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Rotation of slip direction of the Atokura Nappe viewed from micro-structural analyses of brittle shear zones in the Sambagawa belt, Southwest Japan

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Abstract—The Atokura Nappe is mainly composed of Late Cretaceous fore-arc sediments (Atokura Formation) and overlies the Mikabu greenstones of the Sambagawa belt in the Kanto region, Southwest Japan. Meso- and microstructures of the foliated cataclastic fault rocks along the base of the nappe (klippes) are described, and slip directions are determined. Movement of the nappe is divided into three stages based on a difference in fault rocks. The slip direction of the nappe has rotated clockwise from WNW (subparallel to the trend of geologic belts) to N (perpendicular to the trend). Movement of the Atokura Nappe may have changed from a strike-slip to an extensional tectonic setting. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

The Atokura Nappe is one of the best known nappe structures in Japan. It overlies the Mikabu greenstones (commonly called Mikabu green rocks in Japanese literature) within the Sambagawa belt (Kanto region, Southwest Japan; Fujimoto *et al.* 1953). The Atokura Nappe is mainly composed of Late Cretaceous fore-arc sediments (Atokura Formation). It is overthrust by the Kinshozan Nappe which is composed of allochthonous granitic and metamorphic rocks. The age and petrologic characteristics of rocks in the Kinshozan Nappe (e.g. Takagi & Fujimori 1989) is quite different from those exposed in the autochthonous basement complexes in Southwest Japan (Ryoke belt, Sambagawa belt, Chichibu belt, etc.). Therefore, determination of the root zones of the Atokura and of Kinshozan Nappes is a significant factor in reconstruction of the geotectonic evolution of Southwest Japan.

The kinematics of many nappe structures have been analyzed on the basis of microstructural analyses of rocks deformed by crystal plastic processes (e.g. Schmid *et al.* 1981, Tubia & Cuevas 1986). In addition, many studies have focused on the development of shear-sense indicators in rocks deformed by cataclastic processes (e.g. Rutter *et al.* 1986, Chester & Logan 1987). It is difficult to recognize the internal structure of the Atokura Nappe and of the Kinshozan Nappe on a map scale (e.g. imbricate fans and/or duplexes) because of the condition of exposures. Hence, Wallis *et al.* (1990) determined the movement direction of the Atokura Nappe *in the last stage* by a structural analysis of slickensides and orientation of minor fractures on the basal fault.

In this paper, I describe the mesostructural and microstructural characteristics of foliated fault rocks formed by cataclastic processes developed along the basal contact of the Atokura Nappe (in klippes), and along low-angle shear zones in the adjacent footwall (in Mikabu greenstones) and hanging wall (mainly in the Atokura Formation). This evaluation allows detection of several slip-vectors of the Atokura Nappe. Subsequently the different phases of movement are described, and tectonic evolution of the Atokura Nappe is discussed.

GEOLOGICAL SETTING

The Sambagawa belt extends in an WNW–ESE direction in the Kanto region. It is separated from the Ryoke belt to the north by the Median Tectonic Line, and by the Mikabu Tectonic Line from the Chichibu belt to the south. The Atokura Nappe overlies the Mikabu greenstones within the Sambagawa belt in the areas of Shimonita, Kamiyama and Ogawa (Figs. 1 and 2).

The Mikabu greenstones consist mainly of low-grade metabasites (greenstones) and ultrabasic rocks. Greenstones commonly contain pumpellyite and/or alkali-amphibole together with chlorite, epidote, actinolite and albite, indicating that the greenstones have undergone pumpellyite–actinolite facies metamorphism. The Mikabu greenstones and subordinate schists are considered to represent on accretionary complex of Latest Jurassic and/or Early Cretaceous age (Hara *et al.* 1990).

Based on lithofacies (conglomerates and alternating beds of sandstone and mudstone), sandstone petrography (feldspathic arenites) and fossil evidence (Watanabe *et al.* 1990), the Atokura Formation is inferred to consist of Late Cretaceous fore-arc sediments. It has undergone considerable post-consolidation deformation which resulted in the development of complicated fold and thrust structures.

The uppermost Kinshozan Nappe which is composed of Permian granitic rocks and associated hornfels, as well as other allochthonous bodies (Early Cretaceous granitic rocks and low- to medium-P–T metamorphic

