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Opening mode of the Okinawa Trough: paleomagnetic evidence from the South Ryukyu Arc

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Abstract

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More than 250 samples of volcanics and sedimentary rocks were collected from the South Ryukyu Arc for paleomagnetic study and K–Ar dating. Stable primary components of magnetization were isolated from 18 sites after thermal demagnetization. The mean paleomagnetic direction for 15 Eocene volcanic sites ($D = 30.1°$, $I = 40.3°$, $\alpha_{95} = 10.3°$) indicates a direction which is deflected $18.6° \pm 11.6°$ clockwise from the expected field direction calculated from the 40 Ma pole of Eurasia. The clockwise deflection is observed also in the dike rock ($D = -144.0°$, $I = -32.1°$), the age of which is determined to be 9.6 ± 0.8 Ma by the conventional K–Ar dating method. These results indicate that, with respect to Eurasia, the southern part of the Ryukyu Arc has rotated clockwise 19° during the past 10 M.y. We attribute this rotation to the back-arc opening of the southern part of the Okinawa Trough, which occurred by means of the "wedge" mode later than 10 Ma.

Introduction

Island arc–marginal basin systems characterize the convergent plate boundary of the western part of the Pacific. Some of these systems, such as the Japan Arc – Japan Sea and the Ryukyu Arc – Okinawa Trough, have been formed by rifting of fragments from their mother continents (Taylor and Karner, 1983). In these systems, the island arc behaves as a platelet between the marginal basin and the subducting plate, and moves or rotates in association with the opening of the marginal basin. The formation process of the arc – marginal basin system is recorded in the kinematic history of the island arc.

The Ryukyu Arc – Okinawa Trough system (Fig. 1) is believed to be in the initial stage of rifting. High heat flow (Yamano et al., 1989), active hydrothermal mounds (Kimura et al., 1988) and extensional characters of earthquakes (Eguchi and Uyeda, 1983) indicate that the Okinawa Trough is now an active basin.

In this paper, we will show that the opening mode of the south Okinawa Trough is wedge-shaped, using a combination of paleomagnetism and geochronology. Tertiary rocks are focused at the southern part of the Ryukyu Arc. These rocks should retain evidence of opening of the Okinawa Trough. A Miocene age is assigned to the first opening of the Okinawa Trough, on the basis of marine geological studies (Herman et al., 1978; Lee et al., 1980; Kimura, 1985; Letouzey and Kimura, 1986; Sibuet et al., 1987). Post-Eocene rotational motion of the Ryukyu Arc is suggested

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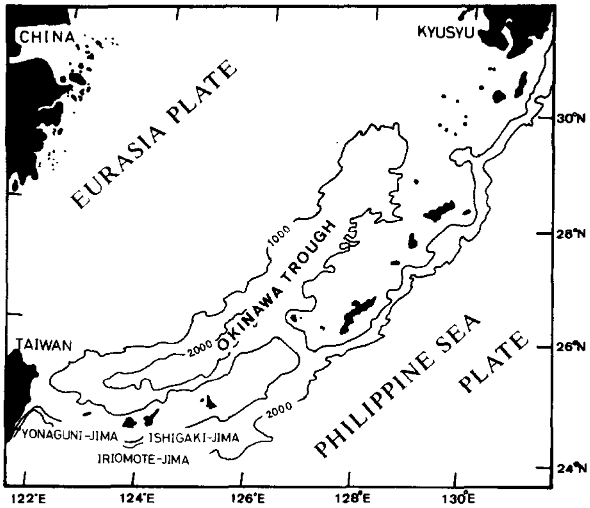


Fig. 1. Index map of the studied area. Samples were collected from Ishigaki-jima Island, Iriomote-jima Island and Yonaguni-jima Island.

from paleomagnetic data (Sasajima, 1977; Jarrard and Sasajima, 1980).

Geology and sampling

Samples were collected from Ishigaki-jima Island, Iriomote-jima Island and Yonaguni-jima Island in the southern part of the Ryukyu Arc, where Tertiary volcanics and sedimentary rocks are distributed (Kizaki, 1986). Horizons and localities of sampling sites are shown in Figs. 2 and 3, respectively.

The Nosoko Formation is mainly exposed on Ishigaki-jima Island and Iriomote-jima Island (Kizaki, 1986; Nakagawa et al., 1982). The formation conformably overlies Eocene sedimentary rocks which in turn cover pre-Cenozoic metamorphic rocks. The formation mainly consists of some series of volcanics (pyroclastic rocks and acid lavas). Fossils (e.g. *Nummulites pengaronensis, Discocyclina javana* and *Pellatispira madraszi*) from the interbedded sedimentary rocks indicate the Late Eocene age. The ages of the formation were estimated to be 43.5 Ma and 44.1 Ma by fission-track dating (Daishi et al., 1987). The total thickness of the formation is about 400 m. Samples of several different rock types were collected from 22 sites; 21 sites on Ishigaki-jima Island and one site on Iriomote-jima Island.

Lower Miocene sedimentary rocks known as the Yaeyama Group unconformably overlie the Nosoko Formation. Early Miocene flora and fauna fossils (e.g. *Chlamys* sp., *Aequipectem* sp., *Turritella* sp. and *Astriclypeus* sp.) have been reported from this group (Nakagawa et al., 1982). The group is mostly exposed on Iriomote-jima Island and Yonaguni-jima Island. Samples were collected at seven sites on Yonaguni-jima Island.

Andesite dikes of unknown age intrude into the Nosoko Formation on Ishigaki-jima Island. Samples were collected from five dikes.

