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S–C fabrics developed in cataclastic rocks from the Nojima fault zone, Japan and their implications for tectonic history

Aiming Lin*

Department of Earth and Planetary Sciences, Faculty of Science, Kobe University, Rokkodai-cho 1-1, Nada-ku, Kobe 657-8501, Japan

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Abstract

S–C fabrics similar to those found in mylonites are observed in foliated cataclastic granitic rocks from the Nojima fault zone, southwest Japan. The foliated cataclastic rocks comprise cataclasite, fault breccia, gouge, and crushing-originated pseudotachylyte. The S–C fabrics observed in these cataclastic rocks involve S-surfaces defined by shape preferred orientation of biotite fragments or aggregates of quartz and feldspar fragments, and C-and C′-surfaces defined by microshears and shear bands, respectively, where fine-grained material is concentrated. Striations on the main fault plane are oriented parallel to the cataclasite lineations. A significant microstructural difference between the foliated cataclastic rocks and S–C mylonites is the absence of dynamically recrystallized grains in the foliated cataclasites. The striations, cataclastic lineations, and the S–C fabrics in the cataclastic rocks formed from the late Tertiary to the late Holocene indicate that the Nojima fault zone has moved as a dextral strike-slip fault, with a minor reverse component since it formed. S–C fabrics in cataclastic rocks provide important information on the tectonic history and are reliable kinematic indicators of the shear sense in brittle shear zones or faults.

1. Introduction

A number of studies during the past decade have described foliations in cataclastic rocks such as fault gouge (e.g. Chester et al., 1985; Chester and Logan, 1987; Evans, 1988; Kano and Sato, 1988; Lin, 1996, 1997a,b) and cataclasite (e.g. Kanaori et al., 1991; Chester et al., 1993; Evans and Chester, 1995; Lin, 1996, 1997b, 1999; Lin et al., 1998a,b; Chester and Chester, 1998). S–C fabrics similar to those found in mylonitic rocks have also been observed in foliated cataclasites and such rocks have been termed S–C cataclasites (Lin, 1999). Although there are many studies on deformational mechanisms and sense of shear in S–C mylonites formed in the ductile zone (e.g. Lister and Snoke, 1984; Simpson, 1985), only few studies have investigated shear sense criteria within cataclastic rocks that formed in brittle conditions (e.g. Chester and Logan, 1987; Lin, 1999). Furthermore, there are few studies on the tectonic history of active faults related to the deformational structures of cataclastic rocks.

The deformation processes and mechanisms of foliated granitic cataclasite have previously been discussed by Lin (1999). This paper focuses on the description of S–C fabrics developed in foliated granitic cataclastic rocks from the late Tertiary to late Holocene Nojima fault zone, southwest Japan. The relationship between the cataclastic lineations and slickenside striations is examined, as is their use for determining sense of shear and tectonic history of this active fault zone. The term S–C fabric, which was first proposed for mylonites by Berthe et al. (1979), and also applied to foliated cataclasites by Lin (1999), is used in this study.

2. Regional geology

The Nojima fault zone is located on the northern side of Awaji Island, at the eastern margin of the Eurasian plate and belongs to the inner zone of southwest Japan (Fig. 1). The basement consists of late Cretaceous to Paleocene granitic rocks (60–90 Ma) and the Eocene–Miocene Kobe Group (6–40 Ma), both unconformably overlain by the Plio-Pleistocene Osaka Group (0.37–2.6 Ma) and Quaternary alluvial and terrace deposits (Mizuno et al., 1990). The Kobe Group is composed mainly of sandstone, conglomerate, sandy mudstone, and thin intercalated lignite beds, whereas the Osaka Group is composed of weakly consolidated to unconsolidated sediment beds of silt-clay, sand, and gravel.

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* Present address. Institute of Geosciences, Faculty of Science, Shizuoka University, Ohya 836, Shizuoka 422-8529, Japan. Tel.: +81-54-238-4792; fax: +81-54-238-0491.

E-mail address: slin@ipc.shizuoka.ac.jp (A. Lin).

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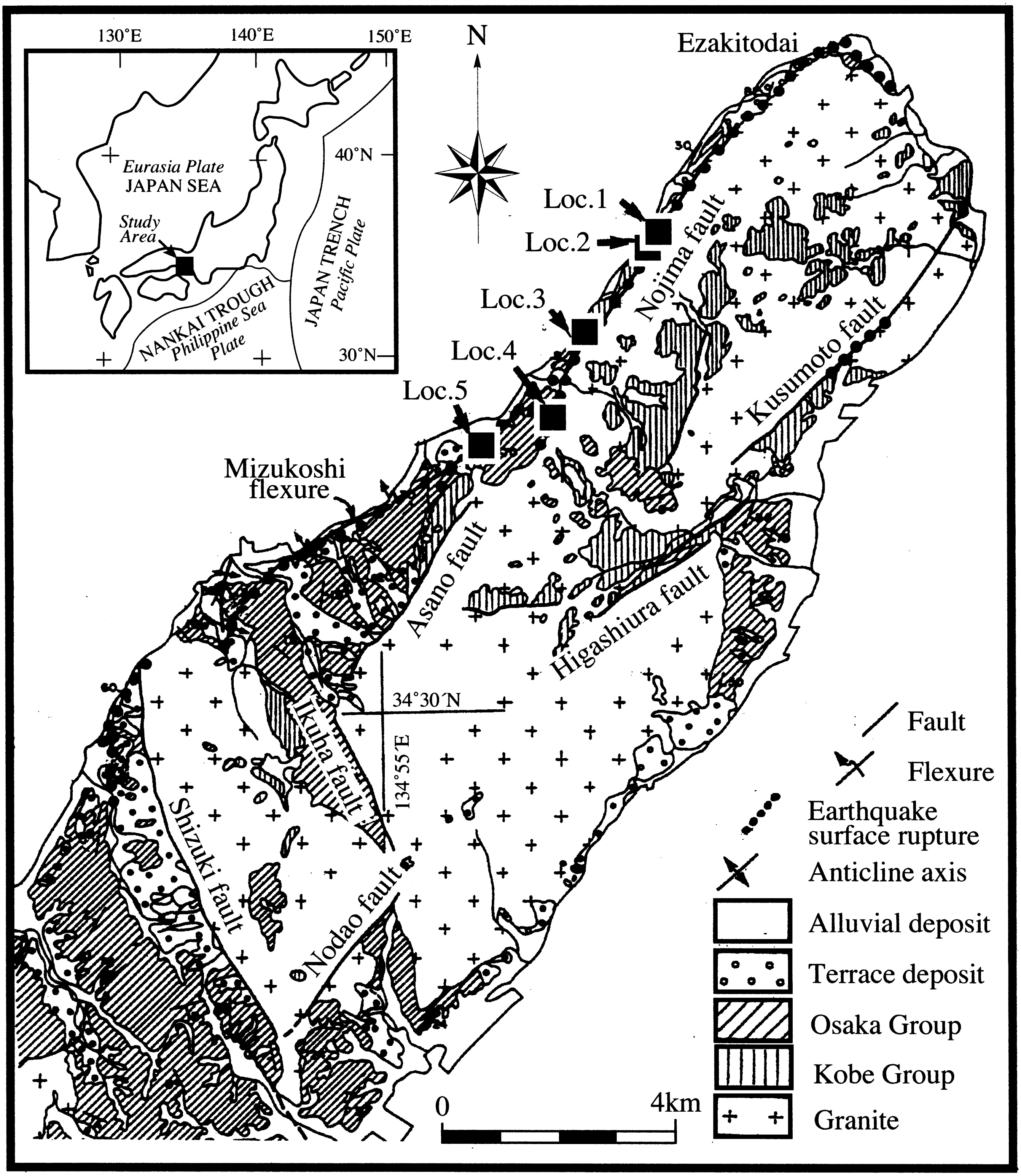

