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Thematic Article

Deformation mechanisms and fluid behavior in a shallow, brittle fault zone during coseismic and interseismic periods: Results from drill core penetrating the Nojima Fault, Japan

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Abstract This paper describes the results of petrographical and meso- to microstructural observations of brittle fault rocks in cores obtained by drilling through the Nojima Fault at a drilling depth of 389.52 m. The zonation of deformation and alteration in the central zone of the fault is clearly seen in cores of granite from the hanging wall, in the following order: (i) host rock, which is characterized by some intragranular microcracks and *in situ* alteration of mafic minerals and feldspars; (ii) weakly deformed and altered rocks, which are characterized by transgranular cracks and the dissolution of mafic minerals, and by the precipitation of zeolites and iron hydroxide materials; (iii) random fabric fault breccia, which is characterized by fragmentation, by anastomosing networks of transgranular cracks, and by the precipitation of zeolites and iron hydroxide materials; and (iv) fault gouge, which is characterized by the precipitation of smectite and localized cataclastic flow. This zonation implies that the fault has been weakened gradually by fluid-related fracturing over time. In the footwall, a gouge layer measuring only 15 mm thick is present just below the surface of the Nojima Fault. These observations are the basis for a model of fluid behavior along the Nojima Fault. The model invokes the percolation of meteoric fluids through cracks in the hanging wall fault zone during interseismic periods, resulting in chemical reactions in the fault gouge layer to form smectite. The low permeability clay-rich gouge layer sealed the footwall. The fault gouge was brecciated during coseismic or postseismic periods, breaking the seal and allowing fluids to readily flow into the footwall, thus causing a slight alteration. Chemical reactions between fluids and the fault breccia and gouge generated new fault gouge, which resealed the footwall, resulting in a low fluid condition in the footwall during interseismic periods.

Key words: Awaji Island, drilling, fault rock, fault zone, Hyogo-ken Nanbu earthquake, meteoric fluids, Nojima Fault, structural analysis, Tsushigawa granite.

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INTRODUCTION

The Nojima Fault is one of the many active faults in Japan (Research Group for Active Faults of Japan 1991). It was activated when the disastrous 1995 Hyogo-ken Nanbu Earthquake (*M*7.2) struck Kobe city and the northern area of Awaji Island, south-west Japan (Nakata *et al.* 1995). The Nojima Fault became visible as a surface rupture measuring more than 10 km long (Awata *et al.* 1995; Lin & Uda 1996) (Fig. 1). After the earthquake, a project to drill through the fault was begun by the University Group. The Nojima Fault was penetrated at a drilling depth of 389.5 m, and a total of more than 500 m of cores (62 mm in diameter) was recovered.

This paper describes the results of petrographic and structural analyses of brittle fault rocks in the recovered cores. The petrographic analysis includes descriptions of meso- to microscopic fractures and alteration products. Preliminary analysis of mineral assemblages in the brittle fault rocks was done using powdered X-ray diffraction (XRD) analysis. Structural analysis includes classifying the types of fault rocks and establishing their modes of occurrence. These analyses elucidate the zonal arrangement of the fault rocks, which exhibit progressively greater fracture density and a greater degree of alteration towards the centralized layer of fault gouge. The aim of the present study is to determine the mode of fracturing and alteration along the fault zone and to investigate

