Voids and Rock Friction at Subseismic Slip Velocity

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Abstract—We found that the amplitudes of transmitted waves across the sliding surfaces are inversely correlated to high slip rate friction, especially when the interfaces slide fast ($> 10^{-3}$ m/s). During the rock–rock friction experiments of metagabbro and diorite at sub-seismic slip rate ($\sim 10^{-3}$ m/s), friction does not reach steady state but fluctuates within certain range. The amplitudes of compressional waves transmitted across the slipping interfaces decrease when sliding friction becomes high and it increases when friction is low. Such amplitude variation can be interpreted based on the scattering theory; small amplitudes in transmitted waves correspond to the creation of large-scale (~ 50 μm) voids and large amplitudes correspond to the small-scale (~ 0.5 μm) voids. Thus, large-scale voids could be generated during the high-friction state and low-friction state was achieved by grain size reduction caused by a comminution process. This was partly confirmed by the experiments with a synthetic gouge layer. The result can be interpreted as an extension of force chain theory to high-velocity sliding regime; force chains were built during the high friction and they were destroyed during the low friction. This mechanism could be a microscopic aspect of friction evolution at sub-seismic slip rate.

Key words: Friction monitoring, subseismic slip velocity, transmitted waves, gouge particles, force chain.

1. Introduction

During an earthquake, friction on the fault plays an important role for the rupture to initiate, to propagate and to terminate. However, it is quite difficult or almost impossible to conduct in situ friction measurements during natural earthquakes. Therefore, many laboratory experiments have been conducted to explore the feature of friction to interpret the dynamics of earthquake ruptures. At slow slip

velocity ($\sim 10^{-6}$ m/s), friction follows the Byerlee's law (Byerlee 1978). But, as slip velocity increases, the coefficient of friction decreases, primarily due to the generation of heat (Di Toro et al. 2011). By looking at the experimental results closely, the coefficient of friction fluctuates at a subseismic slip velocity ($\sim 10^{-3}$ m/s) (e.g., Tsutsumi and Shimamoto 1997; Mizoguchi and Fukuyama 2010; Di Toro et al. 2011).

Although several models have been proposed to explain the state of friction, they are based either on the measurements outside the slipping layer or on the observation of thin sections after the experiments. At high-slip velocity ($> \sim 10^{-3}$ m/s), the contact situation changes very rapidly so that thin section snapshot approach, which was taken by Hirose and Shimamoto (2003), for example, does not work to investigate the contact condition because it changes immediately after the slip terminates. Therefore, simultaneous measurements are required to investigate the detailed mechanisms of friction at high slip velocity. To our knowledge, there exist very limited observations inside the slipping layer at high slip velocity.

The acoustic waves are sometimes used to monitor the contact condition of the frictional interfaces (Kendall and Tabor 1971; Pyrak-Nolte et al. 1990; Nagata et al. 2008, 2012, 2014). It is well known that the amplitudes of transmitted waves change as a function of normal stress when two interfaces are in contact and stationary (Kendall and Tabor 1971; Tullis and Weeks 1986; Pyrak-Nolte et al. 1990; Nagata et al. 2008; Kilgore et al. 2012). In these cases, the transmitted wave amplitudes are discussed in relation to the contact area. However, acoustic waves across the interfaces dislocating for large distances with fast sliding velocity do not seem to be investigated yet.

Mizoguchi and Fukuyama (2010) showed that frictional strength on the fault fluctuates rapidly at

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subseismic slip rate ($\sim 10^{-3}$ m/s) as slip advances, from the rock-on-rock friction experiments of Zimbabwean diorite under 1 $\sim$ 3 MPa normal stress and room temperature–room humidity condition using rotary shear friction testing apparatus. In this slip velocity range, visible melting could not be observed and the oscillation of friction seems caused by a repeatable process. The frequency of oscillation seems dependent on the amount of slip displacement as well as on the rock type. We could see a similar behavior at subseismic slip velocity in Reches and Lockner (2010), Di Toro et al. (2011), and Goldsby and Tullis (2011). According to Goldsby and Tullis (2011), such friction instability seems typical for gabbro and granite rocks.

Inside the gouge layer where many pore spaces should exist, the elastic properties are not well known because of the heterogeneous structure inside the layer. One of the traditional approaches is to apply effective medium theory (Hudson and Knopoff 1989; Liu et al. 2000) to estimate the average elastic properties by comparing observed macroscopic elastic constants with the predicted ones by the effective medium theory. This approach could be useful when the changes in propagation velocity were precisely observed. However, in the present case, since the gouge layer thickness is very thin (could be between 10 and 100 microns) the propagation path is too short to estimate the change in propagation velocity in the layer accurately.

In this paper, to get further information inside the simulated fault layer during high-velocity slipping, we measured the maximum amplitudes of transmitted compressional wave packets during the experiments as a function of time, instead of measuring the elastic velocity change. This maximum amplitude variation corresponds to the transmission coefficient of the sliding interfaces, which could be related to the Rayleigh scattering (Hudson 1981). Thus, the change in amplitudes could be related to the change in scatterers inside the gouge layer. We simultaneously measured the coefficient of friction during the experiments, which was estimated from the measured shear stress divided by the applied normal stress. We discuss the correlation between these observations and propose a model to explain the obtained data.

2. Experiments

We used a pair of cylindrical column specimens of metagabbro and diorite as shown in Table 1. Here we demonstrate two series of experiments (SHRA049 and SHRA067), whose diameters of the specimens are different (25 and 40 mm, respectively, see Table 1 for details).

