Geofísica Internacional (1994), Vol. 33, Num. 1, pp. 25-44

Miocene tectonic deformation of central Japan-Paleomagnetic evidence of intra-arc bending

Masaki Takahashi
Fuel Resources Department, Geological Survey of Japan
Tsukuba, Ibaraki, Japan

Received: April 15, 1993; accepted: July 5, 1993.

RESUMEN

Estudios paleomagnéticos recientes en las montañas de la región de Kanto, en el centro de Japón, han revelado un movimiento en el sentido del movimiento de las manecillas del reloj, del ala este de la estructura flexionada de terrenos geológicos pre-Neógeno. Una rotación de las montañas mencionadas, de más de 90° en el sentido señalado, tuvo lugar entre 15 Ma y 6 Ma. En contraste, el suroeste de Japón y la parte este (área de Nohi) han rotado en el mismo sentido entre 47° y 13°-17° aproximadamente a los 15 Ma, respectivamente. Esta rotación diferencial representa una deformación intra-arco durante el Mioceno. Por otra parte, las investigaciones de campo revelan que el arco Izu-Bonin se ha venido colisionando contra el Japón central desde el Mioceno Medio. De acuerdo con los resultados paleomagnéticos que se muestran, acompañados de estudios geológicos en el Japón central, se puede concluir que una reflexión lateral ocurrió entre 15 Ma y 6 Ma en asociación con la colisión entre las islas Japonesas en deriva hacia el sureste y el arco Izu-Bonin que migra hacia el noroeste.

PALABRAS CLAVE: Rotación tectónica, tectónica de collisión, paleomagnetismo, islas Japonesas, tectónica de arco de islas.

ABSTRACT

Recent paleomagnetic studies in the Kanto Mountains, central Japan, have revealed Miocene clockwise rotation of the east-wing of the bending structure of pre-Neogene geologic terranes. More than 90° clockwise rotation of the Kanto Mountains took place between 15 and 6 Ma. In contrast, Southwest Japan and its eastern part (Nohi area) have rotated clockwise through 47° and 13-17° around 15 Ma, respectively. This differential rotation represents an intra-arc deformation during the Miocene. In addition, the field investigations reveal that the Izu-Bonin arc has been colliding with central Japan since the Middle Miocene. Along with these previous paleomagnetic results accompanied with geological studies in central Japan, it is concluded that lateral bending of central Japan occurred during 15 and 6 Ma in association with the collision between the southeastward drifting Japanese Islands and the northwestward migrating Izu-Bonin arc.

KEY WORDS: Tectonic rotation, collision tectonics, paleomagnetism, Japanese Islands, island arc tectonics

INTRODUCTION

Paleomagnetism is one of the useful methods for analyzing deformations because it can directly detect a component of large latitudinal drift as well as rotation. The Japanese Islands are an active island arc where rotations along very steep or vertical axes are common, as well as vertical movements.

The Japanese Islands are characterized by a zonal distribution of the pre-Neogene geologic terranes as shown in Figure 1. These zones comprise three belts (Sanbagawa Belt: high pressure type metamorphic rocks, Chichibu Belt: Jurassic accretionary complex, Shimanto Belt: Cretaceous-Paleogene accretionary complex) which extend from Kyushu to central Japan. While the trend of this zonal structure is parallel to the axis of the Southwest Japan arc, this zone is sharply bent in central Japan; this bent is called the Kanto Syntaxis. Detailed timing of the formation of the bend has been controversial since the last century.

Kobayashi (1941) explained the bend in terms of Cretaceous deformation of central Japan by the existence of an obstacle in front of the southward migrating Japanese Islands. Tateiwa (1976) considered that this cusp structure was formed in the Cretaceous to Paleogene time. While Matsuda (1978, 1984) also placed the time of this cusp formation in the pre-Miocene, Niitsuma (1982) set forth that the subduction of the Philippine Sea Plate, initiated at 6-7 Ma, caused the bending of the zonal structure. On the other hand, paleomagnetic results of the Late Cretaceous and Miocene on the west-wing of the Kanto Syntaxis indicate that the counter-clockwise rotation relative to the main part of Southwest Japan occurred between 15 and 12 Ma (Itoh, 1986; 1988). Although the timing of the lateral bending of the Kanto Syntaxis is one of the most important problems to discuss the tectonic development of the Japanese Islands, the detailed rotational motion of this bend remains unknown.

