glass 100% - Clay 0%
Multi-velocity test
Glass 0% - Clay 100%
Multi-velocity test
100 μm/s
1 m/s
Dynamic weakening
Friction coefficient
Shear displacement [m]
(c)
300 μm/s
100
30
10
100 μm/s
1 mm/s
3 mm/s
Friction coefficient
Shear displacement [m]
(d)
Slip weakening
Dynamic weakening
Friction coefficient
Velocity [m/s]

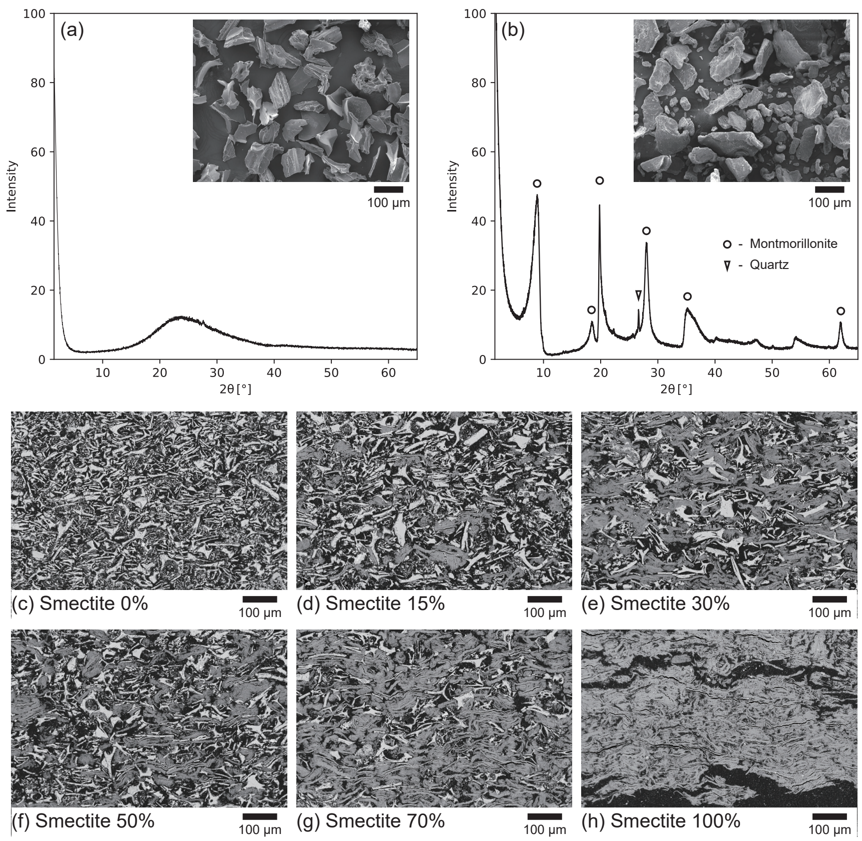

(a)
Friction coefficient
Pre-slip
0.1 m
(b)
(c)
(d)
(e)
100 μm/s
10 μm/s
30 μm/s
100 μm/s
300 μm/s
1 mm/s
3 mm/s
Velocity [m/s]
Shear displacement [m]
Gouge thickness
Friction coefficient (FEM)
Friction coefficient (exp.)
Gouge thickness [mm]
(f)
(g)
(h)
(i)
Direct effect
Evolutionary effect


PHV596, glass = 100%, 10 μm/s – 3 mm/s
Groove on the piston
UDZ
SB
UDZ
(b)
(a) 500 μm
UDZ
SB
(c)
UDZ
(b) 100 μm
(c) 20 μm
PHV591, glass = 100%, 10 μm/s – 300 mm/s
Groove on the piston
UDZ
FR
UDZ
SB
UDZ
(e)
(d) 500 μm
FR
UDZ
SB
LSB
(f)
LSB
(e) 100 μm
LSB
(f) 20 μm
PHV592, smectite = 15%, 10 μm/s – 3 mm/s
Groove on the piston
UDZ
SB
(h)
UDZ
(g) 500 μm
UDZ
SB
(i)
(h) 100 μm
Glass-smectite mixture
Glass
(i) 20 μm
PHV589/590, smectite = 70/100%, 10 μm/s – 300 mm/s
Groove on the piston
(k)
LSB?
(j) 500 μm
(l)
(k) 100 μm
Glass
Smectite
(l) 20 μm


(a)
Temperature [°C]
Shear displacement [m]
PHV596
PHV591
PHV592
PHV588
PHV595
PHV586
PHV590
PHV587
PHV589
(b)
Temperature increase [°C]
Shear displacement [m]
PHV591
PHV596
PHV592
PHV586
PHV587
PHV588
PHV590
PHV595
PHV589
(c)
(d)
Boiling temperature
for 10 MPa water
Maximum temperature
Modeled temperature
at thermocouple position
Measured temperature
Temperature [°C]
Shear displacement [m]
(d)
100
150
200
250
300
50
50
Thermocouple position
Gouge


(a)
(d,e)
Pore pressure [MPa]
Equivalent pore pressure
Imposed pore pressure
Imposed effective normal stress
Corrected effective normal stress
Effective normal stress [MPa]
(b)
Friction coefficient
Corrected friction coefficient
Apparent friction coefficient
(c)
Expelled water volume [cc]
Expelled water amount
Axial shortening
Axial shortening [mm]
Shear displacement [m]
Thermocouple position
26
27
28
Gouge
(d)
10.1
10.2
10.0
Gouge
(e)


(a)
L_c [m]
Smectite content [%]
(b)
Dynamic rupture
Dynamic rupture
Slip velocity
1 mm/s
300 µm/s
Velocity
Time
Short nucleation (then tremor-like slip?)
(i)
L_c = 10-100 m
Space
Time
Rupture propagation
(ii)
L_c = 1-30 km
Long nucleation (SSE-like slip)
(c) Nankai Trough, SW Japan
Megasplay
Accretionary prism
Trench
Old accretionary prism
Décollement
Underthrust sediment
Slow earthquakes
Oceanic crust
Seismogenic zone
Depth [km]
5 km
VE = 1.5x


(a)
Intensity
2θ [°]
100 µm
(b)
Intensity
2θ [°]
100 µm
○ - Montmorillonite
▽ - Quartz
(c) Smectite 0%
100 µm
(d) Smectite 15%
100 µm
(e) Smectite 30%
100 µm
(f) Smectite 50%
100 µm
(g) Smectite 70%
100 µm
(h) Smectite 100%
100 µm

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Potential role of volcanic glass-smectite mixtures in slow earthquakes in shallow subduction zones: Insights from low- to high-velocity friction experiments

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Abstract

Volcanic glass and its mixture with smectite are commonly observed in shallow parts of subduction zones. As volcanic glass layers often act as a glide plane to induce mass transportation such as submarine landslides, and because its alteration product, smectite, is one of the frictionally weakest geological materials, the frictional characteristics of volcanic glass-smectite mixtures are important for fault slip behavior in shallow parts of subduction zones. We performed a series of friction experiments on volcanic glass-smectite mixtures with different smectite contents at various velocity conditions from 10 μm/s to 1 m/s under an effective normal stress of 5 MPa and pore pressure of 10 MPa. In general, friction coefficients negatively depend on the smectite content at any velocity tested. We found that samples with smectite contents of 15-30 % showed a drastic slip-weakening behavior at intermediate velocities of 1-3 mm/s with a characteristic slip displacement of ~0.1 m. Finite element method modeling shows that thermal pressurization does not contribute to the observed weakening behavior. We propose that gouge fluidization or compaction-induced pore pressure increase may be the cause of the weakening. The slip-weakening behavior at intermediate velocities enlarges a critical nucleation length for frictional instability to 1-30 km, or prevent acceleration to seismic slip velocities. Therefore, gouges with minor amount of clay, such as subducting volcanic ash layers, may contribute to the occurrence of the slow earthquakes at shallow depths in subduction zones.

Plain language summary

Materials erupted from volcanoes deposit on the seafloor and subduct at the trench. One such material, volcanic glass, easily turns into mechanically weak clay minerals such as smectite that can cause an enormous slip during an earthquake in subduction zones. In this study, we experimentally examined the frictional properties of mixtures of volcanic glass and smectite to elucidate fault slip behavior in shallow depths of subduction zones. Experiments with varying smectite content showed that a drastic reduction in fault frictional strength was induced when a small amount of smectite was present at moderately high velocity conditions. This behavior may induce slow earthquakes that could be related to huge earthquakes in subduction zones.

Key points

- Small amount of clay mineral induces a drastic slip-weakening at ~1 mm/s.
- Thermal processes do not contribute to the weakening behavior.
- Slip-weakening enlarges critical nucleation length leading to slow earthquakes.

1. Introduction

In subduction zones, the downgoing slab provides fluids to the upper plate leading to melt production and the formation of arc volcanoes. Erupted materials from these arc volcanoes, which mainly consist of volcanic glass, deposit on the incoming plate and subduct at the trench as ash layers or dispersed ash in the incoming sediment (Screaton et al., 2009). At the Nankai Trough, for example, approximately 35% of the incoming sediment is of volcanic origin (Scudder et al., 2018). As volcanic glass reacts progressively with water to form smectite through diagenetic and weathering processes (Compton, 1991), and because smectite is frictionally weak (Morrow et al., 2017), the frictional properties of volcanic glass-smectite mixtures are important for understanding natural hazards associated with subduction zones and volcanic regions, such as earthquakes and landslides. For example, hemipelagic smectite may have been responsible for the large fault slip that occurred near the trench during the 2011 Tohoku-Oki earthquake at the Japan Trench (Chester et al., 2013; Ujiie et al., 2013), with the smectite originating from altered volcanic glass that was deposited on the northwestern part of the Pacific Plate (Kameda et al., 2015). Seismic fault behavior can also occur in these volcanic materials during caldera collapse or magma ascent (Han et al., 2019; Lavallée et al., 2014), and volcanic ash layers may also act as glide planes for subaqueous and terrestrial landslides (Wiemer & Kopf, 2017). Such examples of ash layers at the base of the mass-transport deposits have been reported at the Nankai Trough (Laberg et al., 2017; Strasser et al., 2012), the Middle America Trench (Harders et al., 2010) and Lake Villarrica in Chile (Wiemer et al., 2015), as well as for terrestrial landslides in New Zealand and Japan (Kluger et al., 2020; Moon, 2016; S. Nakamura et al., 2014; Shimizu & Ono, 2016).

Despite its potentially important role in natural hazards, our understanding of the frictional behavior of volcanic glass-smectite mixtures is limited. Previous experimental studies have shown that volcanic glass has friction coefficients of 0.6-0.8 at low velocity conditions less than 1 mm/s (Lavallée et al., 2014; Wiemer & Kopf, 2015), consistent with “Byerlee's rule” for rock friction (Byerlee, 1978). When it is mixed with smectite, the frictional strength of the glass-smectite mixture shows an inverse relationship with smectite content (Wiemer & Kopf, 2015), similar to other previous results where weak clay minerals have been mixed with non-clay minerals (Bedford et al., 2022; Ikari et al., 2018; Logan & Rauenzahn, 1987; Okuda et al., 2021; Takahashi et al., 2007; Tembe et al., 2010). At a high slip-velocity up to 1.3 m/s, the frictional strength of volcanic glass is dynamically weakened (Lavallée et al., 2014). As for smectite, a low friction coefficient of 0.1-0.2 under wet conditions has been reported at low sliding velocities (Morrow et al., 2017). Friction is also low at high sliding velocities, but thermal pressurization additionally plays a significant role in the weakness of wet smectite during high velocity slip (Faulkner et al., 2011; Ujiie & Tsutsumi, 2010). Although we have some constraints on the individual frictional behaviors of smectite and volcanic glass from the previous studies mentioned above, there is a lack of data on their frictional behavior when they are mixed together and sheared over a range of velocity conditions, particularly intermediate velocities of an order of 1 mm/s.

To understand better the frictional behavior of volcanic glass-smectite mixtures, we performed a series of friction experiments from low to high velocity under controlled pore pressure conditions. Based on the obtained frictional properties of glass-smectite mixtures, we discuss the implications for fault slip behavior at shallow subduction zones where volcanic glass is abundant (e.g., the Nankai Trough, SW Japan).

2. Method

2.1. Materials

Volcanic glass samples erupted from the Baekdusan volcano in the North Korea, collected at the southern part of Hokkaido, Japan (Y. Nakamura, 2016; Nakanishi et al., 2020), were used for experiments. This volcanic glass has been used as a chronological marker of the eruption at Baekdusan volcano in 10th century, and few minerals other than glass are present after being transported over 1000 km (Y. Nakamura, 2016). Samples were sieved to obtain particle sizes between 63-250 μm. The broad halo without significant peaks in the XRD profile indicates the sample has little impurity and is predominantly comprised of amorphous glass (Figure 1a). Scanning electron microscope (SEM) images shows that the glass consists of angular shards (Figure 1a). For the smectite sample, we used commercially available purified smectite (“Kunipia-F” provided by Kunimine Industries Co. Ltd., Japan), comprised of montmorillonite with less than 2% quartz as an impurity. Mean grain size is reported to be 2.5 μm, but particle aggregates can be several hundred micrometers in diameter (Figure 1b). No disaggregation procedure was employed. We prepared 10 g testing samples for each experiment by mixing volcanic glass and smectite with different gravimetric smectite content under room dry condition (Table 1).

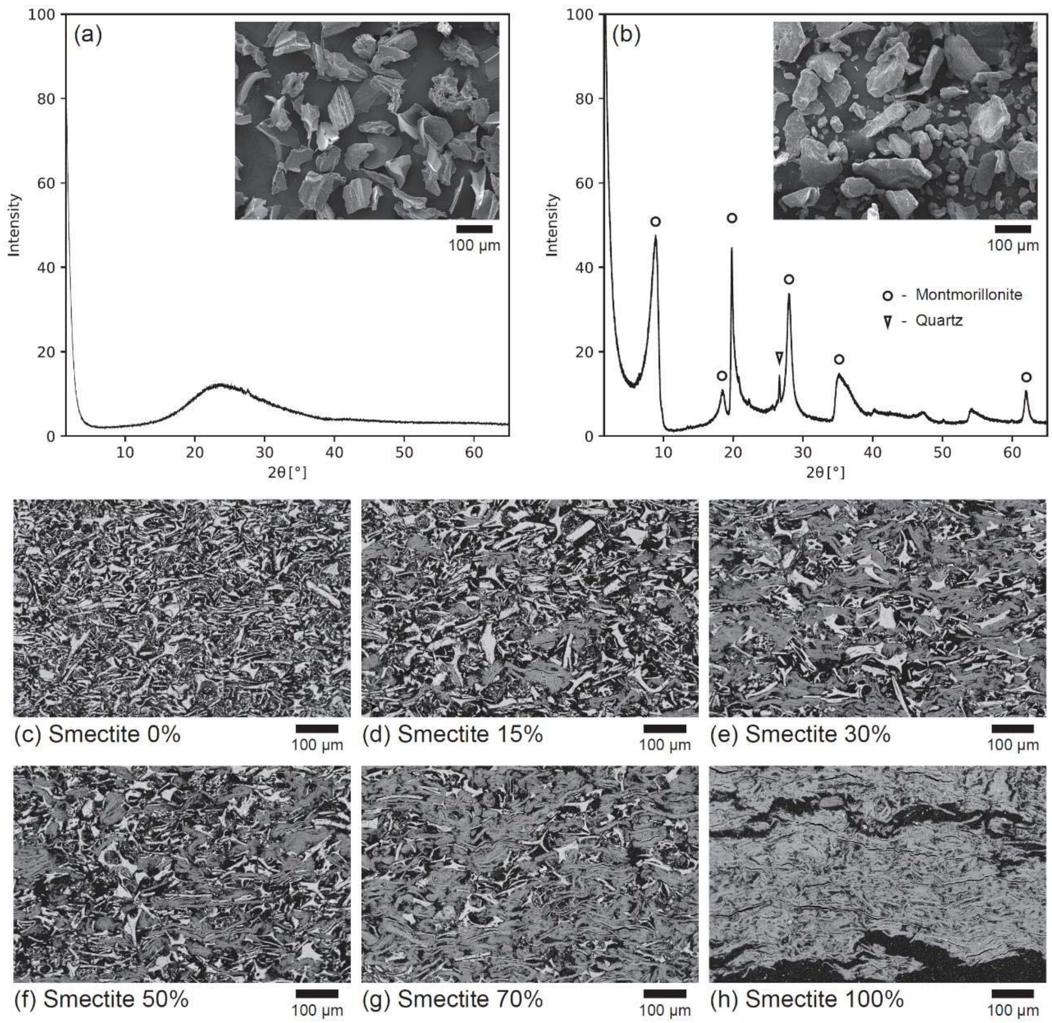

Figure 1.

