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Early Miocene paleomagnetic results from the Ninohe area, NE Japan: Implications for arc rotation and intra-arc differential rotations

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We have carried out a paleomagnetic study on well-dated Early Miocene volcanic rocks from the Ninohe area in northern NE Japan. Dacitic welded tuffs ranging from 24 to 21 Ma possess westerly paleomagnetic directions with normal polarity (formation-mean: $D/I = 294.5°/44.2°$ with $\alpha_{95} = 8.3°$, 8 sites), while the andesite flows formed at 17 Ma exhibit southerly directions with reversed polarity ($D/I = 186.6°/–61.9°$, 2 sites). A positive conglomerate test assures the stability of high-temperature components of remanent magnetization. Our results demonstrate that northern NE Japan rotated counter-clockwise through more than 60° between 21 and 17 Ma, most likely in association with the opening of the Japan Sea. The rotation of northern NE Japan thus preceded the about 15 Ma rapid clockwise rotation of SW Japan, and was synchronous with the possible pre-16 Ma southward translation of it. In comparison with published data, we further suggest that intra-arc block rotations occurred in the back-arc region of NE Japan during and after the arc rotation.

1. Introduction

It is widely accepted that NE and SW Japan rotated counter-clockwise and clockwise, respectively, in late Cenozoic time in association with the opening of the Japan Sea. The rotational process of SW Japan is well established based on the paleomagnetic database that has been growing since the 1980's (Otofuji, 1996, and references therein); it seems to have rotated through more than 40° at about 15 Ma. The rotational process of NE Japan also has been discussed by many researchers based on late Mesozoic to Cenozoic paleomagnetic data (Otofuji *et al.*, 1985, 1994; Celaya and McCabe, 1987; Moreau *et al.*, 1987; Nishitani and Tanoue, 1987; Tosha and Hamano, 1988; Fujiwara, 1992). Recently, Otofuji *et al.* (1994) have emphasized that northern NE Japan rotated counter-clockwise through more than 45° at about 15 Ma as a "single rigid block," accompanying the contemporaneous rapid clockwise rotation of SW Japan. However, we have known that some of 15–16 Ma geologic formations in NE Japan possess no deflected remanent magnetization directions (Tosha and Hamano, 1988; Yamazaki, 1989; Tanaka *et al.*, 1991; Hoshi *et al.*, 1992; Hayashida, 1994; Hoshi and Takahashi, 1997). This suggests either that, as first pointed out by Yamazaki (1989), the coherent rotation of NE Japan had already ended by 15–16 Ma, or that, as illustrated by Jolivet *et al.* (1995), intra-arc deformation with relative block rotations took place in Early to Middle Miocene time. To resolve this issue, we need to further accumulate time-averaged, reliable paleomagnetic directional data from individual areas.

This paper presents new paleomagnetic results from Early Miocene volcanic rocks in the Ninohe area, located on the fore-arc side of northern NE Japan (Fig. 1). Recently, Hayashida (1994) has reported preliminary paleomagnetic results from early Middle Miocene sedimentary rocks of this area. Thus our paleomagnetic approach has been focused on terrestrial volcanic rocks older than 16 Ma. Our newly-obtained data indicate that the area underwent counter-clockwise rotation of more than 60° between 21 and 17 Ma. Taken into consideration with published paleomagnetic data from other areas, we will discuss the amount and timing of counter-clockwise rotation of NE Japan and Early to Middle Miocene intra-arc differential rotations.

2. Geology, Sampling and Tilt Correction

Figures 1 and 2 show a simplified geological map and the generalized stratigraphy of the Lower to Middle Miocene sequence of the Ninohe area, respectively. The Lower to Middle Miocene strata are divided into the following four formations in ascending order; the Nisatai Dacite, Yotsuyaku Formation, Kadonosawa Formation, and Suenomatsuyama Formation. The Yotsuyaku Formation intercalates andesitic volcanic rocks, called the Keiseitoge Andesite, within the middle part. For details of lithostratigraphy and paleontology, refer to Matsubara (1995) and references therein. We carried out paleomagnetic sampling mainly from the Nisatai Dacite, Keiseitoge Andesite, and andesite dikes intruding the lower Yotsuyaku Formation.

The Nisatai Dacite consists mainly of biotite-rich dacitic welded tuffs. A eutaxitic texture can easily be recognized in each outcrop. A K-Ar biotite age of 21.0 ± 0.3 Ma and two fission-track zircon ages of 21.8 ± 1.4 Ma and 23.9 ± 1.4 Ma have been reported from the welded tuffs (Tagami *et al.*, 1995).

