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Differential timing of vertical-axis block rotations in the northern Ryukyu Arc: paleomagnetic evidence from the Koshikijima Islands, Japan

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Abstract

Over 300 samples for paleomagnetic analysis and K-Ar dating were collected from 27 sites at NW–SE and NE–SW trending dike swarms (herein, NW dikes and NE dikes, respectively) in the Koshikijima Islands, northern Ryukyu Arc. The NW dikes are Middle Miocene in age and have directions (D = –37.7°, I = 51.8°, α\textsubscript{95} = 9.6°, and κ = 40.8) that are deflected westward relative to the stable eastern Asian continent. Conversely, the NE dikes, of Late Miocene age, have directions (D = 16.1°, I = 57.7°, α\textsubscript{95} = 7.1°, and κ = 41.9) that show no such deflection. These differences are interpreted as indicating that the Koshikijima Islands underwent approximately 40° of counter-clockwise rotation during the Middle to Late Miocene. A synthesis of the paleomagnetic and structural data suggests a three-stage history of extensional deformation: (1) displacement upon normal faults (F\textsubscript{1} faults)
without vertical-axis block rotation, (2) strike-slip reactivation of F₁ faults and oblique-normal displacement on NE-SW-trending faults (F₂ faults) with vertical-axis block rotation, and (3) oblique-normal displacement on F₂ faults without vertical-axis block rotation. Regional differences in the timing and amount of counter-clockwise vertical-axis block rotations indicate that the northern Ryukyu Arc rotated as several distinct rigid blocks.

**Keywords:** Ryukyu Arc; Koshikijima; Paleomagnetism; K-Ar dating; Block rotation; Fault reactivation

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1. **Introduction**

Deformation of the crust in the brittle regime is commonly accompanied by vertical-axis block rotation, as indicated by paleomagnetic data (e.g., Otofuji and Matsuda, 1983; Luyendyk et al., 1985; Kissek et al., 2003). Block rotations in the brittle regime, including vertical-axis block rotation, result from the accumulation of geological deformation such as fault displacement and/or folding (e.g., Freund, 1970; Nur et al., 1986). Although an understanding of the kinematics of vertical-axis block rotations is important for tectonic reconstruction, such data are complex and consequently require careful consideration.

In this regard, it is important to clarify the geological deformation that contributed to rotation. The direction of rotation depends not only on the vorticity (i.e., the movement direction of the strike-slip component along the block-bounding fault) but also on the shape of the block and the orientation of the bounding fault (Ghosh and Ranberg, 1976; Lamb, 1987; Yamaji,
In a domino block model, involving a set of parallel faults (Ron et al., 1984; McKenzie and Jackson, 1986), each tectonic block rotates by the same amount; consequently, it is difficult to discriminate between different structural scenarios (e.g., deformation of a single rigid block versus several independent blocks bounded by parallel faults) based solely on paleomagnetic data. Given that both of these scenarios could occur in nature, it is necessary to determine which scenario has occurred in a given situation.

To resolve the issues surrounding the kinematics of vertical-axis block rotation, it is important to jointly interpret paleomagnetic and structural data, including paleomagnetic direction data with high spatial and temporal resolution. In particular, knowledge of the timing of cessation of vertical-axis block rotation in different areas is required to compare rotation styles between adjacent areas.

In this paper, we present new paleomagnetic direction data from the Koshikijima Islands, located in the northern part of the Ryukyu Arc (Fig. 1). The ample exposure of arc rocks along the coastline in this region provides a good opportunity to observe detailed geological structures, making it possible to directly compare paleomagnetic data with geological structures throughout the arc. However, no previous study has collected paleomagnetic data for this area. Based on a comparison between new paleomagnetic data and geologic structures, we propose a model of crustal deformation that involves vertical-axis block rotations in the area since the Miocene. In addition, we compare the timing of vertical-axis block rotation in the study area with the timing of rotations in other parts of the northern Ryukyu Arc. Previous studies have reported paleomagnetic data for the arc (Ishikawa and
Figure 1: Regional map around the study area. Arrows indicate movement directions of the Pacific and Philippine Sea plates with respect to Eurasia (Seno et al., 1993, 1996)
Torii, 1986; Kodama et al., 1991; Kodama and Nakayama, 1993; Kodama et al., 1995; Takeda et al., 2001), and some studies determined the timing of vertical-axis block rotation to a high degree of accuracy (Kodama et al., 1995; Takeda et al., 2001).

2. Geologic setting of the Koshikijima Islands

The Koshikijima Islands comprise three main islands (from north to south: Kamikoshikijima, Nakakoshikijima, and Shimokoshikijima islands) and a number of islets. Fig. 2 shows a geologic map of the northern part of the islands, which consists primarily of Upper Cretaceous to Paleogene sedimentary rocks and Miocene igneous rocks (e.g., Inoue et al., 1982; Toshimitsu et al., 2004).

