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Miocene counterclockwise rotation of Northeast Japan : a review and new model

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Abstract : The paleomagnetic studies which have been performed in the forearc side of NE Japan during the last decade are reviewed in detail to elucidate the Miocene rotational process of NE Japan. The areas which are dealt with in this review are as follows ; from north to south, Ninohe, Miyako and Kamaishi Mine in Iwate Prefecture, Shiogama-Matsushima in Miyagi Prefecture, Ryozen in Fukushima Prefecture, and Motegi over a Tochigi-Ibaraki prefectural boundary. We have compiled reliable paleomagnetic directional data from the areas and established variations in declination and inclination with age. In an age-declination diagram, a pronounced change can be seen at about 20 Ma ; declination seems to have varied from ca. 295° at 21 Ma to 0° at 18 Ma. All the data showing large counterclockwise deflection in declination, 60° or more, were taken from the lower Miocene and older formations in the Kitakami Mountains. Two models can account for the observed paleomagnetic rotation. One is a large counterclockwise crustal rotation of NE Japan. This model requires more than 60° of counterclockwise rotation of entire NE Japan. The amount of rotation, however, is much larger than the angle of rotation expected from the reconstruction based on geology and physiography. Another model, which we consider more plausible, explains that differential rotation occurred in NE Japan. This model interprets that the angle of rotation of the Kitakami Mountains was larger than that of the Abukuma Mountains. Dextral displacement on a fault between the Kitakami and Abukuma Mountains, which has been presumed and termed the Chokai-Ishinomaki Tectonic Line, may have accommodated the larger rotation of the Kitakami Mountains.

1. Introduction

During the Cenozoic, an extension has occurred in a belt 6000 km long adjacent to the eastern margin of Eurasia (Taylor and Karner, 1983). As a consequence, some island arc-backarc basin systems have arose ; the Japanese islands-Japan Sea pair is typical of those being in the extensional belt. Migrating from the eastern edge of the mother Asian continent, the proto-Japanese islands were bent at the central part (Kawai *et al*., 1961). This lateral bending resulted in the present arched shape of the islands. Otofuji *et al*. (1985a) suggested that the southwestern and northeastern parts of the islands (hereafter referred to as SW and NE Japan) rotated clockwise and counterclockwise, respectively, during the Miocene opening period of the Japan Sea.

In this paper, we first critically review recent paleomagnetic studies in NE Japan, in order to clarify the rotational process of NE Japan. Stress is devoted to the contribution of paleomagnetic research performed in the forearc side during the last decade. Thus, our review does not deal with earlier paleomagnetic works. Next, we propose two possible models to account for the paleomagnetic rotation observed in the NE Japan forearc.

2. Recent paleomagnetic research in the forearc side of NE Japan

NE Japan is the geotectonic domain bounded on the south and north by the Itoigawa-Shizuoka Tectonic Line and central Hokkaido, respectively (Kimura *et al*., 1991). Paleozoic and Mesozoic rocks, mainly composed of accretionary complexes and plutonic intrusives, crop out extensively in the forearc side of NE Japan (east of the Quaternary volcanic front :

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QVF). They are covered in part by sedimentary and volcanic rocks deposited in late Cenozoic time. In the backarc side (west of the QVF), thick piles of upper Cenozoic strata fill deep sedimentary basins incised into pre-Cenozoic basement. In general, rocks of the forearc region have been less altered than those of the backarc region.

Figure 1 shows locations of the study areas which are reviewed in this section. All areas are in the forearc side, because recent paleomagnetic studies were mostly carried out in this region. We omitted a few studies for Miocene rocks of the backarc region, because (1) rocks of the backarc region have generally affected alteration and intensive diagenesis, (2) it has been intensively faulted and folded under a late Cenozoic contractile stress field (Sato, 1989), and (3) local crustal rotations about vertical axes probably occurred here during and/or after the Japan Sea opening (Momose *et al.*, 1991; Jolivet *et al.*, 1995).

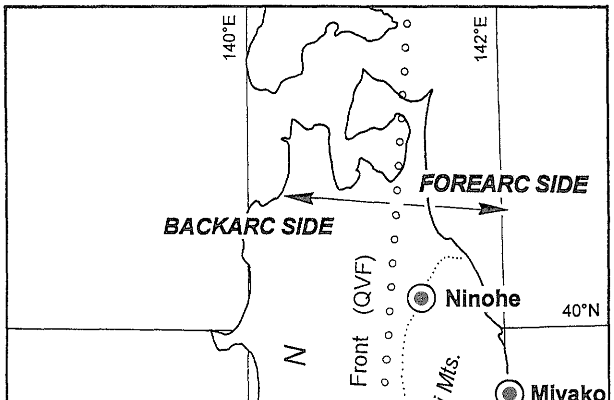

Fig. 1 Index map of the areas reviewed in this paper. All the areas are on the forearc side, the region to the east of the Quaternary volcanic front.

2.1 Ninohe

Hayashida (1994) and Hoshi and Matsubara (1998) carried out paleomagnetic research in the Ninohe area of Iwate Prefecture. Otofuji *et al.* (1985b, 1994) also reported a few site-mean paleomagnetic directions.

Hayashida (1994) reported two time-averaged formation-mean directions. Sedimentary rocks of the lower Miocene Yotsuyaku Formation showed $D=4.1°$ and $I=37.0°$ with $\alpha_{95}=19.0°$ (6 sites). Nine site-mean directions from sedimentary rocks of the lower middle Miocene Kadonosawa Formation gave a mean direction of $D=352.9°$ and $I=55.7°$ with $\alpha_{95}=12.5°$ (Fig. 2). These data suggest that the Ninohe area has not undergone vertical-axis crustal rotation since the deposition of the Yotsuyaku Formation. However, it is very difficult to assign numerical age to the Yotsuyaku mean direction, because (1) Hayashida (1994) did not describe the sampling sites (localities and stratigraphic positions), and (2) the depositional age of the formation has not been determined well (Matsubara, 1995). On the other hand, the depositional age of the Kadonosawa Formation has been constrained through biostratigraphy; it was deposited at about 16 Ma (Irizuki and Matsubara, 1994). Consequently, we can safely say that the area has not experienced vertical-axis rotation since 16 Ma.

Recently, Hoshi and Matsubara (1998) reported paleomagnetic results from well-dated lower Miocene volcanic rocks (Fig. 2). Felsic-composition welded tuffs of the Nisatai Dacite (21.0±0.3 Ma: Tagami *et al.*, 1995) yielded a unit-mean paleomagnetic direction of $D=294.5°$ and $I=44.2°$ with $\alpha_{95}=8.3°$. This mean direction was calculated from eight tilt-corrected site-mean directions; in the study eutaxitic texture was regarded as an indicator of tilting. A positive result of the conglomerate test (Graham, 1949) demonstrates

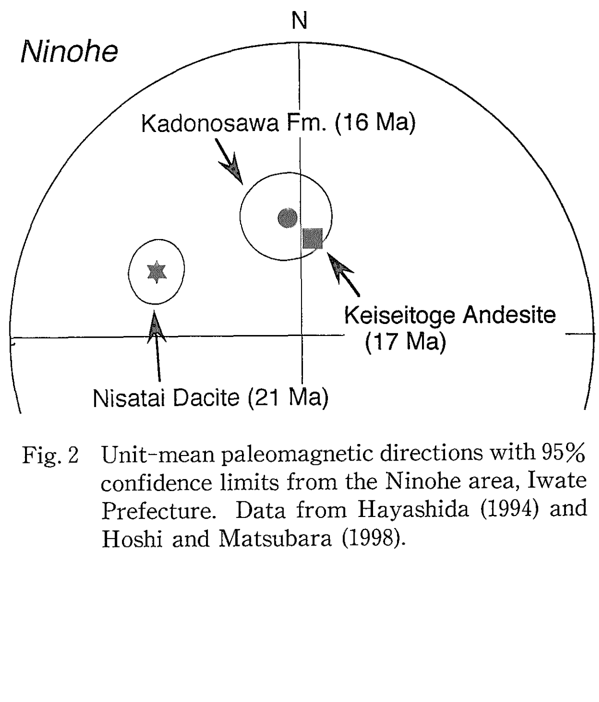

Fig. 2 Unit-mean paleomagnetic directions with 95% confidence limits from the Ninohe area, Iwate Prefecture. Data from Hayashida (1994) and Hoshi and Matsubara (1998).

primary origin of high-temperature magnetic components of the Nisatai Dacite. Thus, the westerly direction indicates large-scale counterclockwise rotation after 21 Ma. In contrast, a few andesite flows of the Keiseitoge Andesite (16.9±0.3 Ma: Ishizuka and Uto, 1995) showed no significant deflection from the north-south (unit-mean: D=186.6° and I=-61.9°). An intraformational volcaniclastic conglomerate provides a positive result of the conglomerate test, demonstrating the primary nature of the remanent magnetization. Thus, the south-seeking unit-mean direction proves no detectable vertical-axis rotation of the study area. Finally, Hoshi and Matsubara (1998) concluded that the area was subjected to counterclockwise rotation between 21 and 17 Ma, and that the amount of rotation reached 72±10°.