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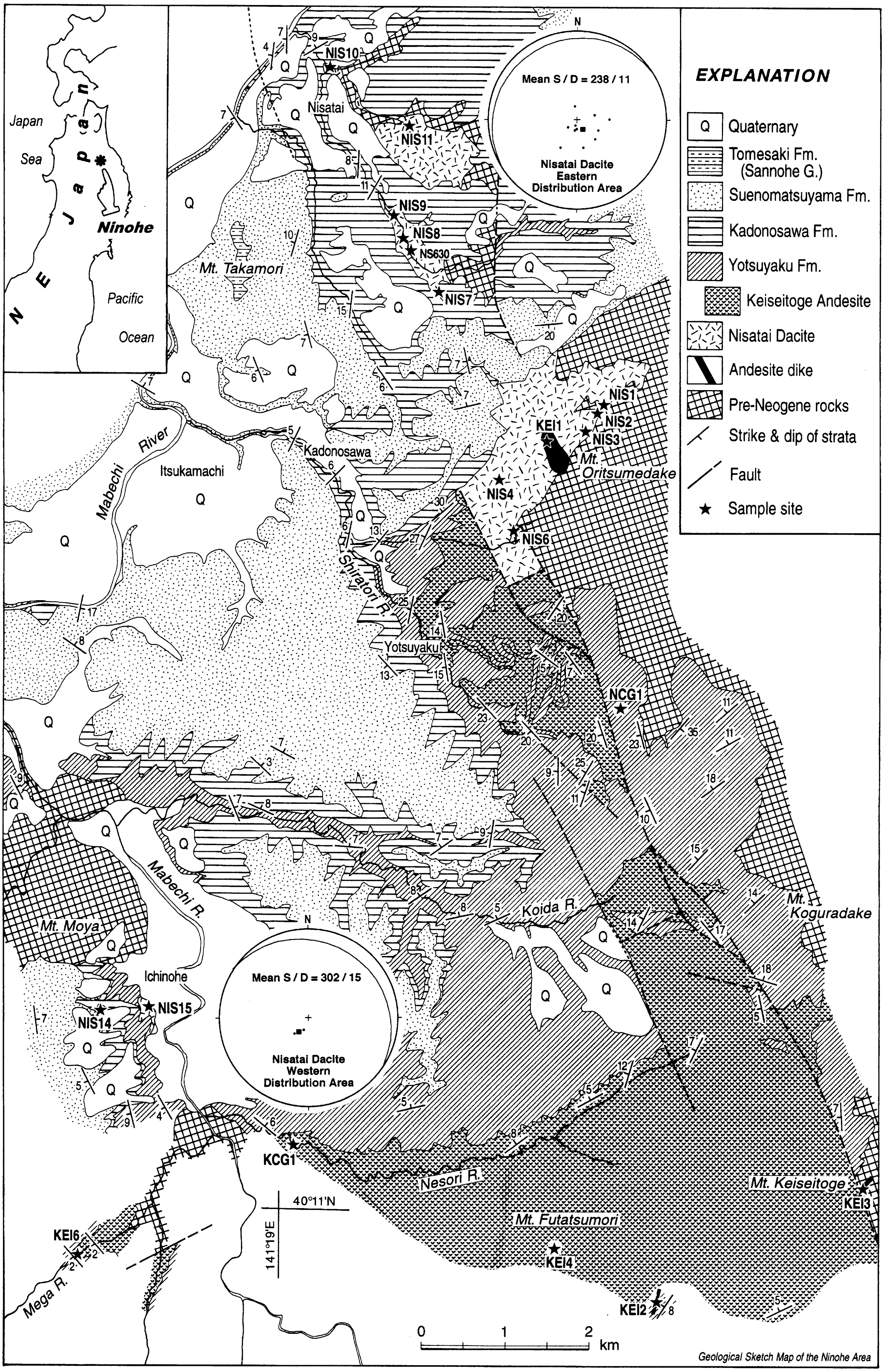

Fig. 1. Simplified geological map of the Ninohe area. Paleomagnetic sampling sites are shown by stars. Site NS630 studied by Otofuji *et al.* (1985) is also plotted. Lower-hemisphere equal-area projections display poles to local foliation of eutaxitic texture in outcrops (dots) and poles to mean foliation (squares).

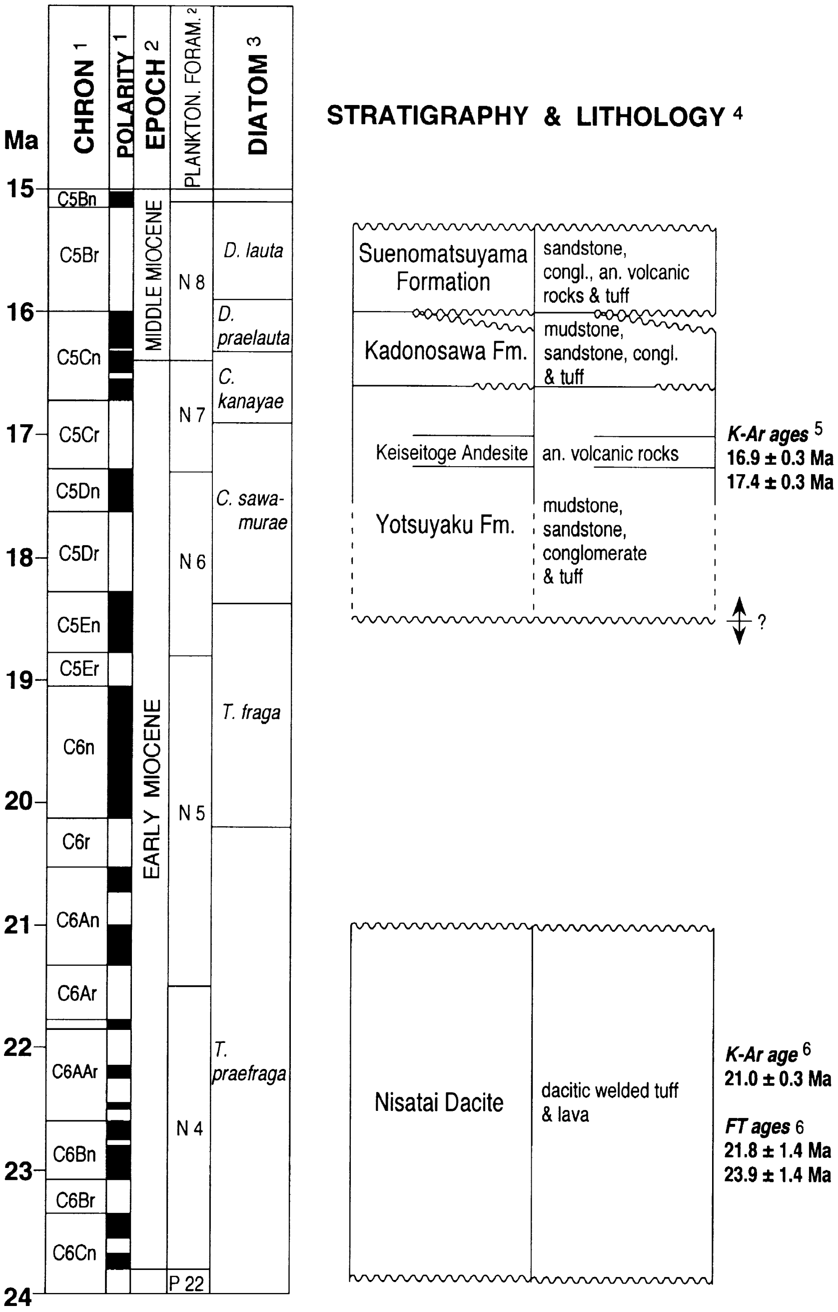

Fig. 2. Generalized stratigraphy of Lower to Middle Miocene strata in the Ninohe area. 1: Cande and Kent (1995). 2: Blow (1969), Berggren *et al.* (1995). 3: Barron and Gladenkov (1995). 4: Samata (1976), Koizumi (1986), Irizuki and Matsubara (1994). 5: Ishizuka and Uto (1995). 6: Tagami *et al.* (1995).