The upper Cretaceous Himenoura Group is distributed throughout the southern and western parts of the study area, and is more than 2,400 m thick (Fig. 2). The group consists mainly of sandstone and mudstone with minor conglomerate, deposited in a shallow marine environment and to a lesser degree a fluvial environment (Tanaka and Teraoka, 1973). The age of this group is determined by *Inoceramus* fossils (Tanaka and Teraoka, 1973; Kanoh et al, 1989). The Paleogene Kamikoshikijima Group, approximately 1,700 m thick, is distributed on Kamikoshikijima Island and the northernmost part of Nakakoshikijima Island (Fig. 2). The lower part of this group consists of conglomerate, sandstone, and mudstone deposited in a fluvial environment (Inoue et al., 1982). The middle part consists of sandstone and mudstone deposited in a transition zone between fluvial and shallow marine environments, and the upper part consists of alternating sandstone and mudstone.
Figure 2: (a) Geologic map of the northern part of the Koshikijima Islands (after Tonai et al., 2008), showing locations of samples collected for K-Ar dating and paleomagnetic analyses. (b) Geological cross-sections through the area. (c) Rose diagrams showing fault and dike trends in the study area.
deposited in a shallow marine environment (Inoue et al., 1982). This group is compared to the Middle Eocene in the west Kyushu area on the basis of the lithofacies (Inoue et al., 1982).

The sedimentary rocks in the study area are intruded by Miocene igneous rocks. Several igneous bodies are exposed in the northern part of Kamikoshikijima Island (Fig. 2), where adjacent sedimentary rocks are thermally metamorphosed. The igneous rocks have equigranular texture and contain plagioclase, quartz, pyroxene, and hornblende. Their age is Middle to Early Miocene, as determined by K-Ar and fission track dating (7.4 ± 0.4 Ma, (Ishihara et al., 1984); 14.0 ± 1.6 Ma, (Miyachi and Takai, 1988)).

Two dike swarms are observed throughout the study area: one trends NW–SE and consists mainly of andesite dikes; the other trends NE–SW and consists mainly of dacite dikes (Fig. 2). In this paper, the former group is defined as the “Koshiki NW-dike swarm (NW dikes)” (Fig. 3a, 3b, and 3e) and the latter group is defined as the “Koshiki NE-dike swarm (NE dikes)” (Fig. 3c, 3d, and 3f). At Taira, on the eastern part of Nakakoshikijima Island showing location in Fig. 2, a NE dike crosscuts a NW dike (Tonai et al., 2008). This observation reveals that the NE dikes are younger than the NW dikes.

3. Geological structures

The strata upon the Koshikijima Islands generally dip to the northeast (Fig. 2). Many map-scale and minor faults are observed in the study area. Two fault populations are identified based on their orientation (Fig. 2), damage zones, and crosscutting faults. These populations are herein referred
Figure 3: (a) Field photograph of a NW–SE-trending dike intruding the Eocene Kamikoshikijima Group, Kamikoshikijima Island (sample number: NKD3), showing location in Fig. 2. (b) Photomicrograph (cross polarized light) of a NW–SE-trending andesite dike (sample number: NKD2). Note the pilotaxitic texture of the plagioclase groundmass. (c) Field photograph of a NE–SW-trending dike intruding the Upper Cretaceous Himenoura Group, Shimokoshikijima Island (sample number: HND1), showing location in Fig. 2. The white circle shows a person for scale. (d) Photomicrograph (cross polarized light) of a NE–SW-trending dacite dike (sample number: TSD4). (e) Photomicrograph (cross polarized light) of a NW–SE-trending andesite dike (sample number: TA7172). (f) Photomicrograph (cross polarized light) of a NE–SW-trending dacite dike (sample number: SA7183). Abbreviations: Bt, biotite; Hbl, hornblende.
to as F_1 and F_2 faults, respectively.

The F_1 faults trend NW–SE, dip to the northeast or southwest at less than 70°, and occur as shear zones of 1–30 m in width. Fig. 4a provides an overview of the Kanoko Fault, which is a typical F_1 fault. The shear zones associated with F_1 faults consist mainly of foliated cataclasite (Fig. 4b). Composite planar fabrics of Y-P-R planes (Rutter et al., 1986) are developed in these shear zone and indicate normal sense of shear. Calcite and quartz veins occur parallel to the foliation within shear zones and in porphyroclasts within cataclasite. Some F_1 fault surfaces contain two sets of slickenlines (Fig. 4c): one that indicates dip-slip displacement and the other strike-slip displacement (Fig. 5). The occurrence of asymmetrical deformation structures in shear zones and the orientations of slickenlines indicate that the F_1 faults formed as normal faults and were later reactivated as strike-slip faults. Some F_1 faults cut NW dikes, and some NW dikes are intruded along F_1 faults.

The F_2 faults strike NE–SW and dip to the northwest or southeast at more than 30°. Fig. 4d shows an outcrop photograph of a typical F_2 fault. Some of the F_2 faults are evident as topographic lineaments (Fig. 4e). Slickenlines on fault surfaces and displaced bedding indicate oblique slip and 2–20 m of normal displacement, respectively. Damage zones associated with F_2 faults are less than 1 m wide and consist of non-foliated fault gouge or breccia. The fault breccias consist of sandstone fragments (up to several centimeters in diameter) within a greenish gray matrix. The damage zones are commonly dominated by apparently randomly oriented calcite and quartz veins. Some of the veins are lenticular in shape and less than 10 cm long. At Tonosaki, on
Figure 4: Photographs of typical faults in the Koshikijima Islands. Localities of photographs are shown in Fig. 2. (a) Overview photograph of the Kanoko Fault in the northern part of Nakakoshikijima Island. (b) Photograph of the hanging wall and fault zone. (c) Sets of superimposed slickenlines on the fault plane. (d) Overview photograph of an $F_2$ fault on Shimokoshikijima Island. (e) NE–SW-trending lineament of an $F_2$ fault upon Shimokoshikijima Island. (f) Crosscutting relationship between an $F_2$ fault and a NE–SW-trending dike.
Figure 5: Orientation of slickenlines observed in the northern part of the Koshikijima Islands. The left panel is the lower-hemisphere stereonet in which the orientations of fault planes are indicated by great circles. Open circles on the great circles designate the orientations of fault striations. One-headed arrows attached to the open circles show the direction of the hanging wall and two-headed arrows depict the sinistral or dextral sense of shear. The right panel shows the rose diagram showing the fault trends and the tangent-lineation diagram (Twiss and Gefell, 1990) showing the orientations of slickenline.