We used the high-velocity rotary shear apparatus at National Research Institute for Earth Science and Disaster Resilience (NIED) which was originally installed in 2007 (Mizoguchi and Fukuyama 2010). We modified the apparatus to conduct transmitted wave experiments as shown in Fig. 1. A major modification was that the upper main shaft was bypassed by rubber belt to extract the signal cables from the upper sample holder (see Fig. 1a). We used a slip ring (MOOG Inc., EC3848) to prevent cable twisting. Stiffness of the apparatus is shown in Appendix A.

Friction is measured continuously during the experiments in exactly the same way as Mizoguchi and Fukuyama (2010) did; normal stress (σ_N) is estimated from the applied axial force measured by the load cell installed above the air actuator (Fig. 1) divided by the slip area. Shear stress (τ_S) is estimated from the torque measured by the torque transducer equipped just beneath the lower sample holder (Fig. 1) and the slip area, by assuming that shear stress is uniform over the fault surface. Coefficient of friction (f) is evaluated as $f = \tau_S / \sigma_N$. Slip velocity is

Table 1
Specification of rock specimens

Sample ID	SHRA049	SHRA067
Rock type	Indian metagabbro ^a	Zimbabwean diorite ^b
Diameter of specimen (mm)	25.05	40.20
Length of upper specimen (mm)	35.27	45.32
Length of lower specimen (mm)	34.13	45.09

^aMineral compositions are plagioclase, diopside, hornblende, biotite, magnetite and quartz, and mean grain size is 0.60 mm (S. Takizawa, personal comm.)

^bMineral compositions are plagioclase, diopside, hornblende, biotite, magnetite and quartz, and mean grain size is 0.46 mm (S. Takizawa, personal comm.)

Figure 1

a Configuration of the apparatus. A pair of cylindrical rock samples is installed in the sample holder. Air actuator applies the normal stress to the specimens. Servomotor applies the rotational force to the sample. Normal and shear forces are measured by the load cell and torque transducer, respectively. Slip velocity is measured by the rotary encoder. **b** Schematic illustration of the observation system. Two piezoelectric transducers (PZTs) are glued at the end surface of each specimen. Upper column rock specimen rotates while the lower specimen was stationary and normal stress is applied from the bottom

evaluated using the effective slip velocity (V) defined by $V = (2\pi/3) R d$ for solid column specimen, where R is rotation speed (in rps, rotation per second) and d is a diameter of the sample (Mizoguchi and Fukuyama 2010). Hereafter, we call V slip velocity on the simulated fault. Friction data were digitized at

an interval of 1 kHz with 24-bit resolution. We measured the axial displacement (z) using the laser displacement meter shown in Fig. 1a. It should be noted that positive z indicates dilation, i.e., extension of the samples including the gouge layer thickness.

After installing the rock specimen to the sample holder (Fig. 1), two steel strings were twisted close to the sliding surface of each specimen to avoid open fracture near the edge of the specimen. These strings apply confining stress normal to the sidewall of the sample when the specimen tried to expand. Before the experiments, we slid the surfaces under σ_N between 0.37 and 0.65 MPa with V of 8.7×10^{-3} m/s for total slip of 877 m for SHRA049 and 1108 m for SHRA067. This pre-sliding procedure homogenized the sliding surface and made both surfaces parallel to contact the entire surface during sliding. Just after each experiment, we collected the gouge particles on the sliding surface, cleaned the surface by brush and wiped using a paper towel with ethanol.

We used a pair of piezoelectric transducers (PZTs) for P-waves glued to the bottom center of each rock specimen. Since the normal load is supported by the sidewall of the specimen held by the sample holder, no external force is applied to the PZT during the measurement. Detailed specification of the PZTs is shown in Table 2. We applied a series of half cycle sine wave pulse to the PZT at the rotation side (Table 2). The PZT waveforms received at the bottom of the stationary specimen were continuously recorded by a 14-bit digitizer (Spectrum Co. Ltd. M2i.4032) at an interval of 20 MHz without pre-amplification. Input waveforms generated by the function generator, shear torque and rotation speed data are simultaneously recorded with the PZT waveforms. For SHRA067 series experiments, normal load and axial displacement were recorded with PZT waveforms as well.

To reduce the high-frequency background noise (> 1 MHz) in the PZT waveforms, which was mainly caused by electromagnetic signals, raw waveform records were stacked to get a transmitted waveform (Table 2). In Fig. 2, snapshots of the stacked traces for SHRA049-05 are shown as a function of lapse time of the experiments. The transmitted maximum amplitudes (A) are picked within the first wave train packet following the onset of the first arrival of the signal, whose time window is shown in Fig. 2.

Regarding the experiment id, first three digits following SHRA stand for the identification number unique to the rock specimens and two digits after the hyphen shows a sequential number of the experiments using the same set of specimens.

3. Results of Experiments

3.1. Transmitted Waves Under Stationary Condition

Before conducting friction measurements under rotation conditions, we conducted experiments (SHRA049-05-load01) without rotations to see the normal stress effect under stationary conditions.