The Keiseitoge Andesite is composed mainly of andesitic volcaniclastic deposits with minor aa- and block-type lava flows. The andesitic volcanics commonly contain large (~3 mm) hornblende phenocrysts, which is a characteristic of the Keiseitoge Andesite. Ishizuka and Uto (1995) have recently reported K-Ar ages of 17.4 ± 0.3 Ma and 16.9 ± 0.3 Ma from a hyaloclastite of this andesite.

A few non-porphyritic andesite dikes have intruded the lower Yotsuyaku Formation (horizons below the Keiseitoge Andesite), Nisatai Dacite, and basement rocks (Fig. 1). These dikes closely resemble each other in lithofacies, and the facies differs markedly from that of the Keiseitoge Andesite, implying that the dikes were not the feeders of the Keiseitoge Andesite. In addition, we could not find the non-porphyritic andesite dikes in the Keiseitoge Andesite and the upper strata. These observations suggest that the intrusion occurred between 21 Ma (Nisatai Dacite) and 17 Ma (Keiseitoge Andesite).

Samples for paleomagnetic measurement were taken from dacitic welded tuffs of the Nisatai Dacite (12 sites), andesite lava flows of the Keiseitoge Andesite (2 sites), non-porphyritic andesite dikes (3 sites), and conglomerate beds within the Yotsuyaku Formation (2 sites). All sites are displayed in Fig. 1, including site NS630 studied by Otofuji *et al.* (1985). At each site, five or more core samples were taken with a portable drill fitted with a 1" coring bit, yielding more than 140 core samples from 19 sites. Samples were oriented with a magnetic compass. One to five specimens,

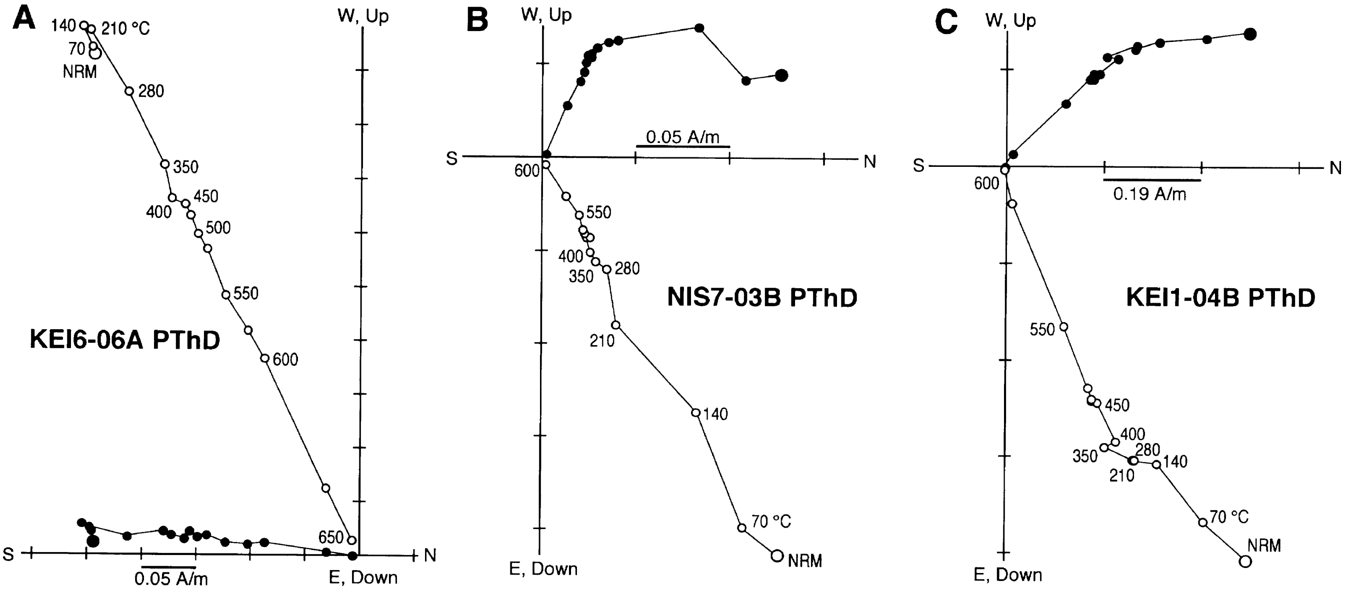

Fig. 3. Orthogonal demagnetization diagrams of representative specimens. A: Keiseitoge Andesite. B: Nisatai Dacite. C: Non-porphyritic andesite dikes. Solid and open circles are projections in the geographic coordinates onto the horizontal and vertical N-S plane, respectively.

22 mm long, were cut from each core sample.

The Nisatai Dacite is exposed in two areas; east and west limbs of a gentle syncline plunging northwest (Fig. 1). A planiform foliation of eutaxitic texture was identified and sampled at each outcrop of welded tuffs. Eutaxitic texture, however, seems not to represent the paleohorizontal because this may have been influenced by a primary slope. To reduce the errors in tilt correction caused by this uncertainty, we calculated a mean dip and strike value for each distribution area (Fig. 1) and utilized the calculated data for tilt correction. For the Keiseitoge Andesite, bedding planes of intercalated fine-grained sedimentary layers were measured for tilt correction. We do not perform tilt correction for non-porphyritic andesite dikes due to a paucity of structural information.

3. Paleomagnetism

3.1 Laboratory procedures and magnetic behavior

Measurement of remanent magnetization was carried out using a Schonstedt SSM-2A spinner magnetometer at Tohoku University. As a pilot study, one specimen per site was chosen for the progressive thermal demagnetization (PThD) analysis. In this study alternating field demagnetization was not applied as in our experience thermal demagnetization is in general more appropriate to effectively demagnetize high-coercivity magnetization in felsic to intermediate volcanic materials. PThD was performed in more than 12 steps up to 650°C. Specimens were heated in air using a noninductively wound electric furnace. Because pilot specimens of sites NIS1, NIS2, NIS3, NIS4, and NIS14 were broken during PThD, experiments on these sites were stopped at this point. After the pilot study, remaining specimens were also subjected to PThD. Results for each specimen were plotted on an orthogonal vector diagram (Zijderveld, 1967). For all specimens demagnetized at three or more steps, principal component analysis (Kirschvink, 1980) was done to determine least-squares best fit of the characteristic component of magnetization as determined from linear decay toward the origin on orthogonal vector diagrams.