2.2 Miyako

Cretaceous volcano-plutonic complexes crop out sporadically in the forearc side of NE Japan, and the typical exposure occurs around Miyako of Iwate Prefecture. There, Cretaceous igneous activity initially produced intermediate- to felsic-composition volcanic products, named as the Harachiyama Formation (Fig. 3A). No sooner had the Harachiyama volcanic activity ceased than the formation was intruded by a granitic body, named as the Miyako-Oura Granite. As a result, rocks of the Harachiyama Formation have suffered contact metamorphism. On the basis of regional stratigraphic correlation, Shibata (1985) suggested that the intrusion occurred during the Barremian-Aptian ages (127.0-112.2 Ma: Gradstein *et al.*, 1994). Rb-Sr and K-Ar geochronology provides dates of 125-116 Ma for the granite (Shibata *et al.*, 1978), being concordant with the stratigraphic age inference. In late Cretaceous time, intense igneous activity occurred again in this area, supplying felsic volcanic rocks (the Heizaki Volcanics). As Fig. 3A shows, they unconformably cover the older Harachiyama Formation, as well as the Miyako-Oura Granite. Takigami (1991) reported an $^{40}Ar/^{39}Ar$ total fusion date of 71.3±2.4 Ma for the Heizaki Volcanics.

Otofuji *et al.* (1997) conducted a paleomagnetic study of Cretaceous rocks in the Omoe Peninsula, located in the southeast of Miyako. Paleomagnetic samples were collected mainly from welded tuffs of the metamorphosed Harachiyama Formation and unmetamorphosed Heizaki Volcanics. They measured attitudes of eutaxitic texture in welded tuff at outcrops, for structural tilt correction of paleomagnetic vectors.

Two sites of welded tuffs of the Harachiyama Formation yielded medium- and high-temperature remanent magnetization components (Fig. 3B). Medium-temperature components (MTC's) characterized large-scale counterclockwise deflection in declination and shallow inclination; two site-mean directions gave an *in-situ* mean direction of D=281.0° and I=17.3°. High-temperature components (HTC's) yielded an *in-situ* mean of D=90.4° and I=-4.7°, which became a direction with large-scale clockwise deflection and shallow inclination (D=94.2° and I=20.4°) after tilt correction. HTC magnetization in the Heizaki Volcanics also showed large-scale counterclockwise deflection with shallow inclination; seven site-mean directions provided a unit-mean of D=283.5° and I=9.4° with α_{95}=8.0° after tilt correction.

Figure 3B summarizes paleomagnetic directions

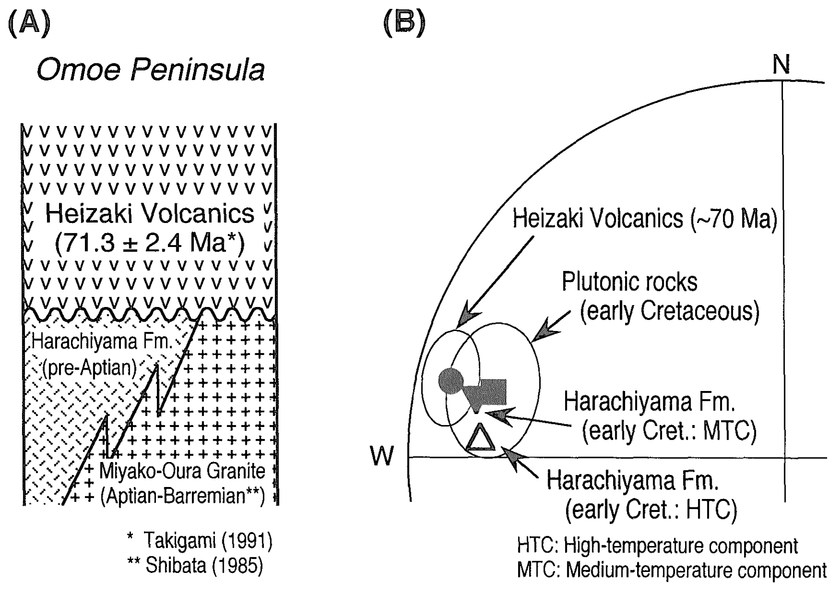

Fig. 3 (A) Simplified stratigraphic framework of Cretaceous strata at the Omoe Peninsula, southeast of Miyako, Iwate Prefecture. (B) Unit-mean paleomagnetic directions with their 95% confidence limits from the Omoe Peninsula. Data from Moreau *et al.* (1987) and Otofuji *et al.* (1997).

obtained from the Harachiyama Formation and Heizaki Volcanics, as well as those from early Cretaceous plutonic rocks in the Kitakami Mountains (Ito and Tokieda, 1986; Moreau *et al.*, 1987). The clockwise-deflecting HTC magnetization in the Harachiyama Formation has been inverted the antipodal direction. Cretaceous igneous rocks in this area are characterized by significant clockwise deflection in declination with very shallow inclination, except for the HTC direction of the Harachiyama Formation. The *in-situ* MTC direction of the Harachiyama Formation is parallel to the *in-situ* mean direction of early Cretaceous Kitakami plutonic rocks. Along with the fact that the Miyako-Oura Granite has intruded into the Harachiyama Formation and affected contact metamorphism, the good accordance of magnetization directions implies that the MTC magnetization is the remagnetization acquired at the time of granite intrusion. The HTC magnetization, on the other hand, could be a primary thermoremanent magnetization (TRM). If the HTC direction ($D=90.4°$ and $I=-4.7°$ *in-situ*) was the remagnetization acquired at the intrusion of the Miyako-Oura Granite, it should have been almost parallel to the magnetization direction of the granite. However, Otofuji *et al.* (1997) revealed that the magnetization in the granite is almost antiparallel to the Harachiyama HTC magnetization. Thus, the remanent magnetization of the Harachiyama Formation may not have been "metamorphosed" completely. The tilt-corrected HTC direction shows a large counterclockwise deflection with shallow negative inclination. Shallow inclination with counterclockwise deflection also characterizes the unmetamorphosed late Cretaceous Heizaki Volcanics. As stated by Otofuji *et al.* (1997), the counterclockwise deflection is most likely due to the younger tectonic rotation of NE Japan. They attributed the observed very shallow inclination to the possible Cenozoic northward migration of the Kitakami massif.

2.3 Kamaishi Mine

Itoh *et al.* (1998) determined paleomagnetic directions of the Kurihashi Granodiorite at the Kamaishi Mine of Iwate Prefecture. It is one of the early Cretaceous granite intrusive bodies penetrating the older Kitakami accretionary complex. Samples were collected along a horizontal drift in the mine. Of all 45 sites, 19 provided stable remanent magnetization of a single component. The 19 site-mean directions tightly clustered about the *in-situ* mean direction ($D=281.0°$ and $I=41.5°$ with $\alpha_{95}=3.1°$), which is characterized by large counterclockwise deflection in declination and slightly shallow inclination (Fig. 4).

2.4 Shiogama-Matsushima

In the early Miocene, a moderately deep and wide sedimentary basin occurred in the Shiogama-Matsushima area of Miyagi Prefecture (Ishii *et al.*, 1982b, 1983a). Figure 5A illustrates the stratigraphic architecture and depositional age of the lower to middle Miocene series. The basin was initially filled with volcanic products (the Shiogama and Sauramachi Formations), then invaded by a marine transgression which caused deposition of a thick sedimentary sequence (the Ajiri, Matsushima and Otsuka Formations).