First, we consider the effect of shortening of the sample due to the normal stress on the amplitudes of transmitted waves. The change in the propagation distance along the two samples, whose total length is 69.4 mm (Table 1) and Young's modulus is 103GPa, becomes about 5 μm under $\sigma_N = 8$ MPa. In Fig. 3, the change in z is 0.1 mm under $\sigma_N = 8$ MPa, which is much bigger than the elastic deformation of the

Table 2
Experimental conditions

Exp. #	SHRA049-05	SHRA049-05-load01	SHRA049-06	SHRA067-01	SHRA067-04/07
Slip velocity (m/s)	0.0054	0	0.053	0.00089/0.0082/0.081	0
Normal stress (MPa)	3.05	0.5–8	2.98	2.98	0–3.2
Ambient temperature ($^{\circ}\text{C}$)	21	21	21	27	25
Ambient humidity (%)	30	25	25	65	50
Resonance freq. of AE sensor (MHz)	0.5	0.5	0.5	1.0	1.0
Diameter of AE sensor (mm)	3	3	3	10	10
Input signal shape	Half sine pulse	Half sine pulse	Half sine pulse	Half sine pulse	Half sine pulse
Input signal freq. (MHz)	0.5	0.5	0.5	0.5	0.5
Input signal amplitude (V)	200	200	200	70	50
Input signal interval (ms)	2	2	2	2	1
Number of stacking	10,000	90,000	1000	1000	1000

Figure 2

An example of stacked waveforms aligned as a function of lapse time of the experiments at an interval of 400 s. Red rectangular window indicates the time window to evaluate the maximum amplitudes of the first wave train. The high-frequency noise recorded at 5 ms is caused by the source pulse propagated as electromagnetic waves

samples. Thus, we consider that z is monitoring mainly the change in the thickness of the simulated fault and we can ignore the effect of shortening in rock samples due to normal stress on the transmitted wave amplitudes.

Then, it should be emphasized that the change in A is due to the change in the contact condition on the fault. In addition, A is linearly proportional to σ_N when σ_N is larger than 3 MPa, suggesting that there might exist non-linear properties of A for $\sigma_N < 3$ MPa. It should also be noted that the relation between A and σ_N are almost similar for upward and downward loading paths. This suggests that the contact condition depends only on the normal stress. The linear relation between A and σ_N has already been reported and interpreted as the change in contact area (e.g., Kendall and Tabor 1971). Our experiments could reproduce the past experimental results.

3.2. Transmitted Waves Under Constant Slip Velocity

In Fig. 4, we show temporal variations of both A and f as well as z for the case of SHRA049-05 ($\sigma_N = 3.05$ MPa and $V = 5.4 \times 10^{-3}$ m/s, see Tables 1 and 2). In Fig. 4a, A , f and z are plotted as a function of time. In Fig. 4b, f is plotted as a function of A . Note that since A is sampled at an interval of 20 s, f and z are resampled at an interval of 20 s after appropriate anti-alias filtering operation to measure the correlation at the same timing.

By comparing these evolutions, we found that A and f are anti-correlated with each other. In contrast, z , which may correspond to the temporal change of gouge layer thickness, does not seem to correlate with f . We computed the correlations between f and A as well as between f and z as shown

in the inset of Fig. 4a. The maximum correlation between f and A is -0.61 at 0 time lag while that between f and z is -0.35 at 0 time lag, respectively. This indicates that A is negatively correlated with f but the correlations between f and z are not obvious. It should be noted that z can be affected by the shortening due to the extrusion of gouge particles during the experiments. Therefore, we could not judge if f and thickness of the gouge layer are correlated or not unless the effects of the gouge leakage are properly taken into account. It should be noted that the rms (root mean square) elevation of the sliding surface of the sample is about $17\ \mu\text{m}$ measured by laser profilometer (Yamashita et al. 2015) while the typical thickness of the gouge layer is about $50\ \mu\text{m}$ estimated by the thin sections prepared after the experiments (Mizoguchi et al. 2009). Therefore, in the present experiments, interlocking of gouge particles does not seem to occur once the gouge layer is formed.

In Fig. 5, we show another example of constant slip velocity test (SHRA049-06, $\sigma_N = 2.98\ \text{MPa}$ and $V = 5.3 \times 10^{-2}\ \text{m/s}$). In this case, when friction reached the steady state (after 230 s in Fig. 5a),

Figure 4
a Time series of friction coefficient (f), maximum amplitudes of the transmitted waves (A), and axial displacements (z) for SHRA049-05 ($\sigma_N = 3.05\ \text{MPa}$ and $V = 5.4 \times 10^{-3}\ \text{m/s}$). In the inset, correlation coefficients between coefficient of friction and maximum amplitudes (red) and between friction and axial displacements (black) are shown. Correlations are computed for the data window shown as a black bar. **b** Correlation plot between the friction coefficient and maximum amplitudes at each sampling time (20 s interval). Color of each point stands for the lapse time during the experiments

friction did not fluctuate as in SHRA049-05. In this case, A also became stable. The correlation between f and A becomes minimum (-0.40) at $+24\ \text{s}$ lag time (Fig. 5a inset). The absolute correlation value is not large enough to be reliable for their correlation.

In Fig. 5b, correlation plot between f and A is shown. Although the overall correlation could not be found from this figure, we could see a negative correlation at the beginning of the experiments until about 200 s. Between 200 and 220 s (green bar in Fig. 5a), the correlation tentatively changed and shifted upward (green broken ellipsoid in Fig. 5b). After 220 s, f and A become stable and located in the

Figure 3

Results of the loading test using the sample of SHRA049 without rotations (SHRA049-05-load01). **a** Normal stress (σ_N) and axial displacements (z) are plotted as a function of time. **b** Maximum amplitudes of transmitted waves (A) are plotted as a function of normal stress (σ_N). Blue curve corresponds to the increasing stage of normal stress and red one is for the decreasing stage

middle of the correlation line until 200 s. We could imagine something happened between 200 and 220 s but we could not identify the cause of this shift. As shown in Appendix B, the temperature rapidly increased to 478 °C on the sliding surface at around 200 s, which might relate to such friction behavior. We think the data except for the period between 200 and 220 s also confirm the relation between f and A shown in SHRA049-05 that when the friction does not fluctuate the transmitted wave amplitude does not change. In this sense, we could monitor f through the observation of A .