XRD profiles and SEM micrographs for (a) volcanic glass and (b) smectite. (c-h) Unsheared microstructures (SEM backscattered electron images) for each tested clay mineral content after applying the effective normal stress of 5 MPa. Bright, angular grains are volcanic glass particles, dark areas are smectite particles, and black areas are epoxy resin.

2.2. Experimental procedure

Friction experiments were conducted using the pressurized high-velocity (PHV) rotary shear apparatus located in Kochi Institute for Core Sample Research, JAMSTEC, Japan (Figure 2a, Tanikawa et al., 2012, 2015). Experimental samples were inserted into the hollow cylindrical sample chamber (outer and inner diameters of 60 and 30 mm, respectively) and sandwiched between metal porous spacers. The samples are confined by Teflon liners and O-rings. The initial thickness of the gouge layer was about 4.5 mm for the 100% glass sample and 2 mm for the 100% smectite sample. Pore water was introduced to the gouge through both the upper and lower porous spacers (Rempe et al., 2017). Pore fluid pressure (P_f) was kept constant at a value of 10 MPa during the experiments and changes in the pore water volume (e.g., due to compaction/dilation) were monitored by the pore pressure generator. Temperature (T) was measured just above the gouge layer by a metal-sheathed thermocouple. Normal stress (σ_n) was applied from the upper loading side to keep an effective normal stress (σ_{eff}) of 5 MPa to simulate the pressure conditions experienced in the shallow regions of subduction zones. The shear stress (τ) was applied by the lower rotational side. As the slip velocity (V) varies depending on the distance from the rotation axis, we use the "equivalent" velocity (V_{eq}) for the representative V (Shimamoto & Tsutsumi, 1994) defined as follows:

$$V_{eq} = \frac{4\pi R(r_o^2 + r_o r_i + r_i^2)}{3(r_o + r_i)}, \#(1)$$

where R is the revolutions rate, r_o and r_i are the inner and outer radii of the hollow cylindrical specimen, which are 15 and 30 mm, respectively. In most tests, V_{eq} was initially set to be 100 μm/s for the first 300 mm of shear displacement (nominally "pre-slip”), and then reduced to 10 μm/s followed by stepwise increases by a factor of 3 up to 300 mm/s (“multi-V test”). Acceleration and deceleration rates were set to be 0.5 m/s^2. Before stepping from 3 mm/s to 10 mm/s, rotation was stopped for a short time to shift from the slow gear to the fast gear. During rotation with the slow gear, the acceleration rate during the velocity steps is quick enough to be regarded as an abrupt change in V_{eq}, up to the step from 1 mm/s to 3 mm/s where the acceleration phase finished in less than 0.004 s. Shear displacements were set to be 15 mm for V_{eq} = 10-300 μm/s, 150 mm for V_{eq} = 1 and 3 mm/s, 1.5 m for V_{eq} = 10 and 30 mm/s, and 4.5 m for V_{eq} = 100 and 300 mm/s (Figure 2b). For samples with smectite contents of 0, 15, and 70%, experiments with low V_{eq} from 10 μm/s to 3 mm/s were also conducted (PHV596, 592, and 595; “low-V test”). For the 15%-smectite sample, V_{eq} was reduced to 10 μm/s after it reached to 3 mm/s, and then increased again to 3 mm/s (PHV592). Additional tests for 100%-smectite and 100%-glass samples were conducted with V_{eq} of 1 m/s for 12.5 m after the pre-slip of 300 mm with V_{eq} = 1 mm/s (PHV593 and 594; “single-velocity test”). Test conditions are summarized in Table 1. Friction coefficient μ is calculated by dividing τ with σ_{eff}. The τ value between Teflon liner and O-ring was less than 0.15 MPa under P_f = 10 MPa conditions at V_{eq} < 3 mm/s; no correction for the seal friction was applied. Axial displacement, volume of pore water expelled from the gouge, and T in the vicinity of the gouge were measured during experiments to evaluate the gouge thickness and fluid expulsion. All experimental data were collected at a sampling rate of 100 Hz.

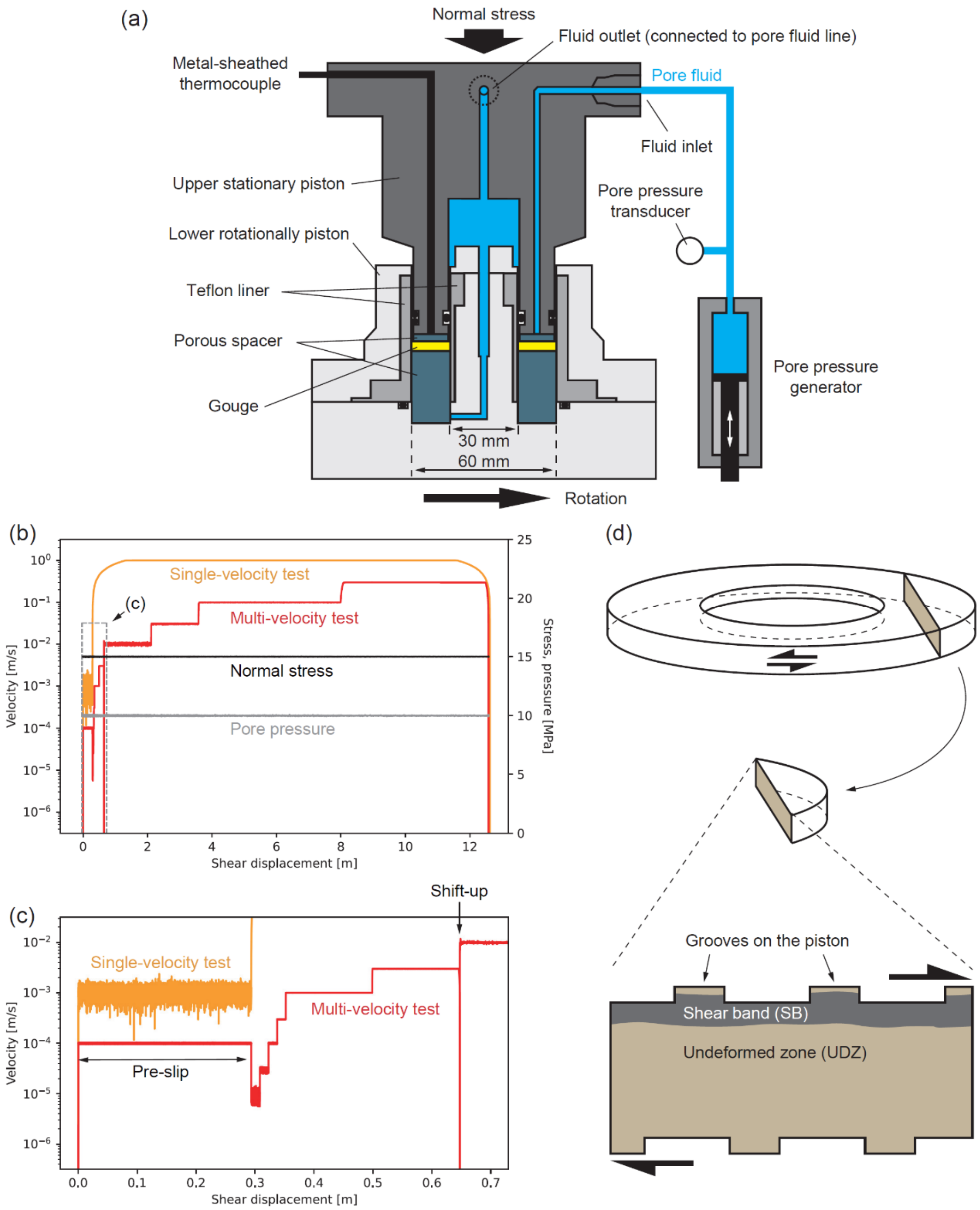

Figure 2.

(a) Schematic view of the experimental configuration. (b and c) Velocity sequences employed in this study. (d) Location for the microstructural observation and the schematic deformation texture.

Table 1.

List of experiments in this study.

Run	Glass / smectite [%]	V_{eq} [m/s]	Displacement [m]	Comment
PHV591	100 / 0	$10^{-5} – 10^{-0.5}$	13	Multi-*V* test
PHV586	85 / 15	$10^{-5} – 10^{-0.5}$	13	Multi-*V* test
PHV587	70 / 30	$10^{-5} – 10^{-0.5}$	13	Multi-*V* test
PHV588	50 / 50	$10^{-5} – 10^{-0.5}$	13	Multi-*V* test
PHV589	30 / 70	$10^{-5} – 10^{-0.5}$	13	Multi-*V* test
PHV590	0 / 100	$10^{-5} – 10^{-0.5}$	13	Multi-*V* test
PHV593	100 / 0	10^{0}	13	Single-*V* test
PHV594	0 / 100	10^{0}	13	Single-*V* test
PHV592	85 / 15	$10^{-5} – 10^{-2.5}$	1.2	Low-*V* test with additional *V* steps
PHV595	30 / 70	$10^{-5} – 10^{-2.5}$	0.7	Low-*V* test
PHV596	100 / 0	$10^{-5} – 10^{-2.5}$	0.7	Low-*V* test

2.3. Microstructural observations

After the experiments, gouge samples were retrieved from the apparatus and impregnated with epoxy resin so they could be cut and polished to obtain cross-sectional microstructural images normal to the gouge layer and subparallel to the shear direction (Figure 2d). The microstructural images were acquired at the Atmosphere and Ocean Research Institute (University of Tokyo, Japan) using a JEOL JXA-8900 scanning electron microscope (SEM) with an accelerating voltage of 15 kV. As it was difficult to recover the entire sample due to the unconsolidated nature of the gouge, we focused our observations on the structures in the vicinity of the shear band that forms near the edge of the gouge layer (SB, Figure 2d), where the shear deformation is localized compared to surrounding undeformed zone (UDZ, Figure 2d).

2.4. Finite Element Method (FEM) modeling

To constrain the T and P_f conditions inside the gouge, we used COMSOL Multiphysics® software and modeled time-dependent heat transfer and fluid diffusion which follow the equations below (Rice, 2006):

$$\frac{\partial T}{\partial t} = \frac{1}{\rho_g C_p} \nabla (K \nabla T) + \frac{A(r)}{\rho_g C_p}, \#(2)$$

$$\frac{\partial P_f}{\partial t} = \frac{1}{\rho_f \phi (\beta_f + \beta_\phi)} \nabla \left(\frac{\rho_f k}{\eta_f} \nabla P_f \right) + \frac{(\gamma_f - \gamma_\phi)}{(\beta_f + \beta_\phi)} \frac{\partial T}{\partial t}, \#(3)$$

where t is time, ρ_f is water density, ρ_g is density of a material, C_p is heat capacity of a material, K is thermal conductivity of a material, γ_f is water thermal expansivity, γ_ϕ is pore space thermal expansivity, β_f is water compressibility, β_ϕ is pore space compressibility, ϕ is porosity, η is water viscosity, k is permeability (see Table 2 for details). We assume $k = 10^{-20}$ m^2 to simulate the low permeability nature of clay-mixed gouge (Oohashi et al., 2015; Takahashi et al., 2007). $A(r)$ is heat generation per unit volume at the distance from the rotation axis r calculated as follows:

$$A(r) = \frac{1}{w_{hs}} V(r)\tau = \frac{1}{w_{hs}} \left(\frac{3}{4} (2r) \frac{r_o + r_i}{r_o^2 + r_o r_i + r_i^2} V_{eq} \right) \tau, \#(4)$$

where w_{hs} is thickness of the heat source where shear localized within the gouge and $V(r)$ is velocity at r. We assumed that τ is independent of r within the limited velocity range from $V(r_i) = 0.64V_{eq}$ to $V(r_o) = 1.29V_{eq}$. Dilation/compaction of the gouge and thermoelastic response of the apparatus are not considered in the FEM modeling.

A schematic representation of FEM configuration is shown in Figure 3. The model was made using the axial symmetry, thus only one side of the gouge layer shown. Fluid diffusion (equation 3) is only considered inside the gouge zone with thickness of 2 mm. We set the initial P_f conditions throughout the entire gouge layer to be 10 MPa, and the P_f was fixed at this value at the top and bottom boundaries of the gouge layer (Dirichlet boundary condition). The inner and outer boundaries have no flow of fluid crossing the boundaries. Based on microstructural observations, the heat source inside the gouge was assumed to be concentrated in the shear localized zone (SB) with w_{hs} = 0.3 mm at 0.1 mm below the top of gouge. We extract T data at r = 22.5 mm at a distance of 1 mm above the gouge layer and compare it with the measured T during experiments. For simplicity, shear forces between O-rings and Teflon liners and the frictional heat generated from the outer and inner contacts are ignored in the FEM model. Based on the computed P_f inside the heat source where shear localized, we define P_{feq} which represents the “equivalent” influence of P_f on frictional behavior as follows (see Appendix A1 for details):

$$P_{feq} = \frac{3}{r_o^3 - r_i^3} \int_{r_i}^{r_o} \int_{z_{hs}^{bot}}^{z_{hs}^{top}} \frac{P_f(r,z) r^2}{w_{hs}} dz\, dr, \#(5)$$

where $P_f\,(r, z)$ is the calculated P_f at r and z (direction vertical to the gouge) inside the shear localized zone, z_{hs}^{top} and z_{hs}^{bot} are z for top and bottom ends of the shear localized zone, respectively, thus $w_{hs} = z_{hs}^{top} - z_{hs}^{bot}$. Equation 5 leads to:

$$\mu_{obs}(\sigma_n - P_{fo}) = \mu_{cor}(\sigma_n - P_{feq}), \#(6)$$

where μ_{cor} is the corrected μ value without the influence of pore pressure variation due to frictional heat, and P_{fo} is the imposed P_f (= 10 MPa in this study).

