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Microstructure of deformed biotite defining foliation in cataclasite zones in granite, central Japan

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Abstract—Foliated cataclasite occurs along both left-lateral faults, striking N10°–40°W, and right-lateral faults, striking N10°–25°E, formed in the Late Cretaceous Naegi-Agematsu granite along and near the Atera fault in central Japan. Quartz and feldspars in the cataclasite are angular to subangular in shape. Biotites, which are granular or elongate, exhibit kink bands and cleavage separation, or cleavage steps and biotite fish Arrays of deformed biotite define a *P*-foliation that formed in the fault zones. The angle (θ) between the *P*-foliation and the (001) biotite cleavage and the ratio (W/L) of apparent width (W) to length (L) of deformed biotites are related to the type of biotite microstructure developed. In the samples studied, there were no values of θ in the ranges 30–75° and 105–150° The cleavage-step microstructure exhibits an angle, θ, of less than 30°, with W/L less than 0.2 Kink band and/or cleavage separation microstructures have an angle, θ, of 75–105°, with W/L between 0.5 and 1.5 Biotite fish have an angle, θ, of more than 150°, with W/L less than 0.2. These data imply that the orientation of cleavage in biotite with respect to the plane of shear strongly controlled the response of biotite to deformation. The resulting microstructures provide good kinematic indicators in biotite-bearing shear zones and faults.

INTRODUCTION

ALTHOUGH there have been many studies of the mode of deformation of quartz and feldspars in the brittle regime (e.g. Chester & Logan 1987, Evans 1988), the brittle–ductile regime (e.g. Simpson 1985) and the purely ductile regime (e.g. Choukroune & Gapais 1983, Gapais & Barbarin 1986), there have been few studies that have concentrated on the micas in deformed granite. In experiments with Westerly granite, Stesky *et al.* (1974) and Stesky (1978) noted that biotite deformed brittlely at room temperature, and ductilely at temperatures greater than 250°C. Janecke & Evans (1988) examined the brittle–ductile transition in a naturally deformed granite and found that the ratio of muscovite to chlorite exerted an influence on the manner of deformation. Goodwin & Wenk (1990) showed, by means of transmission electron microscopy (TEM), that black zones parallel to cleavage surfaces in biotite aggregates were micro-cataclastic or were associated with intracrystalline folding of the mica.

Fault zones with foliated castaclasite are well developed in the Late Cretaceous Naegi-Agematsu granite along the Atera fault in central Japan. In this paper, we describe microstructures of deformed biotites which characterically occur in arrays defining the foliations in the cataclasite. The relationship between the type of microstructure and the sense of shear is also examined.

GEOLOGICAL SETTING

Regional structures

The Naegi-Agematsu granite intruded the Late Cretaceous Nohi rhyolite, and it outcrops extensively near and along the Atera fault (Fig. 1). The granite–rhyolite contact is mainly intrusive, but is locally faulted. The Atera fault is 60 km in length, strikes NW, dips nearly vertically and exhibits a left-lateral sense of slip. The fault zone comprises cataclasite zones, which have a maximum width of about 300 m. Other cataclastic fault zones with widths on the order of tens of meters are systematically aligned with NW–SE and NNE–SSW trends at intervals of 100–500 m. These cataclasite fault zones appear in a lattice pattern (Fig. 1).

Mesoscopic structures

Outcrops of the Naegi-Agematsu granite and Nohi rhyolite lie scattered in the bed of the Tsukechi River, and are located near the town of Tsukechi, in Ena Country, Gifu Prefecture. The outcrops are located between the Atera fault and an unnamed fault, which lies parallel to and about 650 m north-east of the Atera fault. Small-scale cataclasite zones, with N15°–40°W or N10°–25°E strikes and near-vertical dips, are well developed in the outcrops. Outcrop-scale evidence, including Riedel shears and offsets of dikes and joints (Kanaori *et al.* 1990), shows that the N15°–40°W and N10°–25°E cataclasite fault zones have left-lateral and right-lateral slip sense, respectively. Both sets of cataclasite zones were probably formed in association with left-lateral movement on the Atera fault (Kanaori *et al.* 1990). The zones are commonly 5–50 cm wide, with a maxium width of 4 m. Narrow zones of very fine-grained quartz and feldspar, less than 1 cm thick, are found at the boundaries between the cataclasite zones and the country rock.

