Geophysical Research Letters

RESEARCH LETTER
10.1029/2019GL081927

Key Points:
- Drilling investigations were carried out on the Nojima Fault that triggered the 1995 M_w 6.9 Kobe (Japan) earthquake
- A 10- to 30-cm-thick fault gouge zone was observed in nine drill holes at depths of 260-900 m, containing 11-20 thin layers of different colors
- 11-20 thin layers of the gouge zone probably records more than 11-20 seismic faulting events during the late Pleistocene-Holocene

Supporting Information:
- Supporting Information S1

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Citation:
Lin, A., & Nishiwaki, T. (2019). Repeated seismic slipping events recorded in a fault gouge zone: Evidence from the Nojima fault drill holes, SW Japan. *Geophysical Research Letters*, *46*, 1276–1283. https://doi.org/10.1029/2019GL081927

Received 5 JAN 2019
Accepted 13 JAN 2019
Accepted article online 18 JAN 2019
Published online 4 FEB 2019

Repeated Seismic Slipping Events Recorded in a Fault Gouge Zone: Evidence From the Nojima Fault Drill Holes, SW Japan

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Abstract Drilling investigations and structural analysis of drill cores reveal that a fault gouge zone of 10–30 cm in width was observed at depths of ~260 to 900 m in nine drill holes that intersected the Nojima Fault (NF), on which the 1995 M_w 6.9 Kobe (Japan) earthquake occurred. Logging data and an analysis of mesostructures and microstructures in drill cores show that (i) a ~60-m wide fault damage zone containing a 10- to 30-cm-thick fault gouge zone developed in the NF, (ii) the fault gouge zone can be divided into 11–20 thin layers of different color, and (iii) the individually colored layers contain different color breccias of fault gouge that are offset and/or cut by cracks and crack-filled calcite and quartz veinlets. Our results reveal that the fault gouge zone probably records more than 11–20 paleoseismic faulting events along the NF during the late Pleistocene-Holocene.

Plain language Summary Drilling investigations and structural analyses of drill cores reveal that a ~60-m wide fault damage zone containing a 10- to 30-cm-thick fault gouge zone developed along the Nojima Fault (NF), on which the 1995 M_w 6.9 Kobe (Japan) earthquake occurred. The fault gouge zone was observed at depths of ~260 to 900 m in nine drill holes that intersected the NF. Our findings show that (i) the fault gouge zone observed at different depths in the nine drill cores is the principal fault slip zone of the NF, and (ii) the individual colored layers of the fault gouge zone provide a record of repeated seismic slip events within the NF and may therefore represent *earthquake fossils*, as do pseudotachylyte veins and fault scarps that record the systematic offset of valleys and terrace risers along the NF during the late Pleistocene-Holocene.

1. Introduction

It is well known that large intracontinental earthquakes occur repeatedly along mature active faults and that the seismic slip may be recorded by cataclastic rocks, including fault gouge zones, which form at shallow depths in the upper crust (e.g., Lin, 2008; Sibson, 2003). A fault gouge zone, bounded by a principal fault plane, is considered to represent the seismic slip zone that accommodates most of the accumulated fault displacement in the seismogenic regime (e.g., Lin, 2011; Lin et al., 2001; Sibson, 1986, 2003). Therefore, studies of fault gouge zones along mature active faults would provide important information for reconstructing the long-term seismic faulting behavior of such faults, as well as providing new insights into the individual seismic slipping processes of active faults and their paleoseismic histories.

Over the last 3 years, we have undertaken a research project called *Drilling into the Fault Damage Zone* (DFDZ) to develop a comprehensive method for evaluating the recent activity of faults that develop in basement rocks (Lin, 2018; Nishiwaki et al., 2018). The project involved drilling the Nojima Fault (NF) in SW Japan, which triggered the 1995 M_w 6.9 Kobe earthquake. Drilling into the NF had previously been conducted at the study site in 1998 to understand the nature, mechanism of healing, and recovery processes of the fault zone after the 1995 Kobe earthquake (Ando, 2001).