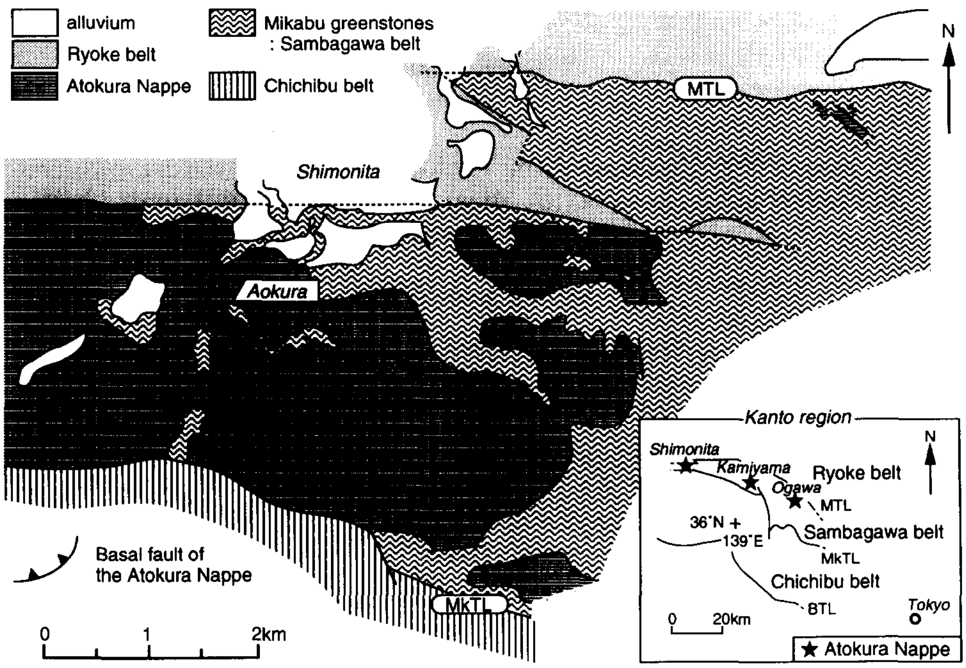

Fig. 1. Tectonic outline of the Kanto region and the tectonic map of the Shimonita area. MTL, Median Tectonic Line; MkTL, Mikabu Tectonic Line; BTL, Butsuzo Tectonic Line. In this map, the Atokura Nappe and the Kinshozan Nappe are illustrated together as the Atokura Nappe.

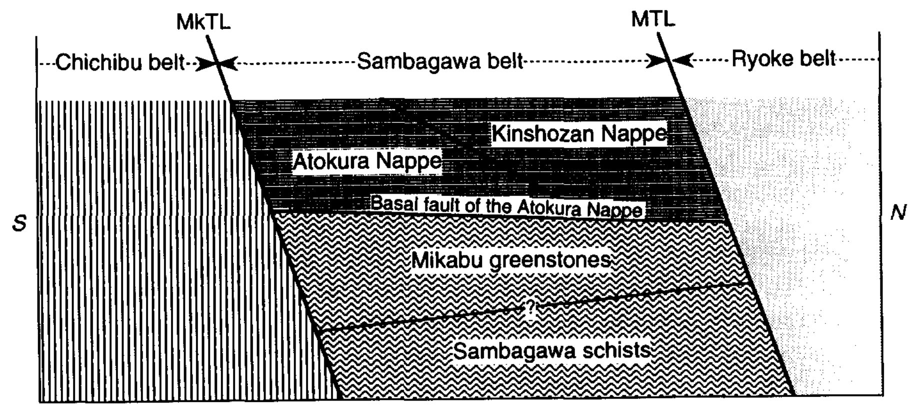

Fig. 2. Schematic structural section in Southwest Japan (Kanto Range). MTL, Median Tectonic Line; MkTL, Mikabu Tectonic Line.

rocks) overlies the Atokura Formation (Takagi *et al.* 1989, Hayama *et al.* 1990). Both the Atokura Formation and the Permian granitic rocks have undergone prehnite–pumpellyite facies metamorphism (Hirajima 1984). However, high-P–T pelitic (and rarer basic) schists are intercalated between the Atokura Formation and the Mikabu greenstones. Locally the schists preserve evidence for metamorphism under higher greenschist facies condition. All the allochthonous bodies (granitic rocks, metamorphic rocks and the Atokura Formation) may have been emplaced onto the Mikabu greenstones after each had undergone separate types of metamorphism.

The low-angle basal fault of the Atokura Nappe is rather well exposed in the Shimonita area and is also found in few outcrops in the Kamiyama and Ogawa areas. On average, the basal contact is dipping 2–3°NW but a considerable variation in dip and dip directions is observed. In view of the outcrop conditions the current study is concentrated on the Shimonita area.

DISTRIBUTION OF FAULT ROCKS

Terminology

All the fault rocks formed by cataclastic processes which occurred along the basal contact of the Atokura Nappe and along low-angle shear zones in the adjacent footwall and hanging wall. These fault rocks are considered to be related to movements of the nappe. They are separated into *cataclasite series* and *fault-gouge series* based on the presence or absence of cohesion. Within the cohesive cataclasite series two end-members can be recognized: *cataclasite* and *microbreccia*, and within the incohesive (or semi-cohesive) fault-gouge series: *fault*