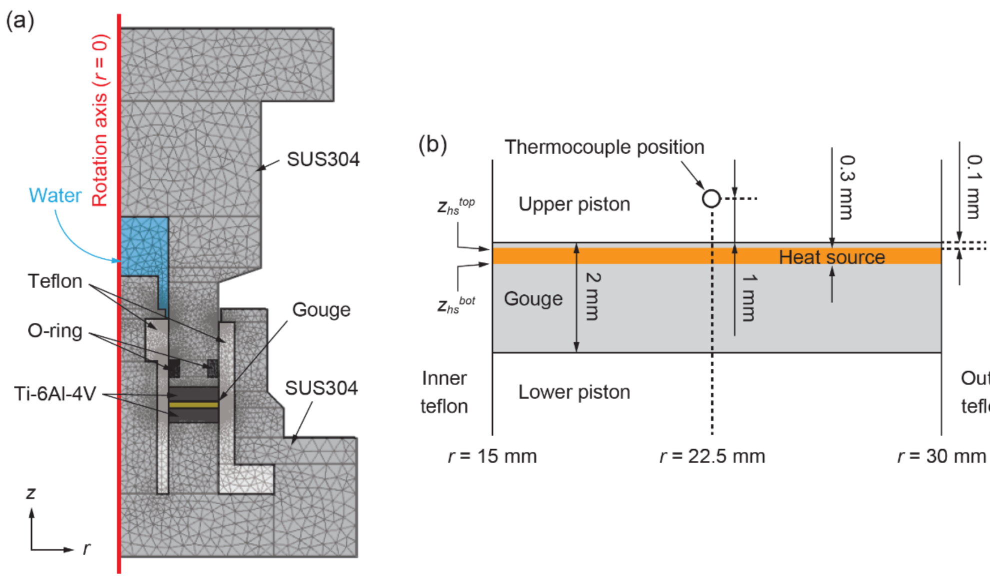

Figure 3.

(a) Geometry and mesh structure for the FEM modeling. (b) Close up view of the gouge with locations of heat source and the thermocouple.

Table 2.

Mechanical properties of components in the FEM model at around room temperature. Dependence on temperature was employed for the parameter with an asterisk.

	Gouge	Pore space	SUS304	Ti-6Al-4V	Teflon	O-ring	Water

ρ [kg/m^3]	2400		*7900	*4420	2200	1800	*1004
C_p [J/kg/K]	1000		*462	*546	1050	1500	*4216
K [W/m/K]	1.5		*14.6	*7	0.25	0.3	*0.56
γ [1/K]		2.4×10^{-5}					5.7×10^{-4}
β [1/Pa]		2.49×10^{-9}					0.49×10^{-9}
ϕ	0.25						
η [Pa.s]							*1.8×10^{-3}
k [m^2]	10^{-20}						

3. Results

3.1. Steady state friction coefficient

Results on frictional strength at all V_{eq} conditions are summarized in Figures 4 and S1. Friction coefficients (μ) of 100%-glass sample ranged from 0.6 to 0.7 with a V-strengthening behavior from V_{eq} = 10 μm/s to 30 mm/s. At V_{eq} = 100 mm/s, μ dynamically weakened from a peak value of 0.8 to a steady state value of 0.2. Such a low μ is also observed at a V_{eq} of 300 mm/s in the multi-V test (Figure 4a) and 1 m/s in the single-V test (Figure 4b).

As smectite content was increased, frictional strength decreased at every V condition. For samples with 15 and 30% smectite, at $V_{eq} \leq$ 300 μm/s, steady state μ values were about 0.5 and 0.3, respectively, with V-neutral or slightly V-weakening trends. At V_{eq} = 1-3 mm/s (intermediate V range), μ decreased to 0.1-0.2 with a characteristic weakening time or distance (see section 3.2) and remained low at higher V_{eq} conditions (Figures 4a and 4c). For samples with more than 50% smectite, μ was as low as 0.1 at every V_{eq} condition, with nearly V-neutral trends.

According to the FEM modeling (section 3.4), at high-V and low-μ conditions ($V > 10^{-2}$ m/s and $\mu < 0.3$), the measured μ may be significantly overestimated by friction between O-ring and Teflon liners. However, it is difficult to estimate exact effect of the seal friction because the amount of gouge materials that extrude from the layer and fill the space between upper and lower pistons and inner and outer Teflon liners may vary with experimental conditions, such as velocity, displacement, and mineral compositions.

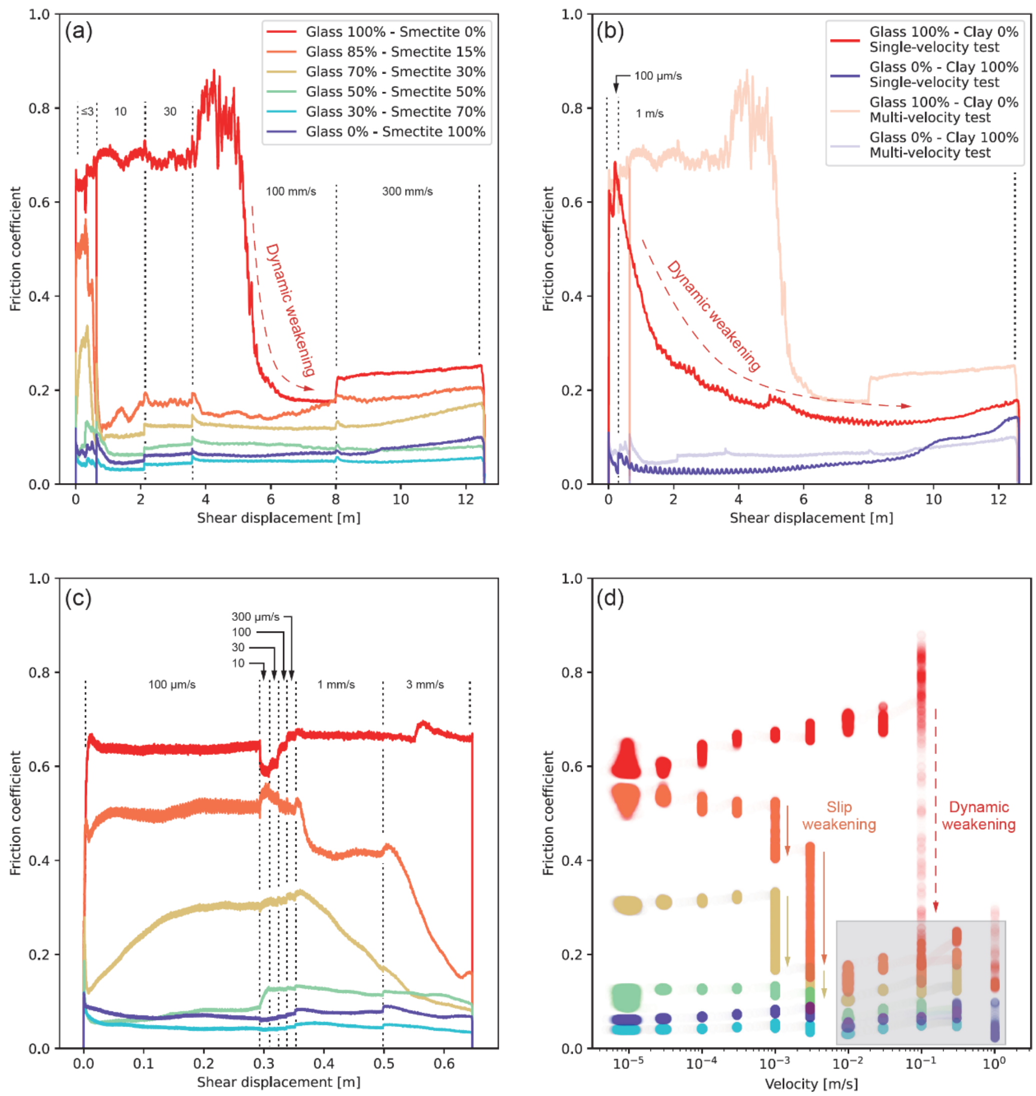

Figure 4.

(a) Mechanical behavior of multi-V tests (V_{eq} = 10 μm/s to 300 mm/s) with different smectite contents. (b) Results of single-V tests (V_{eq} = 1 m/s) for 100%-glass and 100%-smectite cases. Light colors represent the results of multi-V tests and dark colors represent those of single-V tests. (c) Close view of the low-V (V_{eq} < 3 mm/s) part of multi-V tests shown in (a). (d) Relation between μ and V_{eq} for multi-V and single-V tests (V_{eq} = 1 m/s) after the pre-slip stage. Single-V tests were only conducted for the smectite contents of 0 and 100%. Gray area indicates a possible range where friction coefficients are overestimated due to the seal friction.

3.2. Frictional behavior for a sample with 15% smectite at low to intermediate velocity range

To see if the observed weakening behavior for 15%- and 30%-smectite samples at the intermediate V range depend on V_{eq} or on shear strain, we performed an additional experiment (PHV592, 15% smectite) that included both velocity upsteps and downsteps. We found that μ recovered to 0.5 during the V downsteps which is consistent with μ in the low V range before the V upsteps (Figure 5). μ decreased again in the subsequent V upsteps, which implies that the steady-state μ in the intermediate V range is independent of shear strain and only dependent on V.

Just after the V step, μ showed a positive spike followed by a gentle increase and then a decrease to its steady state μ at each V condition (Figures 5b-e). The spikes appear to be comprised of a direct effect and an evolutionary effect described by the rate- and state-dependent friction (RSF) law (Figures 5f-i) (Dieterich, 1979; Ruina, 1983). The evolutionary effect has a characteristic slip distance of ~100 μm. The extent of the increase in μ after the RSF-like behavior seems to be positively related to the imposed V_{eq} conditions, except for the V step from V_{eq} = 1 mm/s to 3 mm/s, although the V steps may be affected by the P_f condition at these slip rates (gray markers in Figures 5b-e; see section 3.4). Little variation in gouge thickness during the V steps was observed (Figures 5b-i). As the V step was imposed within less than 0.004 seconds, and because the gentle increase and decrease in μ occurred after the direct and evolutionary effects, the observed weakening behavior at the intermediate V range to μ = 0.1-0.2 is not a response to V step (like the RSF law) but a slip-weakening behavior toward the steady state μ value for a given V condition. During this behavior, gouge thickness did not vary, whereas the thermocouple captured gentle increases in T especially at V_{eq} = 1 and 3 mm/s (section 3.4).

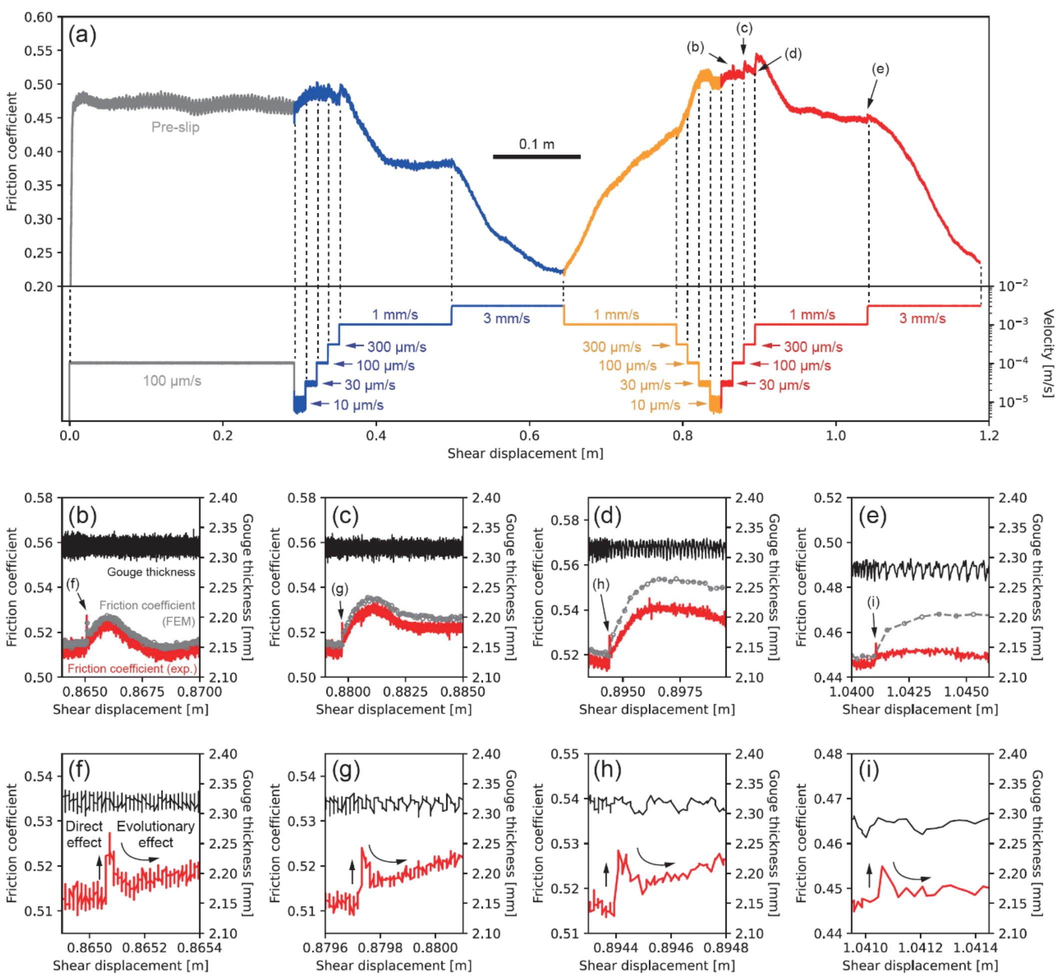

Figure 5.

(a) Experimental result of PHV592 (15% smectite, low-velocity test with additional velocity steps). (b-i) Close-up views of variation in friction coefficient at the velocity steps for PHV592. Red lines are experimental data and gray lines in (b-e) are modeled friction coefficient by FEM after correcting pore pressure effect, and black lines are gouge thickness.

3.3. Microstructure

Before imposing shear deformation, volcanic glass grains kept their original, angular shapes regardless of the smectite content (Figure 1). As the smectite content was increased, volcanic glass grains distributed in the smectite matrix and the numbers of contacts between glass grains reduced. After the shear deformation, samples often showed a localized shear band (SB) in the upper part of the gouge layer, characterized by grain size reduction and an increase in the number of rounded grains compared to the surrounding undeformed zone (UDZ).

The thickness of the SB for the 100%-glass sample sheared at low-V (PHV596, Figures 6a-c) was about 300 μm, with the SB containing more rounded grains than the UDZs. The mean grain size in the SB was less than ~50 μm, with the minimum grain size being <1 μm (Figure 6c).

For the sample with V_{eq} up to 300 mm/s (PHV591, Figures 6d-f), the SB had a similar thickness as the low-V sample (PHV596), however a localized shear band (LSB) with a thickness of 10-20 μm had also formed in the middle of the main SB (Figure 6f). The largest grain size in the LSB was <1 μm, which was significantly smaller than the surrounding SB. The mean grain size in the main SB was several tens of microns, which was a little smaller than that in the SB of the low-V sample (PHV596). In some portions of the SB and UDZ, larger fragments (FR; Figures 6d and 6e) containing features that look like LSBs were observed, possibly indicating reworking of localized bands that formed during previous *V*-steps in the multi-*V* test.

