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Two-phase opening model for the Okinawa Trough inferred from paleomagnetic study of the Ryukyu arc

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Abstract. Tertiary volcanic and sedimentary rocks were collected at 50 sites of both the central Ryukyu arc and the southern Ryukyu arc for a paleomagnetic and geochronological study, in an attempt to understand the opening of the Okinawa Trough back arc basin. Stable primary components of remanent magnetization were isolated through both thermal and alternating field demagnetization experiments from 12 sites of three geological units of the central Ryukyu arc and from 12 sites of two geological units of the southern Ryukyu arc. The paleomagnetic results were compared with the Tertiary apparent pole wander path of Eurasia in order to investigate the tectonic movement of the Ryukyu arc with respect to the Asian continent. The comparison and the radiometric ages indicate that the southern Ryukyu arc rotated clockwise through 25° between 10 Ma and 6 Ma. In contrast, the central Ryukyu arc experienced little rotational motion since 17 Ma. We propose the following two-phase opening model for the Okinawa Trough opening. The first stage took place between 10 Ma and 6 Ma. The southern part of the trough opened by means of a "wedge" mode to cause the clockwise rotation of the southern Ryukyu arc. In the central part the "parallel" opening occurred, and the Ryukyu arc drifted without any rotation. The second phase started recently in the whole Okinawa Trough. It is observed as the present activities in the trough.

Introduction

The Ryukyu arc and the Okinawa Trough are typical of the island arc and back arc basins that together form convergent plate boundaries (Figure 1). The Ryukyu arc rifted away from the Asian continent, leaving a back arc basin known as the Okinawa Trough in its wake. A large body of evidence for the rifting has accumulated over several decades from both geological and geophysical surveys of the area. In particular, seismic reflection and refraction data reveal a typical graben structure in the trough [*Herman et al.*, 1978; *Lee et al.*, 1980; *Kimura*, 1985; *Letouzey and Kimura*, 1986; *Sibuet et al.*, 1987], and en echelon volcanic ridges have been observed along the central axis of the trough [*Kimura*, 1985; *Kimura et al.*, 1986; *Letouzey and Kimura*, 1986; *Sibuet et al.*, 1987].

The exact timing of the trough opening is still controversial. Seismic profiles and geological observation in the trough indicate that the rifting started in the late Miocene [*Herman et al.*, 1978; *Lee et al.*, 1980; *Letouzey and Kimura*, 1986; *Sibuet et al.*, 1987]. The key observation in their studies is a strong Miocene erosional event, which is marked by a sharp angular unconformity in the Okinawa Trough. In contrast, recent seismic refraction data [*Hirata et al.*, 1991] and the age of the volcanic rocks in the trough [*Kimura et al.*, 1986] indicate that the Okinawa Trough is only now in the initial stage of rifting.

Lee et al. [1980] and *Kimura* [1985] regard the magnetic anomalies in the Okinawa Trough as representing a series of normal and reversed magnetized blocks formed due to sea floor spreading: the anomalies can, however, be explained by normal magnetization of dikes or topography of the magnetized layer [*Sibuet et al.*, 1987; *Kitahara et al.*, 1986; *Furukawa et al.*, 1991a; *Oshida et al.*, 1992].

Paleomagnetism is an effective tool for recognizing the horizontal movements of the island arcs during the rifting of a back arc basin. Previous paleomagnetic and geochronological studies indicate that the southern Ryukyu block has rotated since 10 Ma in association with the opening of the Okinawa Trough [*Miki et al.*, 1990].

In this paper the displacement history is established for the central Ryukyu region as well as the southern Ryukyu region. A new kinematic model for the opening of the Okinawa Trough is presented after a discussion of the rotation of the Ryukyu arc since the Miocene.

Geology of the Ryukyu Arc

An outline of the geology is described here following *Kizaki* [1986]. The Ryukyu arc is divided into north, central, and southern domains from both geological and geomorphological view points; the Tokara channel forms the boundary between the northern and the central Ryukyu arc, whereas the Miyako depression forms the boundary between the central and the southern Ryukyu arc (Figure 1). Figure 2 shows the schematic stratigraphy of the central and the southern Ryukyu arc.

Weakly metamorphosed Mesozoic-Eocene sedimentary rocks are widely distributed in the northern and central Ryukyu domain. The sedimentary rocks of Okinawa-jima Island are named the Kayo Formation (Figure 3) and can be dated as Eocene by the presence of the foraminifera fossils (*Nummulites sp.* [*Konishi et al.*, 1973]).

The Mesozoic-Eocene sedimentary rocks are locally intruded by Paleogene granitic rocks, for example, on Amami-oshima Island and Tokuno-shima Island (Figure 4). The

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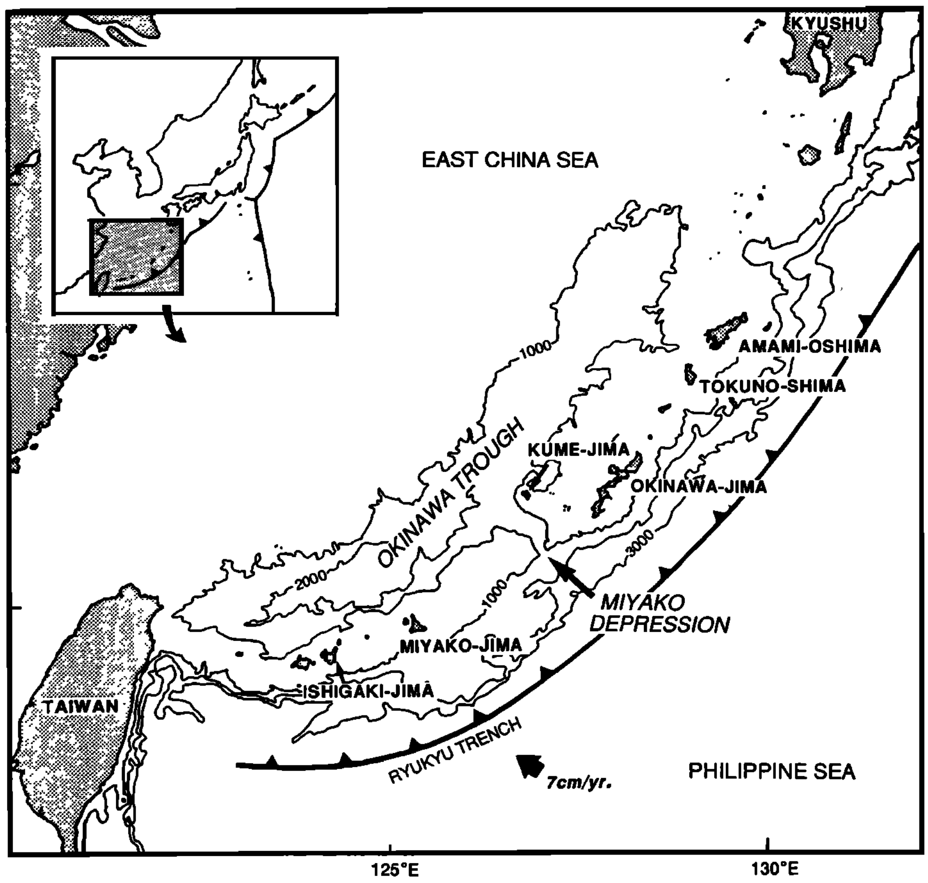

Figure 1. Map of the Ryukyu arc and the Okinawa Trough. The thick arrow indicates the direction and the rate of convergence between the Pacific and the Philippine Sea plates [see *Seno*, 1977].

granitic rocks have been dated using K-Ar ages: 59 Ma [*Kawano and Kato*, 1989] and 61 Ma [*Kawano and Ueda*, 1966] for granodiorites of Tokuno-shima Island and 49-55 Ma [*Shibata and Nozawa*, 1966] for granites from Amami-oshima Island.

The southern Ryukyu domain is characterized by the presence of Eocene volcanics and limestone overlain by lower Miocene sedimentary rocks (Figure 2). The Eocene volcanics on Ishigaki-jima Island (Nosoko Formation; Figure 5) consist of pyroclastic rocks and andesite lavas and contain various

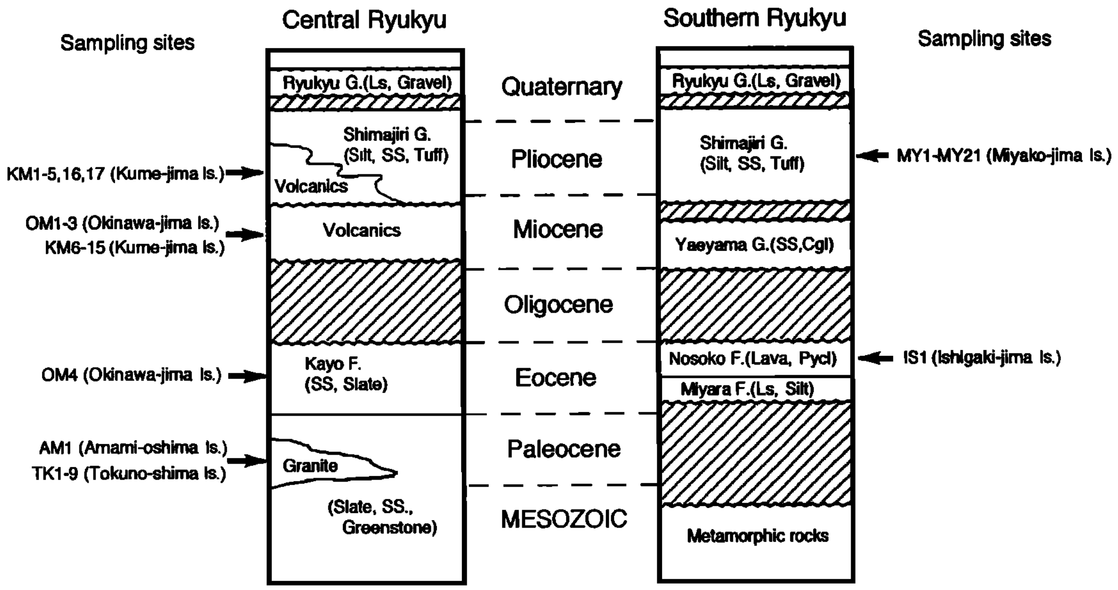

Figure 2. Schematic geological stratigraphy of the central and southern Ryukyu region. Sampling site numbers are also indicated.

foraminifera fossils of Eocene age [*Kizaki*, 1986; *Nakagawa et al.*, 1982]. Fission track ages of zircon were determined to be between 43 Ma and 45 Ma [*Daishi et al.*, 1987]. The paleomagnetic direction of this formation has clockwise deflection of about 30° from the north [*Miki et al.*, 1990].