the eastern part of Kamikoshikijima Island showing the location in Fig. 2, an F2 fault crosscuts an F1 fault (Tonai et al., 2008). In addition, F2 faults crosscut NE dikes at Eishi on the southern coast of Kamikoshikijima Island and at Kurohama in the southern part of Nakakoshikijima Island, as shown in Fig. 4f. These crosscutting relationships indicate that F2 faults post-date F1 faults and intrusion of the dike swarms.

4. K-Ar dating

4.1. Sampling and laboratory procedures

We performed K-Ar dating on two dikes (TA7172, SA7183). The locations of the sampling sites are shown in Fig. 2. Although samples for K-Ar dating were collected from more than 40 sites throughout the Koshikijima Islands,
most of the samples turned out to be intensely weathered or did not contain suitable potassium-bearing dating materials such as micas and potassium feldspar; consequently, they were not considered for dating. Sample TA7172 is a NW–SE-trending andesite dike that contains fresh biotite grains; only the rims of some grains are partly replaced by chlorite (Fig. 3e). SA7183 is a NE–SW-trending dacite dike in which fresh hornblende occurs as discrete fine grains (Fig. 3f).

For mineral separation, samples were crushed to 60–250 mesh size using a jaw crusher. To clean grain surfaces, sieved fractions were washed using distilled water in an ultrasonic bath and then dried in an oven at 60 °C after careful rinsing. Magnetite grains were separated using a hand magnet. Subsequently, magnetite-free grains (e.g., plagioclase grains) were separated using an isodynamic magnetic separator. These processes were repeated several times to ensure pure mineral separates. Finally, we separated 150–200 mesh size biotite from sample TA7172 using a paper-tapping technique, and separated 80–150 mesh size hornblende from SA7183 by hand-picking under a binocular microscope.

Potassium contents were determined in duplicate by flame photometry using a 2000-ppm Cs buffer, with an analytical error within 2% at a 95% (2σ) confidence level. Argon was determined on a 15-cm-radius sector-type mass spectrometer with a single collector system using an isotopic dilution method and an $^{38}$Ar spike. Multiple runs of a standard (JG-1 biotite; 91 Ma) yielded an error for argon analysis of about 1% at the 95% confidence level. Ages and errors were calculated following the method described by Nagao et al. (1984) using the decay constants proposed by Steiger and Jäger (1977).
Table 1: Results of K-Ar dating analyses. Sample locations are shown in Fig. 2.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Analyzed mineral</th>
<th>Grain size</th>
<th>K (wt. %)</th>
<th>Rad. Ar 40 (10^15 STP/g)</th>
<th>K-Ar age (Ma)</th>
<th>Non-rad. Ar (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA7172</td>
<td>Biotite</td>
<td>#150–200</td>
<td>4.259±0.085</td>
<td>243.6±4.7</td>
<td>14.7±0.4</td>
<td>35.1</td>
</tr>
<tr>
<td>SA7183</td>
<td>Hornblende</td>
<td>#80–150</td>
<td>0.389±0.019</td>
<td>10.7±0.8</td>
<td>7.0±0.6</td>
<td>77.2</td>
</tr>
</tbody>
</table>

All K-Ar dating analyses were conducted at Okayama University of Science, Japan.

4.2. Results of K-Ar dating

For biotite in TA7172, we obtained a K-Ar age of 14.7 ± 0.4 Ma (Table 1). The potassium content in the biotite separate was 4.26%, which is less than that expected for a well-purified biotite separate, possibly reflecting contamination by potassium-free minerals such as actinolite or chlorite.

For hornblende in SA7183, we obtained a K-Ar age of 7.0 ± 0.6 Ma (Table 1). The potassium content in the hornblende separate was 0.39%, which indicates sufficient purity.

The above ages are significantly different, and are consistent with the crosscutting relationship observed between NW and NE dikes. Thus, it is likely that the NW and NE dikes were intruded at different times.

5. Paleomagnetism

5.1. Sampling

For paleomagnetic analyses, we collected more than 300 samples from igneous dikes at 27 sites (12 sites for NW dikes, 15 sites for NE dikes) throughout the Koshikijima Islands. The locations of sampling sites are shown in Fig. 2. At 24 of the sites, core samples were collected using a gasoline-powered
drill and were oriented using a magnetic compass. At the other three sites, oriented block samples were obtained by hand sampling.