In the southern Fossa Magna region, several sequences of very thick post-Middle Miocene sediments have been accumulated on the pre-Neogene Systems of the Kanto Syntaxis (Figure 2). Recently, Amano (1991) proposed that there were multiple collisions of the volcanic segments on the Philippine Sea Plate with central Japan since Miocene. A set of thick conglomerate overlying abyssal mudstone is thought to represent the collision of the Izu-Bonin arc. Collision tectonics at the South Fossa Magna

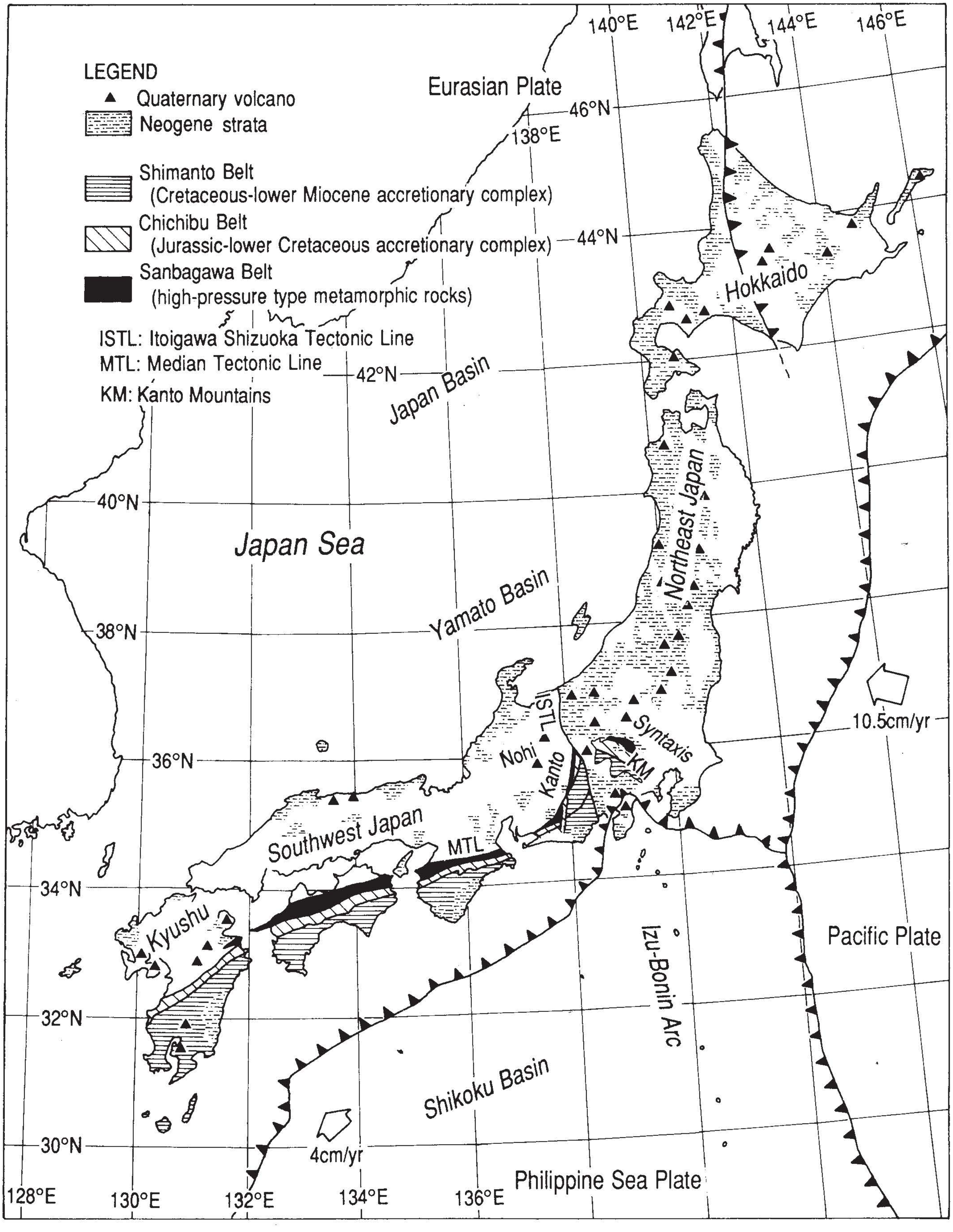

Fig.1. Tectonic sketch of the Japanese Islands. The arrows indicate the present plate motions relative to the Eurasian Plate (Minster and Jordan, 1978, 1979).