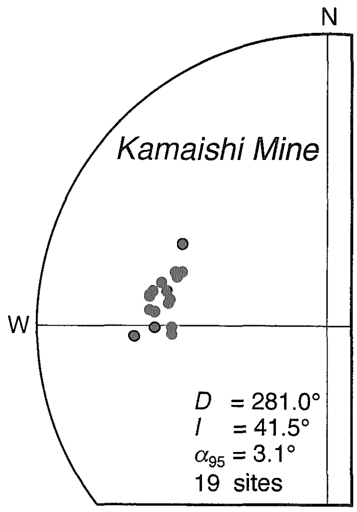

Fig. 4 Site-mean paleomagnetic directions from the Kurihashi Granodiorite at the Kamaishi Mine, Iwate Prefecture. Data from Itoh *et al.* (1998).

Yamazaki (1989) carried out a paleomagnetic study of the lower to middle Miocene sequence of this area. Samples were collected from sedimentary rocks of the Ajiri, Matsushima and Otsuka Formations. These sedimentary units have been dated by means of both diatom biostratigraphy and radiometric dating (Akiba *et al.*, 1982; Ishii *et al.*, 1982a, 1983b). Yamazaki (1989) first established a magnetic polarity stratigraphy for this sequence. Along with existing biostratigraphic information, magnetostratigraphy has precisely determined the depositional ages of the Matsushima and Otsuka Formations; these two formations were formed between ca. 16.5 and 15 Ma (Fig. 5A). The Ajiri Formation was deposited in late early Miocene time. Figure 5B shows site-mean paleomagnetic directions from the three formations (data from the Matsushima and Otsuka Formations are collectively projected onto a stereonet). Six site-mean directions from the Matsushima and Otsuka Formations yielded a time-averaged formation-mean paleomagnetic direction of $D=5.0°$ and $I=45.9°$ with $\alpha_{95}=12.2°$ after tilt correction. There are both normal and reversed polarity sites, and the normal-polarity sites are almost antiparallel to the reversed-polarity sites, indicating a positive reversals test (McElhinny, 1973). The time-averaged mean direction suggests no detectable vertical-axis rotation after 16 Ma. Yama-

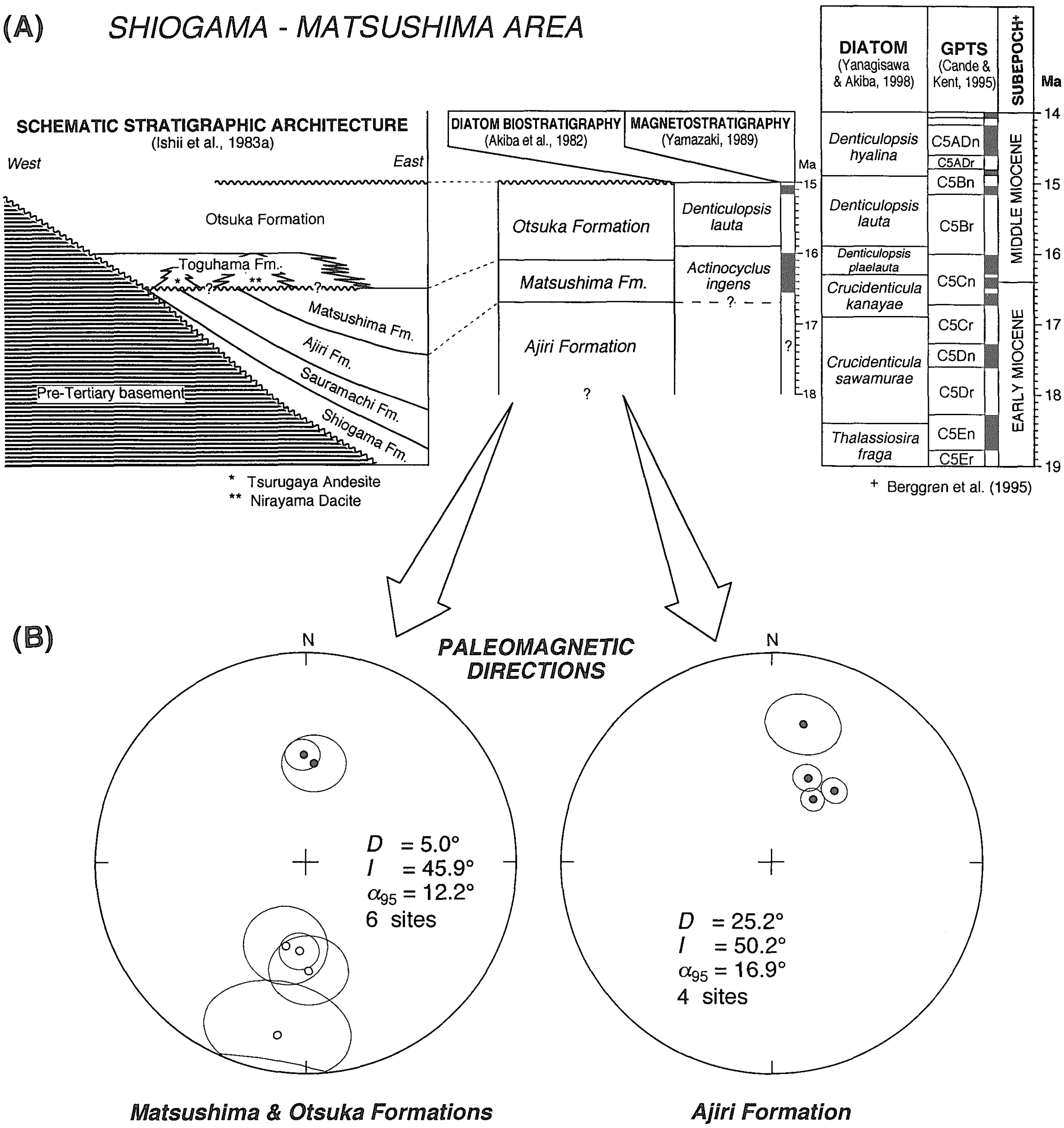

Fig. 5 (A) Stratigraphic outline of Miocene formations in the Shiogama-Matsushima area, Miyagi Prefecture. Diatom biostratigraphy and magnetostratigraphy strictly constrain the depositional age of the Matsushima and Otsuka Formations. (B) Site-mean paleomagnetic directions from the Matsushima and Otsuka Formations (left) and from the Ajiri Formation (right). Data from Yamazaki (1989).

zaki (1989) stated that the possible counterclockwise rotation of NE Japan had completed before 16 Ma. The Ajiri Formation, on the other hand, was characterized by slight clockwise deflection in declination. Four site-mean paleomagnetic directions, all of which had normal polarity, made a formation-mean direction of $D=25.2°$ and $I=50.2°$ with $\alpha_{95}=16.9°$ after tilt correction. Before tilt correction, the formation-mean fell near the axial dipole field direction. Two possibilities were put forward to the origin of magnetization in the Ajiri Formation (Yamazaki, 1989); one interpretation for the single normal polarity is that the formation was deposited during a normal polarity period, and another possibility interprets that the formation has been completely remagnetized. Yamazaki (1989) did not consider the results from the Ajiri Formation in tectonic discussion, as well as in the establishment of magnetostratigraphy.

2.5 Ryozen

Takahashi *et al.* (1997) made a paleomagnetic study of Miocene volcanic rocks from the Ryozen area, Fukushima Prefecture. They collected samples from two different units; the Tenmyosan Volcanics and

Ryozen Formation (Yamamoto, 1996). The former interdigitates with fluvial and shallow marine sedimentary rocks, named as the Shiote Formation, and interbeds a tuff layer dated as 20.0 ± 1.2 Ma with the fission-track method (Yanagisawa *et al.*, 1996). The date indirectly represents an approximate age of the Tenmyosan Volcanics. For the latter, Ohki *et al.* (1993) documented a variety of K-Ar dates ranging from 16.0 to 12.4 Ma from lava flows. However, Yamamoto (1996) has recently reported that a basalt dike which has intruded into volcaniclastic deposits of the Ryozen Formation showed a K-Ar date of 16.3 ± 0.8 Ma. From cross-cutting relationships, the depositional age of the Ryozen Formation is most likely older than or almost identical with the date. As Fig. 6 shows, five site-mean directions from the lower Miocene Tenmyosan Volcanics yielded a formation-mean direction characterized by a counterclockwise deflection in declination and slightly shallow inclination ($D=320.4°$ and $I=41.3°$ with $\alpha_{95}=16.5°$). The lower middle Miocene Ryozen Formation, on the other hand, had north-seeking site-mean remanent magnetization directions (formation-mean: $D=356.4°$ and $I=53.6°$ with $\alpha_{95}=8.7°$, 10 sites). A positive conglomerate test for an intraformational volcanic conglomerate in the Ryozen Formation ascertained the primary origin of the northerly site-mean directions with normal polarity. The directions were calculated without bedding-tilt correction, because of no evidence for significant stratal tilting. Finally, these results suggest that the area was experienced counterclockwise rotation of about 40° between 20 and 16 Ma (Takahashi *et al.*, 1997).

