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The block rotation in the Uetsu area, Northern Part of Niigata Prefecture, Japan

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Paleomagnetic and geologic studies were made in the Uetsu area, NE Japan, to clarify the Miocene intra-arc deformation associated with the Japan Sea opening. We obtained paleomagnetic directions from the Early to Middle Miocene pyroclastic rocks and lavas in the area. The average paleomagnetic direction is $D = 28.0°$, $I = 48.7°$ and $\alpha_{95} = 9.6°$. It suggests that the clockwise rotation occurred in this area, which is opposite to the counter-clockwise rotation of NE Japan. A fault was discovered which could be the boundary of this rotating domain. The dextral movement is recognized for this fault, concordant with the clockwise rotation in the area. These paleomagnetic and structural data suggest that the clockwise block rotations occurred in the Uetsu area, accompanied by the dextral deformation.

1. Introduction

Paleomagnetic studies have shown that NE Japan consisted primarily of counter-clockwise (CCW) rotating blocks when the Japan Sea opened (Sasajima, 1981; Otofuji *et al.*, 1985, 1994; Hoshi and Matsubara, 1998; Yamaji *et al.*, 1999). However, clockwise (CW) deflections are reported from the Takadate, Yanagawa, Matsushima areas, indicating CW rotations (Oda *et al.*, 1989; Yamazaki, 1989). This fact suggests complex intra-arc deformations in NE Japan. They are still matters of debate what kind of geologic structures accommodated those block rotations and that there were blocks with opposite sense of rotation.

The Uetsu area, southwestern NE Japan, is one of the areas where easterly deflected data have been obtained (Fig. 1). They are ascribed to CW block rotations accompanied by strike-slip faultings between CCW rotating blocks (Otofuji *et al.*, 1985; Yamaji *et al.*, 1999). However, their paleomagnetic data are obtained mostly from a single geologic unit that covers a short period of time. Therefore, it is not clear whether they are really tectonic in origin. The purpose of this paper is to present new paleomagnetic data to demonstrate the tectonic origin of easterly deflected paleomagnetic directions and to describe a fault zone that was found in this study and is likely to be related to the block rotations.

2. Geologic Setting and Sampling

2.1 Geology of the study area

In the Uetsu area, there are Early Miocene grabens that are filled with lacustrine and pyroclastic deposits (Takahama, 1976; Agency of Natural Resources and Energy, 1982; Yamaji, 1989; Hataya and Otsuki, 1991). The graben-fills are covered by Middle Miocene transgressive marine sequence. The basement of the graben-fills consists mainly of Mesozoic accretionary complexes, Cretaceous–Paleogene plutonic rocks and the Early Miocene ignimbrites called the Kitaoguni Formation. The stratigraphy of the area is shown in Fig. 2.

The basement of the Miocene deposits consists of plutonic and mylonitic rocks (Yamaji, 1989). A NW–SE trending mylonite zone called the Nihonkoku Mylonite transverses the northern Uetsu area. The mylonite is intruded by granite at its northern border, but grades into the Iwafune Granite to the south of the mylonite (Takahashi, 1998). The mylonitization was Cretaceous in age and microstructures indicate sinistral transtension (Takahashi, 1998). The K-Ar ages ranging from 90 to 50 Ma are reported from the Iwafune Granite (Agency of Natural Resources and Energy, 1982).

The Miocene deposits rest on the basement with unconformity, which consist of the Kitaoguni, Tenjosan, Asahi, Wasada Formations and the Osudo Shale (Agency of Natural Resources and Energy, 1982). The Kitaoguni Formation is extensive rhyolitic ignimbrites which occupy the basal horizon of Miocene sequence, which is composed of rhyolitic lavas and tuffs in the study area. This formation is dated at 22.4 ± 0.6 Ma by fission-track method (Ganzawa, 1987). The K-Ar age at 22 Ma is also reported by Ueda *et al.* (1973). It yields a K-Ar age at 20.2 ± 1.0 Ma in the Tamaniwa area to the southeast of the Uetsu area (Yanagisawa and Yamamoto, 1998). The Tenjosan Formation lies on the Kitaoguni Formation and is composed of altered andesitic lavas and tuffs. This formation is correlated to the Oizumi Formation in the northern Uetsu area that yields K-Ar ages at 19.5 ± 1.0 and 19.9 ± 1.0 Ma (Agency of Natural Resources and Energy, 1982). The Asahi Formation and Osudo Shale consist mainly of marine mudstones. The Asahi Formation yields planktonic foraminiferas which