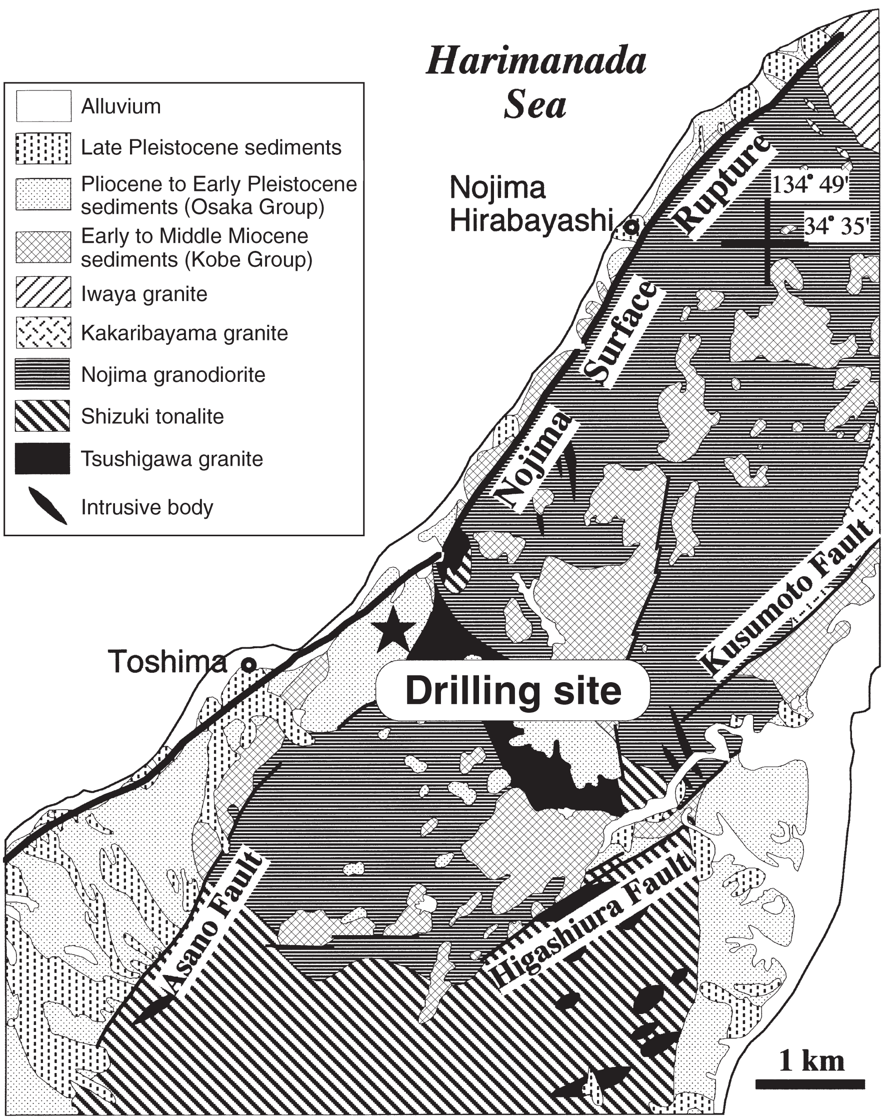

Fig. 1 Geological map showing the Nojima Fault and the drilling site location. Modified from Mizuno *et al.* (1990).

the behavior of fluid in a brittle fault zone at a very shallow depth, during coseismic and interseismic periods.

GEOLOGICAL SETTING

The Nojima Fault trends northeastward along the north-western margin of Awaji Island, and dips to the south-east at a high angle (Mizuno *et al.* 1990; Fig. 1). It juxtaposes Cretaceous granitic rocks (the Nojima Granodiorite and Tsushigawa Granite, 66–88 Ma; Takahashi 1992) that are partly overlain by Neogene and Quaternary sediments to the south-east and north-west. These overlying sediments belong to the middle Miocene Kobe Group and the Plio-Pleistocene Osaka Group and consist mainly of bedded sand and gravel intercalated with thin layers of mud (Mizuno *et al.* 1990).

The drill site is approximately 275 m south-east of the surface rupture of the Nojima Fault near Toshima (Fig. 1), on both sides of which are unconsolidated sediments of the Osaka Group. Drilling was done to a borehole depth of 550 m, at an inclination of approximately 60° to the north-west, and penetrated the Nojima Fault plane at a bore hole depth of 389.52 m. Figure 2a shows the geological cross-section inferred from the drilling data. By extrapolating the surface rupture location to the position of the fault surface in the borehole, the dip of the Nojima Fault is inferred to be 83°. Figure 2a also shows the 235 m reverse offset of the basal surface of the Osaka Group along the dextral oblique–slip fault.

PETROGRAPHIC CHARACTERISTICS AND STRUCTURAL ZONATION OF FAULT ROCKS IN DRILL CORES

DESCRIPTION OF FAULT ROCKS IN THE DRILL CORES

The cores exhibit the full range of deformation and alteration, from faint alteration (without pervasive deformation) near the ground surface, through weakly deformed and altered rocks, to fault breccia and fault gouge on the fault surface itself. An outline of lithologies in the cores is shown in Fig. 2b (see Murata *et al.* 2001 for a detailed description of core lithologies). The fault surface at a drilled depth of 389.52 m forms a boundary between the Tsushigawa Granite in the hanging wall and the unconsolidated sediments of the Osaka Group in the footwall.

A detailed petrographic study was done on a 46.1 m segment of the core, which included the fault surface (the rectangle in Fig. 2b, between borehole depths of 347.9 m and 394.0 m). All 273 core segments along this length were cut in half lengthwise and polished. Most core segments were very fragile and so were repeatedly fixed with epoxy resin during processing. Although extremely time-consuming, this process was necessary for preparing polished surfaces in order to make detailed observations of rock textures. We should note here that the drill core did have unrecovered portions (centimeters to meters in lengths) possibly because of brecciation during drilling. Although these portions could have potential importance for fault rock analysis as they might be weaker than boundary rocks, they could

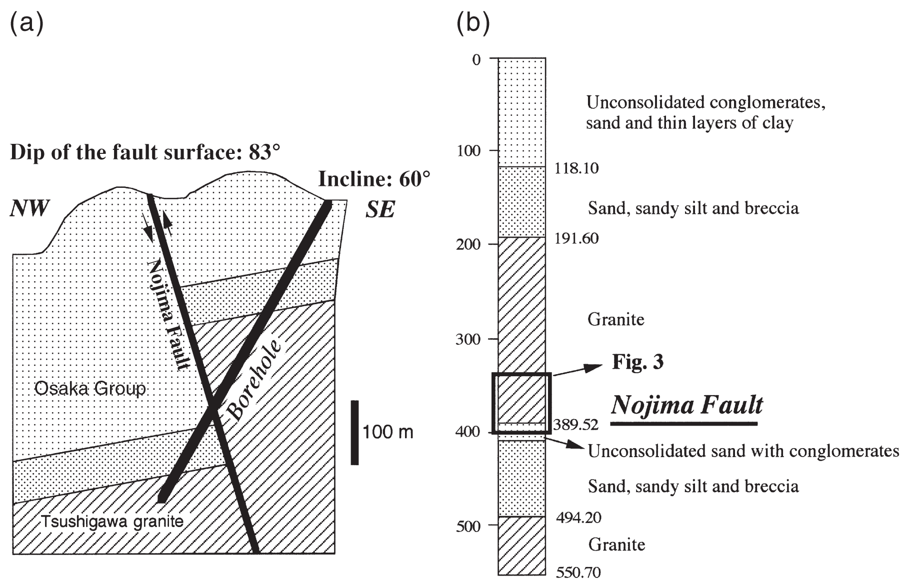

Fig. 2 (a) Geological cross-section across the drilling hole, inferred from the lithology of the drilled core. (b) Outline of the lithology of the recovered cores. Legends are the same as those shown in Fig. 1.