Hand samples were taken and a magnetic compass was used for orientation. Each site typically

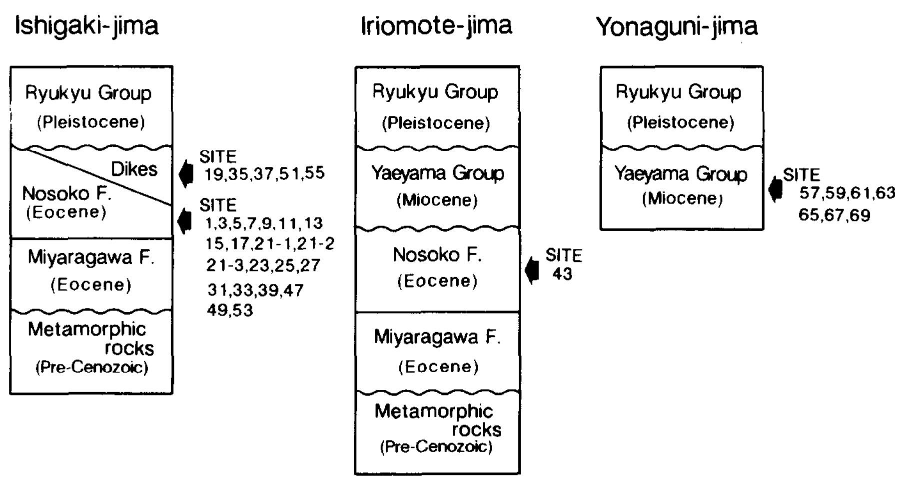


Fig. 2. Stratigraphy of Ishigaki-jima Island, Iriomote-jima Island and Yonaguni-jima Island (simplified from Nakagawa et al., 1982; Yazaki, 1982). Horizons of the sampling sites are attached to the columnar sections.

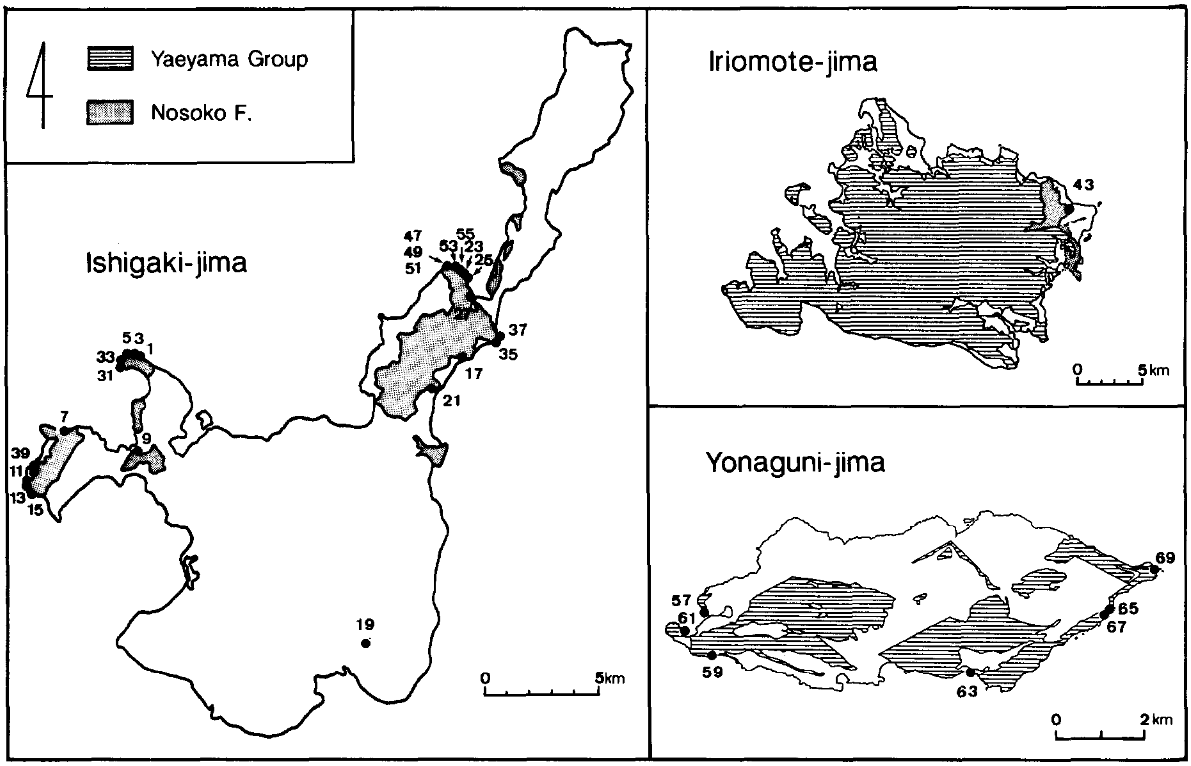


Fig. 3. Simplified geological map showing the sampling localities (solid circles).

comprised ten independently oriented samples, distributed over distances ranging up to 20 m.

Geochronology

K–Ar whole rock dating was attempted on three andesite dikes (sites 19, 51 and 55) from Ishigaki-jima Island. Prior to K–Ar dating, thin sections of the samples were examined (see Appendix). The sample from site 19 is believed to be fresh enough to determine the extrusion age of the andesite. The alteration of pyroxene to chlorite is found in the samples from sites 51 and 55. Samples from these sites were rejected for age determination because the alternation may have caused the loss of radiogenic argon.