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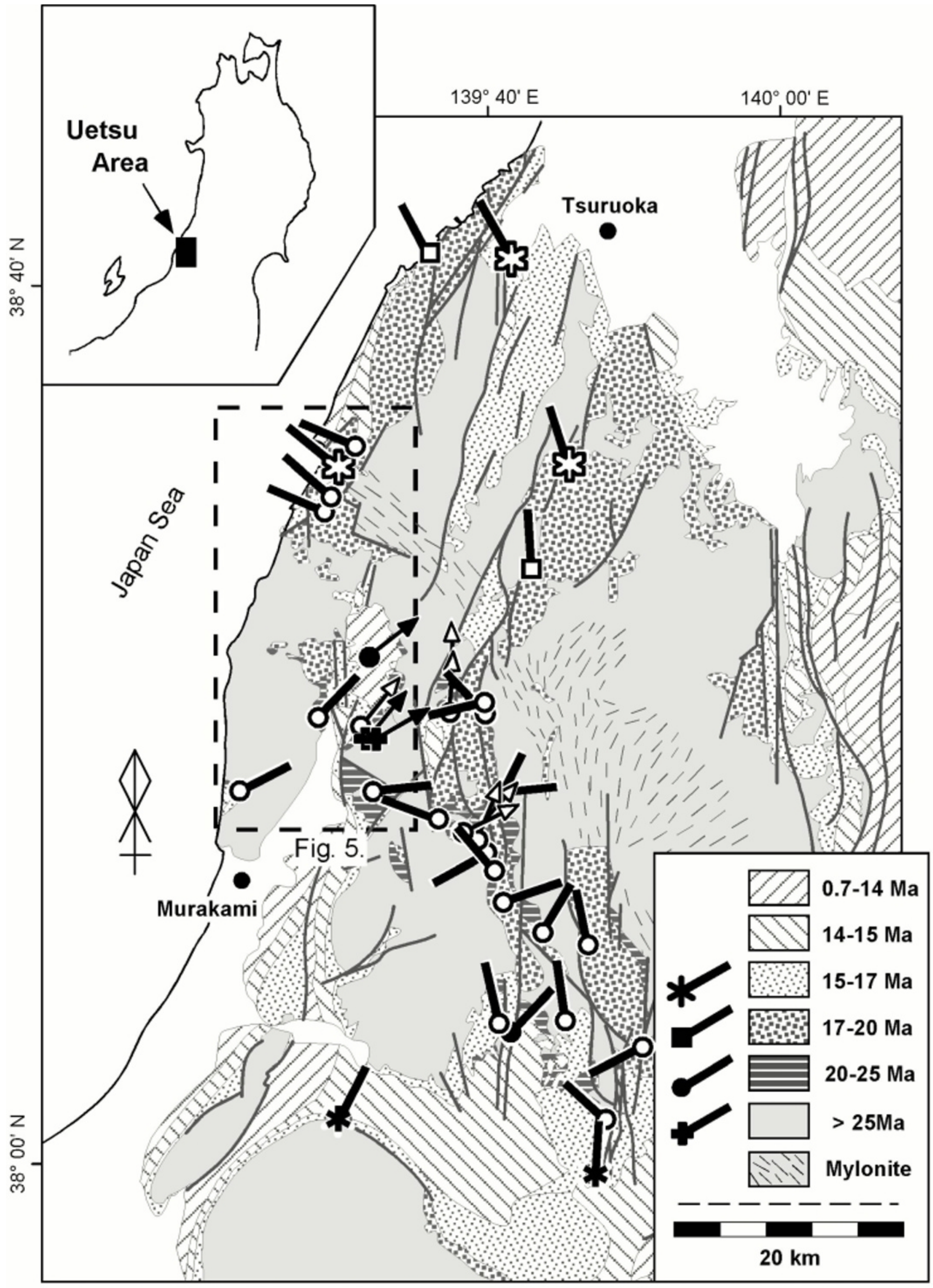

Fig. 1. Geological map of the Uetsu area with paleomagnetic directions reported by preceding studies. Bars and arrows with symbols indicate the paleomagnetic directions obtained by Yamaji *et al.* (1999) and Otofuji *et al.* (1985), respectively. Symbols mean their ages, and solid and open ones indicate paleomagnetic data from normal- and reversed-polarity sites. Those from reversed-polarity sites are inverted by 180°. Geologic map after Yamaji *et al.* (1999).

is correlated to Blow's (1969) N.9 zone (Agency of Natural Resources and Energy, 1982). The Wasada Formation is mainly composed of basaltic to andesitic lavas in the study area.

The Myojin-iwa Andesite is of the Pliocene in age, and unconformably overlies these Miocene strata. This unit consists of andesitic lavas and conglomerates. The K-Ar age at 3.1 ± 0.2 Ma is reported from this formation (Agency of Natural Resources and Energy, 1982).

2.2 Paleomagnetic samples

From these formations, we collected samples at 39 sites for paleomagnetic measurement: 11 sites in the Kitaoguni, eight in the Tenjosan, two in the Asahi, one in the Osudo Shale, one in the Wasada Formation, and 16 in the granite (Fig. 5). Three to six rock samples of hand size were collected at each site. The orientation of each sample was measured using a magnetic compass. The orientations of bedding planes were also measured for tilt correction. Eutaxitic textures in welded tuffs were used as the marker of bedding plane. As for lavas, we used bedding planes of overlying or underlying sediments.

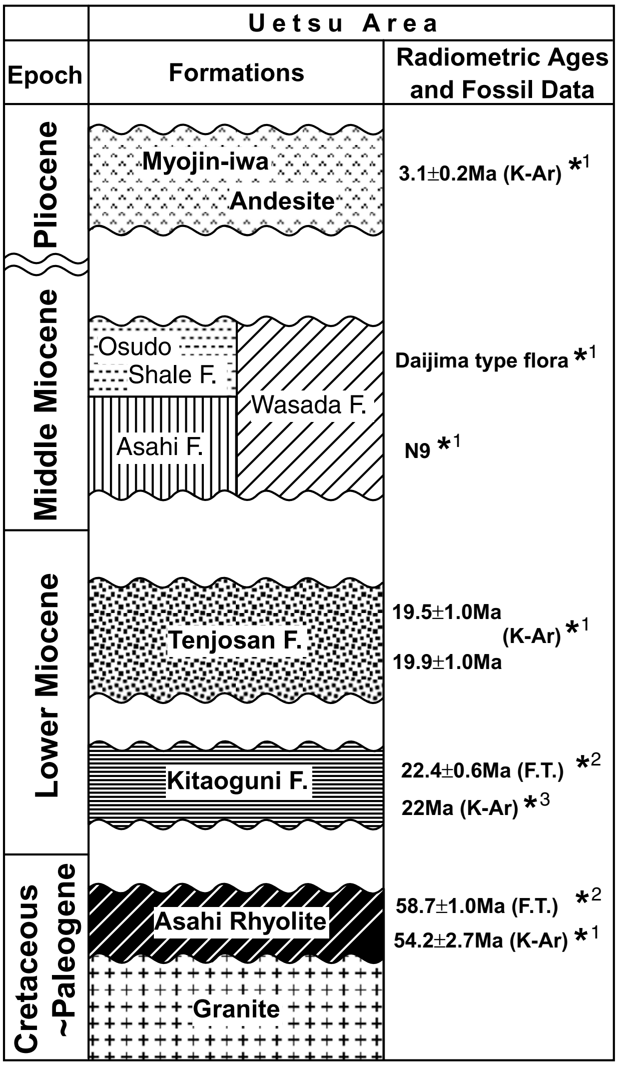

Fig. 2. Stratigraphy in the study area after the Agency of Natural Resources and Energy (1982) and Yamaji (1989). *1: Agency of Natural Resources and Energy (1982), *2: Ganzawa (1987), *3: Ueda *et al.* (1973).