3.3. Transmitted Waves Under Variable Slip Velocity

To investigate the slip velocity dependence of this correlation in more detail, another experiment (SHRA067-01) was conducted where the slip velocity changed stepwise in a single experiment (Fig. 6a). In Fig. 6b, a snapshot of the experimental data is shown in the 10000-s time window starting from 405000 s after the onset of the experiment. It includes three slip velocity experiments (8.95×10^{-4} m/s, 8.17×10^{-3} m/s and 8.10×10^{-2} m/s). Unfortunately, just after the slip velocity reached 8.10×10^{-2} m/s, the output of PZT sensor signal became very small. It should also be noted that a tiny fluctuation in the slowest slip velocity ($\sim 1.6 \times 10^{-4}$ m/s), which was not used in the present analysis, was due to the limitation in the servo controlled motor.

It should be noted again that f and A are very well correlated in this velocity range (minimum correlation reached -0.88). It should also be noted that z , which corresponds to the distance change of the propagation path between two PZT sensors including the thickness variation of the gouge layer, was weakly correlated with f (minimum correlation was -0.56) with some significant time delay (0.56×10^3 s) as shown in the inset of Fig. 6b.

In Fig. 7, we separately show the data for f , A , and z and their correlations in SHRA067-01 for the velocity of 8.95×10^{-4} m/s (a and c) and 8.17×10^{-3} m/s (b and d). We can see a similar behavior for the data window of $V = 8.17 \times 10^{-3}$ m/s to that of SHRA049-05. In both cases σ_N is similar and V is not so different although the radius of the

Figure 5

a Time series of friction coefficient (f), maximum amplitudes of the transmitted waves (A), and axial displacements (z) for SHRA049-06 ($\sigma_N = 2.98$ MPa and $V = 5.3 \times 10^{-2}$ m/s). In the inset, correlation coefficients between coefficient of friction and maximum amplitudes (red) and between friction and axial displacements (black) are shown. Correlations are computed for the data window shown as a black bar. Green bar corresponds to the window where correlation is shifted. **b** Correlation plot between the above friction coefficient and maximum amplitudes at each sampling time (2 s interval). Color of each point stands for the lapse time during the experiments. Green broken ellipsoid indicates the data window shown in a green bar in (a)

sample and rock type are different. Thus, we could say that this feature is a reproducible phenomenon when V and σ_N are similar for such rock specimens. In addition, we could see a correlation between f and A for $V = 8.95 \times 10^{-4}$ m/s. However, in this range the friction change was quite slow so that the correlation in long period term was evident.

In Fig. 8, we plotted the correlation between f and A in the time window between $t = 3.60 \times 10^5$ and 4.14×10^5 s. The data for $V = 8.95 \times 10^{-4}$ m/s are plotted in blue and those for $V = 8.17 \times 10^{-3}$ m/s are in red. Since the measurements were continuously done and the thickness of the gouge layer did not change drastically between two velocity conditions as can be seen in z (Fig. 6b), these two datasets can directly be compared. It is quite interesting that the two datasets shared the same correlation relation whose proportional coefficients are similar. Therefore, we could say that the negative correlation can be seen even in slow V where f does not fluctuate.

4. Interpretations

To interpret the above results, we referred to a theoretical investigation of scattering waves caused by cavities (Yamashita 1990; Benites et al. 1992; Kelner et al. 1999; Kawahara et al. 2010). In the scattering theory, ak defines the type of scattering, where a is the characteristic size of scatterers and k is wavenumber ($= 2\pi/\lambda$, where λ is wavelength) (e.g., Aki 1973). In the present experiments, we measured the transmitted elastic waves observed at the other end of the sample at a fixed frequency (0.5 MHz).

Compressive wave velocity of the material ($v_p = 6.9$ km/s) does not change drastically because most of the wave propagation paths are inside the rock specimens that were not suffered from serious damage during the experiments. It should be noted that the scatterers in this experiments should not be gouge particles but cavities because elastic constant of the cavities should be more different from the host rock than that of the gouge particles. The wavenumber k is evaluated as $5.2 \times 10^2 \text{ m}^{-1}$ and is considered as constant during the experiment. In contrast, the characteristic cavity size a in the gouge layer generated by the slipping might be the same order of the gouge particle size. We measured the size distribution of gouge particles generated during the experiment of SHRA049-05 and collected after the experiment. We use the same method as Wilson et al. (2005) after 30 min circulation. It distributed between 0.5 and 50 μm with an average of 4.5 μm and a mode of 14 μm . Here, we assume that the size of voids is similar to that of grains. Then, ak could be roughly estimated between 2.6×10^{-2} and 2.6×10^{-4} in the present condition, which is classified as the condition of $ak \ll 1$.

The theoretical consideration by Hudson (1981) predicted that inverse of quality factor (Q^{-1}) is proportional to $(ak)^3$ in 3-D isotropic medium when cracks (or cavities) are distributed randomly and $ak \ll 1$. Then, the numerical experiments using 2-D SH model (Yamashita 1990; Benites et al. 1992; Kelner et al. 1999) and 2-D P-SV model (Kawahara and Yamashita 1992) confirmed this feature. Under this condition, it is also known that wave velocity does not significantly change due to scattering, which is consistent with our experiments (Fig. 2). These features can also be seen in recent more realistic simulation using a granular material model (Somfai et al. 2005). If we apply the above theoretical relation to the currently obtained data shown in Fig. 4, a fluctuating by a factor of 2 during the slipping indicates the variation of factor of 8 in Q^{-1} .