The upper Miocene to lower Pleistocene sedimentary sequence, the Shimajiri Group, is distributed throughout the Ryukyu arc including Miyako-jima Island (Figure 6). Its base is always with a sharp unconformity. The group is mainly composed of siltstone interbedded with sandstone and tuff. It is not strongly deformed, with only minor undulations. Planktonic foraminifera zones ranging from N 17 to N 22 (6-2 Ma [*Blow*, 1969]) have been identified on Miyako-jima Island [*Ujiie and Oki*, 1974]. A K-Ar age of 3.64 ± 0.22 Ma was determined from hornblende in a layer of tuff [*Kuramoto and Konishi*, 1989].

The Miocene to Pliocene volcanic rocks are distributed as intrusions or lava flows. The Miocene intrusions are widely distributed throughout the arc from Tanegashima Island in the north to Iriomote-jima Island in the south.

It is the intrusive rocks on Okinawa-jima Island that have been taken as samples for the central Ryukyu arc in this study (Figure 3). Propylitic rocks are distributed along the west coast of Okinawa-jima Island. Fission track ages of around 15 Ma have been determined from zircon [*Daishi and Hayashi*, 1982; *Daishi et al.*, 1986].

The andesite intrusion on Ishigaki-jima Island of the southern Ryukyu arc also shows a clockwise deflected paleomagnetic direction [*Miki et al.*, 1990]. This rock has been dated at 9.6 ± 0.8 Ma by the whole rock K-Ar method.

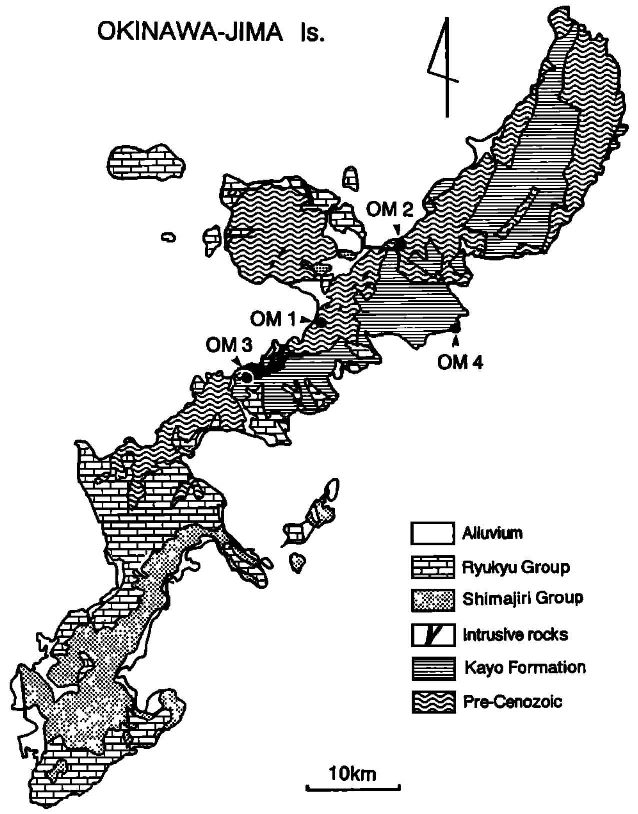

Figure 3. Simplified geological map of Okinawa-jima Island. Solid circles show the sampling localities of the Kayo Formation and dikes.

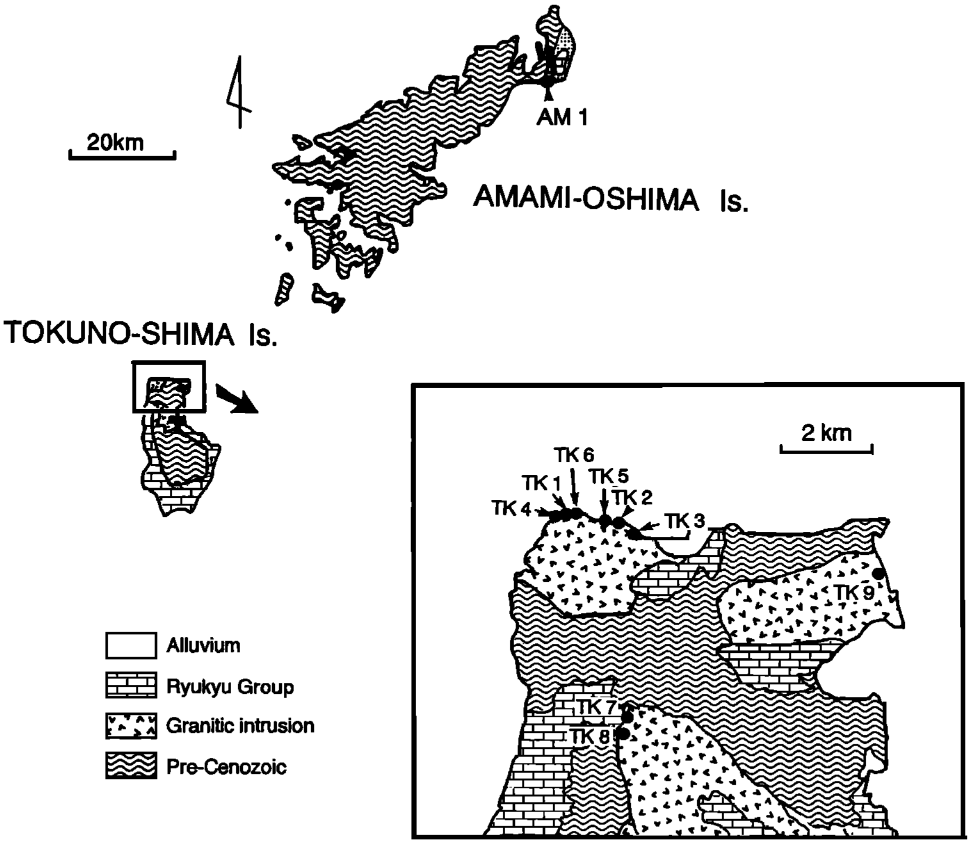

Figure 4. Simplified geological map of Amami-oshima and Tokuno-shima Islands. Solid circles show the sampling localities of granitic igneous rocks.

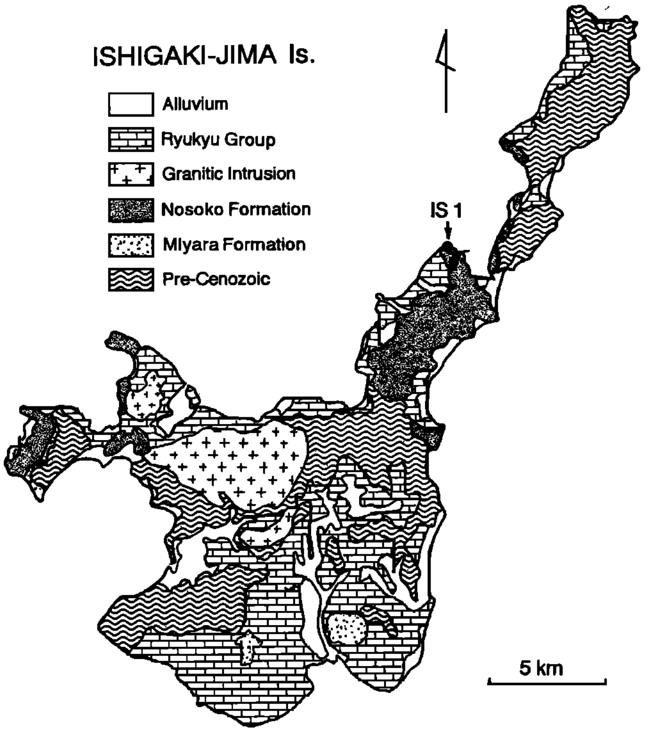

Figure 5. Simplified geological map of Ishigaki-jima Island. A solid circle shows the sampling locality from the Nosoko Formation.

Two volcanic formations are recognized on Kume-jima Island in the central Ryukyu region (Figure 7): the Ara-dake Formation of Miocene age, the Uegusuku-dake Formation of Pliocene age. The Ara-dake Formation is distributed in the southwestern part of the island. The rocks consist of lavas, pyroclastics, and a minor amounts of hyaloclastics. The formation can be subdivided into seven units with a total thickness of over 450 m [*Shinjo and Kato*, 1988]. Ages of lavas obtained by both K-Ar [*Nakagawa and Murakami*, 1975] and fission track methods [*Daishi et al.*, 1987] are between 12 Ma and 17 Ma.