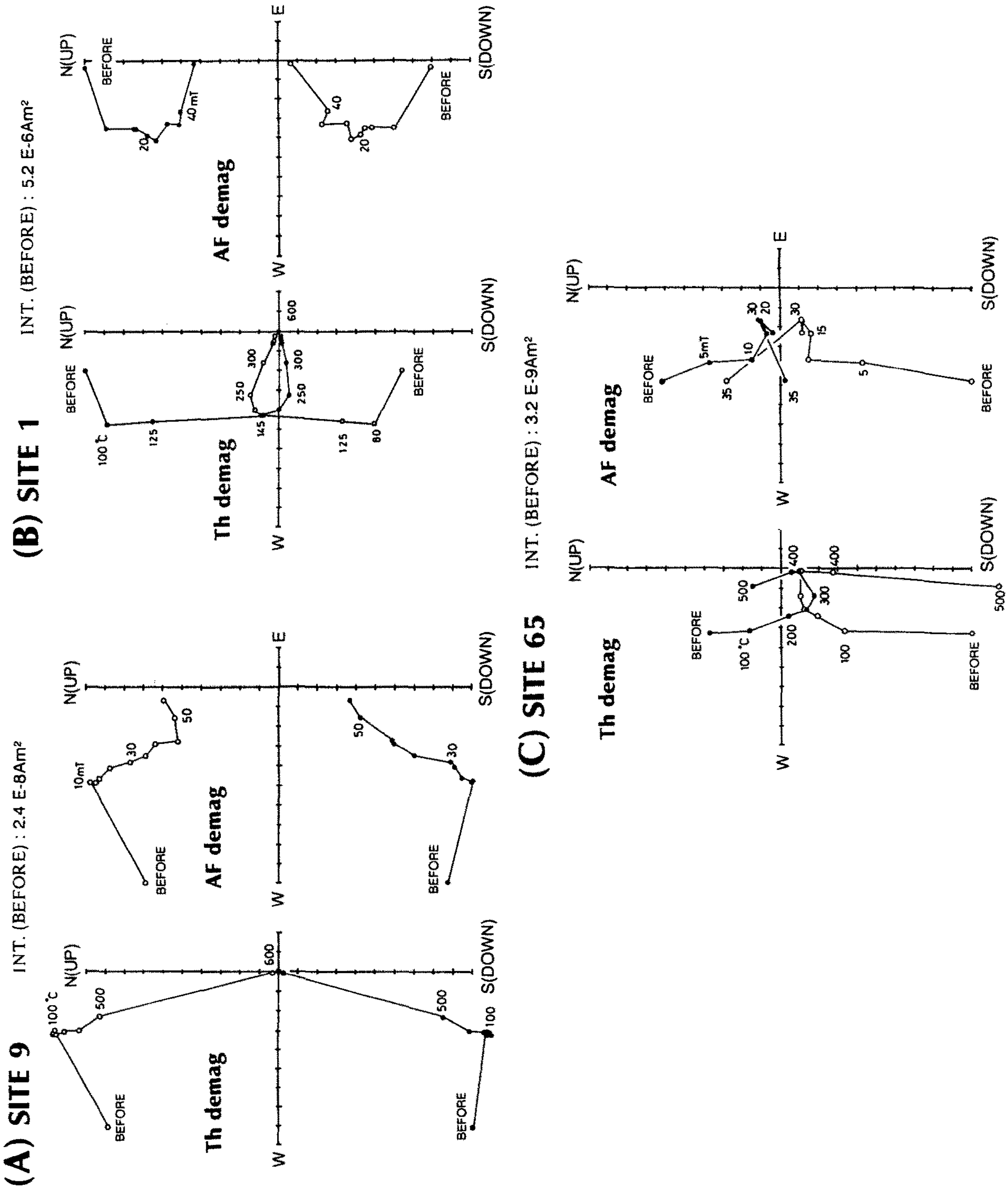
Argon was extracted from a whole-rock sample by fusing 0.5–0.9 g at about 1500°C in a high-vacuum line. The amount of radiogenic ^{40}Ar was determined by the isotope dilution method using an ^{38}Ar tracer, with a mass spectrometer constructed at Okayama University of Science. The sample for argon analysis was baked out at 200°C for a whole day in vacuum conditions prior to fusion, to reduce the atmospheric Ar component on the surface. Potassium analysis was carried out

TABLE 1

Results of K–Ar dating for dike rocks from Ishigaki-jima Island

Sample	Locality	K (wt.%)	$^{40}Ar_{rad}$ ($\times 10^{-8}$ cm^3/g)	Age (Ma)	Ar_{air}/Ar_{total} (%)
Site 19 Andesite	124° 13′11″ E 24° 21′34″ N	0.94	35.2 ± 2.7	9.6 ± 0.8	89.2

The constants for the calculation are $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}, $\lambda_\epsilon = 0.581 \times 10^{-10}$ yr^{-1}, and $^{40}K = 1.167 \times 10^{-4}$ atom per atom of natural potassium (Steiger and Jäger, 1977).


(A) SITE 9
INT. (BEFORE) : 2.4 E-8Am²
Th demag
AF demag
(B) SITE 1
INT. (BEFORE) : 5.2 E-6Am²
Th demag
AF demag
(C) SITE 65
INT. (BEFORE) : 3.2 E-9Am²
Th demag
AF demag
N(UP)
S(DOWN)
W
E
BEFORE
100 °C
10mT
5mT
40mT

by flame photometry using about 2000 ppm of Cs buffer. The K–Ar age and its error were calculated in accordance with Cox and Darlymple (1967).

The results of K–Ar dating from site 19 are given in Table 1. The age obtained (9.6 ± 0.8 Ma) is in the Late Miocene. This dike cuts the Late Eocene volcanics and is covered uncomformably by Pleistocene sediments. This age is consistent with field evidence.