It should be noted that Q^{-1} could be affected by the changes in the thickness of the gouge layer during the experiment even when the cavity density does not change (Kikuchi 1981; Yamashita 1990; Kawahara et al. 2010). If the cavity distribution is uniform, Q^{-1} is proportional to the thickness of the gouge layer.

Figure 6

Experiment results for SHRA067-01. **a** Coefficient of friction (f) and logarithm of slip velocity (V) are plotted as a function of slip. Black arrow indicates the data window for **(b)**. **b** Temporal variation of coefficient of friction, maximum amplitude of transmitted waves (A), slip velocity (V), and axial displacement (z). Data are plotted at an interval of 2 s. *Inset* correlation coefficients between coefficient of friction and maximum amplitudes (red) and between friction and axial displacements (black). Correlations are computed for the data window shown as a black bar

This effect becomes significant at the beginning of the experiment where the gouge layer starts to be created and is being thickened. This effect, however, could be minor at the steady-state stage after sufficient amount of slip because the excessive gouge particles are driven out to maintain the stable configuration of gouge particles inside the sliding layer and it maintains the constant thickness (Mizoguchi et al. 2009). Such differences can be seen as different gradients of the relation appearing in Fig. 4b; at the beginning of the experiment when the gouge layer is constructed, the gradient was steep but at the steady-state stage, its gradient becomes gentle. This difference might be related to the temporal variation of the thickness of the layer, which we could not monitor accurately at this moment. It should also be noted that the void does not have to be empty inside but can be filled with liquid material (Kikuchi 1981; Yamashita 1990; Benites et al. 1992; Kelner et al. 1999; Kawahara et al. 2010). In this case, the theoretical prediction of the absolute values of Q^{-1} could be different but the general tendency with respect to ak does not change.

To confirm the above theoretical predictions on the relation between void size and transmitted wave amplitudes, we conducted some simple experiments (SHRA067-04 and -07). In these experiments, we did not rotate the upper specimen, but tried to reproduce the same condition as that of SHRA067-01. We used polishing powder between the sliding interfaces as simulated gouge particles. Actually, we employed the specimens just after the experiment of SHRA067-01 without releasing the specimens from the sample holder. We used two kinds of polishing powder with different particle size: C3000 and C600 made of black silicon carbide produced by Maruto Co. Ltd. (<https://www.maruto.com>). C3000 is a product for the preparation of #3000 surface and its typical grain size

is between 4 and 8 microns, which we used for SHRA067-04. C600 corresponds to #600, whose typical grain size is between 25 and 35 microns, and we used it for SHRA067-07 (see Table 3). Using these synthetic gouge particles, we tried to simulate

the two different state of friction having different void size inside the gouge layer.

We put the gouge particles on the lower specimen whose side edge was covered with 0.05-mm-thick stainless ribbon and tightened by steel strings. Then,

Figure 7

Close-up views of coefficient of friction (f), maximum amplitudes (A), and axial displacements (z) for **a** $V = 0.895$ mm/s and **b** 8.17 mm/s. Correlation coefficients among f , A , and z for **c** $V = 0.895$ mm/s and **d** 8.17 mm/s

Figure 8

Correlation plot between coefficient of friction (f) and maximum amplitudes (A) for $V = 0.895$ mm/s (blue) and 8.17 mm/s (red). For the case of $V = 0.895$ mm/s, data after $t = 3.6 \times 10^5$ s are plotted

we contacted the upper specimen to the gouges and slowly rotated back and forth to homogenize the layer thickness. Then, we applied 3.2 MPa normal stress for 3 min for compaction. After unloading the normal stress, we applied normal stress at a step of 0.8 MPa for about 40 s each until it reached 3.2 MPa and then released the normal stress in the same way. During the experiments, σ_N , z , and A were measured simultaneously using M2i.4032 digitizer. Gouge layer thickness is estimated from the difference between z values with and without gouge particles.

After several trial experiments, we could achieve similar conditions for C3000 and C600 as shown in Fig. 9 and Table 4. In Fig. 9a, A for C3000 and C600 is shown as a function of σ_N . In Fig. 9b, gouge layer thickness is plotted as a function of σ_N . Figure 9b shows that the same gouge layer thickness is achieved under different normal stress and different gouge

Table 3
Specification of synthetic gouge material

EXP. #	Gouge material	Typical gran Size [μm]	Density (kg/m^3)	Weight (g)	Porosity ^a (%)
SHRA067-04	C3000	4–8	3217	1.960	50.1
SHRA067-07	C600	25–35	3217	2.498	36.4

^a We assume that the layer thickness is 1 mm and thus the total volume is 1.256 cm^3

Figure 9

Results of synthetic gouge tests (SHRA067-04 and SHRA067-07). **a** Maximum amplitudes of the transmitted waves (A) are plotted as a function of applied normal stress (σ_N) for SHRA067-04 and -07. **b** Thickness of the gouge layer is plotted as a function of normal stress during the experiments

particle size. In Table 4, all measured values with their standard deviations are shown. At 3.2 MPa, the gouge layer was slightly thicker for fine grain experiment (C3000, SHRA067-04) than that of gross grain case (C600, SHRA067-07), but A was larger for C3000. The relation in A is the same for lower normal stress cases. These suggest that A is larger for small void case (SHRA067-04) than for large void case (SHRA067-07) under similar layer thickness and normal stress. This is consistent with the theoretical prediction we made based on the scattering theory.

