Geological Records of Coseismic Shear Localization Along the Yangsan Fault, Korea

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Abstract We conducted outcrop-to-nanoscale structural observations on a principal slip zone (PSZ) of the Yangsan fault, a major strike-slip fault in southeast Korea, and some high-velocity rotary shear tests on the PSZ gouges to understand shear localization and physico-chemical processes in the PSZ during earthquakes. At the fault outcrop, the PSZ appears 1–2 cm thick. At smaller scales, the PSZ is subdivided into Units 1 to 4 based on their microstructures. Microscopic observations confirmed the shear localization in Units 1 (20–500 μm in thickness) and 3 (0.8–3 mm in thickness). Further localization was observed in several μm-thick shear bands. Various structural and mineralogical features that recorded physico-chemical processes in slip zones were found in the PSZ, including gouge fluidization structures relevant to thermal pressurization, solidified frictional melt of clay-rich gouge, and mineralogical changes by frictional heating-induced illitization. The gouge melting and mineralogical changes were reproduced in our experiments at 1.3 m s\textsuperscript{-1}. The gouge fluidization has been observed in previous tests at seismic slip rates. Thus, the observations from the natural and experimental faults indicate that the shear localization in the PSZ was coseismic. In a cataclasite zone next to the PSZ, altered veins of pseudotachylyte were found. All these observations indicate temporal changes of the PSZ materials (e.g., formation of solidified melt, alteration of the melt into clay minerals, friction-induced mineralogical changes). Associated with such changes, coseismic slip zone processes and dominant weakening mechanisms may also vary, even at the same location on a fault.

Plain Language Summary Shear strain may be localized into narrow zones of tectonic faults in short-term and long-term scales. We conducted outcrop-to-nanoscale structural observations on a principal slip zone (PSZ) of the Yangsan fault in southeast Korea and shear tests on fault rocks taken from the fault at 1.3 m s\textsuperscript{-1} to understand the short-term shear localization in the fault during earthquakes. Frictional heating-related geological records such as gouge injection structures, solidified frictional melt, and mineralogical changes were found in the principal slip zone. The frictional gouge melting and mineralogical changes were reproduced in our experiments, and the gouge injection structures were observed in previous shear tests at seismic slip rates. Thus, the natural and experimental observations indicate that the shear localization into the PSZ, which is several tens of μm to several mm in thickness, occurred during earthquakes. Further localization was also observed in several μm-thick shear bands in the PSZ. This study gives us an idea of shear localization zone thickness in natural fault zones. Also, it shows, with changes in slip zone materials, physical and chemical processes in fault slip zones during earthquakes may vary with time, even at the same location of a fault.

1. Introduction

In natural fault zones, shear strain is mainly accommodated in fault rocks (or fault materials) that make up the fault core (i.e., a central high-strain zone of a brittle fault; Fossen, 2016). The shear strain may be localized in short-term and long-term scales. The long-term localization has been reported from both seismogenic and aseismic fault zones (e.g., Sibson, 2003). Seismic rupture events may repeatedly occur in a slip zone over a long period, expressed by progressive displacement of geomorphic features (e.g., Lensen, 1968). Also, aseismic fault slip may be accommodated in narrow zones of meters to decimeters in thickness (e.g., the Hayward fault; Bilham & Whitehead, 1997). Aseismic shear localization observed from statically weak faults appears to be promoted by the operation of time-dependent, fluid-assisted deformation mechanisms (e.g., dissolution-precipitation creep) in fault rocks (e.g., Collettini et al., 2009; Gratier et al., 2011;
This study focuses on the other (i.e., short-term, coseismic) type of shear localization in tectonic faults.

Observation of fault cores of seismogenic faults at the outcrop scale reveals principal slip zones, which may be a few millimeters up to several centimeters in thickness (e.g., Chester & Chester, 1998; Sibson, 2003). From the observation at smaller scales, even much narrower slip zones, ranging from tens to hundreds of micrometers, have also been identified (e.g., Chester et al., 2003; De Paola et al., 2008; Han et al., 2020; Heermance et al., 2003; Kim et al., 2020). Similar shear localization has been reported from experimental work at seismic slip rates (e.g., Boutareaud et al., 2008; Brantut et al., 2008; Kitajima et al., 2010; Yao et al., 2013). The thickness of a slip zone is directly related to temperature rise and thermally driven fault weakening (Rice, 2006). Therefore, shear localization and physico-chemical processes in slip zones during earthquakes (i.e., coseismic slip zone processes) are important issues to be explored for improving our understanding of dynamic fault weakening and identifying geological records of past seismic slip events.

Based on theoretical studies, field observations, and friction tests, various coseismic slip zone processes and associated dynamic fault weakening mechanisms have been proposed in the past decades. These include frictional melting and melt lubrication (Brantut et al., 2016; Del Gaudio et al., 2009; Di Toro et al., 2011; Hayward et al., 2016; Hirose & Shimamoto, 2005; Lee et al., 2017; Tsutsumi & Shimamoto, 1997), flash heating-induced weakening (Beeler et al., 2008; Goldsby & Tullis, 2011; Rice, 2006), pore fluid pressurization induced by frictional heating (Ferri et al., 2010, 2011; Kitajima et al., 2010; Lachenbruch, 1980; Noda & Lapusta, 2013; Noda & Shimamoto, 2005; Rice, 2006; Sibson, 1973; Tanikawa & Shimamoto, 2009; Wibberley & Shimamoto, 2005), superplastic flow at elevated temperature by frictional heating (De Paola et al., 2015), thermochemical pressurization (Brantut et al., 2008, 2010, 2011; Sulem & Famin, 2009), powder lubrication (Han et al., 2010, 2011) caused by thermal decomposition (Collettini et al., 2013; Di Toro et al., 2011; Han, Shimamoto, Hirose, et al., 2007; Han, Shimamoto, Ando, et al., 2007; Mitchell et al., 2015), and the formation and lubrication of silica layer (e.g., Di Toro et al., 2004; Kirkpatrick et al., 2013; Reches & Lockner, 2010; Rowe et al., 2019). Some natural fault studies have shown that there may be spatial heterogeneity of coseismic processes even in one event (e.g., Kirkpatrick & Shipton, 2009) and that multiple processes may occur sequentially at one location during a single event (e.g., frictional heating-induced fluid pressure buildup and hydrofracturing, followed by frictional melting; Okamoto et al., 2006). These indicate that the relative efficiency of dynamic fault weakening mechanisms and the resulting fault strength and coseismic displacement may also vary, depending on the location on a fault (Brantut & Mitchell, 2018; Noda & Lapusta, 2013; Perrin et al., 2016; Tanikawa & Shimamoto, 2009). Another arising study issue is the evolution of coseismic processes in natural fault slip zones, which remains limitedly explored (Kirkpatrick & Shipton, 2009). Changes in materials and their properties in fault slip zones may be caused by interseismic (dissolution-precipitation, crack sealing, and neocrystallization due to fluid-rock reaction; Muhuri et al., 2003; Gratier et al., 2011, 2014) and coseismic physico-chemical processes (comminution, thermal decomposition, amorphization, melting, and also damage through fracturing and secondary faulting, Brantut et al., 2008; Chester et al., 2005; Han, Shimamoto, Ando, et al., 2007; Oohashi et al., 2011, 2014; Hirose et al., 2016; Ma et al., 2006; Mitchell et al., 2016) in the seismic cycle. Accordingly, the coseismic processes of a single fault may likely vary with the change in fault rock materials over time. Research on this aspect, however, is challenging to conduct experimentally. So, in order to understand this, observational work on principal slip zones of natural faults is required.

This study was designed to understand how coseismic shear is localized and how coseismic processes may change over time. We conducted an outcrop-scale structural observation on the Yangsan fault, a mature, large-scale strike-slip fault in southeastern Korea. We also conducted mineralogical, chemical, and microstructural analyses of the slip zone materials of the fault at smaller scales. We conducted shear tests on the natural fault gouges at a seismic slip rate to compare the results from the natural fault. Here, we present supporting evidence of coseismic shear localization in the natural slip zones locally as thin as several tens of micrometers. We propose that coseismic processes and dynamic weakening mechanisms may vary temporally even at the same location on a fault, affected by coseismic and interseismic materials' changes in principal slip zones.
2. The Yangsan Fault

The Yangsan Fault System, which includes six NE-striking faults and one NW-striking fault, is the most prominent structure in the southeastern part of the Korean peninsula (Figure 1a). The Yangsan fault is a large-scale, NE-striking strike-slip fault and is the longest out of the seven faults with an inland extension of about 200 km (Figure 1a, Chang et al., 1990; Lee & Jin, 1991). Based on historical \((n = 126)\) and instrumental \((n = 14)\) earthquake data along the fault (Lee & Jin, 1991) and geometrical characteristics identified from its satellite images (Choi et al., 2017), it was proposed that it consists of three (northern, central, and southern) segments. According to previous studies on the internal structure of the fault, the fault width (i.e., the sum of the widths of a core zone and damage zones) is as large as 1.6 km in the southern and central segments (Choi et al., 2009). However, it seems to decrease to several tens to hundreds of meters in the northern segment (e.g., Chang et al., 1990; Cheon et al., 2019; Hwang et al., 2004; Kim et al., 2016). The width of the fault core is also spatially variable and is as small as 0.2 m and >100 m, depending on the location (Cheon et al., 2020). The broad core zones (several tens of meters) usually consist of fault gouge, breccia, cataclasite, and centimeter-to-meter-sized fractured lenses of wall rocks (Cheon et al., 2019, 2020; Kim et al., 2016).

The finite strike-slip displacement along the fault is estimated to be 20–35 km (in the dextral sense of slip) based on the offsets shown by the Cretaceous granitic rocks and sedimentary rocks (Chang et al., 1990; Hwang et al., 2004). Considering the temporal change in the kinematics of the fault motion (sinistral strike-slip, dextral strike-slip, and dip-slip) since the Late Cretaceous (e.g., Chae & Chang, 1994; Cheon et al., 2019; Hwang et al., 2007), the cumulative displacement along the fault should be larger than that. The fault appears still active, according to the observations that itself and the subsidiary faults in its damage zone crosscut the Quaternary deposits at 11 locations so far (e.g., Cheon et al., 2020; Kang & Ryoo, 2009; Kim et al., 2020; Kyung, 2003; Okada et al., 1994). Vertical slip rates estimated with the ages and vertical displacements of the Quaternary deposits cut by the fault were <0.1 mm yr\(^{-1}\) and 0.02–0.07 mm yr\(^{-1}\) at the northern and southern segments, respectively, but horizontal slip rates could not be estimated because of lack of data (Kyung, 2003). An average long-term slip rate of the fault estimated using historical (2–1905 A.D.) and instrumental earthquake (1905–1989) data and the equation for an average slip rate proposed by

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Figure 1. (a) Satellite images showing the Yangsan Fault System, which includes seven major faults (white and red lines), in SE Korea. 1, Jain fault; 2, Miryang fault; 3, Moryang fault; 4, Yangsan fault; 5, Dongnae fault; 6, Ilgwang fault; 7, Ulsan fault. The longest one is the Yangsan fault (red line). (b) Close-up view of the boxed area in (a), where the study area (yellow star) of the Yangsan fault is shown. (c) Route map showing the internal structure of the fault in the study area, modified from Kim et al. (2016).
Brune (1968) is $1.495 \text{ mm yr}^{-1}$. The slip rate estimated for the southern and central segments ($4.4 \text{ mm yr}^{-1}$) is larger than the average (Lee & Jin, 1991). Based on the fault length ($>200 \text{ km}$), age of fault initiation ($\sim70 \text{ Ma}$), maximum long-term slip rate ($\sim0.4 \text{ cm yr}^{-1}$), and total maximum displacement ($>20–35 \text{ km}$), the structural maturity of the fault estimated using the criteria by Manighetti et al. (2007) appears to fit the intermediate class (Class 2).

Mineralogical studies on the fault rocks may roughly constrain the temperature condition of the fault activities. Song et al. (2016) interpreted that 2M1 illite and 1M/1Md illite in the fault rocks might indicate hydrothermal and fault activities at high ($>280^\circ\text{C}$) and lower temperatures ($<180^\circ\text{C}$), respectively. Another study by Chang and Choo (1999) reported that clay minerals of the fault rocks formed at $<100^\circ\text{C}$–$200^\circ\text{C}$, which supports the faulting at shallow depths. However, the results should be interpreted with care because coseismic frictional heating might have affected the mineralogy of the gouges.