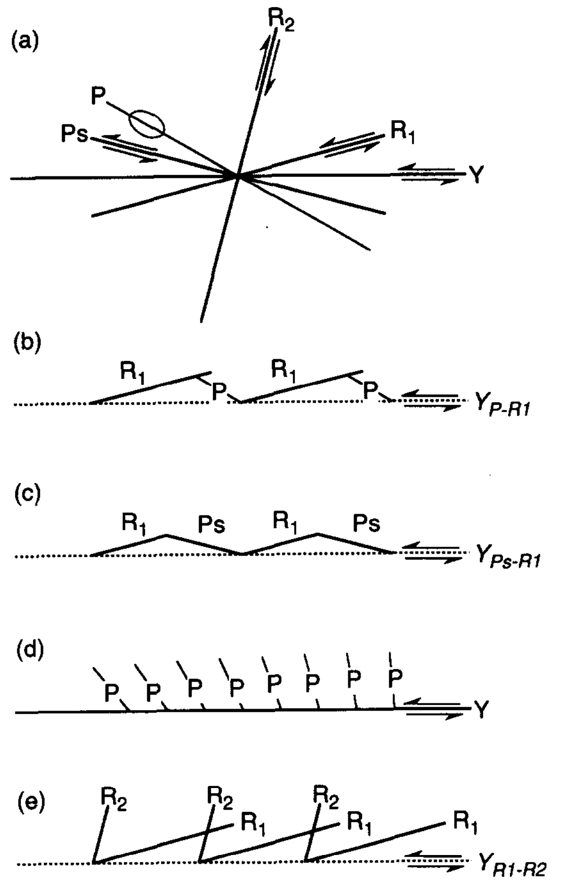

Fig. 3. (a) Terminology for composite planar fabric. (b)–(e) Approximate orientation of structures. (b) & (c) P–R_1 fabric, (d) P–Y fabric and (e) R_1–R_2 fabric.

gouge and *fault breccia*, based on relative volume percent of matrix. Rocks in the cataclasite series and in the fault-gouge series have foliated- or random-fabric (e.g. Gay & Ortlepp 1979, Chester *et al.* 1985, Rutter *et al.* 1986, Chester & Logan 1987, Zulauf *et al.* 1990, Tanaka 1992). The division between foliated- and random-fabric also depends on the scale of observation. For example, some specimens have random fabric at microscopic scale, as well as foliated fabric at mesoscopic scale.

In contrast, some Mikabu greenstones have a weak schistosity formed by crystal plastic processes, probably developed coeval with metamorphism.

In this paper, the meso- and microstructure of fault rocks is described, including those on basal fault surfaces which are combination of R_1–R_2 shears developed on a mesoscopic scale. Such fault surfaces partially disturb the microstructure of pre-existing rocks (cataclasites). In this paper, I mainly use the terminology for composite planar fabric (Fig. 3a) given by Rutter *et al.* (1986).

Occurrence of fault rocks in the Shimonita area

Various kinds of fault rocks occur on each part of the Atokura Nappe. The distribution of fault rocks is determined by the position of the shear zones. Shear zones are classified into four types according to distance from the basal fault of the Atokura Nappe, which is represented by a clear lithologic boundary: immediately below and above the basal fault less than a few meters from the boundary, and internal shear zones about 20–30 m above (in the Atokura Formation) or below (in the Mikabu greenstones) the boundary (Figs. 6a–d).

Incohesive (or semi-cohesive) fault-gouge series rocks mainly derived from greenstones occur immediately below the basal fault (10 outcrops in the Shimonita area), as well as along the internal shear zones within the Mikabu greenstones (six outcrops in the Shimonita area).

Cohesive cataclasite-series rocks are mainly derived from sandstones of the Atokura Formation, and occur immediately above the basal fault (eight outcrops in the Shimonita area). They locally have a foliated fabric, but apart from the basal fault, a random-fabric is predominant. As a whole, the cataclasite zone is at least a few tens of metres in thickness. By contrast, along some high-angle faults no cataclasite-series rock occurs. This kind of fault seems to be newly generated.

Incohesive fault-gouge series rocks (fault breccias), mainly derived from sandstones occur along the internal shear zones within the Atokura Formation (two outcrops in the Shimonita area).

Fault rocks from the outcrop at Aokura

In the Shimonita area, the largest and the best known outcrop of the basal fault is at Aokura, 5 m high and 30 m long (Figs. 1 and 4a & b). It has a lithologic boundary dipping about 30°N. In this outcrop, a detailed structural analysis was carried out to determine the sequence in which the different fault rocks were formed.

The hanging wall in the outcrop is a cohesive cataclasite derived from sandstones of the Atokura Formation (RCZ-FCZ, in Figs. 4a, b & d), whereas the footwall is, as a whole, composed of an incohesive or semi-cohesive fault breccia derived from the Mikabu greenstones. In the footwall, three distinct narrow fault-gouge zones can be defined: (1) a 10 cm thick semi-cohesive facies immediately below the basal fault (SGZ, in Figs. 4a & b); (2) a 10 cm thick incohesive facies in this fault-breccia zone (IGZ); and (3) a wet clayey incohesive facies in IGZ, which varies in thickness from 0.5 to 1 cm (WGZ). Each of these fault-gouge zones have a flat–ramp–flat geometry. In view of the overprinting relations (Fig. 4b) and the difference in cohesion, the sequence in which three gouge zones were formed is SGZ, IGZ and WGZ.

Both the lithologic boundary and the fault-gouge zones are overprinted by a fabric of R_1 and R_2 shears (Fig. 4c). Slickenlines on the R_1 shears are inferred to have originated from asperity ploughing (Means 1987). In addition, lunate fractures (Petit 1987) are observed (Wallis *et al.* 1990).

FABRICS OF FAULT ROCKS

Cataclasite series

The cataclasite-series rocks in the study area are mainly derived from sandstones (feldspathic arenites).

Mesoscopic structures in the fault zones are P foliations, R_1 shears, Y surfaces and stretching lineations (Fig. 5a). The attitude of the P foliations and R_1 shears relative to the Y surfaces are used as a shear-sense indicator (Fig. 3a).