For low-smectite samples (e.g., 15%-smectite, PHV592, low-*V* test), a SB was also observed, however it was a little wider (~500 μm) than 100%-glass case (Figure 6g). The grain size of glass particles was reduced to less than 50 μm (Figure 6h). The grain shape appeared to be a little more angular than 100%-glass case (Figure 6i), and the crushed glass particles were dispersed and mixed with smectite (Figure 6i).

For high-smectite samples, no SB was observed (Figure 6j). No obvious localized feature was observed for the 70%-smectite sample (PHV589) and one shear plane parallel to the deformation was likely observed for 100%-smectite sample (PHV590), although it is potentially an unloading feature. Glass grains in the 70%-smectite sample were not in contact with each other and preserved their original angular shapes and sizes (Figures 1, 6h, and j). As the size of smectite particles was less than 2 μm, we could not easily resolve the deformation within the smectite matrix, although the deformation may be primarily accommodated by smectite matrix.

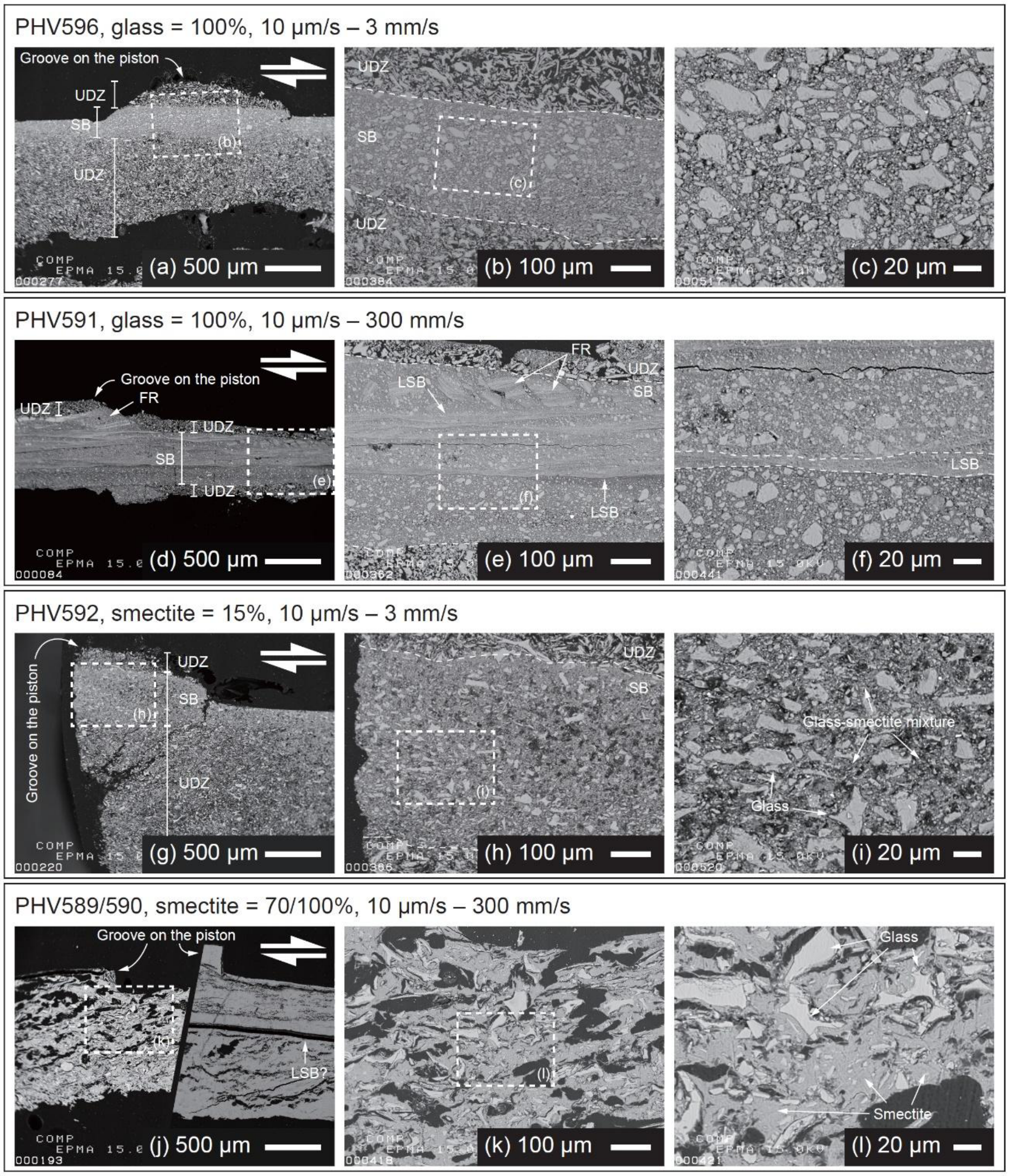

Figure 6.

Microstructures of deformed samples for (a-c) 100%-glass with low-*V* test of PHV596, (d-f) that with multi-*V* test of PHV591, (g-i) 15%-smectite with low-*V* test of PHV592, and (j-l) 70%- or 100%-smectite with multi-*V* tests of PHV589 or 590. The left side of (j) is the microstructure for PHV589 (70% smectite) and the right one is that for

PHV590 (100% smectite). Locations of figures in the center and right columns are shown in the left and center columns, respectively. SB: shear band; UDZ: undeformed zone; LSB: localized shear band; FR: fragment.

3.4. Temperature and pore pressure conditions inside the gouge

In the FEM modeling, we obtained fairly consistent result of *T* with the measured value for the low-*V* tests (Figure 7a). The modeled maximum *T* increase within the gouge is 12°C for 100%-glass, 6-7°C for 85%-glass, and less than 3°C for <70%-glass samples (Figure 7b). For the 100%-glass sample at high-*V* conditions, the modeled *T* at the thermocouple position showed consistent result with measured *T*, at least for shear displacements of <5 m, which is before the friction dynamically weakened (Figure 7c, see also Figure 4a). The maximum *T* inside the gouge reached about 340°C when the shear displacement was 5 m, which was the onset of dynamic weakening (Figure 7d). After the dynamic weakening behavior, the modeled *T* was significantly overestimated, which implies a significant shear resistance between the O-rings and Teflon liners at high-*V* conditions. Such a discrepancy between modeled and measured *T* conditions was also observed for high-*V* conditions with other samples. Hence, the μ of the gouge may be nearly zero at high-*V* conditions, but as we cannot know the true μ as a result of the contribution from O-ring and Teflon friction, we do not discuss the friction values in detail at the *V* conditions of the shaded region in Figure 4d.

The distribution of P_f within the gouge was simultaneously modeled in the FEM modeling. In the case of PHV592 (15% smectite), the maximum *T* increase was only 6-

7°C (Figure 7b) because of slow V and relatively low μ, meaning T within the gouge is far lower than the boiling T of water at $P_f = 10$ MPa (Figure 8c). However, the low permeability nature of the clay-mixed gouge ($k = 10^{-20}$ m^2) caused an increase in P_f inside the gouge of up to 0.3 MPa (Figure 8e), with P_{feq} being about 10.2 MPa just after the V-step from $V_{eq} = 1$ to 3 mm/s (Figure 8a). This P_f build-up caused a reduction in σ_{eff} (Figure 8a) and thus the measured μ was apparently lowered. We corrected the μ in PHV592 by using equations 5 and 6 and found that the measured μ value just after the V-steps from $V_{eq} = 1$ to 3 mm/s was underestimated by about 0.02 (Figure 5e), however this is insufficient to explain the slip-weakening behavior we observe (Figure 8b).

The P_f conditions inside the gouge are also influenced by gouge compaction and dilation, which are not implemented in the FEM modeling. As shear displacement increased during the test, gouge thickness reduced as measured by the shortening in the axial displacement data. The majority of axial shortening occurred during the pre-slip stage, but gouge thickness continuously decreased afterward (Figure 8c). However, the volume of expelled water was consistent with the amount of axial shortening (ideally, the volume of expelled water [cc] = 0.001 [cc/mm^3] × (30 [mm])^2 × π × axial shortening [mm]), suggesting that the P_f build up due to the gouge compaction would be minimal. Furthermore, gouge compaction occurred simultaneously with the slip-hardening in the V downsteps. Therefore, the influence of gouge compaction on P_f is likely to be insignificant and not a dominant cause of the observed slip-weakening behavior and low steady state μ values at $V_{eq} = 1$ and 3 mm/s.

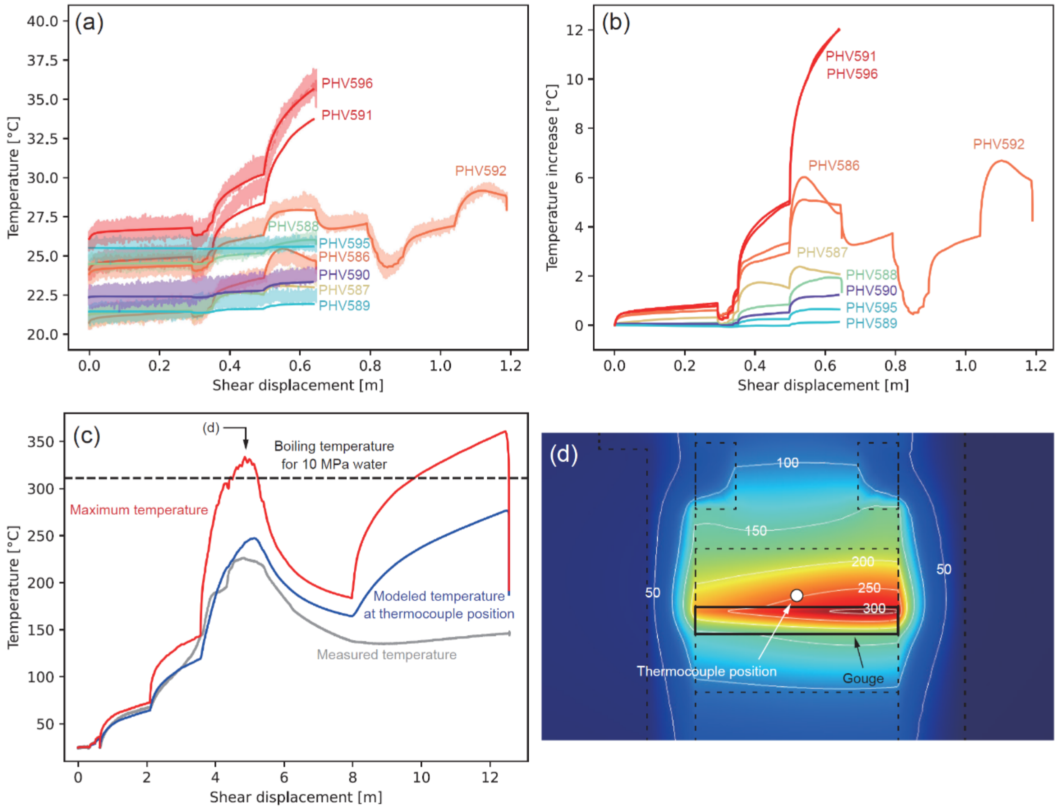

Figure 7.

(a) Measured *T* (light color) and modeled *T* (solid line) at the thermocouple position for low-*V* conditions. (b) Modeled maximum *T* increase within the gouge for low-*V* conditions. (c) Measured *T* (gray), modeled *T* at the thermocouple position (blue) and the maximum *T* inside the gouge (red) for high-*V* conditions of PHV591 (glass 100%). (d) Distribution of *T* around the gouge at the shear displacement of ~5 m indicated in (c).

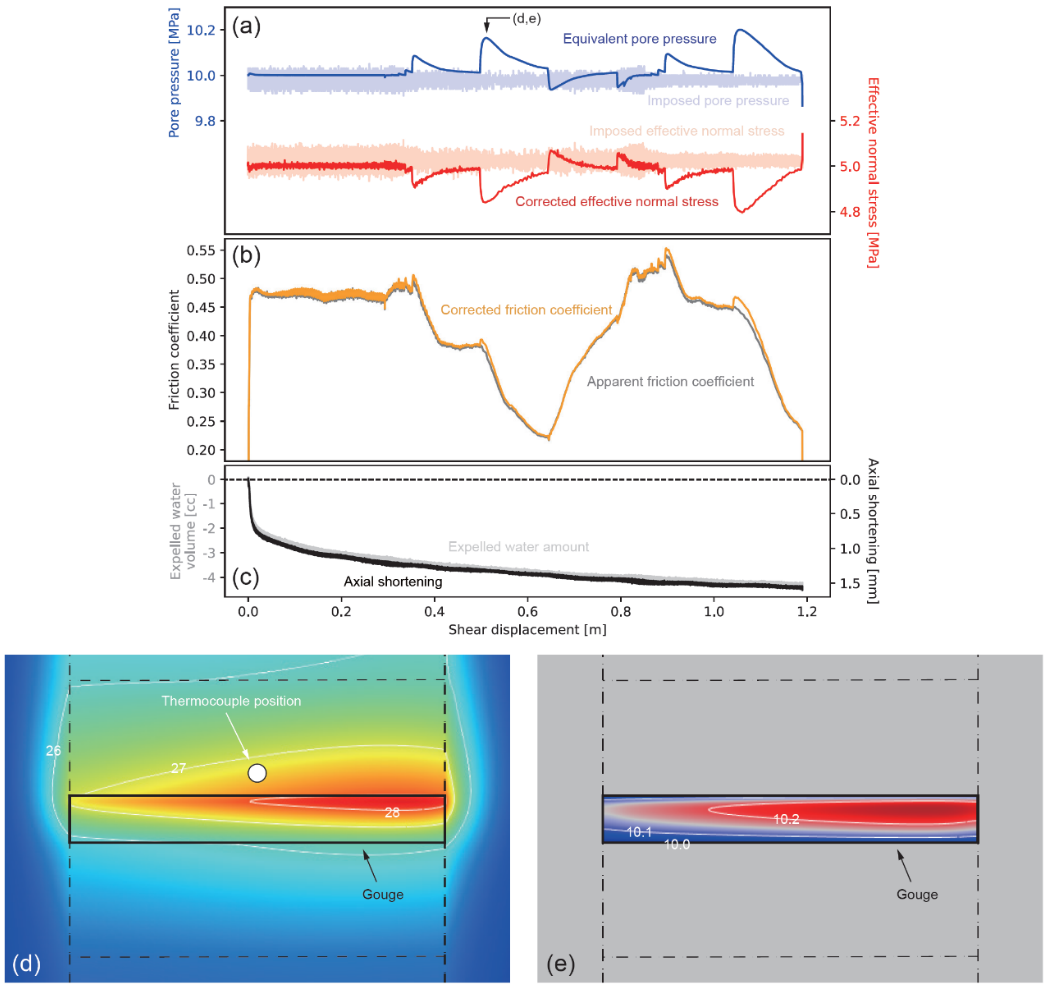

Figure 8.