2.6 Motegi

The Motegi area extends over Tochigi and Ibaraki Prefectures, where lower Miocene rocks, mostly terrigenous and volcanic origin, crop out extensively and unconformably overlie Paleozoic to Mesozoic basement. The lower Miocene series has been lithologically divided into four formations; the Ichiba, Motokozawa, Yamanouchi and Motegi Formations, from base to top (Fig. 7), and these collectively make up the Nakagawa Group (Kawada, 1953; see Hoshi and Takahashi, 1996a, for historical review of the stratigraphy). As Fig. 7 shows, radiometric dating and magnetostratigraphy have determined the depositional ages of the individual formations (Takahashi and Hoshi, 1995, 1996; Hoshi and Takahashi, 1996b; Ishizuka and Hoshi, 1997).

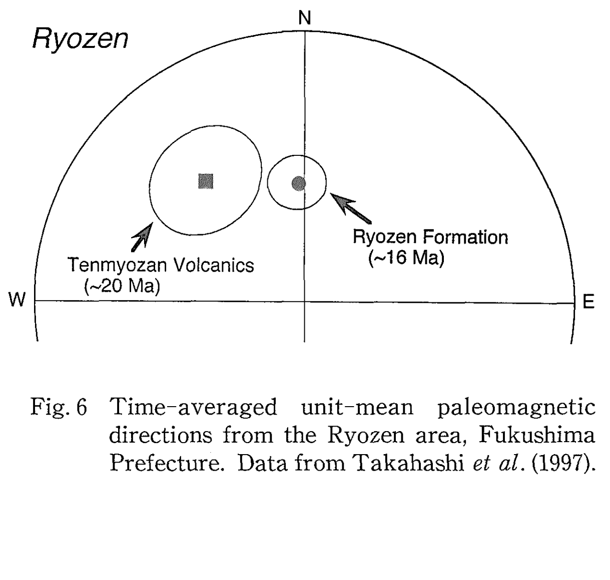

Fig. 6 Time-averaged unit-mean paleomagnetic directions from the Ryozen area, Fukushima Prefecture. Data from Takahashi *et al.* (1997).

Hoshi and Takahashi (1997) measured the remanent magnetization of volcanic rocks of the Nakagawa Group. Samples were collected from lava flows in the Motegi and Yamanouchi Formations and basalt sills (the Motokozawa Basalt) which have intruded into sedimentary rocks of the Motokozawa Formation. After appropriate demagnetization and bedding-tilt correction, northerly paleomagnetic directions characterized all the three units (Fig. 7B). A positive conglomerate test confirmed the reliability of the site-mean paleomagnetic directions obtained from the lava flows (Hoshi and Takahashi, 1995). The reliability was ascertained also from a positive reversals test (b in Fig. 7B).

It should be stressed that the sills of the Motokozawa Basalt possess undeflected remanent magnetization directions. Twenty-five site-mean directions yielded a unit-mean of $D=180.3°$ and $I=-48.3°$ with $\alpha_{95}=3.4°$ after tilt correction, indicating little rotational motion about a vertical axis after intrusion. No radiometric dates have been reported from the sills, but geologic observation suggests that the sills intruded into the sediments just after the deposition of the Motokozawa Formation (Hoshi and Takahashi, 1996b). As displayed in Fig. 7A, the age of the top of the Motokozawa Formation is between the C5Dn/C5Dr geomagnetic polarity chron boundary (17.615 Ma: Cande and Kent, 1995) and the fission-track date for a tuff at a lower horizon of the formation (18.6 ± 1.3 Ma: Takahashi and Hoshi, 1996). Thus, it is considered that the intrusion occurred at about 18 Ma. Hoshi and Takahashi (1997) hence concluded that the area has not undergone vertical-axis rotation since then.

2.7 Other areas

Oda *et al.* (1989) studied the paleomagnetism of Miocene rocks from the Takadate and Yanagawa areas of Miyagi and Fukushima Prefectures, respectively. The results suggest the possibility of localized vertical-axis crustal rotations in these areas at early middle Miocene time. However, we do not include their data in the compilation and discussion of this paper, because (1) they did not perform tilt correction for data from volcanic rocks in spite of tectonic tilting, and (2) the paper does not contain any quantitative and numerical data, other than stereographic

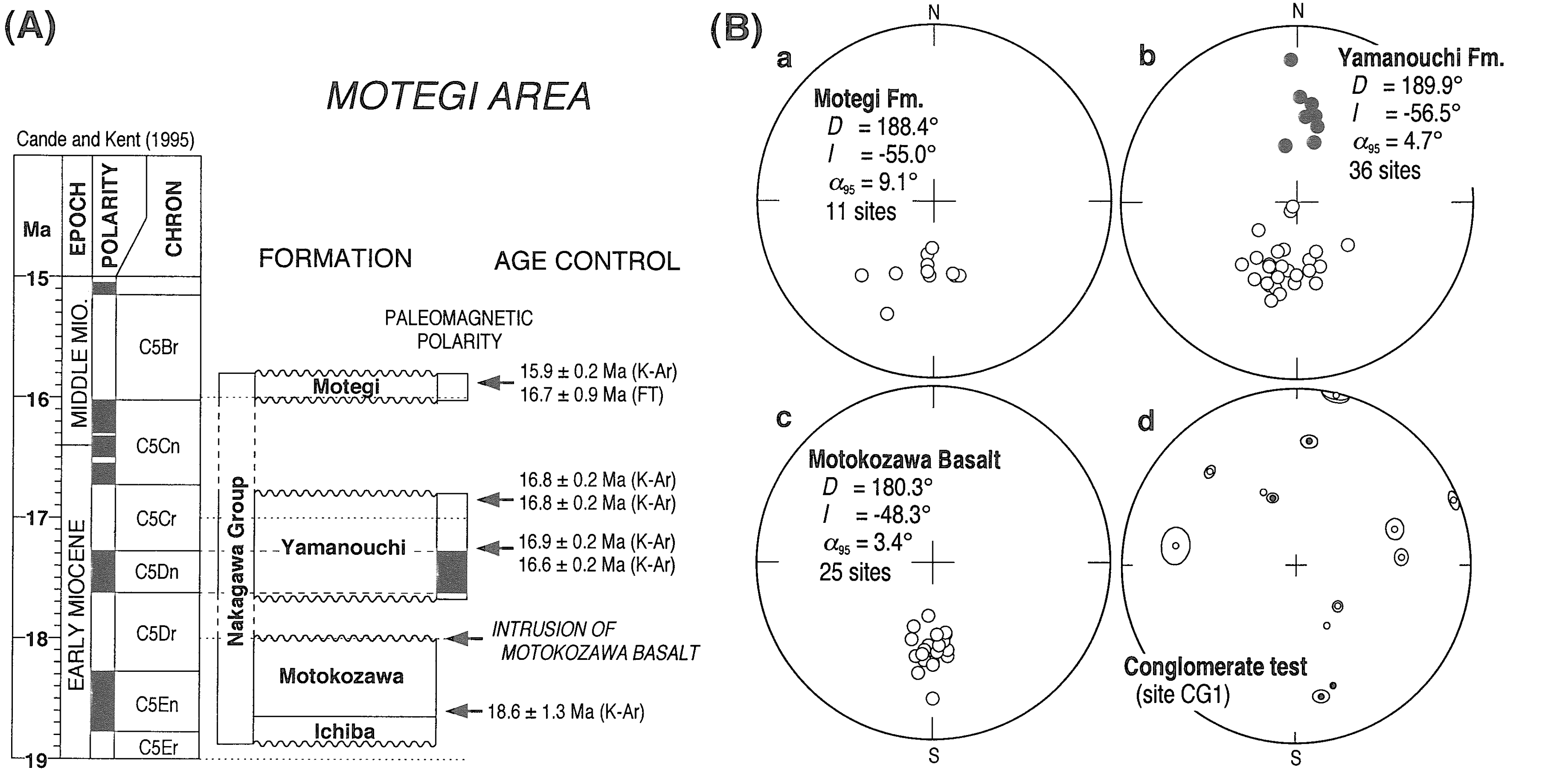

Fig. 7 (A) Stratigraphy and geochronology of Miocene strata in the Motegi area, Tochigi and Ibaraki Prefectures. Many radiometric dates from volcanic rocks give constraints on the depositional age of the strata. Modified from Hoshi (1998). (B) Site-mean paleomagnetic directions from the Motegi Formation (a), Yamanouchi Formation (b) and Motokozawa Basalt (c). A positive conglomerate test (d) for a volcaniclastic flow in the Yamanouchi Formation suggests the primary origin of the site-mean directions.

projections of site-mean directions.