The Y surfaces are the most conspicuous mesoscopic planar features. They are characterized by a composite layering of fine- and coarse-grained seams. The fine-grained seams are microbreccias composed of shale (slate) fragments, or cataclasites composed of sandstone–shale (slate) fragments and quartz grains (10–100 μm) embedded in a fine-grained matrix. Stretching lineations, defined by elongated fragments or aggregates of separated grains are developed both on the P foliations (cataclastic lineations: Tanaka 1992) and the Y surfaces (Fig. 5b). The coarse-grained microbreccias are composed of sandstone-shale (slate) fragments and relatively large (100–200 μm) quartz grains. Stretching lineations, composed of weakly elongated fragments are well developed on the Y surfaces.

Microscopic observations of XY and XZ thin sections indicate that quartz and feldspar grains are essentially free of intracrystalline deformation. The orientation of the foliations in the slate-fragments are random and generally oblique to P foliations and Y surfaces of cataclasites. Some specimens include the aggregates of calcite grains. They are plastically elongated and recrystallized and form stretching lineations with pinch-and-swell structure (Fig. 5b). Preferred shape alignment of quartz-grains and of mica-clay minerals in the ultra-fine matrix are observed on XY thin section, parallel to Y surfaces (Fig. 5c).

Fault-gouge series

The fault-gouge series rocks in the study area are mainly derived from greenstones. P foliations (or P shears), R_1 shears, Y surfaces (Fig. 3a), stretching lineations and slickenlines are well developed. In this paper, I use the term P shears for thrust shears on which weak slickenlines are formed and which are oblique to the P foliations. Based on the composite planar fabrics, fault-gouges derived from greenstones can be classified into two types.

(1) *P–*R_1 *(–Y) type*. The Y surfaces in this fabric type are made up of a composite of microscale P foliations (or P shears) and R_1 shears (Fig. 5e). Some specimens have only P foliations (or P shears) and R_1 shears, and continuous Y surfaces are not visible on mesoscopic scale (Fig. 5d). In these cases, Y_{P-R_1} (or $Y_{P_S-R_1}$) surfaces which are the enveloping surfaces of P foliations (or P shears) and R_1 shears can be defined (Figs. 3b & c).

(2) *P–Y (–R1) type*. The Y surfaces in this fabric type are continuous shears oriented parallel to the fault surfaces. These are relatively planar features both in hand-specimen and on a microscale, and cut P foliations obliquely. P foliations are orientated at 90–135° (intermediate angle to nearly perpendicular) to the shear direction (Figs. 3d and 5f & g). Some specimens have weakly-developed R_1 shears. In general, this type is composed of a high proportion of matrix and fine-grained fragments.

The fault-gouge series rocks derived from sandstone are all fault breccias whose fabrics are similar to those of the P–R_1 (–Y) type.

Within the fault-gouge series rocks two types of lineations are developed: (1) stretching lineations composed of elongated aggregates of actinolite grains or fragments embedded in a matrix of fine-grained chlorite and clay minerals. They occur on the P foliations (cataclastic lineations: Tanaka 1992) and on the Y surfaces in the P–R_1–Y type; (2) the parallel orientation of weak slickenlines are formed on P shears and on R_1 shears in the P–R_1 (–Y) type, and on Y surfaces in the P–Y (–R_1) type. These lineations on P foliations (or P shears) and on R_1 shears are regarded as slip-directions after projection on the Y or Y_{P-R_1} (or $Y_{P_S-R_1}$) surfaces (Lin & Williams 1992, Tanaka 1992).

R_1–R_2 *fabric on the basal fault surface*

The R_1–R_2 fabric is a combination of R_1–R_2 shears which are overprinted on a mesoscopic scale, especially on a hand-specimen scale in pre-existing cataclasite in the study area (Fig. 5h). As the mesoscopic structures, R_1–R_2 shears and slickenlines are formed, and the enveloping $Y_{R_1-R_2}$ surfaces are defined. The combinations of R_1–R_2 shears make incongruous slickensteps (RO type: Petit 1987) on the specimen surfaces. Their orientation can be used as a shear-sense indicator (Figs. 3a & e). The slickenlines developed on R_1 shears are regarded as slip-directions after projection on the $Y_{R_1-R_2}$ surfaces.

SLIP-VECTOR OF THE ATOKURA NAPPE

Shimonita area

The attitudes of foliations (Y or Y_{P-R_1} or $Y_{P_S-R_1}$ or $Y_{R_1-R_2}$ surfaces) and lineations, and the sense of movement in the analyzed fault rocks and in the R_1–R_2 fabrics are illustrated in Figs. 6(a)–(d).

Foliations dip mostly at low- to intermediate-angles. Steeply dipping foliations are occasionally observed in the fault-gouges and in the R_1–R_2 fabrics. The pitches on the foliations show that the relative displacement across the faults varies and strike-slip, normal-slip and thrust movement are all locally recognized.

The major slip directions of the hanging walls vary according to the type of shear zones. The predominant slip directions are shown in Fig. 6: they are WNW along the shear zones within the Mikabu greenstones; N to NW (ranging from WNW to ENE), immediately below the basal fault; W to WNW and NNW to NNE immediately above the basal fault; and N along the shear zones within the Atokura Formation.