Equivalent pore pressure and corrected effective normal stress conditions modeled by FEM calculations for PHV592. Permeability of 10^{-20} m^2 was assumed. (b) Apparent (gray line) and corrected friction coefficients (orange line) by the corrected effective normal stress condition. (c) Comparison between the volume of expelled water (gray line) and axial shortening (black line). Results of FEM simulation on (d) temperature and (e) pore pressure conditions at the shear displacement of ~0.5 m, indicated in (a).

4. Discussion

4.1. Dynamic weakening for 100% glass caused by thermal processes

The μ for 100%-glass sample at V_{eq} = 10 mm/s was higher than that typically observed for quartz-rich rocks, which often shows a reduction in frictional strength at similar intermediate slip velocities due to silica-gel lubrication or the formation of amorphous wear materials (Goldsby & Tullis, 2002; Hayashi & Tsutsumi, 2010; Rowe et al., 2019; Di Toro et al., 2004). In addition, because the dynamic weakening in the 100% glass sample occurred just after the maximum T within the gouge reached the boiling T of 311℃ for water with 10 MPa (Figure 7c), the observed dynamic weakening in the multi-V test may be caused by vaporization of the pore water (Acosta et al., 2018; Chen et al., 2017; Hunfeld et al., 2021). This result supports the idea that thermal processes are important for dynamic weakening and that the amorphous grains themselves do not induce the weakening (Kanagawa et al., 2020). Although the FEM modeling of the single-V test could not estimate the T condition inside the gouge, because the measured T was lower than in the multi-V test, the dynamic weakening in the single-V test may instead be caused by flash heating or thermal pressurization, rather than vaporization. The apparent difference in the slip distance for the dynamic weakening between multi-V and single-V tests might indicate a difference in the weakening mechanisms for the same materials under similar pressure conditions but under different ambient T conditions (higher T for multi-V tests because of the frictional heat generating during preceding slips); further experimental studies will be needed to validate this.

4.2. Athermal slip weakening for low-smectite gouges at intermediate velocity range

The result of PHV592 which included both velocity upsteps and downsteps (section 3.1; Figure 4) indicated that the slip weakening behavior at the intermediate V_{eq} range (1-3 mm/s) for the 15%-smectite sample is not a result of high shear strain but purely a V dependent phenomenon. Also, the FEM modeling showed that the P_f build-up due to frictional heat had minor influence on the reduction in apparent μ values for such a low V_{eq} conditions (Figure 8). Previous studies reported similar weakening at ~1 mm/s for low-clay samples and discussed the possibility of flash heating followed by local thermal pressurization (Oohashi et al., 2013, 2015). In the case of this study, the flash heating T can be calculated by the following equation (Archard, 1959):

$$\Delta T_{flash} = \frac{1}{8}\frac{\pi \mu_a H l V_a}{K}, \#(7)$$

where V_a is the velocity at an asperity contact, and l is the size of an asperity contact, μ_a is the friction coefficient at an asperity contact, and H is the compressive yield strength of 7 GPa (Ben Abdelounis et al., 2009; Yonekura, 2015). We assume that K is 1.5 W/m/K for glass (Romine et al., 2012) and μ_a is identical to the μ value for 100% glass, i.e., $\mu_a = 0.6$, because the asperity contact is the contact between glass grains. As the grain size in the SB was less than 30 μm (Figure 5i), we used an l value of 1-30 μm. The estimated ΔT_{flash} for $V_a = 1$ mm/s is 1-33°C, which is far lower than the melting T of typical rocks (~1,000°C). The ΔT_{flash} of 1-33°C may not be high enough to induce local reduction in shear strength by thermal pressurization near asperity contacts; therefore, other mechanisms would be needed to reduce frictional strength.

One possible process that could reduce μ is a fluid-like behavior of the gouge (fluidization). For the 15%-smectite sample at intermediate V (PHV592), deformation likely occurred within the shear band (SB) with thickness of ~500 μm (Figures 6g-i) rather than a discrete shear surface like observed in the 100% glass sample with V_{eq} up to 300 mm/s (Figures 6d-f). Such distributed shear deformation is one of the characteristics of fluidization. However, further experimental and microstructural studies would be needed to ensure the occurrence of fluid-like behavior because we did not observe grain segregations, which is recognized as a form of evidence for gouge fluidization (Demurtas et al., 2021; Ujiie & Tsutsumi, 2010). In addition, because the fluidized gouge should be insensitive to σ_{eff}, we need to test the same material under different σ_{eff} conditions (Ujiie & Tsutsumi, 2010), which is planned in future work.

Another possibility is compaction-induced pore fluid pressurization. During the experiments, we observed a continuous reduction in gouge thickness which appears to depend on displacement (Figure 8c). Compaction occurred in a short time when V_{eq} was in a higher range. If we consider a simple form of P_f increase without diffusion:

$$\frac{\Delta P_f}{\Delta t} = -\frac{1}{\beta_f\, \phi\, w_g}\frac{\Delta w_g}{\Delta t}, \#(8)$$

where w_g is the thickness of gouge (2 mm), and if we assume the rate of reduction in gouge thickness $\Delta w_g/\Delta t$ of 0.0025 mm/s, P_f increases by 10 MPa in a second. Therefore, the observed weakening in friction can be explained by compaction-induced pressurization, however there is a large uncertainty regarding the value of ϕ because of gouge leakage to the narrow spaces between the O-rings and Teflon liner, thus we cannot separate effects of compaction and gouge leakage on P_f. Note that compaction-induced pressurization has been reported at a high velocity conditions of ~1 m/s for the sediment gouge from the Hikurangi subduction zone (Aretusini et al., 2021), and at a low velocity conditions of ~1 μm/s for gouges with low permeability (Faulkner et al., 2018).

4.3. Low friction coefficient at all velocity conditions for high-smectite samples

As the clay mineral content increases, the permeability of the fault gouge continuously decreases down to ~10^{-21} m^2 for 100% smectite (Takahashi et al., 2007). This low permeability contributes to the fluid overpressure within the gouge. Consequently, the frictional strength becomes quite low even at low-V conditions, such that the samples with more than 50% smectite showed low μ close to or less than 0.1 (Figure 3). Due to the intrinsic weakness of wet smectite (Morrow et al., 2017) and its impermeable nature, frictional heat generation was low and thus thermal pressurization likely did not play a significant role in the observed weakness of the clay. In addition, the chances of grain contacts among volcanic glass grains are less than low-clay samples because the volcanic glass grains are dispersed in the pervasive clay matrix and not comminuted (Figures 6k and l). This observation is consistent with the similar friction coefficients for 50%-, 70%-, and 100%-smectite samples suggesting that the smectite deformation dominantly controls the frictional behavior of the entire gouge when the clay mineral content exceeds 50% (Oohashi et al., 2013). If higher slip velocity and/or longer shear displacement were imposed, increased frictional heat would be generated, and thermal pressurization of pore fluid or water dehydrated from clay could potentially further decrease the apparent frictional strength (Hirose & Bystricky, 2007).

5. Possible impacts of slip weakening at intermediate velocity range on slow and fast earthquakes in the shallow subduction zone

The weakening with V and slip displacement can cause acceleration of fault slip and result in an earthquake. We observed V-neutral or slightly V-weakening trends up to V_{eq} = 300 μm/s for low-clay samples (see section 3.1). Considering a spring-slider model, unstable, self-accelerating slip occurs when the system stiffness K, that is the stiffness of the country rock surrounding a fault, is lower than the critical stiffness K_c, defined by frictional properties of a fault. The K_c for the (quasi-static) RSF law is described as follows:

$$K_{c,RSF} = -\frac{\sigma_{eff}(a-b)}{d_c}, \#(9)$$

where d_c is a characteristic slip distance at the V-step, and $a-b$ is defined as follows:

$$a-b = \frac{\Delta\mu_{ss}}{\Delta \ln V}, \#(10)$$

where $\Delta\mu_{ss}$ and $\Delta \ln V$ are the variation in steady-state friction coefficient and the logarithm of velocity, respectively (Dieterich, 1979; Ruina, 1983). Similarly, the K_c for a slip-weakening behavior can be defined as follows:

$$K_{c,sw} = \frac{\Delta\tau}{\delta_c}, \#(11)$$

where $\Delta\tau$ is the drop in shear stress during a characteristic slip distance δ_c (Ikari et al., 2013). The K_c value can be converted to a critical nucleation length of slip area L_c to initiate self-acceleration of slip as follows:

$$L_c = \frac{\xi G}{K_c}, \#(12)$$

where ξ is a shape-dependent parameter and G is the shear modulus of surrounding rock. When the size of the slip length L becomes larger than L_c, then the dynamic rupture initiates (Dieterich, 1992; McLaskey, 2019). For simplicity, we adopt a ξ value of $7\pi/12$ considering a circular crack with a diameter of L_c (Dieterich, 1986; Eshelby, 1957), and a G value of 10 GPa considering partially consolidated, underthrust or accreted sediment at a shallow depth in a subduction zone (e.g., S-wave velocities of 1.5-2.5 km/s and density of 2.0 g/cm^3 lead to 4.5-12.5 GPa) (Akuhara et al., 2020).

The obtained $a-b$, d_c, and calculated L_c for low V conditions, and $\Delta\tau$, δ_c, and L_c for intermediate V conditions are summarized in Table 3. We used the most negative $a-b$ value for each smectite content to estimate the possible unstable bound of slip. For the 0%-smectite sample, V-strengthening behavior was observed for V_{eq} = 10 μm/s to 300 mm/s; therefore, earthquake nucleation would not be expected to occur under either low or intermediate V conditions. Low-smectite samples (15-30% smectite) showed negative $a-b$ values of −0.012 to −0.003 for 10 μm/s to 300 μm/s, with d_c values of ~0.1 mm. At intermediate velocities, the drastic drops in shear stress $\Delta\tau$ were 1.5-0.9 MPa with δ_c ~ 0.1 m. For high-smectite samples with more than 50% smectite, the $a-b$ values at the low-V conditions are almost velocity neutral (0 to 0.003). The $\Delta\tau$ values at the intermediate-V condition were 0.15-0.05 MPa with δ_c ~ 0.1 m.

The estimated L_c values for low V conditions (V_{eq} < 300 μm/s) are 30-122 m, whereas those for intermediate V conditions (V_{eq} > 1 mm/s) are 1.2-36.7 km (Figure 9a, Table 3). As self-accelerating slip starts when L exceeds L_c, the dependence of L_c on V leads to the following two possible cases of earthquake nucleation and rupture, depending on the slip length L and the slip velocity.

(case i) If L exceeds ~10-100 m (L_c for low V conditions) before the slip velocity reaches 300 μm/s, a rapid acceleration of slip initiates resulting in dynamic rupture propagation. This situation leads to the emission of seismic waves as a result of the stress drop and subsequent slip, which means a regular earthquake. It would be also possible that the slip velocity after the rupture propagation may be suppressed around intermediate V conditions when sufficient strain energy is accumulated on a fault because the shear stress of the gouge becomes minimum at the intermediate V range and fault strength cannot decrease further. Therefore, in some cases, the slip may result in a tremor that are seismologically detected slow earthquakes (Figure 9b).

(case ii) If L does not reach ~10-100 m when the slip velocity reaches 300 μm/s, a coseismic rupture does not initiate and the nucleation phase continues, because L is much smaller than L_c which becomes ~1-30 km (L_c for intermediate V conditions) and it will take a longer duration for nucleating an earthquake resulting in a slow slip event (SSE) like slip on the fault. If L exceeds ~1-30 km, then coseismic rupture will eventually occur. In the case of the Nankai subduction zone, 30 km corresponds to the entire length of the plate boundary fault beneath the outer wedge. Therefore, the coseismic rupture initiation at L > ~1-30 km would generate a megathrust earthquake that ruptures all the shallow part of the plate boundary fault.

The above two cases can be interpreted to be caused by a difference in rupture velocity during the quasi-static rupture propagation: the slower the rupture velocity is, the higher the probability for a long nucleation phase becomes. This means that the large L_c for intermediate V conditions is not necessarily required for an SSE like slip. However, a larger L_c at intermediate V conditions could contribute to suppress acceleration of slip and elongate the duration of nucleation phase. Therefore, the weakening behavior at the intermediate V range could be an important factor that controls a complex spectrum of slip behavior on a fault, although the physical weakening mechanisms and constitutive law must be constrained in detail to be implemented in numerical models. Since the transition from volcanic glass to smectite occurs in the shallow part of subduction zones, and as the smectite content increases with depth, the plate boundary fault would gradually be more likely to host slow earthquakes, as observed in the Nankai Trough where slow earthquakes have been observed beneath the accretionary prism (Figure 9c). At deeper depths where smectite dehydrates into illite at $T \sim 150$°C or σ_{eff} will become high, frictional properties may change, or L_c will decrease, which will make the plate boundary fault more prone to regular earthquakes.

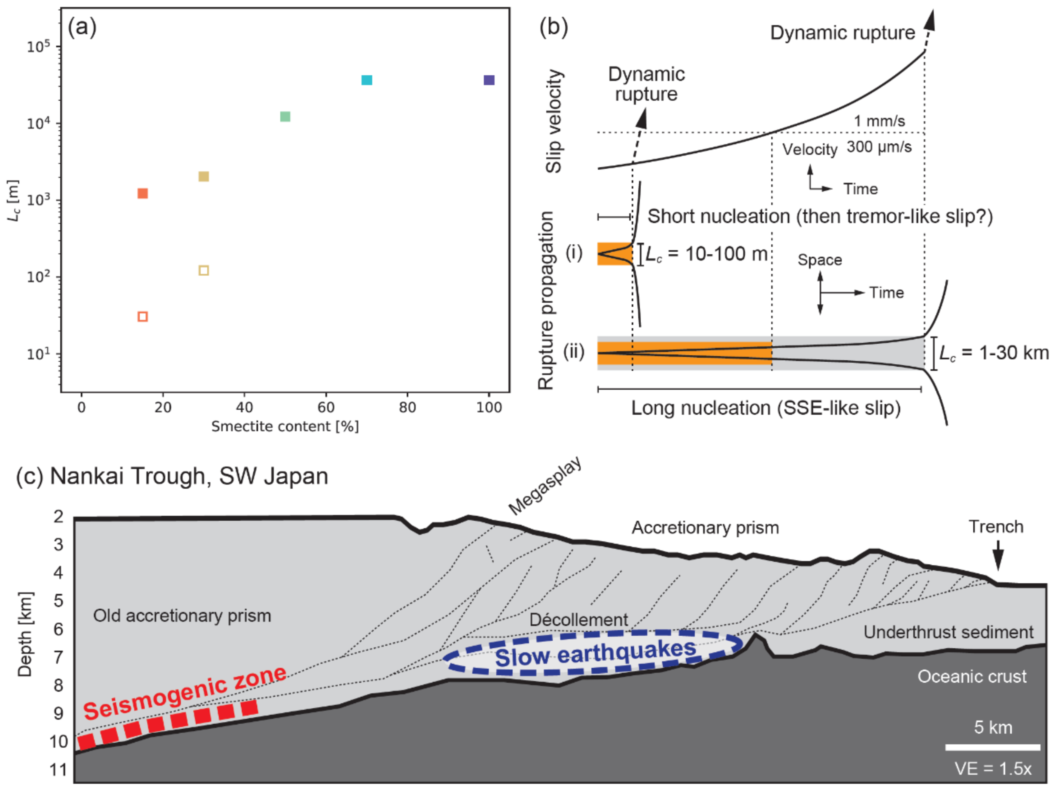

Figure 9.