Figure 2(a) is a photograph of a small-scale structure developed in a cataclasite zone with right-lateral sense of slip. Riedel shears, of *P*-, R_1 and R_2-types (Logan *et al.* 1979), can be seen clearly in the cataclasite. *P*-foliation is

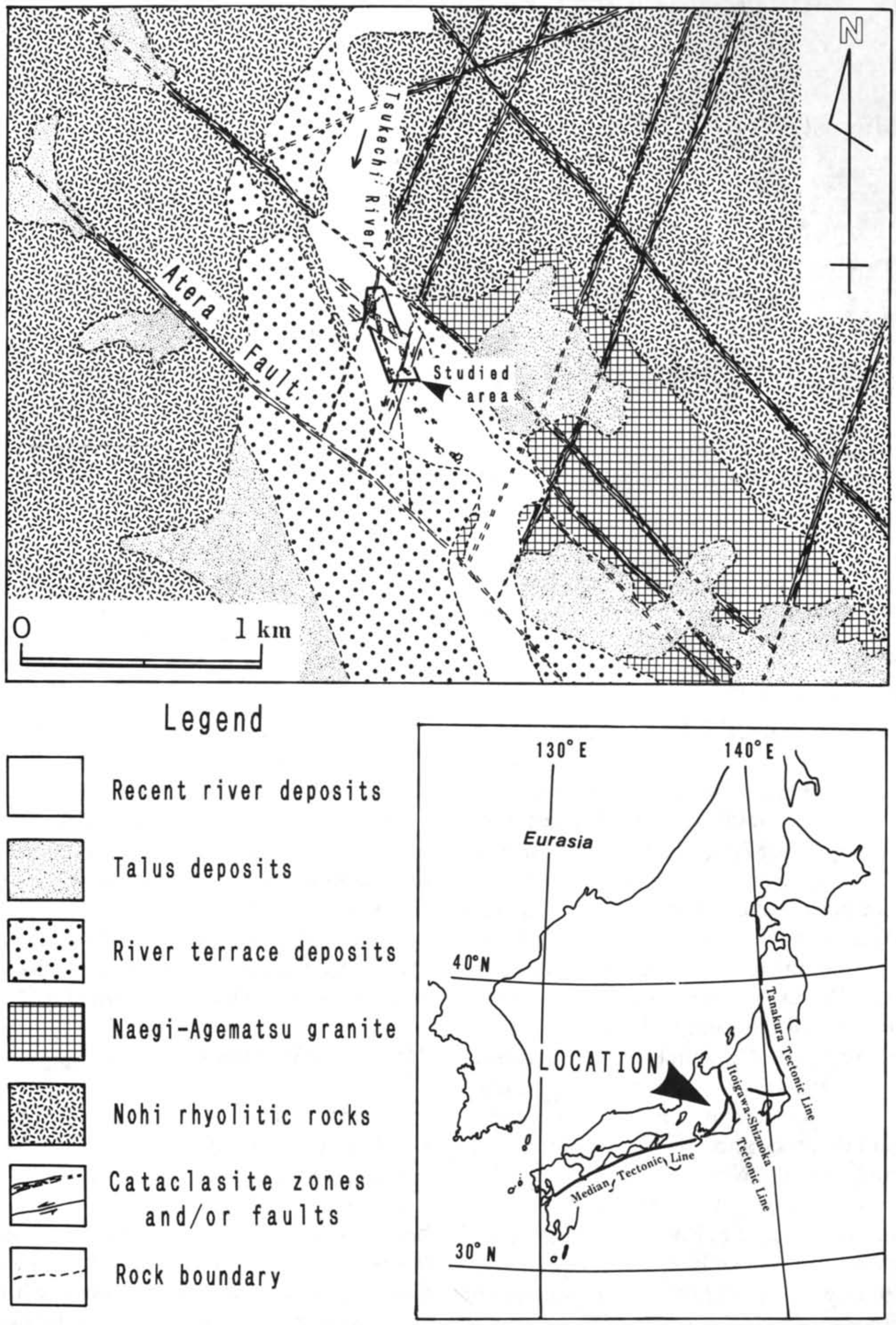

Fig 1 Schematic map showing the distribution of cataclastic fault zones and the location of the area studied near the Atera fault at the town of Tsukechi in Ena County and Gifu Prefecture, central Japan

identified by biotite alignment along the *P*-shears. The *P*-foliations can be traced intermittently as black zones, less than 0.5 mm wide, consisting of deformed biotite. They are slightly wave-like. The black zones are arranged parallel to each other, with a spacing of several millimeters. The *P*-foliations make an angle of less than 30° to the boundaries of the cataclasite zone.

The granite country rock outside the fault zone is a medium- to fine-grained, leucocratic biotite granite, composed of quartz, feldspar and biotite. The rock exhibits no magmatic foliation, and no alignment of the biotite can be detected

MICROSTRUCTURE OF THE BIOTITES

Oriented samples were collected from the cataclasite zones in the Naegi-Agematsu granite. Thin sections taken from a horizontal plane of these were examined with an optical microscope. In these sections, both quartz and feldspars occur as small fragments of various sizes. The fragments are angular to subangular and more or less equidimensional. Biotite is very elongate or equant and occurs in narrow bands (Fig. 2b). It is partially altered to chlorite. The alignment of elongate biotite defines a foliation The matrix surrounding the