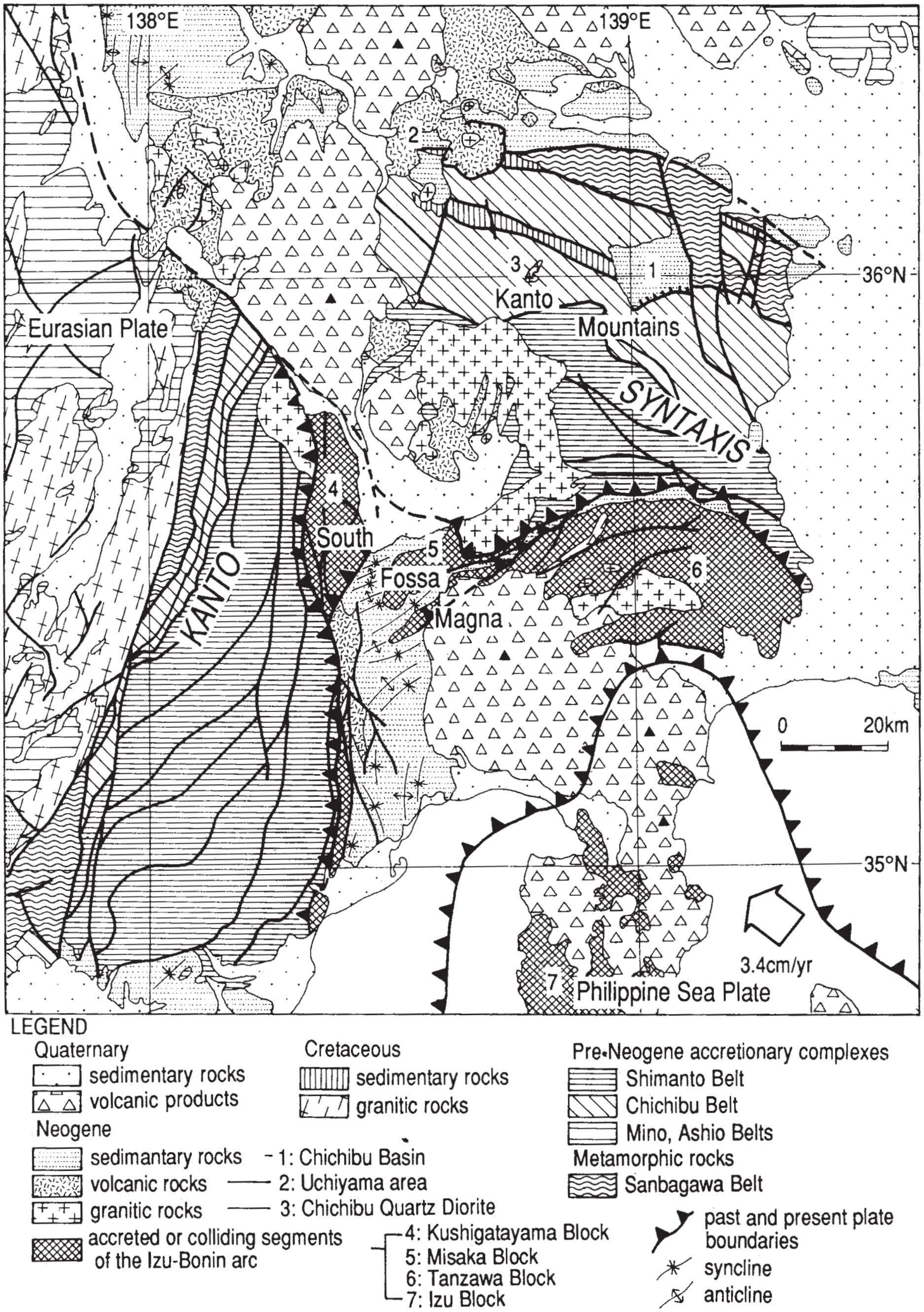

Fig.2. Detailed geological map of central Japan modified from Geological Survey of Japan (1992). Collisions of the Kushigatayama and Misaka Blocks probably took place at 12 Ma and 9-7 Ma, respectively. The Tanzawa Block collided at 5-3 Ma and the Izu Block commenced to collide at 1 Ma (Amano, 1991).

may be the origin of the northward-convex structure of pre-Neogene terranes.