(a) The L_c values for different smectite contents with low velocity range (open square) and intermediate velocity range (filled square). The d_c values are assumed to be 1 mm for low velocity range and 0.1 m for intermediate velocity range. (b) Schematic illustration for the evolutions of slip velocity that can generate slow earthquakes (see text for details). Orange and gray areas represent the critical nucleation length L_c for low and intermediate velocity conditions, respectively. (c) A sketch of the cross section of the Nankai Trough, SW Japan (Moore et al., 2009) overlaid by locations of slow earthquakes and the seismogenic zone.

Table 3.

Summary of velocity dependence at low and intermediate velocity conditions. All parameters are the case for the effective normal stress of 5 MPa. “X” means that L_c cannot be defined because $a-b$ is positive.

	Low V conditions (RSF)			Intermediate V conditions (slip weakening)		
	$(a-b)\sigma_{eff}$	d_c	L_c	$\Delta\tau$	δ_c	L_c
Glass/Smectite = 100/0	0.075 MPa	~0.1 mm	X	0.25 MPa	~0.1 mm	X
Glass/Smectite = 85/15	-0.06 MPa	~0.1 mm	30 m	-1.5 MPa	~0.1 m	1.2 km
Glass/Smectite = 70/30	-0.015 MPa	~0.1 mm	122 m	-0.9 MPa	~0.1 m	2.0 km
Glass/Smectite = 50/50	0.015 MPa	~0.1 mm	X	-0.15 MPa	~0.1 m	12.2 km
Glass/Smectite = 30/70	0 MPa	~0.1 mm	X	-0.05 MPa	~0.1 m	36.7 km
Glass/Smectite = 0/100	0 MPa	~0.1 mm	X	-0.05 MPa	~0.1 m	36.7 km

6. Conclusions

We performed a series of friction experiments on a range of volcanic glass smectite mixtures at different velocity conditions. For low-velocity conditions (<1 mm/s), friction coefficients decreased with increased smectite content. Samples with 15 and 30% smectite characteristically showed a negative velocity dependence of friction coefficients. At intermediate-velocity conditions (1-3 mm/s), samples with 15 and 30% smectite showed marked slip-weakening behavior with a characteristic slip distance of ~0.1 m. At high-velocity conditions (>100 mm/s), the volcanic glass exhibited dynamic weakening behavior caused by thermal processes such as vaporization. Silica-gel lubrication likely does not explain the observed dynamic weakening behavior. Although the underlying physical processes are still undetermined, the marked weakening behavior at intermediate velocity conditions will produce large critical nucleation lengths on the order of 1-30 km. Such weakening behavior at intermediate velocity conditions potentially induces slow earthquakes, as observed in shallow subduction zones such as the Nankai Trough.

Appendix A: Derivation of equivalent pore pressure

To define the equivalent pore pressure P_{feq} (equation 5), we consider the total work for shear deformation similar to the derivation of equivalent velocity V_{eq} (Shimamoto & Tsutsumi, 1994). Assuming μ does not depend on r, the shear stress at r can be written as:

$$\tau(r) = \mu_{obs}\left(\sigma_n - P_{fo}\right) = \mu_{cor}\left(\sigma_n - P_f(r)\right). \#(A1)$$

The work for shear deformation at r can be described as:

$$dw = V(r)\tau(r)(2\pi r)dr = \frac{3}{4}V_{eq}(2r)\frac{r_o + r_i}{r_o^2 + r_o r_i + r_i^2}\tau(r)(2\pi r)dr, \#(A2)$$

and thus the total work on the entire shear plane is:

$$W = \int_{r_i}^{r_o} dw = \int_{r_i}^{r_o} C\, r^2 \tau(r) dr, \#(A3)$$

where

$$C = 3\pi V_{eq} \frac{r_o + r_i}{r_o^2 + r_o r_i + r_i^2}. \#(A4)$$

Since equation A3 can be converted as follows:

$$W = \int_{r_i}^{r_o} C\, r^2 \mu_{obs}\left(\sigma_n - P_{fo}\right) dr = \int_{r_i}^{r_o} C\, r^2 \mu_{cor}\left(\sigma_n - P_f(r)\right) dr, \#(A5)$$

we obtain the following equation:

$$\mu_{obs}\left(\sigma_n - P_{fo}\right)\frac{r_o^3 - r_i^3}{3} = \mu_{cor}\left(\sigma_n \frac{r_o^3 - r_i^3}{3} - \int_{r_i}^{r_o} P_f(r) r^2 dr\right). \#(A6)$$

Considering the average P_f within the shear localized zone with the thickness w_{hs}, we can describe $P_f(r)$ as follows:

$$P_f(r) = \int_{z_{hs}^{bot}}^{z_{hs}^{top}} \frac{P_f(r,z)}{w_{hs}} dz. \#(A7)$$

If we define P_{feq} as follows:

$$P_{feq} = \frac{3}{r_o^3 - r_i^3}\int_{r_i}^{r_o} P_f(r) r^2\, dr = \frac{3}{r_o^3 - r_i^3}\int_{r_i}^{r_o}\int_{z_{hs}^{bot}}^{z_{hs}^{top}} \frac{P_f(r,z) r^2}{w_{hs}} dz\, dr, \#(A8)$$

equation A6 can be converted to:

$$\mu_{obs}\left(\sigma_n - P_{fo}\right) = \mu_{cor}\left(\sigma_n - P_{feq}\right). \#(A9)$$

Therefore, P_{feq} represents the “equivalent” pore pressure for radially heterogenous pore pressure condition, which can be considered as the representative P_f value in the shear localized zone.

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Open research

The experimental data can be available from https://doi.org/10.17632/587wnsdgdb.1.

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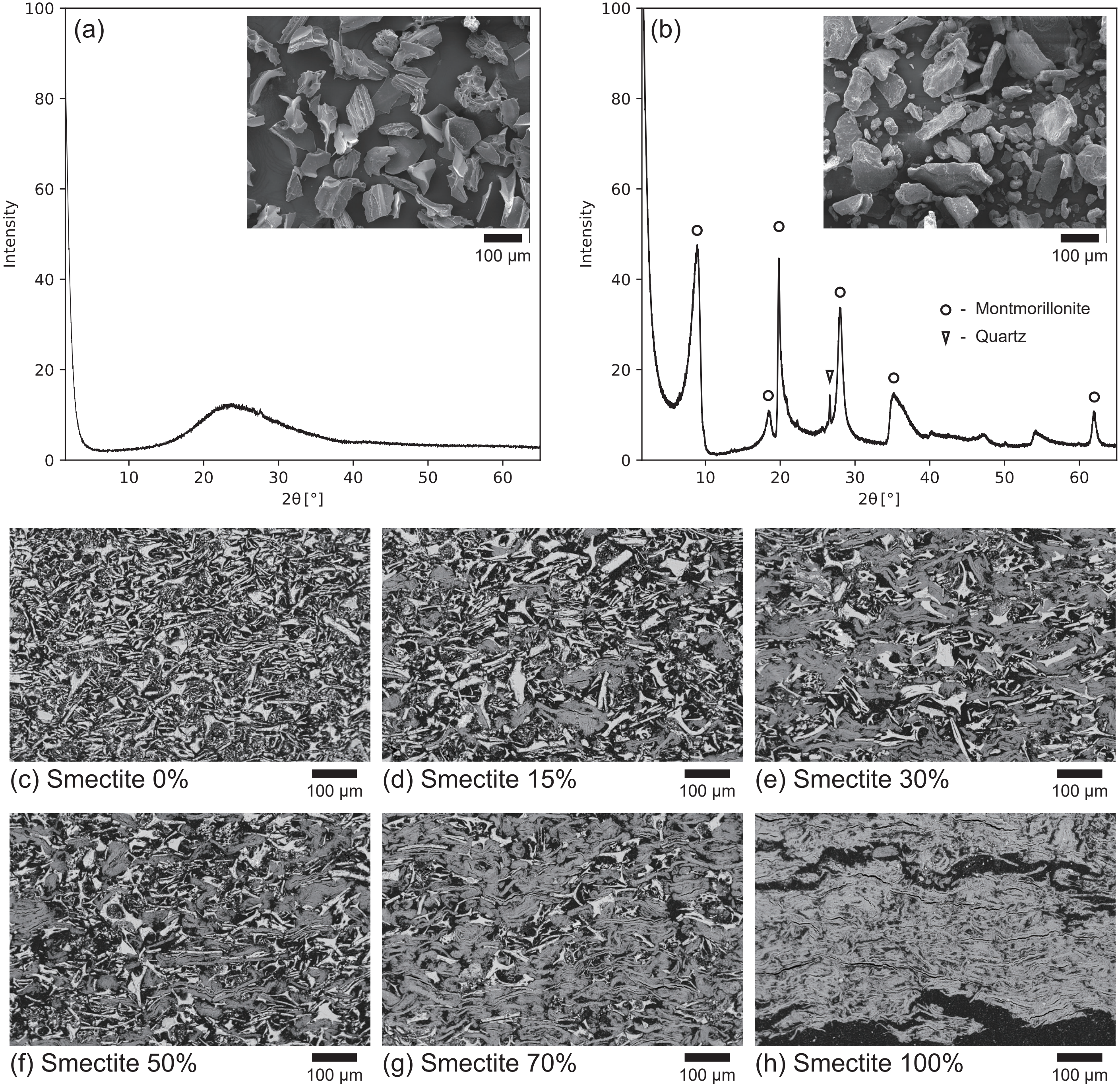
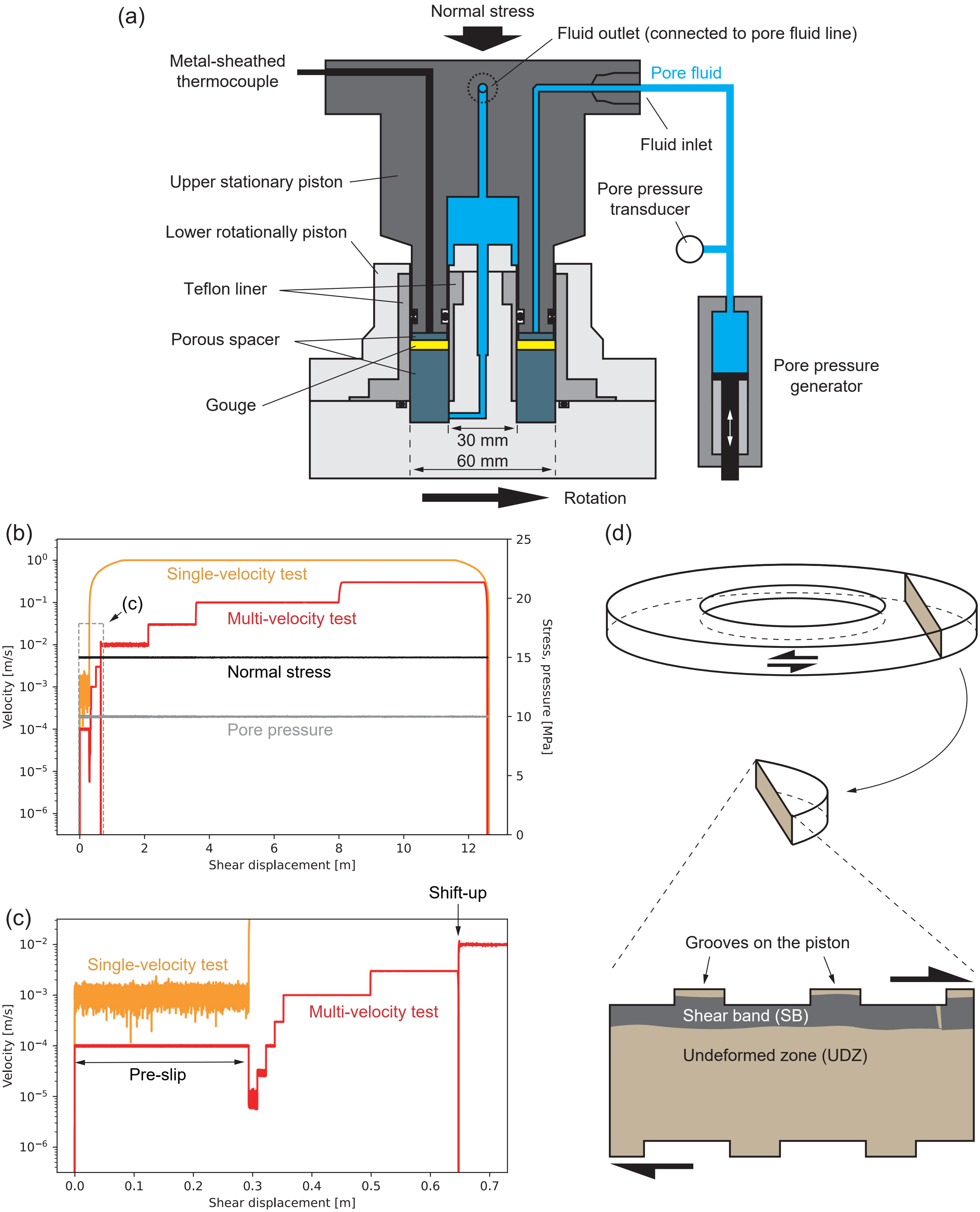
Figure 1.



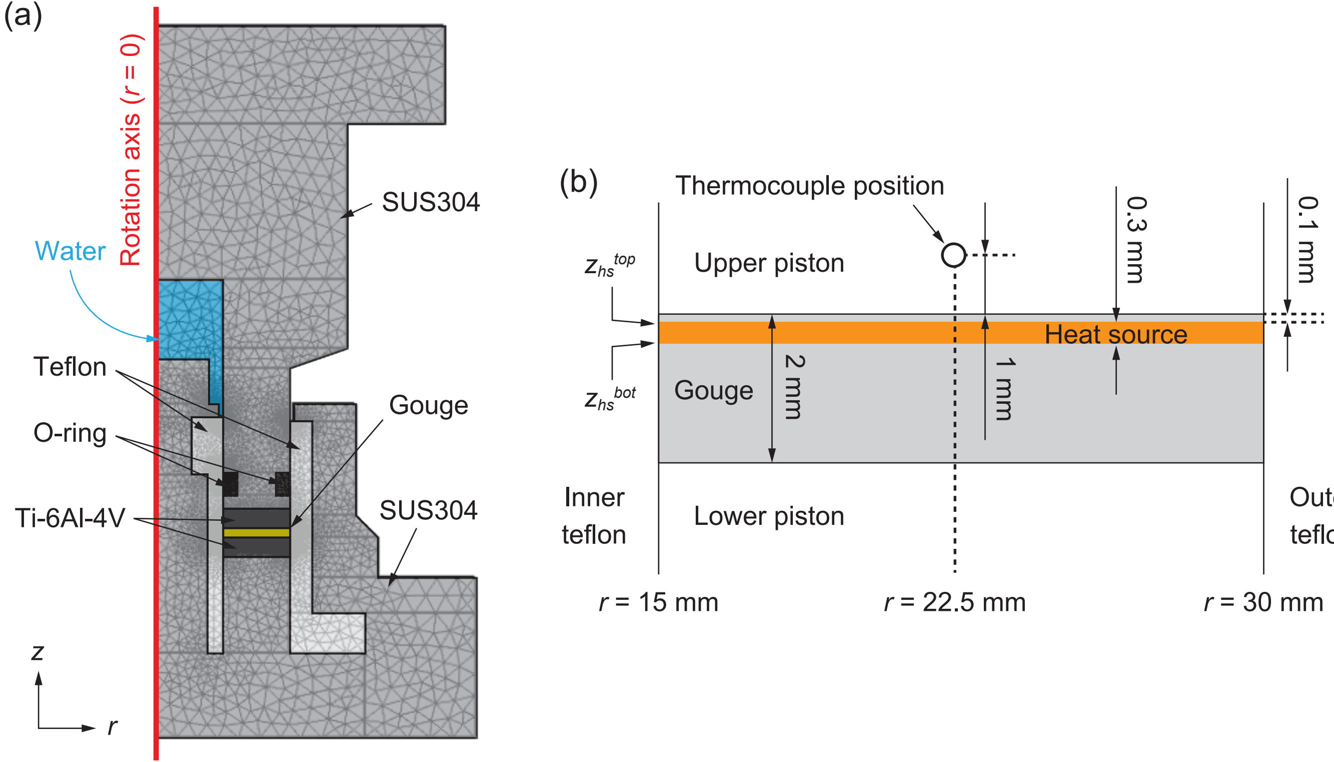
(a)
100 µm
Intensity
2θ [°]
(b)
100 µm
Intensity
2θ [°]
Montmorillonite
Quartz
(c) Smectite 0%
100 µm
(d) Smectite 15%
100 µm
(e) Smectite 30%
100 µm
(f) Smectite 50%
100 µm
(g) Smectite 70%
100 µm
(h) Smectite 100%
100 µm

Figure 2.