The major slip directions also vary with the type of fault rocks. In the cataclasite-series rocks, the slip direc-

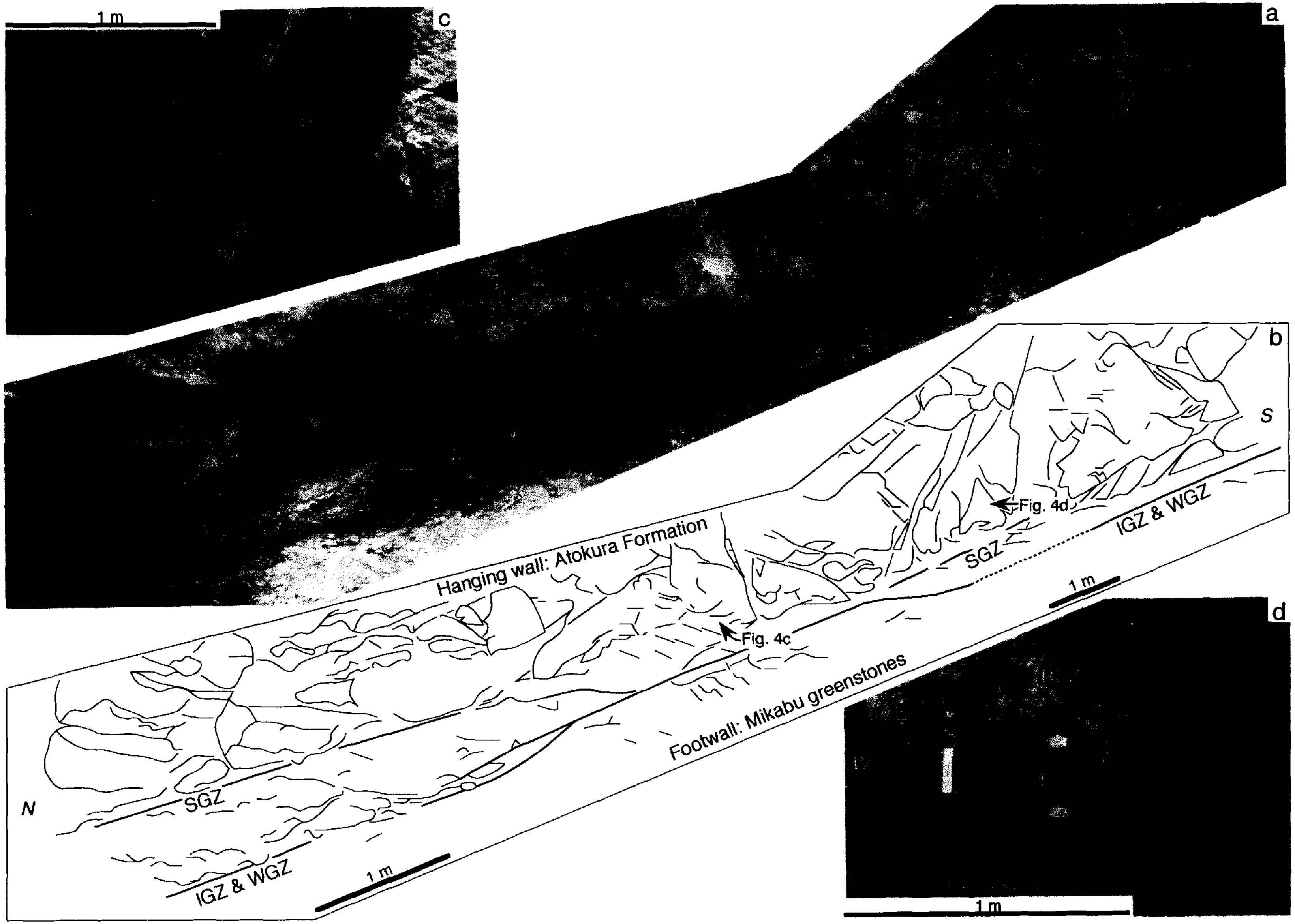

Fig. 4. Photographs and line drawing of the outcrop at the base of the Atokura Nappe at Aokura. (a) & (b) View of the complete outcrop; (c) R_1–R_2 fabric observed at the base of the hanging wall and slickenlines observed on R_1 shear surfaces (arrow); (d) cataclasite zone immediately above the basal fault. RCZ, Cataclasite zone with random fabric; FCZ, cataclasite zone with foliated fabric; SGZ, semi-cohesive fault-gouge zone; IGZ, incohesive fault-gouge zone; WGZ, incohesive fault-gouge zone in wet clay. R_1–R_1 shear. R_2–R_2 shear.

