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Cataclastic lineations

HIDEMI TANAKA

Institute of Earth Science, School of Education, Waseda University, Shinjuku, Tokyo 169-50, Japan

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Abstract—This paper describes a stretching lineation developed on the *S*-foliations of cataclasites and fault gouges from the Akaishi Tectonic Line (ATL), central Japan. The lineation is called a 'cataclastic lineation', and appears to result from homogeneous laminae flow of cryptocrystalline matrix clay minerals and the preferred orientation of fractured porphyroclasts. Slickenlines overprint these textures forming cataclastic lineations. These two kinds of linear structures are developed at large angles to one another.

The orthogonal projection of the perpendicular of the intersection of *S*-foliations, *C*-surfaces and R_1 shears (B-axis) onto the *C*-surface, which defines the shear direction, is parallel to the orthogonal projection of cataclastic lineation on the *C*-surface. In addition, planes cut parallel to the cataclastic lineation and perpendicular to the *C*-surface show distinctive asymmetric structures indicating left-lateral shear, which coincides with the main fault movement of the ATL as defined by displacement of tectonic units, *S–C*-surfaces and R_1 shears. In contrast, planes parallel to the slickenlines and perpendicular to the *C*-surface show no asymmetric fabrics. Thus, cataclastic lineations are considered to indicate the shear direction of the ATL during formation of the cataclasites, whereas the slickenlines indicate shear directions of later, superficial movements along the ATL which have no relationship to the main shear direction.

INTRODUCTION

FAULT rocks commonly display asymmetric structures which indicate the shear direction and the shear sense of fault movement. In the case of fault rocks formed by plastic flow, such as mylonites, the shear direction may be defined by a stretching lineation (Simpson & Schmid 1983). Cataclasites and fault gouges, which are formed by brittle shear, have long been regarded as having only random fabrics (Higgins 1971, Engelder 1974, Sibson 1977, Takagi 1982) and having no structures directly indicative of the shear direction. However, foliations and asymmetric structures have recently been identified in fault gouge (Logan *et al.* 1981, House & Gray 1982, Chester *et al.* 1985, Rutter *et al.* 1986, Chester & Logan 1987). In these studies, the shear direction of the fault was already determined from other information such as subsidiary faults and slickenlines in the host rocks (Rutter *et al.* 1986, Chester & Logan 1987, Tanaka & Hara 1990).

Generally, the formation of cataclasites and fault gouges with foliations and asymmetric structures represents pervasive deformation on the mesoscopic and microscopic scales (Chester *et al.* 1985, Chester & Logan 1987). The penetrative deformation leads to ductile shear, and should produce stretching lineations analogous to those in mylonites.

This paper describes cataclasites and fault gouges from the Akaishi Tectonic Line (ATL), central Japan. Many specimens of cataclasites and fault gouges described here have foliations and asymmetric structures. These fault rocks also contain stretching lineations, and their relationship to the shear direction can be investigated. The terminology and classification used for the fault gouges and cataclasites are shown in Table 1.

Table 1. Classification of the cataclasite series (partly modified after McClay 1987). Foliated fault gouge (1) and foliated cataclasite (2) are called 'fault gouge' and 'cataclasite', respectively, in this paper

Tectonic grain size reduction			
Criteria		Random – Fabric	Foliated
Incohesive	Vol. % of porphyroclasts 30% <	Fault breccia	Foliated fault breccia
	Vol. % of porphyroclasts 30% >	Fault gouge	Foliated fault gouge (1)
Cohesive	Glass/devitrified glass	Pseudotachylite	Foliated pseudotachylite
	Vol. % of porphyroclasts 30% <	Microbreccia	Foliated microbreccia
	Vol. % of porphyroclasts 30% >	Cataclasite	Foliated cataclasite (2)

GEOLOGICAL SETTING

The Akaishi Tectonic Line (ATL) runs along the western margin of the Akaishi Mountains, central Japan, and is one of the largest faults in the eastern part of southwest Japan (Fig. 1). The ATL was probably activated during the Neogene and accounts for approximately 40 km of left-lateral displacement, although minor normal and reverse slip have probably occurred

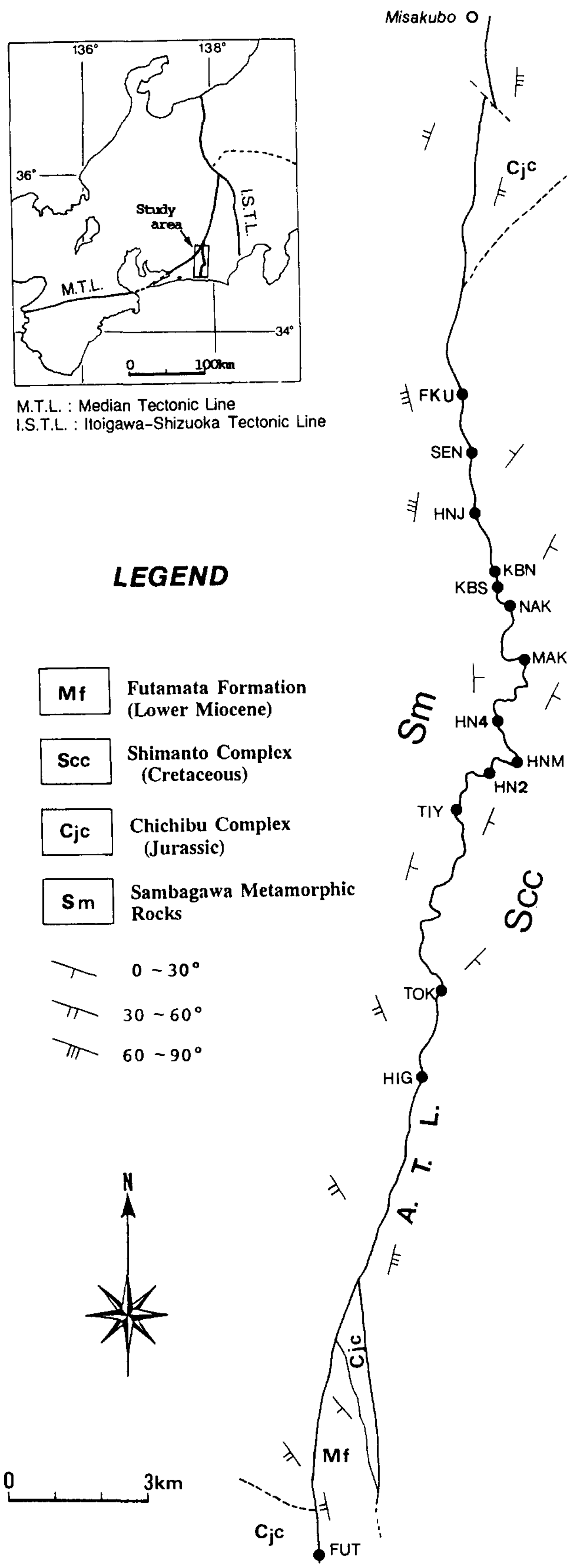

Fig. 1. Simplified geological map along the Akaishi Tectonic Line, central Japan. Solid circles indicate outcrops where specimens of fault gouges and cataclasites were obtained. FKU, Fukusawa; SEN, Sendo; HNJ, Hanjisawa; KBN, Kabakikita; KBS, Kabakiminami; NAK, Nakosawa; MAK, Makinosawa; HN4, fourth branch of Hangaresawa; HNM, Main stream of Hangaresawa; HN2, second branch of Hangaresawa; TIY, Chiyonosawa; TOK, Tokuradani; HIG, Higashiunna; FUT, Futamata.

locally after the main strike-slip movement (Saito & Isomi 1954, Kimura 1961, Matsushima 1973, Kano 1988, Tanaka *et al.* 1989).