5.2. Method

In the laboratory, two or three specimens of 25.4 mm (1 inch) in diameter and 22 mm in length were prepared from each core sample or oriented block sample. Magnetic hysteresis experiments were performed to identify the magnetic minerals in the samples. The specimens were selected from several sites and cut to produce chips of several millimeters in size. Hysteresis loops were measured using a vibrating sample magnetometer (MicroMag 3900; Princeton Measurements Corporation) in magnetic fields up to 500 mT. The ratio of saturation remanent magnetization to saturation magnetization (Mrs/Ms) and the ratio of coercivity of remanence to coercivity (Hcr/Hc) were used to compile a Day plot (Day et al., 1977).

The magnetic stabilities of samples from each site were examined by stepwise thermal demagnetization (ThD) and alternating field demagnetization (AFD) experiments. The temperatures of stepwise ThD were 100 to 580 °C at 15–50 °C intervals. In the case that specimens were not fully demagnetized by 580 °C, an additional ThD analysis was carried out up to 690 °C. Low-field susceptibility was measured using a Kappabridge (AGICO KLY-3S) after each step of the ThD to detect any chemical alteration during the heating and cooling processes. The magnetic field intensities of the stepwise AFD were 2.5 to 50.0 mT at 2.5–7.5 mT intervals. One or two pilot specimens from each site were first subjected to progressive demagnetization experiments. The results obtained for most of the pilot specimens by
AFD were unstable or different from the ThD results. Therefore, we applied ThD to the other specimens. The natural remanent magnetization (NRM) of the specimens was measured using a superconducting rock magnetometer (2G model 755R) or spinner magnetometer (AGICO JR-6) according to the magnetic intensity of the specimens. Characteristic remanent magnetization (ChRM) directions were determined by applying principal component analysis (Kirschvink, 1980). All paleomagnetic experiments were conducted at the Department of Earth and Planetary Sciences, the University of Tokyo, Japan.

5.3. Rock magnetism

The hysteresis loops were classified into two groups (group-A and group-B). The typical hysteresis loops of each group, after correcting for the contribution of a paramagnetic component using high-field slopes, are shown in Fig. 6.

Group-A loops show a rapid increase in magnetic intensity in low magnetic fields (Fig. 6a), and the data are within the single-domain (SD), pseudo-single-domain (PSD), or multi-domain (MD) regions of the Day plot (Fig. 6c). The unblocking temperatures of samples in this group ranged between 530 °C and 560 °C (Fig. 6a). These results indicate that the main magnetic mineral in this group is most likely magnetite or titanomagnetite.

The loops obtained for group-B samples show wasp-waisted shapes (Fig. 6b). Wasp-waisted forms of hysteresis loops are produced by a mixture of two magnetic phases with contrasting coercivities (Roberts et al., 1995). This group shows two components in terms of unblocking temperatures (Fig. 6b): the low-temperature components are unblocked by 340 °C, whereas the high-
Figure 6: (a) and (b), Left: representative magnetic hysteresis loops for the analyzed samples after correcting for a paramagnetic component. Right: normalized intensity of magnetization versus temperature. Abbreviation: $J_0$, initial NRM intensity. (c) Day plot of the hysteresis parameter for selected specimens. Abbreviations: SD, single-domain; PSD, pseudo-single-domain; MD, multi-domain; $H_c$, coercivity; $M_{rs}$, saturation remanent magnetization; $M_s$, saturation magnetization.
temperature components are maintained between 500 °C and 560 °C (Fig. 6b). These results indicate that the magnetization in group-B samples is carried by a mixture of two magnetic minerals.

5.4. Demagnetization

5.4.1. NW dikes

The initial NRM intensities of specimens from 12 NW dikes ranged from $10^{-1}$ to $10^{-5}$ A/m. Representative examples of stepwise ThDs are shown in Fig. 7. Seven sites (ESD1, KMD2, KMD3, KOD1, NKD1, NKD3, and OHD1) displayed coherent demagnetization trajectories unblocked at temperatures between 520 °C and 560 °C (Fig. 7a, 7b, and 7c). The intensities of the remanence magnetization of samples from dikes HSD1, HSD2, and NKD2 were reduced to 10% or less of the initial NRM intensities by 400 °C (Fig. 7d). Because the paleomagnetic directions of the component below 400 °C define a cluster near the present-day direction of the Earth’s magnetic field for the study area, this component is probably a viscous remanent magnetization. Samples from dikes HSD1, HSD2, and NKD2 showed unstable behavior at demagnetization levels above 400 °C (Fig. 7d). Therefore, in the following discussion, we do not consider data obtained from HSD1, HSD2, or NKD2. Samples from dikes ESD2 and TYD1 displayed unstable magnetic components (maximum angular deviations (MADs) greater than 10°); consequently, data from these samples are not considered in the following discussion.

The site-mean directions obtained for dikes ESD1, KMD2, KMD3, KOD1, NKD1, NKD3, and OHD1 are shown in Fig. 8 and Table 2.
Figure 7: Representative examples of progressive thermal demagnetization for the analyzed samples. For each sample, we show the following features: Left: an orthogonal vector plot with solid (open) symbols for data projected onto the horizontal (vertical) plane. Abbreviations: Div., division. Upper right: equal-area projection of change in the direction of magnetization with increasing temperature. Solid (open) symbols indicate a lower-(upper-) hemisphere projection. Lower right: normalized intensity of magnetization versus demagnetization temperature. Abbreviations: $J_0$, initial NRM intensity.
Figure 8: Equal-area projections of site-mean directions obtained for NW dikes before and after tilt correction. Solid circles indicate directions in the lower hemisphere of the projection; open circles indicate directions in the upper hemisphere. Star symbols represent the mean paleomagnetic direction of seven site-mean directions, surrounded by a circle that represents the 95% level of confidence.