The Pliocene Uegusuku-dake Formation is distributed in the northwestern part of Kume-jima Island. The rocks consist of more than 10 sheets of lava flows and a small amount of pyroclastics [*Nakagawa and Murakami*, 1975]. The total thickness is more than 300 m. The ages of lavas have been determined to be 4.6 Ma and 5.5 Ma by the whole rock K-Ar method [*Nakagawa and Murakami*, 1975], and 6.2 Ma by the fission track method [*Daishi et al.*, 1987]. Another Pliocene andesite outcrop is situated in Omu-jima Island, just east of Kume-jima Island with a K-Ar whole rock age of 6.08 ± 0.46 Ma [*Shinjo et al.*, 1991].

Samples for this study were collected from two geological units in the southern Ryukyu arc: (1) rocks of the Eocene Nosoko Formation on Ishigaki-jima Island (1 site) and (2) sedimentary rocks of the upper Miocene to Pliocene Shimajiri Group on Miyako-jima Island (20 sites of siltstone and 1 site of tuff).

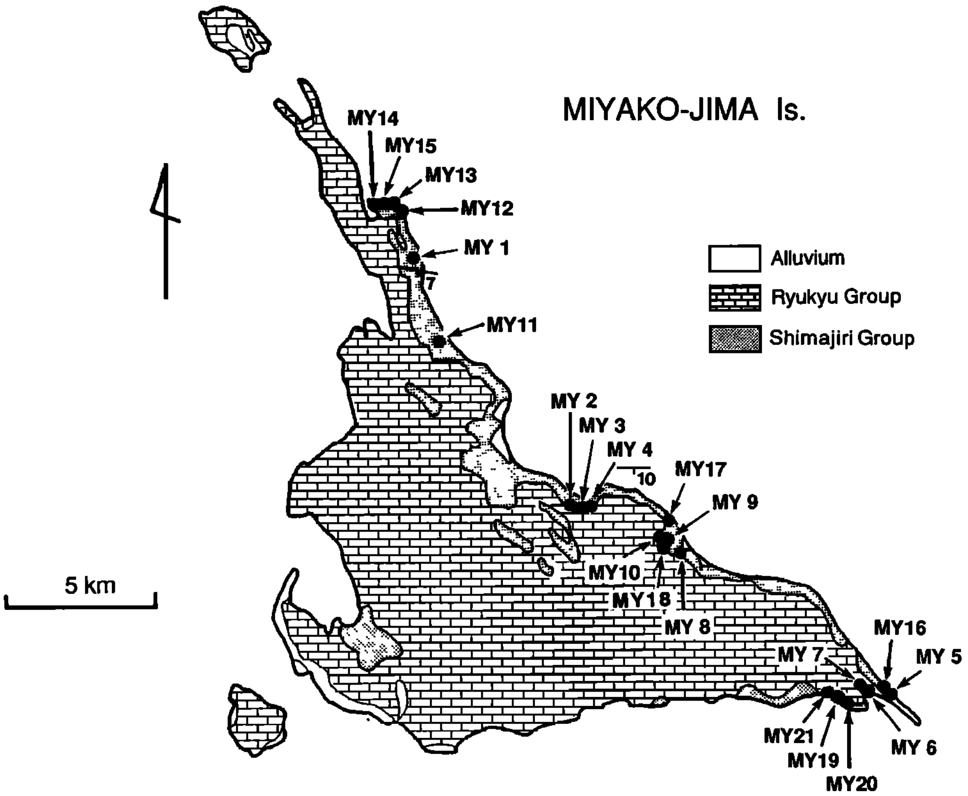

Figure 6. Simplified geological map of Miyako-jima Island. Solid circles show the sampling localities from the Shimajiri Group.

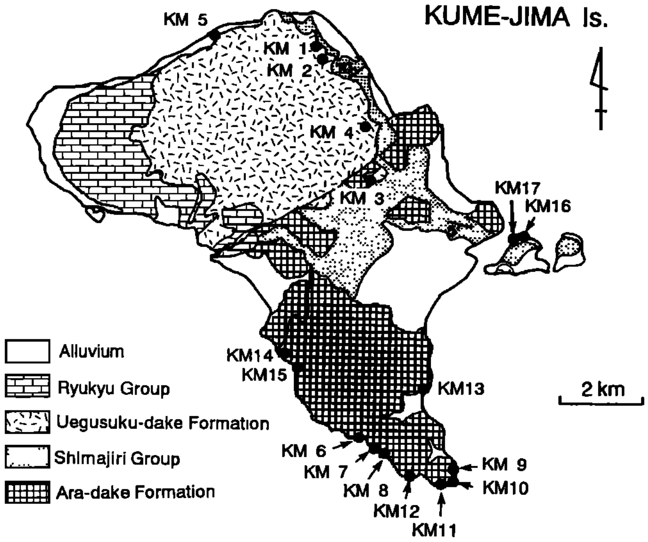

Figure 7. Simplified geological map of Kume-jima Island. Solid circles show the sampling localities of volcanic rocks.

Samples were also collected from four geological units in the central Ryukyu arc: (1) Paleocene granites on Amami-oshima Island (1 site) and Tokuno-shima Island (9 sites); (2) Eocene siltstones (1 site); (3) Miocene andesite dikes (3 sites) on Okinawa-jima Island; and (4) Miocene to Pliocene volcanic rocks on Kume-jima Island and Omu-jima Island (10 sites of six flow units of the Ara-dake Formation, 5 sites of the Uegusuku-dake Formation and 2 sites of Omu-jima andesite).

Hand samples were taken, and a magnetic compass was used to orient them. Each site is typically composed of 10 independently oriented samples, which are distributed over distances ranging up to 30 m. Three or four large (~20 cm) block samples were cut out from the sites of the Shimajiri Group on Miyako-jima Island.

Geochronology

K-Ar whole rock dating was conducted on samples from the Ara-dake Formation and the Uegusuku-dake Formation. Prior to K-Ar dating, thin sections of the samples were examined. The samples from one site of the Uegusuku-dake Formation (KM3) and two sites of the Ara-dake Formation (KM9 and KM13) are fresh enough to determine the age of the eruption according to the criteria discussed by *Mankinen and Darlymple* [1972].

Whole rock samples were prepared for argon analysis by crashing to 80-100 mesh size. A portion of each sample was further ground in an agate mortar and used for potassium analysis. Details of the analytical procedures for potassium and argon isotope determinations have been reported by *Itaya and Takasugi* [1988]. Ages and errors were calculated using the method of *Nagao and Itaya* [1988] and the decay constants of *Steiger and Jäger* [1977].

The volcanic rocks from the Ara-dake Formation (sites KM9 and KM13) have ages of 17.9 ± 0.4 Ma and 17.0 ± 0.4 Ma (Table 1). These ages are concordant with those previously studied (12.6 Ma and 17.6 Ma [*Nakagawa and Murakami*, 1975]).

The volcanic rocks from the Uegusuku-dake Formation (site KM3) have an age of 2.24 ± 0.10 Ma. The formation which overlies the Uegusuku-dake Formation is younger than 2.24 Ma [*Nakagawa and Murakami*, 1975], indicating the observed age is consistent with the stratigraphic sequence. The combination with the ages previously determined [*Nakagawa and Murakami*, 1975; *Daishi et al.*, 1987; *Shinjo et al.*, 1991] indicates that the volcanics of the Uegusuku-dake Formation erupted between 6 Ma and 2 Ma.

Paleomagnetic Methods

Natural remanent magnetizations (NRMs) were measured using a two-axis cryogenic magnetometer or a spinner magnetometer according to the intensity of magnetization. Two or three samples from each site were chosen for a pilot study. One specimen from each pilot sample was subjected to stepwise thermal demagnetization in steps of 50°C up to 500°C and 30°C up to about 700°C. A second specimen was subjected to stepwise alternating field (AF) demagnetization in steps of 2.5 mT up to 10 mT and 5 mT up to about 70 mT. According to the results of the pilot study, the remaining specimens were subjected to either progressive AF or thermal demagnetization. Up to five specimens from each block sample were measured for silt sites on Miyako-jima Island. One specimen from each block sample was measured for the other sites.

Table 1. Results of K-Ar Dating on Lava Flows From Kume-jima Island

Site	Locality	Sample	K, WT%	$^{40}Ar_{rad}$, $10^{-8}cm^3/g$	Age, Ma	Ar_{air}/Ar_{total}, %
			Uegusuku-dake Formation			
KM3	126°47'58"E, 26°21'15"N	andesite	0.756	6.56 ± 0.21	2.24 ± 0.10	61.0
			Ara-dake Formation			
KM9	126°48'49"E, 26°17'18"N	porphyrite	1.90	133 ± 2	17.9 ± 0.4	30.2
KM13	126°48'27"E, 26°18'21"N	andesite	1.55	103 ± 2	17.0 ± 0.4	31.6

The constants used in the calculation are $\lambda_\beta = 4.962 \times 10^{-10} yr^{-1}$, $\lambda_\varepsilon = 0.581 \times 10^{-10} yr^{-1}$, and $^{40}K = 1.167 \times 10^{-4}$ atom per atom of natural potassium [*Steiger and Jäger*, 1977].