Part of the Yangsan fault's northern segment is exposed in the study area, very close to the Bogyeongsa temple, Pohang, SE Korea. The fault juxtaposes sedimentary rocks of the Cretaceous Hayang Group with dacitic volcanic rocks of the Yucheon Group (Chang et al., 1990; Yun et al., 2000, Figure 1c). The attitude (strike and dip) of the fault surface is N10°E/80°NW to 90°. The rake of the striation on the fault surface is 05°N. The fault consists of a core zone ($\sim10 \text{ m}$ in width) and surrounding damage zones with a minimum measurable thickness of 200 m (Kim et al., 2016). The core zone includes cataclasite zone (CZ), brown gouge zone (BZ), and blue-purple gouge zone (BPZ) (Figure 2). A 1–2 cm-thick principal slip zone (PSZ), the main structure discussed in this study, is observed between the CZ and BZ in the core zone (Figure 2). The BPZ includes many fractured lenses of the sedimentary wall rock. Details of the core zone are described in Section 4.1. In the damage zones, the sedimentary and volcanic rocks show high densities of shear and extension fractures and calcite veins; the fracture density appears to increase toward the core zone (Kim et al., 2016). There are some noticeable subsidiary faults with millimeters-to-decimeters-thick clay-rich gouges (Kim et al., 2016; Woo et al., 2016).

3. Methods

3.1. Structural Observations

Fault rocks may give critical information on deformation mechanisms and deformation styles (e.g., distributed or localized) and show structural records of past seismic slip. We conducted observations of fault rocks of the Yangsan fault at rock slab-to-nanoscales to figure out their structural characteristics. At the fault outcrop (Figure 2), we took four oriented block samples of the fault rocks: Three samples, including the PSZ and surrounding materials (parts of the CZ and BZ), and one sample, including the BZ and BPZ (see Figure 2d for their locations). Rock slabs and thin-sections used for the structural observations were made from the block samples as follows. First, we dried the blocks at room temperature for one day. Next, we impregnated them with a low-viscosity epoxy for their consolidation and then prepared rock slabs and chips by cutting them perpendicular to the fault surface (or cataclastic foliation) and parallel to the slickenline. During all the sample preparation processes (cutting, grinding, polishing), we used a low-viscosity oil (electrical discharge machining fluid) instead of water to prevent possible damage to water-sensitive, clay-rich fault rock samples. Then, we scanned the polished rock slabs and chips with a scanner (Epson Perfection V800 Photo) and obtained high-resolution (1,200 dpi) images.

We observed microstructures (e.g., sizes and fractions of minerals and clasts, foliation, fractures, veins, and any other structures defined by materials' spatial distributions at the microscale) of the fault rocks with an optical microscope (Olympus BX53). Additional observations at micro-to-nanoscales were made at the Center for Research Facilities, Gyeongsang National University, Korea, using a field emission-scanning electron microscope (FE-SEM; JEOL JSM-7610F) equipped with an energy dispersive X-ray spectrometer (EDS; Oxford X-Max 50). Back-scattered electron (BSE) images were taken using the electron microscope. The acceleration voltage and beam current were 15 kV and 1 nA, respectively. Specimen (5 × 5 μm in size) preparation for transmission electron microscopy (TEM) was performed with a focused ion beam (FIB) instrument (Quanta 3D FEG) at the Korea Basic Science Institute (KBSI). TEM observation and chemical analyses were conducted at the Korea Institute of Science and Technology (KIST) using an electron
Figure 2.
microscope (Tecnai G2 F20) equipped with an energy dispersive X-ray spectrometer (EDAX; PV9761 Si [Li] detector) at an acceleration voltage of 200 kV.

To characterize the fault rocks quantitatively, we measured clast sizes and clast fractions of them. For the measurement, we took BSE images of representative areas in each fault rock sample. Then, we prepared binary images showing the distribution of clasts, where clasts smaller than 3 μm were excluded. We measured clast sizes and fractions in the images with NIH ImageJ and then averaged the results from three different areas.

3.2. Shear Experiments

To get insight into what coseismic physico-chemical processes may occur in the slip zone of the Yangsan fault slip zones and what structures and materials may be characteristic of seismic slip, we conducted rotary shear tests on wet and dry gouges taken from the fault at a seismic slip rate. The sample preparation procedure for the high-velocity rotary shear tests is as follows. By sieving, particles smaller than 125 μm were collected. For each wet gouge experiment, a wet gouge paste layer was prepared by mixing 1 g of the powder with 0.4 g of distilled water. For the dry experiment, only 1 g of the powder was used. The gouge was then placed between a pair of solid rock cylinders (i.e., stationary and rotary cylinders) of gabbro (Belfast, South Africa), of which diameter and height are 25 and ∼20 mm, respectively. A Teflon sleeve with a 24.95 mm inner diameter was then placed around the rock cylinders to prevent gouge leakage during the experiments. Also, we prepared another sample assembly for temperature measurement during slip, as follows. A hole of 1.3 mm in diameter was made in the stationary rock cylinder of gabbro, using a microdrilling machine. It was located 5 mm inward from the periphery of the stationary rock cylinder. A K-type thermocouple (TC) was put into the hole and then installed by filling the gap of the hole with a ceramic bond. The sample was kept at room temperature for one day for the curing of the ceramic bond.

The friction experiments were performed using the high-velocity rotary shear apparatus at Yamaguchi University (HVR apparatus; see Hirose & Shimamoto, 2005 for details). They were conducted at normal stresses of 2 and 5 MPa (wet and dry conditions, respectively) with an equivalent slip rate of 1.3 m s⁻¹. The initial thickness of the gouge layer was estimated at 1.1–1.3 mm. Mechanical data were collected at sampling rates of up to 100 Hz. In one run (HVR4691), slip zone temperature was measured using the sample assembly in which the TC was installed. After the experiments, the samples were recovered for microstructural and materials analyses. Thin-sections were made from them and observed as described in Section 3.1.

3.3. Mineralogical Analyses

We conducted mineralogical analyses of the natural fault rocks and the recovered experimental gouges to get information on mineral compositions, fractions of mineral phases, and possible mineralogical changes with temperature rise. The natural fault rocks for XRD analyses were sampled from the outcrop. Considering the material heterogeneity and the small thickness of the PSZ and BZ materials, several samples at different places were collected. Some materials, which could be identified only in the rock slabs, were collected with a microdrill (FBS 240/E, Proxxon; Kim et al., 2017). The materials were then ground to fine powders (<5 μm in size) for 10 min using a micronizing mill (McCrone Microscopes & Accessories), and then oven-dried at 50°C for one day. All the XRD analyses on bulk samples were performed with an X-ray diffractometer (Bruker D8 Advance A25) at the Center for Research Facilities, Gyeongsang National University, using CuKα radiation at 40 kV/40 mA with a step width of 0.02° from 4 to 45° (2θ) and a scan speed of 9.0°/min.
0.1° s⁻¹. Besides the bulk samples, clay-sized (or clay-fraction) samples were also analyzed. The samples were prepared as follows. First, we mixed the powder of each bulk sample with a diluted solution made with 20 ml of a dispersing agent (sodium hexametaphosphate) and 500 ml of distilled water. Clay-sized particles under 2 μm were separated by sedimentation from the mixture and then concentrated at 7,500 rpm for 5 min in a centrifuge. For clay mineral identification, oriented samples were prepared from both air-dried and ethylene glycol (EG)-treated clays at 60°C for 8 h. The oriented samples’ analytical condition was the same as that for the bulk samples, except for the narrower scan range (3–30° of 2θ) and the slower scan speed (1° min⁻¹). The use of the dispersing agent caused the shift of peak positions (2θ) of smectite and illite-smectite mixed-layer minerals of high smectite proportion from 7.2° to higher degrees in the AD and ~5° in the EG samples, presumably due to the exchanges of cations in the minerals with Na⁺ in the agent. The mineral phases were quantified with Siroquant software (version 3.0). Rietveld refinement was repeatedly conducted to reach the chi-squared value under three by adjusting the crystallographic parameters and changing phases (Rietveld, 1969). Also, semi-quantitative calculation of the relative abundances of four major clay minerals (smectite, illite, kaolinite, chlorite) was conducted following the method by Biscaye (1965).

To examine possible mineralogical changes induced by frictional heating, we recovered the sheared wet and dry gouges after the shear tests with different displacement, prepared powder samples using the gouges taken from their inner (a circular area of 12 mm in diameter) and outer parts, and conducted XRD analyses on them. Because of the small amount of the experimental gouges, we could not prepare their ethylene glycol (EG)-treated samples. Also, we examined the changes in statically heated gouges. For this, first, we put 2 g of powder (<125 μm in size) from the gouge in the PSZ in an alumina ceramic container and heated it to each target temperature (100°C, 200°C, 300°C, 400°C, and 500°C) at a rate of 10°C min⁻¹ under the air-flowing condition. We kept the powder at the target temperature for 20 min. After the natural cooling of the powder, we analyzed its mineral composition by XRD.

4. Materials and Structures of the Principal Slip Zone

4.1. Outcrop- and Rock Slab-Scale Observations

The fault core zone, which is estimated at 9–10 m in thickness (Kim et al., 2016), consists of a brown gouge zone (BZ), a blue-purple gouge zone (BPZ), and a blue-gray cataclasite zone (CZ) (Figures 2a–2c). The CZ, which is ~1 m wide, is severely altered and contains a fractured lens up to 50 cm in size (Figure 2b). In the fault’s western damage zone close to the CZ, there is a 3–20-cm-thick subsidiary fault of N15°–20°E/70°NW (Figure 2b). The fault shows several subparallel shear localization zones (Figure 2c, blue arrows), which occur as mm-thick clay-gouge bands (Figure 2c inset). The BZ is about 30–50 cm wide and shows strong foliation (Figures 2d and 2e). In the BZ, the size of clasts is usually less than 1 cm, but it appears to increase toward the BPZ. The BPZ, which develops between the BZ and the eastern damage zone, is estimated at 8–9 m wide (Kim et al., 2016). The boundary between the BZ and BPZ is relatively transitional (Figure 2d). The BPZ shows clay-rich foliated gouge anastomosing around fractured lenses of the sedimentary wall rocks (several cm to up to 1 m in size) (Figure 2f, Kim et al., 2016).

At the outcrop, the PSZ, which is about 1–2 cm wide at the outcrop, shows very sharp planar boundaries with the CZ to the west and the BZ to the east (Figures 2b–2d, and 2e). The PSZ has a reddish-brown color overall. It has a much smaller clast size than the surrounding fault rocks, and the content of clasts is also noticeably smaller (Figure 2e).

Each region of the fault core was observed through the rock slabs made out of four bulk samples taken from the outcrop (three samples including the PSZ and surrounding materials, one sample including the BZ and BPZ) (Figure 3). The CZ observed in the rock slab is bluish-gray and is severely fractured. It shows weak foliation subparallel to the PSZ. Many fractures are high angle (>70°) to the PSZ, and some of them are filled with calcite (Figure 3a). Also, there are brown injection materials, which show the color contrast with the surrounding materials. They occur as high angle (60°–70°) veins to the PSZ, but some of them are observed along with the fractures subparallel (<15°) to the PSZ (Figure 3c). The PSZ shows a distinct boundary with CZ. Its thickness is measured at 1–2 cm. The clast content in the PSZ is very small, and the particle size is too small to be seen with the naked eye. Within the PSZ, subzones show different colors (Figures 3a–3c).
Clasts-mixed zones (CMZ; Figures 3a and 3d) and dark-gray gouge zones (DGZ; Figures 3b and 3c), which are not recognized in the outcrop, develop between the PSZ and BZ. The PSZ has distinct boundaries with the zones as well. The CMZ consists of a mixture of angular clasts (up to 1 cm in size) derived from various rocks and minerals (volcanic rocks, sedimentary rocks, quartz, feldspar, calcite), and it shows local cataclastic foliation. The DGZ comprises a small fraction of clasts and a dark gray matrix, and it also contains some gouge fragments (Figures 3b and 3c). Additional images of (micro)structures of the DGZ are given in Figure S3.