Table 2: Paleomagnetic data from igneous dikes in the northern part of the Koshikijima Islands. Paleomagnetic directions are shown before tilt correction. Abbreviations: N, number of samples used in calculating site-mean directions; D, declination; I, inclination; $\alpha_{95}$, Fisher’s semi-angle confidence cone; $\kappa$, Fisher’s precision parameter.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude (N)</th>
<th>Longitude (E)</th>
<th>Dike orientation</th>
<th>Bedding orientation</th>
<th>Dike group</th>
<th>N</th>
<th>D (°)</th>
<th>I (°)</th>
<th>$\alpha_{95}$ (°)</th>
<th>$\kappa$</th>
</tr>
</thead>
<tbody>
<tr>
<td>KOD1</td>
<td>31°46’15.7’’</td>
<td>129°50’20.5’’</td>
<td>N82°E78°N</td>
<td>N62°W12°W</td>
<td>NW dikes</td>
<td>3</td>
<td>160</td>
<td>-57.3</td>
<td>41.5</td>
<td>9.9</td>
</tr>
<tr>
<td>KMD2</td>
<td>31°45’37.6’’</td>
<td>129°48’14.5’’</td>
<td>N60°W70°N</td>
<td>N58°W15°N</td>
<td>NW dikes</td>
<td>7</td>
<td>141.5</td>
<td>-51.8</td>
<td>6.4</td>
<td>85.9</td>
</tr>
<tr>
<td>KMD3</td>
<td>31°45’37.6’’</td>
<td>129°48’14.5’’</td>
<td>N60°W55°N</td>
<td>N58°W15°N</td>
<td>NW dikes</td>
<td>6</td>
<td>-74.1</td>
<td>53.4</td>
<td>14.7</td>
<td>21.6</td>
</tr>
<tr>
<td>HSD1</td>
<td>31°44’20.7’’</td>
<td>129°46’44.7’’</td>
<td>N75°W73°N</td>
<td>N60°W21°S</td>
<td>NW dikes</td>
<td>5</td>
<td>9.0</td>
<td>63.3</td>
<td>9.9</td>
<td>61.0</td>
</tr>
<tr>
<td>HSD2</td>
<td>31°44’14.7’’</td>
<td>129°46’48.2’’</td>
<td>N65°W63°N</td>
<td>N45°W52°S</td>
<td>NW dikes</td>
<td>5</td>
<td>19.3</td>
<td>65.6</td>
<td>17.8</td>
<td>19.4</td>
</tr>
<tr>
<td>ICD2</td>
<td>31°51’22.3’’</td>
<td>129°55’47.4’’</td>
<td>N12°E79°W</td>
<td>N61°E31°N</td>
<td>NE dikes</td>
<td>5</td>
<td>185.9</td>
<td>-48.4</td>
<td>4.9</td>
<td>246.8</td>
</tr>
<tr>
<td>TS03</td>
<td>31°47’38.1’’</td>
<td>129°50’26.6’’</td>
<td>N2°E90°E</td>
<td>N21°E19°E</td>
<td>NE dikes</td>
<td>7</td>
<td>69.2</td>
<td>56.1</td>
<td>3.4</td>
<td>316.1</td>
</tr>
<tr>
<td>TS02</td>
<td>31°47’37.9’’</td>
<td>129°50’27.5’’</td>
<td>N36°E48°E</td>
<td>N21°E19°E</td>
<td>NE dikes</td>
<td>5</td>
<td>206.7</td>
<td>-62.9</td>
<td>2.3</td>
<td>1091.0</td>
</tr>
<tr>
<td>TS01</td>
<td>31°47’37.8’’</td>
<td>129°50’29.0’’</td>
<td>N30°E70°</td>
<td>N21°E19°E</td>
<td>NE dikes</td>
<td>6</td>
<td>23.1</td>
<td>57.3</td>
<td>6.2</td>
<td>117.3</td>
</tr>
<tr>
<td>TS04</td>
<td>31°47’37.4’’</td>
<td>129°50’12.7’’</td>
<td>N19°E72°E</td>
<td>N58°E12°S</td>
<td>NE dikes</td>
<td>7</td>
<td>207.9</td>
<td>-59.1</td>
<td>4.2</td>
<td>203.1</td>
</tr>
<tr>
<td>HZ01</td>
<td>31°46’45.8’’</td>
<td>129°48’20.4’’</td>
<td>N30°E67°E</td>
<td>N34°W25°N</td>
<td>NE dikes</td>
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<td>N57°E19°N</td>
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<td>N27°E11°W</td>
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These site-mean directions show an antipodal relationship with the NW–SE trend. The mean paleomagnetic direction calculated for all the considered sites reveals that the precision parameter $\kappa$ of the mean paleomagnetic directions of the seven sites increases from 24.5 to 40.8 after correction for tilting (Fig. 8). This result indicates that the magnetic directions were acquired before tilting of the strata.