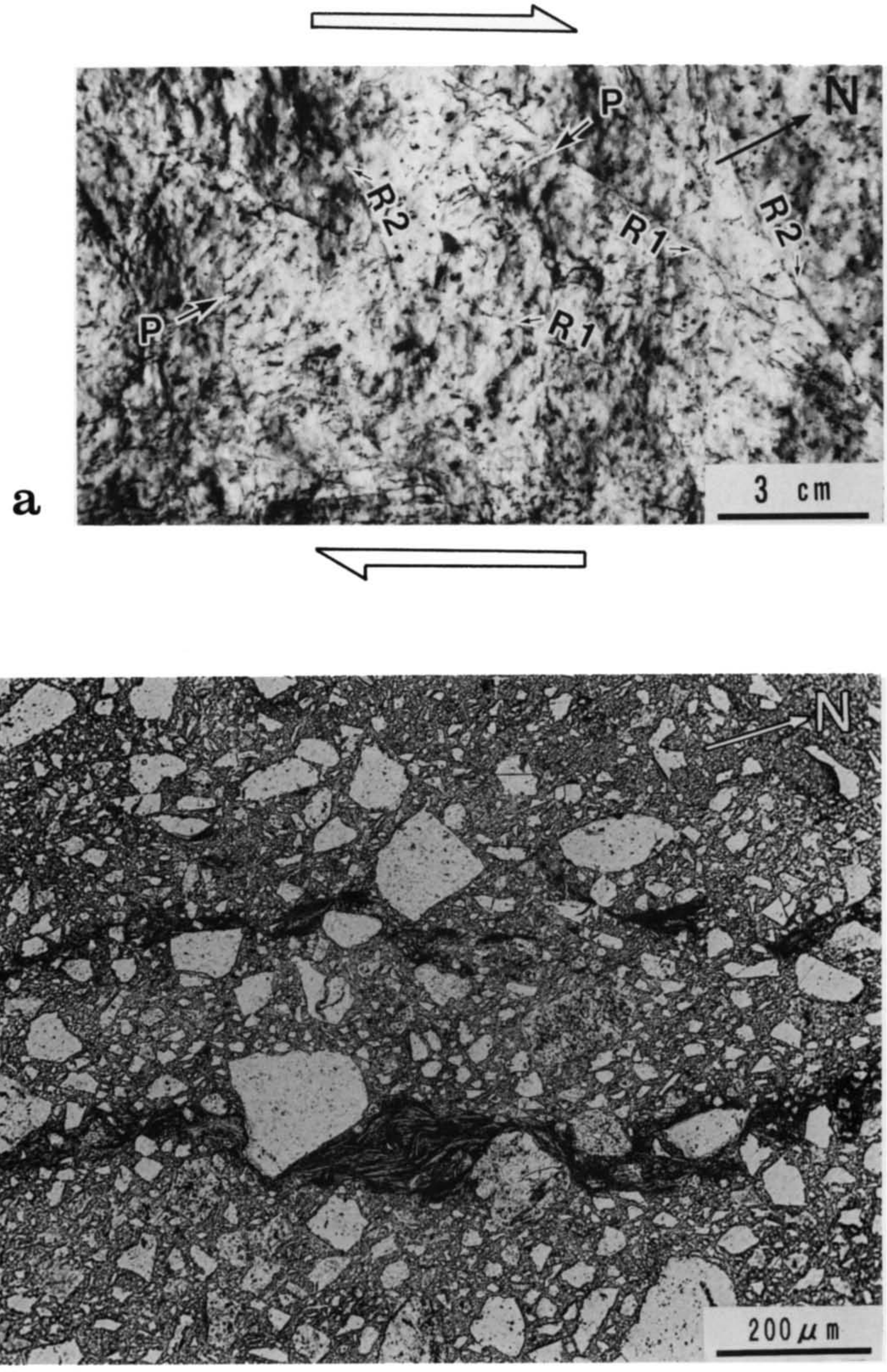

Fig. 2. (a) Photograph of an outcrop of a cataclastic fault zone in the Naegi-Agematsu granite, with a right-lateral sense of movement The outcrop surface is nearly horizontal. R_1-, R_2- and P-shears are marked. (b) Photomicrograph of a horizontal section of the cataclasite. Arrays of dark biotite define a foliation in a right-lateral cataclasite zone, in plane polarized light Light grains are quartz and feldspar.