In the present study, we focused on the structural features of the fault gouge zone observed in drill cores acquired from nine holes that were drilled through the NF at different depths from ~260 to 900 m at the Ogura site (Figures 1b and 1c). Such deep drill cores may be free from the physical and chemical weathering that commonly affects rocks near the ground surface, thus providing fresh samples for studying the primary fault deformation structures and chemical changes induced by seismic slipping within the fault zone.

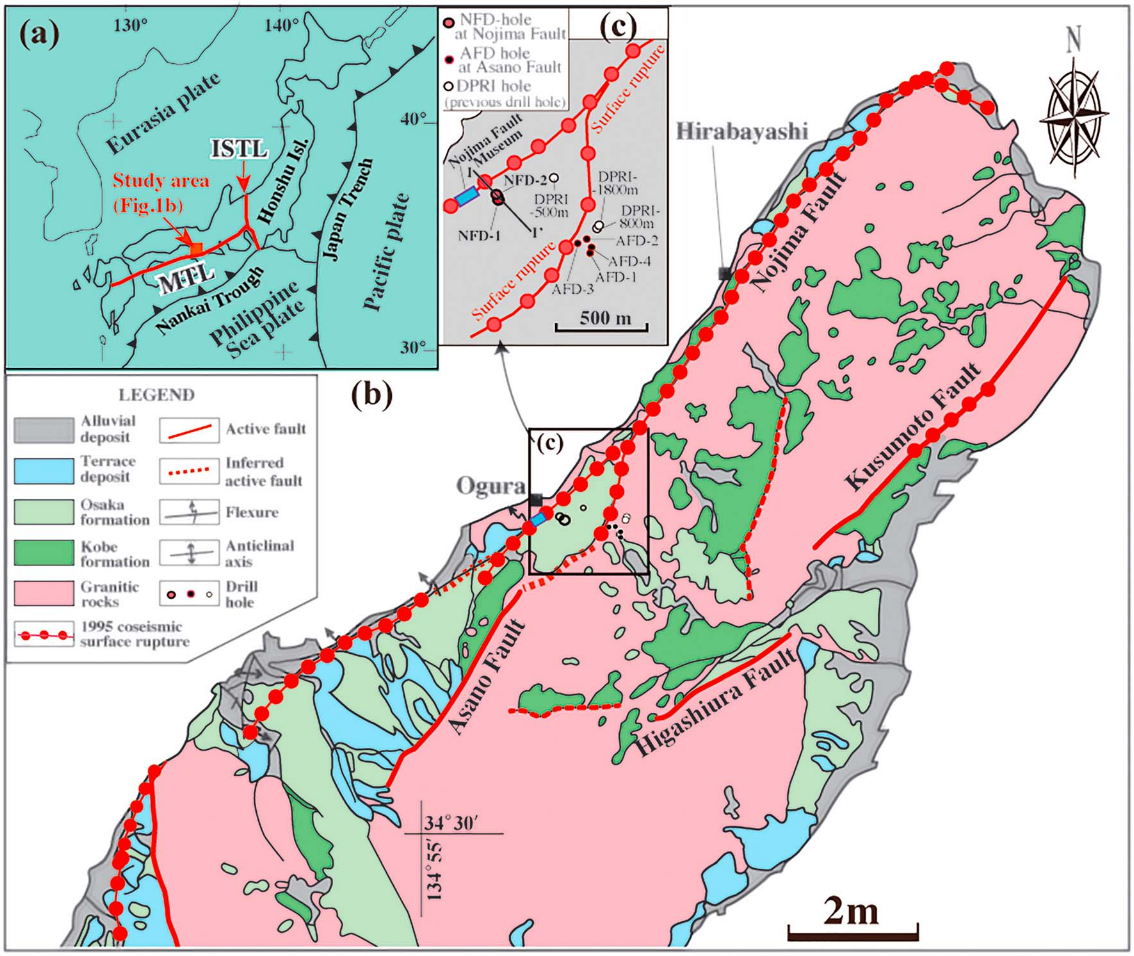

Figure 1. (a) Index map of the tectonic setting of the Japanese Islands. (b) Geological map of the northern part of Awaji Island. The area of (b) is shown on (a), and (c) gives the locations of drilling sites. The geological map is modified from Mizuno et al. (1990). Active fault data are from RGAFJ (1991) and the coseismic surface rupture zone is from Lin and Uda (1996). NFD-1 is the drill hole of this study. AFD-1 to AFD-4 are drill holes on the Asano fault. DPRI 500 m, 800 m, and 1,800 m are the holes drilled in 1998 (Ando, 2001). MTL: Median tectonic line. ISTL: Itoigawa-Shizuoka tectonic line. I-I′: Geological profile shown in Figure 2a.