We also carried out a reversal test following the method proposed by McFadden and McElhinny (1990). The mean paleomagnetic direction after tilt correction for the NW dikes with reversed polarity (three sites) was $D = 145.5^\circ$, $I = -56.4^\circ$, with $\alpha_{95} = 14.4^\circ$; values for dikes with normal polarity (four sites) were $D = -39.8^\circ$, $I = 48.3^\circ$, with $\alpha_{95} = 17.1^\circ$. These two mean paleomagnetic directions show an antipodal relationship at the 95% confidence level, but are rejected the reversal test. This negative result may be due to a small number of site-mean directions. In the light of the high unblocking temperature and the result of tilt correction, we interpret that the NW dikes probably preserve the primary thermoremanent magnetization, while results of the reversal tests are insufficiently supportive.

5.4.2. NE dikes

The initial NRM intensities of specimens from 15 NE dikes range from $10^{-1}$ to $10^{-4}$ A/m. Representative examples of the stepwise ThDs are shown in Fig. 7. The ChRM directions obtained for seven sites (KMD1, MSD1, NYD1, TSD1, TSD2, TSD3, and TSD4) display coherent demagnetization trajectories unblocked by temperatures of 560 $^\circ$C (Fig. 7e, 7f, 7g, and 7h). Samples from four sites (HND2, HZD1, ICD2, and MND1) have two components of NRM: low-temperature components unblocked until 340 $^\circ$C and
Figure 9: Equal-area projections of site-mean directions for NE dikes before and after correction for tilting. Solid circles indicate directions shown in the lower hemisphere of the projection; open circles indicate directions shown in the upper hemisphere. Star symbols represent the mean paleomagnetic direction of 11 site-mean directions, surrounded by a circle that represents the 95% level of confidence.

high-temperature components maintained between 500 °C and 560 °C. The other four sites (HND1, HSD3, ICD1, and MGD1) show unstable magnetic components (MADs greater than 10°). Thus, these four sites were excluded from directional analysis.

The site-mean directions for 11 NE dike sites are shown in Fig. 9 and Table 2. All site-mean directions obtained for the NE dikes (except for TSD3) show an antipodal relationship with the N–S trend prior to correction for tilting. The $\kappa$ values obtained for the mean paleomagnetic directions for the 11 sites decrease from 41.9 to 11.9 after correction for tilting (Fig. 9). This decrease indicates that the magnetization of the NE dikes was recorded after tilting of the strata.

The reversal test by McFadden and McElhinny (1990) shows positive
result for site-mean directions of in situ formation for the NE dikes. The mean paleomagnetic direction of in situ formation for the NE dikes with reversed polarity (seven sites) was $D = 192.4^\circ$, $I = -57.2^\circ$, with $\alpha_{95} = 7.5^\circ$; values for dikes with normal polarity (four sites) were $D = 25.4^\circ$, $I = 57.7^\circ$, with $\alpha_{95} = 18.9^\circ$. These two mean paleomagnetic directions show an antipodal relationship at the 95% confidence level, thereby passing the reversal test with a quality classification of C. The results of the reversal test indicate that the NE dikes preserve a reliable primary thermoremanent magnetization. Therefore, intrusion of the NE dikes occurred after tilting of the strata.

6. Discussion

6.1. Counter-clockwise rotation of the Koshikijima Islands

The above paleomagnetic data from the Koshikijima Islands reveals that two trends of dike swarms preserve primary thermoremanent magnetizations. In addition, the presence of normal and reversed polarities indicates that the mean paleomagnetic directions represent the averages of sufficiently long time period (Figs. 8 and 9). Thus, the paleomagnetic directions of these two dike swarms are probably free from the effects of paleosecular variation, representing tectonic movements in this area. The mean paleomagnetic directions of the NW and NE dikes are different at the 95% confidence level, indicating that tectonic movement occurred during the interval between intrusion of the two swarms (Figs. 8 and 9).

To interpret the amount of vertical-axis block rotation and/or latitudinal displacement of the Koshikijima Islands, we compared the mean paleomagnetic directions of the dike swarms with the Miocene paleomagnetic direction.
of the stable eastern Asian continent (herein termed EA) (Bretstein, 1988; Zhao et al., 1990; Zheng et al., 1991). The declination of the NW dikes is deflected westward by $37.7^\circ \pm 9.6^\circ$, whereas the inclination shows no significant difference with respect to that of EA. This mean paleomagnetic direction indicates that counter-clockwise (CCW) rotation of this area occurred relative to EA after intrusion of the NW dikes.

The paleomagnetic direction of the NE dikes is similar to that of EA in terms of both declination and inclination. Hence, there occurred no significant vertical-axis block rotation in this area, relative to EA, subsequent to intrusion of the NE dikes. The K-Ar age of TA7172 (14.7 ± 0.4 Ma) and the crosscutting relationships observed between faults and dike swarms indicate that intrusion of the NW dikes had ceased by the Middle Miocene. In addition, a sample from one of the NE dikes (SA7183) yields a K-Ar age of 7.0 ± 0.6 Ma. Thus, the CCW rotation of this area occurred after the Middle Miocene and before 8–6 Ma.