The ATL strikes approximately N–S, and dips vertically in the southern and northern sections, whereas in the middle section it dips shallowly to the east. The ATL joins the Median Tectonic Line (M.T.L. in Fig. 1) to the north and is covered by alluvium to the south. It juxtaposes the Jurassic and the Cretaceous subduction complexes of the Chichibu and the Shimanto terranes to the east and the Cretaceous crystalline schists of the Sambagawa Terrane and the complex of the Chichubu Terrane to the west (Kimura 1961) (Fig. 1).

The Miocene Futamata group is distributed near the southern end of the ATL and consists of an interbedded sequence of conglomerate, sandstone and mudstone, which was deposited in a wedge shaped graben formed at the southern end of the ATL (Fig. 1) (Makiyama 1934).

DESCRIPTION OF THE CATACLASITES AND FAULT GOUGES

General remarks on mesoscopic scale

Within the study area, cataclasites and fault gouges of the ATL are exposed at over 20 locations along the ATL. The fractured zone is about 15 m wide on both sides of the ATL, and is characterized by cataclasite and fault gouge. The fractured zone is distinguished from the undamaged zone based on a relatively high density of subsidiary faults, although the boundary between the zones is gradational. The cataclasites are derived primarily from pelitic schists of the Sambagawa metamorphic complex, mudstones of the Shimanto Complex, the Chichibu Complex and the Futamata Group.

The matrix of the cataclasites is commonly black, dark brown or dark green in color and moderately indurated. Well developed *S*-foliations, subparallel to the fault plane of the ATL, are defined by variation in color and preferred orientations of porphyroclasts. Quartz segregation veins up to 10 cm in width are typically intercalated parallel to the foliation. Veins are fractured, and fracture density increases towards the axial part of the cataclasite zone where segregation veins are brecciated to yield porphyroclasts of quartz (Fig. 2a). Most porphyroclasts range from 1 mm to 10 cm in diameter with the maximum size being 20 cm.

Fault gouges, up to 2 m in width, are developed along the axial part of the fractured zone only at the locations FKU, SEN and MAK in Fig. 1. They consist of a dark brown, poorly indurated matrix of clay minerals and quartz porphyroclasts. Porphyroclasts are rounded in shape, commonly 2 mm to 2 cm, rarely as large as 10 cm in diameter. *S*-foliations are defined by color banding in the matrix and by the preferred orientation of porphyroclasts (Fig. 2b). The abundance, mean size and crack density of the porphyroclasts in the fault gouge are less than those in the cataclasite.

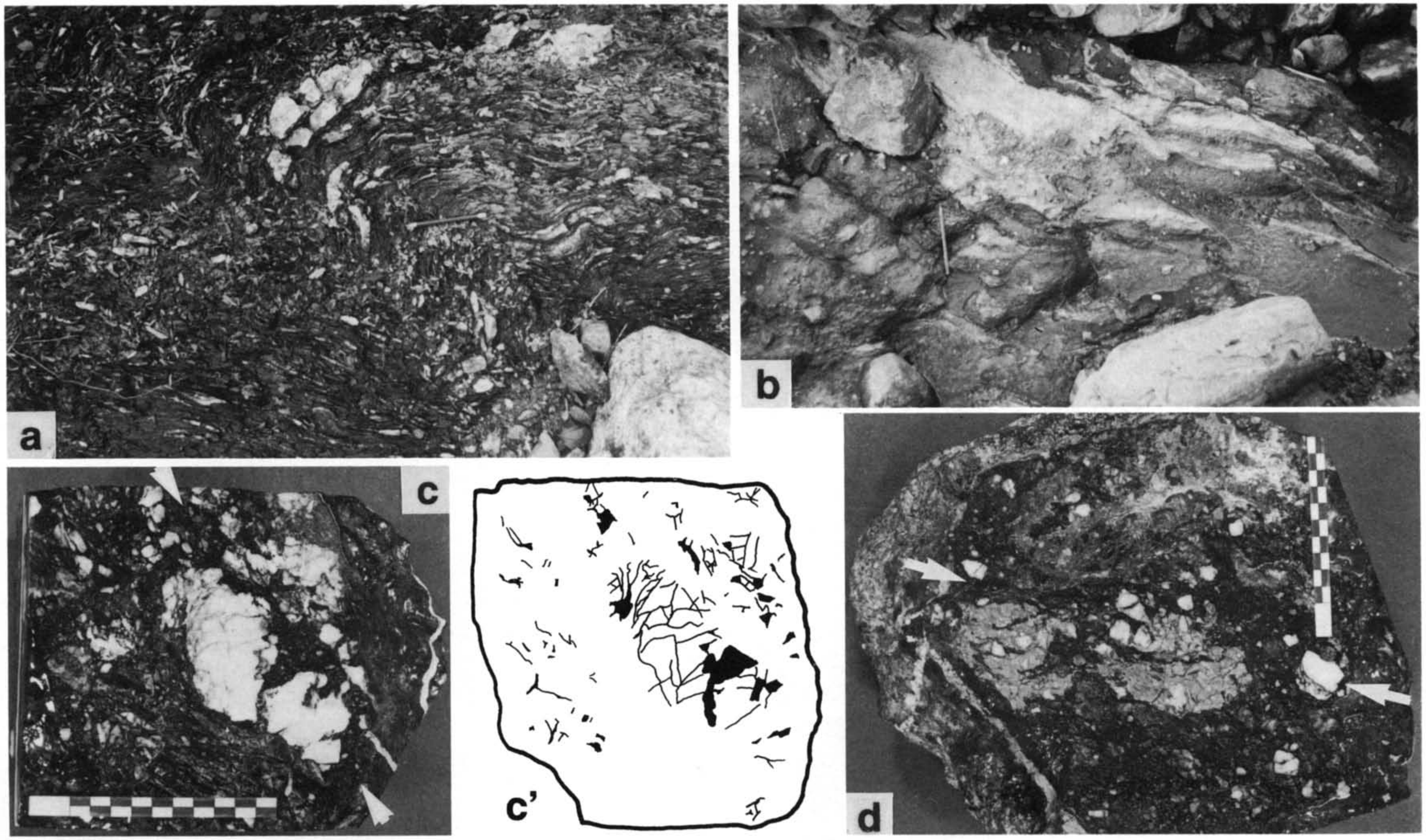

Fig. 2. Photographs of the fault rocks along the ATL and of polished *S*-surfaces of cataclasite and fault gouge. (a) Field photograph: cataclasite zone. Pencil scale 10 cm. (b) Field photograph: gouge zone. Pencil scale 10 cm. (c) Hand specimen of cataclasite (KBN-1). Bar scale 1 cm. (c') Line of drawing of (c) showing cracks developed in porphyroclasts. (d) Hand specimen of fault gouge (SEN-2). Bar scale 1 cm. Arrows in (c) and (d) indicate alignment of long axes of the porphyroclasts.