Fig. 1. Geological map of northern Awaji Island, Japan (modified from Mizuno et al., 1990; Lin and Uda, 1996). Locs. 1–5: main fault outcrops observed in this study.

There are many active faults in the study area, including the Nojima, Asano, Kusumoto, and Higashiura faults that strike NE–SW and dip 75–85°SE or NW, and the Ikuha and Shizuki faults that strike NW–SE (Fig. 1). All of these faults displace the Eocene–Pleistocene Kobe–Osaka Groups and the Quaternary alluvial deposits (Research Group for Active Faults of Japan, 1991). Surface ruptures formed during the 1995 $M = 7.2$ Southern Hyogo Prefecture earthquake (also

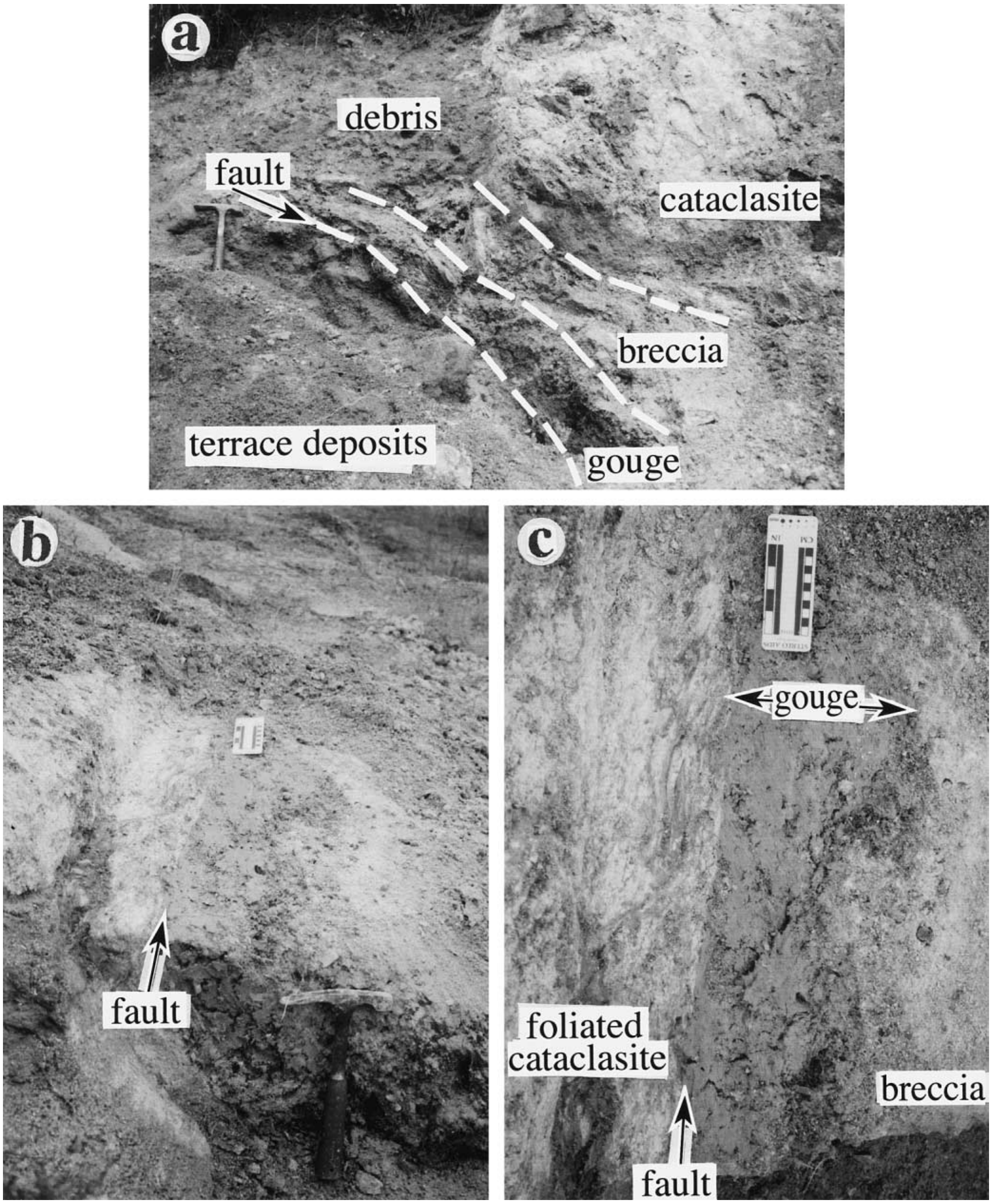

Fig. 2. Photographs of fault breccia, gouge zones and non-foliated cataclasites at Loc. 1 (a), and fault gouge zone bounded with foliated cataclasite at Loc. 4 (b,c). (c) is a close-up view of (b). Note that the cataclastic rocks were thrust over the terrace deposits. The fault gouge zone of (b,c) is 15–20 cm thick, and foliations are defined by color bending.

called the Kobe earthquake), mainly along the pre-existing Nojima fault, extends southwestward about 18 km and the Kusumoto fault for about 1.5 km (Lin and Uda, 1996; Lin, 1997b,c). The pre-existing Nojima fault striking N 20–60°E, dipping 75–85°SE, borders the western fringes of the northern Awaji mountains along the northwestern coastal line of Awaji Island (Fig. 1). The Nojima fault zone includes the pre-existing fault and the 1995 seismic surface rupture zone, and displaces the late Quaternary alluvial fans and terraces from a few meters to a few tens of meters both dextrally and vertically. Geological and geomorphological evidence constrains the average vertical and horizontal slip rates of this fault zone to be 0.4–0.5 and 0.9–1.0 mm/yr respectively (Mizuno et al., 1990; Research Group for Active Faults of Japan, 1991).