We then interpret the anti-correlation between the transmitted wave amplitudes (A) and friction coefficients (f) observed in Figs. 4 and 6. Here, we consider the force chain model (e.g., Liu et al. 1995; Howell and Behringer 1999). A number of force chains should be created inside the gouge layer to support the normal and shear traction outside the layer. Such model has already been proposed and numerically reproduced by discrete element method (Yoshioka and Sakaguchi 2006). Force chains could be built and broken during slipping and the macroscopic friction

Table 4
Synthetic gouge test results

EXP. #	Normal stress (MPa)	Thickness (mm)	Maximum amplitude (mV)
SHRA067-04 ^a	3.178 ± 0.004	1.0003 ± 0.0002	2.75 ± 0.04
	2.359 ± 0.000	1.0179 ± 0.0002	2.37 ± 0.04
	1.567 ± 0.000	1.0410 ± 0.0003	1.81 ± 0.04
SHRA067-07 ^a	3.164 ± 0.000	0.9803 ± 0.0002	2.02 ± 0.03
	2.402 ± 0.006	0.9983 ± 0.0003	1.58 ± 0.04
	1.600 ± 0.000	1.0203 ± 0.0002	1.30 ± 0.03

^a Results are shown at three different normal stress conditions for each experiment

Figure 10

Schematic illustration of the creation and collapse of the force chains. **a** The configuration of gouge particles when friction is high and **b** that for friction is low. Black big balls in **(a)** indicate the particles that consist of force chains. Gray small balls in **(b)** are created from the force chain particles (black big balls) in **(a)** due to the comminution process during the sliding. Because of the breakage of force chains and creation of small particles, many particles loosely support the friction force

measured outside the gouge layer is controlled by how many force chains are alive at each moment as schematically shown in Fig. 10. It should be noted that the difference from Yoshioka and Sakaguchi (2006) is that the particle size changes during the experiments. From the result of the experiments, we could draw a picture that when force chains support the friction, gouge particles surrounding the chains become free and act as voids. Then, when the force chains collapsed, surrounding gouge particles have to support the traction and the surrounding free space

will be filled and voids become small. In addition, to facilitate the creation of force chains, fewer particles per chain could be preferred, suggesting that larger particles are required to build force chains.

Finally, it could be interesting to consider the effect of heating on the sliding surfaces because frictional force generates heat and thus temperature of the specimen increases during the experiments. In addition, elastic wave attenuation is related to the temperature (e.g., Jackson et al. 1992; Kern et al. 1997). Therefore, to investigate the effect of heating, we conducted finite element simulations to estimate the distribution of the temperature as shown in Appendix B. For the case of the SHRA049-05 (Fig. 13), the maximum temperature on the sliding surface was less than 50 °C. Taking into account the previous experimental results that the change in Q^{-1} due to the above heating is less than a few percent (e.g., Jackson et al. 1992; Kern et al. 1997), we think the temperature rise effect might not be significant in this case. For the case of the SHRA049-06 (Fig. 14), by referring to the experimental results (Jackson et al. 1992; Kern et al. 1997), the change in attenuation is not significant in that temperature change. The variation of Q^{-1} value is still less than a few tens of percent, which is much smaller than that due to the voids. Therefore, we consider that the effect of temperature change due to the friction heating could be small in the present experimental data.

5. Discussion

In Fig. 4, we found a negative correlation between A and f , which seems contradictory to our physical intuition. It comes from the result of the stationary experiments where large amplitudes are observed for large contact area (i.e., large friction). This feature has been interpreted as the increase of real contact area between the interfaces that makes the waves transmitted through the interfaces more efficiently (Kendall and Tabor 1971). Even in this case, we can alternatively interpret based on the scattering theory (e.g., Hudson 1981; Kawahara and Yamashita 1992) that due to the compaction caused by the normal

stress increase void size becomes smaller that results in the increase in transmitted wave amplitude.

We can consider other possibilities for anti-correlation between f and A . For example, tensile cracks might be generated by shear heating (thermal cracking) and be opened in response to the change in shear stress if radial stress around the sample is low enough (S. Nielsen, personal comm.). Although confining pressure is applied by twisting the samples using steel strings in the present experiments, we could not measure the radial stress normal to the sidewall so we could not evaluate how low the radial stress is. If this happens inside the gouge layer, extrusion of gouge material could occur when shear stress changes. However, we did not observe such phenomenon by visual inspections during the experiments. Therefore, we think it might not be feasible at this moment.

When two interfaces are moving each other at high slip rate (i.e., time span of interest is much longer than the time needed to slip across asperities), the interpretation based on the contact theory might not be appropriate because the contact pairs on both interfaces change rapidly at any moment. In addition, during the rock-on-rock experiments, gouge particles are continuously supplied from the host rock immediately after the sliding starts due to the wear process (Tullis and Weeks 1986). And they are extruded when the thickness of the gouge layer reaches a critical condition. Their size distribution changes due to the comminution process (Biegel et al. 1989), which makes the estimate of contact area complicated.