Paleomagnetism

Stability examinations

A total of 250 oriented samples were collected from 34 sites. The block samples were drilled into 2.5 cm diameter cores and cut into individual specimens, 2.5 cm long, in the laboratory. Two or three specimens were obtained from each sample. Measurements of natural remanent magnetization (NRM) were performed using a laboratory-built spinner magnetometer or a ScT SQUID magnetometer, depending on the intensity of magnetization.

Stability of magnetization of rocks from each site was examined through progressive demagnetization experiments. The experiments were applied to pilot specimens of each site. One or two pairs of specimens, each pair being taken from the same sample, were chosen from each site as the pilot specimens. One specimen from each pair was submitted to thermal demagnetization in steps of 30 ° C or 50 ° C up to 625 ° C, while the other was demagnetized in alternating fields (AF) in steps of 5 mT up to 100 mT using a three-axis tumbler system. The NRM directional stability during the demagnetization was assessed by an orthogonal demagnetization plot and a principal-component analysis (Kirschvink, 1980).

Thermal demagnetization experiments revealed that NRM in most of the samples consisted of two or three components with different unblocking temperatures (Figs. 4A, B). Lower-temperature components were removed, up to about 250 ° C. The typical direction of these components is similar to that of the present geomagnetic field. A high-temperature component which appears above 250 ° C has a reversed polarity. This component is clearly defined as a linear segment, decaying toward the origin on the orthogonal plot.

The NRM is eliminated at around 580 ° C, corresponding to the Curie temperature of magnetite. For some samples in particular, NRM intensity drops by an order of magnitude after demagnetization between 570 ° C and 600 ° C. These results indicate that the magnetic carrier of the high-temperature component is titanium-poor magnetite.

Behavior during the AF demagnetization experiment is compared with that during the thermal demagnetization experiment (Fig. 4). This comparison leads us to divide the sampling sites into two groups. Group A (Fig. 4A) consists of ten sites from the Nosoko Formation and two sites from the andesite dikes. The high-temperature component which is defined during progressive thermal demagnetization can be isolated by the AF technique, although the demagnetization curve on the orthogonal plot of the AF technique is a little erratic. The high-temperature component appears after AF demagnetization between 20 mT and 50 mT. Group B (Fig. 4B) consists of five sites from the Nosoko Formation and two sites from the andesite dikes. The high-temperature component cannot be identified during AF demagnetization runs. The lower-temperature components are observed up to 40 mT. NRM shows erratic behavior during further demagnetization, and so on components are identified above 40 mT. According to this comparison, we concluded that

Fig. 4. Orthogonal projection plots for NRM stability examinations. Typical examples of comparison between behaviors during progressive thermal and AF demagnetization for pilot specimens. A, B. A high-temperature component is defined as a linear segment decaying to the origin by thermal technique. A. The high-temperature component is also observed between 20 mT and 50 mT by the AF technique. B. The high-temperature component above 250 ° C is not defined by the AF technique. C. No stable components are identified. *Th demag*—thermal demagnetization; *AF demag*—alternating field demagnetization; open (solid) symbols show the magnetic vectors projection on the vertical (horizontal) plane; tectonic tilt correction has not been applied.

TABLE 2

Comparison of characteristic directions estimated by different two analyses

Site No.	Specimen No.	A			B			C
		range (°C)	dec. (°)	inc. (°)	ODT (°C)	dec. (°)	inc. (°)	angular distance (°)
1	0111	300–origin	246.3	−19.9	300	245.3	−18.3	1.9
7	0711	350–origin	201.4	−47.1	350	202.5	−46.4	1.0
9	0911	100–origin	196.5	−45.8	200	196.1	−46.3	0.6
11	1121	200–origin	195.7	−35.1	200	195.9	−34.8	0.3
17	1721	200–origin	194.8	−29.5	250	195.6	−29.4	0.7
19	1911	100–origin	212.6	−30.3	100	213.8	−29.8	1.2
21–1	2111	200–origin	137.8	−24.3	300	140.1	−24.9	2.2
21–2	2161	200–560	176.5	−34.9	300	182.4	−39.7	6.7
21–3	2211	200–origin	214.5	−30.8	300	213.9	−30.7	0.5
23	2332	200–origin	240.9	−47.0	300	239.5	−47.1	1.0
25	2521	200–origin	219.2	−52.1	250	217.8	−52.1	0.9
27	2716	250–560	182.4	−45.3	250	188.3	−40.3	6.6
33	3351	200–origin	156.0	−62.0	200	162.3	−64.5	3.8
35	3532	300–origin	259.7	−21.4	400	257.4	−20.8	2.2
37	3712	250–origin	195.2	23.2	350	192.1	19.7	4.5
39	3941	200–530	199.7	−38.8	300	195.7	−34.3	5.5
47	4751	250–500	219.8	−36.0	300	221.4	−42.5	6.6
53	5321	200–origin	211.4	−46.6	300	208.8	−48.1	2.3
55	5512	100–origin	220.3	−55.2	200	219.5	−54.4	0.9

Characteristic directions were obtained for a pilot specimen from each site by a principal-component analysis (Kirschvink, 1980) and an optimum temperature analysis. A—The characteristic direction obtained by the principal-component analysis (Kirschvink, 1980); B—the characteristic direction obtained after thermal demagnetization at a optimum demagnetization temperature; C—the angular distance between two directions of A and B for each pilot specimen. The mean angular distance is 2.6° ± 0.5° for 19 specimens. Range—The range of steps along the thermal demagnetization path, in which a characteristic direction is isolated by the principal-component analysis. ODT—Optimum demagnetization temperature for each pilot specimen (see text).

thermal demagnetization was better for magnetic cleaning.