2. Geologic Setting

The study area is located on the northwestern side of Awaji Island, where some of the coseismic surface ruptures produced by the 1995 M_w 6.9 Kobe (Japan) earthquake have been protected and exhibited in the Nojima Fault Museum (see Figure 1 for location). The basement rocks of the study area consist of pre-Neogene granitic rocks, the Miocene Kobe Group, and the Pliocene-Pleistocene Osaka Group, all of which are overlain unconformably by late Quaternary alluvial and terrace deposits (Mizuno et al., 1990). The granitic rocks are medium-grained and consists mostly of quartz, feldspar, biotite, and subsidiary amphibole. The Kobe Group is mainly composed of sandstone, conglomerate, sandy mudstone, and thin intercalated lignite beds, and the Osaka Group consists mainly of weakly consolidated to unconsolidated sediments including alternating beds of silt-clay, sand, and gravel. There are four major active faults developed in the northeastern part of Awaji Island, and among these are the Nojima and Asano faults that make up the Nojima fault zone (NFZ), and the Kusumoto and Higashiura faults. All these faults strike NE–SW (Figure 1b) and cut the Miocene–Pleistocene Kobe and Osaka groups and the Quaternary alluvial deposits (Research Group for Active Faults of Japan, RGAFJ, 1991). The coseismic surface rupture zone produced by the 1995 M_w 6.9 Kobe earthquake occurred along the preexisting NFZ for ~18 km, and for ~2 km along the Kusumoto Fault on the northeastern side of Awaji Island (Figure 1b, Lin & Uda, 1996). The mesostructural and microstructural features of cataclastic rocks developed within the NFZ also demonstrate a right-lateral strike-slip-dominated tectonic history for the fault (Lin, 2001; Lin et al., 2001).