The Nisatai Dacite and non-porphyritic andesite dikes are characterized by two distinct components (B and C in Fig. 3). The low-temperature component (LTC) of most samples had a north-seeking in-situ direction with normal polarity, and was unblocked by 350°C. The high-temperature component (HTC) was demagnetized by 600°C, suggesting that the component primarily resides in magnetite. On the other hand, all samples of the Keiseitoge Andesite displayed a single magnetic component with unblocking temperature of 210–650°C (Fig. 3(A)). Small viscous remanent magnetization (VRM) components were removed during the first few steps. Both magnetite and hematite probably carry the stable component.

3.2 Magnetic components

Table 1 lists the site-mean paleomagnetic directions. Figure 4 shows the equal-area projections of tilt-corrected site-mean directions of HTC.

Dacitic welded tuffs from 7 sites of the Nisatai Dacite provided reliable paleomagnetic records. All sites had normal polarity and northwesterly to westerly directions. Otofuji *et al.* (1985) also reported a westerly deflected site-mean direction from the Nisatai Dacite (site NS630: Fig. 1). Values of the radius of the 95% confidence circle (α_{95}; Fisher, 1953) were less than 8° for every site-mean, indicating homogeneous magnetization. The formation-mean direction, $D/I = 294.5°/44.2°$ with $\alpha_{95} = 8.3°$, was derived from the tilt-corrected site-means of 8 sites (including NS630). The paleomagnetic north pole was at 34.7°N, 58.5°E with $A_{95} = 8.4°$.

Two reliable site-mean directions with reversed polarity were obtained from andesite lava flows of the Keiseitoge Andesite. These site-mean directions were taken from distinct, separate lava flows (Fig. 1). The α_{95} values were less than 8° for the site-means. The site-mean directions coincide

Table 1. Paleomagnetic data from the Ninohe area.

Site	N	Rock	*In-situ*		Tilt-corrected		α_{95} (°)	k	North VGP		Locality	
			D (°)	I (°)	D (°)	I (°)			θ (°N)	ϕ (°E)	Lat. (°N)	Long. (°E)
Keiseitoge Andesite												
KEI4 (HTC)	4	HA	195.6	–67.2	183.3	–61.7	8.0	134.4	86.3	182.7	40.1794	141.3566
KEI6 (HTC)	4	HA	187.5	–63.6	189.9	–62.0	3.2	832.2	82.0	205.6	40.1783	141.2886
HTC mean (2 sites)					186.6	–61.9	—	—				
HTC north paleomagnetic pole									84.3	198.4		
Nisatai Dacite												
NIS1		DWT	(Pilot specimen was broken at 450°C through PThD)								40.2703	141.3628
NIS2		DWT	(Pilot specimen was broken at 450°C through PThD)								40.2694	141.3614
NIS3		DWT	(Pilot specimen was broken at 450°C through PThD)								40.2672	141.3600
NIS4		DWT	(Pilot specimen was broken at 450°C through PThD)								40.2625	141.3481
NIS6 (HTC)	4	DWT	287.5	42.2	292.8	33.5	4.3	460.6	28.9	51.5	40.2567	141.3497
NIS7 (HTC)	4	DWT	291.9	36.7	295.8	27.6	2.7	1168.9	29.0	46.1	40.2825	141.3389
NIS7 (LTC)	4		8.2	60.5	—	—	3.0	916.2	83.7	217.8		
NIS8 (HTC)	4	DWT	290.4	55.6	298.0	46.4	1.6	3330.6	38.2	57.6	40.2881	141.3339
NIS8 (LTC)	3		357.1	56.5	—	—	14.0	78.3	86.1	357.3		
NIS9 (HTC)	4	DWT	275.4	52.3	284.7	44.9	2.3	1609.1	27.5	63.9	40.2906	141.3328
NIS9 (LTC)	4		352.7	58.2	—	—	7.4	154.6	84.2	39.6		
NIS10 (HTC)	3	DWT	259.1	63.2	276.1	57.7	7.9	243.5	27.7	79.6	40.3067	141.3236
NIS10 (LTC)	4		4.0	56.0	—	—	9.2	101.7	85.1	280.3		
NIS11 (HTC)	4	DWT	310.9	55.8	314.4	45.2	5.0	341.3	50.1	45.9	40.3006	141.3347
NIS11 (LTC)	4		351.5	50.6	—	—	6.1	228.2	78.7	1.4		
NIS14		DWT	(Pilot specimen was broken at 450°C through PThD)								40.2044	141.2922
NIS15 (HTC)	3	DWT	282.8	47.4	299.8	50.2	5.6	493.9	41.1	60.3	40.2050	141.2986
NIS15 (LTC)	4		339.2	61.9	—	—	9.1	103.5	74.2	68.8		
NS630* (HTC)	10	DWT	282.7	52.7	290.9	44.4	2.3	446.9	31.9	60.0	40.2883	141.3333
HTC mean (8 sites)					294.5	44.2	8.3	45.3				
HTC north paleomagnetic pole									34.7	58.5	(A_{95} = 8.4°)	
Andesite dikes												
KEI1 (HTC)	4	NPA	325.6	64.2	—	—	5.2	310.0	64.5	75.7	40.2661	141.3542
KEI1 (LTC)	2		358.2	52.6	—	—	—	—	82.8	333.4		
KEI2 (HTC)	3	NPA	318.8	19.5	—	—	8.6	207.5	42.7	23.4	40.1736	141.3700
KEI2 (LTC)	3		30.8	60.9	—	—	49.4	7.3	66.8	216.9		
KEI3 (HTC)	3	NPA	160.2	–30.4	—	—	8.5	209.5	60.6	2.9	40.1858	141.3986
KEI3 (LTC)	1		18.3	67.8	—	—	—	—	73.4	185.6		
HTC mean (3 sites)			328.3	38.2			39.9	10.6				
HTC north paleomagnetic pole									59.1	30.0	(A_{95} = 34.2°)	
LTC overall mean (9 sites)			1.3	59.1			5.9	77.4				
LTC north paleomagnetic pole									88.7	232.0	(A_{95} = 8.3°)	

HTC, LTC = high-temperature component and low-temperature component, respectively. N = number of samples used for calculating the site-mean direction. Rock: DWT = dacitic welded tuff, HA = hornblende andesite, NPA = non-porphyritic andesite. D, I = declination and inclination. α_{95} = radius of cone of 95% confidence. k = precision parameter. θ, ϕ = latitude and longitude of virtual geomagnetic pole (VGP), respectively. Data denoted by asterisk are from Otofuji *et al.* (1985).

well with each other after tilt correction. The formation-mean direction calculated from the tilt-corrected site-means was D/I = 186.6°/–61.9°. Site-mean virtual geomagnetic poles (VGPs) yielded a paleomagnetic north pole of 84.3°N, 198.4°E.