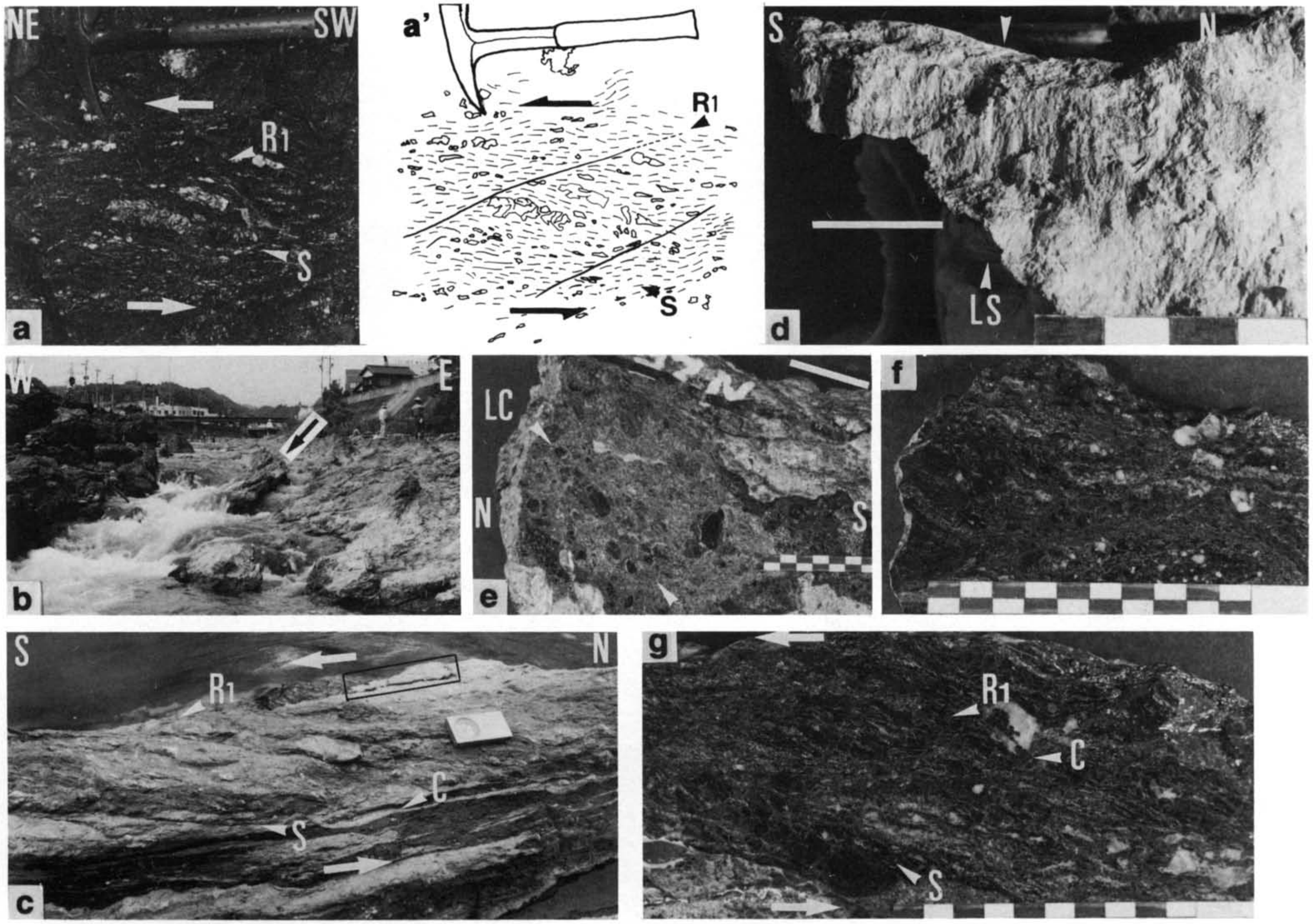

Fig. 3. Structures developed in cataclasites. Scale bars are 1 cm. (a) Asymmetric structures showing left-lateral shear in outcrop at location HNM. The hammer used for scale is 30 cm. (a′) Sketch of (a). (b) Fault outcrop at location FUT. Fault surface (arrow) dips moderately to the west. (c) Asymmetric left-lateral shear pattern at the point shown by an arrow in (b). The compass for a scale is 10 cm. Arrows indicate sense of shear. Labels S, C and R1 are *S*-foliation, *C*-surface and R_1 shear surface, respectively. (d) Close up of an area marked by rectangle in (c). Note slickenlines (LS) subparallel to the dip of the fault plane. The surface of the photograph is parallel to the fault plane moderately dipping to the west. N, north; S, south. White bar indicates the horizontal line. (e) Cataclastic lineations (LC) gently plunging to the south. Specimen from location FUT. The surface of the photograph is parallel to the fault plane (*S*-foliation). White bar indicates the horizontal line. N, north; S, south. (f) The surface cut parallel to the slickenline and perpendicular to the *C*-surface. Specimen from location FUT. Note that no asymmetric structures caused by shearing are observed. (g) The same specimen as (f) cut parallel to the cataclastic lineation and perpendicular to the *C*-surface. Note that distinctive shear patterns indicative of left-lateral shear are observed. Arrows indicate sense of shear.

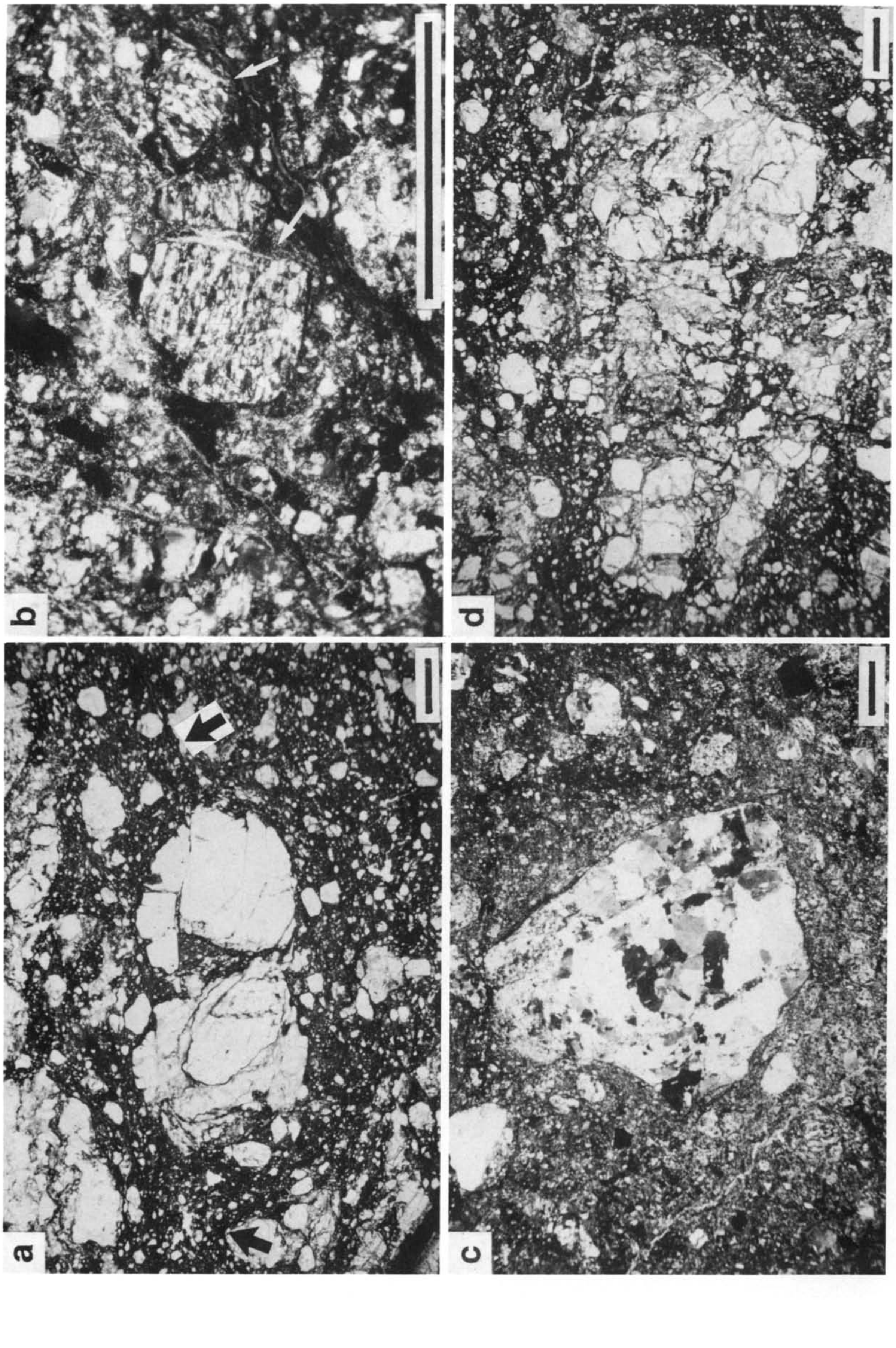

Fig. 4. Photomicrographs of *S* thin-sections. (a) Fluxion structure around the porphyroclast. Arrows indicate tails. (b) Porphyroclasts derived from schist (arrows). (c) Porphyroclast derived from the segregation vein (center). (d) Quartz porphyroclasts with filled fractures. Long axis of the broken porphyroclast may indicate stretching direction. Scale bars are 0.5 mm.