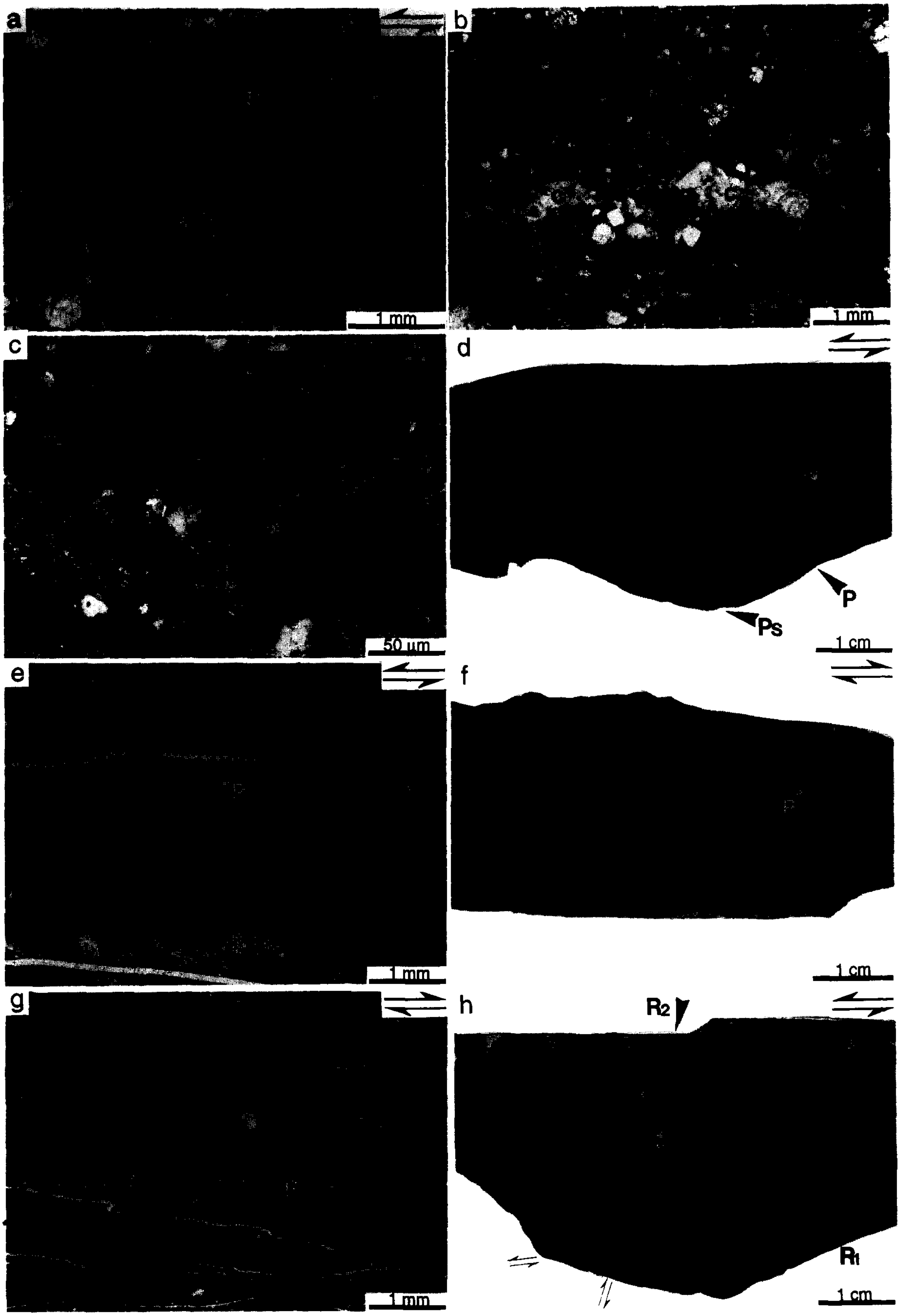

Fig. 5. Photographs of rock slices and thin sections of fault rocks derived from the base of the Atokura Nappe. (a)–(c) Cataclasite derived from sandstone. (a) *XZ* thin section, (b) & (c) *XY* thin sections; c, aggregate of calcite grains. (d)–(e) P–R_1 type fault-gouge derived from greenstone, (d) *XZ* polished slice, (e) *XZ* thin section. (f) & (g) P–*Y* type fault-gouge derived from greenstone, (f) *XZ* polished slice, (g) *XZ* thin section. (h) R_1–R_2 fabric overprinted on the cataclasite, *XZ* polished slice. P–P foliation; P_s–P shear; R_1–R_1 shear; R_2–R_2 shear.