This paper presents a brief review of the paleomagnetic knowledge of the Kanto Mountains as well as Southwest and Northeast Japan arcs, and discusses the interrelations among the rotations of Southwest and Northeast Japan, collision tectonics at the South Fossa Magna and lateral bending of the Kanto Syntaxis.

PALEOMAGNETIC RESULTS

Paleomagnetic investigations are necessary for studying the tectonics of island arcs, where rotational motions are common as well as vertical movements. This section presents the paleomagnetic results of the Kanto Mountains, Southwest and Northeast Japan arcs and the Nohi area. Changes in paleomagnetic directions of the Kanto Mountains and the Nohi area represent the rotational history of the east- and west-wing of the Kanto Syntaxis, respectively. The time scale of Berggren *et al.* (1985) is used for reference of the paleomagnetic, biostratigraphic and chronologic data through out this paper.

Kanto Mountains

Only three paleomagnetic directions (Chichibu Basin, Uchiyama area and the Chichibu Quartz Diorite) were obtained from the Kanto Mountains (Figure 3). Details of the paleomagnetic results as well as ages are listed in Table 1.

The Miocene Chichibu Basin is situated in the central part of the Kanto Mountains (Figure 2), where more than 5,000m-thick sediments were deposited in spite of its small size (about 160km^2). Paleomagnetism in the sedimentary rocks of the Chichibu Basin was measured by Hyodo and Niitsuma (1986). For a reconnaissance, they collected oriented samples from 133 sites on the Early Miocene marine sediments in the basin. One specimen from each hand sample was cleaned stepwise in an alternating field (AF) up to 30mT. About half the samples show irregular and scattered directions within the hand sample, probably due to the inhomogeneity of the initial magnetizationprocess or to the weathering of these samples. In some sites, the remanent magnetizations remain parallel to the present geomagnetic field before tilt-correction after of AF-demagnetization up to 35mT. These samples can be regarded to have remagnetized by the present magnetic field after tilting of the strata. Only 12 samples showed stable remanent magnetizations under AF-treatment. At least two additional samples from these 12 sites were collected to average out the error of sample orientation and the inhomogeneity between sample magnetization. One sample showed a large dispersion of remanent directions and was rejected.

In addition to AF-demagnetization, Hyodo and Niitsuma (1986) tried thermal (Th) demagnetization of the samples from these 11 sites and from some of the rejected sites, by microwave heating MW-demagnetization: Hale *et al.*, 1978). While the rejected samples did not show systematic trends after MW-demagnetization, all samples of the above 11 sites were found to be stable by MW-demagnetization up to 240°C. Consequently these 11 sites are considered as showing reliable paleomagnetic directions.

The obtained paleomagnetic directions of the 11 sites are listed in Table 1. The mean paleomagnetic direction of the Chichibu Basin is D=93.7° and I=52.7° with a 95% confidence radius (α_{95}) of 8.3°, after inversion of the reversed polarity direction to normal polarity. While the mean inclination is not significantly different from that of the geocentric axial dipole field (56°), the mean declination is deflected easterly from north. The Chichibu Basin includes both normal and reversed polarities, which suggests that the mean direction represents a period long enough to average the geomagnetic secular variation. The age of the sedimentary rocks in the Chichibu Basin is zone N.8 (Blow,1969) based on planktonic microfossils (Takahashi *et al.*, 1989; Takahashi, 1992). The duration of zone N.8 can be calibrated at 16.6-15.2 Ma after Berggren *et al.* (1985). Consequently, the eastward deflected paleomagnetic direction of the Chichibu Basin is due to clockwise rotation of the Kanto Mountains since 15.2 Ma (Figure 4).

Recently, Takahashi and Watanabe (1993) reported paleomagnetic results from the Uchiyama area, at the northwestern corner of the Kanto Mountains (Figure 3). They measured paleomagnetism of many fresh andesite lavas (Yaekubo Formation) and some porphyrite (Takonomine Porphyrite). The total number of samples and specimens are 47 and 271, respectively. The K-Ar ages of these andesite lava (11.9±0.9 Ma, 12.2±0.4 Ma, 12.4±0.4 Ma) and of the Takonomine Porphyrite (12.5±0.4 Ma) suggest a close relation between the intrusion of the porphyrite and the eruption of the andesite lava (Nomura and Kosaka, 1987; Nomura and Ebihara, 1988). By careful treatment of Th- and/or AF-demagnetizations, reliable paleomagnetic directions were obtained for all samples. The formation mean direction, D=34.7°; I=51.2°; α_{95}=4.4°, was calculated from the tilt-corrected site mean directions. Based on the radiometric data and the paleomagnetic polarity, the upper Yaekubo Formation can be correlated with Chron C5A (Figure 4). The paleomagnetic direction of the Yaekubo Formation shows eastward deflection after inversion of reversed to normal polarity direction, which strongly suggests a clockwise rotation of the study area since 12 Ma. The Takonomine Porphyrite (12.5 Ma) also has eastward deflected declination with normal polarity, which is concordant with that of the Yaekubo Formation. Consequently, it can be concluded that an eastward deflected direction of about 35° is probably due to the clockwise rotation of the Kanto Mountains since 12 Ma.