3. Description of fault rocks

The Nojima fault zone is distinguished from the undeformed granitic country rocks by an increased density of subsidiary faults and cracks. The zone is about 40–50 m wide in the hanging wall on the southeast side of the main fault plane where granitic rocks are thrust over the Osaka Group and the Quaternary alluvial deposits (Lin et al., 1998b). This fracture zone is also recognized in the hanging

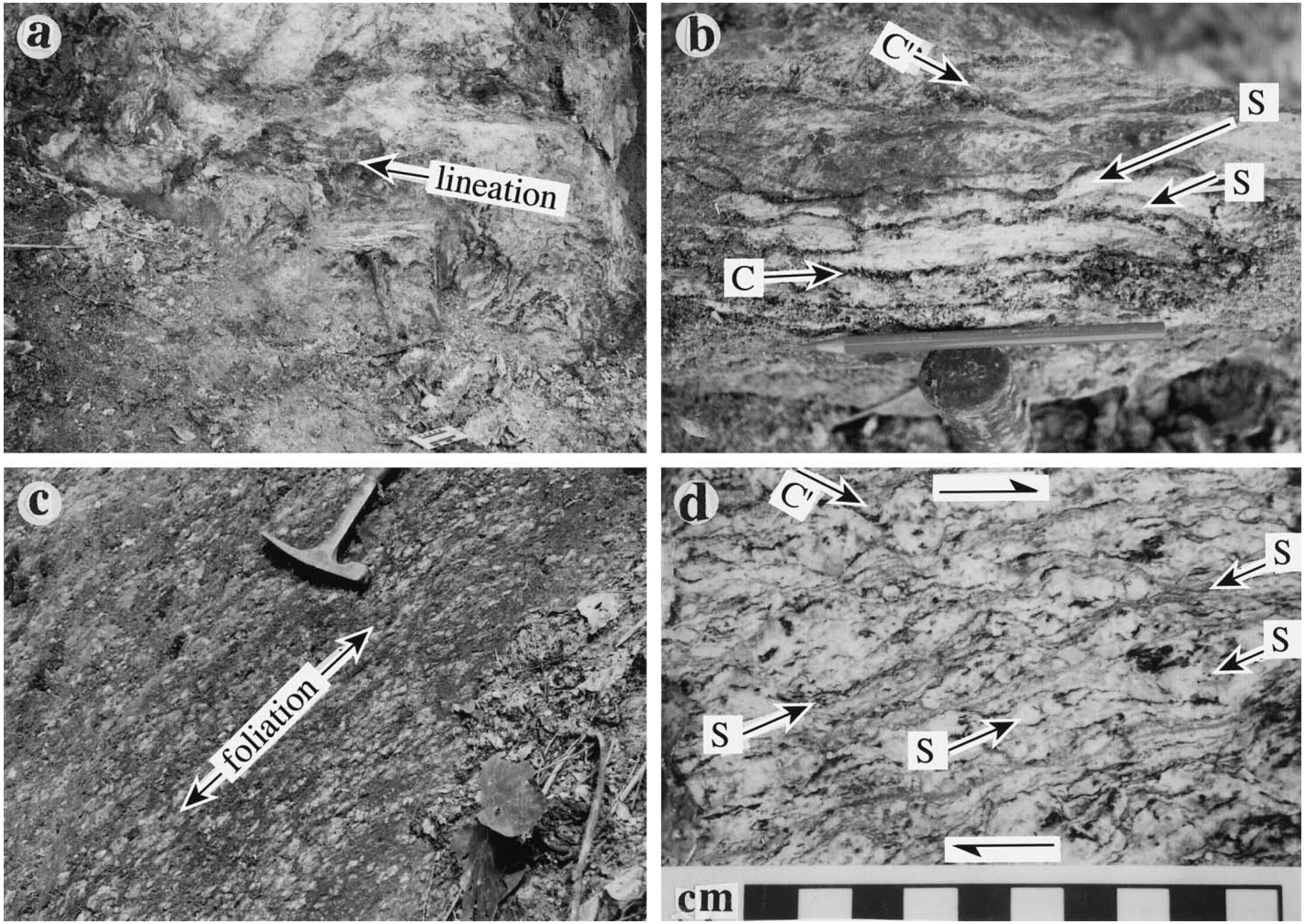

Fig. 3. Photographs of S–C foliated cataclastic rocks from Locs. 2 (a,b) and 4 (c,d). (d) is a polished hand sample *XZ* section. S, S-surface; C, C-surface; C$'$, shear bands which are developed in the Reidel shear R1 direction.

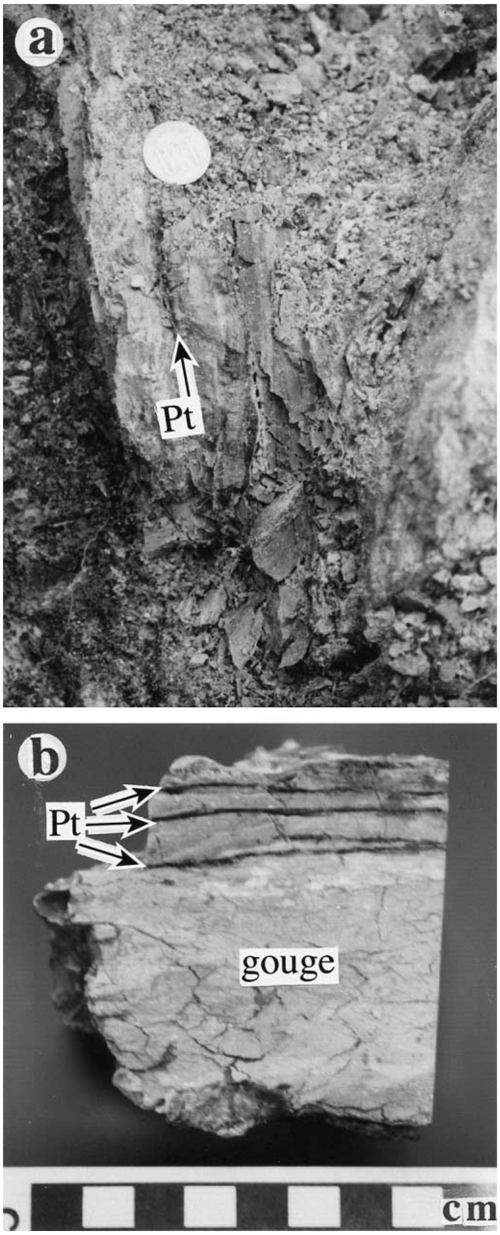

Fig. 4. Photographs of interlayered fault gouge and pseudotachylyte veins (Pt) at Loc. 1.