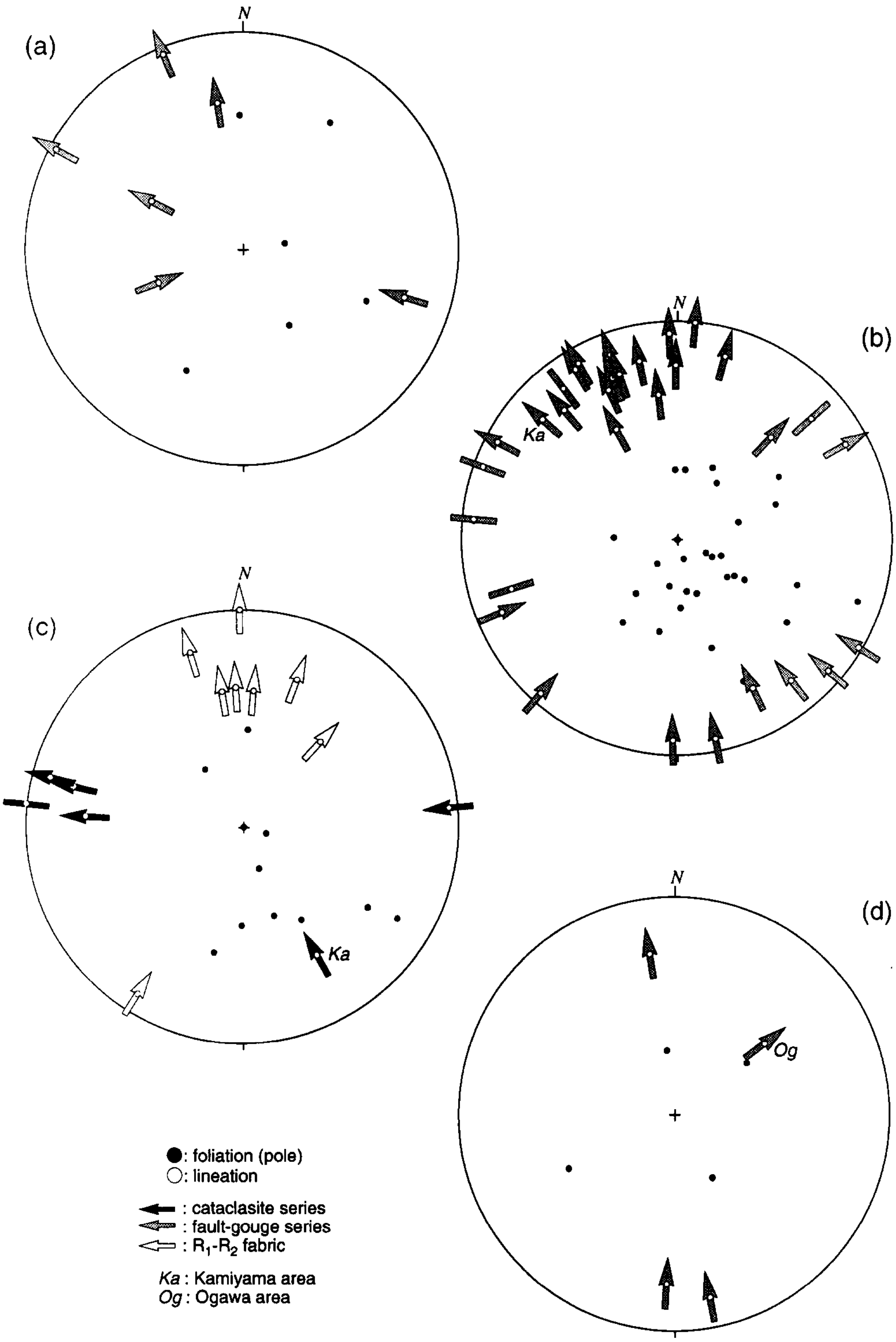

Fig. 6. Attitudes of foliations, lineations, slip senses (arrows) and indeterminate slip senses (bars) in shear zones within the Mikabu greenstones (a); immediately below the basal fault (b); immediately above the basal fault (c); in the shear zones within the Atokura Nappe (d). Equal-area lower-hemisphere projections.

tions range from W to WNW (from a specimen in the Kamiyama area, NNW). In the fault-gouge series rocks, the major-slip direction ranges from NW to N; in the R_1–R_2 fabrics on the lithologic boundary, from N to NE.

The outcrop at Aokura

In the outcrop at Aokura, the three fault-gouge zones (SGZ, IGZ and WGZ in Fig. 4b) were investigated in detail. Sixteen attitudes of foliations and lineations, and 12 slip directions were determined.

The major slip directions are as follows: ENE in SGZ; N to NW in IGZ; and N in WGZ. As a whole, the attitudes of the foliations and lineations of the fault-gouges are scattered widely, and the slip directions vary from WNW to ENE.

In contrast, the R_1–R_2 fabrics indicate that the hanging wall moved northward in the outcrop at Aokura

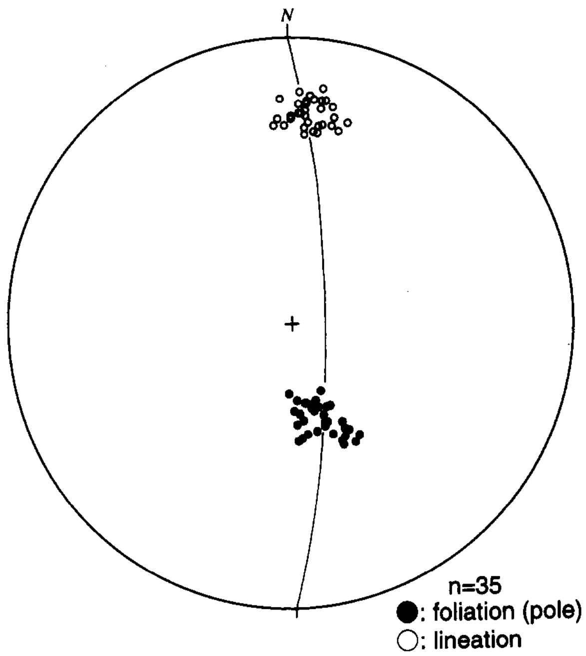

Fig. 7. Attitudes of slickensides, slickenlines and their symmetry plane (great circle) on the basal fault in the outcrop at Aokura. Equal-area lower-hemisphere projections. The mean attitude of slickensides is N71E28NW, and of slickenline N05E26.