The Chichibu Quartz Diorite intrudes into the pre-Neogene rocks of the Chichibu Belt. This igneous suite consists of stocks of medium-grained massive quartz diorite and small dykes of quartz porphyry and porphyrite. The paleomagnetic direction of the Chichibu Quartz Diorite was measured by Takahashi and Nomura (1989). The total number of oriented samples and specimens is 51 and 304, respectively. The mean paleomagnetic direction of the Chichibu Quartz Diorite (D=3.5°; I=64.4°; α_{95}=5.1°) is calculated after inversion of the reversed polarity directions to

Table 1

Site	*N*	*n*	*Jn*	Demag. (mT)	Dec. (°)	Inc. (°)	Dec.* (°)	Inc.* (°)	α95 (°)	*k*	Lat.(N) (°)	Long.(E) (°)	lithology, key microfossils & radiometric age	
Chichibu Basin (Hyodo & Niitsuma, 1986)														
CB48		3		10	68.2	59.9	93.7	63.6	16.5	56.8	22.9	171.9	sandstone	*Orb. suturalis*
OG28		5		20	29.8	51.8	70.4	63.6	3.7	424.2	37.5	164.3	tuff	*Gds. sicanus*
OG12		5		15	-135.4	-57.4	-105.1	-61.4	12.3	39.6	33.5	162.4	sandstone	*Grt. peripheroronda*
OG32		5		25	-124.1	-57.5	-99.7	-44.6	15.9	24.3	22.5	147.9	sandstone	*Pro. glomerosa curva*
OG40		5		20	3.9	-63.1	-110.6	-40.2	8.5	81.3	29.4	139.2	tuffaceous sandstone	*Pro. transitoria*
OG35		5		20	14.8	-51.5	-80.4	-49.6	18.1	18.7	10.4	161.1	tuffaceous sandstone	
HK16		4		25	-101.7	-42.7	-75.8	-39.4	12.9	51.8	2.3	157.2	tuffaceous sandstone	
HK19		5		25	-102.1	-56.4	-52.6	-56.6	5.8	173.1	2.1	178.3	tuffaceous sandstone	*Pro. glomerosa curva*
HK13		6		20	-89.1	-50.2	-83.2	-55.6	16.6	17.3	15.6	164.6	tuffaceous sandstone	*Gds. sicanus*
HK12		5		25	-109.5	-56.6	-78.0	-44.0	8.8	76.8	6.0	158.7	sandstone	*D. deflandrei*
HK04		5		15	-92.0	-33.0	-73.8	-40.5	19.7	16.0	1.3	158.9	sandstone	*S. heteromorphus*
mean					80.0	61.4			16.2	8.9	30.0	-164.0		
mean*							**93.7**	**52.7**	**8.3**	**31.4**	**15.8**	**-160.1**	**zone N.8 (16.6-15.2Ma)**	
Uchiyama Area (Takahashi & Watanabe, 1993)														
TK-1	3		140.62	10	22.8	49.1			2.6	2206.4	70.0	-121.0	porphyrite	12.5±0.4Ma
TK-2	3		140.62	10	34.0	63.1			2.4	2737.8	62.9	-161.1	porphyrite	
YK-1	5		449.95	20	-123.4	-45.7	-134.3	-41.8	9.1	71.5	49.1	-127.3	andesite lava	11.9±0.9Ma
YK-2	4		161.76	20	-127.4	-43.3	-139.9	-55.3	6.0	233.0	57.8	-142.9	andesite lava	12.2±0.3, 12.4±0.4Ma
YK-3	4		284.97	20	-101.4	-63.8	-147.4	-56.7	5.8	252.8	64.0	-143.6	andesite lava	
YK-4	4		188.62	20	-140.8	-47.8	-149.3	-48.5	9.8	88.3	63.5	-125.6	andesite lava	
YK-5	4		175.89	20	-115.9	-51.1	-142.5	-55.0	15.0	38.4	59.8	-141.4	andesite lava	
YK-6	5		342.89	20	-146.6	-47.1	-157.5	-48.5	8.5	82.2	70.0	-118.1	andesite lava	