Table 2. Summary of Paleomagnetic Results From the Southern Ryukyu Arc

Site	N	Strike / Dip	Uncorrected		Corrected		k	α_{95}, deg	Rock Type
			D, deg	I, deg	D, deg	I, deg			
				Ishigaki-jima Nosoko Formation (Eocene)					
ISA (m)	14	80.0 / 6.0	195.3	-49.0	200.5	-54.1	273.4	2.4	tuff
ISA(h)	12	80.0 / 6.0	22.6	19.3	24.1	23.8	22.3	9.4	tuff
				Miyako-jima Shimajiri Group (Miocene-Pliocene)					
MY1	7(7)	102.5 / 7.2	1.9	39.1	1.0	46.2	103.0	6.0	siltstone
MY4	7(7)	90.0 / 10.0	174.7	-3.3	174.7	-13.4	123.4	5.5	tuff
MY5	3(14)	121.0 / 16.0	201.2	4.3	201.1	-11.7	114.7	3.7	siltstone
MY6	3(12)	161.0 / 9.5	169.0	-18.1	165.8	-19.8	40.4	6.9	siltstone
MY7	3(13)	87.5 / 11.0	357.4	-23.3	357.1	-12.3	49.3	6.0	siltstone
MY9	3(15)	310.5 / 10.6	181.7	-26.2	184.1	-17.4	275.6	2.3	siltstone
MY10	3(11)	351.0 / 9.0	181.5	-27.0	185.7	-24.4	532.3	2.0	siltstone
MY12	4(15)	118.0 / 14.0	351.6	30.7	345.5	42.0	38.0	6.3	siltstone
MY19	3(15)	340.0 / 10.0	163.9	-29.5	169.3	-27.7	35.2	6.5	siltstone
MY20	3(15)	101.0 / 15.0	185.9	-34.7	185.2	-49.6	180.6	2.9	siltstone
MY21	3(13)	102.0 / 18.0	176.4	-34.3	170.4	-51.1	52.6	5.8	siltstone

ISA(m) and ISA(h) mean the intermediate- and high-temperature components, respectively. N is number of rock samples. Up to five specimens are taken from each rock sample for the site on Miyako-jima Island. Numbers of specimens are given in parentheses. One specimen from each rock sample for other sites. Strike/dip refers to strike and dip of the bedding; D is declination, and I is inclination (uncorrected/corrected for bedding tilt).

Principal component analysis [*Kirschvink*, 1980] was used to calculate the best fit demagnetization lines for linear demagnetization trajectories. The maximum angular dispersion (MAD) of the least squares lines were used as a selection criterion: 10° in MAD is generally recognized as a criterion for rejecting the sample for further study (this is reduced to 5° for rocks of Kume-jima volcanics as mentioned below).

Paleomagnetic Results

Southern Ryukyu Arc

Paleomagnetic results were obtained from one tuff site (IS 1) of the Eocene Nosoko Formation on Ishigaki-jima Island and 11 sites of the Miocene Shimajiri Group on Miyako-jima Island (Table 2).

The samples of the Nosoko Formation (IS1) have three components of NRM. These three components appeared during the stepwise thermal demagnetization (Figure 8). The low-temperature component is identified up to 200°C or 250°C. The direction of this component is northward with a positive inclination. The intermediate component is identified between 200°C and 450°C. The direction of this component is reversed polarity with a clockwise deflection of about 20° in declination. The mean direction of 14 samples is declination D = 200.5°, inclination I = -54.1° with α_{95} = 2.4° after tilt correction. The high-temperature components are obtained

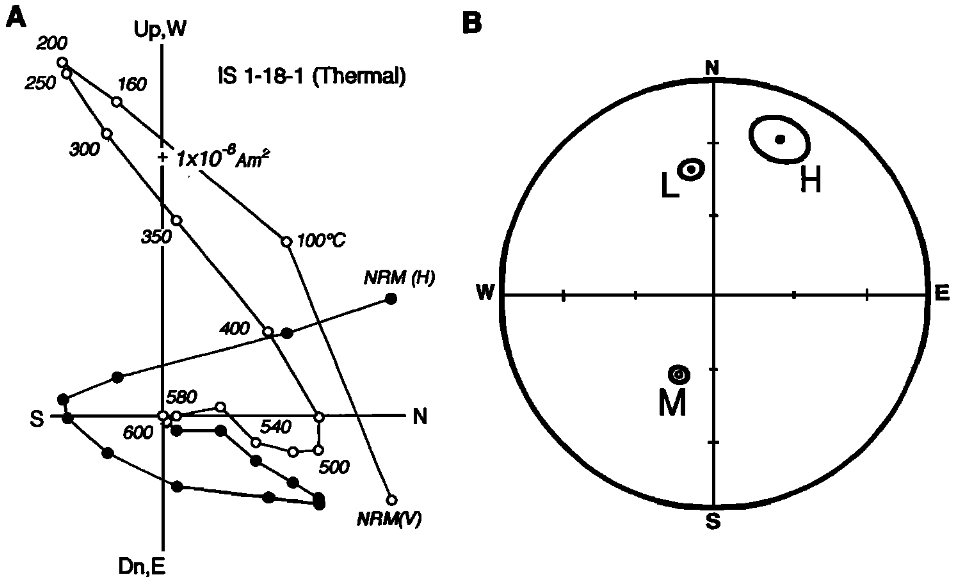

Figure 8. Paleomagnetic results of samples from Ishigaki-jima Island. (a) Orthogonal projection plots for thermal demagnetization experiment. Open (solid) circles are on the vertical (horizontal) plane. (b) The site mean directions of three components of remanent magnetization. Low-(L), intermediate-(M), and high-(H) temperature components were identified through thermal demagnetization. Equal-area projections.

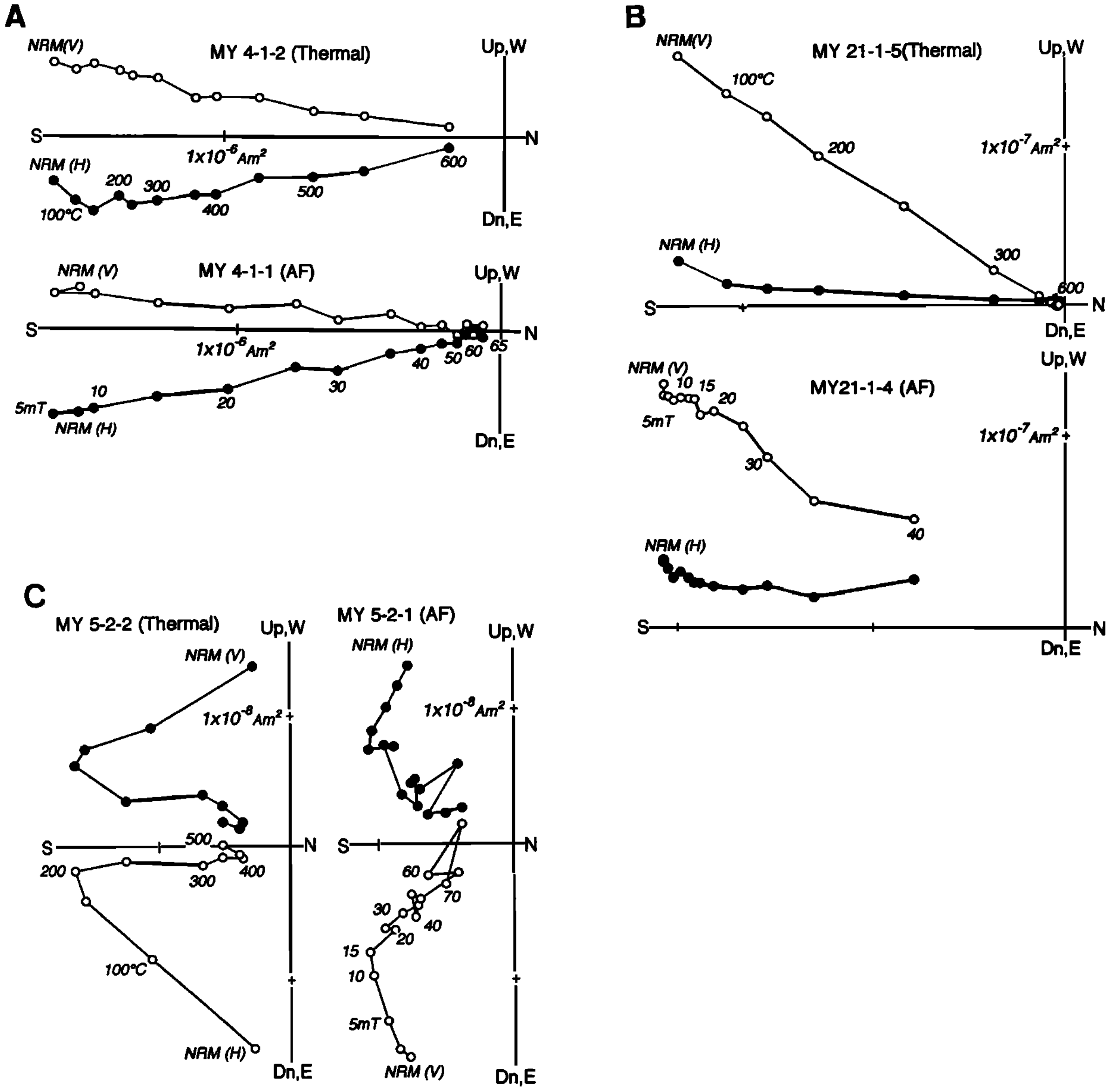

Figure 9. Orthogonal projection plots of stepwise thermal and alternating field demagnetizations for samples from Miyako-jima Island. (a) One-component magnetization from a tuff sample. (b) One-component magnetization from a siltstone. (c) Two-component magnetization from a siltstone. Open (solid) circles are vertical (horizontal) plane.

from 12 samples. The unblocking temperature of this component is 580°C, indicating that the magnetic carrier is titanium poor magnetite. This component has a normal polarity with an eastward deflection in declination. The mean direction is D = 24.1°, I = 23.8°, α_{95} = 9.4° after tilt correction. The directions of the intermediate- and high-temperature components are antipodal to each other.