(Fig. 4c, and Wallis *et al.* 1990), and the attitudes of slickensides and slickenlines concentrate in a narrow range (Fig. 7).

DISCUSSION

Division of the Atokura Nappe movement into stages

The sequence in which the fault rocks were formed in each outcrop of the basal faults of the Atokura Nappe can be determined on the basis of meso- and microstructures and slip directions.

For example, in the outcrop at Aokura, *Y* surfaces of cataclasites are subparallel to the lithologic boundary or to R_1 shears (slickensides). Three groups of the slip directions can be detected; the stretching lineations observed on the *Y* surfaces and determined slip directions of cataclasites range from W to WNW, the slickenlines and R_1–R_2 fabrics on the slickensides indicate the slip directions to be northward, and the slip directions of fault-gouges range from WNW to ENE. Such variations are observed in most outcrops. The movement stage of the Atokura Nappe is classified into three stages, I, II and III, as shown in Table 1.

(1) *Stage I–stage II.* Cataclasites have strong cohesion and cataclastic flow fabrics. Plastic behaviour of calcite grains and preferred-orientated mica-clay minerals (while quartz grains behave in a brittle manner) suggest that the cataclasites have formed in a different rheological regime at a deeper crustal level than that of the fault-gouges. Few fault-gouges in the study area include calcite grains, all of which deform in a brittle manner.

Since the cataclasites were only derived from clastic rocks but not from greenstones, they probably formed apart from the Mikabu greenstones. During and/or after the juxtaposition of the Atokura Nappe onto the Mikabu greenstones, near-surface deformation was only localized in the greenstones to form the fault-gouges. In other words, the formation of the cataclasite zone (RCZ–FCZ) was followed by the formation of the fault-gouge zones (SGZ and IGZ), and can be divided into stages I and II, respectively (Table 1). This division is applicable in all outcrops of the basal fault of the Atokura Nappe.

(2) *Stage II–stage III.* The attitude of the foliations and lineations of the fault-gouges are scattered widely. However, multiple slip directions on a single fault surface can be generated by fault interaction without a change of the regional stress field (e.g. Cashman & Ellis 1994). Hence, although the slip directions of fault-gouges in IGZ vary from N to NW, it is difficult, however, to further divide the period in which these fault-gouges are formed.

In contrast, the attitudes of slickensides (R_1 shears) and slickenlines concentrate in a narrow range (Fig. 7). In addition, the fault-gouge in WGZ, which is the last formed fault-gouge zone, indicates the sense of movement as N directed. R_1–R_2 fabrics (slickensides and slickenlines) on the lithologic boundary indicate the same sense. The crustal regime in which the R_1–R_2 fabrics observed on the lithologic boundary formed is difficult to divide from that of the fault-gouges. Hence, the R_1–R_2 fabrics and part of the fault-gouges, at least in WGZ, may have formed during the last period, stage III (Table 1).

Dynamics of the Atokura Nappe

The major-slip directions of each hanging wall are: stage I—ranging from W to WNW; stage II—ranging from NW to N; and stage III—N (Table 1). In other words, the slip direction of the Atokura Nappe has rotated clockwise.

The fault-rocks are characterized by cataclasite series in stage I and by fault-gouge series in stage II. The depth of fault movement has been gradually decreasing.

Viewed from the detritus in sandstones of the Atokura Formation, the cataclasites have been formed in the Chichibu belt, whose basement rocks are mainly composed of Jurassic clastic–accretionary complexes. The major slip direction (from W to WNW) in stage I is subparallel to the trend of the geologic belts in Southwest Japan (Kanto Range). Hence, the formation of the cataclasite zone might have been closely associated with the strike-slip tectonics of Southwest Japan (e.g. Faure 1985, Wallis *et al.* 1992).

In stage II, the upper part of the cataclasite zone which constitutes the hanging wall of the Atokura Nappe has been emplaced northwestward onto the Mikabu greenstones, and deformation has been localized in the fault-gouge zones immediately below the basal fault and in the fault-gouge zones within the Mikabu greenstones.

Subsequently, the *R*1–*R*2 fabrics overprinted older

Table 1. Characteristics of the fault rocks and their implications for slip history

Stage	Fault rocks	Composite-planar fabrics	Lineation	Major slip direction
I	Cataclasite series	P–R_1–Y	Stretching lineations	W to WNW
II	Fault-gouge series	P–R_1 (–Y) or P–Y (–R_1)	Stretching lineations or slickenlines	N to NW
III	—	R_1–R_2	Slickenlines	N

fabrics in stage III. Wallis *et al.* (1992) suggested that the Atokura Nappe has formed under extensional tectonics, based on the analysis of the outcrop at Aokura. Although, the mode of fault movement (pitches of lineations) varies among outcrops in the Shimonita area, the slip directions are concentrated to be northward. Hence, taking account of the gradual shallowening of fault movement, the Atokura Nappe might have moved downward under the increasing influence of gravity sliding caused by the differential exhumation of the Chichibu belt relative to the Sambagawa belt.

In conclusion, the driving force of the movement of the Atokura Nappe has been transferred from a strike-slip tectonic-setting to extensional tectonic-setting. As a result, the slip direction of the Atokura Nappe has rotated clockwise.

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