The BZ near the PSZ shows a matrix-supported structure, and most of the clasts are fragments of volcanic and sedimentary rocks and minerals (quartz, feldspar, calcite). The brown clay-rich matrix shows strong foliation parallel to the PSZ (Figures 3a–3c). On the other hand, the BZ close to the BPZ has relatively large clasts (up to 5 cm) and shows cataclastic foliation defined by the alignment of the clasts and clay-rich matrix (Figure 3e). The boundary between the BZ and BPZ is transitional and unclear. The BPZ shows much larger clasts than the BZ, and the space between the clasts is filled with a network of clay gouge bands (Figure 3e). See Table 1 for the summary of the mesoscale structural observations.

4.2. Micro-to-Nano Scale Observation

The PSZ, which is 1–2 cm thick, is divided into four subzones (Units 1–4) based on their colors at the rock chips and their overall microstructures (e.g., clast size, clast fraction, foliation intensity) (Figure 4). The clast
### Table 1

*Summary of Structural and Mineralogical Characteristics of the Fault Core Zone*

| Meso-scale structures | Microstructures | Mineral composition |
|-----------------------|-----------------|---------------------|
| **Cataclasite zone (CZ)** |                |                     |
| Cataclasite (near the PSZ) | ~1 m wide; blue-gray-colored; high fracture density; some fractures filled with calcite | – | Nonclay minerals: 61 wt.%; clay minerals: 39 wt.%; more enriched with calcite than in other fault rocks; smectite (80%) is the most abundant out of the clay minerals |
| Injection materials | ~5-cm long and 1–5-mm wide; brown-colored matrix; developed at high-angles (60°–70°) to the PSZ boundary; found ~1 cm away from the PSZ, but their connection to the PSZ has not been observed | Strong preferred orientation of clay minerals along the margins; local U-shaped foliation; clast fraction of ~5.5%; quartz clasts showing embayed boundaries; matrix composed of biotite microlites, smectite-dominant clay minerals, and Fe- and Ti-oxides; Flow banding structure defined by thin layers of biotite microlites; hexagonal to circular biotite grains of 0.2–1.2 μm in size; tabular biotite grains of 0.15–2 μm in size | – |
| **Principal slip zone (PSZ)** |                |                     |
| Unit 1 | 1–2-cm wide; reddish brown-colored matrix (locally showing thin layers with different colors); mostly composed of ultrafine clasts; contacting sharply with the CZ | 20–500-μm wide; strongly foliated with clay minerals throughout the unit; clast fractions of 5.3% and 7.2%; clasts of down to 100 μm in size; clay minerals of down to 100 nm in size; no evidence of amorphous material in the unit; injection into Unit 2; brecciation structures at some locations | Nonclay minerals: 43–46 wt.%; clay minerals: 54–57 wt.%; noticeably scarce calcite; smectite is the least out of the clay minerals; similar chlorite content in all the units; illite content: Unit 1 > Unit 2 > Units 3, and 4 |
| Unit 2 | 5–7.3-mm wide; preferred orientation of clay minerals; clast fractions of 9.4% and 15.7%; clasts of down to 100 μm in size; two types of fragments: (a) Unit 1-like fragments and (b) dark-gray fragments of which matrix is mostly composed of biotite and smectite nanograins | – | – |
| Unit 3 | 0.8–3-mm wide; overall strongly foliated with clay minerals, but weakly foliated in some areas; looks brighter than the other units under plane-polarized light; clast fractions of 9.5% and 15.7%; clasts of 1–50 μm in size; injection into Unit 4 | – | – |
| Unit 4 | 5–9.5-mm wide; no preferred orientation of minerals; clast fractions of 15.7% and 20.1%; pores filled with calcite | – | – |
| **Brown gouge zone (BZ)** | Brown-colored matrix; clasts of ~5 cm in size; matrix-supported structure; clay minerals in the matrix showing strongly interconnected foliation | – | Nonclay minerals: 36–41 wt.%; clay minerals: 59–64 wt.%; relatively high smectite content |
| **Blue-purple gouge zone (BPZ)** | 8–9-m wide; grayish brown-, blue- and purple-colored matrix; clasts of several centimeters to 1 m in size; a network of fractured lenses of the sedimentary wall rocks and anastomosing clay-rich gouge bands (Kim et al., 2016) | – | – |

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Kim et al., 2016

Figure 4. Four units of the principal slip zone (PSZ). (a) Clast size, clast fraction, color, and foliation intensity of the units. (b–d) Scanned rock-chip (Rc) and thin-section (Ts) images showing four units of the PSZ from three different locations. Left column: Rc images; middle column: Ts images; right column: images showing the units shaded with different colors.
size and fraction were estimated using the BSE images of two representative areas (240 × 180 μm in size) in each unit (Figure S1). Smaller clasts than 3 μm were excluded from the analysis (see also Section 3.1). Unit 1 shows the smallest clast fractions (5.4% and 7.2%), and average clast sizes (5.2 and 5.9 μm); Units 2 and 3 show similar clast fractions (9.4% and 15.9% for Unit 2, and 9.5% and 15.7% for Unit 3), and the clast sizes (7.4 μm) in Unit 2 are smaller than in Unit 3 (7.6 and 10.7 μm). Unit 4 has the highest clast fractions (15.7% and 20.1%) and clast sizes (10.1 and 11.4 μm) (Figure 4a). In the following, we describe the microstructural characteristics of the units and the injected material in the CZ.

4.2.1. Unit 1

Unit 1, which is in direct contact with the CZ (Figures 4b–4d), is a narrow zone with a 20–500 μm thickness. It shows a uniform interference color and a strong preferred orientation of clay minerals in optical transmission microscopy (Figures 5a and 5b). It is noteworthy that shear was further localized into a several μm-thick zone in Unit 1 (Figure 5b). Under a scanning electron microscope (SEM), it is confirmed that Unit 1 is composed of ultrafine to nanometric granular particles and aligned clay minerals (Figure 5c). Unit 1 has a sharp boundary with Unit 2 (red arrows in Figure 5c). It is hard to observe the characteristics of individual grains clearly, however. A transmission electron microscope (TEM) observation reveals that the matrix in the unit consists of subrounded or subangular clasts of 10–500 nm in size and nanometric clay minerals <100 nm in length (Figure 5d). Some of the clasts are surrounded by aligned clay minerals (Figure 5e). A TEM-EDS analysis shows that the ultrafine to nanometric clasts are quartz, feldspar, and small amounts of calcite and apatite. The clay minerals might be illite-smectite mixed-layer minerals of high illite proportion (Figure 5d). The electron diffraction pattern taken from Unit 1 shows diffraction rings, diffraction spots, and relatively weak diffuse rings. These indicate the mostly crystalline nature of the material in Unit 1 and the possible existence of small amounts of amorphous phases (Figure 5e). In some areas of Unit 1, it is observed that the material is injected into the next zone (Unit 2) at a low angle (∼30°). This injection is noticeable because the material of Unit 1 appears less dense and shows a lighter color (Figure 5f). Some fragments of Unit 2 are evident and isolated in the injected material (Figure 5f). In other areas of Unit 1, a breciated structure is seen, which is 100–300 μm thick and consists of fragments (a few μm to 500 μm in length) of the Unit 1 material (Figure 5g). Some of them display an internal network of calcite microveins (Figure 5h). The spaces between the fragments remain open without any mineral precipitation (Figures 5g and 5h).

4.2.2. Unit 2

Unit 2 is about 5–7.3 mm in thickness and broader than Units 1 and 3 (Figures 4 and 6a). Unit 2 shows a uniform interference color indicating the alignment of minerals. However, it is weaker than in Unit 1, and foliation in P-direction is observed in some areas (Figure 6b). It is also notable that Unit 2 contains two types of characteristic fragments (Figures 6a–6d). The first one is similar to Unit 1, composed of ultrafine grains showing strong internal foliation (Figure 6c). The fragments are mainly rectangular to subangular, 50–200 μm in size, and oriented parallel or subparallel to the unit boundary (Figure 6c). The second type of fragments consists of either single dark gray or black bands or multibanded materials (darkgray band and light-colored band showing strong preferred orientation) (Figure 6d). The fragments are subangular to subrounded, varying in size from 10 to 500 μm, and they are scattered in Unit 2 without any preferred orientation. Fragments like these are also present in Unit 4. A TEM observation of the second type of fragments reveals many subangular to subrounded mineral fragments (quartz, feldspar, apatite) with several μm in size and Ti-oxides with several nm in size in them (Figure 6e). The dark gray band's matrix portion is filled with biotite grains (50–100 nm in size) that look circular or platy (Figures 6e–6h). Some of the biotite grains were altered into chlorite (S-05, Figure 6h). The pores between the biotite grains are dominantly filled with smectite (Figures 6g and 6h). The clast fractions of two dark-gray fragments in Unit 2 measured with their BSE images (160 × 130 μm) following the same method used for those of the units in the PSZ are 8.7%–34.1%, varying with the measurement locations (Figure S2).

4.2.3. Units 3 and 4

Units 3 and 4 have thicknesses of 0.8–3 mm and 5–9.5 mm, respectively (Figures 4b–4d). In Unit 3, the matrix is light-colored and strongly foliated (Figures 7a–7d), though weakly foliated regions are locally observed (Figures 7e and 7f). The clasts (measured up to a few hundred μm in size) are primarily fragments of volcanic and sedimentary rocks and minerals (Figures 7a–7d). Under an SEM, foliation defined by the
Figure 5. Microstructures of Unit 1 in the principal slip zone (PSZ). (a) A strong preferred orientation of clays identified by a single interference color in Unit 1 (crossed-polarized light; gypsum plate inserted). (b) Close-up view of Unit 1 (crossed-polarized light; gypsum plate inserted). Note that shear was further localized into a ∼5-μm-thick zone (indicated by yellow arrows). (c) Back-scattered electron (BSE) image showing both Units 1 and 2. Unit 1 consists of ultrafine to nanometric granular particles and aligned clay minerals. The boundary between the units is sharp in this image (red arrows). (d) Scanning transmission electron microscope (STEM) image showing the ultrafine and nanometric clasts and clay matrix (Qz, quartz; Pl, plagioclase; Ap, apatite). The inset shows TEM-energy dispersive X-ray spectrometer (EDS) (energy dispersive X-ray spectrometer) data taken at two sites (S-01 and S-02, red boxes in (d)) in the clay matrix. (e) Bright-field transmission electron microscope (BF-TEM) image showing the quartz clasts and clay matrix. The electron diffraction pattern (inset) over the whole area in (e) indicates crystalline materials. (f) Injection of the Unit 1 gouge into Unit 2 (yellow arrows; plane-polarized light). (g) Brecciation structures found in some areas of Unit 1. (h) Gouge-clasts formed by the fragmentation of calcite-filled gouge in Unit 1.
Figure 6. Microstructures of Unit 2 in the principal slip zone (PSZ). (a) Representative photomicrograph of Unit 2, which is bounded by the red dashed lines (plane-polarized light). Note that two types of fragments, or Unit 1-like fragments (yellow arrows) and dark-gray fragments (blue arrows), are present. (b) Boundary area of Units 2 and 3. The P-foliation in Unit 2 is contrasted with the stronger, boundary-parallel foliation in Unit 3. Unit 3 does not show any fragments like those in Unit 2 (crossed-polarized light; gypsum plate inserted). (c) Foliated gouge fragments similar to Unit 1 (crossed-polarized light; gypsum plate inserted). Unit 2 has a weaker preferred orientation of clays in the matrix than Unit 1. (d) Dark-gray fragments (plane-polarized light). The inset image shows that each dark fragment consists of a dark band and a strongly oriented clay-rich gouge band, indicated by white arrows (crossed-polarized light; gypsum plate inserted). (e) Scanning transmission electron microscope (STEM) image of the dark band in the dark fragments. (f) Bright-field transmission electron microscope (BF-TEM) image showing the nanometric biotite grains in the matrix. Small-boxed area in (e). (g) Close-up view of the large-boxed area in (e) showing numerous nanograins of biotite. (h) TEM-energy dispersive X-ray spectrometer (EDS) spectra from two grains with different shapes. Boxed areas in (g). S-04: biotite; S-05: chlorite. Pl, plagioclase; Qz, quartz; Ap, apatite; Bt, biotite; Sme, smectite; Ti, Ti-oxide.
preferred orientation of clay minerals and many smaller clasts (1–50 μm in size) is also observed (Figure 7g). Unit 4, unlike other units, does not show an overall preferred orientation. Interestingly, injection structures similar to those between Units 1 and 2 are observed along the boundary between Units 3 and 4 (yellow arrows and dashed lines in Figures 7a–7d). Also, Unit 4 gouges isolated by Unit 3 injection structures are found (dashed lines in Figures 7a and 7c). The matrix of Unit 4 shows similar material composition and
structure to Unit 3 under an SEM (Figure 7h). However, in Unit 4, calcite or Ba-bearing calcite networks are common (Figure 7h). In some places, the fragments of Unit 4 are isolated by the calcite networks (Figure 7h). The calcite grains do not show any evidence of internal deformation.