3. Compilation of paleomagnetic data from the forearc side of NE Japan

Table 1 lists paleomagnetic data from the areas which have been reviewed in the preceding section. All data are tilt-corrected unit-mean directions. Confidence limits on declination and inclination (*dD* and *dI* : Kellogg and Reynolds, 1978) are also shown. The table does not include the data from the Kurihashi Granodiorite in the Kamaishi Mine (Itoh *et al.*, 1998), because of no appropriate tilt correction. Also disregarded in the compilation is the formation-mean direction of the Ajiri Formation in the Shiogama-Matsushima area (Yamazaki, 1989), owing to the possibility of remagnetization. The paleomagnetic data in the table range in age from 125 to 15.9 Ma.

Figure 8 shows temporal changes in declination observed in the forearc side of NE Japan. We can clearly recognize that a pronounced change in declination, from ca. 300° to 0°, occurred at about 20 Ma within a short duration of 3 m.y. Declination seems to have varied gradually also from 120 to 21 Ma, but this may be insignificant when the confidence limits for declination are considered.

The late Mesozoic to Cenozoic change in inclination observed in the forearc side is shown in Fig. 9. Inclination seems to have increased with time, from -20° at 120 Ma to 40-60° in early Miocene time. Otofuji *et al.* (1997) attributed the apparent increase in inclination to a large-scale northward migration of the Kitakami massif. Any significant increase or decrease cannot be observed between 22 and 15 Ma, suggesting little latitudinal movement since the early Miocene.

4. Discussion

Our compilation indicates that counterclockwise paleomagnetic rotation of more than 60° took place in

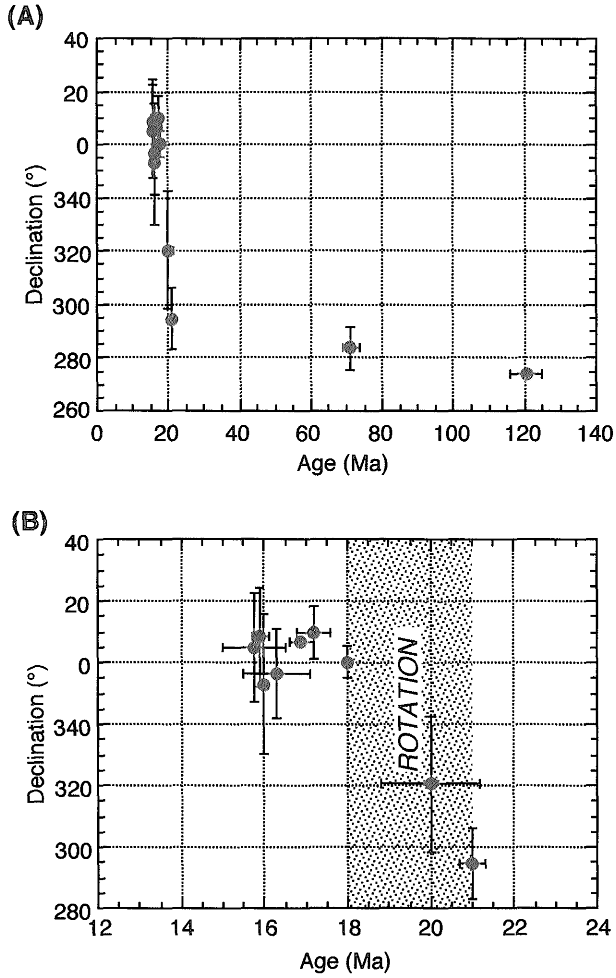

Fig. 8 (A) Temporal declination changes observed in the forearc side of NE Japan after 140 Ma. A noticeable change can be seen at about 20 Ma, and the close-up is presented in (B). Declination seems to vary gradually from 300° at 21 Ma to 0° at 18 Ma.

Table 1 List of selected paleomagnetic data from the forearc side of NE Japan.

Area	Unit	Age (Ma)	*N*	*D* (°)	*dD* (°)	*I* (°)	*dI* (°)	α_{95} (°)	Ref.
Ninohe	Kadonosawa Fm.	16	9	352.9	22.6	55.7	12.5	12.5	Hayashida (1994)
	Keiseitoge Andesite	16.9 ± 0.3	2	6.6	-	61.9	-	-	Hoshi and Matsubara (1998)
	Nisatai Dacite	21.0 ± 0.3	8	294.5	11.6	44.2	8.3	8.3	ditto
Miyako	Heizaki Volcanics	71.3 ± 2.4	2	283.5	8.1	9.4	8.0	8.0	Otofuji *et al*. (1997)
	Harachiyama Fm.	125 - 116	2	274.2	-	-20.4	-	-	ditto
Matsushima	Otsuka/Matsushima Fms.	16.5 - 15	6	5.0	17.7	45.9	12.2	12.2	Yamazaki (1989)
Ryozen	Ryozen Fm.	16.3 ± 0.8	10	356.4	14.8	53.6	8.7	8.7	Takahashi *et al*. (1997)
	Tenmyosan Volcanics	20.0 ± 1.2	5	320.4	22.2	41.3	16.5	16.5	ditto
Motegi	Motegi Fm.	15.9 ± 0.2	11	8.4	16.0	55.0	9.1	9.1	Hoshi and Takahashi (1997)
	Yamanouchi Fm.	17.6 - 16.8	36	9.9	8.5	56.5	4.7	4.7	ditto
	Motokozawa Basalt	18	25	0.3	5.1	48.3	3.4	3.4	ditto

N : number of sites. *D* and *dD* : declination and its confidence limit ($dD = \sin^{-1}[\sin \alpha_{95}/\cos I]$). *I* and *dI* : inclination and its confidence limit ($dI = \alpha_{95}$). α_{95} : radius of the 95% confidence limit.

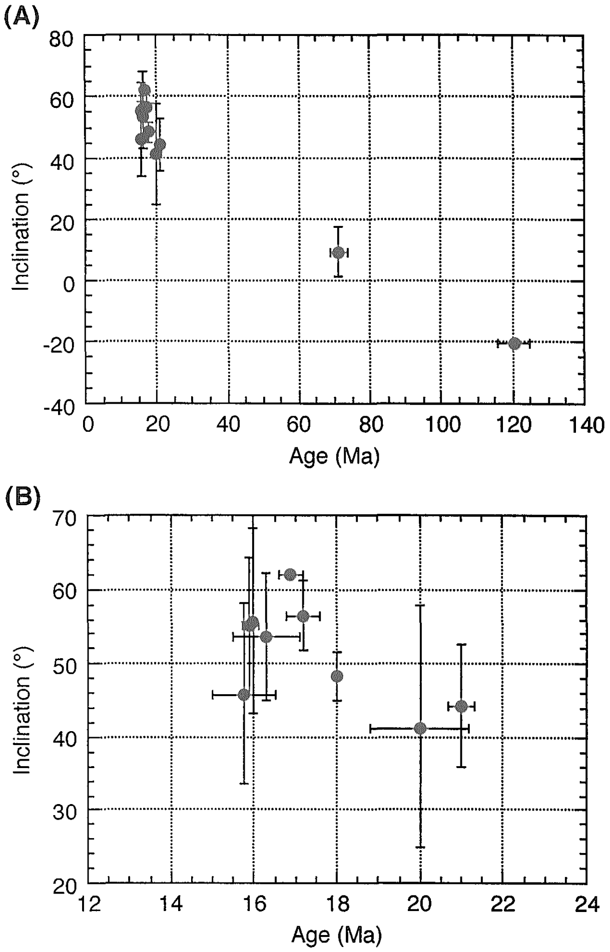

Fig. 9 (A) Temporal inclination changes observed in the forearc side of NE Japan after 140 Ma, and (B) that between 24 and 12 Ma.

the forearc side of NE Japan at about 20 Ma (Fig. 8). Cretaceous formations in the Kitakami Mountains gave paleomagnetic declinations deflecting markedly counterclockwise (ca. 280°). A large-scale counterclockwise deflection in declination (295°) was observed also in the 21-Ma Nisatai Dacite. The Tenmyosan Volcanics, which have been dated as 20 Ma, possess a lesser amount of counterclockwise deflection (320°). Little deflection was detected from the 18-Ma Motokozawa Basalt. Any detectable deflection cannot be observed in the formations which are younger than 18 Ma. Declination seems to vary progressively from ca. 295° at 21 Ma to 0° at 18 Ma via 320° at 20 Ma, suggesting uniform paleomagnetic rotation between 21 and 18 Ma.