3. Paleomagnetic Measurements and Results

Cylindrical specimens, 25 mm in diameter and 23 mm in length, were prepared in the laboratory from each rock sample. Natural remanent magnetizations (NRMs) of specimens were measured by a spinner magnetometer (Natsuhara Giken) or a cryogenic magnetometer (2G Enterprise) depending on their intensity. Stability of NRM was assessed by progressive thermal demagnetization (PThD). Measurement and PThD processes were carried out in a magnetically shielded room. The ambient magnetic field is lower than 1 μT around the center of the room where measurements were performed. Samples were heated and cooled down in the furnace in which the residual field was lower than 5 nT. For each site, all specimens were heated from 100 to 500°C with intervals of 50°C, and with 20°C intervals above 500°C. Typical magnetic behaviors are shown in Fig. 3. They exhibited linear trends of vector endpoints decaying toward the origins of the vector endpoint diagrams (Zijderveld, 1967) at the demagnetization levels above 500°C (Fig. 3). This high-temperature (high-T) component was regarded as a characteristic remanent magnetization (ChRM) for each specimen. Its direction was determined based on Kirschvink's (1980) method, anchoring the best fit line on the origin of the diagram. A site-mean direction was determined from ChRMs for each site, and its relevance was tested by Fisher's (1953) statistics: if the radius of the 95% confidence circle is smaller than 20°, the average is supposed to be significant. These site-mean directions were tilt-corrected by the conventional method. The formation-mean directions were calculated from them, and it was investigated whether tilt correction alters the degrees of concentration.

In the Kitaoguni Formation, stable magnetic behaviors were obtained from rhyolitic welded tuffs at eight sites out of 11 sites. They consist of one or two components (Fig. 3). The low-temperature (low-T) components were removed by heating up to 250°C. They are parallel to the present geomagnetic field, suggesting viscous remanent magnetizations (VRMs) in origin due to the recent geomagnetic field. After the removal of low-T components, these specimens showed ChRMs around the temperature range between 500 and 600°C. All of these high-T components were obtained from reversed-polarity sites. This supports the suggestion that the Early Miocene rhyolitic tuffs and lavas in the Uetsu area belong to a single pyroclastic flow sheet (Yanagisawa and Yamamoto, 1998). Samples from the other three sites exhibited complete removals of magnetization below 250°C or erratic behaviors during PThD, providing no stable NRM.

In the Tenjosan Formation, specimens of seven sites showed stable magnetic behaviors. They are of altered andesitic welded tuffs. NRMs from six sites exhibited two components, and those from one site (site 6) showed four components (Fig. 3). The components isolated below 250°C had similar directions to the present geomagnetic field. They may also be VRMs. Above 500°C, 30 to 40% of the initial intensity still remained unremoved for each specimen, and this high-T component was cleared off at about 620°C. All of them are from normal-polarity sites. Two kinds of middle-temperature components were obtained from the site 6. The lower-temperature (M1) component ranged between about 250 and 400°C, and the higher-temperature (M2) component between about 400 and 500°C (Table 1). The M1 and M2 components were observed only at one site. Therefore, their origins are not discussed in this paper.

In the Wasada Formation, specimens from only one site showed stable magnetic behaviors, which consist of one stable component (Fig. 3). They are of basaltic to andesitic lavas. They were stable above 500°C and completely removed at 630°C (Fig. 3). The stable components exhibit abrupt drops in intensity between 560 and 630°C.

Granite samples showed complete removal of magnetizations under the temperature level lower than 300°C. It is not probable that they are characteristic, so they are not taken into consideration in the following discussion.

Site-mean directions with α_{95} smaller than 20° were obtained from 12 sites: six from the Kitaoguni, five from the Tenjosan and one site from the Wasada Formation (Table 1). Figure 4 shows these site-mean directions before and after tilt correction. By tilt correction, the paleomagnetic data from the Kitaoguni and Tenjosan Formations were judged