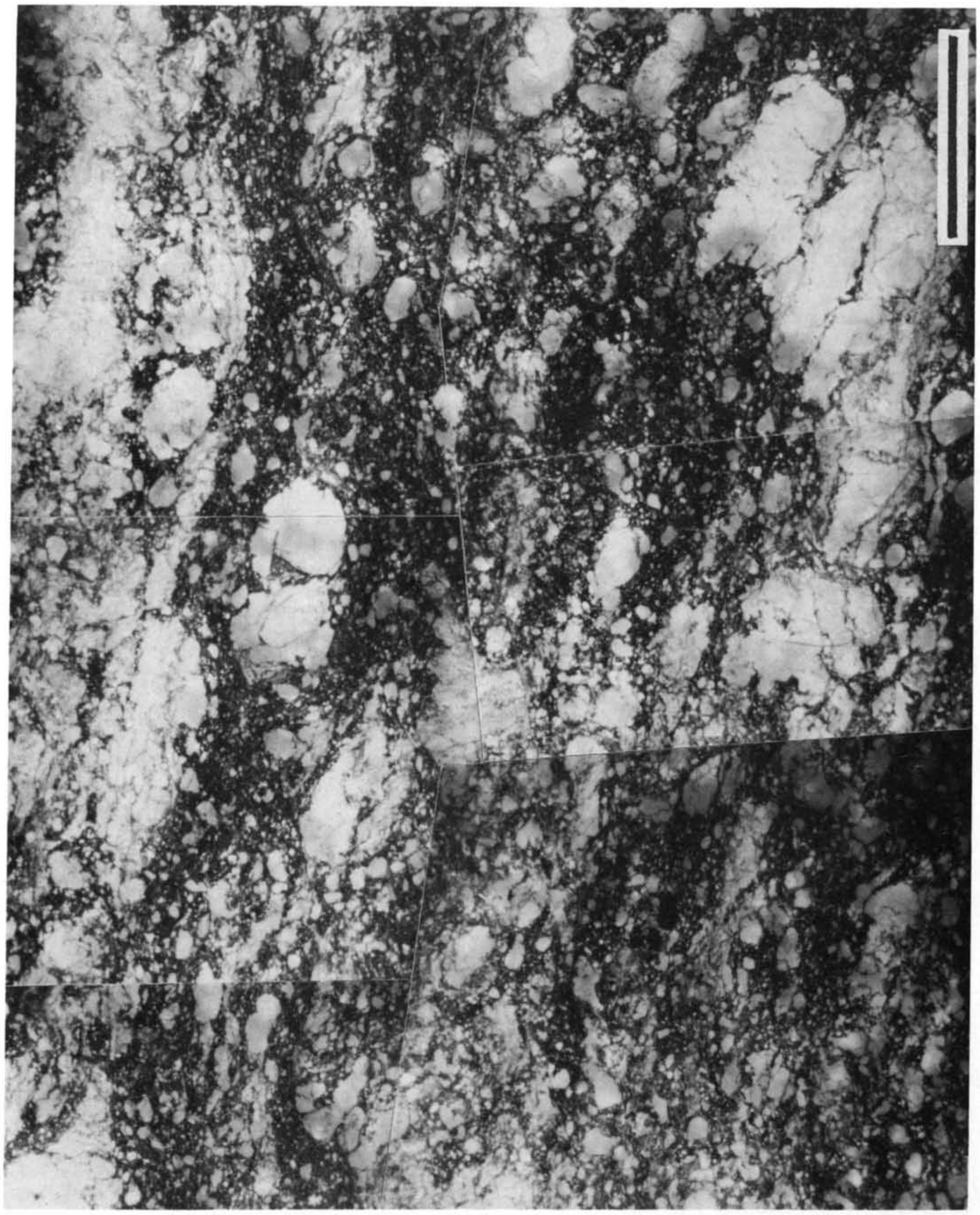

Fig. 5. Photomicrograph mosaic showing preferred alignment of the porphyroclasts on a thin section (HN4-1) cut parallel to the *S*-foliation. Scale bar is 5 mm.

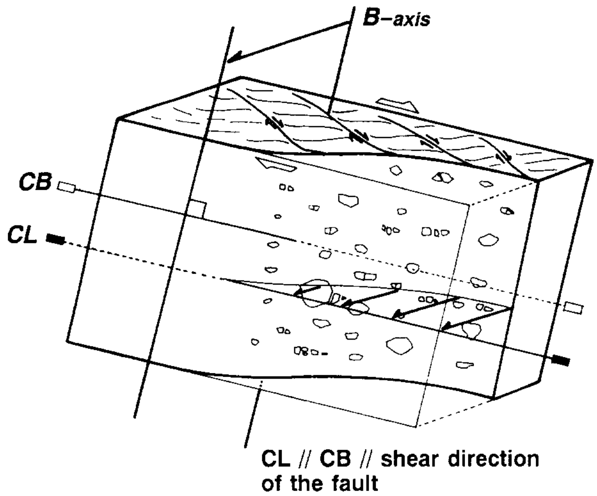

Fig. 7. Block diagram showing how to obtain the shear direction from B-axis of the asymmetric fabrics (CB) and from cataclastic lineation (CL). The CB and CL, projected on the *C*-surface, are parallel to one another.

Fault zone structure and cataclasite fabrics

At two locations (HNM and FUT in Fig. 1), distinctively asymmetric structures are directly observed in the fractured zone.

At location HNM, foliations of the fractured zone dip moderately to the southeast. *S*-foliations are defined by an arrangement of long axes of quartz porphyroclasts and a schistosity developed in the matrix. R_1 shears cut and drag the *S*-foliations. The former are oriented anticlockwise by about 10–20° to the main fault surface (*C*-surface), and the latter are clockwise to it (Figs. 3a & a′). Therefore, they constitute a composite planar fabric (Chester & Logan 1987) and indicate a left-lateral shear sense which is in agreement with the main fault movement of the ATL.

The surfaces of *S*-foliations and *C*-surfaces are usually semi-polished and contain slickenlines defined by furrows, grooves and scratches. They are regularly arranged at 0.5–1.5 mm intervals. Only rarely can more than one slickenline orientation be observed on a single surface.