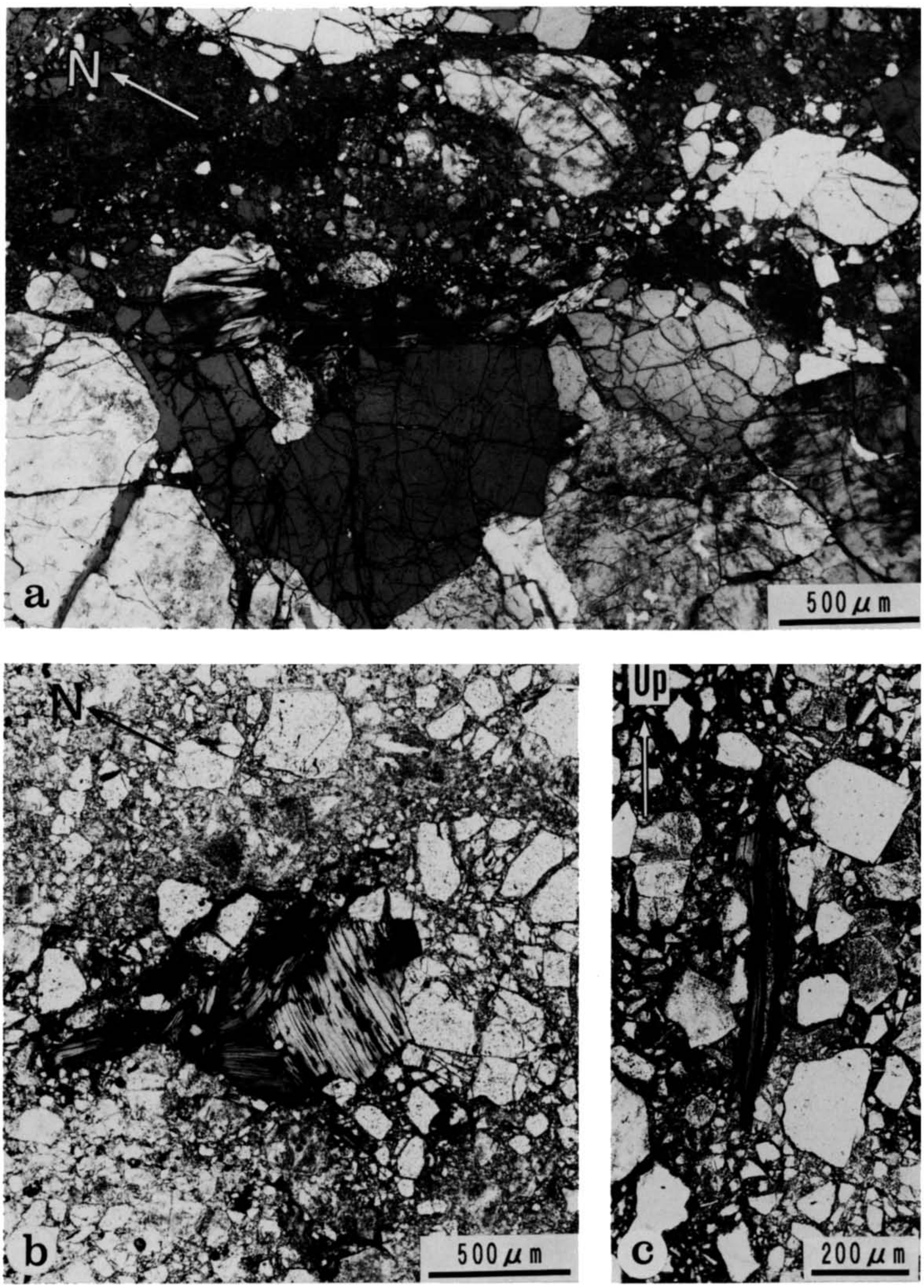

Fig 3 Photomicrographs of cataclasite in horizontal sections (a & b) and a vertical section (c) perpendicular to cataclasite zone boundaries (a) A smeared-out biotite grain in a left-lateral cataclasite zone, in crossed polarizers. Kink bands in the biotite are well developed. (b) A biotite grain in a left-lateral cataclasite zone, in plane polarized light. Quartz fragments to the right of the biotite grain form a carapace-like pattern. (c) A biotite in a right-lateral cataclasite zone, in plane polarized light