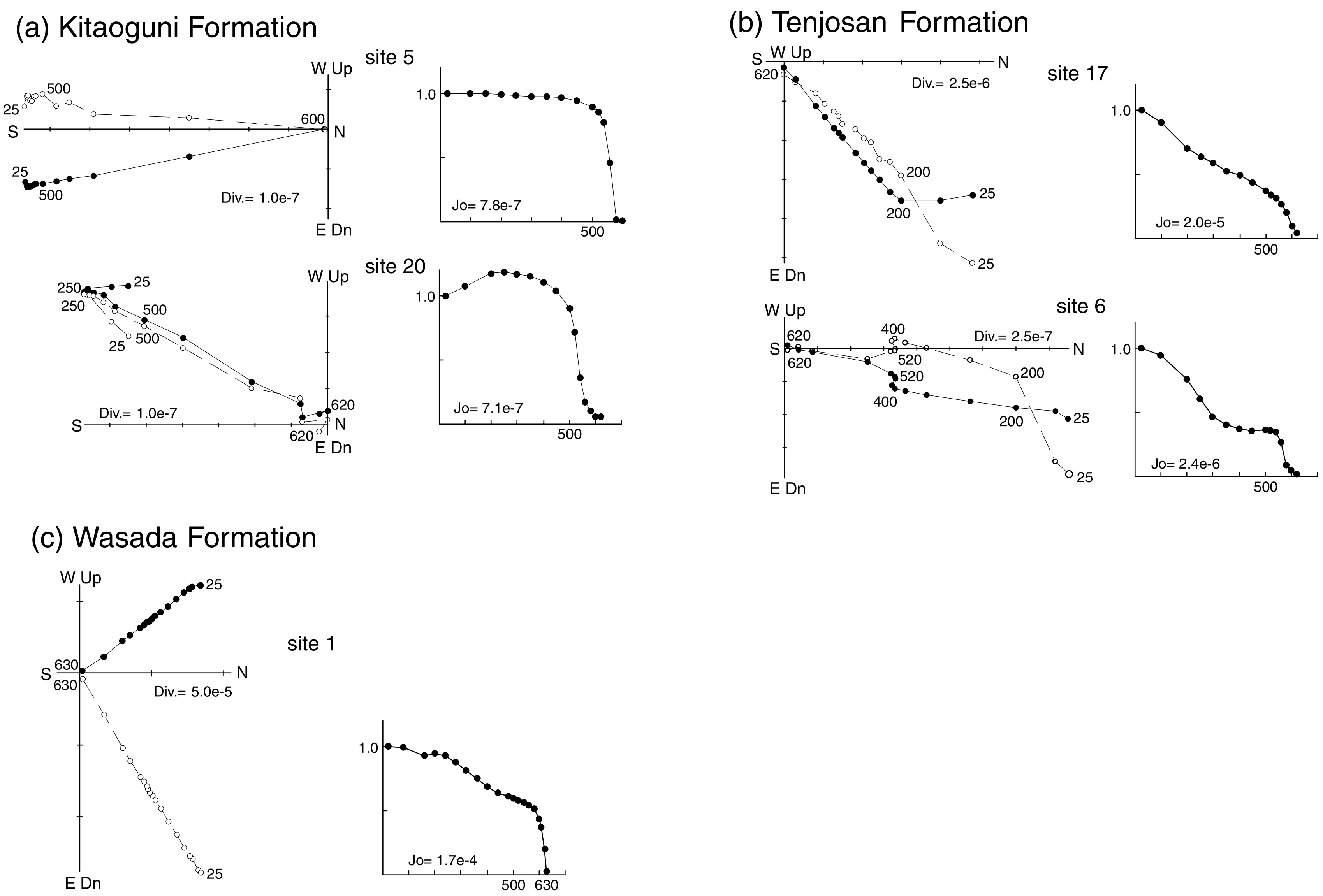

Fig. 3. Vector demagnetization diagrams of typical samples (Zijderveld, 1967) [left]. Solid and open circles are projections in the geographic coordinates onto the horizontal and the vertical N-S plane, respectively. Remanent magnetization intensities versus temperature are also shown [right].

Table 1. Paleomagnetic data from the study area. N = number of specimens. Dec. and Inc. = site-mean declination and inclination. α_{95} = radius of 95% confidence circle. k = precision parameter.

							in situ		tilt corrected			
Loc. No.	Longitude	Latitude	Lithofacies	Formation	Bedding	N	Dec.	Inc.	Dec.	Inc.	α_{95}	k
1	139°31′11″	38°29′29″	basaltic tuff	Wasada	N6E 14E	4	−27.0	49.1	−14.5	62.6	8.8	111.2
5	139°33′10″	38°23′52″	rhyolitic tuff	Kitaoguni	N64E 59S	4	161.7	−9.9	174.6	−67.5	10.6	75.5
6	139°33′23″	38°23′48″	altered andesitic tuff	Tenjosan	N78E 49S	5	13.3	0.2	24.0	42.9	3.2	564.3
(M1)							14.6	14.7	36.1	54.2	4.7	260.8
(M2)							112.1	−53.5	41.4	−52.2	13.7	32.0
7	139°33′23″	38°23′47″	altered andesitic tuff	Tenjosan	N66E 50S	6	9.5	10.2	30.3	47.8	3.9	298.8
9	139°32′49″	38°23′01″	rhyolitic tuff	Kitaoguni	N5E 19E	3	−164.4	−30.3	−155.0	−25.2	7.8	252.9
10	139°32′57″	38°22′59″	rhyolitic tuff	Kitaoguni	N15W 21W	3	177.1	−40.5	158.6	−41.6	33.3	14.8
11	139°32′55″	38°23′02″	rhyolitic tuff	Kitaoguni	N60W 11S	4	−153.6	−43.3	−154.5	−54.3	8.1	129.4
12	139°33′01″	38°22′37″	rhyolitic tuff	Kitaoguni	N59E 58S	6	−168.8	−18.9	−129.5	−49.9	8.9	57.1
14	139°33′54″	38°23′00″	altered andesitic tuff	Tenjosan	N38W 14W	4	55.4	19.9	55.8	33.8	32.5	8.9
15	139°33′51″	38°23′01″	altered andesitic tuff	Tenjosan	N15E 23W	4	68.8	25.5	58.4	42.8	8.2	126.9
16	139°33′44″	38°23′00″	altered andesitic tuff	Tenjosan	N60E 34S	3	54.7	38.8	101.3	61.2	75.4	3.8
17	139°33′52″	38°23′02″	altered andesitic tuff	Tenjosan	N23W 23W	6	44.9	31.9	32.3	50.1	7.6	77.8
18	139°33′47″	38°21′24″	rhyolitic tuff	Kitaoguni	N37W 22W	4	103.5	−28.0	96.4	−13.1	41.1	10.1
19	139°33′50″	38°21′25″	rhyolitic tuff	Kitaoguni	N22W 48W	6	−139.5	−26.1	−175.4	−62.4	3.1	475.2
20	139°33′54″	38°21′25″	rhyolitic tuff	Kitaoguni	N23W 44W	6	−144.4	−21.1	−170.8	−48.1	19.3	13.0
22	139°37′04″	38°22′16″	altered andesitic tuff	Tenjosan	N19E 36E	6	8.3	31.7	30.5	31.1	19.3	13.0