4.2.4. Injected Materials in the Cataclasite Zone

The injection structures occurring in the CZ have a similar brownish color to that of the PSZ (Figure 8a). They are not observed in the PSZ and BZ, and they measure up to 5 cm long and ~1–5 mm thick. Most of them are oriented 60°–70° to the PSZ boundary, and only a few occur along with the CZ’s secondary fractures (Figures 8a and 8b). Some calcite veins, oriented nearly perpendicular to the PSZ boundary, and fractures occur around the injection structures (Figures 8a and 8b). The connection of the injection structures, found ~1 cm away from the PSZ, to the PSZ has not been observed. At their borders and ends, smaller-sized sharp injection structures are observed, from which flow directions may be inferred (Figures 8c and 8d).

In the sharp injection structure, a U-shaped foliation is observed at its end (Figures 9a–9b). Clast fractions at three different areas (580 × 340 μm in size) of the injected material (Figure 9b) were measured following the same method used for those of the units in the PSZ. The average value of the fractions is about 5.52%, and most of the clasts are quartz, feldspar, Fe-oxides, and Ti-oxides. Some quartz clasts show an embayment structure (Figure 9c inset). According to SEM and TEM analyses, most of the injected materials are layered silicate minerals (Figures 9c and 9e). The minerals, with similar size and shape, appear to define a flow band.
Figure 9.
structure (Figure 9d). The plate-shaped and hexagonal or circular layered silicate mineral grains, which are relatively bright in the BSE images, are biotite grains, according to an EDS analysis (Figures 9e, 9e, and 9f). The size of the hexagonal to circular biotite particles is 200 nm–1.2 μm, and the length of the plate-shaped biotite particles is 150 nm–2 μm (Figures 9g, 9e, and 9g). Besides the biotite particles, the fine clay minerals that make up the matrix show the smectite composition (Figures 9e and 9f). In the bright-field images of TEM (BF-TEM), the biotite grains show their crystalline nature (Figures 9g–9i), and cleavage planes are observed from the plate-shaped biotite particles (Figures 9g and 9h). See Table 1 for the summary of the microstructural observations of the PSZ and the neighboring fault rocks.

4.3. Mineralogical Characteristics

XRD analyses were performed for the comparison of the mineral compositions of the wall rocks (dacitic tuff and sedimentary rocks), the fault core materials next to the PSZ (CZ [cataclasite zone] and BZ [brown gouge zone]), and the four units of the PSZ. For the BZ, which is quite thick (30–50 cm), two samples were taken, one close to the PSZ and the other close to the BPZ, respectively. Units 3 and 4 were analyzed as one sample because it was difficult to separate and collect them. Except for the wall rocks, each material’s average and standard deviation were obtained by analyzing several samples taken at different locations. The numbers of the samples are as follows. WR (dacitic tuff): n = 3; CZ: n = 2; CZ (near the PSZ): n = 3; Unit 1: n = 3; Unit 2: n = 3; Units 3 and 4: n = 4; BZ (near the PSZ): n = 4; BZ (near the BPZ): n = 2; WR (sedimentary rocks): n = 5 (Figure 10a).

The main constituent minerals of the wall rocks and fault core zone materials are clay minerals, quartz, feldspar, and calcite (Figure 10a). The western wall rock, dacitic tuff, has high contents of quartz (35.6 ± 5.2 wt.%) and plagioclase (37.4 ± 5.9 wt.%) and a low content (8.9 ± 2.1 wt.%) of clay minerals. Although there is spatial heterogeneity of mineral composition, the sedimentary rocks, which are the eastern wall rock, appear to have high contents of quartz (33.1 ± 7.8 wt.%) and plagioclase (46.9 ± 10.8 wt.%) and a low content (10.3 ± 5 wt.%) of clay minerals. In the fault zone materials, the quartz content is relatively high in the CZ (28–30 wt.%) and the PSZ (23–25 wt.%). Also, the CZ has high contents of plagioclase (45.9 ± 4.4 wt.%) and K-feldspar (10.3 ± 0.5 wt.%). However, there is no significant difference in their contents from the other fault core zone. The calcite content is the highest in the CZ near the PSZ (8.8 ± 1.8 wt.%) and the lowest in the PSZ (1.5–2.5 wt.%). The total clay content is the lowest in the CZ and high in the PSZ (54–56 wt.%) and the BZ (60–62 wt.%) (Figure 10a).

Using a semi-quantitative method (Biscaye, 1965), the relative abundance of clay minerals (smectite, illite, chlorite) was obtained for the PSZ and other fault materials (CZ, and BZ near the PSZ) (Figure 10b). The PSZ shows a lower smectite content and higher illite content compared to the other materials. It is noteworthy that Unit 1 has a low content of smectite (10%) but the highest illite content (57%).

Figure 11 shows the XRD patterns of bulk samples of all the materials and the clay-fraction XRD patterns after ethylene-glycolated samples. The bulk samples’ XRD patterns show that smectite, illite, and chlorite are present in all the materials (Figure 11a). In Units 1 and 2 of the PSZ, however, the smectite peaks are low, and the peaks of illite and illite/smectite mixed layer do not change in their intensities (Figure 11a). Even in the clay-fraction XRD patterns after the ethylene-glycol (EG) treatment, the smectite peaks of Units 1 and 2 of the PSZ are very low, whereas the illite peaks are maintained (Figure 11b). These results were compared with those from air-dried (AD) clay-fraction samples (Figure S4). In the AD samples, shifts of peak positions (2θ) of smectite minerals (including I/S mixed-layer minerals of high smectite proportion)
can be observed. The shifts are from $\sim 6^\circ$ to $\sim 7.2^\circ$ in the AD samples and $\sim 5^\circ$ in the EG samples. The shifts are presumably due to the exchanges of cations in the minerals with sodium ions in a dispersing agent used to prepare the clay-fraction samples. Zeolite peaks are observed in both the CZ and Unit 1, which is the closest to the CZ (Figure 11b). See Table 1 for a summary of the mineralogical characteristics of the PSZ and the neighboring fault rocks.

5. High-Velocity Friction Experiments and Static Heating Tests on the PSZ Gouge

5.1. Results of Friction Experiments

We conducted four high-velocity friction experiments on the wet gouge paste made from the PSZ gouge at a normal stress of 2 MPa and a slip rate of 1.3 m s$^{-1}$ (Figures 12a and 12b). In one of them (HVR4691), of which fault displacement (8.2 m) is much shorter than the others (32–50 m), we tried to constrain shear localization zone temperature with a K-type TC (Figure 12b). The TC tip was confirmed by SEM observation to contact the shear localization zone developed in the HVR4691 sample. However, it should be noted that the temperature output from the TC is an average temperature over the area of the TC tip ($\sim 160 \mu m$ in size).
The friction coefficient ($\mu$) initially increased to a peak of $\sim0.25–0.4$ in the tests, then decreased to $\sim0.1–0.15$, showing some fluctuations. Since the normal stress was limited for the unconfined sample assembly, we used the extraordinarily large fault displacement to simulate significant temperature rise (hundreds of degrees) during seismic slip. Axial displacement showed finite shortening or compaction (indicated by the positive values of 0.05–0.4 mm), and temporal dilation (or decrease in its value) in the tests. The weakening in HVR4691 seems correlated with the axial dilation. However, those in the other experiments are not well correlated with the axial displacement data and cannot be simply explained by a weakening mechanism. Considering the low permeability expected for wet clay-rich gouges (e.g., Tanikawa & Shimamoto, 2009), the weakening in our experiments may be closely related to thermal fluid pressurization. Note that the maximum temperature measured in HVR4691 was about 125°C (Figure 12b), which indicates $T > 125^\circ$C in the shear localization zone. Thus the large dilation during the displacement of $\sim10–20$ m in HVR4512 is highly likely to have occurred due to water vaporization at a much larger temperature than 125°C (e.g., Chen et al., 2017) and/or new input of released water from the clay minerals (e.g., Brantut et al., 2010). A detailed discussion of the weakening mechanisms that may have operated in the experiments is out of the scope of this study. We also conducted two experiments on the dry gouge of the PSZ at a normal stress of 5 MPa and a slip rate of 1.3 m s$^{-1}$ (Figure 12c). The friction increased to a peak of $\mu \sim 0.84$ and then decreased to a steady-state value of $\sim0.2$ in 1.3 m of fault displacement. Unlike in the wet gouge experiments, the axial displacement continued to increase, indicating that the dry gouge underwent continuous compaction.

5.2. Microstructures of the Experimentally Sheared Gouges

In the sheared wet gouge (HVR4512, Figure 13a), a localized slip zone ($\sim100 \mu$m in thickness) characterized by strong foliation and a uniform interference color is observed. As in Unit 1 of the natural PSZ gouge, shear was further localized into a band as narrow as $\sim5 \mu$m (see the band in Figure 15e). Fragments that appear to have been detached from the slip zone are scattered in the gouge (white arrows in Figure 13a; see also Figure 6c for comparison). The BSE image of the experimental principal slip zone shows that it consists of ultrafine grains (Figure 13b). The above microstructures of the experimentally sheared gouges are similar to those in Units 1 and 2 of the natural PSZ. A TEM observation on a selected area of the PSZ (indicated by the red bar in Figure 13b) reveals that the PSZ material is mainly composed of ultrafine quartz-feldspathic...
Figure 12.
clasts and nanometric clay minerals. The amorphous material in the part of the PSZ (Figure 13c) with a chemical composition similar to illite-smectite (Figures 13d and 13e) may be a product of either severe comminution (Aretusini, Spagnuolo, et al., 2019; Kaneki et al., 2020) or thermal dehydration (see Brantut et al., 2008 for this kind of example of the formation of amorphous material during experimental seismic slip). In the sheared dry gouge (HVR4516), many dark patches or fragments of thin dark layers are observed (Figure 13f). SEM and TEM observations reveal that the dark patches are composed of clasts and amorphous glassy matrix with vesicles (Figures 13g–13i). The glassy matrix is chemically similar to illite-smectite (Figures 13i–13j; see also Figures 6d–6h for comparison). The dark patches are thus a product of frictional melting, mostly of the clay minerals. Overall, the dark patches are similar to the dark gray fragments in Unit 2 (Figure 6d) in the natural PSZ.

5.3. Mineral Compositions of the Experimentally Sheared and Statically Heated Gouges

To examine possible mineralogical changes during slip at seismic rates, we conducted XRD analyses on the experimentally sheared gouges (Figures 14a and 14b). The samples for the analyses were collected with a microdrill from the inner and outer parts of sheared gouge layers, of which the diameter is 25 mm. The inner part is a circular disk of 6 mm in radius, located at the central area of the gouge layer, and the outer part is the remaining layer except for the inner part (see the sketch of sample in Figure 14). Because only a small amount of the experimental gouges were available, we could not prepare their ethylene glycol (EG)-treated samples. The high plagioclase peaks in HVR4513 (outer) appear to originate from the contamination by the plagioclase in the experimental wall rock (gabbro). The outer and inner samples of HVR4691, in which the measured maximum temperature was 125°C, show slightly sharper illite (including illite-smectite mixed-layer minerals of high illite proportion) peaks at 2θ = 8.8° than that of the starting material (Figures 14a and 14b). The outer and inner samples of HVR4513 and HVR4516, which are likely to have experienced higher temperature than HVR4691 because of their larger normal stress or displacement, shows weaker smectite (including illite-smectite mixed-layer minerals of high smectite proportion) peaks at 2θ = 6.2°. In contrast, the outer samples of the sheared gouges show relatively sharp peaks of illite (Figures 14a and 14b).

Also, we examined temperature-dependent mineralogical changes in the PSZ gouge samples by conducting static heating experiments and XRD analyses on them (Figures 14c and 14d). The sample heated at 100°C does not show any noticeable difference from the starting material, except for the slightly higher smectite peak at 2θ = 6.2°. In the samples heated at 200°C and at higher temperatures, the illite peak at 2θ = 8.8° becomes higher with increasing temperature. The change may be interpreted to be caused by smectite dehydridation (at 100°C–200°C) and illitization (at 150°C–200°C; Bird et al., 1984) in the heated samples. Thus, these experimental results support that the mineralogical differences observed in the units of the natural PSZ may have originated from frictional heating during past seismic slip events.