Poles of the *S*-foliations (Figs. 3a & a′), slickenlines and the perpendicular to the B-axis projected on the *C*-surfaces are plotted in an equal-area projection (Fig. 6a). The B-axis can be obtained from an intersection of *S*-foliations, *C*-surfaces and R_1 shears. It is perpendicular to the shear direction on the fault plane (Hancock

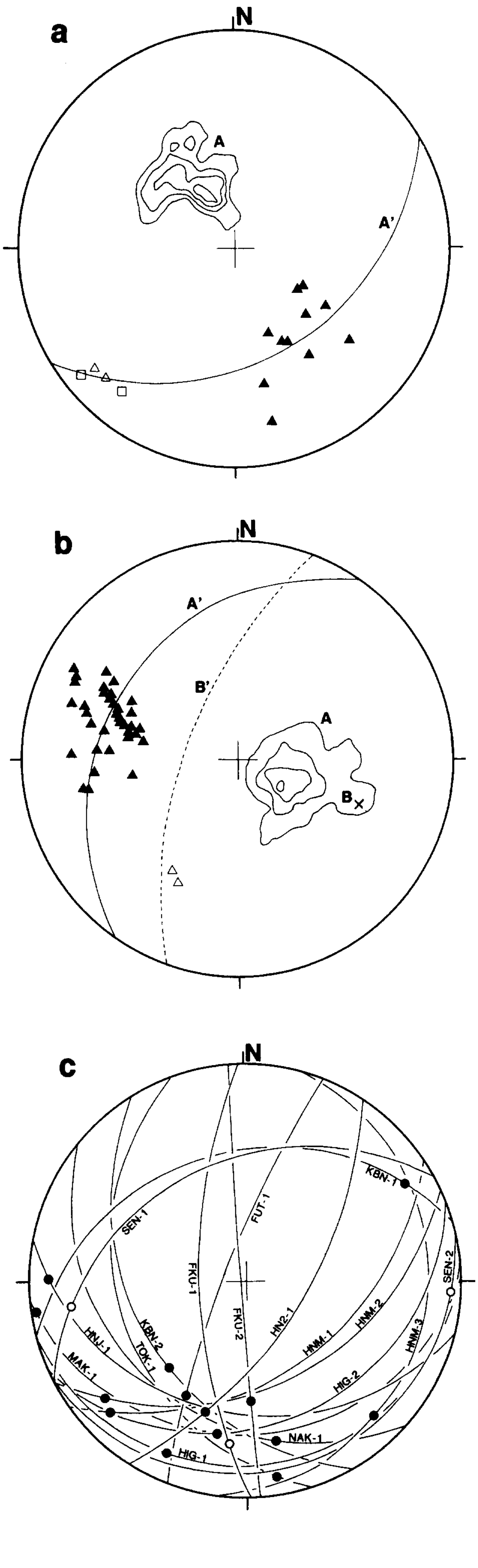

Fig. 6. Equal-area lower-hemisphere projection of several structures of cataclasites and fault gouges from the ATL. (a) Location HNM. Poles of foliations (A); mean orientation of foliations (A′); slickenlines (solid triangles); the direction at right angles to the B-axis (see Fig. 7) on the *C*-surface (open squares) and cataclastic lineations on the *C*-surface (open triangles). Contours are at 5, 10, 15 and 20% interval. (b) Location FUT. Poles of foliations (A), mean orientation of foliations (A′), slickenlines (solid triangles), cataclastic lineations (open triangles) and an orientation of a foliation on which the cataclastic lineation is seen (B and B′). Contours are at 10, 20, 30 and 40% interval. (c) Fault planes and cataclastic lineations for localities shown in Fig. 1. Solid circle, cataclasite; open circle, fault gouge.

1985), so that the perpendicular to the B-axis on the *C*-surface defines the shear direction of the fault (Fig. 7). If the slickenlines had formed at the same time as the asymmetric structures indicating left-lateral shear, slickenlines should be parallel to the perpendicular of the B-axis projected on the *C*-surface. However, they plot far away from one another (Fig. 6a).

At location FUT (the southernmost location in Fig. 1), the fault surface and associated foliations dip moderately to the west at similar angles (Fig. 3b). Slickenlines developed on the *S*-foliations and the *C*-surfaces are almost parallel to the dip of the main fault plane (*C*-surface) (Figs. 3d and 6b). This implies that the plane cut parallel to the slickenline and perpendicular to the *C*-surface strikes WNW and dips almost vertically. However, the asymmetric structures indicating left-lateral shear are exposed on a nearly horizontal surface (Fig. 3c). Therefore, slickenlines do not indicate the shear direction at the stage when the asymmetric structures were formed.

The composite planar fabric is less developed except for the above locations. At other locations, the *S*-foliation is developed almost parallel to the *C*-surface due to high shear strain. Thus, the shear direction cannot be obtained from their intersection, the B-axis. Other information, such as stretching lineations, is necessary to determine the shear direction. However, stretching lineations are not directly observed in outcrop, but only when rocks are cut and polished parallel to the *S*-foliation in the laboratory, as described below.

CATACLASTIC LINEATIONS

Mesoscopic scale

Oriented specimens were obtained from the locations shown in Fig. 1. Specimens were cut and polished parallel to the *S*-foliation, hereafter referred to as polished *S*-surfaces.

On the polished *S*-surfaces, a preferred alignment of the long axes of the porphyroclasts is typically observed (Figs. 2c & d) both in fault gouge and cataclasite. This structure is referred to as a cataclastic lineation. In addition, cracks are especially well developed in large porphyroclasts, over 1 cm in size, in the cataclasite (Fig. 2c′), and somewhat less developed in those in the fault gouge. Fluxion structures, discerned by the alignment of the fine-grained material of the matrix, accompanied by smaller porphyroclasts with their axes oriented likewise, are occasionally recognized around the isolated relatively larger porphyroclasts. Tails on both ends of the fluxion structures are systematically extended nearly parallel to the long axes of the core porphyroclasts.

Microscopic scale

Four oriented specimens of cataclasites were thin-sectioned parallel to the *S*-foliation (hereafter, referred to as *S* thin-sections). Preparation techniques are similar to those utilized by Chester & Logan (1987). Of four specimens, HN2-1, HN2-2 and HN4-1 originate from the pelitic schists of the Sambagawa metamorphic complex and HNM-1 from mudstone of the Shimanto complex.

Regardless of the source rocks, the cataclasite is composed of very fine grained ($<10\,\mu$m) matrix, single- and polycrystal quartz porphyroclasts, and calcite- and sericite-filled fractures. Most quartz porphyroclasts show undulatory extinction. As shown in Fig. 4(a), fragments of the porphyroclasts are distributed around the relatively large porphyroclasts and the loci of their long axes clearly exhibit fluxion structures accompanied by tails on both sides of the core porphyroclast. As in the case of the tails observed on polished *S*-surfaces, those on the microscopic scale extend nearly parallel to the long axes of the larger porphyroclasts.

Two types of porphyroclasts of polycrystalline quartz are recognized in the cataclasites derived from pelitic schist:

(1) porphyroclasts consisting of well-oriented quartz crystals of similar size (Fig. 4b);

(2) porphyroclasts consisting of randomly-oriented quartz crystals of variable size (Fig. 4c).

The first type appear to have been derived from crystalline schists, and tend to be smaller and less abundant towards the axial part of the fracture zone. The second seem to have been derived from segregation veins and are more relevant and retain their size towards the axial region. This suggests that the matrix is generated by comminution and alteration of the pelitic schists. Porphyroclasts, with fractures filled by minerals which have themselves been fractured, are commonly observed (Fig. 4d).

Orientations of porphyroclasts and microfractures

The features of the cataclastic lineation are examined both at mesoscopic and microscopic scales, by analyzing the orientation-distribution of the long axes of the porphyroclasts and of the cracks developed within porphyroclasts in both the cataclasites and gouges.

Polished *S*-surfaces were prepared on 20 cataclasite specimens and four fault gouge specimens. *S* thin-sections were prepared from four of the cataclasite specimens, displaying the best mesoscopic lineations. *S* thin-sections of fault gouges were not prepared, because fault gouges contain only small amounts of porphyroclasts.

Orientations of the long axes of the porphyroclasts on the polished *S*-surfaces were recorded on a transparent poly-acetate film, and digitized by a computer-connected digitizer (resolution: 100 μm, Graphtec KD3838) and statistically processed (Fig. 8a). A group of porphyroclasts which were obviously derived from a single porphyroclast (e.g. see Fig. 4d) was treated as a single porphyroclast for measurement purposes.