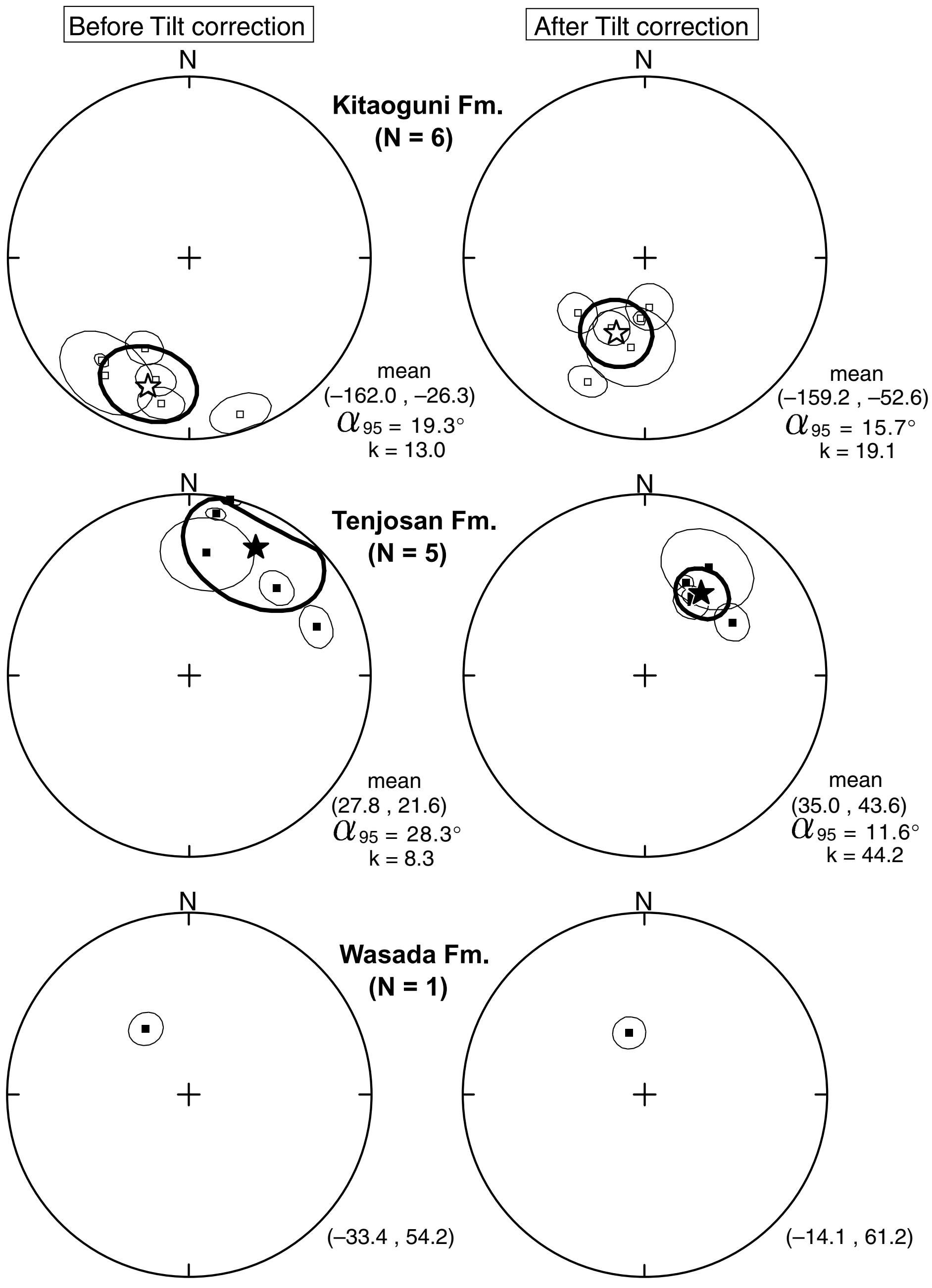

Fig. 4. Equal area projections of site-mean direction with 95% confidence circle for each formation. Solid symbols refer to the lower hemisphere, and open symbols to the upper hemisphere. Stars indicate the formation-mean directions before and after tilt correction.

to be improved. In the Kitaoguni Formation, the α_{95} decreases from 19.3° to 15.7°, and the precision parameter k increases from 13.0 to 19.1 by tilt correction (Fig. 4). In the Tenjosan Formation, the α_{95} of the formation-mean direction decreases from 28.3° to 11.6°, and the k increases from 8.3 to 44.2. Thus, it is suggested that the Kitaoguni and Tenjosan Formations should have obtained ChRMs before tilting, indicating that they were of primary.

The Wasada Formation yielded the paleomagnetic data only at one site. Accordingly, we use the tilt-corrected data of this formation as the primary component hypothetically in the following sections.

4. Discussion

4.1 Interpretation of paleomagnetic directions

Site-mean paleomagnetic directions obtained in this study and those of previous researches are plotted on a geological map (Fig. 5). The spatial change in declination allows us to divide the area into two subareas; the northern subarea with westerly deflected magnetizations and the southern subarea with easterly deflected ones.

For the southern subarea, the representative direction was determined by averaging the site-mean directions (Fig. 6). The results are $D = 28.0°$, $I = 48.7°$ and $\alpha_{95} = 9.6°$. The tectonic rotation is the most likely explanation of these CW deflections for the following reasons: (1) the area-mean