wall in drill cores that penetrate the fracture zone at a depth of about 500 m (Lin et al., 1998b), by seismic wave characteristics (Ouchi and Kikuchi, 1997), and electrical resistivity structures (Inokuchi and Yamaguchi, 1997) observed in profiles across the fracture zone. The fracture zone generally consists of cataclastic rocks such as cataclasite, foliated cataclasite, fault breccia, gouge, and crushing-originated pseudotachylyte (using the cataclastic rock terminology of Schmid and Handy, 1991). Away from the fracture zone, the granitic rocks are almost undeformed with rare visible cracks. The granitic wall rocks are medium-grained and largely composed of quartz, feldspar, biotite, and a little amphibole. The original fabrics of granitic rocks are preserved within the fragments in the cataclasites and fault breccia but cannot be observed in the fault gouge and pseudotachylyte.

The cataclasites are divided into nonfoliated and foliated cataclasites. The nonfoliated cataclasites occur over a wide area in domains bounded by fault gouge and breccia zones near the main fault plane (Fig. 2a) and far from the fault plane as regions within the host granitic rocks. The foliated cataclasites occur in a 5–20 m wide zone within the fracture zone, and are characterized by developed foliations that are parallel to sub-parallel to the main fault plane. The foliation is defined by variation in color, preferred orientations of clasts, and cataclastic shear bands (visible cracks) in outcrops (Figs. 2b and c and 3a–c). Porphyroclasts of quartz and feldspar are predominantly oriented sub-parallel to the fault plane, and can be observed at the outcrop and in hand sample (Fig. 3).

Incohesive fault breccia occur along the main and subsidiary faults in multiple narrow zones less than a few meters wide (Fig. 2a). The boundaries between the fault breccia and country rocks are generally sharp. The fault breccia is gray, brown to yellowish brown and is composed of angular to sub-angular fragments.

Fault gouge occurs along the main fault plane (Fig. 2) and subsidiary faults (Locs. 1–5, Fig. 1) and varies in thickness from a few cm to 20 cm. The boundary between the fault gouge and fault breccia and cataclasite is generally sharp (Fig. 2b and c).

Pseudotachylyte veins occur near the main fault plane, inter-layered with fault gouge, and range in thickness from a few hundred μm to a few mm (Fig. 4). Dark pseudotachylyte clasts are also included in the fault gouge layers. Pseudotachylyte veins are generally compact and aphanitic in appearance, dark-brown to black in color, and locally display a vitreous luster similar to that of glassy pseudotachylytes described by Lin (1994a,b). Petrologic and powder X-ray diffraction analyses show that these pseudotachylyte veins are composed mainly of finegrained clasts originated from the host granitic rocks (Lin et al., 1998b). This type of pseudotachylyte has previously been described from the Iida-Matsukawa fault in central Japan and have been termed crushing-originated pseudotachylyte (Lin, 1996, 1997a).

4. Cataclasite lineations and S–C fabrics

4.1. Striations and cataclastic lineations

A number of striations and grooves generated during the 1995 seismic event are recognized on the main fault plane (Fig. 5) at three main locations where the fault movement is well constrained by the displacement of surface markers such as roads, fences, terraces, and alluvial fans (Locs. 2, 3, and 5, Fig. 1). The striations generated on the pre-existing fault plane of the Nojima fault during the 1995 earthquake

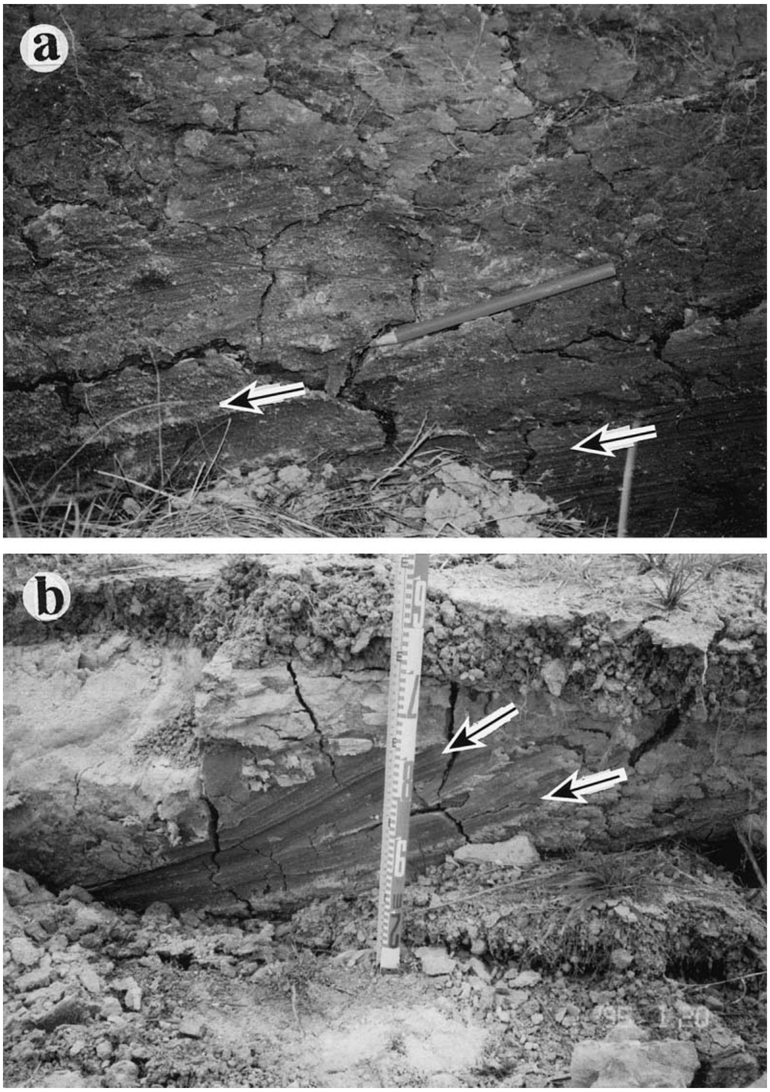

Fig. 5. Striations and slickensides generated during the 1995 Southern Hyogo Prefecture earthquake at Locs. 2 (a) and 5 (b). The pencil shown in (a) is oriented parallel to the striations, which plunge 10–30°NE. The visible clasts are concentrated on the streaks parallel to striations (a) and grooves (b) which defined the cataclastic lineations on the fault plane. Arrows indicate the plunge of the striations. Note that the fault scarp (b) generated during the 1995 earthquake is about 50 cm high.

in these three locations were generated on a thin layer of fresh fault gouge and marked by parallel lineations in the fine-grained materials, and grooves a few mm to several cm wide (Fig. 5). Locally, the striations display strong curvature with variable rakes on the fault plane. Slickensides with striations usually contain small steps oriented in a direction normal to the striations and are also used as an indicator of the shear sense. The striations were measured and plotted on the Schmid net as shown in Fig. 6. The striations plunge shallowly to the NE at all three locations on a fault plane that dips at ~80° to the SE. The striations and fault steps indicate a dextral displacement sense which is consistent with that indicated by the displacement of man-made and topographical features along the Nojima surface rupture zone (Lin and Uda, 1996).