6.2. Kinematics of vertical-axis block rotation in the Koshikijima Islands

Block rotations in the brittle regime commonly occur via stepwise displacement along faults (Garfunkel, 1989). Accordingly, we now consider the pattern of fault activity throughout the Koshikijima Islands. As stated above, field observations reveal the occurrence of NW–SE-trending $F_1$ faults, and NE–SW-trending $F_2$ faults (Fig. 2). The $F_1$ faults began as normal faults but were reactivated as strike-slip faults, as indicated by the orientations of slickenlines (see Section 3). The strike-slip reactivation of previously extensional faults is relatively common along the basin shoulders (e.g., Rossetti et al., 2000; Storti et al., 2001). In contrast, slickenlines indicate that the $F_2$
Figure 10: Schematic tectonic map of the northern part of the Koshikijima Islands.

faults are oblique-normal faults (Fig. 5).

A component of this fault activity is expected to correlate with the CCW rotation recorded in this area. Inversion analysis, based on fault-slip data obtained from minor faults that cut sedimentary strata in this area, indicate the past occurrence of two tensional paleostress regimes (Tonai et al., 2008). This analysis also revealed that strike-slip displacement along the F_1 faults and oblique-normal displacement along the F_2 faults occurred within the same paleostress regime. On this basis, Tonai et al. (2008) argued that reactivation of the F_1 faults coincided with displacement along the F_2 faults. In addition, reactivation of the F_1 faults and displacement along the F_2 faults are kinematically consistent with the CCW rotation recorded in this area (Fig. 10). The nature of asymmetric microstructures on F_1 fault planes reveals dextral strike-slip displacement, whereas most F_2 faults contain slickenlines that record sinistral displacement. If displacement along F_1 and F_2
faults had been associated with CCW rotation, the expected slip sense would be dextral and sinistral, respectively, as observed. In contrast, dip-slip displacement along the F1 faults made no contribution to vertical-axis block rotation in this area, as it contains no horizontal component.

In light of the above kinematic model of vertical-axis block rotation, we consider the deformation history of the northern part of the Koshikijima Islands. The proposed history is divided into three stages, each described below (Fig. 11).

The first deformation stage is characterized by normal displacement upon F1 faults (Fig. 11). Although the present-day F1 faults trend approximately NW–SE, it is likely that they originally had approximately N–S trends (Fig. 11). The extensional deformation during this stage involved no significant vertical-axis block rotation. The K-Ar ages of authigenic clay minerals in a shear zone associated with an F1 fault are 17.9–24.8 Ma (Tonai et al., 2007). The asymmetry of deformation structures within the shear zone indicates normal dip-slip. Based on these data, Tonai et al. (2007) estimated that normal displacement upon the F1 faults continued until the late Early Miocene. Thus, this stage commenced after Paleogene sedimentation and presumably continued until the late Early Miocene (about 15 Ma). The crosscutting relationships, K-Ar age data, and paleomagnetic directions indicate that the NW dikes were emplaced during this stage.

The second deformation stage is characterized by strike-slip displacement along F1 faults, oblique-normal displacement upon F2 faults, and vertical-axis block rotation caused by these complex fault populations (Fig. 11). The change in deformation style (from stage 1 to stage 2) occurred in response
**First deformation stage (~ Early Miocene)**
- NNW–SSE-trending normal faulting (F₁ faults)

**Second deformation stage (Middle Miocene)**
- NE–SW-trending oblique normal faulting (F₂ faults)
- Reactivation of F₁ faults
- CCW vertical-axis block rotation

**Third deformation stage (Late Miocene ~)**
- NE–SW-trending oblique normal faulting (F₂ faults)

---

normal fault  
oblique normal fault  
normal fault reactivated as strike-slip fault  
inactive fault  
counter-clockwise vertical-axis block rotation  
extensional direction

Figure 11: Model of extensional deformation throughout the northern part of the Koshikijima Islands.
to a change in the orientation of the tensional stress regime throughout the Koshikijima Islands. This change in stress regime probably occurred during the Middle to Late Miocene, as indicated by the cessation of normal displacement on F1 faults. Reorientation of the tensional stress regime resulted in reactivation of F1 faults (Fig. 11). These complex fault populations divided study area into several rotational blocks. The occurrence of block rotations creates space problems that are probably solved by the development of minor faults around master faults or by the emplacement of intrusive igneous rocks or dike swarms (Fig. 11). In the study area, there are many minor faults in different directions near larger map-scale faults. In addition, igneous rocks were intruded during this stage. It is possible that these intrusions occurred along some boundaries between rotational blocks to fill gaps (Fig. 11). Paleomagnetic data indicate that no significant vertical-axis block rotation occurred subsequent to intrusion of the NE dikes. The crosscutting relationships between F2 faults and NE dikes indicate that these faults were active both before and after intrusion of the dikes (Fig. 4f). Thus, displacement upon F2 faults continued after cessation of CCW rotation in this area.

The third deformation stage is characterized by oblique-normal displacement upon the F2 faults, without any significant vertical-axis block rotation (Fig. 11). During this stage, the extensional stress field remained the same as during the second stage (Fig. 11). Vertical-axis block rotation probably ceased because the strike of F1 faults became parallel to the principal stress axis of the extensional stress field, after about 40° of vertical-axis block rotation (Fig. 11).
6.3. Kinematics of vertical-axis block rotation in the northern Ryukyu Arc

To investigate the regional-scale kinematics of vertical-axis block rotation, we compiled paleomagnetic directions reported from Cenozoic rocks in the northern Ryukyu Arc (Table 3). Fig. 12a shows the compiled paleomagnetic declinations, including our new data, along with 95% confidence limits in and around the northern Ryukyu Arc.