not be presented in the structural zonation analysis and columnar section presented in Fig. 4. The fault-related rocks in this 46.1 m section are classified into four types: (i) host rocks; (ii) weakly deformed and altered rocks; (iii) fault breccia; and (iv) fault gouge.

Host rocks

Mafic minerals or their alteration products are scattered in aggregates of feldspar grains, which are pale yellow or pale red in color, and quartz grains (Fig. 3a). Intragranular microcracks predominate, especially in quartz grains. Some transgranular cracks are zigzags that cut the intragranular microcracks. The lengths of these transgranular cracks vary from a few grains to more than several tens of millimeters, with spacings of tens of millimeters. In the present study, this lithology is referred to as the host rock because it is the freshest occurrence of granitic rocks in the drill core, and because all these features are present in undeformed but weakly weathered granitic rocks throughout Japan (e.g. Kimiya 1975).

Weakly deformed and altered rocks

Mafic minerals are reduced in volume and replaced almost completely by green-brown clay minerals that fill transgranular microcracks in nearby grains of quartz or feldspars (Fig. 3b). Randomly oriented transgranular microcracks with spacings of a few millimeters cut across the intragranular cracks that are densely developed in the quartz and feldspar grains. In Fig. 3c, mafic minerals and their alteration products have lost their original shapes, whereas thin layers of clay minerals are present in the microcracks, which lack a dominant orientation and occur with spacings of a few millimeters. Some transgranular cracks have widths of a few millimeters, and are stained with dark brown alteration materials. These are effectively microscopic brittle shear zones.

Fault breccia

Fault breccia is composed of fragments and surrounding fine-grained matrix (Fig. 3d). Dark reddish brown-colored minerals produced by alteration are much more abundant than in weakly deformed and altered rocks and serve as an aphanitic matrix. Fragments are subangular in shape with no preferred orientation at a millimeter scale. Textures within the fragments are similar to those in weakly deformed and altered rocks, suggesting that brecciation becomes increasingly localized, from weakly deformed and altered rocks to fault breccia.

Fault gouge

Fault gouge consists mainly of fine-grained fragments and unindurated clay matrix that are pale gray-green or pale brown in color (Fig. 3e). The fault gouge is well foliated subparallel to the fault surface due to the preferred orientations of the clay minerals. Fragments are a few millimeters or smaller in diameter and are more rounded than those in the fault breccia. As seen in Fig. 3e, there is a gradual change in texture from fault breccia to fault gouge (i.e. a change in color from dark red-brown to pale gray-green), and a corresponding change in clast size from larger to smaller. In some places, green-gray colored fault gouge has been brecciated and incorporated into the fault breccia as fragments (Fig. 3f), suggesting that fault gouge was repeatedly brecciated.

STRUCTURAL ZONATION OF THE FAULT ROCKS

The distribution of fault rocks was studied using the categories described earlier. Three subzones are present in cores from the hanging wall, based on the dominance of one of the four categories (Fig. 4), although boundaries between the subzones are gradational. The non- to weakly deformed and altered subzone consists of unmodified to weakly deformed and altered host rocks (from 347.90 m to 362.46 m in borehole depth; >8 m true thickness; i.e. parallel to the fault). A weakly deformed and altered subzone consists mainly of weakly deformed and altered rocks (362.46–379.91 m in borehole depth; 9.6 m true thickness). A fault breccia subzone consists mainly of fault breccia and fault gouge (379.91–389.52 m in drilled depth; 5.3 m true thickness). Some very thin layers of fault gouge occur in each of the three subzones (Fig. 4). In contrast to the hanging wall, a single 15 mm-thick gouge layer is present in the footwall, just below the surface of the Nojima Fault. Unaltered and unconsolidated sediments appear just 0.2 m below the surface of the Nojima Fault (Fig. 5). This illustrates the asymmetrical structure of the fault zone, which is much more widely deformed and altered in the hanging wall than in the footwall.