It should be noted that this force chain model is intrinsically similar to the Hertzian contact model (e.g., Greenwood and Williamson 1966) in the case of normal loading where no shear force is applied to the sliding surface. When shear force is applied by rotating the sample, force chains incline to support the shear force. In contrast, since the original Hertz contact model does not take into account the friction in the contact surface, the contact area could depend on the shear force applied. We prefer force chains here because the gouge layer has a finite thickness and the thickness itself is important. In addition, since the fault surfaces are slipping during the measurements, the concept of contact area is not clear but force chain model is more straightforward. As a very rough estimate of the dimension of a force chain, the

thickness could be equivalent to the grain size of gouge particles ($\sim 5 \mu\text{m}$). The length of the chain could equal to the gouge layer thickness ($\sim 50 \mu\text{m}$). In the present experiments, it was difficult to estimate the chain density because we could only measure the relative change in attenuation of the transmitted wave amplitude.

Strain localization was observed inside the gouge layer and the thickness of the localization layer depends on the slip rate on the fault (e.g., Smith et al. 2015). In our experiments, slip rate was kept constant or piecewise constant, so that once the strain localization occurs, its thickness might be related to f as well as A (thus Q^{-1}).

In Fig. 4 of Mizoguchi and Fukuyama (2010), friction did not fluctuate at slow slip rate ($< \sim 5 \times 10^{-3} \text{ m/s}$) as well as at high slip rate ($> \sim 5 \times 10^{-2} \text{ m/s}$). But in between, friction fluctuated. It should be interesting to point out that at the slip rate slightly faster than the slow one, friction stayed more on high friction value and as slip rate increases friction stayed more on low friction value. One of the possible interpretations based on the present study is that when slip rate is slow, force chains maintained for longer period, and as slip rate increases, force chains collapsed more frequently and thus friction stays more at low friction value. It should also be noted that this kind of phenomenon might not be so common in nature because it might occur under a particular range of work rate ($\tau_s \times V$).

Reches and Lockner (2010) proposed a powder lubrication mechanism, where the existence of gouge materials weakens the fault. This was predicted theoretically many years ago as a slip-weakening mechanism (Matsu'ura et al. 1992). Our data and its interpretation in the present study are basically consistent with their result except for the strengthening mechanism during the subseismic slip. Following the interpretation of the friction weakening in the present study, once small particles are generated by wearing or comminution process, they fill the voids. In the present study, we considered that the strengthening occurred when large gouge particles are peeling off from the host rock. Our experiments successfully monitored the change in the condition inside the slipping layer during both strengthening and weakening of the fault at subseismic slip rate.

Anthony and Marone (2005) reported that angular gouge particles tend to create force chain more easily than smooth round particles. This mechanism might enhance our interpretation because gouge particles peeled off from the host rock might be big and angular and due to the comminution they become small and round. Han et al. (2011) also reported that nanoparticles become round after the experiments suggesting the roller lubrication. Unfortunately, our measurements could not monitor the shape of gouge particles in the present study. However, we could point out that their results are consistent with our interpretation where round particles might be rather difficult to create force chains.

Shear strength of the friction in a granular layer is reported to be partially controlled by the dilatation process (Marone 1991; Makedonska et al. 2011). It could be interesting to discuss the dilatation effect in the present study. However, because we could not seal the edge of the sliding surfaces of the column specimens during the experiment, the gouge particles leaked outside when the gouge layer reached a critical thickness, which realized a sort of steady-state stage. This process maintains the thickness of the gouge layer more or less constant. This gouge leakage could cause ambiguous correlations between f and z with significant delay as depicted in the insets of Figs. 4a and 6b. Thus, it was quite difficult to measure the dilatation effect from this experiment because of the leakage of gouge particles. We could not deny that dilatation effect is included in the experiments but we could not extract this effect from the experiment.

It should be noted that we assumed a characteristic dimension of voids when interpreting the variation of transmitted wave amplitude based on the scattering theory in the previous section. Of course, it is natural that void size is not uniform but follows a certain distribution function. Since the present discussion is qualitative, we did not introduce the distribution function of void size. But, we think it should be important to include the size distribution of voids when deriving the quantitative relation between the friction and transmitted wave amplitudes. According to Eq. 5.4 in Sato and Fehler (1997), if a single scattering model is applicable to the distribution of voids, the attenuation and characteristic length

of voids will be linear, suggesting that total attenuation due to scattering can be evaluated as a superposition of each void size. We, however, are not certain if the assumption for the single scattering model holds in the present case; we need to investigate carefully the assumptions we can make for the present situations.

Recently, Yamashita et al. (2014) measured electric conductivity across the sliding interface during high slip velocity friction experiments. They showed apparent temporal correlation between conductivity and friction coefficient during the experiment. Assuming constant conductivity of asperities, they interpreted that the temporal variation of conductivity is caused by the change in real contact area of the sliding interface. They further speculated that high friction could be achieved due to increase in the number of force chains. It should be noted that electric conductivity should be related to the size of real contact area where the electric current transmits. In contrast, the transmitted wave amplitudes are related to the distribution of voids that become scatterers of the elastic waves. Therefore, the observations by Yamashita et al. (2014) are complementary to those in the present study. At this moment, unfortunately, we could not measure the transmitted waves and electric conductivity simultaneously in the same experiment because of the electric isolation issue. But we can see that the results are consistent with each other; to increase the friction, force chains become strong, suggesting the increase in real contact area. Meanwhile, voids structure developed around the force chains as expected from the transmitted wave amplitudes.

6. Conclusions

From rock-on-rock friction experiments of metagabbro and diorite at subseismic slip velocity, we observed that the maximum amplitudes of transmitted waves (A) across the simulated fault correlated with coefficient of friction (f). Then we interpreted such amplitude variation is caused by the variation of characteristic void size inside the gouge layer based on the scattering theory. And we experimentally confirmed this relation using simulated gouge

particles. We then found that the voids become large during the high-friction stage and they become small when the friction becomes small. We speculated the obtained result based on the force chain model as follows. When the friction is high, force chains are built and large-scale voids are created in the surroundings. When friction decreases, the scale of voids becomes small due to the collapse of the force chains. Therefore, the creation of voids could be important information to understand the variation of friction at subseismic velocities. The present result will contribute to the understanding of the friction of granular layers at high strain rate shearing.