Cataclastic lineations were also observed on the fault plane at Loc. 5, and exposed C-surfaces at Loc. 2 in the foliated cataclasite zone 10–50 cm from the main fault plane (Fig. 3a). Mistaken interpretation of tectonic conditions may arise if the cataclastic lineation is assumed to be parallel to the shear direction (Tanake, 1992). To avoid errors, all cataclastic lineations described here are observed on the C-surface as described by Lin and Williams (1992). The cataclastic lineations observed on the main fault plane (Fig. 7) are characterized by the alignment of clasts parallel to the striations similar to trailed material (TM) type slickenside indicators (Doblas, 1998). The cataclastic lineations have a mean plunge of 10–20°NE, sub-parallel to the striations observed at both locations (cf. Loc. 7 and Fig. 6a).

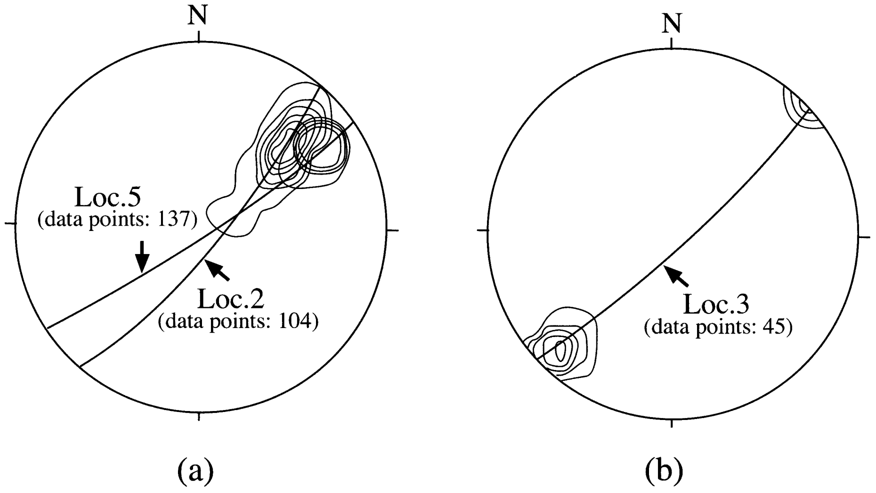

Fig. 6. Equal area stereographic projections of striations measured at Locs. 2, 5 (a) and 3 (b) (lower hemisphere, modified from Lin and Uda, 1996). Counters (per 1% area): 1, 10, 20, 30, 40, 50, 60%. Contouring method is based on the work of Davis and Reynolds (1996).

4.2. S–C fabrics in foliated cataclasite

To observe the textures, the *XY*, *XZ* and *YZ* planes of the finite strain ellipsoid were determined from the orientation of foliations and lineations within the shear zone at excavated sections. The fabrics were examined on *XZ* sections cut perpendicular to the foliations and parallel to the cataclastic lineations in the outcrops, hand samples, and thin sections. The exposed *XZ* sections dip 10–20°NE at Loc. 2 and 4. The typical fabrics are shown in Fig. 8a and b, which were drawn by tracing on the polished surface of hand samples. The foliated cataclasites are characterized by developed S–C fabrics, which are defined by variation in color, preferred orientations of fragments including mica 'fish' (S-surface), microshears (C-surfaces) and shear bands (C′-surfaces) (using the definition of Simpson and Schmid, 1983) which are developed in the Reidel shear R1 direction, at both meso- (Figs. 3 and 8) and microscale (Fig. 9b and c). On polished *XZ* sections of hand samples (Fig. 3d), transparent and light-gray fragments and aggregates of fine-grained clasts are oriented predominantly subparallel to the microshears (C-surfaces). These fragments or aggregates of fine-grained clasts are asymmetrically shaped, and indicate a dextral shear sense (Figs. 3b and 8). Dark-green to black mineral laminations composed of biotite wrap around the oriented fragments or aggregates of fine-grained fragments.

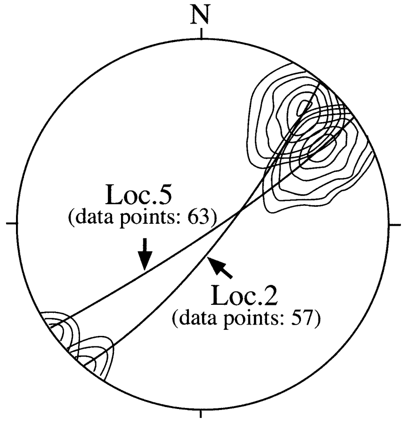

Fig. 7. Equal area stereographic projection of cataclastic lineations at Locs. 2 and 5 (lower hemisphere). Counters (per 1% area): 1, 3, 5, 7, 9, 11%. Contouring method is based on the work of Davis and Reynolds (1996).

The host granitic rocks are isotropic and generally undeformed, with only minor fracturing. The quartz, feldspar, and biotite crystals are randomly oriented. Under the microscope, the nonfoliated cataclasite shows a random fabric with fractured fragments ranging from a few tens to a few hundreds of μm in diameter (Fig. 9a). The randomly oriented fragments consist predominantly of quartz and feldspar, with minor biotite, and have an angular to subangular shape. The matrix of this cataclasite is commonly gray, dark gray or dark green in color and moderately indurated. Foliations observed under the microscope are defined by alignment of elongated biotite, preferred orientation of clasts, and fine-grained mineral aggregates (Fig. 9b and c). The fragments of quartz and feldspar consist of two textural types: (1) well-oriented fragments comprising single grains or grain aggregates which are asymmetrically shaped (S-surface) and (2) randomly oriented fragments of variable size. The proportion of fine-grained matrix to the fragments increases and is concentrated into the microshears (C-surface) or shear bands (C′-surface). Unlike the cataclastically deformed quartz and feldspar, most of biotite crystals have been elongated in the foliations and show mica 'fish' shapes similar to those of mylonites (Fig. 9b and c). The mica 'fish' fragments are usually linked by trails to the next biotite fragment, and therefore define the S-foliation, which indicate a dextral shear sense. The 'fish' trails' generally contain very fine-grained clasts and are linked by microshears (C-surface). These biotites are aligned subparallel to the oriented fragments or aggregates of