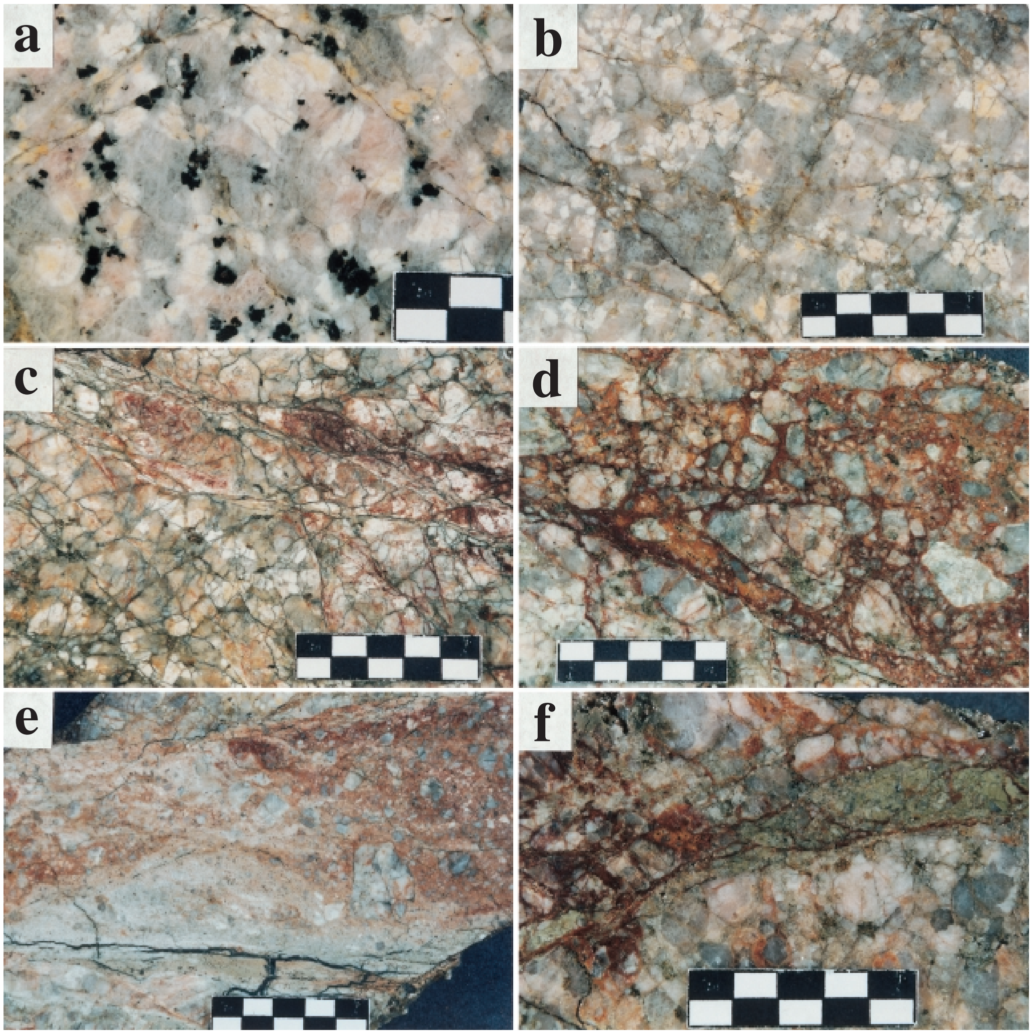

Fig. 3 Photomicrographs showing the textures of fault rocks in the recovered cores. Bars = 1 cm for black and white markers. (a) Host rock; (b,c) weakly deformed and altered rock (granite); (d) fault breccia; (e) fault gouge; (f) brecciated fault gouge involved in the fault breccia.

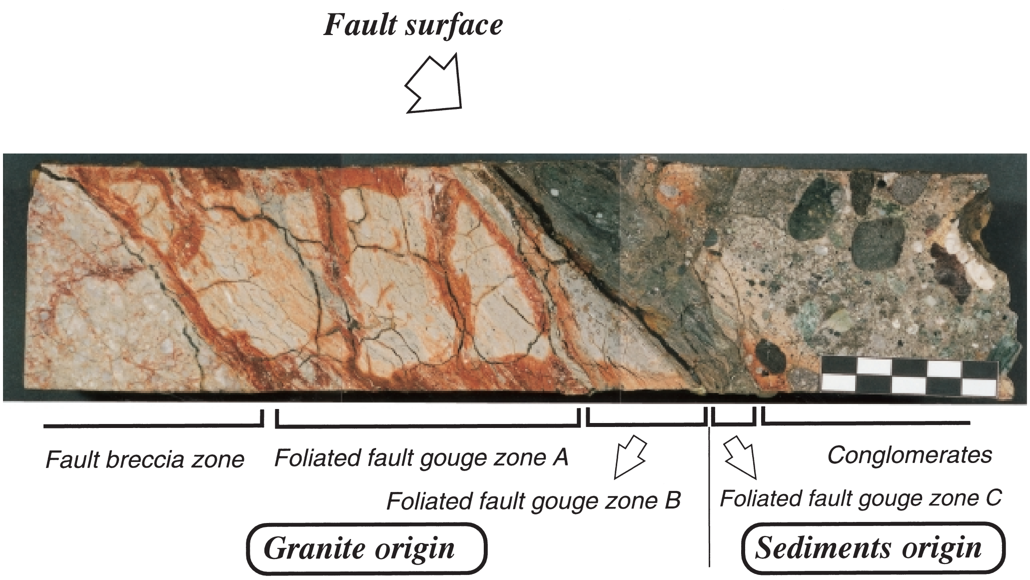

Fig. 5 Photograph showing the occurrence of the central layers of the Nojima Fault including the fault surface. Bars = 1 cm.