6. Discussion

6.1. Shear Localization in the Fault Core Zone

In the core zone of the Yangsan fault, we see two structurally different zones. One is an 8–9-m-thick, blue-purple gouge zone (BPZ) exhibiting a network of large, fractured lenses and Anastomosing, clay-rich gouge bands. The other is a ~30–50-cm-thick, clay-rich, brown gouge zone (BZ) (Figures 2 and 15a). The BZ shows a much smaller clast size and a lower clast content than the BPZ, which might indicate that larger fault displacement was accommodated in the BZ rather than in the BPZ (Kim et al., 2016). The BZ is a shear localization zone at the fault core zone scale (Figure 15a, modified from Kim et al., 2016). However, at the

Figure 12. Results of high-velocity shear tests on the principal slip zone (PSZ) gouge. (a–b) Frictional behaviors of wet gouges sheared at a normal stress of 2 MPa and a slip rate of 1.3 m s⁻¹. During HVR4691, the temperature was measured with a K-type thermocouple to constrain the shear localization zone temperature. (c) Frictional behavior of dry gouge sheared at a normal stress of 5 MPa and a slip rate of 1.3 m s⁻¹. The increase and decrease in the axial displacements indicate compaction (or shortening) and dilation, respectively. Note that the dry gouge did not show any dilation, whereas the wet gouges showed the alternation of compaction and dilation (the large dilation during the displacement of ~10–20 m in HVR4512, for example). After the experiments, HVR4691, 4513, and 4516 gouges (marked by asterisks) were recovered and analyzed by XRD.
Figure 13. Microstructures of the experimentally sheared principal slip zone (PSZ) gouge. (a–e) Sheared wet gouge (HVR4512). (f–j) Sheared dry gouge (HVR4516). (a) Shear localization zone developed at the gouge's upper boundary area, and foliated gouge fragments detached from the zone (white arrows). Crossed-polarized light; gypsum plate inserted. (b) Back-scattered electron (BSE) image showing an area of the shear localization zone (boxed area in (a)). (c) bright-field images of transmission electron microscopy (BF-TEM) image showing both the clay-rich gouge (right) and amorphous material (left; see also the diffraction pattern in the inset) in an area of the shear localization zone (observation area indicated by the red bar in (b)). (d) Close-up view of the boxed area in (c). (e) TEM-energy dispersive X-ray spectrometer (EDS) data from the amorphous material (S-09) and the clay-rich matrix (S-10) showing almost the same chemical composition. (f) Dark gray to black materials (red arrows) in the lighter-colored gouge (plane-polarized light). (g) BSE image of the boxed area in (f), where the dark material looks brighter than the neighboring gouge. Note many tiny vesicles in the material (inset). (h) BF-TEM image of the dark material (the red bar area in (g)) showing the vesicle-bearing glassy matrix. The diffraction pattern in the inset indicates the amorphous nature of the matrix. (i and j) TEM-EDS data shows that the glassy matrix (S-11) has a similar chemical composition to the clay-rich matrix (S-10 in (e)).
smaller scales, we observe a much narrower slip zone with 1–2 cm in thickness, and we call it the principal slip zone (PSZ) in this study (Figures 2a and 15b). Again, we see shear localization zones in the PSZ, which are 20–500-μm-thick Unit 1 and 0.8–3-mm-thick Unit 3 (Figures 4–7, 15c and 15d). In Unit 1, we see the narrowest shear band of ∼2 μm in thickness (Figure 15c), which is similar to individual shear bands in the shear localization zone of the experimental gouge (HVR4512) sheared at 1.3 m s⁻¹ (Figure 15c). Thus shear

| Exp. number | Slip conditions |
|-------------|-----------------|
| HVR4516     | σ_n = 5 MPa; V = 1.3 m s⁻¹; D = 1.3 m; Dry gouge |
| HVR4513     | σ_n = 2 MPa; V = 1.3 m s⁻¹; D = 39 m; Wet gouge |
| HVR4691     | σ_n = 2 MPa; V = 1.3 m s⁻¹; D = 8.15 m; Wet gouge |

**Figure 14.** (a and b) Results of XRD analyses on the wet (HVR4513, HVR4691) and dry (HVR4516) gouges sheared at 1.3 m s⁻¹. From each gouge, two samples were collected at the inner and outer parts (see the sketch for the sampling locations). σ_n, normal stress; V, slip rate; D, fault displacement. (c and d), Results of XRD analyses on the principal slip zone (PSZ) gouges statically heated at different temperature conditions. Sme, smectite; Ilt, illite; Zeo, zeolite group; Chl, chlorite; Pl, plagioclase; I/S, illite-smectite mixed-layer minerals; Qz, quartz; Cal, calcite.
localization zone thickness depends on observation scales, and the narrowest localization zone can be identified only by careful microscopic observations. The anastomosing gouge network in the BPZ indicates the overall distributed shear deformation and may be related to the velocity-strengthening behavior of the clay-rich gouge bands (e.g., Faulkner et al., 2003; Morrow et al., 1992; Reinen, 2000). Then, an arising question is why shear deformation was localized into the very narrow zone in the clay-rich PSZ. Previous friction tests on the clay-rich gouge of the BZ at low slip rates (1–10 μm s⁻¹) show velocity-weakening and velocity-strengthening at 5 MPa and 10–20 MPa, respectively (Woo et al., 2015). Also, it is now known that frictional behavior at low slip rates may depend on effective normal stress and temperature (e.g., den Hartog et al., 2012; Saffer et al., 2001). Some previous studies have reported very narrow (micronscale) shear localization zones in experimental gouges showing velocity-weakening at low (or subseismic) slip rates (e.g., Aretusini, Plümper, et al., 2019; Beeler et al., 1996; Ikari, 2015; Reinen, 2000). Therefore, an idea for the shear localization in the PSZ is that it could occur because the clay-rich gouge had a velocity-weakening behavior at depths when sheared at subseismic slip rates. Another idea is that the shear localization in the clay-rich gouge was possible due to pronounced dynamic fault weakening. Recent experimental and numerical studies have proposed that fault rupture nucleated at seismogenic depths can be propagated through clay-rich gouges or sediments, due to dynamic weakening, even though the materials show velocity-strengthening at subseismic slip rates (e.g., Faulkner et al., 2011; Han et al., 2020; Noda & Lapusta, 2013; Tanikawa & Shimamoto, 2009; Tarling et al., 2018; Ujiie et al., 2013). In experimental clay-rich gouges dramatically weakened at seismic slip rates, narrow localization zones (thinner than several hundreds of μm) have been commonly observed (e.g., Boutareaud et al., 2008; Brantut et al., 2008; Ferri et al., 2011; Han et al., 2014; Kitajima et al., 2010; Ujiie et al., 2013; Yao et al., 2013). Furthermore, recent theoretical and numerical work by Rice et al. (2014) and Platt et al. (2014) have shown that a very narrow (micrometers to tens of micrometers thick) shear localization zone may develop in rapidly sheared fluid-saturated gouge associated with thermal pressurization. A similar result was also expected for the slip zones where thermal decomposition occurs (Platt et al., 2015). These results are, however, not able to explain the observations of experimental shear localization zones developed at the subseismic slip rates. Then, questions are arising: How can we know if a narrow shear localization zone in the field experienced past seismic slip or not? Are the experimental observations of shear localization zones at constant subseismic slip rates applicable to natural shear localization zones where slip may be accelerated in velocity-weakening gouges? We think this should be addressed based on further detailed investigations.
observations on natural and experimental shear localization zones. In the next section, we discuss whether the shear localization in the natural PSZ is coseismic.

6.2. Geological Records of Coseismic Shear Localization in the PSZ

In the PSZ and CZ, we observed various mesoscopic and microscopic structures and mineralogical changes reported from natural seismogenic faults and experimental faults slipped at seismic rates. These include pseudotachylyte veins, shear localization zones showing nanofoliation, cohesive foliated gouges, solidified melts of the clay-rich gouge, gouge fluidization structures, and the change in clay mineral content (possibly due to illitization). In the following, we discuss whether the features may be geological records of seismic fault slip.

In the CZ, brownish injection structures (or veins) are observed. In natural faults, such injections of fault materials are not rare. They have been reported as either injections of cataclastic materials (e.g., gouge and ultracataclasite) or injection veins of frictional melt (or pseudotachylyte) (e.g., Coppola et al., 2021; Cowan et al., 2003; Lin, 2011; Fondriest et al., 2012; Kirkpatrick & Rowe, 2013; Han et al., 2020; Rowe et al., 2012; Sibson, 1975; Smith et al., 2011). The injection veins in the CZ are composed mostly of ultrafine (150 nm to 2 μm) grains of biotite and smectite and a small number of clasts. They also show a flow structure defined by the zonal distribution of biotite microlites, embayments in the quartz clasts, and U-shaped foliation (Figure 9). All of these observations support the idea that the injection veins are frictional melt origin. The very low clast fraction (~5.5%) in the injection veins may be interpreted that the slip zone temperature was so high that most of the clasts could be melted (e.g., Han et al., 2019; Kim et al., 2019) or that the veins originated from the frictional melting of clay-dominant gouges. The biotite microlites and smectite grains may be the products of primary crystallization from frictional melt and secondary crystallization (or devitrification) of glass, respectively. The latter has been reported from natural (e.g., Hasegawa et al., 2019; Ishikawa & Ujiie, 2019; Janssen et al., 2013; Kirkpatrick & Rowe, 2013; Kuo et al., 2009; Phillips et al., 2019; Ujiie et al., 2007; Uysal et al., 2006) and experimental faults (Fondriest et al., 2020). The orientation of the veins high angle (60°–70°) to the boundary of the PSZ (Figure 8) may be explained by the preferential opening of fractures under the dynamic stress field during seismic rupture propagation (e.g., Di Toro et al., 2005; Rowe et al., 2012). Currently, we cannot find the remnant of the pseudotachylyte vein in the PSZ, now composed of the clay-rich gouge, which might indicate there was no pseudotachylyte in the zone. However, it is reasonable to think that a pseudotachylyte vein occurred previously in the PSZ, considering the following: (a) The veins are traceable in the areas as close as 1 cm from the PSZ (Figure 8); (b) The injection direction inferred from the U-shaped foliation is toward the CZ from the PSZ (Figures 8 and 9); (c) The pseudotachylyte veins may look disconnected from the slip zone in sections cut obliquely to their injection direction. The disappearance of the pseudotachylyte from the slip zone may be interpreted to be caused by fluid-rock interaction, or hydrothermal alteration, of the former glass into clay minerals (e.g., Fondriest et al., 2020; Ishikawa & Ujiie, 2019; Kirkpatrick & Rowe, 2013; Ujiie et al., 2007). The pseudotachylyte alteration into clay minerals with low frictional strength may explain (a) why pseudotachylytes are apparently scarce in natural faults, and (b) how the strength of pseudotachylyte-bearing faults become significantly lower over time, although fault strengthening due to the welding effect of pseudotachylytes may also occur (e.g., Hayward & Cox, 2017; Mitchell et al., 2016; Proctor & Lockner, 2016).

Unit 1 in the PSZ, 20–500 μm in thickness, is a strongly foliated, shear localization zone (Figure 5a). Such a localization was generated in the experimental gouge sheared at 1.3 m s⁻¹ (HVR4512, Figures 13 and 15) and has also been observed in the previous studies on clay-rich natural and experimental gouges (e.g., Boulton et al., 2017; Boutareaud et al., 2008; French & Chester, 2018; Han et al., 2014, 2020; Ujiie et al., 2011; Yao et al., 2013). The experimental reproductions of the localization structure at the seismic slip rates might indicate that the natural shear localization zone is possibly the coseismic origin, although similarly narrow shear localization zones have been observed to form at subseismic rates too. A relevant experimental observation on the shear localization zone was recently made by Aretusini, Plümper, et al. (2019). They found shear localization zones showing nanofoliation of smectite clays (i.e., a foliation made of aligned subparallel smectite crystals anastomosing around clasts observable only at the nanoscale) developed at subseismic to seismic slip rates in their experiments. Then, they proposed highly localized nanofoliation-showing shear zones may indicate past seismic slip because the structure was observed only
at seismic slip rates. Interestingly, their nanofoliation-showing, experimental shear localization zone (Figure S5b) is quite similar to Unit 1 of the natural PSZ in this study (Figures 5d, 5e, and S5c). Nevertheless, it is still uncertain whether such nanofoliation-showing shear localization zone structures alone can indicate the occurrence of seismic slip in natural faults unambiguously or not.