We regarded the direction of the high-temperature component as a characteristic direction of each pilot specimen. The characteristic directions were obtained from the pilot specimens from 15 sites of the Nosoko Formation and four sites of the andesite dikes. No stable components were obtained from seven other sites of the Nosoko Formation, nor from any of the seven sites from the Yaeyama Group (see Fig. 4C). No further work was carried out on these sites.

The characteristic direction is obtained by demagnetization at an optimum demagnetization temperature (ODT) as well as by the principal-component analysis (Table 2). An ODT for a pilot specimen was defined as the lowest temperature above which the high-temperature component was completely identified. The characteristic directions obtained by the two analyses for the pilot specimens are compared in Table 2. There is little difference between the two directions. The difference is less than 7°, with a mean of 2.6°. This is due to the linearity of the high-temperature component on the orthogonal plot. We concluded that the direction observed at the ODT was a characteristic NRM direction. Remaining specimens for each site were demagnetized at an ODT at which the characteristic directions for the pilot specimens could be obtained.

Paleomagnetic results

Reliable paleomagnetic results were obtained from the Nosoko Formation and the andesite dikes. All of the results were from Ishigaki-jima Island. Paleomagnetic data are summarized in Table 3. The site mean directions are calculated by

TABLE 3

Summary of paleomagnetic results for Ishigaki-jima Island

Geological sequence	Site	Demag. group	ODT (°C)	N	Uncorrected		Corrected		α_{95}	k	Rock type
					D (°)	I (°)	D (°)	I (°)			
Nosoko Fm.	1	B	300	10 (29)	−108.3	−28.6			3.6	56.3	rhyolitic lava
	7	B	350	9 (21)	−134.9	−22.2			13.7	6.3	rhyolitic lava
	9	A	100	10 (22)	−159.5	−41.2			6.3	25.1	rhyolitic lava
	11	A	200	10 (32)	−165.9	−38.5	−178.4	−49.6	2.9	79.5	tuff
	17	A	250	10 (26)	−158.3	−25.0	−154.9	−33.9	8.3	12.6	tuff
	21-1	A	300	3 (7)	−145.9	−9.5			7.0	74.8	rhyolitic lava
	21-2	A	300	4 (9)	−168.9	−21.0			18.1	9.0	rhyolitic lava
	21-3	A	300	5 (12)	−149.2	−29.7			4.3	103.1	rhyolitic lava
	23	B	300	5 (13)	−122.8	−48.1	−130.4	−50.5	1.6	655.2	tuff
	25	B	250	6 (19)	−143.6	−49.6	−158.3	−49.0	1.9	302.3	tuff
	27	A	250	6 (21)	−177.2	−43.6			10.8	9.7	rhyolitic lava
	33	A	200	7 (14)	176.6	−65.5	−166.2	−47.8	4.3	87.5	welded tuff
	39	A	300	10 (18)	−160.5	−42.1	−173.8	−54.2	7.7	21.3	tuff
	47	B	300	6 (14)	−137.6	−53.3	−122.2	−52.9	6.1	43.1	tuff
	53	A	300	6 (16)	−126.0	−41.8	−128.7	−42.0	4.3	75.2	tuff
Dikes	19	A	110	9 (24)	−144.0	−32.1			4.0	55.0	andesite
	35	B	400	9 (22)	−91.9	−26.0			5.4	34.0	andesite
	37	B	350	9 (24)	−162.0	29.3			17.5	3.9	andesite
	55	A	200	5 (7)	−140.3	−58.7			2.6	551.4	andesite

Demag. group—The group defined by the progressive demagnetization experiments for pilot specimens (see text); ODT—optimum demagnetization temperature (see text); N—number of rock samples (specimens); D—declination; I—inclination, uncorrected/corrected for structural tilt; α_{95}, radius of 95% confidence circle; k—precision parameter.

assigning a unit weight to the specimens. Within-site scatter in direction is small; α_{95} values range from 1.6° to 18.1° with a mean of 7.2°.

Tilt correction is only applied to the eight sites of the Nosoko Formation. No bedding planes were observed at other sites. It is likely, however, that only slight errors were introduced without tilt correction for these sites, because the general dip of the Nosoko Formation is sufficiently gentle, less than 20°. Therefore, the andesites which intrude into the Nosoko Formation, also have been subjected to negligible tilt effects.

The Nosoko Formation

All characteristic NRM directions from the Nosoko Formation are of reversed polarity. They have consistently clockwise-deflected magnetic declinations, ranging up to 70°.

The following evidence implies that the observed field directions are of primary remanent magnetizations of Late Eocene age:

(1) All directions have reversed polarity.

(2) NRM directions of almost all sites are tightly clustered after magnetic cleaning, e.g. α_{95} of site 53 decreases from 23.9° to 4.3°.

(3) Similar characteristic NRM directions are observed in rock samples of different types (tuff, welded tuff and rhyolitic lava).

(4) The magnetic carrier is titanium-poor magnetite, which is rarely produced in an oxygenic environment.