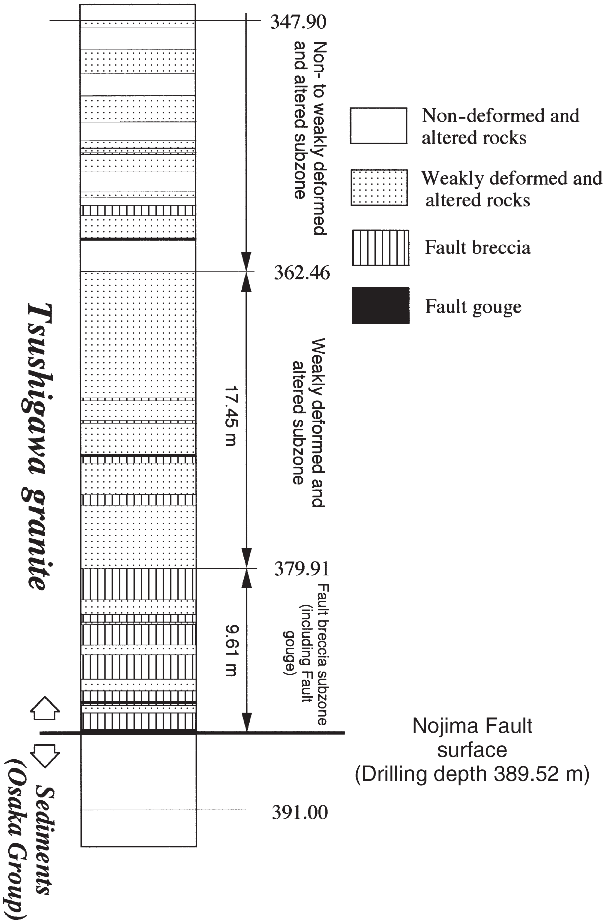

Fig. 4 Distribution of fault rocks in the drill core. Three subzones; that is, non- to weakly deformed and altered subzone, weakly deformed and altered subzone, and fault breccia subzone are distinguished with regard to the dominance of each of the four categories of fault rocks.

A sharply defined fault surface is present in a core segment at a borehole depth of 389.52 m (Fig. 5), accompained by a distinct centimetre scale zonation of the rocks on either side. Five zones are present in this core segment, and each one is bounded by clear-cut shear surfaces subparallel to the Nojima Fault. Three zones on the hanging wall side originated from granite, which is identified by differences in the color of fault rocks: a pale brown zone of fault breccia (thicker than 50 mm); a gray-brown Zone A of foliated fault gouge (90 mm thick); and a gray-white Zone B of foliated fault gouge (15 mm thick). The dark gray-green Zone C of fault gouge (15 mm thick) is the only fault rock in the footwall. Undeformed and unaltered sediments occur below Zone C. The fault gouge in Zone B is intermediate in color between Zones A and C.

MINERAL ASSEMBLAGE

Thirty samples were selected at intervals of approximately 1.5 m from the extent shown in Fig. 4 (Table 1). Samples had generally been fragmented, except for a few. Browning is a feature common to all samples. Whole rock mineral assemblages from these samples were examined by qualitative powdered XRD (Table 1). Among the primary minerals, quartz, orthoclase and plagioclase are common in three subzones, while biotite is generally depleted and was not even detected in the fault breccia subzone. Zeolite is the most dominant constituent among secondary or authigenic minerals; laumontite was present in all such samples, except one obtained from just above the fault surface. Stilbite is less common than laumontite and is present in a few samples, except for those close to the fault surface. Carbonate minerals are detectable as minor constituents. Smectite is the only clay mineral present in two samples from very close to the fault surface. Clay minerals and brown-colored minerals (possibly iron hydroxide minerals) are known to be present as thin layers and crack fillings in many samples, but they were not detected by whole-rock XRD analysis, perhaps because of their less crystallized nature and/or less common occurrence compared to other host rock minerals.

DISCUSSION

DEFORMATION/ALTERATION PROCESS OF THE FAULT ROCKS

Analysis of fault rock distribution shows that the intensity of brecciation and the degree of alteration (as shown by the amounts of alteration products such as clay minerals) increase progressively inward from the undeformed and unaltered subzone, through the weakly deformed and altered subzone, to the central zone of fault breccia and gouge. This zonation indicates that the fault rocks in the drill cores were generated and matured by fluid-assisted brecciation that was localized in the central zone of fault gouge. Analysis of mineral assemblages shows that the mafic minerals are almost depleted from the fault breccia subzone, and that smectite was generated as newly crystallized minerals in the centralized layer of fault gouge, suggesting also that dissolution and precipitation processes were dominant in the formation of fault rocks. Both the zonal arrangement of fault rocks and the mode of progressive deforma-

Table 1 Mineral assemblages detected by whole rock XRD analysis. Samples are taken from the extent of 'depth' ±25 mm