Counterclockwise tectonic rotation of entire NE Japan could explain the observed counterclockwise paleomagnetic rotation. It has been widely believed that when the Japan Sea opened in an extensional regime, NE and SW Japan rotated counterclockwise and clockwise, respectively (Otofuji *et al.*, 1985a). If the forearc side of NE Japan behaved as a single rigid sliver during rotation, the paleomagnetic rotation observed in the forearc side represent the tectonic rotation of entire NE Japan. In this context, NE Japan rotated counterclockwise through more than 60° between 21 and 18 Ma. Unfortunately, however, we have no clue to verify whether or not the forearc side was a single, coherent rigid block during the opening period of the Japan Sea, because in NE Japan there are no useful strain markers, such as a zonal geologic structure as seen in the outer part of SW Japan.

From geologic and physiographic points of view, more than 60° of counterclockwise rotation is unacceptable. Several researchers have tried to restore the paleoposition of the Japanese islands. Otsuki (1990) achieved the most elegant reconstruction, based largely on present geographic and bathymetric features. According to his paper, the amount of counterclockwise rotation of NE Japan is about 30°, which is half the paleomagnetically-suggested angle of rotation. However, it should be noted that his reconstruction disregards effects of crustal extension. Recent geologic studies have revealed that large-scale crustal extension occurred throughout NE Japan during early to middle Miocene time (Sato, 1994). For example, 115% of crustal extension occurred in the Motegi area at about 16 Ma (Takahashi and Hoshi, 1996). Early to middle Miocene extensional tectonics is suggested to have occurred also in the Ninohe and Shiogama-Matsushima areas (Nakamura, 1992; Tsujino *et al.*, 1996). In the backarc side, Yamaji (1990) revealed many extensional basins (mostly half grabens) bounded by normal faults. Hence, taking effects of intra-arc crustal extension into account, the amount of counterclockwise rotation would be 40-30°.

Another more plausible interpretation is that the forearc side was not a single rigid sliver but composed of two or more blocks. In Fig. 8, we should note that all the paleomagnetic data showing large-scale counterclockwise deflection in declination (>60°) were obtained only from the Kitakami Mountains. Thus, it is possible to interpret that only the Kitakami Mountains were experienced large counterclockwise rotation of more than 60°, and that other parts (Abukuma and Yamizo Mountains) were undergone lesser rotation (Fig. 10). This kind of interpretation was first proposed by Kawai *et al.* (1971). Takeuchi (1986) also illustrated a discontinuous boundary between the Abukuma and Kitakami Mountains. Possible differential rotation in the forearc side ceased before 16 Ma, because northerly or southerly declinations have been observed in the 16-Ma formations on the Kitakami, Abukuma and Yamizo Mountains.

Geologic and geophysical evidences support the discontinuity between the Abukuma and Kitakami Mountains. As illustrated in Fig. 10, a prominent fault, the Hatakawa Tectonic Line, runs approximate-

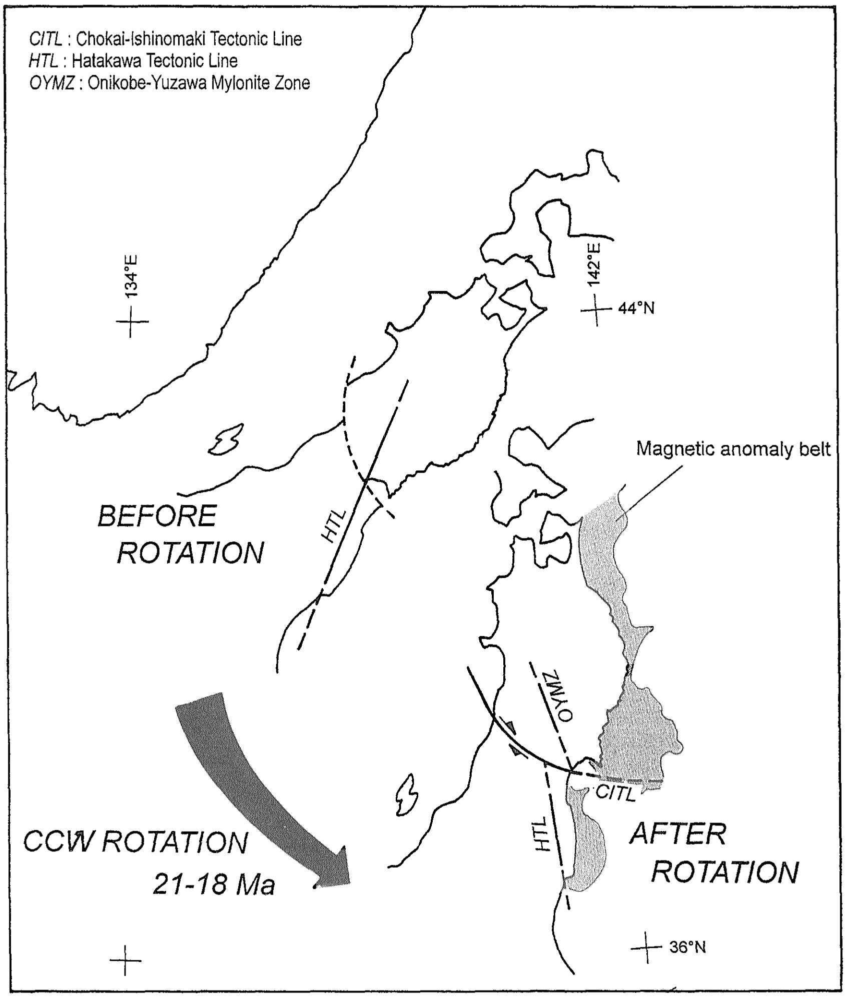

Fig. 10 Model for the counterclockwise rotation of NE Japan associated with the opening of the Japan Sea. For explanation, see text.

ly N8°W across the Abukuma Mountains (Kubo *et al.*, 1990, 1994; Yanagisawa *et al.*, 1996). It was active mainly during the Cretaceous as a sinistral strike-slip fault (Otsuki and Ehiro, 1992). To the north, it is hidden by upper Cenozoic formations near Takadate of Miyagi Prefecture. Further to the north, its equivalent (Onikobe-Yuzawa Mylonite Zone: OYMZ) again appears to the surface, but its strike changes to N25° W (Sasada, 1984, 1985). In addition, the Hatakawa Tectonic Line and OYMZ do not align with each other; they seem to have been shifted dextrally by a hidden transverse fault. This hypothetical transverse fault has been called the Chokai-Ishinomaki Tectonic Line (CITL). Otsuki and Ehiro (1978) estimated the dextral displacement along the CITL to be 20 km. Furthermore, at the eastern extension of the CITL off Matsushima, a north-south-trending magnetic anomaly belt (Finn, 1994) seems to be shifted dextrally by a possible counterpart of the CITL. Thus, most likely the CITL was the kinematic boundary with dextral slip between the Kitakami and Abukuma Mountains at about 20 Ma. Further paleomagnetic studies, especially for the pre-20-Ma rocks in the areas south of the CITL, are needed to verify the differential rotation in the forearc side of NE Japan.

5. Conclusions

(1) We compiled late Mesozoic to Cenozoic paleomagnetic data from the forearc side of NE Japan and established declination and inclination changes as a function of age. As a result, pronounced counterclockwise paleomagnetic rotation of more than 60° was observed between 21 and 18 Ma.

(2) Two possibilities were discussed to account for the observed paleomagnetic rotation. One is that the large counterclockwise rotation in paleomagnetic declination results from large tectonic rotation of entire NE Japan. In this model, however, the amount of counterclockwise rotation (>60°) is much larger than the rotation angle expected from the reconstruction based on geologic and physiographic features (40-30°). Another more plausible interpretation is that differential rotation took place in NE Japan; the

angle of rotation of the Kitakami Mountains was larger than that of the Abukuma Mountains. Dextral movement on the Chokai-Ishinomaki Tectonic Line may have accommodated the larger rotation of the Kitakami Mountains.