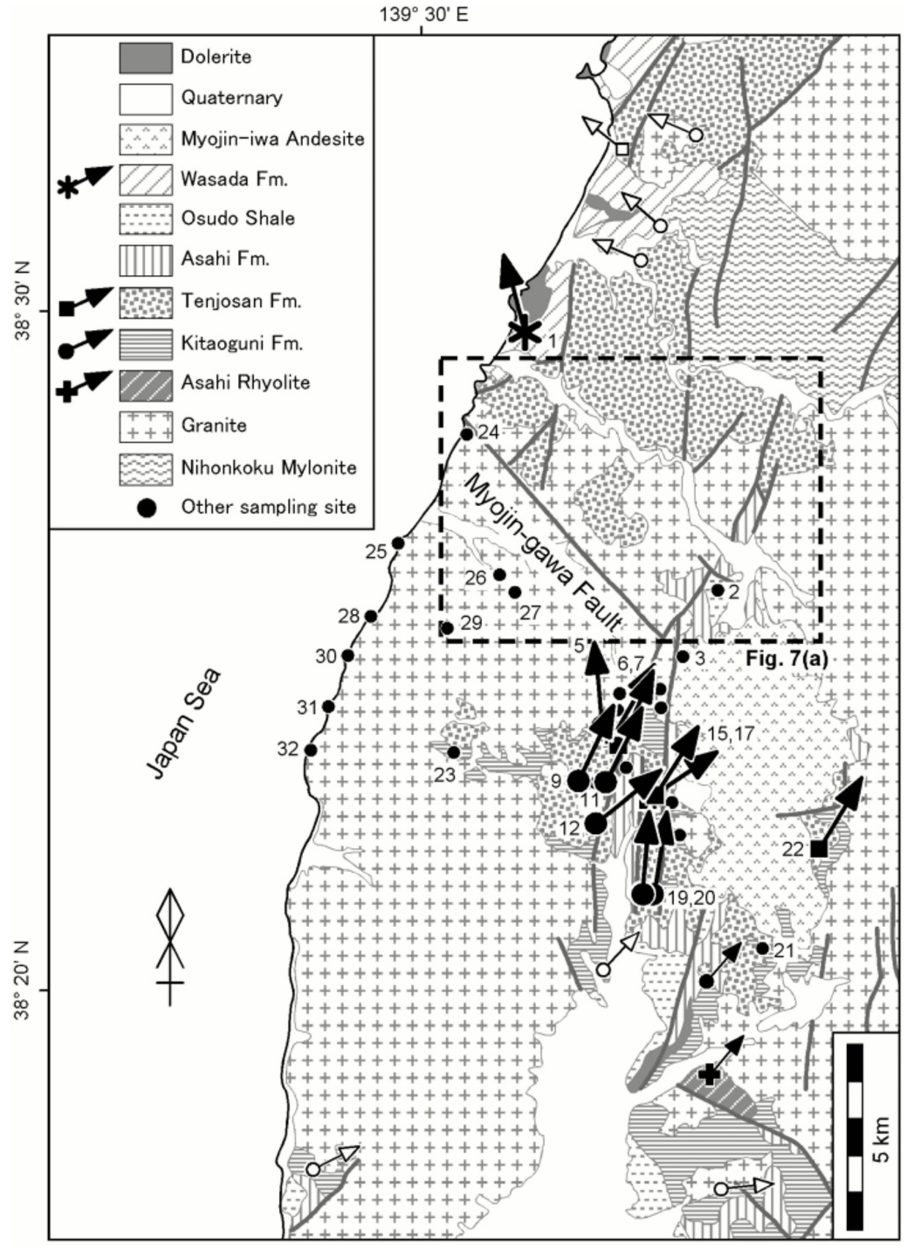

Fig. 5. Tilt-corrected paleomagnetic directions in the study area. Large arrows show declinations obtained in this study. Open and solid small arrows show data by Yamaji *et al.* (1999) and Otofuji *et al.* (1985), respectively. Solid circles show locations of sampling site with no reliable paleomagnetic data. The geological map is based on Agency of Natural Resources and Energy (1982).

direction is significantly deflected from the Miocene geographic north pole, which is not different so much from the present one (Fig. 6), (2) the direction averaging site-mean directions with normal-polarity is almost antipodal to the direction averaging those with reversed-polarity, (3) sampling horizons cover the time interval that is significantly longer than the time-scale of the secular variation (Fig. 2). These lines of evidence suggest the CW rotation in the southern subarea.

These NE-trending directions were obtained from the Kitaoguni and Tenjosan Formations. This suggests that the CW rotation was active after the deposition of the Tenjosan Formation. Therefore, the rotation is supposed to have occurred after 19–20 Ma (Fig. 2). Unfortunately, we cannot determine when this rotation had stopped because of the lack of paleomagnetic data from upper horizons than the Tenjosan Formation.

For the northern subarea, we have only one paleomagnetic direction, and it is impossible to analyze its significance statistically. However, the CCW rotation is supposed to have occurred in this area, based on the paleomagnetic data from the Atsumi area which also reports the NW-trending magnetizations (Yamaji *et al.*, 1999).

4.2 Differential rotation in the Uetsu area

The northern and southern subarea rotated in the opposite sense to each other. What kind of geologic structures did accompany these rotations? The lack of paleomagnetic data around the boundary between two subareas make it impossi-

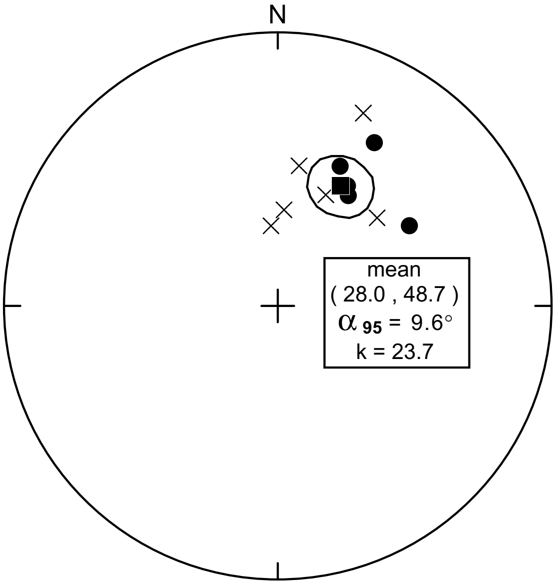

Fig. 6. Equal area projection of the direction averaging the paleomagnetic data obtained in the southern subarea (indicated by square) with 95% confidence circle (lower hemisphere), calculated by inverting site-mean directions from reversed-polarity sites by 180°. Circles show site-mean directions from normal-polarity sites, and crosses from reversed-polarity sites.

ble to describe the spatial change of rotation angles in detail (Fig. 5). However, the boundary does not coincide with the Nihonkoku–Miomote Mylonite Zone that is the northern extension of the Tanakura Shear Zone, one of major faults in NE Japan. It is not probable that this mylonite zone divides these two subareas.