			Occurrence of samples (Naked eye observations)		XRD Results							
					Primary minerals				Zeolites		Clays	Carbonates
Samples	Depth (m)	Subzone	Nature	Browning	Q	Or	Pl	Bt	Lmt	Stb	Sm	
54-1	352.30		FR	○	◎	○	○	Tr	△	△	–	–
54-2	355.80		FR	○	◎	○	○	–	×	–	–	–
55-1	356.25	NWDAS	FR	○	◎	○	◎	×	Tr	Tr	–	–
55-2	359.50		FR	○	◎	○	○	–	△	△	–	–
56-1	362.20		CP	△	◎	△	○	–	Tr	–	–	–
56-2	364.25		CP	△	◎	○	○	–	△	–	–	–
57-1	367.20		CP	△	◎	○	○	Tr	×	–	–	–
57-2	369.95		PD + FR	○	◎	△	○	–	○	–	–	–
58-1	370.60		FR	○	◎	○	◎	–	△	Tr	–	–
58-2	371.60		FR	○	◎	△	○	–	×	–	–	–
58-3	372.20		PD + FR	○	◎	○	○	–	△	–	–	Tr
58-4	372.80	WDAS	FR	○	◎	○	○	–	×	–	–	Tr
58-5	373.50		CP	○	◎	○	○	–	×	Tr	–	Tr
59-1	374.40		FR	○	◎	○	○	–	×	△	–	–
59-2	375.75		PD + FR	○	◎	○	○	Tr	△	–	–	–
59-3	376.40		PD + FR	○	◎	○	○	×	△	–	–	–
59-4	377.50		FR + PD	○	◎	○	○	–	×	Tr	–	–
59-5	378.70		FR	○	◎	○	○	Tr	△	–	–	–
60-1	379.60		FR	△	◎	○	○	–	×	Tr	–	–
60-2	380.20		FR	△	◎	○	○	–	○	–	–	–
60-3	380.90		FR	○	◎	○	○	–	×	Tr	–	–
60-4	381.90		FR + PD	○	◎	○	○	–	△	Tr	–	–
60-5	383.45		PD + FR	○	◎	○	○	–	△	–	–	–
61-1	384.55		PD + FR	○	◎	○	○	–	×	–	–	Tr
61-2	385.60	FBS	PD	○	◎	○	○	–	△	–	–	–
61-3	386.40		PD	○	◎	○	○	–	△	–	–	Tr
61-4	387.15		PD	○	◎	○	○	–	×	–	–	–
61-5	388.20		PD	○	◎	○	○	–	△	–	–	Tr
61-6	388.27		PD	△	◎	○	○	–	Tr	–	×	Tr
61-7	388.33		PD	△	◎	○	○	–	–	–	×	Tr

NWDAS, Non- to weakly deformed and altered subzone; WDAS, weakly deformed and altered subzone; FBS, fault breccia subzone; CP, core piece; FR, fragments smaller than 50 mm in size; PD, fragments smaller than 5 mm in size and powder; PD + FR indicates that amounts of PD are more dominant than those of FR, and so on. Degree of browning is qualitatively classified into four grades: (○) intense; (△) moderate; (×) slight; and (—) none. Abbreviations of mineral names are: Q, quartz; Or, orthoclase; Pl, plagioclase; Bt, biotite; Lmt, laumontite; Stb, stilbite; Sm, smectite. 'Carbonates' includes calcite, dolomite, and siderite. Amounts of detected minerals are classified qualitatively into the following six grades: (◎) very abundant; (○) abundant; (△) common; (×) less common; Tr, trace; (—) not detected.

tion and alteration along the Nojima Fault are similar to those observed along the San Andreas Fault (Chester & Logan 1986; Chester *et al.* 1993), and are well known in brittle regimes at shallow levels in the crust (Mogi 1968; Tsuneishi *et al.* 1975; Yoshida 1985).

Detailed structural observations indicate that fluid-assisted brecciation proceeded through the following four stages. Stage I: Formation of intragranular microcracks and *in situ* alteration of mafic minerals and feldspar, which are both commonly seen in the host rocks and weakly deformed and altered rocks. Stage II: Formation of transgranular cracks and dissolution of mafic minerals, and precipitation of their alteration products. Stage III: Brecciation by anastomosing networks of transgranular cracks, and precipitation of alteration products in microscopic, brittle shear zones. Stage IV: Localized cataclastic flow in the fault gouge and formation of smectite. These are the common fracture and alteration processes of confined rocks in a brittle regime (Fitzgerald & Stünitz 1993; Kamineni *et al.* 1993), in weathering environments on the Earth's surface, and in hydrothermal alteration processes in shallow parts of the crust (Endo & Kimiya 1987; Yoshida *et al.* 1989). Thus, the most straightforward conclusion is that these processes took place within the Nojima Fault Zone at a shallow crustal level.

At all stages of its development, the fault was weakened by the combined effects of brecciation and chemical alteration, as the presence of smectite clay minerals in the central zone of the fault generally reduce frictional strength (Wu *et al.* 1975; Summers & Byerlee 1977; Shimamoto & Logan 1981; Logan & Rauenzahn 1987; Wintsch *et al.* 1995) relative to the surrounding host rocks. The results of laboratory experiments on clay minerals indicate that they tend to produce a rate-strengthening behavior (Wang *et al.* 1980; Logan & Rauenzahn 1987; Marone & Scholtz 1988; Morrow *et al.* 1992), which is defined as an increase in the steady state coefficient of friction with an increase in slip velocity. Thus, foliated clay gouge was not likely to have been formed by coseismic, high-velocity motion, and we point out the possibility that it formed by creeping motion during postseismic or interseismic episodes. This should be clarified in more detail by conducting deformation experiments that use clay minerals mixed with various amounts of granular minerals, such as quartz and feldspar. However, if it is correct, we should mention that the Nojima Fault surface, which is defined as the boundary between granitic rocks and Quaternary sediments (Fig. 5), that was obtained in the drill cores, may not be the surface of the main rupture of the 1995 Hyogoken-Nanbu earthquake. In fact, as the drill core has many unrecovered portions, as mentioned earlier, the main rupture surface could be contained in these portions. This should be discussed in further detail after completing all observations on microstructures in a method similar to that done for the GSJ–Nojima cores (Tanaka *et al.* 2001).