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References

Akiba, F., Yanagisawa, Y. and Ishii, T.(1982) Neogene diatom biostratigraphy of the Matsushima area and its environs, Miyagi Prefecture, Northeast Japan. *Bull. Geol. Surv. Japan*, **33**, 215-239.*

Berggren, W. A., Kent, D. V., Swisher, C. C., III and Aubry, M. P.(1995) A revised Cenozoic geochronology and chronostratigraphy. *In* Berggren, W. A., Kent, D. V., Aubry, M. P. and Hardenbol, J., eds., *Geochronology, Time Scales and Stratigraphic Correlation*. Society of Sedimentary Geology Special Publication, no. 54, 129-212.

Cande, S. C. and Kent, D. V.(1995) Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *Jour. Geophys. Res.*, **100**, 6093-6095.

Finn, C.(1994) Aeromagnetic evidence for a buried Early Cretaceous magmatic arc, northeast Japan. *Jour. Geophys. Res.*, **99**, 22165-22185.

Gradstein, F. M., Agterberg, F. P., Ogg, J. G., Hardenbol, J., van Veen, P., Thierry, J. and Huang, Z.(1994) A Mesozoic time scale. *Jour. Geophys. Res.*, **99**, 24051-24074.

Graham, J. W.(1949) The stability and significance of magnetism in sedimentary rocks. *Jour. Geophys. Res.*, **54**, 131-167.

Hayashida, A.(1994) Paleomagnetic directions of the Kadonosawa area and the rotation of Northeast Japan. *Chikyu Monthly*, **16**, 135-138.**

Hoshi, H.(1998) Modification and significance of magnetostratigraphic polarity zones for the Lower to Middle Miocene Nakagawa Group in the Motegi area (Tochigi Prefecture, southern NE Japan). *Jour. Geol. Soc. Japan*, **104**, 60-63.*

Hoshi, H. and Matsubara, T.(1998) Early Miocene paleomagnetic results from the Ninohe area, NE Japan: Implications for arc rotation and intra-arc differential rotations. *Earth, Planets and Space*, **50**, 23-33.

Hoshi, H. and Takahashi, M.(1995) Primary magnetization of the Early Miocene volcanic rocks in the Motegi area, Tochigi Prefecture, central Japan: Paleomagnetic conglomerate test. *Bull. Geol. Surv. Japan*, **46**, 537-553.*

Hoshi, H. and Takahashi, M.(1996a) Stratigraphy and geologic structure of the Lower Miocene in the Motegi area: The relationship between N-S trending fault activity and tectonics in Miocene Northeast Japan. *Jour. Geol. Soc. Japan*, **102**, 25-39.*

Hoshi, H. and Takahashi, M.(1996b) Magnetostratigraphy of the Early to Middle Miocene volcanic sequence in the Motegi area, Northeast Japan, and the time of volcanic activity. *Jour. Geol. Soc. Japan*, **102**, 573-590.*

Hoshi, H. and Takahashi, M.(1997) Paleomagnetic constraints on the extent of tectonic blocks and the location of their kinematic boundaries: Implications for Miocene intra-arc deformation in Northeast Japan. *Jour. Geol. Soc. Japan*, 103, 523-542.

Irizuki, T. and Matsubara, T.(1994) Vertical changes of depositional environments of the Lower to Middle Miocene Kadonosawa Formation based on analyses of fossil ostracode faunas. *Jour. Geol. Soc. Japan*, **100**, 136-149.*

Ishii, T., Yanagisawa, Y. and Yamaguchi, S. (1983a) *Geology of the Shiogama district*. With geological sheet map at 1: 50,000, Geol. Surv. Japan, 112p.*

Ishii, T., Yanagisawa, Y. and Yamaguchi, S. (1983b) Fission-track ages of the Miocene pumice tuff in the region around Matsushima Bay, Miyagi Prefecture. *Bull. Geol. Surv. Japan*, **34**, 139-152.*

Ishii, T., Yanagisawa, Y., Yamaguchi, S. and Abe, T.(1982a) K-Ar ages of Miocene volcanic rocks from the Shiogama district: Contribution to the age between the *Actinocyclus ingens* Zone and the *Denticulopsis lauta* Zone. *Bull. Geol. Surv. Japan*, **33**, 425-431.*

Ishii, T., Yanagisawa, Y., Yamaguchi, S., Sangawa, A. and Matsuno, K.(1982b) *Geology of the Matsushima district*. With geological sheet map at 1: 50,000, Geol. Surv. Japan, 121p.*

Ishizuka, O. and Hoshi, H.(1997) K-Ar ages of Early to Middle Miocene volcanic rocks from the Motegi area in Tochigi Prefecture, Northeast Japan. *Jour. Geol. Soc. Japan*, **103**, 964-970.*

Ishizuka, O. and Uto, K.(1995) K-Ar ages of Neogene volcanic rocks in the Ninohe area. *Programme and Abstracts, Volcanological Society of Japan, No. 2*, 4.**

Ito, H. and Tokieda, K.(1986) Tilting movements of the Japanese islands inferred from Cretaceous and Early Tertiary paleomagnetic data. *Jour. Geomag. Geoelectr.*, **38**, 361-386.

Itoh, Y., Amano, K. and Danhara, T.(1998) Rotational motion of the Kurihashi Granodiorite distributed in the Kamaishi Mine, Northeast Japan, inferred from paleomagnetic analyses. *Jour. Geol. Soc. Japan*, **104**, 42-51.*

Jolivet, L., Shibuya, H. and Fournier, M.(1995) Paleomagnetic rotations and the Japan Sea opening. *In* Taylor, B. and Natland, J., eds., *Active Margins and Marginal Basins of the Western Pacific*. AGU Geophysical Monograph, no. 88, 355-369.

Kawada, K.(1953) Geological studies on the Yamizo, Torinoko and Toriashi mountain blocks and their neighborhood in the northeastern Kwanto district. *Sci. Rep. Tokyo Bunrika Daigaku, Ser. C.*, **2**, 217-307.

Kawai, N., Ito, H. and Kume, S.(1961) Deformation of the Japanese islands as inferred from rock magnetism. *Geophys. Jour. Roy. Astr. Soc.*, **6**, 124-130.

Kawai, N., Nakajima, T. and Hirooka, K.(1971) The evolution of the island arc of Japan and the formation of granites in the circum-Pacific belt. *Jour. Geomag. Geoelectr.*, **23**, 267-293.

Kellogg, K. S. and Reynolds, R. L.(1978) Paleomagnetic results from the Lassiter Coast, Antarctica, and a test for oroclinal bending of the Antarctic Peninsula. *Jour. Geophys. Res.*, **83**, 2293-2299.

Kimura, T., Hayami, I. and Yoshida, S.(1991) *Geology of Japan*. University of Tokyo Press, Tokyo, 287p.

Kubo, K., Yanagisawa, Y., Yoshioka, T. and Takahashi, Y.(1994) *Geology of the Namie and Iwaki-Tomioka district*. With geological sheet map at 1 : 50,000, Geol. Surv. Japan, 104p.*

Kubo, K., Yanagisawa, Y., Yoshioka, T., Yamamoto, T. and Takizawa, F.(1990) *Geology of the Haramachi and Omika district*. With geological sheet map at 1 : 50,000, Geol. Surv. Japan, 155p.*

Matsubara, T.(1995) Fossil Mollusca of the Lower Miocene Yotsuyaku Formation in the Ninohe district, Iwate Prefecture, Northeast Japan : Part 1. General consideration of the fauna. *Trans. Proc. Palaeont. Soc. Japan, N. S.*, no. 180, 303-320.

McElhinny, M. W.(1973) *Palaeomagnetism and plate tectonics*. Cambridge University Press, Cambridge, 358p.

Momose, H., Torii, M. and Yamaji, A.(1991) Paleomagnetism of the Uetsu and Tsugawa regions, Northeast Japan : implications for Northeast Japan tectonics during the Japan Sea formation. *Rock Mag. Paleogeophys.*, **18**, 86-89.

Moreau, M. G., Courtillot, V. and Besse, J.(1987) On the possibility of a widespread remagnetization of pre-Oligocene rocks from Northeast Japan and the Miocene rotational opening of the Japan Sea. *Earth Planet. Sci. Lett.*, **84**, 321-338.