In this study, a fault zone was discovered around the boundary, that seems to have accommodated some part of the differential rotation. It runs along the Myojin River from NW to SE, which is referred to as the Myojin-gawa Fault (Fig. 5). It is observed in the basement granite and not affect the Myojin-gawa Andesite of Pliocene. It crops out at localities A, B and C in Fig. 7(a). At the locality A, the fault zone is wider than 150 m. It consists of granitic cataclasites and sheared rhyolitic dikes. Most shear planes strike NW-SE and dip at high angles. The pitch angles of striae on the planes are relatively shallow, indicating strike-slip movements (Fig. 7). Asymmetric microstructures in fault zones are useful to determine the sense of shear (Petit, 1987). Some small clasts have a thin ridge on the left hand side of them, making 'comet' patterns (Fig. 8(a)). A fault movement involves mechanical fragmentation, sliding and rotation of fragments; so-called cataclastic flow (Passchier and Trouw, 1996). These clasts disturbed cataclastic flow in the fault zone to form the asymmetric ridges and grooves (Fig. 8(b)), indicating the dextral shear of the Myojin-gawa Fault.

The trace of the Myojin-gawa Fault coincides with the line on which Yamaji *et al.* (1999) assume the boundary between the CW and CCW rotating domains. The dextral shear suggested by the microstructures is concordant with the CW rotation in the southern subarea. The dextral deformation is also suggested at a larger scale along the Nihonkoku–Miomote Tectonic Line from a left-step echelon array of Early Miocene grabens (Hataya and Otsuki, 1991). The 'domino model' relates a vertical-axis rotation with a strike-slip faulting, and states that the dextral deformation generally accompanies CW block rotations (Ron *et al.*, 1984). These facts support the dextral motion of the Myojin-gawa Fault as the reason of the CW rotation in the southern subarea. However, it is difficult to explain the complexity of paleomagnetic data in the southern subarea by such a simple model (Fig. 1). It is argued that elliptical bodies embedded in homogeneously deforming matrix can rotate in both senses (Ghosh and Ramberg, 1976; Yamaji, 2000). In this case, the pure shear can bring rotations of blocks as well as the simple shear. Analogous mechanisms might bring these complex paleomagnetic directions in the study area. More detailed geologic and paleomagnetic data are necessary to relate geologic structures and paleomagnetic directions precisely.

What does this CW rotation mean in the tectonic history of the NE Japan? Hirooka *et al.* (1986) reported NW-trending magnetizations in the Sado and Fukushima areas which locates to the south of the Uetsu area. It indicates the Uetsu area belongs to the CCW-rotated NE Japan. Based on the paleomagnetic study, Yamaji *et al.* (1999) suggests the general CCW rotation of the NE Japan with local CW block rotations due to dextral transtension. However, all of their paleomagnetic data were obtained from reversed-polarity sites, and they possibly represented the geomagnetic fluctuations. Our data, which are from both normal- and reversed-polarity sites, confirm the tectonic origin of those CW deflections and the kinematic model of Yamaji *et al.* (1999).

5. Conclusion

The paleomagnetic and geological study in the Uetsu area clarified the following points.

1. The paleomagnetic directions were obtained from the Kitaoguni and Tenjosan Formations of the Lower Miocene and the Wasada Formation of the Middle Miocene. The results combined with other studies divides the area into two subareas. The remanent magnetizations point NE in the southern subarea ($D = 28.0°$, $I = 48.7°$ and $\alpha_{95} = 9.6°$). From the northern subarea, one site-mean direction which was westerly deflected was obtained. It is concordant with the paleomagnetic data of Yamaji *et al.* (1999).

2. The consistent paleomagnetic directions from both the Kitaoguni and Tenjosan Formations suggest that the NE-trending magnetizations in the southern subarea were resulted from CW rotations. It means that the CW rotation was active after the deposition of the Tenjosan Formation (19–20 Ma).

3. The NW–SE trending Myojin-gawa Fault was discovered around the boundary between the northern and southern subareas. Its location coincides with that of the domain boundary suggested by Yamaji *et al.* (1999). The dextral motion is suggested in this fault, which is consistent with the CW rotation in the southern subarea. It is probable that the movement of this fault bring CW block rotations in the southern subarea.