There are two possible origins for these two components with higher unblocking temperatures. (1) The high-temperature component is a primary component and the intermediate-temperature component is a secondary component. (2) The high-temperature component has been acquired as the secondary component through some rock magnetic process such as a self-reversal phenomenon. The chance of self-reversal origin is, however, probably very low because this phenomenon has been observed only in special kind of rocks such as andesite or dacite pumice [e.g., *Heller et al.*, 1986]. I interpret the normal high-temperature component as the primary and the reversed intermediate-temperature component as the secondary, although further work is needed to explain the acquisition mechanism of the secondary component.

The new direction from IS 1 is concordant with the characteristic direction of the Nosoko Formation reported by *Miki et al.* [1990], although all the directions previously observed have reversed polarity. A normal direction with clockwise deflection is also observed in this study. We calculated a new mean direction of the Nosoko Formation by combining the new direction with the previous ones. The mean direction of 16 sites is D = 29.6°, I = 39.2°, and α_{95} = 9.8°. The new direction is almost same as the mean direction of the previous work.

The low-temperature component up to 250°C is probably due to overprinting by the present geomagnetic field, judging

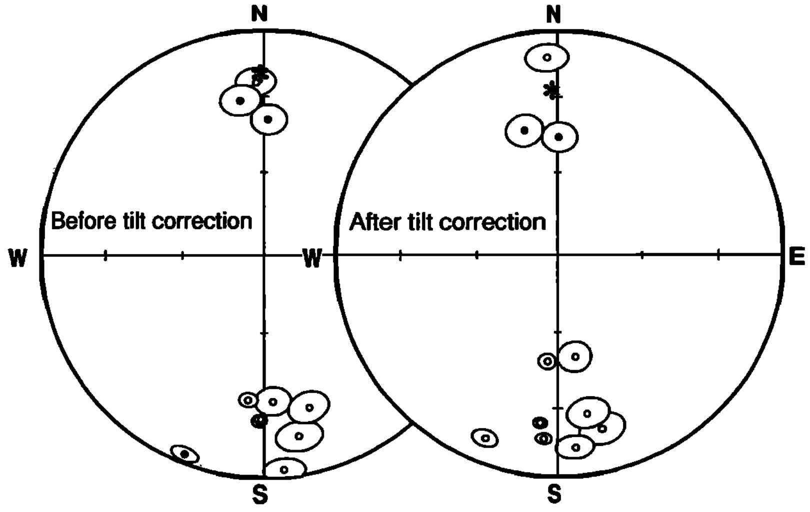

Figure 10. Paleomagnetic site mean directions with 95% confidence circles for the Shimajiri Group from Miyako-jima Island. The asterisks show the mean direction of 11 sites. Open (solid) circles are on the upper (lower) hemisphere. Equal-area projections.

from the fairly low unblocking temperature and the northward direction before the tectonic correction.

The characteristic directions from the 11 sites of the Shimajiri Group are identified during both AF and thermal demagnetization. The unblocking temperature of this component is about 600°C in tuff samples (site MY4, Figure 9a), indicating that the magnetic carrier is magnetite. The unblocking temperature is about 400°C in siltstones (Figure 9b), and the magnetic carrier is probably titanomagnetite. A low-temperature component with an unblocking temperature of 200°C is observed in samples from three sites (Figure 9c). The direction of this component is northward with a positive inclination. This component is probably due to overprinting in recent times.

The high-temperature component directions of the 11 sites are fairly tightly clustered in each site. The α_{95} ranges from 3° to 7°. Three sites show the normal polarity, whereas eight sites show reversed polarity (Figure 10). They are antipodal to each other: the difference between mean directions calculated from normal polarity directions and reversed polarity directions is 184.7°. The mean direction of 11 sites before tilt correction is $D = 358.7°$, $I = 20.2°$, and $\alpha_{95} = 12.5°$ (projected to normal polarity), and that after tilt correction is $D = 358.5°$, $I = 27.0°$, and $\alpha_{95} = 12.5°$.

The following evidence indicates that the observed field directions represent primary remanent magnetization of Pliocene time: (1) both normal and reversed polarities are present, (2) similar characteristic directions are observed in

Table 3. Summary of Paleomagnetic Results From the Central Ryukyu Arc

Site	*N*	*D*, deg	*I*, deg	*k*	α_{95}, deg	Rock Type
			Okinawa-jima (Miocene)			
OM3	10	354.7	36.6	259.6	3.0	andesite
			Kume-jima Ara-dake Formation (Miocene)			
KM7	9	8.6	24.9	22.3	11.2	andesite lava
KM8	8	11.6	32.3	22.1	12.0	andesite lava
KM9	10	30.0	37.7	129.3	4.3	porphyrite
KM11	9	23.6	49.5	129.2	4.5	porphyrite
KM12	7	7.3	29.0	65.9	7.5	andesite lava
			Uegusuku-dake Formation (Pliocene)			
KM1	9	177.5	-48.7	66.0	6.4	andesite lava
KM2	6	164.0	-24.3	82.6	7.4	andesite lava
KM3	7	218.1	-70.2	18.4	14.4	andesite lava
KM5	7	179.2	-21.7	214.5	4.1	andesite lava
			Omu-jima (Pliocene)			
KM16	10	9.6	39.3	497.2	2.2	andesite lava
KM17	11	14.7	38.9	236.3	3.0	andesite lava

N, number of rock samples; *D*, declination; *I*, inclination.

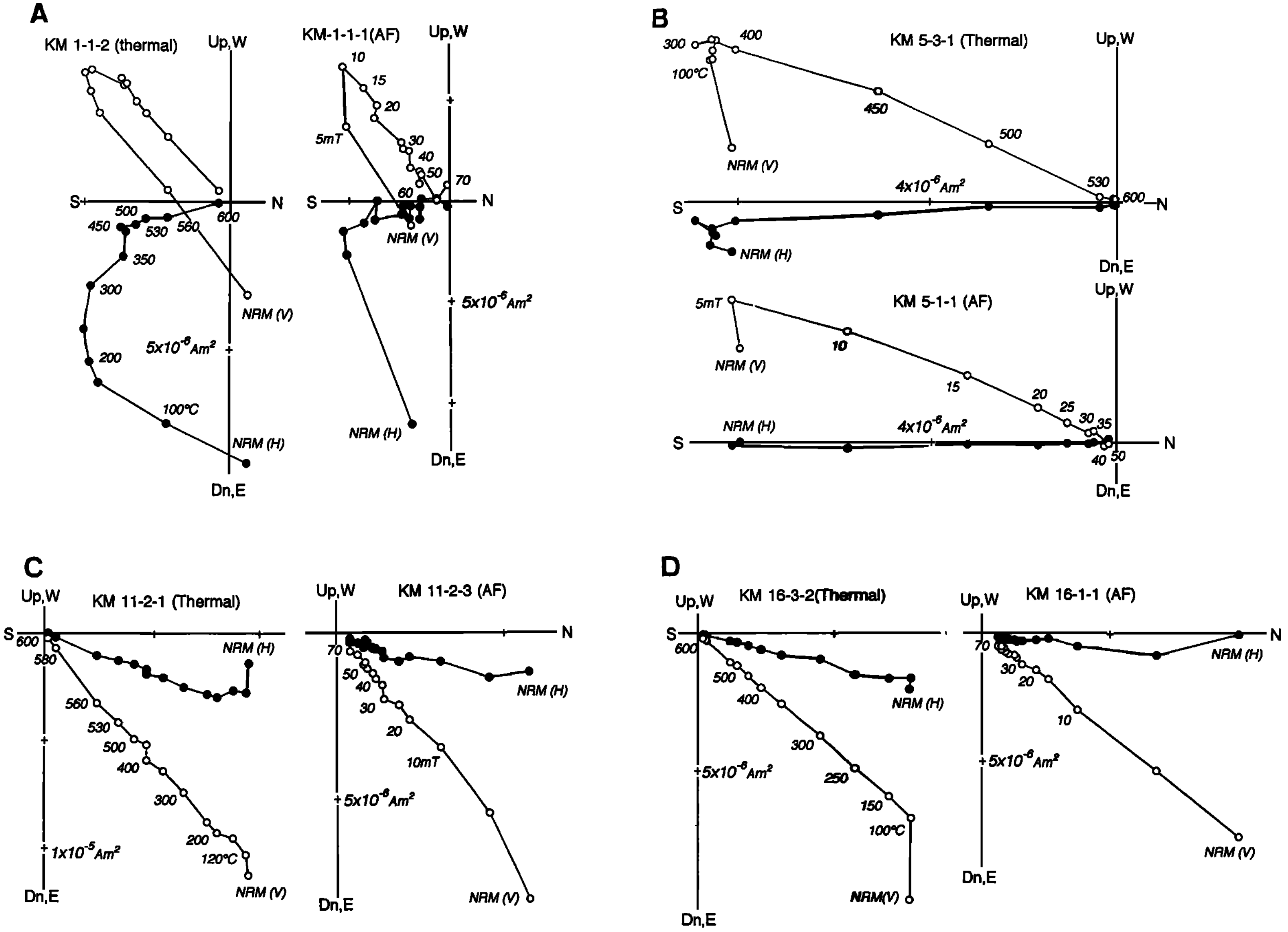

Figure 11. Orthogonal projection plots of stepwise thermal and alternating field demagnetizations for samples from Kume-jima Island. (a)(b) Examples for lava flows from the Miocene Ara-dake Formation. (c)(d) Examples for lava flows from the Pliocene Uegusuku-dake Formation. Open (solid) circles are on the vertical (horizontal) plane.