A simple fold is observed in the Nosoko Formation along the northern coast of Ishigaki-jima Island. A fold test can be applied for several sites (sites 23, 25, 47 and 53) which are distributed on the both sides of the fold. The change in direction scatter after tilt correction is not significant enough to determine whether the characteristic directions were acquired before or after tilting ($D = -132.1°$, $I = -48.5°$, $\alpha_{95} = 9.2°$, $k = 101$ vs. $D = -134.8°$, $I = -49.4°$, $\alpha_{95} = 13.0°$, $k = 51$). This insignificance is probably due to the small bedding dips, ranging from 3° to 13°. The α_{95} value increases slightly after the correction: this is

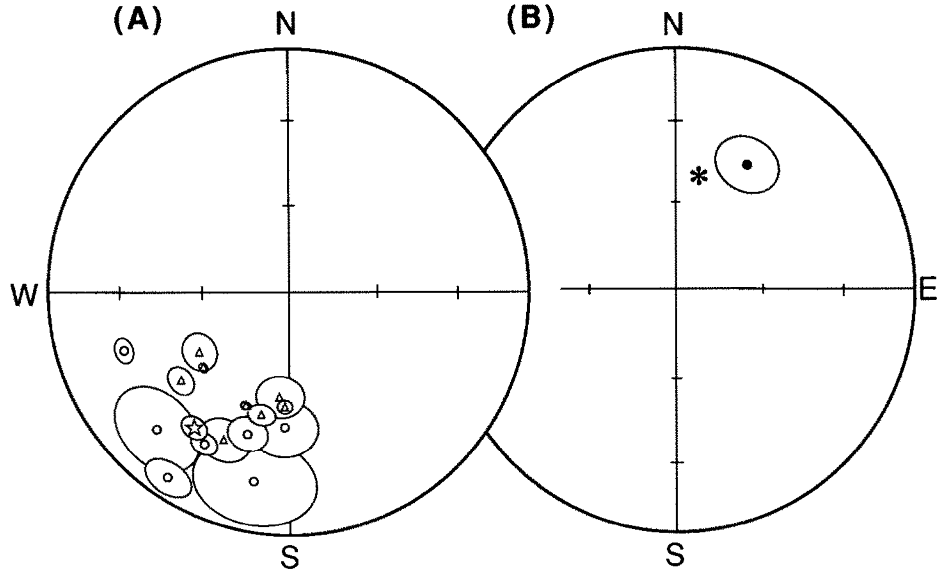


Fig. 5. Characteristic paleomagnetic directions from Ishigaki-jima Island. A. The site mean directions from the Late Eocene volcanics (circles and triangles) and the dike of 10 Ma (star) with 95% confidence circles. Tectonic tilt corrections have been applied to eight sites from the Late Eocene volcanics (triangles). B. The mean magnetic direction of the Late Eocene volcanics with a 95% confidence circle calculated from 15 site means (circle), and the expected geomagnetic field direction from the 40 Ma pole of Eurasia (asterisk).

probably due to errors in making the corrections rather than to remagnetization. The error in determining in the bedding planes is of the order of $\pm 5°$ and is compatible with the bedding dip.

The mean characteristic NRM direction for 15 sites of the Nosoko Formation is $D = 30.1°$, $I = 40.3°$, $\alpha_{95} = 10.3°$ (Fig. 5). This value shows a significant clockwise deflection from either the present axial dipole field direction ($D = 0°$, $I = 42.2°$) or the present geomagnetic field direction ($D = -3.2°$, $I = 33.8°$) on Ishigaki-jima Island.

Andesite dikes

The 9.6 Ma andesite dike (site 19) has a characteristic NRM direction of $D = -144°$, $I = 32.1°$. This direction also shows clockwise deflection. This is the direction of the original primary magnetization, based on its reversed polarity and freshness of mineral in the specimens obtained for microscopic observations.

The characteristic directions also were obtained from three other dikes. The dikes from sites 35 and 55 have clockwise-deflected NRM directions. These directions are consistent with that of the dike of 9.6 Ma. The samples from site 37 have a curious NRM direction: they show southward declination with positive inclination. This curious direction is probably due to overprinting, because the α_{95} value at this site is rather large (17.5°), despite of a large number of specimens ($N = 24$). Since the age of these three dikes could not be determined, the results of these dikes were excluded from further work in this study.

Discussion

Tectonic rotation of the South Ryukyu Arc

The clockwise deflection in the declination value of Ishigaki-jima Island can be ascribed to either tectonic rotation or geomagnetic secular variation. The following evidence indicates that geomagnetic secular variation is adequately averaged out in the paleomagnetic directions of the Nosoko Formation:

(1) Various kinds of rock samples were collected widely in the Nosoko Formation, the stratigraphic thickness of which is fairly large (about 400 m). The formation contains some layers of

marine sedimentary rocks. The samples cover a long time period.

(2) The angular dispersion observed from the Nosoko Formation is greater than that expected. The amount of angular dispersion expected at this latitude is about 18° (McFadden and McElhinny, 1984), whereas the angular dispersion observed in the Nosoko Formation is 19.5°. This large dispersion shows sufficient sampling of secular variation.

(3) The clockwise deflection is also observed from the andesite dikes, the age of which is different from that of the Nosoko Formation.

We conclude that the clockwise NRM deflection from the Nosoko Formation is not due to secular variation but to tectomic rotation.

We evaluated the amount of block motion of Ishigaki-jima Island with respect to Eurasia. The observed paleomagnetic direction of the Nosoko Formation was compared with the expected field direction for Eurasia calculated from the 40 Ma pole (Irving, 1977). The difference between the declinations of the observed data and the expected data is $18.6° \pm 11.6°$ (Fig. 5). The 95% confidence limit is estimated using the method of Demarest (1983). Ishigaki-jima Island has undergone a clockwise rotation of 19° since the Late Eocene. The inclination data shows a slight difference between the observed and expected values: $I_{ob} - I_{ex} = -9.4 \pm 9.3°$. The South Ryukyu Arc may have experienced N–S translation with respect to Eurasia. However, the difference is compatible with the 95% confidence level, so that further work is needed to make it clear. We conclude here that this island has undergone significant clockwise rotation later than the Late Eocene.