The actual width of the Nojima Fault zone, approximately 15 m (thickness normal to the fault surface), is defined as the total width of the weakly deformed and altered subzone and the fault breccia subzone and, based on the fault zone width–displacement relationship (Otsuki 1978; Nagahama 1991), is thought to have formed by displacing a distance of a few kilometers along the Nojima Fault. However, the relationship is not definitive because Otsuki and Nagahama presented it as a log–log relationship in their papers. Tsushigawa Granite was located at a shallow crustal level after the latest Cretaceous, as evidenced by its non-conformity with the Upper Cretaceous Izumi Group (Mizuno *et al.* 1990). Afterwards, the Nojima Fault was active at a shallow crustal level during the Cenozoic, with an average displacement rate of the order of 0.01–0.1 m/1000 year. In contrast, the 235 m reverse component of displacement along the Nojima Fault since the deposition of the Osaka Group sediments (1.8 Ma; Murata *et al.* 2001) indicates an average dip–slip displacement rate of approximately 0.15 m/1000 year. These values for the average displacement rate are commonplace for active faults in Japan (Research Group for Active Faults of Japan 1991).

BEHAVIOR OF FLUIDS IN THE FAULT ZONE

Core studies and whole-rock mineral analysis indicate that the depletion of mafic minerals occurred particularly in the fault breccia subzone along the Nojima Fault. The weakly deformed and altered rocks and fault breccia are typically reddish brown in color, which may be due to the formation of iron hydroxide minerals [FeO(OH)] such as goethite and lepidocrosite. Thus, these processes are thought to have proceeded under oxidizing conditions. This would have been possible at a very shallow level of the crust, where meteoric water penetrates and influences rock mineralogy (Evans *et al.* 1997). The general lack of carbonate minerals also suggests the influence of acidic meteoric water. In contrast, the fault gouge zones may have had a deoxidizing environment relative to the weakly deformed and altered rocks and the fault breccia, as evidenced by their pale green color (Fig. 3e). This may also be evidenced by the formation of smectite, as smectite precipitation requires a neutral rather than acidic fluid environment (Utada 1981). Oxygen seems to have been shut out by the very fine-grained and less permeable clay minerals, resulting in gradual deoxidation and changes in the color of the fault gouge layer, as seen in Fig. 3e. Considering the fact that: (i) the occurrence of oxidized rocks is similar to their occurrence at the Earth's surface; (ii) there is little evidence of oxidization and alteration in the footwall rocks, except those very close to the fault surface; and (iii) the fault zone is sampled at a shallow level in the crust, then the acidic water responsible for the dissolution and oxidization in the hanging wall was of meteoric origin and percolated along the fault zone in the hanging wall (Fig. 6a). Such percolation could have been possible in a fault zone with dense micro- and macrocracks (Chester & Logan 1986). At the same time, little acidic fluid flowed into the footwall sediments, suggesting that the mere 0.11 m-thick gouge layer of the Nojima Fault acted as a barrier to the fluid, as reported for faults elsewhere (Mino 1985; Wallace & Morris 1986). This flow regime during interseismic periods is regarded as an *in situ* counterpart by Evans *et al.* (1997), who concluded from core plug-scale permeability tests that fault