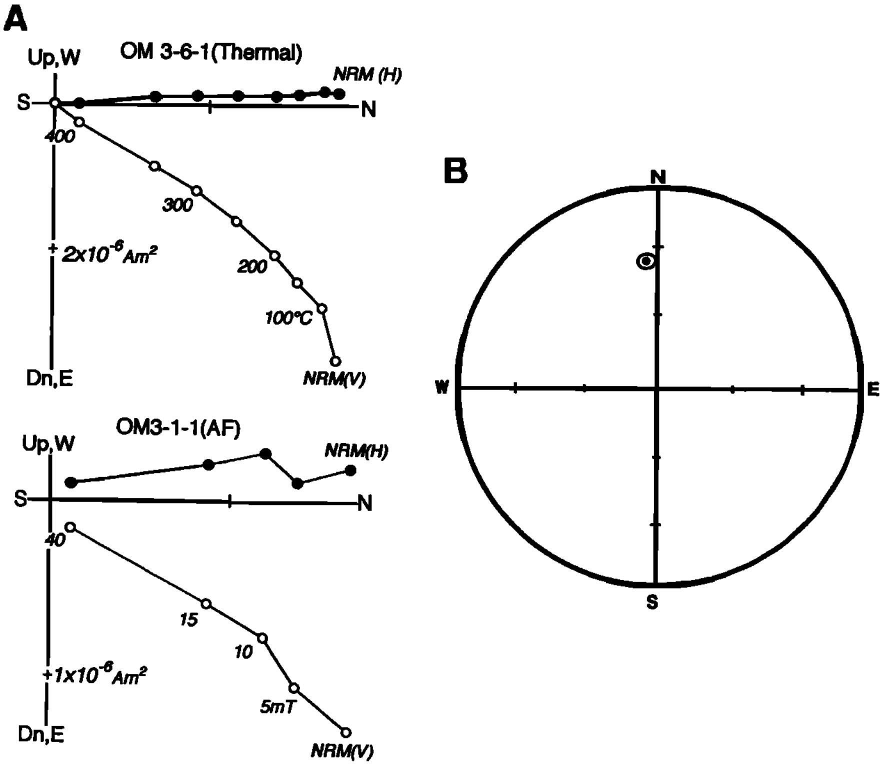

Figure 12. Paleomagnetic results from Okinawa-jima Island. (a) Orthogonal projection plots of stepwise thermal and alternating field demagnetizations. Open (solid) circles are on the vertical (horizontal) plane. (b) Site mean direction of site OM3. An equal-area projection.

both tuffs and siltstones, and (3) no alteration of the samples is observed. The fold test is ineffective because the structure is monoclinal.

Central Ryukyu Arc

Paleomagnetic directions were obtained from Miocene and Pliocene volcanic rocks in the central Ryukyu arc (Table 3). Miocene directions were identified from five sites of the Ara-dake Formation on Kume-jima Island and one site of a dike on Okinawa-jima Island. Pliocene directions were identified from four sites of the Uegusuku-dake Formation on Kume-jima Island and two sites of the Omu-jima andesite.

The stable characteristic component of these samples has a high unblocking temperature of about 600°C (Figures 11 and 12). The magnetic carrier is probably magnetite. Some samples of the Ara-dake and the Uegusuku-dake Formations have a second component with a low unblocking temperature below 400°C (Figure 11). This component is generally northward with a positive inclination and is probably due to recent overprinting. The characteristic directions can also be obtained through AF demagnetization. The directions were

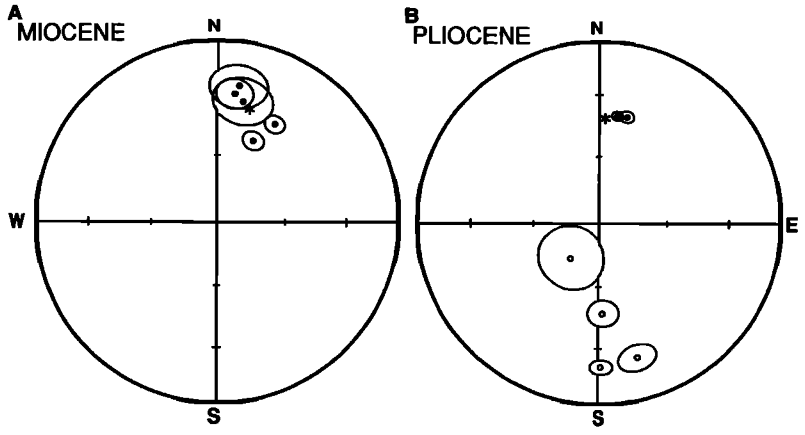

Figure 13. Paleomagnetic site mean directions with 95% confidence circles from Kume-jima Island. (a) Directions from the Miocene Ara-dake Formation. (b) Directions from the Pliocene Uegusuku-dake Formation and Omu-jima andesite. The asterisks show the mean directions. Open (solid) circles are on the upper (lower) hemisphere. Equal-area projections.

identified after demagnetization at about 20 mT, and the intensity of magnetization becomes 10% or less at about 60 mT. Thermal demagnetization is preferred for the calculation because of the smaller MAD value on thermal demagnetization paths.

The characteristic directions of the Miocene Ara-dake Formation have a normal polarity with a small eastward deflection (D = 7°-30°; Figure 13a). For the results from the Ara-dake Formation, MAD of 5° was used to distinguish the direction of the high-temperature component from that of the low-temperature component. This is because the direction of both components is similar in some samples. The mean direction of five sites is $D = 15.5°$, $I = 35.0°$, with $\alpha_{95} = 11.9°$. The site mean direction for the intrusive rock on Okinawa-jima Island (site OM3) is $D = 354.3°$, $I = 36.6°$, with $\alpha_{95} = 3.0°$ (Figure 12b). A fission track age of 11.3 ± 1.0 Ma is determined from zircon in this rock [*Daishi and Hayashi*, 1982].

The characteristic directions from the 6-2 Ma Uegusuku-dake Formation are southward with a negative inclination (Figure 13b). These directions are antipodal to the directions of the Omu-jima andesite. The Pliocene mean direction calculated for the Uegusuku-dake Formation and the Omu-jima andesite is $D = 3.3°$ and $I = 41.3°$ ($N = 6$) with $\alpha_{95} = 18.0°$.

The following evidence supports that the high-temperature component of the volcanic rocks in the central Ryukyu region is a primary component of NRM. (1) Microscopic studies do not reveal any signs of significant alteration or weathering. (2) Both the stable high-temperature component of NRM and the geochronological age are obtained from samples of the same andesite outcrop. The unblocking temperature of the high-temperature component is higher than the closure temperature for K-Ar or fission track ages indicating that the high-temperature component blocked before the radiometric age. (3) The magnetic carrier is titanium poor magnetite. Chemical remanent magnetizations (CRMs) in magnetite are considered to be uncommon [*McCabe et al.*, 1983]. (4) Reversed polarity magnetization has been recognized in the Uegusuku-dake Formation.

Although no tilt correction was applied for the volcanics, geological observations suggest that the tilt is small. The flatlying early Pliocene formation underlies the Uegusuku-dake Formation on Kume-jima Island, indicating that little tilt occurred since at least the early Pliocene. Only minor local tectonic effects can be recognized on the basis of the field observation. No significant tectonic tilt could be recognized in the Miocene Ara-dake Formation by detailed field surveys [*Shinjo and Kato*, 1988].

No stable paleomagnetic components are observed from the granitic rocks on Amami-oshima and Tokuno-shima Islands and the Eocene sedimentary rocks of the Kayo Formation. In these samples the NRM intensity is generally rather weak (10^{-5}-10^{-6} A/m). These rocks were therefore excluded for the rest of this study.

Discussion

Rotation of the Southern Ryukyu Arc

Significant clockwise deflection can be recognized in the paleomagnetic direction from the Eocene Nosoko Formation and a Miocene dike on Ishigaki-jima Island [*Miki et al.*, 1990](Table 4). A deflected direction with a normal polarity is recognized in this study from the Nosoko Formation. The existence of both normal and reversed geomagnetic polarities confirms that the deflection in declination is best ascribed to tectonic rotation rather than to geomagnetic secular variation. Using the K-Ar age data (9.6 Ma, [*Miki et al.*, 1990]) of the dike in combination with the deflected paleomagnetic

Table 4. Summary of the Paleomagnetic Results From the Ryukyu Arc

Age, Ma	Locality	*N*	*D*, deg	*I*, deg	*k*	α_{95}, deg	VGP Latitude, deg	VGP Longitude, deg	VGP k	VGP α_{95}, deg	References
					Central Ryukyu Arc						
11.3 (F.T.)	Okinawa-jima	1	354.0	37.0	-	-	82.0	352.4	-	-	1
12-17 (F.T., K-Ar), 17.0, 17.9 (K-Ar)	Kume-jima	5	15.5	35.0	42.0	11.9	73.9	237.8	49.0	11.0	2, 3
Post-10 Ma mean		6	12.0	35.5	37.7	11.1	77.0	243.1	36.9	11.2	
2-6 (F.T., K-Ar), 2.2 (K-Ar)	Kume-jima and Omu-jima	6	3.3	41.3	14.8	18.0	85.6	220.4	14.1	18.5	2, 3
					Southern Ryukyu Arc						
43-45 (F.T.)	Ishigaki-jima	16	29.6	39.2	15.2	9.8	63.3	211.2	14.9	9.9 *	2
43-45 (F.T.)	Ishigaki-jima	(15	30.1	40.3	14.8	10.3	63.0	209.3	14.2	10.5)	4
9.6 (K-Ar)	Ishigaki-jima	(1	36	32.1	-	-	55.7	219.3	-	-)	4
2-6 (Planktonic), 3.6 (K-Ar)	Miyako-jima	11	358.5	27.0	14.2	12.5	80.6	315.7	26.6	9.0	5, 6

N, number of site. Paleomagnetic results of the previous study are in parentheses. References are 1, *Daishi and Hayashi* [1982]; 2, *Daishi et al.* [1987]; 3, *Nakagawa and Murakami* [1975]; 4, *Miki et al.* [1990]; 5, *Ujiie and Oki* [1974], and 6, *Kuramoto and Konishi* [1989]. F.T. (K-Ar) ages were obtained by fission track (potassium argon) method.