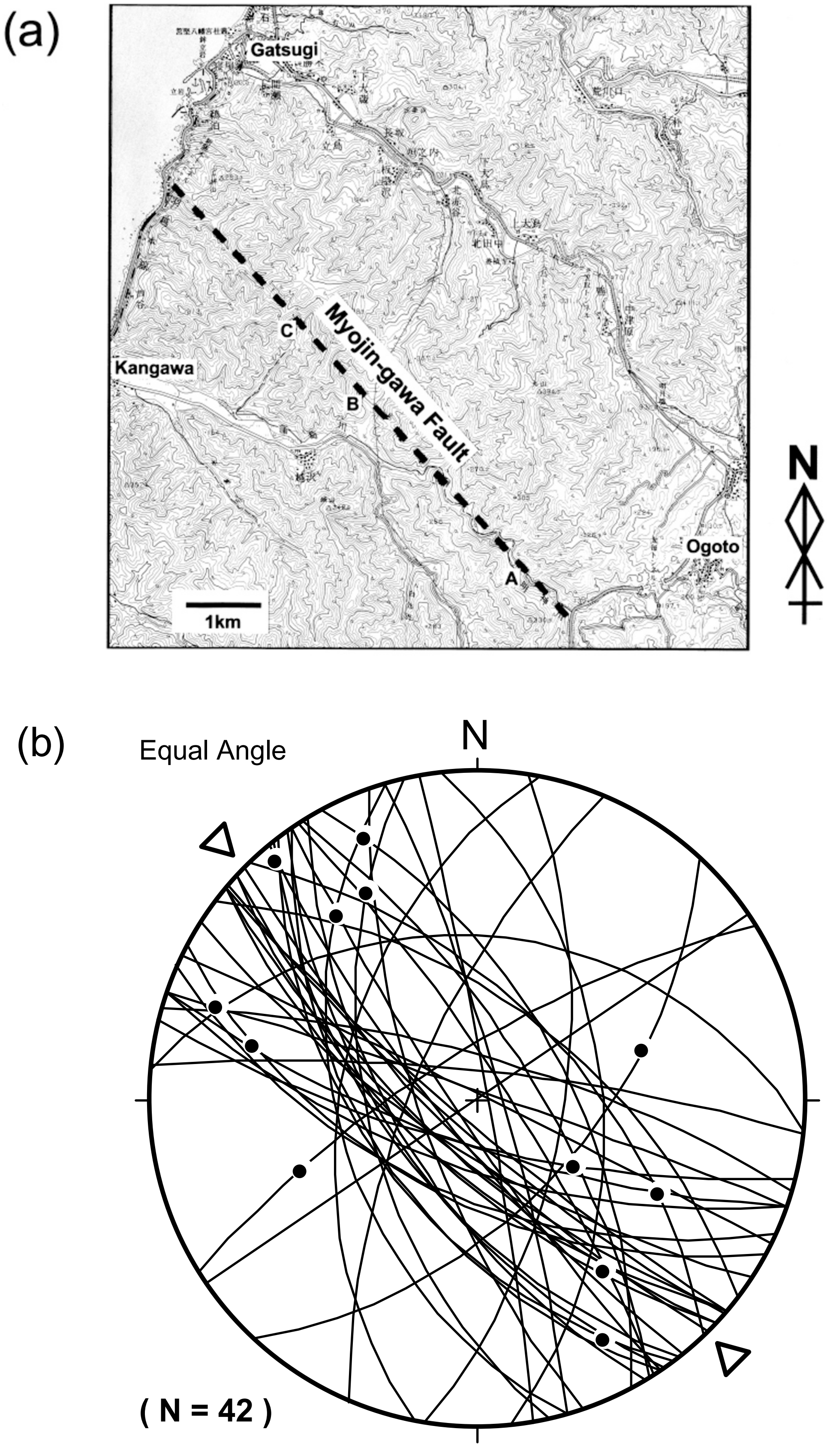

Fig. 7. (a) Map showing the trace of the Myojin-gawa Fault. The fault zone crops out at the localities A, B and C. (b) Lower hemisphere, equal-angle projection showing fault planes in the zone. Great circles exhibit the directions of fault planes. Solid circles on great circles show the directions of striations observed on fault planes, indicating slip directions. Triangles indicate the general trend of the fault zone.

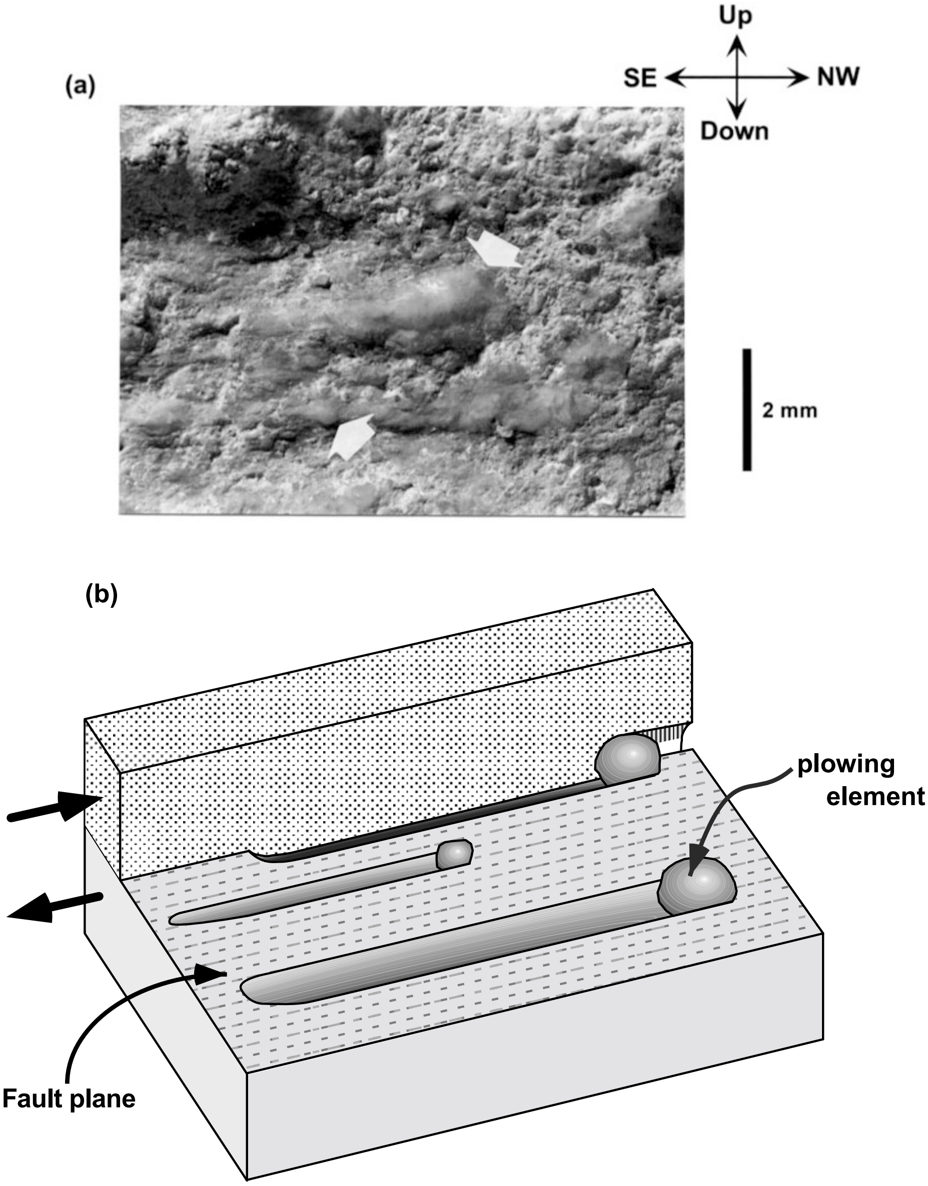

Fig. 8. Asymmetric structures indicating a dextral sense of movement on a shear plane in the Myojin-gawa fault zone. (a) Close-up photograph of striations due to rotating clasts on a shear plane. The clasts have made ridges on their left side as their traces. (b) Schematic picture showing asymmetric ridges and grooves produced by rotating clasts on a shear plane with a dextral sense of movement.

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