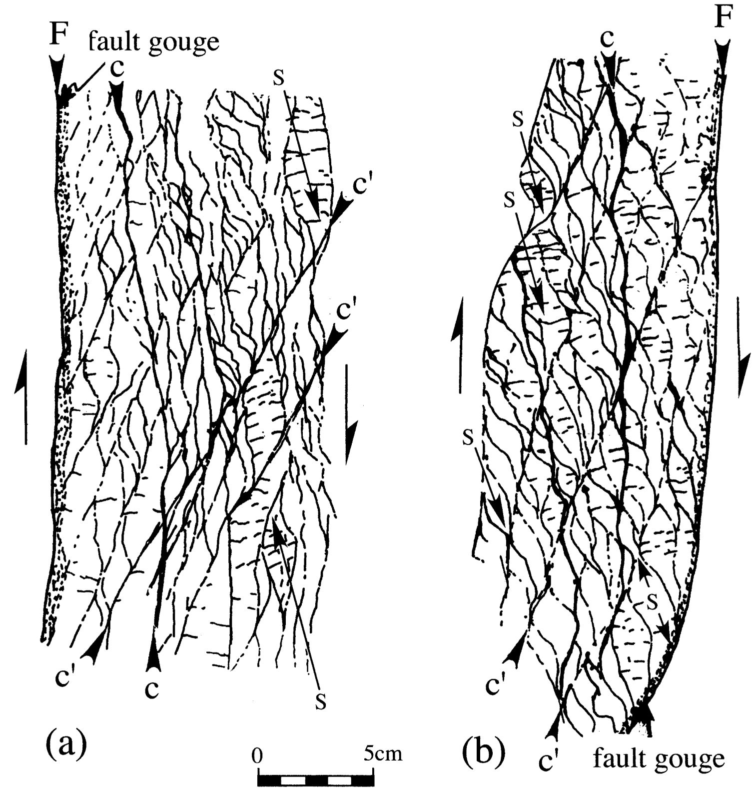

Fig. 8. Sketches of S–C fabrics observed on *XZ* sections in foliated cataclasites from Locs. 2 (a) and 4 (b). These sketches were drawn by tracing directly from the polished surface of hand samples.

fragments. The 'trails' of mica 'fish' and 'shadows' of asymmetrical fragments or aggregates (similar to pressure shadows observed in mylonites) are generally composed of very fine-grained clasts which also define the C-surfaces.

4.3. S–C fabrics in fault breccia and gouge zones

The textures of the fault breccia and gouge zones cannot be observed clearly in the outcrops. Oriented samples of fault breccia and gouge were taken from the fault scarps, which formed during the 1995 earthquake. Asymmetric textures and microshears or shear bands were also observed on the polished *XZ* sections of hand samples of fault breccia and gouge (Fig. 10). In one gouge sample, an asymmetrically-shaped vein of carbonaceous material that originated from grass roots yielded a ^{14}C dating age of 8265 ± 150 yr BP (Code no: Gak-18647) and is parallel to the foliations of the gouge zone (Fig. 10a). This indicates that the asymmetric fabric formed at shallow depth near the surface in the Holocene. In order to avoid the local variation in preferred orientation of fabric elements, large thin sections ($\sim 6 \times 10$ cm^2) covering the entire fault gouge zone were prepared to observe fabrics within this zone. Fault gouge is generally gray to yellowish-brown in plane-polarized (PPL) light and gray-brown to dark-brown in cross-polarized light (CPL). Foliations similar to those observed in the foliated cataclasites are observed on *XZ* sections (Fig. 11). The S-surfaces are characterized by aggregates of rigid quartz and feldspar clasts. The C-and C′-surfaces are defined by the fine-grained matrix material (Figs. 10 and 11). Mica fragments cannot be recognized under the microscope. The principal microstructural difference between the foliated cataclasite and the fault gouge is the absence of oriented biotite fragments in the fault gouge zone. Most of the clasts are angular to sub-angular in shape. These aggregates of clasts have asymmetric shapes, similar to asymmetric porphyroclasts with pressure shadows observed in mylonites (Fig. 11a). The core part of the asymmetric aggregate generally consists of a larger clast and the 'pressure shadows' are filled by fine-grained material (Fig. 11). The asymmetrical textures of the fault gouge indicate a dextral shear sense (Figs. 10 and 11), which coincides with that indicated by the S–C fabrics observed in the foliated cataclasites as described earlier.

5. Discussion and conclusions

5.1. Relationship between striations and cataclastic lineations and S–C fabrics as shear sense indicator

The relationship between slickenside striations and cataclastic lineations can be of major importance to decipher the shear sense of fault zones and interpret the