* mean direction calculated by combining the direction of the high-temperature component of site IS1 with the directions of the pervious study [*Miki et al.*, 1990].

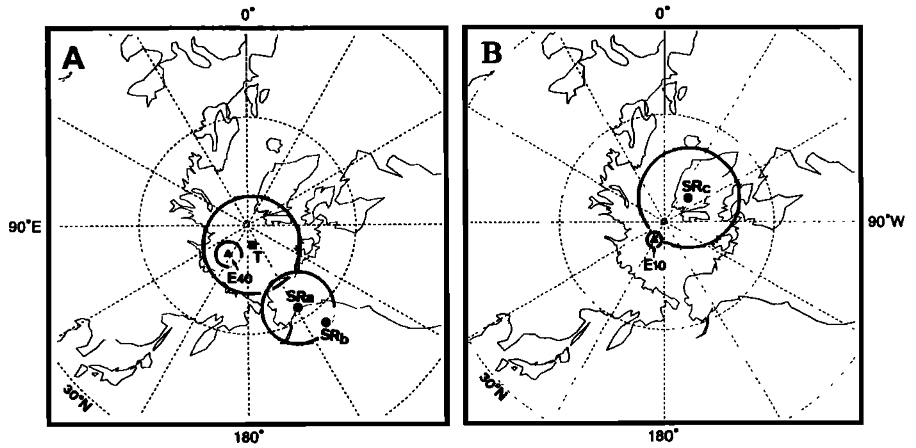

Figure 14. The paleopole positions with 95% confidence circles of the southern Ryukyu arc and the reference points. (a) The poles by about 10 Ma. (b) The poles after about 10 Ma. Solid circles are those of the southern Ryukyu arc. SRa and SRb are poles of the Eocene Nosoko Formation and the 9.6 Ma andesite dike [*Miki et al.*, 1990], respectively. SRc is the pole of the upper Miocene (~ 6 Ma) to Pliocene (~ 2 Ma) Shimajiri Group. E10 and E40 (triangles) are the 10 Ma and 40 Ma poles of the Eurasian continent [*Besse and Courtillot*, 1991]. T (square) is the pole of Miocene northern Taiwan [*Miki et al.*, 1993]. Stereographic projections.

declination, I conclude that the southern Ryukyu arc rotated clockwise later than 10 Ma.

The amount of rotation of the southern Ryukyu arc is evaluated with respect to the Asian continent. The paleomagnetic field direction from Ishigaki-jima Island (D = 29.6°, I = 39.2°) is compared with the expected field direction calculated from reference poles (Figure 14a). The Eurasian 40 Ma pole of *Besse and Courtillot* [1991] is accepted to be the reference pole of Asian continent. The rotation angle of the southern Ryukyu arc with respect to the Asian continent is 25.4° ± 10.6°. The error is a 95% confidence limit calculated using the method of *Demarest* [1983]. I conclude that the southern Ryukyu arc has rotated clockwise about 25° with respect to the Asian continent. The difference in inclination is 13.8° ± 8.3°. This is also significant to the 95% confidence level. However, it appears not to be due to the north-south translation of the Ryukyu arc with respect to east Asia. The shallow inclination is a common phenomenon in the east part of Eurasia. The Cenozoic poles from east Asia tend to be far sided with respect to the apparent polar wander pass for Eurasia [*Enkin et al.*, 1992], which would imply that the region involving east Asia and Ryukyu was a few hundred kilometers south of its present position relative to Eurasia. Further work is needed to clarify this point. I suggest here, however, that the rotation of the southern Ryukyu arc was not accompanied by significant north-south translation.

A rotation angle of 25° is larger than the 19° rotation determined by *Miki et al.* [1990]. The larger angle of rotation in this study arises because of a different choice of reference pole for the Asian continent. The present study uses the Eurasian pole of *Besse and Courtillot* [1991] as reference, whereas the previous study used the pole of *Irving* [1977]. The data quality is higher in the recent work because of the larger data sets and the strict selection criteria. The amount of 25° is a realistic estimate for the rotation of the southern Ryukyu arc with respect to the Asian continent.

Little deflection has been observed from the late Miocene-Pliocene paleomagnetic direction of Miyako-jima Island which is located on the 90 km east of Ishigaki-jima Island (Table 4). The direction is close to that expected from the 10 Ma Eurasian pole [*Besse and Courtillot* ,1991](Figure 14b). A slightly shallower paleomagnetic inclination is probably due to the inclination error that sometimes occurs in finegrained sedimentary rocks [e.g., *Arason and Levi*, 1990]. Miyako-jima Island appears to have undergone little tectonic rotation or north-south translation with respect to the Asian continent after the beginning of the sedimentation of the Miocene-Pliocene Shimajiri Group at about 6 Ma. I therefore propose the following model: (1) The southern Ryukyu block includes the Miyako-jima Island and Ishigaki-jima Islands. (2) The rotation of the southern Ryukyu arc took place between 10 Ma and 6 Ma.

An alternative explanation for the different paleomagnetic results of the Eocene Ishigaki-jima Island and the Miocene-Pliocene Miyako-jima Island is that Ishigaki-jima Island and Miyako-jima Island belong to different tectonic blocks and that only the Ishigaki-jima Island block has rotated later than 10 Ma. Geomorphological observations, however, indicate that Ishigaki-jima Island and Miyako-jima Island form a single block within the southern Ryukyu arc. The explanation of distinct blocks with different rotation requires a large fault between Ishigaki-jima Island and Miyako-jima Island. In other regions, for instance, the Aleutian arc, where block rotations have been recognized, the boundaries between adjacent rotating blocks are delineated by distinct canyons which are deeper than 1000 m [*Geist et al.*, 1988]. Between Ishigaki-jima Island and Miyako-jima Island, there is no distinct block boundary. The region is shallower than 500 m, and there are no large faults between these islands. I conclude that the Ishigaki-jima and Miyako-jima Islands rotated together as a rigid block within the southern Ryukyu arc.

Taiwan, the island arc southwest of the Ryukyu arc, has been fixed to the Asian continent since 10 Ma [*Miki et al.*, 1993]. The Neogene northern Taiwan pole [*Miki et al.*, 1993] is close to the Eurasian pole (Figure 14a). The amount of rotation of the southern Ryukyu arc with respect to Taiwan is calculated to be 23.9° ± 15.7°. The southern Ryukyu arc has also rotated with respect to Taiwan. The difference in

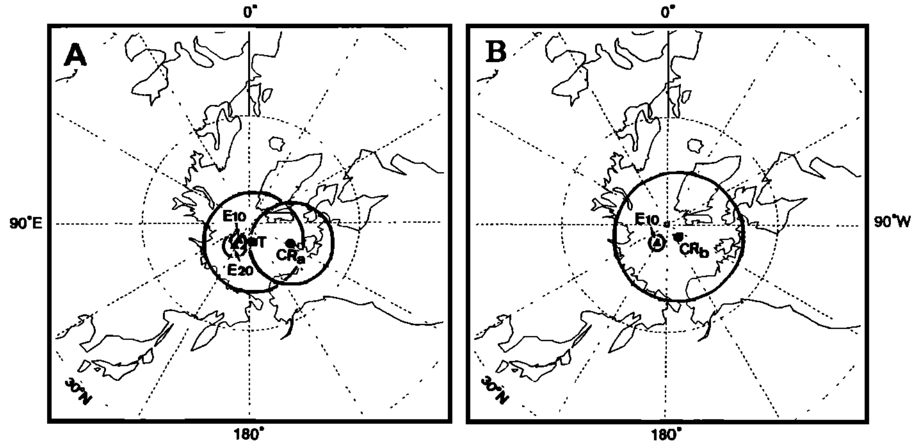

Figure 15. The paleopole positions with 95% confidence circles of the central Ryukyu arc and the reference points. (a) The poles by 10 Ma. (b) The poles after 10 Ma. Solid circles are of the central Ryukyu arc. CRa is the post-10 Ma pole obtained from the combination of about the 17 Ma Ara-dake Formation and the 11 Ma dike on Okinawa-jima Island. CRb is the pole obtained from the 6-2 Ma Uegusuku-dake Formation and Omu-jima andesite. E10 and E20 (triangles) are the 10 Ma and 20 Ma poles of the Eurasian continent [*Besse and Courtillot*, 1991]. T (square) is the pole of Miocene northern Taiwan [*Miki et al.*, 1993]. Stereographic projections.

inclination is, however, not significant (4.2° ± 16.2°). This comparison supports the suggestion that there has been no north-south translation between the Ryukyu arc and the Asian continent.