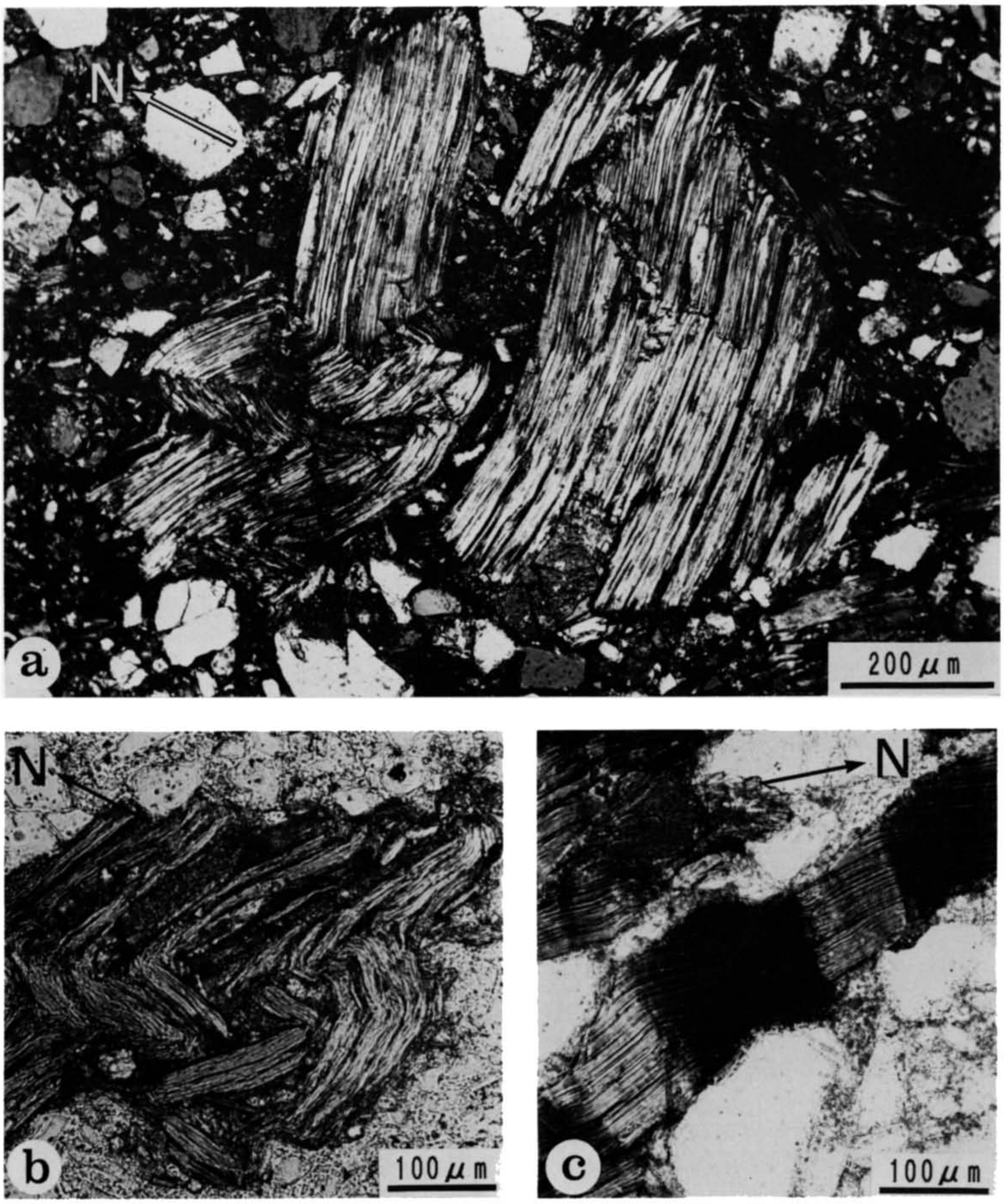

Fig. 4. Photomicrographs showing kink bands and/or cleavage separation of biotite in horizontal sections of cataclasite. (a) A conjugate kink band with cleavage separation in a left-lateral cataclasite zone, in crossed polarizers. (b) A single kink band in a left-lateral cataclasite zone in plane polarized light. (c) Biotite showing single-sense kink bands in a right-lateral cataclasite zone, in plane polarized light.