Three in-situ site-mean directions were obtained from non-porphyritic andesite dikes with both normal and reversed polarities. All site-means had a tendency to deflect counter-clockwise from the north-south in spite of no tilt correction. Inclination values were diverse (19.5–64.2°). After inverting the reversed polarity site-mean direction to the normal polarity one, the mean paleomagnetic direction for these dikes became D/I = 328.3°/38.2° with α_{95} = 39.9°. The paleomagnetic north pole was observed at 59.1°N, 30.0°E with A_{95} = 34.2°. These results from the dikes are not considered in the following tectonic discussion due to their fairly large uncertainty.

Low-temperature components (LTCs) were revealed from 6 sites of the Nisatai Dacite and 3 sites of non-porphyritic andesite dikes. Each component was estimated using at least four endpoints with maximum angular deviation (MAD) smaller than 10°. The in-situ overall mean was D/I = 1.3°/59.1° with α_{95} = 5.9°, which is statistically indistinguishable from the geocentric axial dipole field direction (I = 59.5°) expected at the latitude of the study area. Upon structural correction at each site, the mean direction shifted slightly upward (D/I = 358.1°/52.4° with α_{95} = 7.4°). Thus it is most likely that the LTCs are secondary overprints of VRM

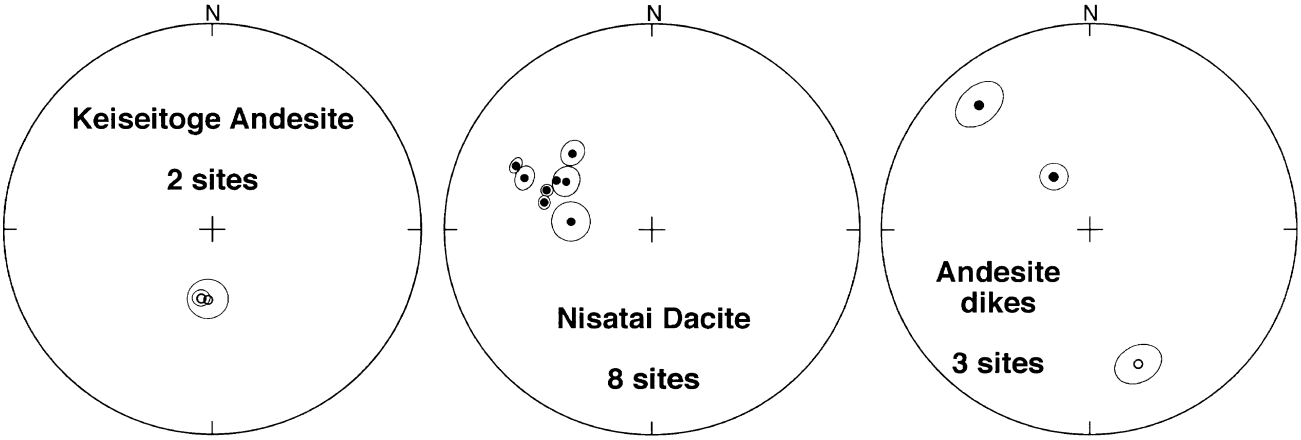

Fig. 4. Site-mean directions with 95% confidence circles from high-temperature components. The Keiseitoge Andesite and Nisatai Dacite: directions after tilt correction. Andesite dikes: in-situ directions. Equal-area projections with solid circles on the lower hemisphere and open circles on the upper hemisphere.

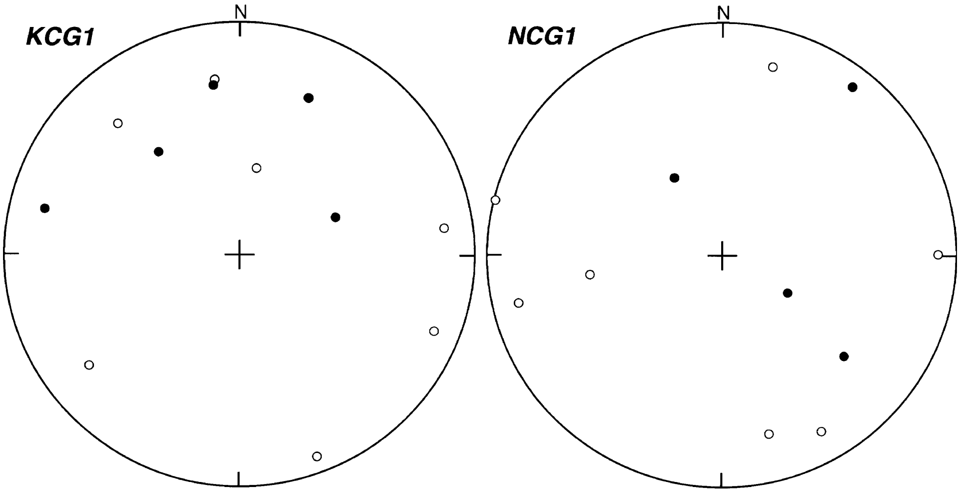

Fig. 5. Equal-area projections of high-temperature component directions after thermal demagnetization for andesite clasts in an interbedded volcaniclastic sequence of the Keiseitoge Andesite (KCG1) and welded tuff clasts in an intraformational conglomerate within the lower part of the Yotsuyaku Formation (NCG1). Open symbols represent the projections on the upper hemisphere, and solid symbols on the lower hemisphere.

acquired during the Brunhes normal polarity chron after tectonic stratal tilting.

3.3 Conglomerate test

A conglomerate test (Graham, 1949) was carried out to verity the origin and stability of the HTCs of the Nisatai Dacite and Keiseitoge Andesite. Conglomerate clasts were collected from sites NCG1 and KCG1; the former is in an intraformational conglomerate bed within the lower part of the Yotsuyaku Formation, and the latter is within an interbedded volcaniclastic sequence of the Keiseitoge Andesite. Site NCG1 contains welded tuff clasts derived from the Nisatai Dacite, and almost all clasts within site KCG1 comprise andesite boulders derived from the Keiseitoge Andesite. At each site, twelve clasts were sampled. One specimen was prepared from each sample in the laboratory. PThD was employed for all specimens. Eleven clasts from NCG1 and all the measured clasts from KCG1 provided stable HTCs with randomly distributed directions (Fig. 5); Fisher's (1953) precision parameter $k_{\mathrm{NCG1}} = 1.0$, $k_{\mathrm{KCG1}} = 1.3$. Passage of the conglomerate test confirms that the HTC directions of the Nisatai Dacite and Keiseitoge Andesite are of primary thermoremanent magnetization (TRM) origin.