Tectonic Implications for the Central Ryukyu Arc

The paleomagnetic directions of the 17 Ma Ara-dake Formation show small clockwise deflections of the declination. The deflection can be ascribed to either paleomagnetic secular variation or tectonic rotation of the central Ryukyu arc. I suspect that the secular variation has not been averaged out from the results of the Ara-dake Formation. The paleomagnetic directions show only normal polarity. The angular dispersion calculated from the VGPs is 11.2° and smaller than the expected value (18°) calculated from the model of *McFadden and McElhinny* [1984]. Furthermore, the paleomagnetic direction from Okinawa-jima Island shows no deflection. The clockwise deflection could therefore be due to the secular variation of the geomagnetic field.

Even if the deflection is ascribable to the tectonic rotation, the rotation hypothesis is rejected with 95% confidence level. The post-10 Ma paleomagnetic direction is obtained from the combination of the 17 Ma Ara-dake Formation and the 11 Ma dike on Okinawa-jima Island. The mean direction of six sites is $D = 12.0°$, $I = 35.5°$, and $\alpha_{95} = 11.1°$. The rotation with respect to the expected value from the 20 Ma Eurasian pole [*Besse and Courtillot*, 1991](Figure 15a) is 8.72° ± 11.2° and is insignificant with 95% confidence level.

The central Ryukyu arc has experienced little clockwise rotation. I conclude here that the central Ryukyu arc has behaved as an independent tectonic block distinct from the southern Ryukyu arc where significant clockwise rotation occurred between 10 Ma and 6 Ma.

The paleomagnetic direction from the 6-2 Ma Uegusuku-dake Formation and Omu-jima andesite shows no deflection of declination. The pole calculated from this paleomagnetic direction and 10 Ma Eurasian pole of *Besse and Courtillot* [1991] are in agreement with 95% confidence (Figure 15b), indicating that the central Ryukyu arc has experienced little rotation or north-south translation with respect to the Asian continent since about 6 Ma.

Opening Model of the Okinawa Trough

The clockwise rotation of the southern Ryukyu arc can be ascribed to the opening of the Okinawa Trough [*Miki et al.*, 1990]. The paleomagnetic data indicate that the opening of the trough occurred after 10 Ma and ceased by 6 Ma. In contrast, various geophysical and geological data suggest that the Okinawa Trough is only now in the initial stage of opening [*Hirata et al.*, 1991; *Oshida et al.*, 1992]. Active rifting in the trough is indicated by high heat flow [*Yamano et al.*, 1989], earthquakes with an extensional focal mechanism [*Eguchi and Uyeda*, 1983], and hydrothermal mounds [*Kimura et al.*, 1988; *Halbach et al.*, 1989]. I propose a two-phase opening model for the Okinawa Trough (Figure 16) to reconcile the paleomagnetic results from the Ryukyu arc and the present geoscientific observation in the Okinawa Trough.

Phase I: Miocene opening. Phase I is a period of tectonic activity between 10 Ma and 6 Ma. The Okinawa Trough opened with a wedge-shape behind the Ryukyu arc in the southern part. As a result of the opening, the southern Ryukyu arc was rotated 25° around a hinge located in the Ilan Plain in Taiwan [*Miki et al.*, 1990].

My paleomagnetic results show there was no significant tectonic rotation of the central Ryukyu arc during phase I. In the central part, therefore, parallel opening occurred, which cannot be recognized from the paleomagnetic data. The Okinawa Trough is geographically continuous from north to south. No offset has been observed between the central and southern part of either the Ryukyu arc or the Okinawa Trough. The geographical continuity indicates that the central and the southern Okinawa Trough opened at the same time. The central Ryukyu arc has drifted from the Asian continent without any significant relative rotation.

The affects of the phase I opening are in the present geomorphology of the Okinawa Trough. The present arcuate

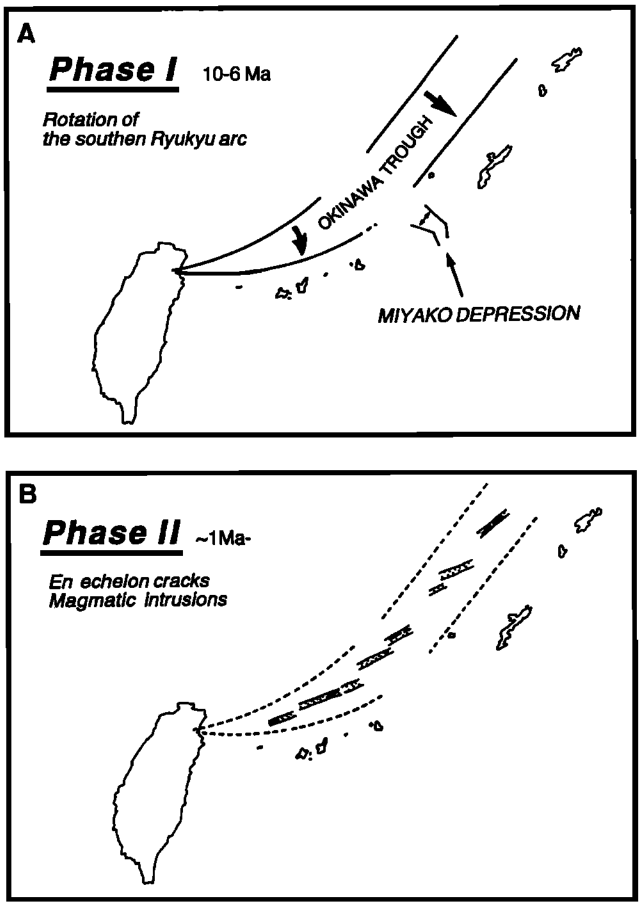

Figure 16. The opening model of the Okinawa Trough. (a) Phase I occurred between 10 Ma and 6 Ma. The Okinawa Trough opened and the southern Ryukyu arc rotated clockwise 25°. The Miyako depression separates the Ryukyu arc into the central and the southern domains. (b) Phase II began at about 1 Ma. The rifting activities are observed in the Okinawa Trough.

shape of the Ryukyu arc was formed by phase I deformation. There is a deep tectonic depression (Miyako depression) between the central Ryukyu arc and the southern Ryukyu arc. The depression separates the Ryukyu arc into the central and the southern tectonic blocks. The southeastward drifting of the central Ryukyu arc and the clockwise rotation of the southern Ryukyu arc should have been associated with the extension along the arc. I suggest that the extension divided the island arc and consequently formed the Miyako depression.

A variety of geological observations in the Ryukyu arc and the Okinawa Trough give further evidence for the phase I Miocene opening. (1) An unconformity is observed at the base of late Miocene to early Pleistocene Shimajiri formation throughout the Okinawa Trough and the Ryukyu arc [e.g., *Kimura*, 1985; *Letouzey and Kimura*, 1986]. This observation can be interpreted as the result of widespread subsidence in Miocene time associated with the opening. (2) Pre-Miocene to Miocene rocks are observed in the Ryukyu arcs and seismic reflection studies suggest these in the shallow shelf of the East China Sea basin [*Furukawa et al.*, 1991b]. However, no pre-Miocene formation is observed in the Okinawa Trough. The sedimentation in the trough appears to have started after the opening in Miocene.

Phase II: Reactivation of opening. Phase II started at around 1 Ma. The phase II opening is observed in the present rifting activities and the surface structure of the trough. The formation of en echelon graben characterizes phase II. Some volcanic intrusions have occurred along the ridge axis of the graben [*Kimura*, 1985; *Kimura et al.*, 1986; *Letouzey and Kimura*, 1986; *Sibuet et al.*, 1987]. Paleomagnetic results indicate that little rotation of the arc has occurred in this phase.

A phase of opening later than 1 Ma is supported by radiometric ages of the dredged samples and magnetic anomalies in the trough. Dredged samples from the ridge intrusion are younger than 1 Ma [*Kimura et al.*, 1991]. The magnetic anomaly observed in the Okinawa Trough can be explained by a volcanic intrusion in the latest normal epoch of the geomagnetic field [*Sibuet et al.*, 1987; *Furukawa et al.*, 1991a; *Oshida et al.*, 1992] younger than 0.78 Ma [*Baksi*, 1993]

On a larger scale, the two-phase opening mode of the Okinawa Trough is ascribable to the change of the direction of the subducting Philippine Sea plate. There was a change in the direction of movement of the Philippine Sea plate between 10 Ma and 4 Ma from northeastward to northwestward [*Seno and Maruyama*, 1984]. During phase II, the Philippine Sea plate was subducting almost perpendicular to the Ryukyu arc. The wedge-shaped or small fan-shaped opening is somewhat similar to that of the Japan Sea [*Otofuji and Matsuda*, 1987], where the subducting plate is almost perpendicular to the trench. The second phase may have began associated with the start of the oblique subduction.

Conclusion

Using paleomagnetic studies of the Ryukyu arc, combined with the geophysical and geological observations, I suggest the following features for the opening of the Okinawa Trough. (1) The opening of the Okinawa Trough was a two-phase process. (2) Phase I occurred in a period between 10 Ma and 6 Ma. Wedge mode opening occurred in the southern Okinawa Trough, whereas parallel opening occurred in the central Okinawa Trough. The southern Ryukyu arc has rotated about 25° with respect to China and Taiwan. (3) Phase II began at about 1 Ma after a stable period of several million years.

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