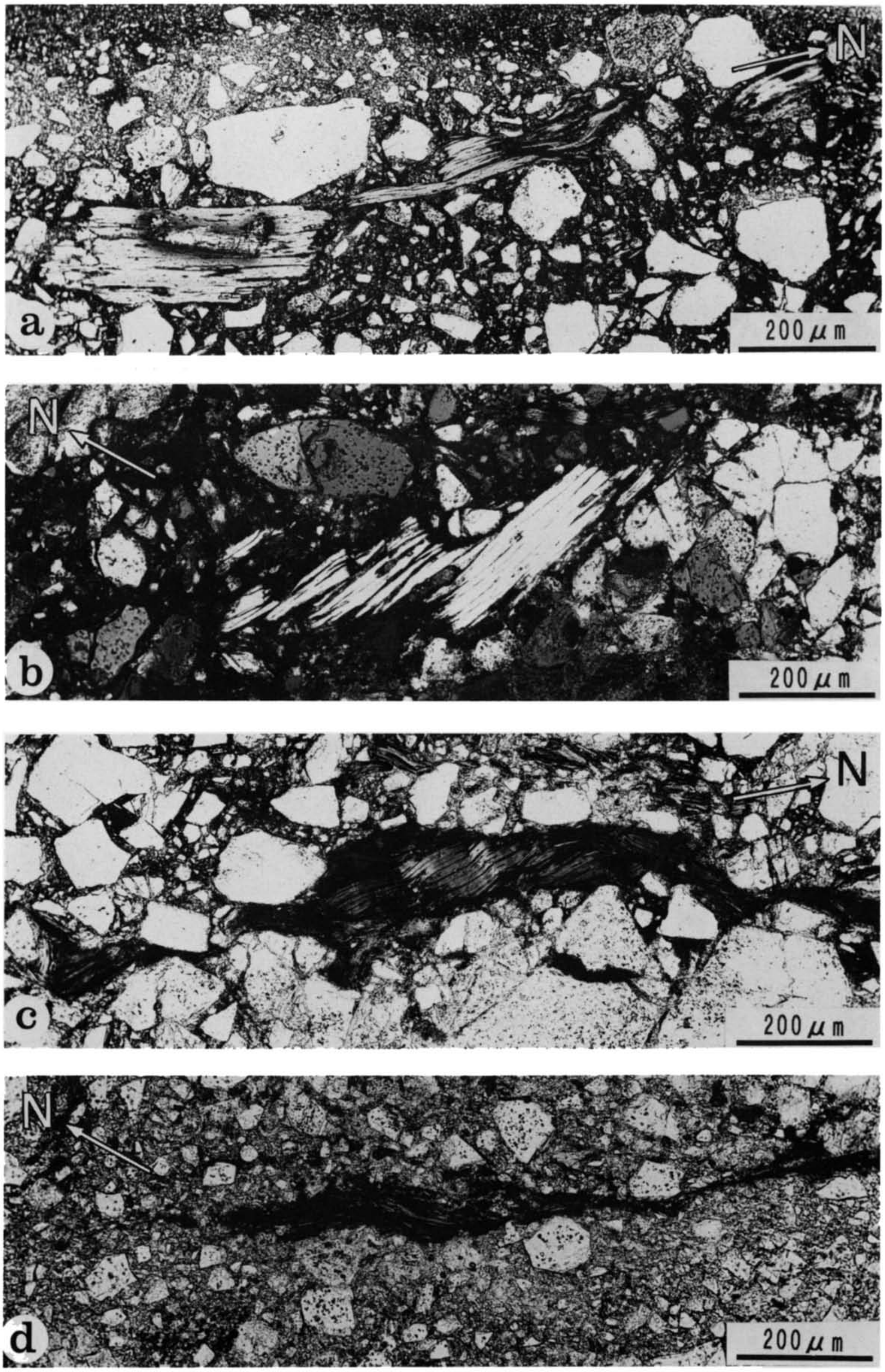

Fig. 5 Photomicrographs of cleavage steps and biotite fish in horizontal sections of cataclasite (a) Right-lateral steps of a biotite with little or no overlapping, in plane polarized light (b) Left-lateral steps of a biotite with overlapping, in crossed polarizers (c) A biotite fish tapering off at both ends, in a right-lateral cataclasite zone in plane polarized light (d) Very elongate biotite fish in a left-lateral cataclasite zone, in plane polarized light

fragments and the biotite is composed mainly of finer grained quartz and feldspar.

Kink bands are commonly developed in the biotite, which exhibits undulatory extinction (Fig. 3a). Biotite grains are elongate due to shear along (001) cleavage (left-lateral in Fig. 3b). The orientation of the (001) cleavage in the elongate biotites is different from that in the equant biotites. Biotites are highly stretched in vertical sections perpendicular to the cataclasite zone (Fig. 3c). They are also elongate along the trend of the *P*-foliation. The microstructures found in most biotite grains can be categorized into three types: (1) kink band and/or cleavage separation (microboudinage); (2) cleavage steps; and (3) biotite fish (Figs. 3–5). Two different sub-types of biotite fish and cleavage steps can ordinarily be distinguished. They are mirror images of each other, depending on whether the shear sense of the cataclasite zone is left-lateral or right-lateral (cf. Fig. 5).

Kink bands and/or cleavage separation (microboudinage)

Kink bands are common in granular biotite in the cataclasite zone. Based on the kink band classification of Weiss (1968), they are of conjugate type (Fig. 4a), or single type (Figs. 4b & c). The axial surfaces of the kink bands are usually oriented about 15° clockwise or anticlockwise from the *P*-foliation. Separation along the (001) cleavage can occur in biotite both with and without kink bands (Fig. 4a). Kink bands similar to those described here have been reported in studies of naturally and experimentally deformed rocks (Borg & Handin 1966, Hörz 1970, Etheridge *et al.* 1973, Etheridge & Hobbs 1974, Bell 1979, Wilson & Bell 1979, Vernon *et al.* 1982, Kawakami *et al.* 1990, Williams & Price 1990).

Cleavage steps

Biotite can be drawn out along the (001) cleavage to form steps (Figs. 5a & b). The (001) cleavage is either parallel to the *P*-foliation (Fig. 5a) or tilted in a forward sense with respect to the sense of shear. Transfer from one step to the next occurs with or without overlapping, and is highly variable in individual grains. The variation is probably related to the amount of shear strain along the foliation. Left-stepping and right-stepping in the biotite are essentially associated with *P*-foliations in right-lateral and left-lateral cataclasite zones, respectively, as can be seen in Figs. 5(a) & (b). The morphology of this type of cleavage step is similar to that of muscovite found in *S–C* mylonites (Lister & Snoke 1984).