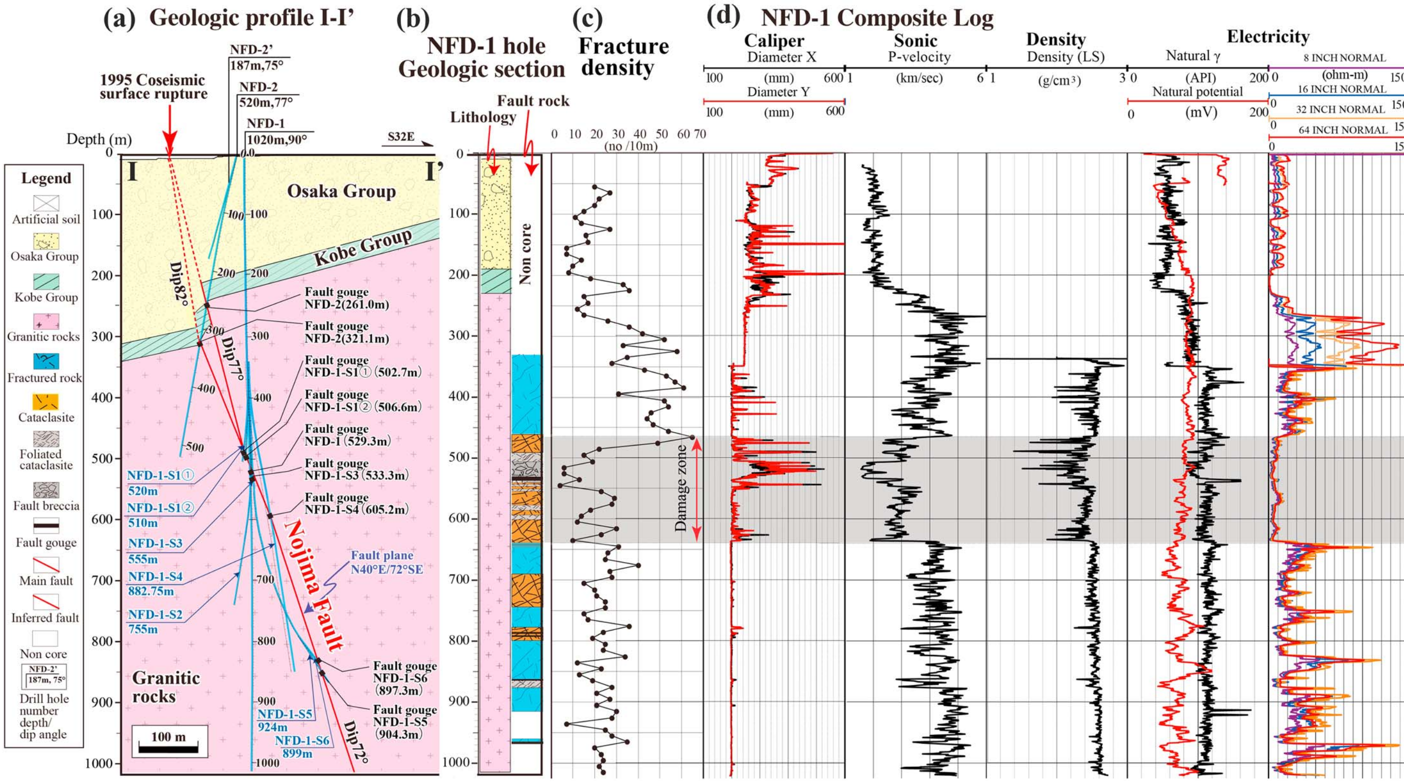

Figure 2. Diagrams showing the (a) geological profile (I-I′), (b) geologic section, (c) fracture density, and (d) composite logging profiles of the NFD-1 hole at the Ogura drilling site. The geologic section is modified from Nishiwaki et al. (2018).

3. Drilling Investigations

For this study, we selected a drilling site at Ogura, ~100 m east of the Nojima Fault Museum, where the previous drilling project had been conducted 20 years ago (see Figure 1 for location). The drill holes were designed to constrain the location of the main fault plane so that we could take core samples of fault gouge at different depths on the NF from the same hole by bending the branch (sidewall) holes using a controlled drilling technique (Figure 2a). This approach made it possible to acquire more core samples of fault gouge from different depths in the same fault at limited expense. Two pilot holes were designed to understand the fault zone structure, including the dip of the fault within the sedimentary rocks of the Osaka and Kobe groups, thus enabling us to recover a fault gouge zone at hole depths of 261 m and 321 m, where the fault dip is estimated to be 77° and 82°, respectively (Figure 2a). After the pilot drilling, we designed a deep drill hole called NFD-1 to reach a depth of ~1,000 m. The hole had six branch (bending) holes at depths from 530 to 900 m, based on the dip of the principal fault plane as revealed by the pilot (NFD-2) and the NFD-1 drill holes (Figure 2a).

All the drill holes, except the pilot hole (NFD-2′), were drilled through the NF, and cores of fault gouge zone (15- to 30-cm wide) were acquired at nine depths from 261 to 902 m (Figure 2a). In the NFD-1 hole, drill core was obtained for depths between 350 and 1,000 m. Structural analyses of the fault rock in the drill cores and the fracture density from borehole images, as well as logging data (e.g., caliper, sonic, density, and electrical analyses of the hole wall) showed anomalies in the NFD-1 hole at depths between 460 and 650 m, in which the fracture density, *P*-velocity, rock density, and electricity show lower values than that of other bounded parts in the hole wall (Figures 2b–2d), and a fault gouge zone of ~20 cm in width, bounded by a distinct fault plane with a dip of ~75°, was observed at a depth of ~529 m (Figure 2). The fault plane varies dip angle from 77–82° at depth of < ~500 m to 72° at the depth of > ~500 m (Figure 2). The fault damage zone consists of cataclastic rocks including cataclasite, fault breccia, and fault gouge (Figure 2b).