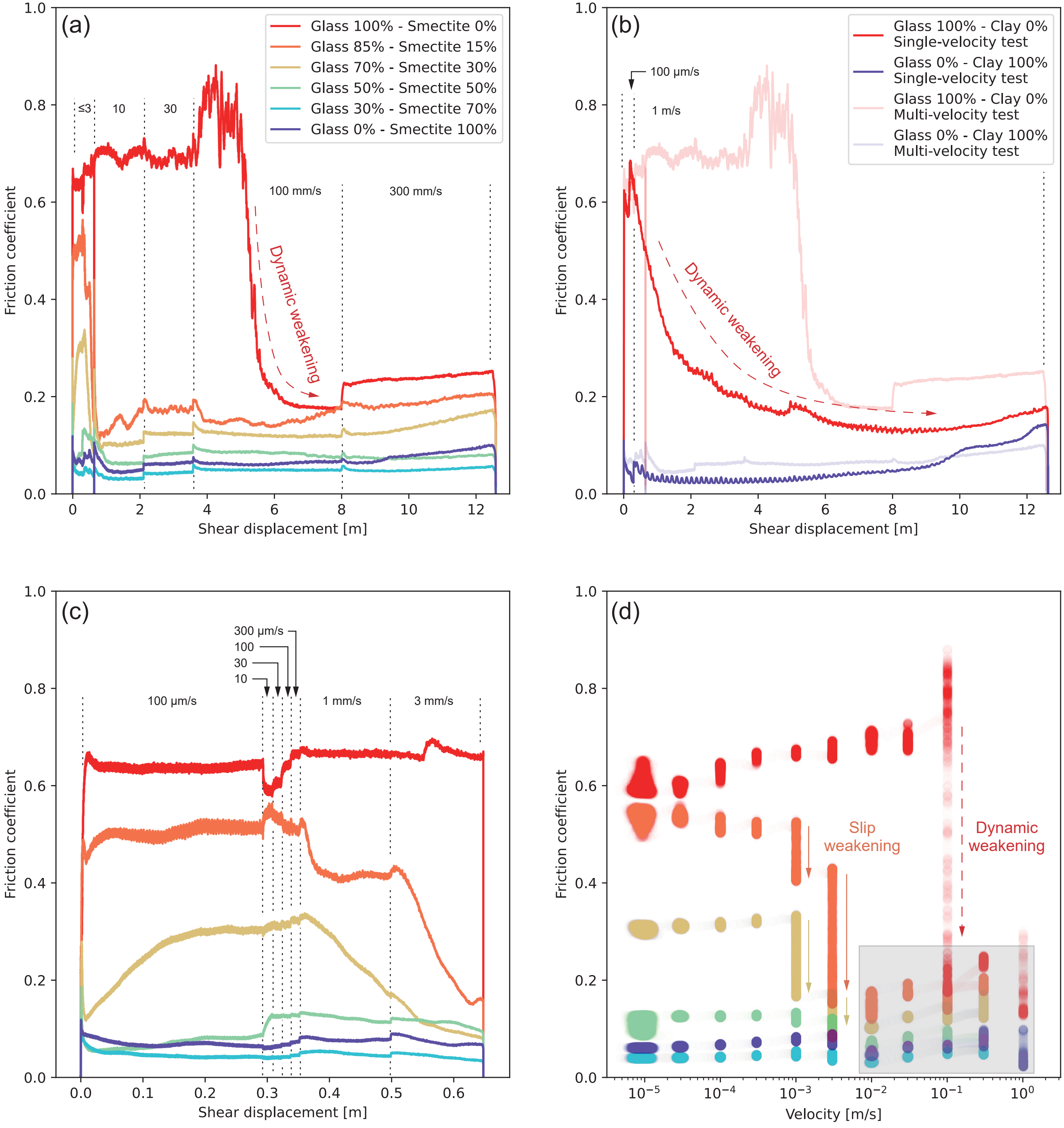
(a)
Normal stress
Fluid outlet (connected to pore fluid line)
Metal-sheathed thermocouple
Pore fluid
Fluid inlet
Upper stationary piston
Pore pressure transducer
Lower rotationally piston
Teflon liner
Porous spacer
Pore pressure generator
Gouge
30 mm
60 mm
Rotation
(b)
Single-velocity test
(c)
Multi-velocity test
Normal stress
Pore pressure
Velocity [m/s]
Stress, pressure [MPa]
Shear displacement [m]
(d)
(c)
Shift-up
Single-velocity test
Multi-velocity test
Pre-slip
Velocity [m/s]
Shear displacement [m]
Grooves on the piston
Shear band (SB)
Undeformed zone (UDZ)

Figure 3.



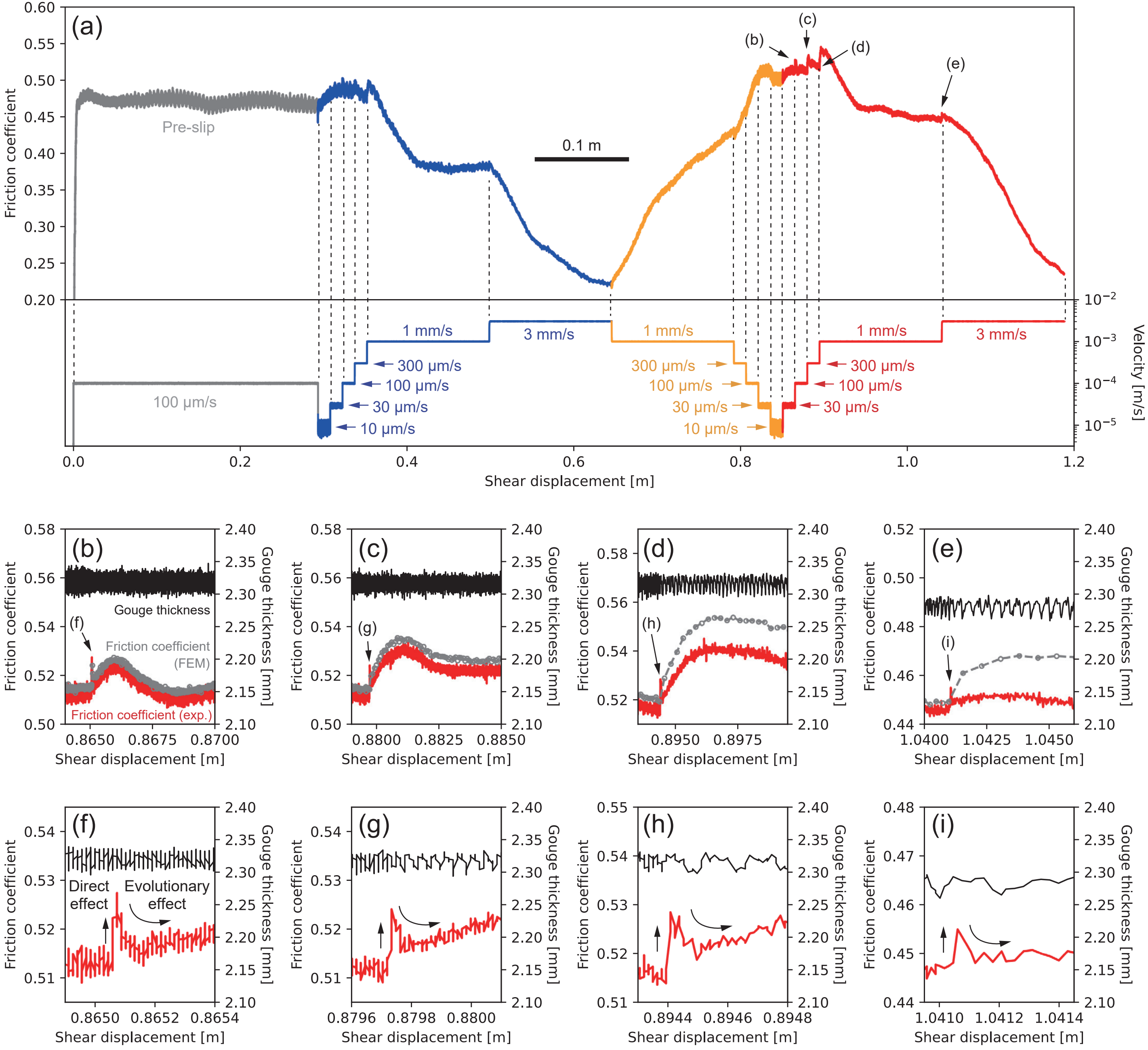
(a)
Rotation axis (r = 0)
Water
SUS304
Teflon
O-ring
Gouge
Ti-6Al-4V
SUS304
z
r
(b)
Thermocouple position
Upper piston
z_{hs}^{top}
z_{hs}^{bot}
Heat source
Gouge
2 mm
1 mm
0.3 mm
0.1 mm
Inner teflon
Lower piston
Outer teflon
r = 15 mm
r = 22.5 mm
r = 30 mm

Figure 4.



(a)
Glass 100% - Smectite 0%
Glass 85% - Smectite 15%
Glass 70% - Smectite 30%
Glass 50% - Smectite 50%
Glass 30% - Smectite 70%
Glass 0% - Smectite 100%
≤3
10
30
100 mm/s
300 mm/s
Dynamic weakening
Friction coefficient
Shear displacement [m]
(b)
Glass 100% - Clay 0%
Single-velocity test
Glass 0% - Clay 100%
Single-velocity test
Glass 100% - Clay 0%
Multi-velocity test
Glass 0% - Clay 100%
Multi-velocity test
100 μm/s
1 m/s
Dynamic weakening
Friction coefficient
Shear displacement [m]
(c)
300 μm/s
100
30
10
100 μm/s
1 mm/s
3 mm/s
Friction coefficient
Shear displacement [m]
(d)
Slip
weakening
Dynamic
weakening
Friction coefficient
Velocity [m/s]

Figure 5.



(a)
Friction coefficient
Pre-slip
0.1 m
(b)
(c)
(d)
(e)
100 μm/s
10 μm/s
30 μm/s
100 μm/s
300 μm/s
1 mm/s
3 mm/s
1 mm/s
300 μm/s
100 μm/s
30 μm/s
10 μm/s
1 mm/s
300 μm/s
100 μm/s
30 μm/s
3 mm/s
Velocity [m/s]
Shear displacement [m]
(b)
Gouge thickness
(f)
Friction coefficient (FEM)
Friction coefficient (exp.)
(c)
(g)
(d)
(h)
(e)
(i)
Gouge thickness [mm]
(f)
Direct effect
Evolutionary effect
(g)
(h)
(i)

Figure 6.

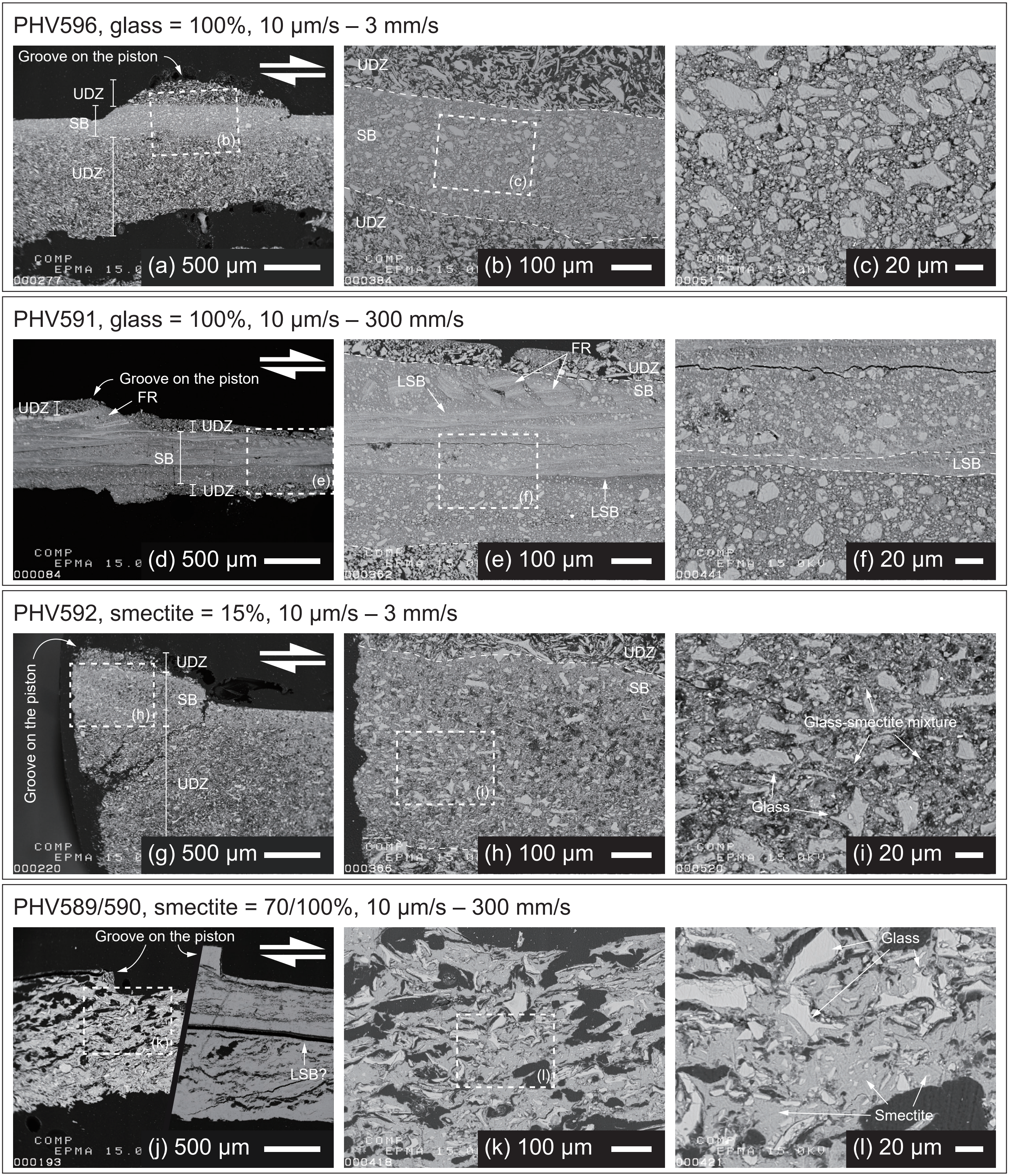

PHV596, glass = 100%, 10 μm/s – 3 mm/s
Groove on the piston
UDZ
SB
UDZ
(b)
(a) 500 μm
UDZ
SB
(c)
UDZ
(b) 100 μm
(c) 20 μm
PHV591, glass = 100%, 10 μm/s – 300 mm/s
Groove on the piston
UDZ
FR
UDZ
SB
UDZ
(e)
(d) 500 μm
FR
UDZ
LSB
SB
(f)
LSB
(e) 100 μm
LSB
(f) 20 μm
PHV592, smectite = 15%, 10 μm/s – 3 mm/s
Groove on the piston
UDZ
SB
(h)
UDZ
(g) 500 μm
UDZ
SB
(i)
(h) 100 μm
Glass-smectite mixture
Glass
(i) 20 μm
PHV589/590, smectite = 70/100%, 10 μm/s – 300 mm/s
Groove on the piston
(k)
LSB?
(j) 500 μm
(l)
(k) 100 μm
Glass
Smectite
(l) 20 μm

Figure 7.