For *S* thin-sections, porphyroclast orientations were measured on photomicrographs of the entire thin-

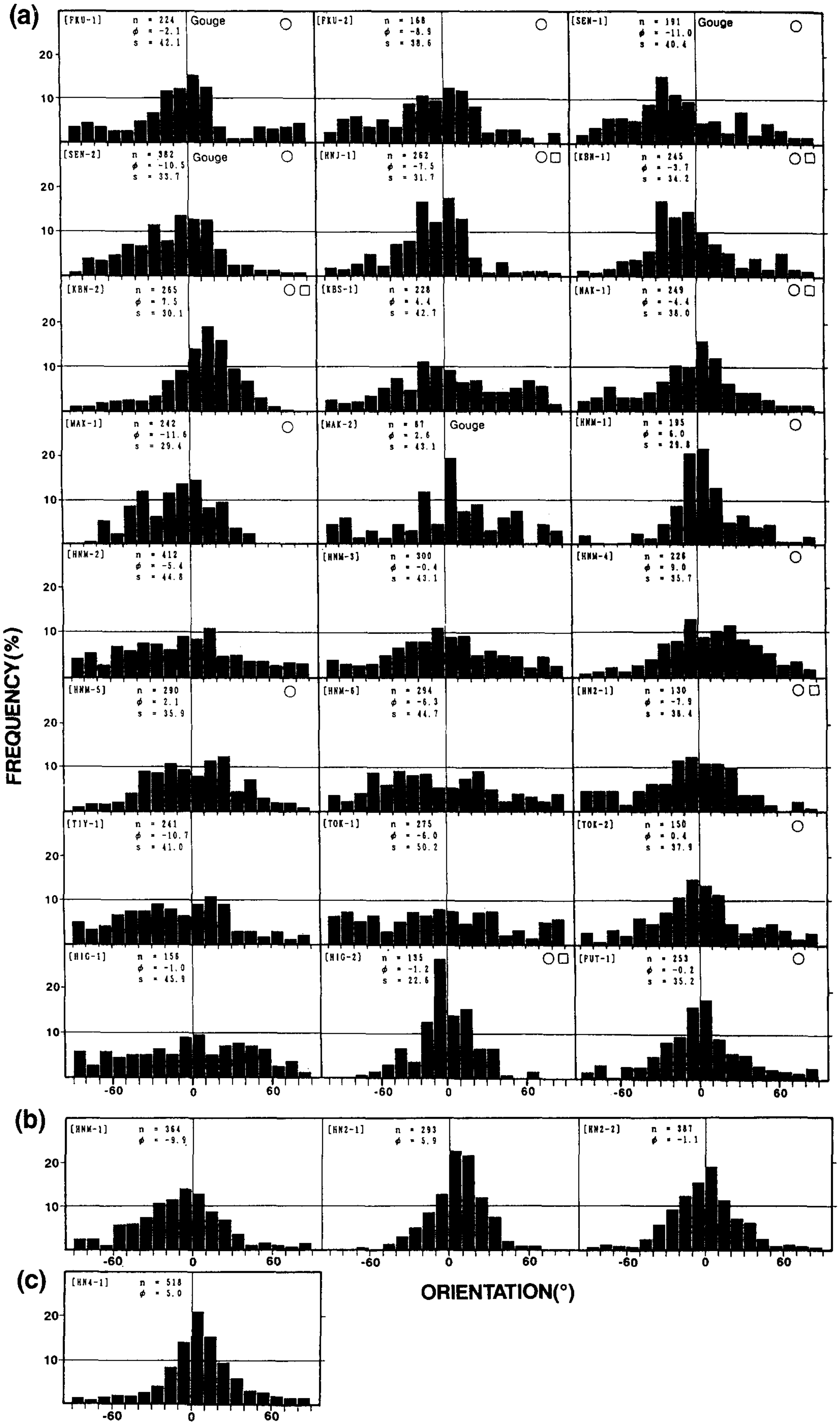

Fig. 8. (a) Orientation-distributions of the long axes of the porphyroclasts on polished *S*-surfaces. Specimens showing high concentration (see text) are indicated by an open circle. *S* thin-sections prepared are indicated by an open square. (b) & (c) are as (a), but on *S* thin-sections. Magnification is ×20 for (b), and ×40 for (c). Clockwise angle measurement. Abbreviations: n = number, ϕ = mean, S = standard deviation.

sections under plane-polarized light. Magnification of photomicrographs is ×20 (Fig. 8b) for HN2-1, HN2-2 and HNM-1, and ×40 (Fig. 8c) for HN4-1. The basal direction (0°), determined by eye, indicates the most prevalent preferred alignment of the long axes of the porphyroclasts and represents the cataclastic lineation referred to above.

Orientations of the long axes of porphyroclasts on the polished *S*-surfaces are generally unimodal and symmetric with a large angular deviation (Fig. 8a). In the *S* thin-sections, orientation-distributions are also unimodal but typically show smaller angular deviation (Figs. 8b & c). The preferentially oriented long axes of porphyroclasts are shown in a photomicrograph of an *S* thin-section (Fig. 5).

Although frequency decreases systematically away from the mode of distribution, it rarely falls down to 0% both in the polished *S*-surfaces and *S* thin-sections (Fig. 8), so that angular deviations remain relatively large. This tendency will be discussed later when the crack orientation-distribution is examined. Here, specimens in which at least a few peaks in excess of 10% juxtapose the mode are regarded to have well-oriented porphyroclasts. According to this screening, 14 specimens of cataclasites and three of fault gouges on the polished *S*-surfaces (Fig. 8a), and all of four cataclasites on the *S* thin-sections (Figs. 8b & c), show preferred orientation of the porphyroclasts. The position of the mode of distribution roughly coincides with the cataclastic lineation determined by eye both in cataclasites and fault gouges. The cataclastic lineation is defined as the direction occupied by the maximum ratio of orientation-distribution of the porphyroclasts.

The orientation-distribution of cracks developed in porphyroclasts of cataclasites was analyzed on polished *S*-surfaces of six selected specimens (Fig. 9a) and on *S* thin-sections of three specimens (Figs. 9b & c), in which porphyroclasts are well oriented and well cracked. The basal direction (0°) represents the cataclastic lineation. Crack orientations are highly variable with no preferred orientation in any specimen (Figs. 9a–c). However, when all of the crack orientations are collectively expressed for each class of crack width (Figs. 9d–f), the following common characteristic features are revealed.

(1) Orientation-distributions are symmetric with respect to the cataclastic lineation. Cracks oriented at right angles to and parallel to the lineation are predominant (top histograms of Figs. 9d–f).

(2) Both groups of cracks mentioned above increase in frequency with the crack width (downward from the top of Figs. 9d–f). This tendency is more prevalent for cracks at right angles to the cataclastic lineation than for those parallel to it. In contrast, cracks diagonal to it become less frequent with the increase in crack width.

Hereafter, each group is referred to as perpendicular cracks, parallel cracks and diagonal cracks, respectively. As observed in the photomicrograph shown in Fig. 4(d), the fact that cracks of these three groups cut one another testifies to their concurrent origin.

Shear direction of the fault

At two locations (HNM and FUT in Fig. 1), I can test the hypothesis that the cataclastic lineation defines the shear direction of the fault. However, significant errors may arise if the cataclastic lineation is interpreted to be parallel to the shear direction. Thus, to avoid errors, cataclastic lineations described here are all orthogonally projected on the *C*-surface (Lin & Williams 1992b).

At location HNM, the cataclastic lineations plunge approximately 5° to the southeast and are nearly perpendicular to the B-axes projected on the *C*-surface, even though slickenlines plot far away from both of them (Fig. 6a). At location FUT, slickenlines developed on the *S*-foliations and *C*-surfaces are parallel to the dip of the fault plane, whereas cataclastic lineations plunge at low angles to the south (Fig. 6b, Figs. 3d & e). This implies that the surface cut parallel to the cataclastic lineations and perpendicular to the *C*-surface dips at shallow angles to the south. This is also in good agreement with the fact that asymmetric structures are exposed on the nearly horizontal surface (Fig. 3c).