10.1029/2019GL081927

4. Structural Features of the Fault Gouge Zone

Polished sections were acquired from bisected cores of the fault gouge zone and bounded cataclasite and fault breccia from the nine drill holes. The samples came from different depths where the core contained the fault gouge zone, bounded by cataclastic rocks on both sides of the zone. Sketches of the polished sections of five represented fault gouge zone cores are shown in Figure 3 and supporting information Figure S1. The fault gouge zones range from 15 to ~90 cm in core length, which corresponds to a zone that is 10–30 cm wide perpendicular to the main 72–77°-dipping fault plane (Figure 2a). Except for the NFD-2 hole, in which the gouge zones developed along the boundary between the granitic rocks and the sedimentary rocks of the Kobe Group, all other fault gouge cores were sourced from the host granitic rocks. Structural features of the fault gouge zone can be observed well in the computed topography scanning images and polished sections of bisected cores (Figures 3 and S1). The gouge zones are characterized by 11–20 layers of different colors that vary from light brownish gray to dark gray generally with sharp color boundaries, and there is a distinct foliation that is parallel or subparallel to the margins of the colored layers (Figures 4a, 4b, and S1–S3). The colored layers vary from 1–2 mm to ~10 cm (generally <1 cm) in width (Figures 3, 4, S1, and S2a–S2c), and they often contain fault gouge breccias of different colors, some of which are offset and/or cut by main fault planes and cracks, crack-filled calcite and clay veinlets, and cemented by fine-grained calcite (Figures 4c–4f and S2b–S2g). Some gouge layers show a pseudotachylyte vein (Pt) appearance, which are dark, aphanitic, and dike-like hard rock, interlayered with the foliated fault gouge layers with calcite veins, and offset and injected by numerous calcite veinlets (Figures 4d–4f, S1c, and S3a–S3e). Fine-grained gouge materials are also injected in the neighbored gouge layers and Pt-like veins, locally mixed with calcite materials, indicating fluidization of gouge materials (Figures 4e, S1c, and S3a–S3e). The main fault plane is identified by a sharp planar boundary between two gouge layers, indicating that the most recent seismic slip event occurred on the main plane (Figures 3, 4a, 4b, and S2a–S2d). In contrast, the boundaries between individual gouge layers located farther from the main fault plane show irregularly curved geometries, indicating that deformation has occurred after the formation of these gouge layers (Figures 3, 4a, and S2a–S2d). The Pt-like veins consist of fine- to superfine-grained angular grains and clasts that range in size from submicron to 5 μm, but generally <3 μm, comparable with that of unconsolidated soft fault gouge layers (Figures S3f and S3g in the supporting information).

5. Discussion

Previous studies over the past two decades showed that the bulk of coseismic slip caused by individual large earthquakes is accommodated within highly located slip zones less than a few centimeters based on the geological observations (e.g., Chester & Chester, 1998; Lin, 2008; Shigetomi & Lin, 1999; Sibson, 2003; Smith et al., 2011). The coseismic slip zone is localized mainly within a narrow zone of fault gouge that is 1- to 10-mm wide (e.g., Lin, 2008; Sagy & Brodsky, 2009; Sibson, 2003), but generally <2- to 3-mm wide (Lin, 2011). This gouge zone is bounded by the striated fault plane along which the principal coseismic displacement occurred, as in the cases of the 1995 M_w 6.9 Kobe earthquake (Lin et al., 2001), the 1999 M_w 7.6 Chi-Chi (Taiwan) earthquake (Lin et al., 2005), and the 2008 M_w 7.9 Wenchuan earthquake (Lin, 2011). Mesostructural and microstructural features show that the coseismic slip zones observed in recent large earthquakes are sharply bounded with a main fault plane within a preexisting fault gouge zone (Lin, 2008, 2011), indicating that a fault plane-bounded gouge layer probably recorded at least one seismic slipping event. Geological observations also show that the reliable indicators of past coseismic slip, such as: the Pt formed along the distinct slip plane and injected in the gouge-breccia zone (e.g., Lin, 2011), the truncated clasts along sharp fault plane (e.g., Fondriest et al., 2013), the occurrence of fluidized gouge layers (e.g., Brodsky et al., 2009; Lin, 2008). As described herein, the fault gouge layers showing a Pt vein appearance, which consist of fine-grained materials as that of unconsolidated fault gouge, are considered to be a kind of Pt veins that have also been observed at outcrops (Shigetomi & Lin, 1999) and drill cores (Boullier et al., 2001) along the NF. The presence of fluid inclusions in the NF Pt demonstrates that partial melt occurred (Boullier et al., 2001), indicating a seismic slipping event. The occurrence of gouge veins injected in the gouge layers and Pt veins indicates that the fine-grained gouge materials have been fluidized and injected during seismic faulting (Brodsky et al., 2009; Lin, 2008, 2011). The truncated clasts and old gouge breccias, which are cemented by calcite materials and involved in the gouge layers, have been cut and offset along the sharp fault planes, clacks, and calcite veins (Figures 4a, 4c, and S2b–S2g). These