4. Amount and Timing of Counter-Clockwise Rotation in the Ninohe Area

Up to the present, there have been only two site-mean paleomagnetic directions for the Nisatai Dacite (Otofuji *et al.*, 1985, 1994) In this study we have obtained a reliable formation-mean direction from the total of 8 sites. Since each site is at the different stratigraphic position within a sequence of the dacite, the formation-mean can be regarded as representing a time-averaged geomagnetic field direction. The formation-mean direction displayed westward deflection in declination (*D* = 294.5°), indicating large counter-clockwise rotation of the study area since the formation of the dacite (~21 Ma: Tagami *et al.* 1995). On the other hand, the Keiseitoge Andesite retains little deflected declinations, demonstrating that the counter-clockwise rotation had ended by 17 Ma.

To quantify the amount of vertical-axis rotation in the study area since 21 Ma, we calculated the amount of rotation with respect to the North China Block (NCB: Lin *et al.*, 1985) in the Asian continent. The pole-space method (Beck *et al.*, 1986) was applied, in which vertical-axis rotation of the study area relative to the reference NCB was determined; we made a comparison between the Early to Middle Miocene paleomagnetic pole for the NCB (85.2°N, 238.4°E with A_{95} = 5.6°: Zhao *et al.*, 1994) and the observed pole (34.7°N, 58.5°E with A_{95} = 8.4°) determined from the 21 Ma Nisatai Dacite in the study area located at a representative geographic location (40.3°N, 141.3°E). Our calculation yields R (rotation estimate) $\pm dR$ (uncertainty: Demarest, 1983) = −72 ± 10°. R is defined as negative for counter-clockwise rotation. We therefore conclude that the Ninohe area rotated 72 ± 10° counter-clockwise with respect to the NCB between 21 and 17 Ma

5. Paleomagnetic Rotations in NE Japan

Figure 6(A) shows paleomagnetic declinations with their 95% confidence limits of 24–21 Ma rock units in northern NE Japan. Our newly-obtained direction from the Nisatai Dacite is also indicated. Early Early Miocene (24–21 Ma) felsic to intermediate volcanic rocks are sporadically distributed in NE Japan, and a number of paleomagnetic investigations have been carried out on these rocks (Otofuji *et al.*, 1985, 1994; Nishitani and Tanoue, 1987; Tosha and Hamano, 1988; Fujiwara, 1992). The Fukuyama Formation in the Oshima Peninsula and the Daijima Formation in the Oga Peninsula, as well as the Nisatai Dacite in the Ninohe area, are well dated with radiometric methods (Nishimura and Ishida, 1972; Suzuki, 1980; Ganzawa, 1983, 1987; Kimura, 1986; Koshimizu *et al.*, 1986; Tagami *et al.*, 1995). Only one fission-track age of 24.7 ± 1.2 Ma for the Kunitomi Formation in the Oshima Peninsula, which is part of unpublished data of T. Matsuda, is introduced by Otofuji *et al.* (1994). No radiometric ages have hitherto been published from the Gongenzaki Formation in the Tsugaru Peninsula; but the lithofacies (mainly andesitic volcanics including welded tuffs and lava flows) resembles closely that of the Fukuyama Formation. We therefore consider the depositional age of the Gongenzaki Formation to be almost identical with that