The ultrafine and nanometric clast size in Unit 1 (10 nm to several hundred μm) are similar to those in some natural (Chester et al., 2003; Ma et al., 2006) and experimental slip zones (e.g., Arutusini et al., 2017; Brantut et al., 2008, 2011, Figure 13), which underwent natural or simulated seismic slip. However, again, the clast size alone does not necessarily indicate the localization zone’s seismic slip origin because it may also be observed in gouges sheared at subseismic slip rates (e.g., Yund et al., 1990).

Cohesive gouge fragments are a notable structure in Unit 2, and we examined the certainty of the structure in indicating seismic fault slip (see the scattered subangular fragments in Figures 6c and S6). Given the same appearance of the fragments as the foliated gouge in Unit 1, it seems that they were detached from Unit 1, just like the foliated gouge fragments detached from the shear localization zone in HVR4512. Thus, we named them “Unit 1-like fragments” in Figure 6c. This kind of gouge fragments have been reported from previous experiments at seismic slip rates and interpreted as a product of sintering or welding at highly elevated temperatures based on microstructural observations of welded grains (Shimamoto & Togo, 2012; Togo & Shimamoto, 2012). The sintering of slip zone materials was proposed to cause slip hardening and could result in the shift of slip zone and the consequent development of a wider slip zone (Han et al., 2014; Shimamoto & Togo, 2012). The overall microstructures of the cohesive gouge fragments in Unit 2 (Figure S6) look similar to the welded grain aggregates called sintered gouge in the experimental studies and those in our experimental gouge sheared at 1.3 m s⁻¹ (Figure S7). However, it should be noted that the welded appearance is not necessarily a product of high-temperature sintering because similar structures may form by shear-induced compaction, porosity reduction, and densification at low temperatures when sheared at subseismic slip rates (e.g., Hadizadeh et al., 2015; Ikari, 2015). Thus, given the limited observations of the structure in natural and experimental fault zones, whether the cohesive gouge fragments “alone” can indicate past seismic slip in “natural” fault zones remains inconclusive.

Another type of fragments found in the PSZ is 10–500-μm-sized, dark-gray fragments in Unit 2 (Figure 6d). They are composed of a large number of subangular to subrounded quartz-feldspathic clasts (several μm in size), Ti-oxides (several nm in size) (Figure 6e), and the matrix. The matrix consists of biotite nanograins (50–100 nm in size) (Figures 6e–6h) and pore-filling smectite (Figures 6g and 6h). Notably, some dark-gray fragments consist of a dark band and a lighter-colored band (Figure 6d). The latter is the cohesive foliated gouge discussed above. Meanwhile, the former is the product of frictional heating and melting of the latter at high temperatures. This kind of structure is found in our sheared room-dry gouge (HVR4516, Figures 13f–13j) and previous experimental studies (see Figures 1 and 3 of Han et al., 2014). One difference between the natural and experimental ones is that the former’s matrix consists of biotite nanograins and smectite, whereas the latter’s matrix consists of glass (Figure 13h; see also Figure 3 of Han et al., 2014). These observations may be interpreted as follows. (a) The dark-gray fragments are pseudotachylytes (solidified friction-induced melt), and the biotite and smectite grains in them are the products of primary and secondary crystallization (e.g., Fendriest et al., 2020), respectively, like the injection veins of pseudotachylyte in the CZ; (b) Given the larger clast fraction in the dark-gray fragments in Unit 2, those may be a product of selective frictional melting mostly of clay minerals with relatively low melting temperatures. This kind of melting structure has been reported from natural fault zones: for example, Chelungpu fault in Taiwan (Boullier et al., 2009; Hirono et al., 2006), Nojima fault (Otsuki et al., 2003), Iida-Matsukawa fault in Japan (Ozawa & Takizawa, 2007), and also an ancient caldera fault in Korea (Han et al., 2019; Kim et al., 2019). The finding that the dark-gray fragments are solidified frictional melt indicates the neighboring cohesive foliated gouge also experienced frictional heating. Thus, the cohesive gouge fragments in Unit 2 may be a product of shear compaction and frictional heating during rapid shear.

The next one is structures formed due to gouge fluidization. Fluidization, or a kind of liquidization, is the process during which the sediment strength is lost through moving interstitial pore fluids buoying the particles (Maltman & Bolton, 2003). In rapidly sheared gouges at seismic rates, pore fluid volume may increase due to frictional heating with or without a new input of fluids generated by thermal dehydration of clay minerals, and pore fluid pressure is built up quickly in low-permeability clay-rich gouges (Brantut
et al., 2010; Rice, 2006). Such a generation of overpressure in the gouge may cause gouge fluidization. Fluidized materials are typically less dense and less viscous than surrounding materials (Maltman & Bolton, 2003). Once a fluid pressure gradient across the gouge is established, the fluidized gouge may inject (or intrude) into neighbors with lower fluid pressure. Along the boundary between Units 1 and 2, injections of fluidized gouge are found (Figure Sf). The pinching out of Unit 1 material in Unit 2 indicates the former was injected into the latter. The structure has been observed in natural faults (e.g., Brodsky et al., 2009; Coppola et al., 2021; Fondriest et al., 2012; Han et al., 2020; Otsuki et al., 2003; Rowe et al., 2012; Smeraglia et al., 2017; Smith et al., 2011) and experimental gouges sheared at seismic slip rates (Han et al., 2020; Tanikawa et al., 2012; Ujiie et al., 2013). Therefore, the gouge fluidization and injection from Unit 1 into Unit 2 are highly likely to be caused by thermal fluid pressurization in Unit 1 during seismic slip. The fluidization structures are also found along the boundary between Units 3 and 4 (Figures 7a–7d). This observation implies that the seismic slip associated with fluidization occurred at a few different places of the PSZ, although the relative timing of the slip events is uncertain. One thing that is not well understood is why the gouge fluidization structures coexist with the dark-gray (pseudotachylyte) fragments in Unit 2. Both the structures originated from Unit 1. The former may indicate the effective operation of thermal pressurization and the inhibited temperature rise in Unit 1. In contrast, the latter indicates a significant temperature rise to the melting points of gouge materials in Unit 1. One interpretation is that the structures formed during different slip events: The pseudotachylyte layer formed earlier (probably in Unit 1) was destroyed and preserved only as some dark-gray fragments in Unit 2. The other idea is a single slip event scenario as follows: The gouge fluidization occurred in Unit 1 due to thermal pressurization during the early stage of seismic slip; The pore pressure dissipation in Unit 1 followed the injection of fluidized gouge into Unit 2; With continuing slip, the temperature in Unit 1 increased enough to induce the melting of the clay-rich gouge and the formation of a very thin melt layer; The melt was cooled rapidly, fractured, and incorporated in Unit 2 during the late stage of seismic slip. Experimental observations in this (Figure 13) and previous studies (Han et al., 2014; Ujiie et al., 2011) indicate that fragments of shear localization zone materials similar to the dark-gray fragments in Unit 2 can form in a single seismic event. Thus, both the multiple-slip scenario and the single-slip origin should be considered to interpret such fragments in natural fault slip zones.

The next one to be discussed is mineralogical changes due to the temperature rise during seismic slip. Our semi-quantitative XRD analyses show the difference in mineral compositions of the PSZ, CZ, and BZ (brown gouge zone). A notable result is that the CZ and BZ are rich in smectite, whereas the PSZ is poor in smectite but rich in illite (including illite-smectite mixed-layer minerals of high illite proportion) (Figures 10 and 11b). A possible interpretation of the high illite content in the PSZ, in particular, in Unit 1, where the evidence of seismic slip is present, is that it originated from the illitization of smectite (including illite-smectite mixed-layer minerals of high smectite proportion) assisted by frictional heating during seismic slip (Kameda et al., 2013; Yamaguchi et al., 2011). The decrease in smectite content and the increase in illite content in Units 1 and 2, compared with Units 3 and 4 and the CZ, are clearly shown in the XRD patterns of the air-dried clays (Figure S4). The temperature of illitization, constrained by the high-velocity shear tests and static heating experiments (Figures 12b and 14), is about 150°C–200°C. In Units 3 and 4, where the gouge injection structures are found and thermal pressurization is inferred to have operated, we could not find evidence of illitization. We see a variation of chlorite content in the PSZ and neighboring rocks, so we also examined the possibility of coseismic chloritization of smectite-chlorite mixed-layer minerals in clay-rich gouges (Kameda et al., 2011). However, we could not find any unambiguous supporting evidence for it so far. Considering that friction is strongly material dependent, the coseismic mineral changes, together with other high-temperature processes (e.g., thermal decomposition, frictional melting), if ever, may significantly affect the evolution of the frictional properties of slip zones.

Some of the observations discussed so far (e.g., the shear localization zone and gouge fragments) do not necessarily indicate past seismic slip because they may form even at subseismic slip rates. However, considering the other mesoscopic and microscopic structures and mineralogical changes in the PSZ together, we conclude that coseismic shear localization occurred in the zone. The thickness of the shear localization zone (Unit 1) is as small as 20–500 μm. Again, we see the narrowest shear band of ~2 μm in thickness in Unit 1. It is uncertain whether the shear band was active at an instant of the slip or for a longer period. Interestingly, the thickness of the shear localization zone is remarkably similar to that expected by the recent theoretical and numerical studies on coseismic shear localization (e.g., Platt et al., 2014; Rice et al., 2014). However, in
Unit 3, another shear localization zone, we cannot see such extremely thin shear bands, and shear appears to have occurred in the mm-thick zone. We think how a shear localization zone (and its thickness) evolves during seismic slip may be an important topic to be explored in more detail.

Another important implication from the observations in this study is that fault rocks evolve with time, affected by various coseismic and interseismic processes at different temperature and pressure conditions. The formation of a pseudotachylyte vein in a fault slip zone may strengthen the fault (e.g., Mitchell et al., 2016; Proctor & Lockner, 2016). However, the vein may be altered into a clay-rich material in a short time (Fondriest et al., 2020). Such an alteration of the slip zone material may weaken the fault dramatically. The clay-rich gouge may be fluidized due to thermal fluid pressurization at a certain condition, but it may be melted by frictional heating at another condition. Then, the melt may be altered into a clay (smectite)-rich material again. Mineralogical changes in fault rocks (e.g., from smectite-rich to illite-rich, as Units 1 and 2) also affect their frictional properties. Therefore, we think, together with fracturing, comminution, and fluid-rock interactions, the changes in fault rocks mentioned above may significantly affect the mechanical properties (including frictional and hydraulic properties) of faults. Then, dominant coseismic processes occurring in the evolving slip zone and relative efficiency of weakening mechanisms will also change with time, even at the same location on a fault. This aspect should be considered in the mechanics of fault slip during earthquakes, together with spatial heterogeneity of coseismic processes in one event.

Our observations on both the natural and experimental gouges and possible interpretations are summarized in the following text and Figure 16.

1. Frictional melting, interseismic alteration, and formation of the clay-rich gouge. During seismic slip, frictional melt was generated along the principal slip zone (PSZ) and injected into the cataclasite (CZ). During the cooling of the frictional melt, biotite microlites were crystallized, and glass formed. Later, the glassy matrix was mostly devitrified to smectite. The alteration of the pseudotachylyte probably contributed to the formation of the clay-rich PSZ.

2. Formation of the cohesive foliated gouge, melting, and mineralogical change in the clay-rich principal slip zone. Shear localized into Unit 1 of the PSZ induced the comminution and segregation of clasts, shear compaction, and significant temperature rise, resulting in the formation of cohesive foliated gouge showing nanofoliation. With further heating, frictional melt of the clay-rich gouge formed. From the melt, biotite microlites and glass formed during rapid cooling. Later, the glassy matrix was mostly altered into smectite. The cohesive foliated gouge and the solidified frictional melt were detached from Unit 1 and incorporated as gouge fragments in Unit 2. Some of the fragments clearly show the cohesive foliated gouge next to the solidified melt, which supports the melting of the foliated gouge with further heating. The illite-rich gouge in Unit 1 showing larger illite and smaller smectite fractions than its surrounding gouges may indicate frictional heating-induced illitization of smectite (and illite-smectite mixed-layer minerals of high smectite proportion). In this study, given the association with the solidified melt and mineralogical change, the cohesive foliated gouge showing nanofoliation and the gouge fragments may be interpreted to have formed during seismic slip in the natural PSZ. However, it is inconclusive whether the structures alone can be reliable indicators of seismic slip in natural slip zones.