Nakamura, K.(1992) Inversion tectonics and its structural expression. *Structural Geology (Kozo Chishitsu)*, no. 38, 3-45.*

Oda, H., Torii, M. and Hayashida, A.(1989) Paleomagnetic study and fission-track dating in Yanagawa and Takadate areas, Northeast Japan. *Rock Mag. Paleogeophys.*, **16**, 51-56.

Ohki, J., Shuto, K., Watanabe, N. and Itaya, T. (1993) K-Ar ages of the Miocene Ryozen basalts from the northern margin of the Abukuma Highland, Japan. *Jour. Min. Petr. Econ. Geol.*, **88**, 313-319.

Otofuji, Y., Matsuda, T. and Nohda, S.(1985a) Opening mode of the Japan Sea inferred from the palaeomagnetism of the Japan Arc. *Nature*, **317**, 603-604.

Otofuji, Y., Matsuda, T. and Nohda, S.(1985b) Paleomagnetic evidence for the Miocene counter-clockwise rotation of Northeast Japan : rifting process of the Japan Arc. *Earth Planet. Sci. Lett.*, **75**, 265-277.

Otofuji, Y., Sato, K., Iba, N. and Matsuda, T. (1997) Cenozoic northward translation of the Kitakami massif in northeast Japan : paleomagnetic evidence. *Earth Planet. Sci. Lett.*, **153**, 119-132.

Otofuji, Y., Kambara, A., Matsuda, T. and Nohda, S.(1994) Counterclockwise rotation of Northeast Japan : Paleomagnetic evidence for regional extent and timing of rotation. *Earth Planet. Sci. Lett.*, **121**, 503-518.

Otsuki, K.(1990) Westward migration of the Izu-Bonin Trench, northward motion of the Philippine Sea Plate, and their relationships to the Cenozoic tectonics of Japanese island arcs. *Tectonophysics*, **180**, 351-367.

Otsuki, K. and Ehiro, M.(1978) Major strike-slip faults and their bearing on spreading in the Japan Sea. *Jour. Phys. Earth*, **26**, Suppl., 537-555.

Otsuki, K. and Ehiro, M.(1992) Cretaceous left-lateral faulting in Northeast Japan and its bearing on the origin of geologic structure of Japan. *Jour. Geol. Soc. Japan*, **98**, 1097-1112.*

Sasada, M.(1984) The pre-Neogene basement rocks of the Kamuro Yama-Kurikoma Yama area, northeastern Honshu, Japan: Part 1, Onikobe-Yuzawa Mylonite Zone. *Jour. Geol. Soc. Japan*, **90**, 865-874.*

Sasada, M.(1985) The pre-Neogene basement rocks of the Kamuro Yama-Kurikoma Yama area, northeastern Honshu, Japan: Part 2, Boundary between the Abukuma and Kitakami Belts. *Jour. Geol. Soc. Japan*, **91**, 1-17.*

Sato, H.(1989) Degree of deformation of late Cenozoic strata in the Northeast Honshu Arc. *Mem. Geol. Soc. Japan*, no. 32, 257-268.*

Sato, H.(1994) The relationship between late Cenozoic tectonic events and stress field and basin development in northeast Japan. *Jour. Geophys. Res.*, **99**, 22261-22274.

Shibata, K.(1985) Radiometric ages for the Cretaceous Period: with special reference to the time scale. *Mem. Geol. Soc. Japan*, no. 26, 119-133.*

Shibata, K., Matsumoto, T., Yanagi, T. and Hamamoto, R.(1978) Isotopic ages and stratigraphic control of Mesozoic igneous rocks in Japan. *In* Cohee, *et al.*, eds., *Contr. Geol. Time Scale*. Am. Assoc. Pet. Geol., 143-164.

Tagami, T., Uto, K., Matsuda, T., Hasebe, N. and Matsumoto, A.(1995) K-Ar biotite and fission-track zircon ages of the Nisatai Dacite, Iwate Prefecture, Japan: A candidate for tertiary age standard. *Geochem. Jour.*, **29**, 207-211.

Takahashi, M. and Hoshi, H.(1995) Radiometric ages of the Early Miocene volcanic rocks in the Motegi area, Tochigi Prefecture, central Japan. *Jour. Geol. Soc. Japan*, **101**, 821-824.*

Takahashi, M. and Hoshi, H.(1996) Geologic age of the Nakagawa Group in the Motegi area, Tochigi Prefecture: Tectonic significance. *Bull. Geol. Surv. Japan*, **47**, 317-333.*

Takahashi, M., Hoshi, H. and Yamamoto, T. (1997) Tectonic rotation of the Abukuma Mountains inferred from paleomagnetism of the Miocene volcanic rocks in the Ryozen area, Northeast Japan. *Abstracts of 1997 Japan Earth and Planetary Science Joint Meeting*, 769.**

Takeuchi, A.(1986) Oligocene/Miocene rotational block-movement and paleostress field of Japan. *Jour. Geomag. Geoelectr.*, **38**, 495-511.

Takigami, Y.(1991) ^{40}Ar-^{39}Ar ages of igneous rocks near Miyako-City, Northeast Japan. *Res. Bull. Kanto Gakuen Univ.*, **18**, 105-114.**

Taylor, B. and Karner, G. D.(1983) On the evolution of marginal basins. *Rev. Geophys. Space Phys.*, **21**, 1727-1741.

Tsujino, T., Tsubamoto, T., Yamaji, A., Matsubara, T. and Chinzei, K.(1996) Early Miocene graben in the Kadonosawa area, NE Japan. *Abstracts of the 103rd annual meeting of the Geological Society of Japan*, 386.**

Yamaji, A.(1990) Rapid intra-arc rifting in Miocene Northeast Japan. *Tectonics*, **9**, 365-378.

Yamamoto, T.(1996) Stratigraphy and eruption styles of Miocene volcanic rocks in the Ryozen district, NE Japan. *Jour. Geol. Soc. Japan*, **102**, 730-750.*

Yamazaki, T.(1989) Paleomagnetism of Miocene sedimentary rocks around Matsushima Bay, Northeast Japan and its implication for the time of the rotation of Northeast Japan. *Jour. Geomag. Geoelectr.*, **41**, 533-548.

Yanagisawa, Y. and Akiba, F.(1998) Refined Neogene diatom biostratigraphy for the northwest Pacific around Japan, with an introduction of code numbers for selected diatom biohorizons. *Jour. Geol. Soc. Japan*, **104**, 395-414.

Yanagisawa, Y., Yamamoto, T., Banno, Y., Tazawa, J., Yoshioka, T., Kubo, K. and Takizawa, F.(1996) *Geology of the Somanakamura district*. With geological sheet map at 1: 50,000, Geol. Surv. Japan, 144p.*

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東北日本の中新世反時計廻り回転運動：レビューおよび新モデル

星　博幸・高橋雅紀

要　旨

本論文は，最近10年間（1989-1998）に東北日本の前弧側地域でおこなわれた古地磁気研究を詳しくレビューする．本論文の目的は，日本海の拡大にともなって反時計まわりに回転したとされる東北日本の運動過程を明らかにすることである．このレビューで対象になる地域は，二戸（岩手県），宮古（岩手県），釜石鉱山（岩手県），塩竈-松島（宮城県），霊山（福島県），茂木（栃木・茨城県）の６地域である．筆者らは，これらの地域から報告されている古地磁気データのうち信頼性の高いものを選び，時間軸にそって偏角データと伏角データを並べてみた．その結果，偏角については約20Maに規模の大きい急変が認められ，21Maから18Maにかけての300万年間に偏角が約300°から０に移りかわっているようにみえる．ここで注意しておきたいことは，60°を超える大きな西偏は，すべて北上山地から得られていることである．上記のように認められた偏角の時間変化を説明するために，２つの可能性が考えられる．一つは，東北日本が21-18Maに一枚岩として60°以上反時計まわりに回転したことである．しかし，この60°という回転角度は，地質や海底地形から期待される回転量（40-30°）に比べて，かなり大きい．もう一つは，前弧域において差別回転運動が起きた可能性であり，筆者らはこの可能性を好んでいる．北上山地の回転量は，阿武隈山地の回転量よりも大きく，両山地の間には回転ブロック境界（＝断層）が存在する．その断層はかつて唱えられた鳥海-石巻構造線に一致する．東北日本の回転時に，このレンチ断層にそって右横ずれ運動が起き，そのことで北上山地が相対的により大きく反時計まわりに回転したと推定される．