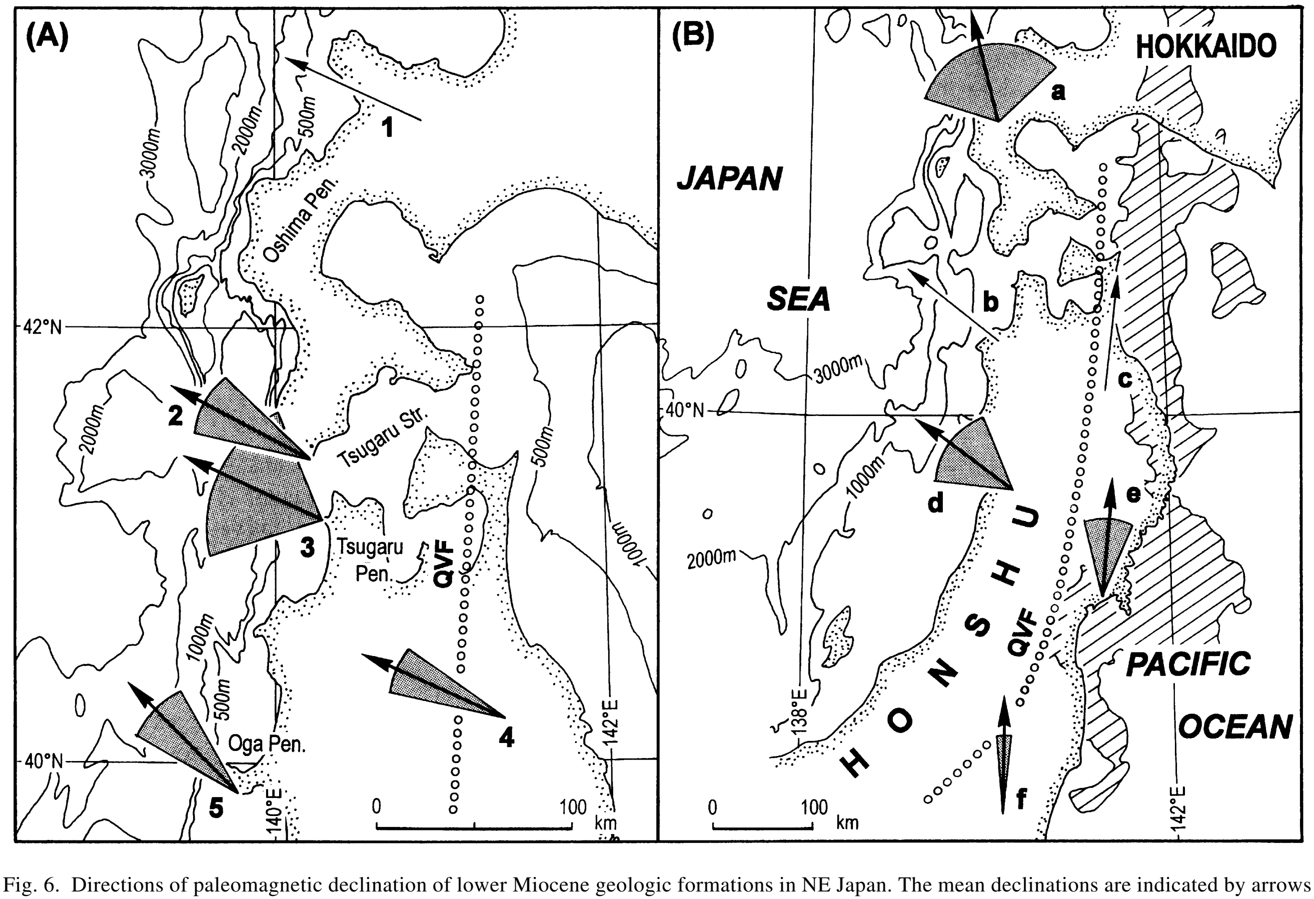

Fig. 6. Directions of paleomagnetic declination of lower Miocene geologic formations in NE Japan. The mean declinations are indicated by arrows along with the 95% confidence limits ($dD = \sin^{-1}[\sin\alpha_{95}/\cos I]$, where α_{95} is the radius of the 95% confidence circle and I is the inclination: Kellogg and Reynolds, 1978). QVF: Quaternary volcanic front. (A) 24–21 Ma. 1: Kunitomi Formation in the Oshima Peninsula (D/I = 295.8°/64.8°, 2 sites: Otofuji *et al.*, 1994). 2: Fukuyama Formation in the Oshima Peninsula (D/I = 298.2°/50.4° with α_{95} = 10.2°, 9 sites: Fujiwara, 1992; Otofuji *et al.*, 1994). 3: Gongenzaki Formation in the Tsugaru Peninsula (D/I = 295.1°/55.6° with α_{95} = 22.7°, 3 sites: Otofuji *et al.*, 1994). 4: Nisatai Dacite of the Ninohe area (D/I = 294.5°/44.2° with α_{95} = 8.3°, 8 sites: this study). 5: Daijima Formation in the Oga Peninsula (D/I = 315.0°/50.8° with α_{95} = 9.8°, 6 sites: Otofuji *et al.*, 1985; Tosha and Hamano, 1988). (B) 18–16 Ma. a: Masukawa Formation in the Oshima Peninsula (D/I = 346.6°/57.7° with α_{95} = 27.3°, 3 sites: Otofuji *et al.*, 1994). b: Odose Formation of the Tsugaru area (D/I = 308.1°/67.3°, 1 site: Otofuji *et al.*, 1994). c: Keiseitoge Andesite of the Ninohe area (D/I = 6.6°/61.9°, 2 sites: this study). d: Yashiozawagawa Formation of the Yashima area (D/I = 306.9°/59.0° with α_{95} = 15.2°, 3 sites: Otofuji *et al.*, 1994). e: Otsuka and Matsushima Formations of the Matsushima Bay area (D/I = 5.0°/45.9° with α_{95} = 12.2°, 6 sites: Yamazaki, 1989). f: Motokozawa Basalt of the Motegi area (D/I = 0.3°/48.3° with α_{95} = 3.4°, 25 sites: Hoshi and Takahashi, 1997). A positive magnetic anomaly belt (Segawa and Oshima, 1975: oblique-line area) is clearly recognized from the Matsushima area to Hokkaido.

of the Fukuyama Formation (i.e., 24–21 Ma).

It is unambiguously recognized in Fig. 6(A) that individual declinations deflect uniformly counter-clockwise and are parallel or subparallel to each other. The large counter-clockwise deflections are observed in the area east of the Quaternary volcanic front (Sugimura and Uyeda, 1973; Ohguchi *et al.*, 1989) as well as west of it. This remarkable feature led Otofuji *et al.* (1994) to assert that northern NE Japan, including northern Honshu and southwestern Hokkaido, rotated counter-clockwise after 20 Ma as a "single rigid block." Otofuji *et al.* (1994) further calculated the amount of rotation by fitting a function on their paleomagnetic data. Finally, they concluded that the rotation occurred at about 15 Ma, and that the amount of rotation was 46.4°. As stressed by Jolivet *et al.* (1995), the uniformity of paleomagnetic directions, however, may also be produced by intra-arc deformation in a strike-slip regime. In a simple block model with a simple geometry (Ron *et al.*, 1984, 1986; McKenzie and Jackson, 1986; Nur *et al.*, 1986), crustal blocks rotate by the same amount and thus it might be impossible to detect a difference in the distribution of paleomagnetic rotations between a single rigid block and several dominoes bounded by parallel or subparallel strike-slip faults. In this context, it is quite important in study of tectonic rotations to examine geologic structures of the given region. Unfortunately, more than half of NE Japan has been masked by thick volcanic and sedimentary sequences which have accumulated up since an early Middle Miocene marine transgression (e.g., Yamaji, 1990). In addition, an intensive contractile stress field since the latest Miocene has complicated the geologic structures, especially in the back-arc side (Sato, 1989). Thus it is virtually impossible to delineate the possible intra-arc block rotations in NE Japan through geologic structural approach. Nevertheless, we consider that northern NE Japan was not a single rigid block but a multi-block system in Early Miocene time, the reason being found in the following.

Figure 6(B) shows the paleomagnetic declinations of 18–16 Ma geologic units in NE Japan. All units we selected here, except the Odose Formation of the Tsugaru area, have been well dated with radiometric and magneto-biostratigraphic methods. While the Odose Formation has little information about its depositional age, the fossiliferous marine sediments overlying the formation suggest that the upper limit of the formation is as old as 17 Ma (Hirayama and Uemura, 1985; Suzuki and Nemoto, 1995), and a local correlation of lithostratigraphic units implies that the lower limit is younger than 20 Ma (Fukudome *et al.*, 1990). The fore-arc region of NE Japan is characterized by the dominance of northward declinations. The Motokozawa Basalt in the Motegi area (Hoshi and Takahashi, 1997), dated as about 18 Ma, has no deflected declinations. Hoshi and Takahashi (1997) further measured the paleomagnetism of upper formations and clarified that the Motegi area has undergone no tectonic rotation since 18 Ma. Yamazaki (1989) also pointed out that no rotational motion has occurred in the Matsushima Bay area since 16 Ma. Our result from the Ninohe area demonstrates little rotational motion since 17 Ma. These paleomagnetic evidence indicates that the whole of the fore-arc region has not experienced any significant rotation since at least 17 Ma, most likely 18 Ma. In opposition to the fore-arc region, the declinations in the back-arc region deflect significantly westward. Apparently, this fact represents intra-arc deformation with relative block rotations in NE Japan.