A specimen taken at location FUT was cut and polished parallel to the cataclastic lineations and slickenlines, respectively. On surfaces cut parallel to the cataclastic lineation and perpendicular to the *C*-surface, asymmetric structures indicative of left lateral shear are well developed. In contrast, on surfaces cut parallel to the slickenlines and perpendicular to the *C*-surface, asymmetric shear criteria are absent (Figs. 3f & g).

These observations lead to the conclusion that it is not slickenlines but cataclastic lineations that define the shear direction at the stage when the asymmetric structures were formed. Orientations of the *C*-surfaces in the fracture zone and of cataclastic lineations are shown in Fig. 6(c). Many of the cataclastic lineations dip at shallow angles to the south, although their concentration is low. These features reveal the complicated deformation history of the ATL.

DISCUSSION

Recognition of the cataclastic lineation

As shown in Fig. 4(d), the porphyroclasts have been fractured and elongated in the *S*-foliation, especially in cataclasites, so that the long axis of the broken porphyroclast is representative of the stretching direction. Perpendicular cracks are the widest of all cracks and, as defined, represent extension fractures. Tails are composed of the aligned matrix material of cryptocrystalline clay minerals and of oriented small porphyroclasts, and are the products of fluxion mechanisms as shown in Fig. 4(a). They occur parallel to the long axes of the porphyroclasts. Thus, the extension orientation of tails also indicates the stretching direction.

The parallel cracks are next in width to the perpendicular cracks, and may contribute to emphasize the

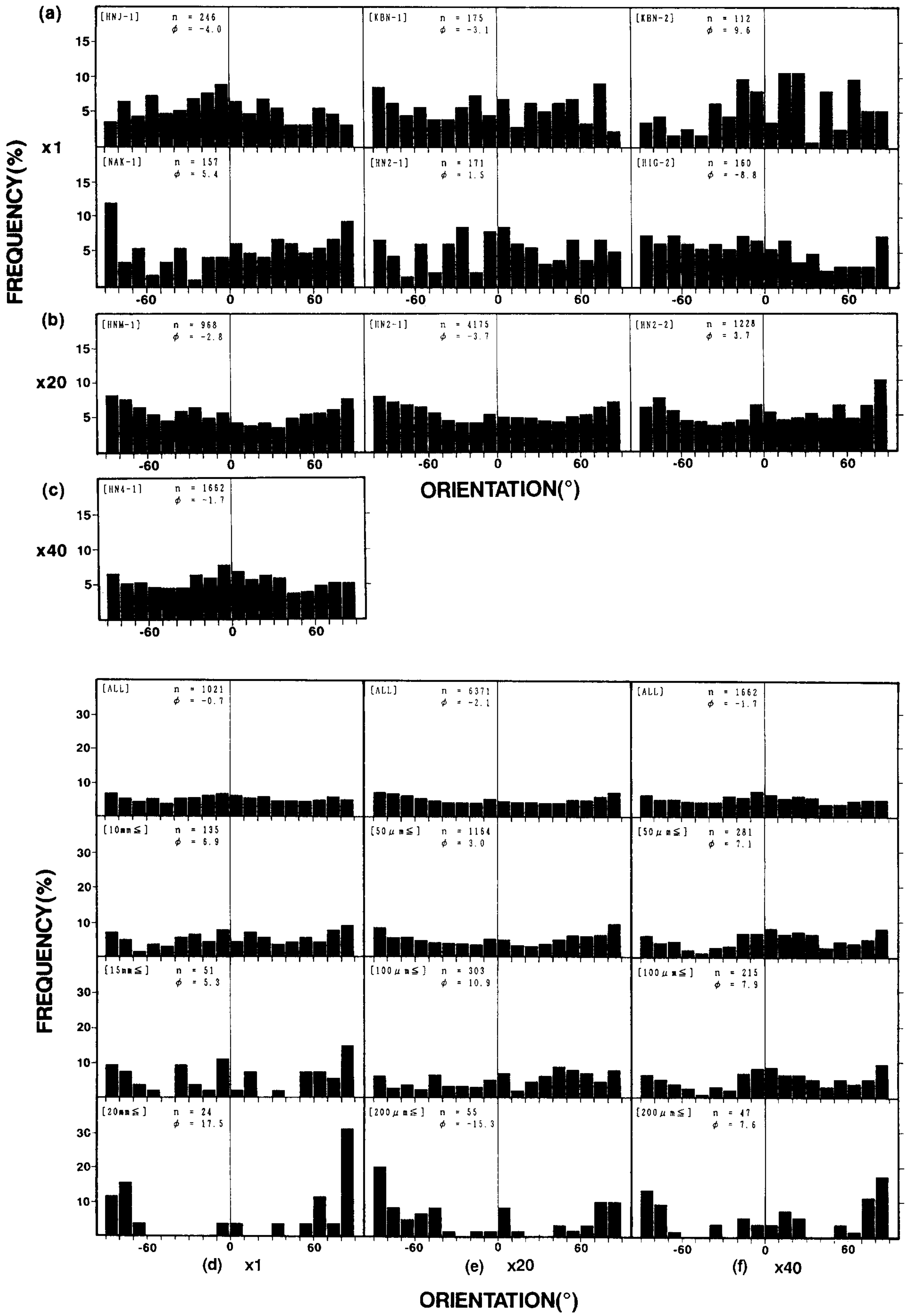

Fig. 9. (a)–(c) Crack orientations and (d)–(f) combined data of crack orientations for all the polished *S*-surfaces and the *S* thin-sections. (a) Crack orientations on polished *S*-surfaces in cataclasites. (b) Crack orientations on *S* thin-sections of magnification of ×20. (c) As (b) but magnification of ×40. (d) All polished *S*-surfaces. Threshold crack widths are: top, 0 mm or more; second, 10 mm or more; third, 15 mm or more; bottom, 20 mm or more, respectively. (e) All *S* thin-sections of magnification of ×20. (f) As (e) but magnification of ×40. Both on (e) and (f), threshold crack widths are: top, 0 μm or more; second, 50 μm or more; third, 100 μm or more; bottom, 200 μm or more, respectively. Same abbreviations as in Fig. 8.