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Appendix A: Stiffness of the Apparatus

To characterize the apparatus, we measured both normal and shear stiffness. Normal stiffness is measured using the data of SHRA049-05-load01. We used the load cell data to measure the normal stress and displacement sensor data to measure the shortening distance due to the applied normal stress. The

Figure 11

Normal stress (σ_N) and axial displacement (z) for upgoing part of the SHRA049-05-load01 is plotted as blue. Red line stands for the best-fit least square line and the coefficients are shown as an inserted equation. The fitting was done using the data for $\sigma_N > 3$ MPa

locations of these sensors are shown in Fig. 1. In Fig. 11, the applied normal stress is plotted as a function of axial displacements for the upward loading stage from zero to 8 MPa. The gradient of this data corresponds to the stiffness against the normal stress. Since the linearity between A and σ_N is observed above 3 MPa, we used the data between 3 and 8 MPa for the least square fitting to estimate the stiffness. The obtained stiffness was 79.4 GPa/m.

Shear stiffness was measured using a single column sample instead of using a pair of columns. This single column sample is made of Indian metagabbro, similar to the SHRA049 sample. It is a proxy of the case where two fault surfaces are firmly contacted and no slip occurs between them. The diameter and

Figure 12

Computation model for the temperature distribution. Rotation axis which is a symmetrical axis of the computation is located at the upper side. Sliding surface is located at the left side. Lower and right sides are set as a heat transfer boundary

Figure 13

Snapshots of the temperature distribution computed by finite element simulations for the experiment of SHRA049-05. Half cross section of the specimen is shown. Symmetry axis is located at the upper horizontal edge and left side edge is the contact surface between the specimens (see Fig. 12 for details). Thus, the left upper corner indicates the center of the sliding surface. Maximum temperature and time are shown at the right upper and lower part of each panel, respectively. The unit of the scale is in degrees Celsius. Vertical axis is the distance from the center of the specimen ranging from 12.5 mm to 0 mm. Horizontal axis is the distance from the sliding surface ranging from 0 mm to 35 mm

length of the sample are 39.90 mm and 83.91 mm, respectively. We measured the stiffness by applying a tiny rotation by the motor and we measured the amount of rotation and amount of torque by rotary encoder and torque gauge, respectively, whose locations are shown in Fig. 1. The measured stiffness was 84.5 GPa/m. It should be noted that this stiffness depends on the area of slip surface. We derived a general conversion relation as follows:

$$S = S_0 \frac{\varphi_0^4}{(\varphi_{\text{out}}^2 + \varphi_{\text{in}}^2 + \varphi_{\text{in}}\varphi_{\text{out}})^2} \frac{\varphi_{\text{out}} + \varphi_{\text{in}}}{\varphi_{\text{out}} - \varphi_{\text{in}}} \quad (1)$$

where S_0 is the stiffness measured using the column sample whose diameter is φ_0 . S is the stiffness for the hollow cylinder sample whose inner and outer diameters are φ_{in} and φ_{out} , respectively ($\varphi_{\text{in}} = 0$ for solid column sample). In the present case, $S_0 = 84.5$ GPa/m and $\varphi_0 = 39.90$ mm.

Figure 14

Snapshots of the temperature distribution computed by finite element simulations for the experiment of SHRA049-06. Half cross section of the specimen is shown. Symmetry axis is located at the upper horizontal edge and left side edge is the contact surface between the specimens (see Fig. 12 for details). Thus, the left upper corner indicates the center of the sliding surface. Maximum temperature and time are shown at the right upper and lower part of each panel, respectively. The unit of the scale is in degrees Celsius. Vertical axis is the distance from the center of the specimen ranging from 12.5 mm to 0 mm. Horizontal axis is the distance from the sliding surface ranging from 0 mm to 35 mm

Appendix B: Estimation of Heat Distribution During the Experiments

We numerically calculated the temperature distribution in the specimen. The calculation was done assuming an axi-symmetric 2-D problem using a published computer program of the finite element method by (Kuroda 2001). The radius and length are 12.5 mm and 35 mm, respectively, and the mesh size is 0.5×0.5 mm (Fig. 12). Half of the sliding surface was divided into 25 units and the average heat flux from the sliding surface was determined for each unit

from time-varying shear stress and slip rate data. It was assumed that all frictional work converts into heat. The surfaces of the specimen other than the sliding one were treated as a heat transfer boundary to air. Heat loss due to extrusion of gouge from the sliding surface was not incorporated into the calculation. Thermal properties of the rock used in the calculation are: thermal conductivity of 2 W/mK, specific heat capacity of 800 J/kgK, density of 2600 kg/m³, and heat transfer coefficient of 150 W/m²K in flowing air (Hirose and Bystricky 2007;

Mizoguchi et al. 2009). The initial temperature in the calculation area was 20 °C.

In Fig. 13, snapshots of the temperature distribution for the case of SHRA049-05 are shown. One can see that the variation of the temperature is not large, about 80 °C at most and generally around 50 °C on the sliding surface. For the case of SHAR049-06 where one order of magnitude faster loading velocity is applied (Fig. 14), temperature rose up to 500 °C on the sliding surface and the temperature remains above 200 °C in the region within 10 mm from the sliding surface.

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