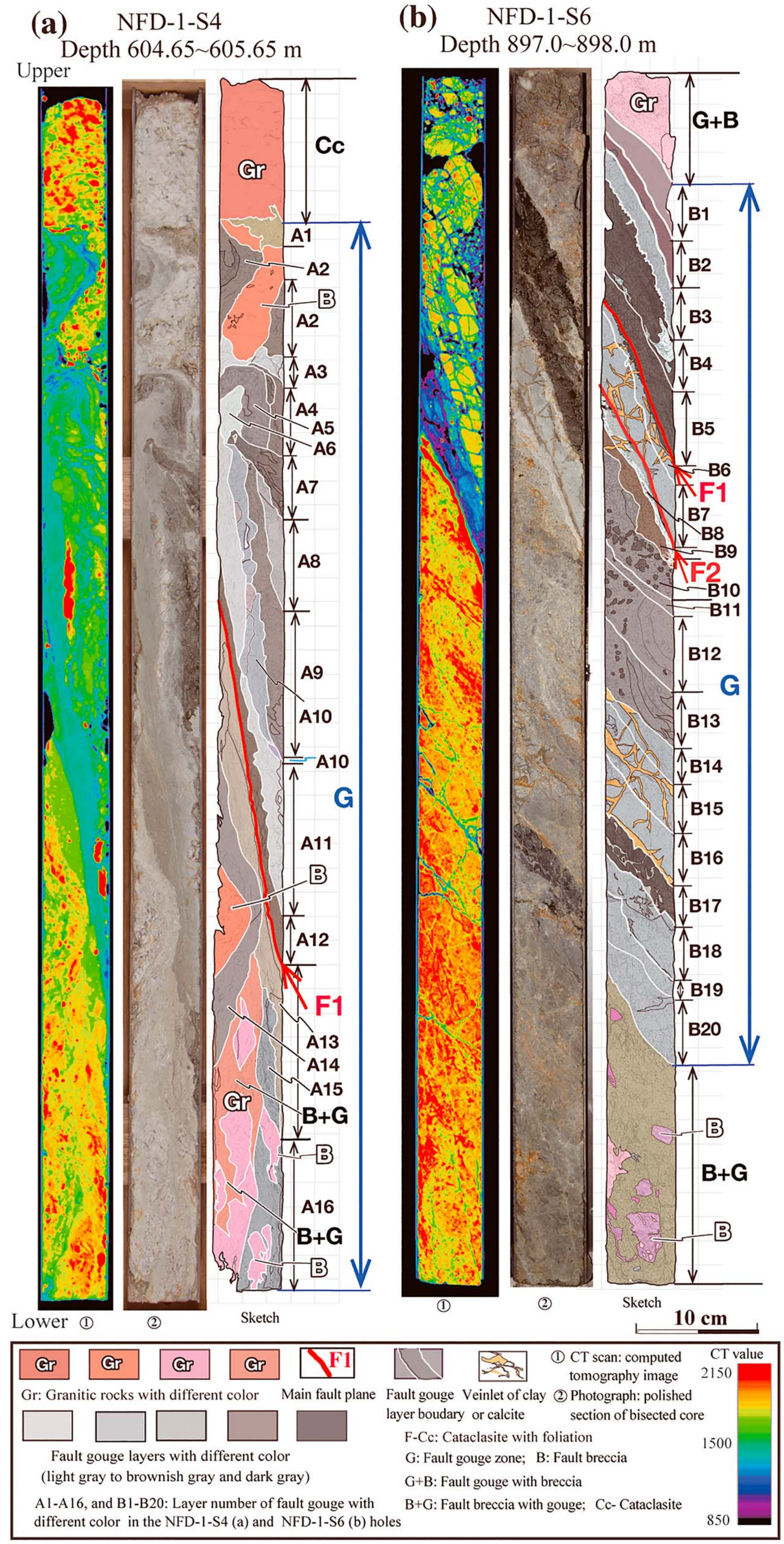

Figure 3. Photographs and corresponding sketches of the representative fault gouge cores acquired from two drill holes at different depths in the NFD-1-S4 and NFD-1-S6 holes (see Figures 1 and 2 for drill hole locations). (a) NFD-1-S4 hole at depth 604.65–605.65 m. (b) NFD-1-S6 hole at depth 897.0–898.0 m. F1–F2: Main fault plane along which the most recent slipping event occurred.