3. Pore-pressure build-up and gouge fluidization. By the effective operation of thermal pressurization during seismic slip, the clay-rich gouge in the PSZ was fluidized. The injection of the fluidized gouge from Unit 1 to Unit 2 occurred. Such shear localization associated with gouge fluidization also happened along the boundary between Units 3 and 4. The temperature rise during seismic slip along Unit 3 is interpreted to be not enough for any mineralogical change to occur.

7. Conclusions

We conducted outcrop-to-nano-scale structural observations and mineralogical analyses of the fault rocks from the Yangsan fault, a major strike-slip fault in SE Korea, and some shear tests at a seismic slip rate to understand shear localization and physicochemical processes in the slip zone during earthquakes.

At the outcrop scale, fault slip appears to have been localized into a 1–2-cm-thick zone called the principal slip zone (PSZ) in this study. However, more localized shear in narrower zones (20–500-μm-thick Unit 1 and 0.8–3-mm-thick Unit 3, which are subzones of the PSZ) are observed at smaller scales. The narrowest
Figure 16. Coseismic shear localization and its geological records inferred from the principal slip zone and cataclasite zone.

Notes
1. Smectite clay nanofoliation in shear localization zones as a possible indicator of past seismic slip was discussed by Aretusini, Plumper, et al. (2019) based on experimental observations.
2. See also earlier work on coseismic illitization by Yamaguchi et al. (2011) and Kameda et al. (2013).
3. Cohesive (foliated) gouges have been observed in experimental gouges. Those gouges sheared at seismic slip rates looked welded and were called sintered or welded gouges (Togo & Shimamoto, 2012; Han et al., 2014). However, gouges showing sintered appearance are also found in experiments at sub-seismic slip rates (e.g., Ikari, 2015; Hadizadeh et al., 2015). Further work is needed to answer whether it can be a seismic slip indicator in natural slip zones.
4. For another example of clay-rich gouge melting, see Han et al. (2014).
5. For more examples of gouge fluidization structures, see Ujiie et al. (2013), Smeraglia et al. (2017), and Han et al. (2020). Smeraglia et al. (2017) used the terms fluid-like, flame-like, and intrusion structures for fluidization structures.
shear band in Unit 1 is ~2 μm in thickness. The thickness is remarkably similar to those observed in the experimentally sheared gouge at 1.3 m s⁻¹ and also expected by recent theoretical work on coseismic shear localization. We observed various structural and mineralogical features in the PSZ gouge and the cataclasite zone (CZ), which are geological records of physico-chemical slip zone processes. These include gouge fluidization structures (gouge injections) relevant to frictional heating-induced fluid pressure build-up (or thermal pressurization), fragments of solidified frictional melt of the clay-rich gouge, and lower smectite and higher illite contents in Unit 1 than its neighboring gouge presumably caused by coseismic illitization. In the CZ adjacent to the PSZ, altered injection veins of pseudotachylyte are found. The alteration of the pseudotachylyte possibly contributed to the formation of the clay-rich PSZ gouge. The frictional melting of the clay-rich gouge and the illitization were reproduced in our experiments conducted on the PSZ gouge at a slip rate of 1.3 m s⁻¹. The injections of fluidized gouges have been reproduced in previous experimental studies on clay-rich gouges. Considering the natural and experimental observations together, we interpret the μm-to mm-scale slip zones as coseismic shear localization zones.

This study shows that slip zone materials evolve with time, affected by various coseismic and interseismic processes at different temperature and pressure conditions. The material changes (e.g., formation of solidified melt, alteration of the melt into clay minerals, mineralogical changes in the clay minerals due to frictional heating), together with fracturing, comminution, and other fluid-rock interactions, may significantly affect the mechanical properties of faults. Associated with the changes, dominant coseismic slip zone processes and relative efficiency of weakening mechanisms will also change with time, even at the same location on a fault. These temporal changes should be considered in the mechanics of earthquake faulting, together with spatial heterogeneity of coseismic processes in one event.

Data Availability Statement

Data files of friction tests and XRD analyses are available on the Open Science Framework at https://osf.io/f2wrp/quickfiles.

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References

Aretusini, S., Mittempergher, S., Pümpfer, O., Spagnuolo, E., Gualtieri, A. F., & Di Toro, G. (2017). Production of nanoparticles during experimental deformation of smectite and implications for seismic slip. Earth and Planetary Science Letters, 463, 221–231. https://doi.org/10.1016/j.epsl.2017.01.048

Aretusini, S., Pümpfer, O., Spagnuolo, E., & Di Toro, G. (2019). Subseismic to seismic slip in smectite clay nanofloration. Journal of Geophysical Research: Solid Earth, 124(7), 6589–6601. https://doi.org/10.1029/2019JB017364

Aretusini, S., Spagnuolo, E., Dalconi, M. C., Di Toro, G., & Rutte, E. H. (2019). Water Availability and deformation processes in smectite-rich gouges during seismic slip. Journal of Geophysical Research: Solid Earth, 124, 10855–10876. https://doi.org/10.1029/2019JB018229

Beeler, N. M., Tullis, T. E., Blanpied, M. L., & Weeks, J. D. (1996). Frictional behavior of large displacement experimental faults. Journal of Geophysical Research, 101(B4), 8697–8715. https://doi.org/10.1029/96JB00411

Beeler, N. M., Tullis, T. E., & Goldsby, D. L. (2008). Constitutive relationships and physical basis of fault strength due to flash heating. Journal of Geophysical Research, 113, B01401. https://doi.org/10.1029/2007JB004988

Bilham, R., & Whitehead, S. (1997). Subsurface creep on the Hayward fault, Fremont, California. Geophysical Research Letters, 24(11), 1307–1310. https://doi.org/10.1029/97GL01244

Bird, D. K., Schiffman, P., Elders, W. A., Williams, A. E., & McDowell, S. D. (1984). Calc-silicate mineralization in active geothermal systems. Economic Geology, 79(4), 671–695. https://doi.org/10.2113/gsecongeo.79.4.671

Biscaye, P. E. (1965). Mineralogy and sedimentation of recent deep-sea clay in the Atlantic Ocean and adjacent seas and oceans. The Geological Society of America Bulletin, 76, 803–832. https://doi.org/10.1130/0016-7606(1965)76<803:masoand>2.0.co;2

Boullier, A. M., Yeh, E. C., Boutareaud, S., Song, S. R., & Tsai, C. H. (2009). Microscale anatomy of the 1999 Chi-Chi earthquake fault zone. Geoscience, Geophysics, Geosystems, 10, Q03016. https://doi.org/10.1029/2008GC002252

Boulton, C., Yao, L., Faulkner, D. R., Townend, J., Toy, V. G., Sutherland, R., et al. (2017). High-velocity frictional properties of Alpine Fault rocks: Mechanical data, microstructural analysis, and implications for rupture propagation. Journal of Structural Geology, 97, 71–92. https://doi.org/10.1016/j.jsg.2017.02.003

Boutareaud, S., Calugaru, D.-G., Han, R., Fabbrt, O., Mizoguchi, K., Tsutsumi, A., & Shimamoto, T. (2008). Clay-clast aggregates: A new textural evidence for seismic fault sliding? Geophysical Research Letters, 35, 105302. https://doi.org/10.1029/2007GL032554

Brantut, N., Han, R., Shimamoto, T., Findling, N., & Schubnel, A. (2011). Fast slip with inhibited temperature rise due to mineral dehydration: Evidence from experiments on gypsum. Geology, 39, 59–62. https://doi.org/10.1130/G31424.1

Brantut, N., & Mitchell, T. M. (2018). Assessing the efficiency of thermal pressurization using natural pseudotachylyte-bearing rocks. Geophysical Research Letters, 45, 9533–9541. https://doi.org/10.1029/2018GL078649

Brantut, N., Passelegue, F. X., Deldicque, D., Rouzaud, J.-N., & Schubnel, A. (2016). Dynamic weakening and amorphization in serpentinite during laboratory earthquakes. Geology, 44, 607–610. https://doi.org/10.1130/G37932.1

Brantut, N., Schubnel, A., Corvisier, J., & Sarot, J. (2010). Thermochemical pressurization of faults during coseismic slip. Journal of Geophysical Research, 115, B05314. https://doi.org/10.1029/2009JB006533
Brantut, N., Schubnel, A., Rouzaud, J.-N., Brunet, F., & Shimamoto, T. (2008). High-velocity frictional properties of a clay-bearing fault gouge and implications for earthquake mechanics. *Journal of Geophysical Research, 113*, B10401. https://doi.org/10.1029/2007JB005551

Brodsky, E. E., Rowe, C. D., Meneghini, F., & Moore, J. (2009). A geological fingerprint of low-viscosity fault fluids mobilized during an earthquake. *Journal of Geophysical Research, 114*, B01303. https://doi.org/10.1029/2008JB005633

Brune, J. N. (1968). Seismic moment, seismicity, and rate of slip along major fault zones. *Journal of Geophysical Research, 73*(2), 777–784. https://doi.org/10.1029/JB073i002p00777

Chao, B. G., & Chang, T. W. (1994). Movement history of Yangsan fault and its related fractures at Chongha-Yongdok area, Korea. *Journal of the Geological Society of Korea, 30*, 379–394. (In Korean with English abstract)

Chang, K. H., Woo, B. G., Lee, J. H., Park, S. O., & Yoo, A. (1990). Cretaceous and early Cenozoic stratigraphy and history of eastern Yongyang Basin, S. Korea. *Journal of the Geological Society of Korea, 26*, 471–487

Chang, T., & Choo, C. (1999). Faulting processes and K-Ar ages of fault gouges in the Yangsan fault zone. *Journal of the Korean Earth Science Society, 20*, 25–37. (In Korean with English abstract)

Chen, J., Niemeijer, A., Yao, L., & Ma, S. (2017). Water vaporization promotes coseismic fluid pressurization and buffers temperature rise. *Geophysical Research Letters, 44*(5), 2177–2185. https://doi.org/10.1002/2016GL071932

Cheon, Y., Cho, H., Ha, S., Kang, H.-C., Kim, J.-S., & Son, M. (2019). Tectonically controlled multiple stages of deformation along the Yangsan Fault Zone, SE Korea, since Late Cretaceous. *Journal of Asian Earth Sciences, 170*, 188–207. https://doi.org/10.1016/j.jseaes.2018.11.003

Cheon, Y., Choi, J.-H., Choi, Y., Bae, H., Han, K.-H., Son, M., et al. (2020). Understanding the distribution and internal structure of the main zone of the Yangsan Fault Zone: Current trends and future work. *Journal of the Geological Society of Korea, 56*, 619–640. https://doi.org/10.1016/j.jgsok.2020.06.5.619. (In Korean with English abstract)

Chester, F. M., & Chester, J. S. (1998). Ultracataclasite structure and friction processes of the Punchbowl fault, San Andreas system, California. *Tectonophysics, 295*, 199–221. https://doi.org/10.1016/S0040-1951(98)00121-8

Chester, J. S., Chester, F. M., & Kronenberg, A. K. (2005). Fracture surface energy of the Punchbowl fault, San Andreas system. *Earth and Planetary Science Letters, 232*, 133–136. https://doi.org/10.1016/j.epsl.2005.02.050

Chester, J. S., Kronenberg, A. K., Chester, F. M., & Guillemette, R. N. (2003). Characterization of natural slip surfaces relevant to earthquake mechanics. *American Geophysical Union, Fall Meeting 2003*, San Francisco.