Biotite fish

For biotite fish, the (001) cleavages are either subparallel to the direction of biotite elongation (Fig. 5d) or tilted back against the sense of shear (Fig. 5c). Their width gradually decreases toward both ends, creating an elongate, fusiform shape (Figs. 5c & d). This feature is

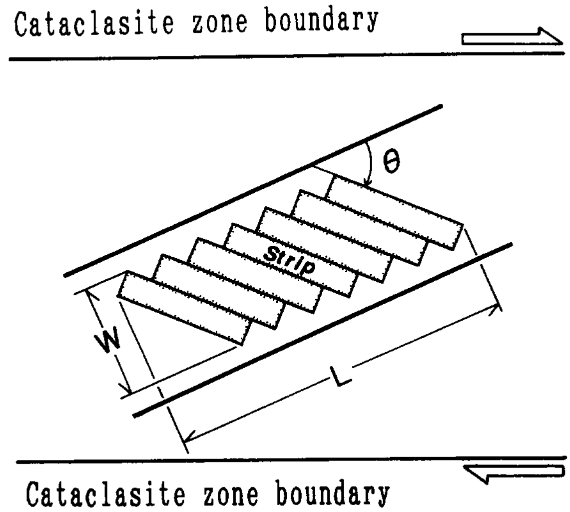

Fig. 6. Schematic representation of a deformed biotite to show the definition of apparent width, *W*, apparent length, *L*, and the angle *θ*, between the (001) cleavage and the direction of the *P*-foliation.

termed a biotite 'fish', analogous to the muscovite 'fish', typically found in Type II *S–C* mylonites (Eisbacher 1970, Choukroune & Lagarde 1977, Berthé *et al.* 1979, Lister & Snoke 1984, Goldstein 1988). As in the case of the cleavage steps, biotite fish define a foliation within a cataclasite zone having either right-lateral slip (Fig. 5c) or left-lateral slip (Fig. 5d). In this study, the former are donoted as right-lateral fish, while the latter as left-lateral fish.

Some biotites are strongly elongate, forming a string-like shape with optically indiscernible cleavage surfaces. A biotite fish links one string to the next to form a chain similar to Type III asymmetric boudinage proposed by Goldstein (1988). When this type of biotite fish is more elongate, it can only be traced as a thin dark band in the cataclasite fault zone. This suggests that dark bands may be fine-grained biotites or a biotite–chlorite mixture in the fault, rather than solution seams as have been commonly suggested (e.g. Mitra 1984).

ANGLE BETWEEN THE (001) CLEAVAGE AND *P*-FOLIATIONS

Figure 6 schematically shows the angle *θ* between the *P*-foliation and the (001) cleavage. Also shown are the apparent width (*W*) and length (*L*) of a deformed biotite crystal. Since the orientation of (001) cleavage varies with position in biotites of kink band and/or cleavage separation types, the angle *θ* in these types was recorded as an average of several values measured along the cleavage trace. The angle *θ* and the ratio *W*/*L* are related essentially to the type of biotite microstructure displayed (Figs. 7a & b). The cleavage-step type biotites have an angle *θ* of less than 30°, with *W*/*L* less than 0.2. The kink band and/or cleavage separation type biotites have an angle *θ* of 75–105° and *W*/*L* of 0.5–1.5. Biotite fish, on the other hand, have an angle *θ* of more than 150°, with *W*/*L* less than 0.2. The three groups are

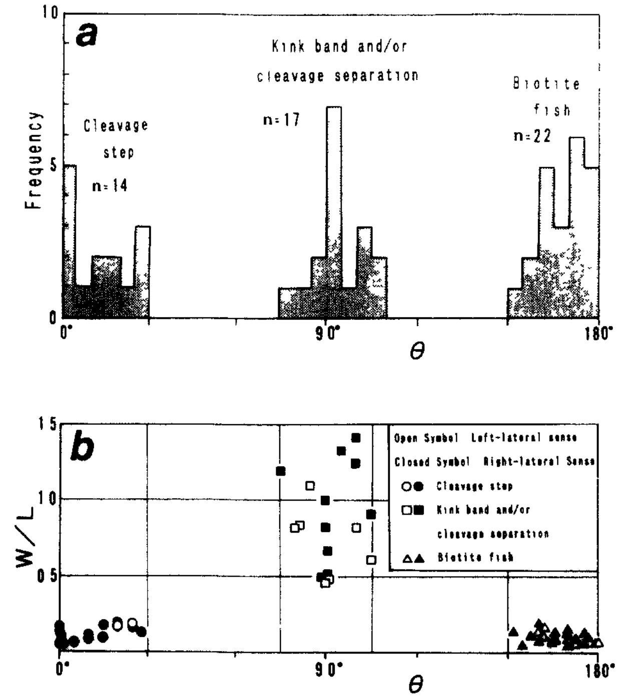

Fig. 7. Results of measurement of biotites in a cataclasite fault zone. (a) Histogram of the angle θ. (b) *W/L* ratios as a function of θ.

clearly separated on the histogram, with no angles in the ranges of θ=30–75° and θ=105–150°.