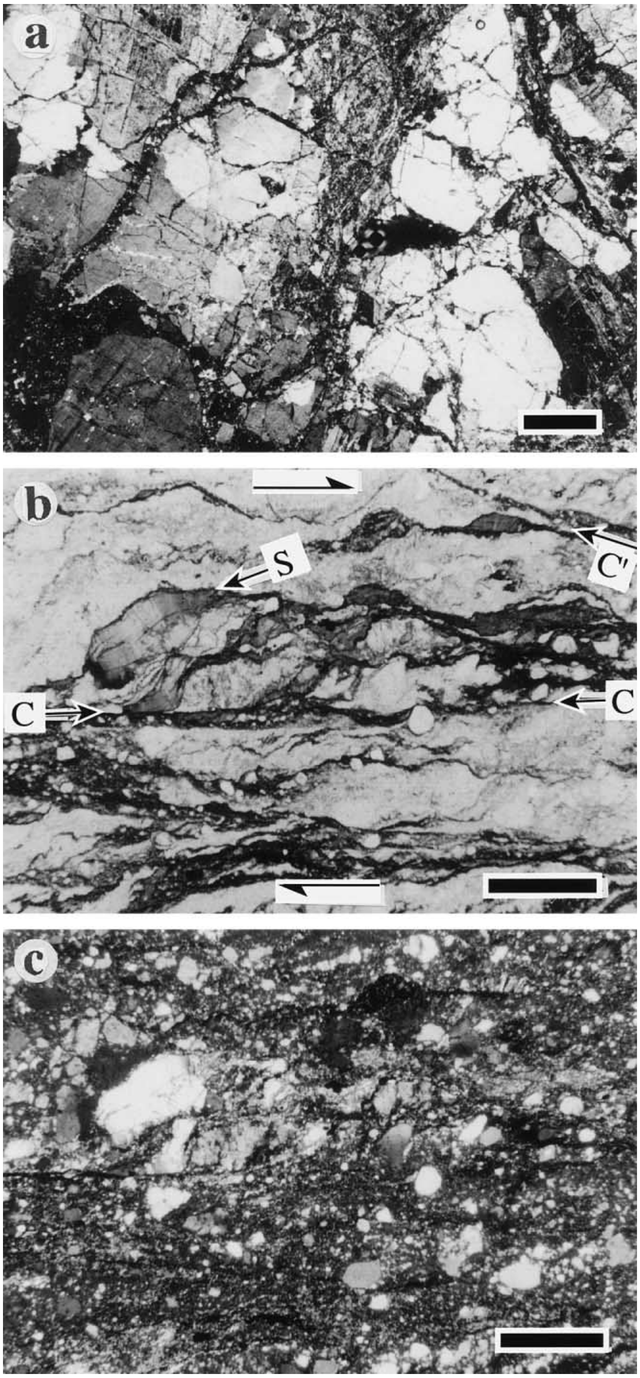

Fig. 9. Photomicrographs of microstructures within nonfoliated cataclasite (a) and foliated cataclasite (b,c) from Loc. 4. The foliations are defined by dark-brown layers, microshears (C-surfaces), shear bands (C′-surfaces) (a), and asymmetric fragments or aggregates of fragments (b,c). All other rock-forming minerals were cataclastically-deformed except the biotites. Large arrows indicate the shear sense; cross polarized light; (b): PPL of (c). Scale bars are 250 μm.

tectonic conditions under which they formed. Slickenside striations are generally produced by frictional abrasion along the fault surface during differential displacement of wall rocks. Striations with a strong preferred orientation on the fault plane generally indicate the shear direction of the fault during the formation of the striations (Davis and Reynolds, 1996). Tanaka (1992) reported that the shear direction indicated by cataclastic lineations in foliated cataclastic rocks of the Akaishi Tectonic Line (ATL), Japan, is inconsistent with that indicated by slickenside striations. Based on this difference, Tanaka concluded that the lineations and striations are not kinematically related and are formed at different times and tectonic conditions. In this study, the orientation of striations measured on the main fault plane of the Nojima fault zone is found to be similar to that of the cataclastic lineations in the cohesive foliated cataclasite and incohesive fault gouge. Geological and geomorphological evidence suggests that there is a cumulated horizontal displacement in the Cretaceous basements and the Holocene terrace and alluvial deposits along the Nojima fault zone (Mizuno et al., 1990). This indicates that the fault has moved as a strike-slip fault since the late Tertiary. This coincidental orientation of the striations and cataclastic lineations indicates a main horizontal displacement sense which is consistent with that indicated by the geological and geomorphological evidence. This, in turn, suggests that the fault has had a consistent displacement history since the late Tertiary. This shows that the statistical data of the striations on the fault plane can be used to determine the sense of the movement displacement. Generally, fault surfaces are rough where there are a lot of hard asperities. When asperities break off, they can break into pieces of hard debris that float along the fault surface and create ‘tails’ and ‘spiles’ and other microridges of material (Means, 1987). That the cataclastic lineations are created by scratching and furrowing and remained on the fault planes indicate a shear direction parallel to that of striations and shows that both the cataclastic lineations and the striations are reliable indicators of the shear sense along the Nojima fault zone.

S–C relationships in mylonitic rocks are generally used to determine the sense of shear of ductile shear zones (e.g. Berthe et al., 1979; Simpson and Schmid, 1983; Lister and Snoke, 1984). In the past decade, it has also been recognized that cataclastic rocks such as fault gouge, fault breccia and cataclasites that contain S–C fabrics similar to those of mylonites provide reliable shear sense indicators in brittle shear zones (e.g. Chester et al., 1985; Lin, 1997b, 1999). Foliated cataclastic rocks are characterized by well developed S–C fabrics which are defined by variation in color, preferred orientations of fragments including mica ‘fish’ (S-surfaces), microshears (C-surfaces), and shear bands (C′-surfaces) at both the meso- and microscales as shown earlier. The S-foliation, for example, may result from the preferred orientation of platy minerals due to mechanical rotation of rigid, inequant grains by cataclastic flow on a fine-scale, particularly in clay-rich gouge (Chester et al., 1985; Rutter et al., 1986). The S-foliations found in this study are defined mainly by the orientation of rigid fragments or aggregates and asymmetrical biotite ‘fish’ and dragged biotite fragments. The C- and C′-surfaces are

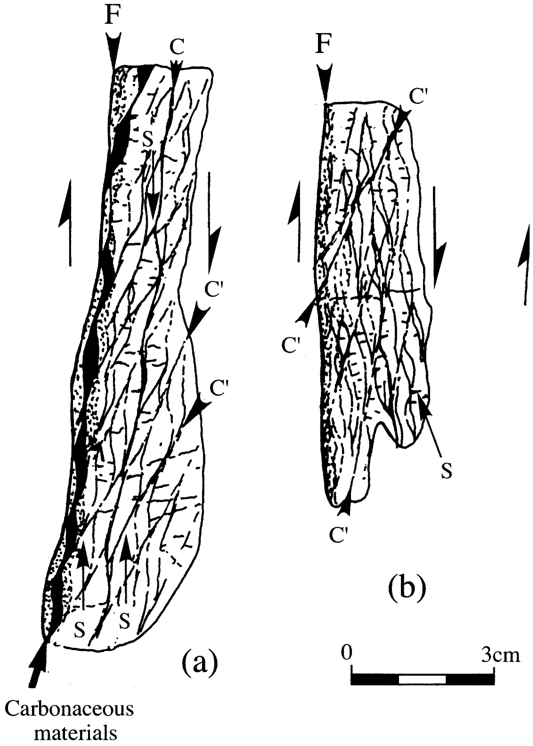

Fig. 10. Sketches of S–C fabrics observed on the *XZ* sections in fault gouge from Locs. 3 (a) and 2 (b) and breccia from Loc. 3 (c). The dark areas shown in (a) are composed of carbonaceous materials, derived from grass roots, and yield a ^{14}C age of 8265 ± 150 yr BP. These sketches were drawn by tracing directly from polished surfaces of hand samples.