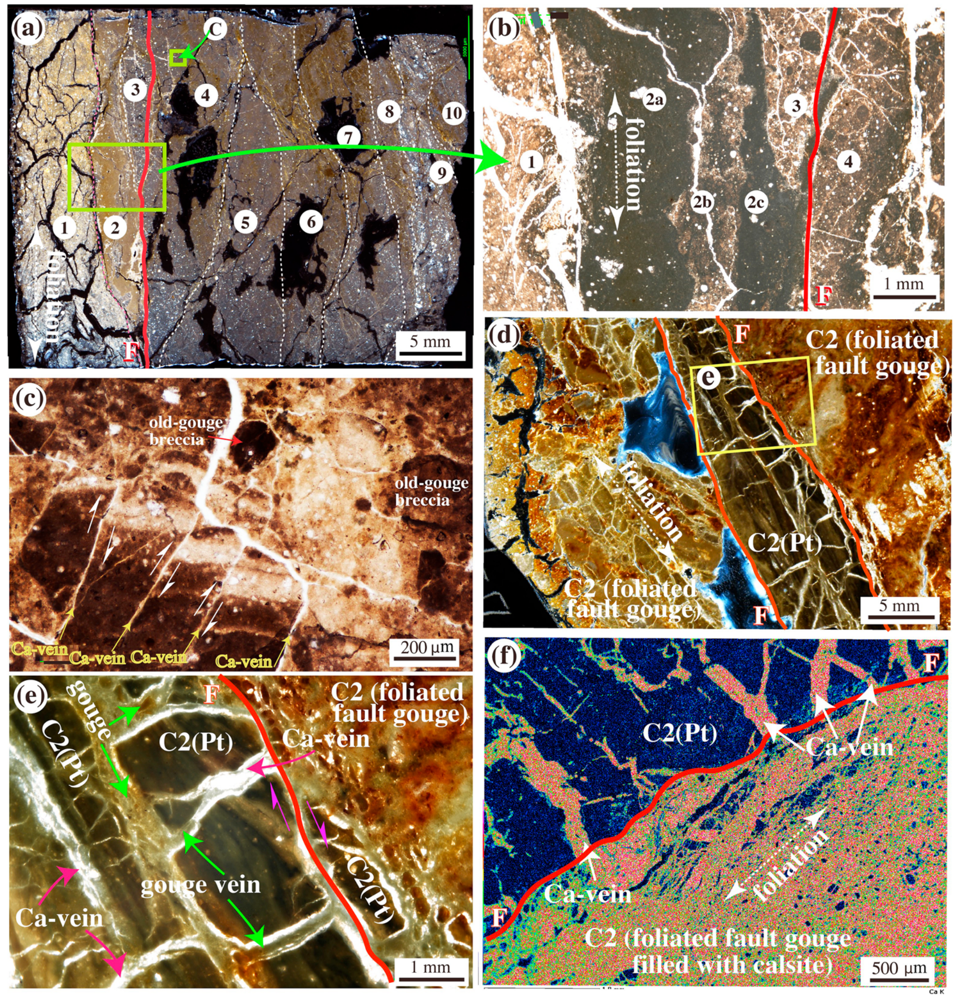

Figure 4. Photomicrographs (a–e) and EDS (energy dispersive X-ray spectrometry) Ca map (f) showing the microstructures of the fault gouge zone at a depth of 605.05 m in the NFD-1-S4 hole (a–c) and a depth of 529.15 m in the NFD-1 hole (d–f). (a) Polished section of the fault gouge zone. F: main fault plane. (b) Layering structures in the fault gouge (indicated by numbers 1, 2a–2c, 3, and 4). (c) Fault gouge cut and offset by cracks that are now filled with calcite veins (Ca-vein). (d, e) The Pt-like [C2(Pt)] gouge veins cut and offset by calcite (Ca-vein), fault gouge material, and calcite-gouge mixed veins. (f) EDS Ca map of the boundary area between the [C2(Pt)] gouge and the foliated fault gouge layers. Reddish and bluish colors indicate the higher and lower Ca concentrations, respectively. (b–e) Plane polarized light.

brittle deformation features of fault gouge layers cannot be formed by creep or ductile deformation during aseismic periods.