The results of our study are compared with those obtained by Sasajima (1977), and Jarrard and Sasajima (1980). They reported a clockwise rotation of about 40° for Ishigaki-jima Island. Their estimation of rotation is more than twice as large as our estimation of 19°, although both of the paleomagnetic directions deflect in a clockwise direction. Their large amount of rotation is probably due to the following insufficient treatments:

(1) Lack of thermal demagnetization. The paleomagnetic directions in their studies were obtained only by using AF demagnetization techniques. In our study the AF technique was found to be imperfect for isolating the characteristic directions from several sites. The NRM during AF demagnetization experiments gives a vector sum of the low-temperature component with normal polarity and of the high-temperature component with deflected reversed polarity. The overprinting of the low-temperature component on the high-temperature component makes the clockwise deflection larger.

(2) Lack of consideration of the apparent polar wander effect. The expected field direction from the 40 Ma pole has a clockwise deflection in declination of about 11°. The estimation without considering the apparent polar wander effect provides a larger clockwise rotation, by 11°.

We believe that our estimate of 19° is a more realistic value for the amount of rotation.

Clockwise deflection is also observed in the paleomagnetic direction from the andesite dike of about 10 Ma. The observed field direction deflects 36° clockwise from the axial dipole field. The deflection is probably caused by a tectonic rotation, because it is larger than the angular dispersion expected for this area, and is too large to be explained by the apparent polar wander effect at 10 Ma. Although we cannot estimate the amount of rotation using the 10 Ma data because of the paucity of results, we can conclude that the clockwise block rotation of Ishigaki-jima Island has occurred later than 10 Ma.

Iriomote-jima Island has been subjected to the clockwise rotation together with Ishigaki-jima Island, as a rigid block. The Nosoko Formation of Iriomote-Jima Island has a eastward-deflected paleomagnetic direction with reversed polarity (Sasajima, 1977) which is compatible with the direction observed on Ishigaki-jima Island. It is also considered, topographically, that Ishigaki-jima Island and Iriomote-jima Island form a rigid block. Both of the islands are on one planation which is shallower than 200 m (Hamamoto et. al., 1979), and there are few faults between these two islands.

Taiwan appears to have undergone little rotational motion. It lies at the junction of the Ryukyu Arc and the Taiwan–Luzon Arc. A paleomagnetic direction of $D = 1°$, $I = 30°$ is reported from Miocene volcanics in Taiwan (Hsu et al., 1966).

This direction shows no clockwise deflection in declination. The boundary of the rotational region lies between Iriomote-jima Island and Taiwan, on the southwest edge of the Ryukyu Arc.

Opening mode of the Okinawa Trough

The Ryukyu Arc is bounded to the northwest by the Okinawa Trough and to the southeast by the Ryukyu trench. The former is an accreting plate boundary between the Ryukyu Arc and the Eurasian Plate, whereas the latter is a convergent plate boundary where the oblique subduction of the Philippine Sea Plate takes place (Seno, 1977). The clockwise rotation of the islands on the Ryukyu Arc is caused either by the opening of the Okinawa Trough or by block rotations associated with the oblique subduction.

Various lines of evidence indicate that the back-arc opening is responsible for the clockwise rotation of the South Ryukyu Arc:

(1) According to marine geological evidence, back-arc spreading in the Okinawa Trough associated with the rifting of the Ryukyu Arc is believed to have started later than the Miocene (Herman et al., 1978; Lee et al., 1980; Kimura, 1985; Letouzey and Kimura, 1986; Sibuet et al., 1987). The rotation later than 10 Ma implied from paleomagnetism corresponds with the timing of the opening of the trough.

(2) The opening mode of the Okinawa Trough is the wedge-shaped type rather than the pull-apart type. The through has a wedge shape in the southwesternmost part. The overall width of the graben is about 60–100 km in the south (Sibuet et al., 1987) and decreases in a southwesterly direction (see Figs. 1 and 6). The southwestern tip of the trough seems to reach to the Ilan Plain in Taiwan, where an extensional strain pattern is observed (Kosuga et al., 1988). The transform faults which characterize the pull-apart basin are not observed in the basement at the southwestern end of the Okinawa Trough.

(3) On the basis of the paleomagnetic data, the amount of translation of Ishigaki-jima Island associated with the wedge-shaped opening of the Okinawa Trough can be estimated. The hinge position is assigned in the west of the Ilan Plain at 24.7° N, 121.7° C (see Fig. 6). The distance from the hinge to Ishigaki-jima Island is 255 km. Assuming that the angle of the opening at the hinge corresponds to the amount of rotation of the South Ryukyu Arc of 19°, the amount of translation of Ishigaki-jima Island is about 70 km. This estimation of 70 km is surprisingly consistent with the width of the Okinawa Trough behind Ishigaki-jima Island.