Biotite crystals in the surrounding country rock exhibit no alignment and show no preferred orientations. Thus, biotite crystals must have been distributed randomly just prior to the formation of the *P*-foliations. This implies that the original angles, θ_0, must have been uniformly distributed through the range 0–180°. However, no biotite with θ in the range 30–75° or 105–150° has been detected in the cataclasite examined during this study (Fig. 7). This means that the biotite crystals with original angles, θ_0, falling in these ranges have been rotated away from what are inferred to be the instantaneous shortening and elongation directions. In a biotite crystal inclined to the shear direction the bulk flow in the cataclasite zone caused rotation of the crystal (Lister & Williams 1983). This enabled shear-induced slip on cleavage and resulted in the formation of fish and step type microstructures. Similar rotations of biotite have been found to occur in metamorphic rocks during schistosity formation (Zwart 1963, Mukherjee & Sen 1971, Glen 1980, Vernon 1988).

DISCUSSION

Logan *et al.* (1979) and Chester *et al.* (1985) found distinct foliations which they identified as types of Riedel shears in a natural (Punchbowl) fault zone and in experimental shear zones formed in sliding experiments. Kano & Sato (1988) also found foliated cataclasites within the Sakai-Toge fault zone of cental Japan. However, their study did not include the examination of grain size characteristics of the foliation.

In the cataclasite fault zones examined in this study, foliations are defined by arrays of deformed biotites. Microstructures of these deformed biotites include kink bands and/or cleavage separation, cleavage steps, and biotite fish. The kink band shape shown in Fig. 4(c) is similar to that which is found in the biotite on both sides of an ellipsoidal grain during progressive, inhomogeneous, simple shear (Bell 1981). Cleavage steps and biotite fish occur in two modes that are mirror images of each other in left-lateral and right-lateral cataclasite zones. These microstructures can be used as a sense-of-shear criterion that has been applied, not only to various types of muscovite fish and steps in *S–C* mylonites (Eisbacher 1970, Berthé *et al.* 1979, Lister & Snoke 1984), but also to displacements along cleavages and to the rotation of porphyroclasts in mylonites or mylonitic rocks (Simpson & Schmid 1983, Hanmer 1984, Lister & Snoke 1984, Blumenfeld & Bouchez 1988, Takagi & Ito 1988). Since the angle, θ, between the *P*-foliation and the (001) cleavage is closely related to the type of microstructure developed in biotite, the type of microstructure must have been controlled by the angle, θ_0, prior to foliation formation. This implies that the orientation of cleavage in biotite with respect to the shear plane and the sense of shear displacement strongly control the response of biotite to deformation (e.g. Lister & Williams 1983).

The types of Riedel shear formed during simple shear in cataclasite and fault breccia zones (Logan *et al.* 1979) reflect the sense of shear. In particular, *P*-foliations, together with R_1- and R_2-shears give a clear indication as to whether slip is left-lateral or right-lateral (Logan *et al.* 1979, Chester *et al.* 1985, Kano & Sato 1988). The three types of biotite microstructure which formed foliations in cataclasite associated with fault zones in the present study provide diagnostic, grain-scale, kinematic indicators of the sense of shear along the foliation and the sense of movement in the shear zone. They allow the biotite fabric to be identified as a *P*-foliation.

The black zones parallel to cleavage in biotite aggregates (e.g. Fig. 4b) are strikingly similar to the features reported by Goodwin & Wenk (1990). These authors demonstrated in a TEM study that black zones in some fault zones formed by micro-cataclasis or are associated with intracrystalline folding of mica. Tullis & Yund (1987) suggested that it may be impossible to detect optically brittle behavior in a cataclastic flow regime. Further TEM studies are needed to determine whether biotite in the cataclasite fault zones studied here behaved plastically or whether the black zones parallel to cleavages are in fact micro-cataclasite.

CONCLUSIONS

P-foliations were traced as arrays of deformed biotite grains in cataclasite zones developed in the Late Cretaceous Naegi-Agematsu granite along and near the Atera fault in central Japan. The cataclasite was probably produced during movement on the Atera fault. The biotite exhibits diagnostic types of microstructure, including kink bands and/or cleavage separation, cleavage steps and biotite fish. The angle between the (001) cleavage of biotite and the orientation of the *P*-foliation is critically related to the type of microstructure formed.

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