These paleomagnetic directions in the northern Ryukyu Arc show uniformly the CCW rotation (Table 3). However, geochronological data obtained for these rocks indicate that the timing of CCW rotation differs by location (Fig. 12b). Vertical-axis block rotations in the Koshikijima Islands occurred during the Middle and Late Miocene. The area to the east of the Koshikijima Islands in south Kyushu underwent rotation after the Late Miocene. The paleomagnetic directions of primary thermoremanent magnetization of Late Miocene volcanic rocks at Makurazaki are deflected westward by about 20°, while the chemical magnetization (CRM) of these rocks shows no significant deflection (Takeda et al., 2001). Takeda et al. (2001) argued that the CRM in this area was acquired by hydrothermal alternation, which ceased at 3 Ma. Thus, CCW rotation in this area occurred from 6 to 3 Ma, significantly younger than the rotation of the Koshikijima Islands. Based on paleomagnetic direction data and the biostratigraphic age of Miocene and Pliocene sedimentary rocks in the Miyazaki area, Kodama et al. (1995) suggested that a CCW rotation of −21.4° ± 7.8° commenced during the Latest Pliocene (2 Ma) and is ongoing today.

The timing of vertical-axis block rotations in the northern Ryukyu Arc ranges from the Middle Miocene to the present (Fig. 12b). The difference in
Figure 12: (a) Directions of paleomagnetic declination with 95% confidence limits since the Paleogene in the northern Ryukyu Arc and western part of Southwest Japan Arc (see also Table 3). Declination data in the western part of Southwest Japan Arc are after Ishikawa et al. (1989), Ishikawa and Tagami (1991), Ishikawa (1997), Otofuji and Matsuda (1987), and Otofuji et al. (1991). (b) Timing of rotation versus distance from the present-day trench for deflected areas in the northern Ryukyu Arc. The numbers refer to the geographical locations in (a).
Table 3: Compilation of paleomagnetic data for volcanic and sedimentary rocks of the Ryukyu Arc since the Oligocene. Abbreviations: n, number of samples used to calculate the mean age; N, number of samples used to calculate site-mean directions; D, declination; I, inclination; $\alpha_{95}$, Fisher’s semi-angle confidence cone; $\kappa$, Fisher’s precision parameter; *, recalculated; F.T., fission track dating; W.R., whole rock. Underlined values are mean ages. Note that paleomagnetic data are shown in italics. Correlation of planktonic foraminifera zone with numerical time scale is based on Berggren et al. (1995).

<table>
<thead>
<tr>
<th>Locality</th>
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<td></td>
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<td>K-Ar (biotite)</td>
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<td>-21.4</td>
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timing among different areas indicates that the region rotated as several (at least two) tectonic blocks. It is possible that these rotations of the arc were related to extension within the Okinawa Trough since the Middle Miocene (Sibuet et al., 1987; Furukawa, 1991; Miki, 1995; Fournier et al., 2001), which was the major tectonic event in the arc at this time. In the Koshikijima Islands, the timing of displacement upon F$_2$ faults, which triggered the rotation in this area, is coincident with extension within the trough (Oiwane et al., 2007; Tonai et al., 2008). Other rotated regions may have similar kinematics to those of the Koshikijima Islands. An interesting point is that these rotations occurred and migrated to various parts of the arc rather than across the entire arc during the period of extension within the trough. To discuss more detailed kinematics of vertical-axis block rotation in the arc, it would be necessary to examine the relationship between rotations and fault activity in other parts of the arc (in addition to those areas considered in the present study).

7. Summary

We examined the paleomagnetic directions recorded by Miocene dike swarms in the Koshikijima Islands to determine the relationship between vertical-axis block rotations and fault activity in a backarc region. The paleomagnetic directions of two dike swarms indicate that the Koshikijima Islands experienced about 40° of counter-clockwise rotation during the Middle to Late Miocene. Based on a comparison between paleomagnetic directions and fault activity, we reconstructed the history of extensional deformation in this area since Paleogene sedimentation. The history consists of the following
three stages.

1. Normal displacement upon F$_1$ faults without vertical-axis block rotation.

2. Strike-slip displacement along F$_1$ faults and oblique-normal displacement upon F$_2$ faults, accompanied by vertical-axis block rotation.

3. Oblique-normal displacement upon F$_2$ faults without vertical-axis block rotation.

The initiation of vertical-axis block rotation in this area probably occurred in response to the reactivation of F$_1$ faults due to reorientation of the stress field. Block rotations ceased when the strike of F$_1$ faults became parallel to the orientation of the principal stress axis of the tensional stress regime, after about 40° of rotation.

A comparison of paleomagnetic directions and geochronological data obtained for the northern Ryukyu Arc reveals that CCW rotation occurred at different times in different areas. Thus, the northern Ryukyu Arc rotated as several tectonic blocks.

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Research highlights

- We present new paleomagnetic data from the Koshikijima Islands, northern Ryukyu Arc
- The study area rotated counter-clockwise about 40° during the Middle to Late Miocene
- Timing of rotations several regions in the northern Ryukyu Arc are different
- The northern Ryukyu Arc rotated as several distinct rigid blocks