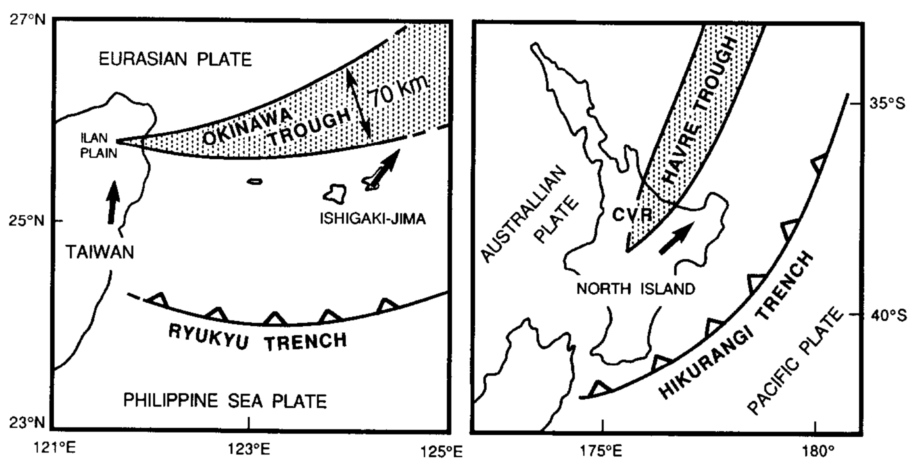


Fig. 6. A comparison of the wedge-shaped opening of the Okinawa Trough with the Central Volcanic Region (CVR) of New Zealand. CVR is southward continuation of the Havre Trough, which is an active back-arc basin behind the Hikurangi trench. The South Ryukyu Arc and the eastern North Island of New Zealand have been rotated clockwise in association with the wedge-shaped back-arc spreading. The opening width of the Okinawa Trough (70 km) estimated on the basis of the paleomagnetic direction is in agreement with the geographic feature. Arrows are paleomagnetic directions of Miocene age.

This agreement of geometry and paleomagnetic data strongly suggests that the island rotation of the southwestern part of the Ryukyu Arc can be attributed to the opening of the back-arc basin.

An alternative explanation of the rotation is that of ball-bearing block rotation due to shear stress associated with the oblique subduction of the Philippine Sea Plate beneath the Ryukyu Arc. However, this is not plausible on the basis of geological and geophysical observations. The southern part of the Ryukyu Arc is difficult to divide into several rotating blocks, because there are no deep depressions or channels between the Miyako Depression and Taiwan (Fig. 1). The submarine features in the South Ryukyu Arc are shallower than 400 m. Although small faults with a strike from NW to SE are observed in this area (Hamamoto et al., 1979), they are too short to intersect across the South Ryukyu Arc. No geological study has observed right-lateral faults on the north of Ishigaki-jima Island.

Mechanical coupling between the Ryukyu Arc and the Philippine Sea Plate appears to be too weak to cause block rotation of the arc. The Ryukyu trench is defined to be a Mariana-type subduction zone, because the Ryukyu Arc has an extensional active back-arc basin, and few large earthquakes are observed at the plate boundary (Uyeda and Kanamori, 1979). This condition has been present since the Miocene age when the back-arc opening started. Because the mechanical coupling at the Mariana-type boundary is fairly weak and the subducting slab falls freely into the mantle without causing strong earthquakes, the Ryukyu Arc has not been subjected to large shear stress that might cause block rotation since the Miocene. Block rotation due to oblique subduction seems to occur only in Chilean-type subduction zones (e.g. the Chile trench—Beck, 1987; or the Aleutian trench—Geist et al., 1988).

We have concluded that back-arc opening of the Okinawa Trough is the most plausible mechanism for the rotation of Ishigaki-jima Island. In turn, this conclusion has implications for the opening mode of the Okinawa Trough: (1) The opening mode is wedge-shaped; (2) the wedge shape has its hinge close to the Ilan Plain and has an angle of about 19°; (3) the opening has started later than 10 Ma; (4) the southern part of the Ryukyu Arc has a resulting rotation of 19°.

An analogue of the proposed wedge-shaped opening would be the Central Volcanic Region (CVR) of New Zealand's North Island (Stern, 1987; Fig. 6). This area is an apparent southward continuation of the Havre Trough into the continental lithosphere of New Zealand. The south Okinawa Trough and the CVR have the following similarities: (1) these areas are in the initial stage of rifting; (2) the wedge-shaped opening has occurred in the southern part of the basin; (3) the eastern block of the basin has rotated clockwise by more than 15°, forming a wedge-shaped opening of the basin (Wright and Walcott, 1986). The wedge-shaped opening is probably the most plausible pattern in the opening of a basin in which extensional activities are dominant. The wedge-shaped opening may be the initial stage of the fan-shaped opening of a mature basin, such as the opening of the Japan Sea (Otofuji and Matsuda, 1987) north of the Okinawa Trough.

APPENDIX

Petrographical descriptions of the samples for K–Ar dating

Site 19: aphanitic andesite

Abundant microphenocrysts are of plagioclase (partly replaced by smectite) and bronzite. Small amounts of microphenocrysts of augite are also present. The same minerals and clear pale-brown glass constitutes the groundmass.

Site 51: porphyritic pyroxene andesite

The phenocrysts are of plagioclase, pyroxene (pseudomorph) and opaque minerals. Most of the plagioclase phenocrysts are fresh. Pyroxene phenocrysts are altered mostly to chlorite and partly to smectite.

The groundmass has intersertal texture with fresh plagioclase, lath pyroxene altered to chlorite, and opaque minerals. These are embedded in cryptocrystalline matrix in which secondary smectite partly yields.

Site 55: porphyritic pyroxene andesite

Plagioclase and pyroxene (pseudomorph) constitute the phenocrysts. Plagioclase is mostly fresh and pyroxene is altered to chlorite. The groundmass shows intersertal texture with fresh plagioclase, altered pyroxene to chlorite, and opaque minerals. These lie in a cryptocrystalline base, partly altered to chlorite and smectite.

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