Choi, J.-H., Kim, Y.-S., & Klinger, Y. (2017). Recent progress in studies on the characteristics of surface rupture associated with large earthquakes. *Journal of the Geological Society of Korea, 53*, 129–157. https://doi.org/10.14770/jgsk.2017.53.1.129

Choi, J.-H., Yang, S.-J., & Kim, Y.-S. (2009). Fault zone classification and structural characteristics of the southern Yangsan fault in the Sangcheon-ri area, SE Korea. *Journal of the Geological Society of Korea, 45*, 9–28. (In Korean with English abstract)

Collettini, C., Niemeijer, A., Viti, C., & Marone, C. (2009). Fault zone fabric and fault weakening. *Nature, 462*(7275), 907–910. https://doi.org/10.1038/nature08585

Collettini, C., Viti, C., Tessi, T., & Mollo, S. (2013). Thermal deformation along natural carbonate faults during earthquakes. *Geology, 41*, 927–930. https://doi.org/10.1130/G34421.1

Coppola, M., Correale, A., Barberio, M. D., Billi, A., Cavollo, A., Fondriest, M., et al. (2021). Meso-to nano-scale evidence of fluid-assisted low- to high-velocity frictional properties of the clay-rich gouges from the slipping zone of the 1963 Vaiont slide, northern Italy. *Earth and Planetary Science Letters, 568*, 117010. https://doi.org/10.1016/j.epsl.2021.117010

Cowan, D. S., Cladouhos, T. T., & Morgan, J. K. (2003). Structural geology and kinematic history of rocks formed along low-angle normal faults. *Terra Nova, 15*, 152–160. (In Korean with English abstract)

Di Toro, G., Han, R., Hirose, T., De Paola, N., Nielsen, S., Shimamoto, T., et al. (2011). Fault lubrication during earthquakes. *Journal of Geophysical Research: Solid Earth, 116*, B01306. https://doi.org/10.012/2008JB005990

den Hartog, S. A., Peach, C. J., de Winter, D. M., Spiers, C. J., & Shimamoto, T. (2012). Frictional melting of megathrust fault gouges at low sliding velocities: New data on effects of normal stress and temperature. *Journal of Structural Geology, 38*, 156–171. https://doi.org/10.1016/j.jsg.2011.12.001

De Paola, N., Holdsworth, R. E., Viti, C., Collettini, C., & Bullock, R. (2015). Can grain size sensitive flow lubricate faults during the initial stages of earthquake propagation? *Earth and Planetary Science Letters, 431*, 48–58. https://doi.org/10.1016/j.epsl.2015.09.002

Di Toro, G., Hirose, T., De Paola, N., Nielsen, S., Mizoguchi, K., et al. (2011). Fault lubrication during earthquakes. *Nature, 471*, 494–498. https://doi.org/10.1038/nature09838

Faulkner, D. R., Mitchell, T., Behnsen, J., Hirose, T., & Shimamoto, T. (2011). Stuck in the mud? Earthquake nucleation and propagation through accretionary forearcs. *Geophysical Research Letters, 38*, L16305. https://doi.org/10.1029/2011GL048552

Ferri, F., Di Toro, G., Hirose, T., Han, R., Noda, H., Shimamoto, T., et al. (2011). Low- to high-velocity frictional properties of the clay-rich gouges from the slipping zone of the 1963 Vaiont slide, northern Italy. *Journal of Geophysical Research, 116*, B09208. https://doi.org/10.1029/2011JB008138

Ferri, F., Di Toro, G., Hirose, T., & Shimamoto, T. (2010). Evidence of thermal pressurization in high-velocity friction experiments on smectite-rich gouges. *Terra Nova, 22*, 347–353. https://doi.org/10.1111/j.1365-3121.2010.00955.x

Ferri, F., & Di Toro, G., Hirose, T., & Shimamoto, T. (2009). High-velocity frictional properties of a clay-bearing fault gouge and implications for earthquake mechanics. *Journal of Geophysical Research, 113*, B10401. https://doi.org/10.1029/2007JB005551
Kim, C.-M., Han, R., Jeong, G. Y., Jeong, J. O., & Son, M. (2016). Internal structure and materials of the Yangsan fault, Boryeong area, Pohang, South Korea. Geosciences Journal, 20, 759–773. https://doi.org/10.1007/s12303-016-0019-8

Kim, C.-M., Han, R., Kim, J. S., Sohn, Y. K., Jeong, J. O., Jeong, G. Y., & al. (2019). Fault zone processes during caldera collapse: Jangsan Caldera, Korea. Journal of Structural Geology, 124, 197–210. https://doi.org/10.1016/j.jsg.2019.05.002

Kim, C.-M., Jeong, J. O., Gu, D., & Han, R. (2017). Identification of materials in principal slip zones of faults by X-ray diffraction analysis using a small amount of sample. Journal of the Geological Society of Korea, 53, 873–883. https://doi.org/10.14770/jsgk.2017.53.6.873

Kirkpatrick, J. D., & Rowe, C. D. (2013). Disappearing ink: How pseudotachylytes are lost from the rock record. Journal of Structural Geology, 52, 183–198. https://doi.org/10.1016/j.jsg.2013.03.003

Kirkpatrick, J. D., Rowe, C. D., White, J. C., & Brodsky, E. E. (2013). Silica gel formation during fault slip: Evidence from the rock record. Geology, 41, 1015–1018. https://doi.org/10.1130/G34483.1

Kitajima, H., Chester, J. S., Chester, F. M., & Shimamoto, T. (2010). High-speed friction of disaggregated ultracataclasite in rotary shear: Characterization of frictional heating, mechanical behavior, and microstructure evolution. Journal of Geophysical Research, 115, B08408. https://doi.org/10.1029/2009JB007038

Kuo, L.-W., Song, S.-R., Yeh, E.-C., & Chen, H.-F. (2009). Clay mineral anomalies in the fault zone of the Chelungpu Fault, Taiwan, and their implications. Geophysical Research Letters, 36, 18. https://doi.org/10.1029/2009GL039269

Kyung, J. B. (2003). Paleoseismology of the Yangsan fault, southeastern part of the Korean peninsula. Annals of Geophysics, 46(5), 983–996.

Lachenbruch, A. H. (1980). Frictional heating, fluid pressure, and the resistance to fault motion. Journal of Geophysical Research, 85, 6097–6112. https://doi.org/10.1029/JB085i11p06097

Lee, K., & Jin, Y. G. (1991). Segmentation of the Yangsan fault system: Geophysical studies on major faults in the Kyeongsang Basin. Journal of the Geological Society of Korea, 27, 434–449

Lee, S. K., Han, R., Kim, E. J., Jeong, G. Y., Khim, H., & Hirose, T. (2017). Quasi-equilibrium melting of quartzite under extreme friction. Nature Geoscience, 10, 436–441. https://doi.org/10.1038/ngeo2951

Lensen, G. J. (1968). Analysis of progressive fault displacement during downcutting at the Branch River terraces, South Island, New Zealand. The Geological Society of America Bulletin, 79(5), 545–556. https://doi.org/10.1130/0016-7606(1968)79[545:APFDD]2.0.CO;2

Lin, A. (2011). Seismic slip recorded by fluidized ultracataclasitic veins formed in a coseismic shear zone during the 2008 Mw 7.9 Wenchuan earthquake. Geology, 39, 547–550. https://doi.org/10.1130/G32065.1

Ma, K.-F., Tanaka, H., Song, S.-R., Wang, C.-Y., Hung, J.-H., Tsai, Y.-B., et al. (2006). Slip zone and energetics of a large earthquake from the Taiwan Chelungpu-fault Drilling Project. Nature, 444, 473–476. https://doi.org/10.1038/nature05253

Maltman, A., & Bolton, A. (2003). How sediments become mobilized. In F. Van Rensbergen, R. R. Hills, A. J. Maltman, & C. K. Morley (Eds.), Subsurface sediment mobilization (pp. 9–20). Geological Society, London, Special Publication. https://doi.org/10.1134/gsp.2003.216.01.02

Manighetti, I., Campillo, M., Bouley, S., & Cotton, F. (2007). Earthquake scaling, fault segmentation, and structural maturity. Earth and Planetary Science Letters, 253, 429–438. https://doi.org/10.1016/j.epsl.2006.11.004

Mitchell, T. M., Smith, S. A. F., Anders, M. H., Di Toro, G., Nielsen, S., Cavallo, A., & Beard, A. D. (2015). Catastrophic emplacement of giant landslides aided by thermal decomposition: Heart Mountain, Wyoming. Geology, 43, 429–432. https://doi.org/10.1130/G34483.1

Mitchell, T. M., Toy, V., Di Toro, G., Renner, J., & Silbon, R. H. (2016). Fault welding by pseudotachylyte formation. Geology, 44, 1059–1062. https://doi.org/10.1130/G38373.1

Morrow, C. A., Radney, B., & Byerlee, J. D. (1992). Frictional strength and the effective pressure law of montmorillonite and illite clays. In B. Evans, & T.-F. Wong (Eds.), Fault mechanics and transport properties of rocks (pp. 69–88). New York: Academic Press. https://doi.org/10.1016/S0074-6142(08)62815-6

Muhuri, S. K., Dewers, T. A., Scott, T. E., Jr, & Reches, Z. (2003). Interseismic fault strengthening and earthquake-slip instability: Friction or cohesion? Geology, 31, 881–884. https://doi.org/10.1130/0091-7613(2003)31[881:IFSAES]2.0.CO;2

Noda, H., & Lapusta, N. (2013). Stable creeping fault segments can become destructive as a result of dynamic weakening. Nature, 493, 518–521. https://doi.org/10.1038/nature11703

Noda, H., & Shimamoto, T. (2005). Thermal pressurization and slip-weakening distance of a fault: An example of the Hanaore Fault, Southwest Japan. Bulletin of the Seismological Society of America, 95, 1224–1233. https://doi.org/10.1785/0120040089

Okada, A., Watanabe, M., Sato, H., Jum, M.-S., Jo, W.-R., Kim, S.-K., et al. (1994). Active fault topography and trench survey in the central part of the Yangsan fault, Southwest Japan. Journal of Geophysics, 103, 111–126. https://doi.org/10.5026/geography.103.2.111

Okamoto, S., Kimura, G., Takizawa, S., & Yamaguchi, H. (2006). Earthquake fault rock indicating a coupled lubrication mechanism. eEarth Discussions, 1, 135–149. https://doi.org/10.5194/eed-1-135-2006

Oohashi, K., Han, R., Hirose, T., Shimamoto, T., Omura, K., & Matsuda, T. (2014). Carbon-forming reactions under a reducing atmosphere during seismic fault slip. Geology, 42, 787–790. https://doi.org/10.1130/G35703.1

Oohashi, K., Hirose, T., & Shimamoto, T. (2011). Shear-induced graphitization of carbonaceous materials during seismic fault motion: Experiments and possible implications for fault mechanics. Journal of Structural Geology, 33, 1122–1134. https://doi.org/10.1016/j.jsg.2011.01.007

Otsuki, K., Monzawa, N., & Nagase, T. (2003). Fluidization and melting of fault gouge during seismic slip: Identification in the Nojima fault zone and implications for focal earthquake mechanisms. Journal of Geophysical Research, 108(B4), 2192. https://doi.org/10.1029/2001JB001771

Ozawa, K., & Takizawa, S. (2007). Amorphous material formed by the mechanochemical effect in natural pseudotachylyte of crushing origin: A case study of the Iida-Matsukawa Fault, Nagano Prefecture, Central Japan. Journal of Structural Geology, 29, 1855–1869. https://doi.org/10.1016/j.jsg.2007.08.008

Perrin, C., Manighetti, I., Ampuero, J.-P., Cappa, F., & Gaudemer, Y. (2016). Location of largest earthquake slip and fast rupture controlled by along-strike change in fault structural maturity due to fault growth. Journal of Geophysical Research: Solid Earth, 121, 3666–3685. https://doi.org/10.1002/2015JB012671

Phillips, N. J., Rowe, C. D., & Uijie, K. (2019). For how long are pseudotachylytes strong? Rapid alteration of basalt-hosted pseudotachylytes from a shallow subduction complex. Earth and Planetary Science Letters, 518, 108–115. https://doi.org/10.1016/j.epsl.2019.04.033

Platt, J. D., Brantut, N., & Rice, J. R. (2015). Strain localization driven by thermal decomposition during seismic shear. Journal of Geophysical Research: Solid Earth, 120, 4405–4433. https://doi.org/10.1002/2014JB014193
Yun, S. H., Lee, M. W., Koh, J. S., Kim, Y. L., & Han, M. K. (2000). Petrology of the Bogyeongsa volcanics in the northeast Gyeongsang basin. *Journal of the Korean Earth Science Society, 21*, 595–610.

Yund, R., Blanpied, M., Tullis, T., & Weeks, J. (1990). Amorphous material in high strain experimental fault gouges. *Journal of Geophysical Research, 95*, 15589–15602. [https://doi.org/10.1029/JB095iB10p15589](https://doi.org/10.1029/JB095iB10p15589)