Based on the mesostructural and microstructural features documented above, including the layering structures, Pt veins, truncated clasts and old fault gouge breccias involved in gouge layers, and interlayered foliated and nonfoliated fault gouge layers, we suggest that each of the individual colored layers of the fault gouge zone described herein was formed by at least one seismic faulting event within a coseismic shear zone that was bounded by the principal seismic fault plane. Therefore, the 11–20 colored layers of the fault gouge zone found in the drill cores of the NF can be considered to record more than 11–20 seismic faulting events within the NF.

The geological evidence and logging data reveal that the anomalies in the NFD-1 hole at depths between 460 and 650 m (Figures 2b–2d), indicating a fault damage zone of ~60-m wide (perpendicular to the main fault plane; Nishiwaki et al., 2018), including a 10- to 30-cm-thick fault gouge zone. Field investigations and structural analysis also show that a fault damage zone containing a fault gouge zone (10- to 30-cm wide; Lin, 2001; Shigetomi & Lin, 1999), which can be observed at many outcrops along the NFZ where the 1995 coseismic surface ruptures formed with dextral displacements of up to 1.8 m, as well as lesser vertical components (Lin & Uda, 1996). The fault gouge zones were also observed in the drill cores acquired in 1998 during the previous drilling project (Lin et al., 2001). The geological section constrained by data from the drill holes and cores shows that there is only one fault gouge zone (10- to 30-cm wide) bounded by the principal fault planes (Figures 2, 3, and S1).

Previous studies have shown that the main active faults in the area around the Awaji Island were reactivated during the late Tertiary or Quaternary and that displacements have accumulated on topographical markers such as valleys and terrace risers (Lin, 2018) and on fault damage zones (Lin et al., 2001). The NFZ is characterized by a zone of systematic deflections/offsets of mountain ridges, river channels, gullies, and terrace risers, and it was along this existing zone that the coseismic surface rupture zone of the 1995 Kobe earthquake was formed (Lin & Uda, 1996). In the study area around the Ogura drilling site, the NFZ dextrally offsets the Nojima River and the late Pleistocene-Holocene alluvial terrace risers by ~48 m, indicating the amount of accumulated displacement for the past ~20 ka (Lin, 2018). Recent trench investigations have revealed that the most recent event prior to the 1995 Kobe event took place in AD ~1000 and that the average recurrence interval is ~900 years for large earthquakes on the NFZ (Lin, 2018). We propose, therefore, that this fault gouge zone was formed along the principal fault plane during multiple faulting events that occurred in the late Pleistocene-Holocene.

6. Conclusions

Based on the findings described herein, we conclude that (i) the fault gouge zone (10- to 30-cm thick) observed at different depths in the drill cores is the principal fault core zone of the NF, and (ii) the individual colored layers of the fault gouge zone provide a record of repeated seismic slip events within the NF and may therefore represent *earthquake fossils*, as do pseudotachylyte veins and fault scarps that record the systematic offset of valleys and terrace risers along the NF during the late Pleistocene–Holocene.

Acknowledgments
We thank M. Miyawaki, J. Uchida, and T. Satsukawa for administrating the DFDZ project and for discussing the scientific aspects of the study. We are grateful to the Oyo Corporation for operating the drilling investigations over the last 3 years. Our thanks are also due to N. Akiyama for arranging the project and Y. Yoshida for drafting the figures. The contracted research project *Drilling into the Fault Damage Zone* was supported by the Secretariat of the Nuclear Regulation Authority of Japan and partially by JSPS KAKENHI grant JP18H01309. We have shown all the data in the supporting information of this paper as supporting information figures.

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