6. Discussion

6.1 Counter-clockwise rotation of northern NE Japan

Air-borne and ship-borne surveys have revealed features in magnetic intensity anomalies in and around Japan (e.g., Okubo *et al.*, 1994). A north-south, magnetic intensity anomaly belt under the fore-arc region of northern NE Japan (Fig. 6), running from Matsushima to the southern part of Hokkaido (Segawa and Oshima, 1975; Finn, 1994; Okubo *et al.*, 1994) may result from a Cretaceous batholith, 120–70 km wide and at least 15–10 km thick (Finn, 1994). Because the anomaly is coherent, we interpret that the fore-arc region of northern NE Japan has behaved as a single block since the Cretaceous (Hoshi and Takahashi, 1997).

Our paleomagnetic results from the Ninohe area suggest that the fore-arc region of northern NE Japan has experienced counter-clockwise rotation sometime between 21 and 17 Ma. The 24–21 Ma Nisatai Dacite yielded a time-averaged, formation-mean paleomagnetic direction deflecting markedly (>60°) counter-clockwise. Although in the fore-arc region this is the only result showing counter-clockwise deflection in declination, we consider, on the basis of the above implication from magnetic intensity anomalies, that the region ranging from at least Matsushima to southern Hokkaido uniformly rotated counter-clockwise through more than 60° after 21 Ma. Since we have seen in a previous section that the whole of the fore-arc side of NE Japan has not undergone rotational motion since 17 Ma, we conclude that the region rotated counter-clockwise through more than 60° in the period between 21 and 17 Ma. In other words, northern NE Japan must have rotated by the same amount at that time.

Our conclusion seems to be consistent with some statistical estimates of the amount of counter-clockwise rotation of NE Japan (Otofuji *et al.*, 1994; Jolivet *et al.*, 1995), but apparently discordant with that of Tosha and Hamano (1988). Tosha and Hamano estimated the amount of rotation at only about 20°. This value was obtained by comparing a Cenozoic apparent polar wander path (APWP) for the Oga Peninsula with that for the Kilchu-Myongchon Graben in North Korea (Kang, 1966; Sasajima, 1981). The ages of the APWP for the Kilchu-Myongchon Graben, however, have been not determined precisely, as stated in the Tosha and Hamano's own paper. In addition, paleomagnetic directions of Eocene to Miocene geologic formations of the Kilchu-Myongchon Graben seem to be somewhat questionable; these deflect counter-clockwise about 20° (therefore the rotation of NE Japan was estimated rather small). Such a westerly deflection is inconsistent with the recent paleomagnetic data from the nearby North and South China Blocks (Zhao *et al.*, 1990, 1994; Zheng *et al.*, 1991). We think the depositional age and regional geology should be reassessed for the paleomagnetic sites in the Kilchu-Myongchon Graben in North Korea. The Early Miocene counter-clockwise rotation of northern NE Japan must have reached more than 60°.

Northern NE Japan is considered to have rotated before 17 Ma, whereas SW Japan rapidly rotated clockwise at about 15 Ma (Hayashida, 1986; Nakajima *et al.*, 1990; Otofuji *et al.*, 1991). This suggests diachronic differential rotation in the Japan Arc in the opening period of the Japan Sea. Otofuji *et al.* (1985, 1994) urged that the Japan Sea opened in a "bar-door" fashion with almost concurrent differential rotations of two arcs (NE and SW Japan) at about 15 Ma. However, recent Ocean Drilling Program (ODP) and marine geological/geophysical results from the Japan Sea (Kaneoka *et al.*, 1990, 1992; Burckle *et al.*, 1992; Nomura, 1992; Pouclet and Bellon, 1992; Rahman, 1992; Tamaki *et al.*, 1992) have revealed that the basins underlain by oceanic or highly stretched continental crust have existed before 15 Ma, partly at about 20 Ma. Our assertion that northern NE Japan rotated before 17 Ma seems to be concordant with the offshore data. Hayashida *et al.* (1991) proposed an interesting kinematic model for SW Japan; it has been translated southward without detectable rotation before 16 Ma and then rotated clockwise. It is hence highly probable that the counter-clockwise rotation of northern NE Japan and the possible southward translation of SW Japan were contemporaneous with each other.

6.2 Intra-arc block rotations in NE Japan

Paleomagnetic rotations have been observed in Middle Miocene formations as well as Early Miocene ones in the back-arc region of NE Japan, suggesting block rotations in the region during and after the counter-clockwise arc rotation. The Gongenyama Formation in the Japan Sea coastal area, dated as 14–15 Ma through biostratigraphic correlations, shows a slight counter-clockwise deflection in declination (Momose *et al.*, 1990), implying a small rotation since then. A Middle Miocene counter-clockwise deflection was also reported from the Masukawa Formation in the Oshima Peninsula (Otofuji *et al.*, 1994: Fig. 6). Thus it is most likely that intra-arc deformation with relative rotations occurred at various scales in several areas of the back-arc region during and after the Early Miocene arc rotation. Otofuji *et al.* (1994) concluded, on the basis of their own paleomagnetic data mainly sampled from the back-arc region, that NE Japan rotated counter-clockwise at about 15 Ma. We think some Middle Miocene paleomagnetic directions influenced by local block rotations led them to conclude so.

Jolivet *et al.* (1995) try to reconcile observed paleomagnetic rotations in the Japan Arc with a geologically supposed dextral strike-slip environment in a single kinematic model. Their model interprets that NNE-SSW trending major dextral strike-slip faults guided the opening of the Japan Sea in a pull-apart manner. This model appears to account partly for the local block rotations in the Japan Sea coastal area of NE Japan, while the model in turn cannot account for the amount of the counter-clockwise arc rotation. Further paleomagnetic, chronological and geological studies and tectonic consideration are required to thoroughly describe the geodynamic history of the Japan Arc.

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