mainly characterized by microshears and shear bands filled by aggregation of very fine-grained materials. Based on the microstructural characteristics, it is documented that the biotite 'fish' contained in the foliated cataclasite deformed by a combination of brittle-plastic shear processes, and quartz and feldspar underwent brittle deformation (Lin, 1999). Microstructurally, one of the most significant differences between mylonitic rocks and foliated cataclastic rocks is the absence of dynamically recrystallized grains in the foliated cataclasite. Chester and Logan (1987) inferred the shear sense from the asymmetric structures in fault gouges from the Punchbowl fault that coincides with those determined from the structures in the host rocks. Kano and Sato (1988) show a consistent shear sense between those inferred from the foliated gouges and geological evidence from the Sakai-toge and Narai faults. Tanaka (1992) studied catalastic lineations developed in foliated cataclastic rocks and applied them to infer the sense and direction of shear of the ATL, central Japan. The S–C fabrics including the slickenside striations observed in the foliated cataclastic and fault gouges in this study clearly indicate a dextral strike-slip shear sense with a minor reverse component in the Nojima fault zone which coincides with the known shear sense indicated by the cumulated dextral displacement along the fault (Mizuno et al., 1990) and displacement of surface markers generated during the 1995 seismic surface rupture zone (Lin and Uda, 1996; Lin, 1997c). These studies demonstrate that the shear senses inferred from foliational cataclastic fabrics coincide with those indicated by geological and geomorphological evidence, and that the foliational fabrics of cataclastic rocks are reliable indicators of shear sense of brittle shear zones of faults.

5.2. Tectonic history of the Nojima fault zone

Fault rocks that formed at different levels in the crust become gradually uplifted and exposed, resulting in exposure within the fault zone of a variety of fault rocks formed under different conditions (Scholz, 1990). It is possible, therefore, to understand the deformational process throughout the faulting history by studying the structures in fault rocks exposed at the surface. Cataclasite is generally considered to form at depths >5 km, and fault breccia and gouge form at shallow depths <5 km (Sibson, 1977). The coexistence of cataclasites, fault breccia and gouge in the Nojima fault zone indicates that fault movement continued during the formation of cataclastic rocks. Based on the coexistence of dominantly plastically-deformed biotite and cataclastically-deformed quartz and feldspar, it is suggested that the foliated granitic cataclasite formed at temperatures between 150 and 250°C, corresponding to depths of 5–8 km at a geothermal gradient of 30°C/km (Lin, 1999). It was reported that the Cretaceous–Paleocene granitic rocks and Eocene–Miocene Kobe Group were displaced vertically 490–540 m in both sides of the Nojima fault (Murata et al., 2001). This suggests that the fault formed later than

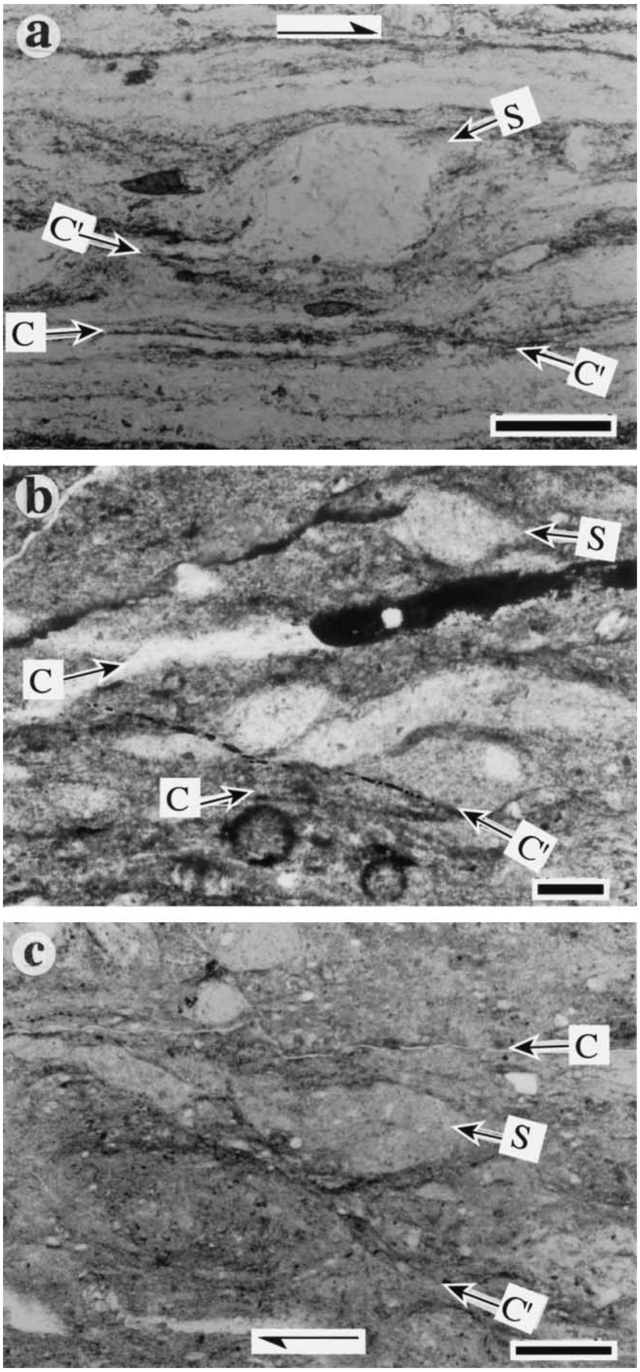

Fig. 11. Photomicrographs of microstructures within fault gouge sampled at Locs. 3 (a), 2 (b) and 5 (c). Foliations are defined by microshears (C-surfaces) and shear bands (C'-surfaces) as well as asymmetric fragments and aggregates of fragments (S-surfaces) which indicate a dextral shear sense. (a–c): PPL. Large arrows indicate the shear sense. Scale bars are 250 μm.

the Miocene. Because *XZ* sections dip 10–20°NE, the net vertical displacement component on the Nojima fault is estimated to be about one third of the horizontal displacement. This proportion between the vertical and horizontal displacements coincides with that of the 1995 seismic surface rupture zone along the pre-existing Nojima fault (Lin and Uda, 1996). The total horizontal displacement of the Nojima fault zone, therefore, is estimated to be greater than 1.5 km. The average horizontal slip rate of the Nojima fault is 0.9–1.0 mm/yr (Mizuno et al., 1990), therefore, it is suggested that > 1.5 km displacement has accumulated during the past 1.5–2.0 Ma. The average uplift rate in the Rokko-Awaji area is estimated to be about 2.5 mm/yr during the past 2 Ma (Lin, 1999). This means that 2 Ma of uplift is required to expose the cataclasites formed at depths of 5–8 km. These arguments support the previous conclusion that the Nojima fault zone has moved continuously from the late Tertiary to the Holocene. Foliated carbonaceous material included in the fault gouge zone yielded an age of 8265 ± 150 yr BP indicate that there is at least one seismic fault event occurring in the Holocene, which has a dextral shear sense. The S–C fabrics developed in the foliated cataclasite and fault gouge indicate that the Nojima fault zone was formed before the Quaternary and has moved as a right-lateral strike-slip fault with a minor reverse component since it formed.

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