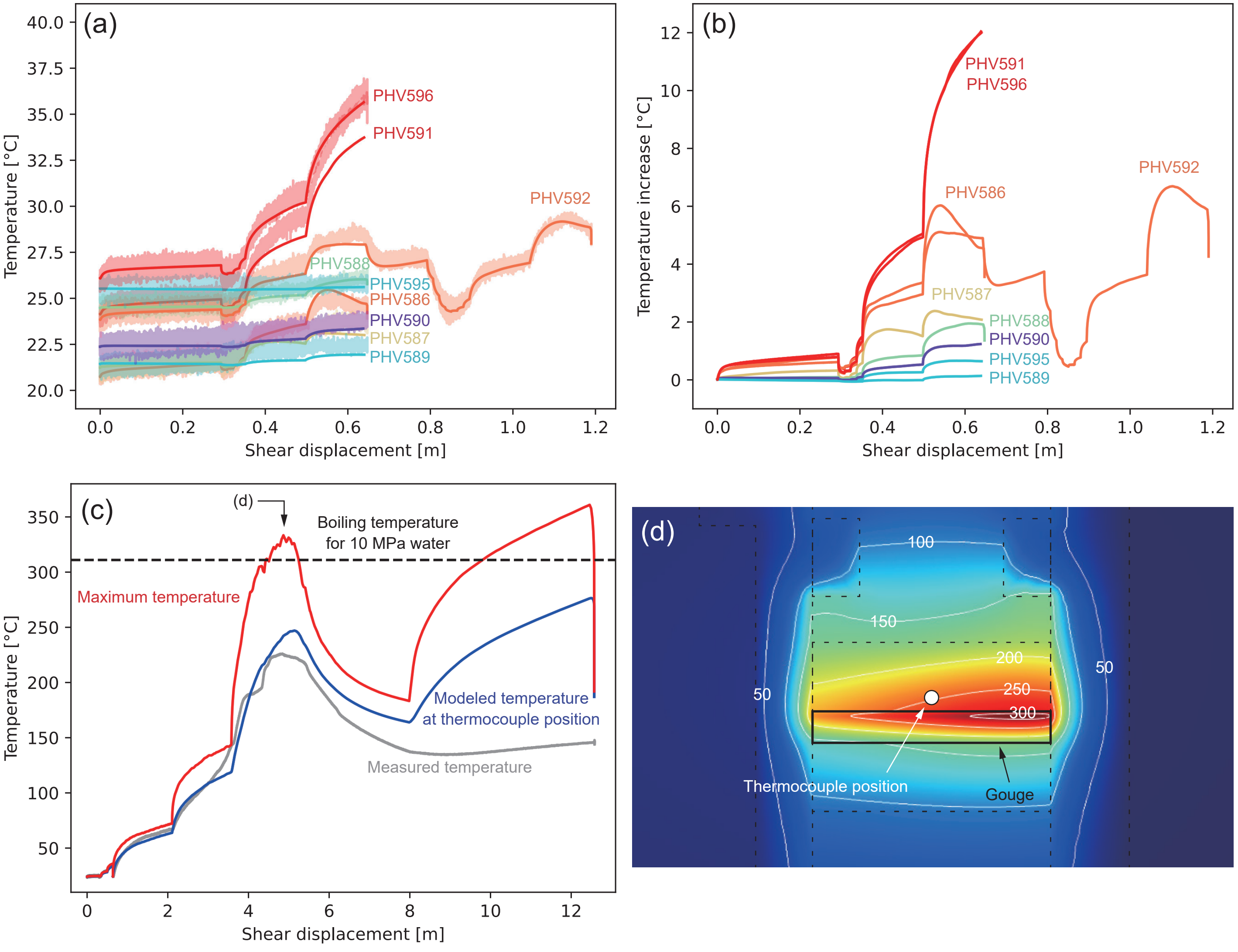

(a)
Temperature [°C]
Shear displacement [m]
PHV596
PHV591
PHV592
PHV588
PHV595
PHV586
PHV590
PHV587
PHV589
(b)
Temperature increase [°C]
Shear displacement [m]
PHV591
PHV596
PHV586
PHV592
PHV587
PHV588
PHV590
PHV595
PHV589
(c)
(d)
Boiling temperature
for 10 MPa water
Maximum temperature
Modeled temperature
at thermocouple position
Measured temperature
Temperature [°C]
Shear displacement [m]
(d)
100
150
200
250
300
50
50
Thermocouple position
Gouge

Figure 8.

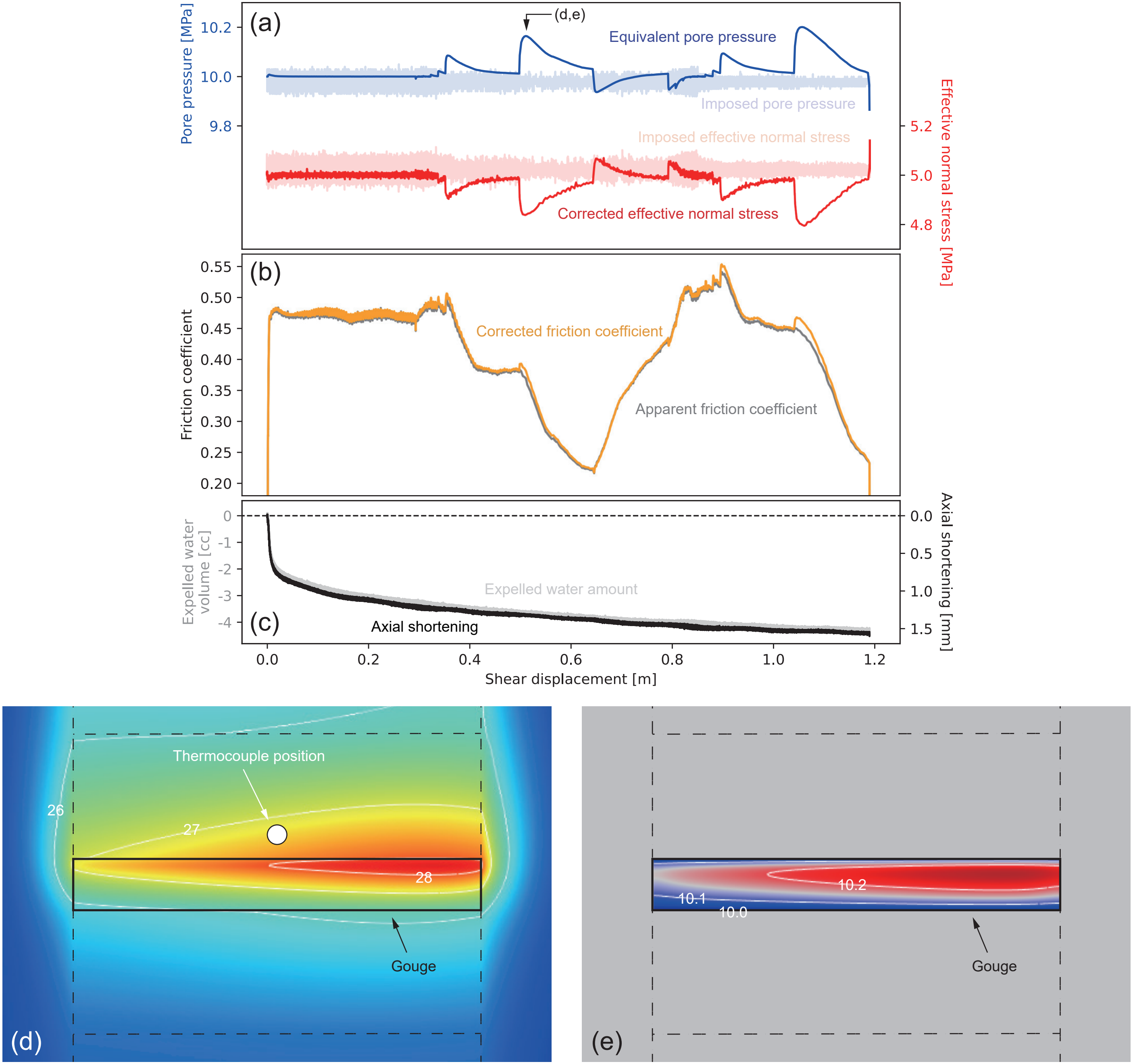
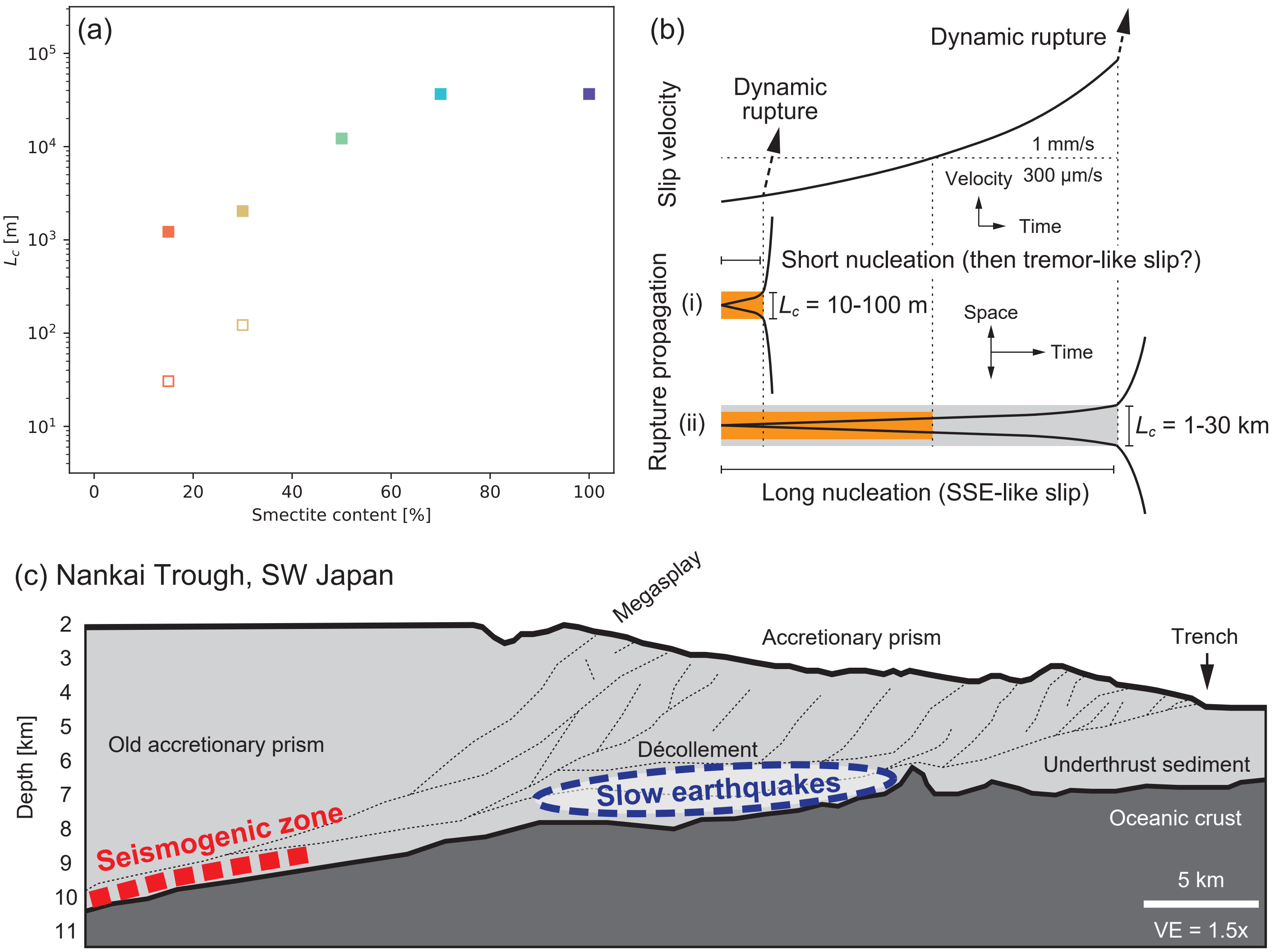

(a)
(d,e)
Equivalent pore pressure
Imposed pore pressure
Imposed effective normal stress
Corrected effective normal stress
Pore pressure [MPa]
10.2
10.0
9.8
Effective normal stress [MPa]
5.2
5.0
4.8
(b)
Corrected friction coefficient
Apparent friction coefficient
Friction coefficient
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
(c)
Expelled water amount
Axial shortening
Expelled water volume [cc]
0
-1
-2
-3
-4
Axial shortening [mm]
0.0
0.5
1.0
1.5
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Shear displacement [m]
(d)
Thermocouple position
26
27
28
Gouge
(e)
10.2
10.1
10.0
Gouge

Figure 9.



(a)
10^5
10^4
10^3
10^2
10^1
L_c [m]
0
20
40
60
80
100
Smectite content [%]
(b)
Dynamic rupture
Dynamic rupture
Slip velocity
1 mm/s
Velocity
300 μm/s
Time
Short nucleation (then tremor-like slip?)
Rupture propagation
(i)
L_c = 10-100 m
Space
Time
(ii)
L_c = 1-30 km
Long nucleation (SSE-like slip)
(c) Nankai Trough, SW Japan
Megasplay
Accretionary prism
Trench
Depth [km]
2
3
4
5
6
7
8
9
10
11
Old accretionary prism
Décollement
Underthrust sediment
Slow earthquakes
Oceanic crust
Seismogenic zone
5 km
VE = 1.5x