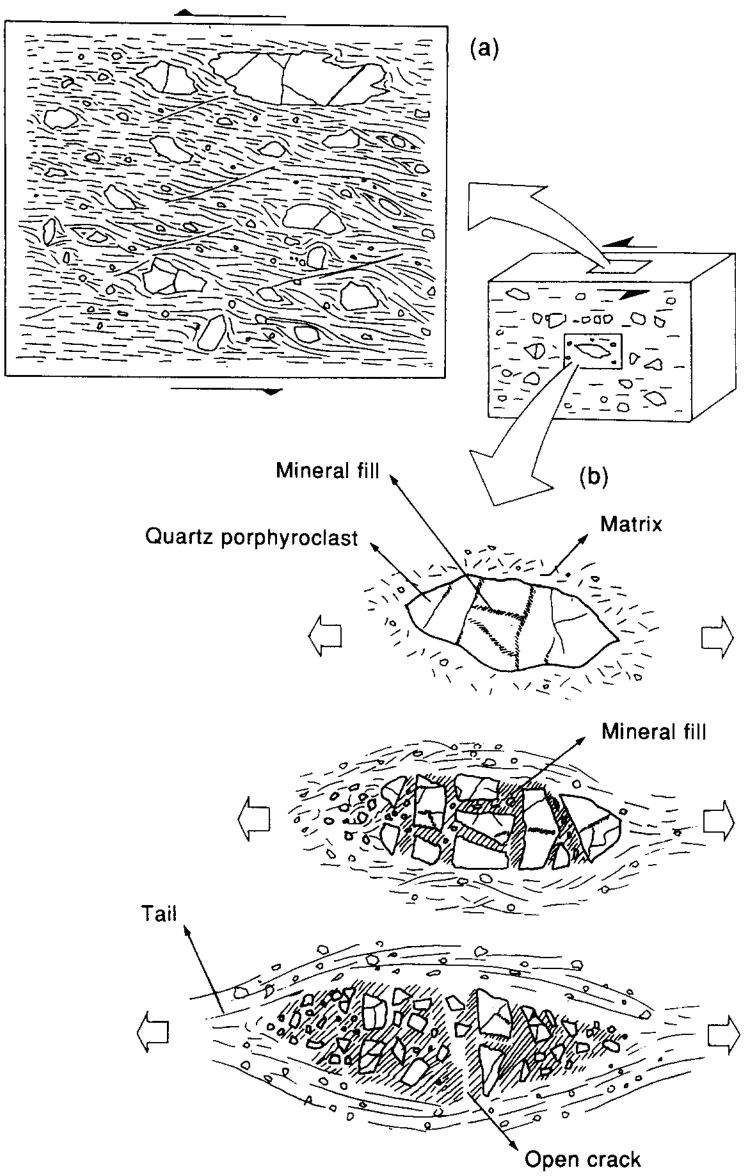

Fig. 10. Process of growth of the cataclastic lineation. (a) Asymmetric structures indicative of left-lateral shear (in the case of ATL), on the surface cut parallel to the cataclastic lineation and perpendicular to the *C*-surface. (b) Process of growth of the cataclastic lineation.

preferred orientation as two pieces of the original porphyroclast, separated by a relatively wide parallel crack, may be regarded as two individual porphyroclasts. Existence of parallel cracks suggests that the cataclastic lineation was not formed in plane strain deformation because the extension caused by parallel cracks is nearly perpendicular to the stretching direction.

Cracks of different orientation cut the porphyroclasts into smaller porphyroclasts with variably oriented long axes (Fig. 4d), resulting in a lowering of the concentration of orientation-distributions of the long axes of the porphyroclasts. The stretching direction is difficult to determine where these smaller porphyroclasts dominate. It is observed that the porphyroclasts with older cracks, filled by minerals, have been broken up again by younger cracks (Fig. 5), and orientations of cracks of both types are much the same, in spite of their difference in age. These observations suggest that the porphyroclasts were subjected to several stages of fault movement and that the shear direction was essentially the same during each stage.

Although porphyroclasts in the fault gouge are smaller in size and contain less cracks than those in cataclasite, the statistically prevalent direction of their long axes may represent the stretching direction, judging from their relatively high concentration. The preferential alignment of porphyroclasts in the fault gouge may be attributed to cataclastic flow of the matrix and to rotation of porphyroclasts in the course of cataclastic flow.

Based on the above discussion, the direction parallel to the cataclastic lineations and perpendicular to the widest cracks (perpendicular cracks) is regarded as a stretching lineation, and the orthogonal projection of it onto the *C*-surface is taken to be the shear direction during faulting. Cataclastic lineations form through a sequence of stages shown in Fig. 10(b), and associated dominant asymmetric structures are developed on the surface cut parallel to the cataclastic lineation and perpendicular to the C-surface (Fig. 10a).

Comparison between cataclastic lineation and slickenlines

Although slickenlines are developed on the S-foliations and C-surfaces constituting the composite planar fabric, their orientation is at large angles to the shear direction obtained from the B-axis of the shear fabrics. This suggests that the asymmetric structures are overprinted by the slickenlines. In contrast, on the surface cut parallel to the cataclastic lineations and perpendicular to the C-surfaces, composite planar fabrics are well developed. In addition, cataclastic lineations were clearly formed by the cataclastic flow, as represented by extended tails. These facts suggest that cataclastic lineations and composite planar fabric were originated concurrently under the ductile condition.

The possibility that the observed slickenlines were formed prior to cataclastic lineations is unlikely, because once the cataclastic flow was commenced, pre-existing slickenlines would have been obliterated. Instead, the shear surfaces which had formed at the same time as the cataclastic lineations provided pre-existing weak planes for later movement and associated slickenlines. Therefore, although slickenlines which formed under relatively ductile conditions have been reported elsewhere (Burg & Ponce de Leon 1985, Means 1987, Will & Wilson 1989, Lin & Williams 1992a), here they have formed under more brittle conditions.

Although the depth at which cataclastic lineations were formed is not clear, it is highly probable that they have developed at low temperatures (lower than 300°C), because the crack-filling calcite has been mechanically broken after its emplacement (Fig. 3d). In addition to the purely tectonic approach, examinations of syntectonically generated minerals (Evans 1988) and the relationship between temperature and mode of deformation of these minerals (Tullis & Yund 1977, 1987, Kanaori *et al.* 1990) are necessary to determine the depth of the formation of these cataclastic lineations.

Practical determination of the shear direction and related problems

Cataclastic lineations are formed by two different mechanisms. One is cataclastic flow of the cryptocrystalline matrix and the other is brittle failure of the porphyroclasts. The former makes the cataclastic lineation clear, and the latter makes it ambiguous. In such a situation, the stretching direction in the cataclasite and the fault gouge is determined by cataclastic lineations only when the following conditions are satisfied.

(1) Long axes of the porphyroclasts show a good preferred orientation.

(2) Tails on both ends of the elongated porphyroclasts extend parallel to the cataclastic lineation.

(3) The elongated porphyroclasts are broken by relatively wide cracks perpendicular to the long axis.

However, because in a brittle shear zone, deformation should not be expected to be homogeneous even in a single fault outcrop, there must be a statistically valid sampling of orientation data to overcome the local variation.

CONCLUSIONS

(1) Foliated cataclasites and foliated fault gouges are developed along the Akaishi Tectonic Line (ATL), one of the major sinistral strike-slip faults of central Japan. They typically contain quartz porphyroclasts derived mainly from segregation veins. Cracks are well developed especially in large (over 1 cm in size) porphyroclasts in the cataclasites. Many of the crack-filling minerals have themselves been fractured. Porphyroclasts in foliated fault gouges are more rounded and finer grained than those in the cataclasites. The number of cracks and the crack density for the porphyroclasts are less than those for the cataclasites.

(2) On the S-foliation (polished S-surfaces and S thin-sections), a preferred alignment of the long axes of the porphyroclasts is observed in more than half of the specimens of cataclasite and most of the specimens of fault gouge. Much finer porphyroclasts are distributed around relatively large porphyroclasts. The loci of their long axes are extended parallel to the long axes of the core porphyroclasts and further extended from the both ends of the porphyroclast to form tails. Cracks perpendicular to the long axes of the porphyroclasts are the most dominant and the widest of all cracks, irrespective of magnification (×1, ×20 and ×40) of observation. Cataclastic lineation is defined as the preferred orientation of the long axes of the porphyroclasts and perpendicular to the widest cracks (perpendicular cracks).

(3) Asymmetric structures showing left-lateral shear are observed on surfaces cut parallel to the cataclastic lineations and perpendicular to the C-surface, whereas no asymmetric structures are observed on the plane cut parallel to the slickenlines and perpendicular to the C-surface. This fact indicates that the cataclastic lineations represent the stretching direction on the S-foliation. Thus, orthogonal projection of it onto the C-surface indicates the shear direction at a late deformation stage when left lateral shearing took place along the ATL. Moreover, they are products of more penetrative deformation than that responsible for slickenlines, although they are considered to have been formed under low-temperature conditions (lower than 300°C).

(4) Slickenlines indicate the shear directions of later, superficial movements on the ATL which are considered to have no relationship to the main shear direction.

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