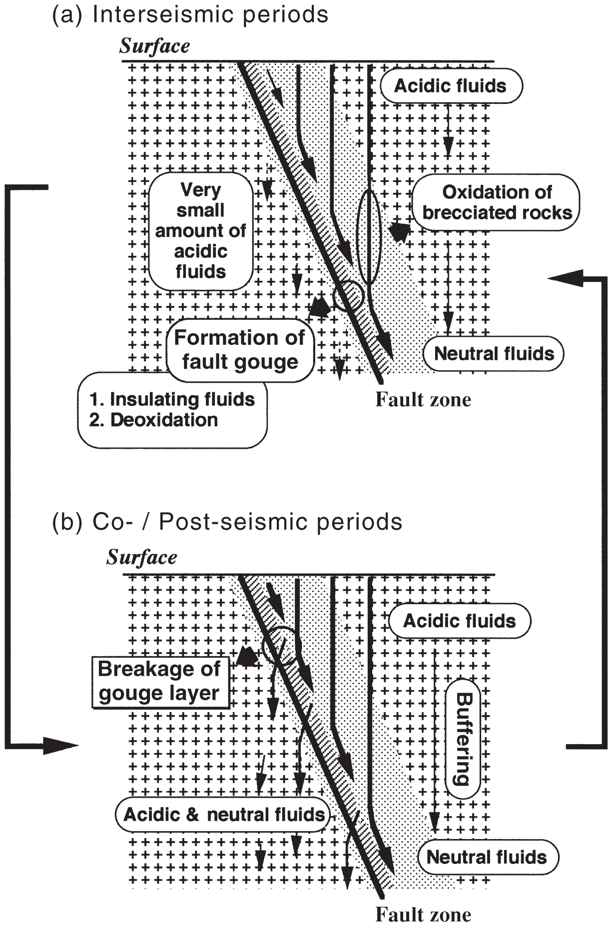

Fig. 6 Model showing fluid behavior in a brittle fault zone at a shallow level in the Earth's crust. Fluid behavior during (a) an interseismic period and (b) during a coseismic/postseismic period, is shown. Arrows on both sides of the figures show the cyclic occurrence of these processes.

zones with well-developed damage zones in the shallow crust can lead to an enhanced flow of fluid through a relatively thin tabular region parallel to the fault plane, whereas the fault core restricts fluid flow across the fault.

The flow regime for interseismic periods is apparently inapplicable to coseismic or postseismic periods, which is when fault gouge layers became broken and fluids in the hanging wall readily flowed into the footwall (Fig. 6b). In fact, the underground water level lowered on the mountain side at the hanging wall and waters came up from underground at the area of the footwall side of the Nojima Fault when the Hyogoken-Nanbu earthquake struck in this area, suggesting that water flowed through the fault zone (Tokunaga 1999). Footwall material was seen to be altered in cores obtained by the Geological Survey of Japan (GSJ; drilled depth of approximately 700 m; Tanaka *et al.* 1999; Fujimoto *et al.* 2001) and by the National Research Institute of Earth Science and Disaster Prevention (NIED; drilled depth of approximately 1140 m; Kobayashi *et al.* 2001; Matsuda *et al.* 2001), suggesting the influence of co- or postseismic inflows of water from the hanging wall. The brecciated rocks reacted with fluids and subsequently formed a new fault gouge zone. Again, the fault gouge zone kept fluids from flowing into the footwall so that only a little fluid was present in the footwall at some point after the earthquake. The fact that fault gouge was again fragmentated and incorporated into the fault breccia as shown in Fig. 3f implies that this process occurred repeatedly during the long history of activity of the Nojima Fault.

CONCLUSION

Based on the detailed petrography seen on the polished surfaces of Nojima Fault cores, there are four types of fault-related rocks present in the fault zone: (i) host rocks, which are characterized by slight alteration and with little apparent deformation; (ii) weakly deformed and altered rocks, which are characterized by altered mafic minerals, dense microcracks and microscopic, brittle shear zones; (iii) random fabric fault breccia with a matrix of fine-grained alteration products; and (iv) foliated fault gouge characterized by submillimeter-sized clasts and a matrix of clay minerals. Based on the relative presence of each of the four types of fault rocks, there are three subzones in the hanging wall of the Nojima Fault zone: (i) the unchanged to weakly deformed and altered subzone (>8.0 m wide); (ii) the weakly deformed and altered subzone (9.6 m wide); and (iii) the fault breccia subzone (5.3 m wide). They occur in this order from the margin of the fault zone to its center.

The degree of brecciation and alteration progressively increases inward toward the fault breccia subzone. These fault rocks are formed during four stages of fluid-enhanced deformation: (i) formation of intragranular microcracks and *in situ* alteration of mafic minerals and feldspars; (ii) formation of transgranular cracks and dissolution of mafic minerals, plus precipitation of their alteration products; (iii) brecciation by anastomosing networks of transgranular cracks, plus the precipitation of alteration products; and (iv) localized cataclastic flow within the fault gouge and the formation of clay minerals. The results described in the present study suggest that the Nojima Fault has been weakened by the combined effects of these four stages of brecciation and hydrothermal alteration.

The fault zone in the hanging wall is considered to be a zone of dissolution and oxidization, owing to the presence of acidic meteoric water at a shallow level in the crust. This condition resulted in petrochemical characteristics such as: (i) alteration of feldspars; (ii) dissolution of mafic minerals; (iii) absence of carbonate minerals; and (iv) precipitation of iron hydroxide minerals. In contrast, the condition in the fault gouge layer may have been deoxidising, with oxygen having been shut off by the very fine-grained and less permeable clay minerals. Little evidence of oxidization and alteration is recognized in the footwall.

In summary, the evolution of the Nojima Fault Zone is thought to have taken place as follows. During interseismic periods, meteoric and acidic fluids flowed and percolated down along dense micro- and macrocracks and dissolved mafic minerals in the hanging wall of the fault zone. Chemical reactions between brecciated rocks and fluids in the fault gouge layer resulted in the formation of smectite and the deoxidization of fault gouge materials. Only small amounts of acidic fluid flowed into the footwall rocks, which were mostly sealed by the thin layer of gouge along the Nojima Fault. However, this barrier of fault gouge was broken during coseismic or postseismic periods, and fluids in the hanging wall then readily flowed into the footwall, where rock materials were then altered. Brecciated rocks subsequently reacted with fluids and formed a new zone of fault gouge. This new fault gouge zone again prevented fluids from flowing into the footwall so that, eventually, only a small amount of meteoric fluid was present in the footwall following an earthquake.

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