YK-7	4		260.61	20	-139.9	-49.5	-151.7	-49.9	3.5	698.0	65.8	-126.4	andesite lava	
YK-8	6		228.17	20	-119.9	-62.8	-145.4	-56.4	7.9	72.5	62.4	-143.4	andesite lava	
YK-9	5		227.04	20	-111.7	-54.4	-140.8	-47.3	10.8	51.2	56.2	-129.5	andesite lava	
mean					-126.7	-52.5			7.3	50.1				
mean*							**34.7**	**51.2**	**4.4**	**141.0**	**61.1**	**-133.1**	**12.4-11.9Ma**	
Chichibu Quartz Diorite (Takahashi & Nomura, 1989)														
1	1	7	0.34	20	-21.0	72.5			8.1	56.0	64.2	112.8	quartz diorite	
2	1	8	0.29	20	34.4	76.5			1.8	964.6	55.0	164.0	quartz diorite	
5	1	6	0.035	20	170.4	-57.4			5.8	132.4	82.1	66.4	porphyrite	
8	1	8	0.77	20	-170.0	-69.9			1.9	900.6	70.9	157.1	quartz diorite	6.6±0.3Ma
11	1	8	0.11	20	-173.0	-55.6			9.1	37.8	84.3	-134.7	quartz diorite	
12	1	9	0.065	20	-154.8	-38.9			3.0	294.7	64.0	-105.4	quartz diorite	
14	1	7	0.070	20	-170.8	-59.6			5.3	129.9	81.5	-165.5	quartz diorite	
15	1	4	0.20	20	-41.4	-50.5			1.0	9306.9	55.5	53.1	quartz diorite	
26	1	6	0.20	20	0.5	76.9			8.0	71.9	61.0	139.2	quartz diorite	5.9±0.3, 6.1±0.7Ma
27	1	5	0.31	20	28.4	70.5			3.1	593.0	63.0	176.1	quartz diorite	
28	1	8	0.69	20	3.3	65.8			1.8	921.5	77.7	149.2	quartz diorite	
30	1	6	0.34	20	1.8	66.6			4.1	270.2	76.8	144.0	quartz diorite	
31	1	6	0.17	20	171.3	-71.8			1.1	3459.5	68.5	125.7	quartz diorite	
32	1	5	0.14	20	8.4	70.7			1.2	4128.3	70.1	153.1	quartz diorite	
36	1	6	0.015	20	11.7	75.6			5.2	164.6	62.2	150.3	quartz diorite	
38	1	3	0.32	20	-1.0	57.7			3.5	1262.2	87.5	120.3	quartz diorite	
39	1	9	0.14	20	12.2	67.4			1.4	1346.5	73.3	166.8	quartz diorite	
42	1	5	0.11	20	18.9	61.8			1.6	2392.6	73.9	-162.7	quartz diorite	
43	1	4	0.067	20	9.3	51.6			5.1	326.9	81.4	-107.9	quartz diorite	
50	1	5	0.29	20	176.2	-64.7			6.4	144.1	79.0	125.0	quartz diorite	
51	1	9	0.47	20	174.3	-48.1			6.7	59.4	81.6	-4.7	quartz diorite	
mean					**3.5**	**64.4**			**5.1**	**40.2**	**79.4**	**152.1**	**6.6-5.9Ma**	

Paleomagnetic directions obtained from the Chichibu Basin, Uchiyama area and the Chichibu Quartz Diorite. Some important planktonic microfossils and the radiometric data are also listed. *N* and *n* are the number of the samples and specimens, respectively; *Jn* is intensity of natural remanent magnetization (NRM) ($\times 10^{-3}$ emu/cm^3); Demag. is demagnetization level; Dec. and Inc. are declination and inclination of remanent magnetization after alternating field demagnetiza-tion; Dec.* and Inc.* are declination and inclination after tilt-correction; α_{95} is radius of 95% confidence limit in degrees; *k* is precision parameter; Lat. (N) and Long. (E) are latitude and longitude of virtual geomagnetic pole (VGP).

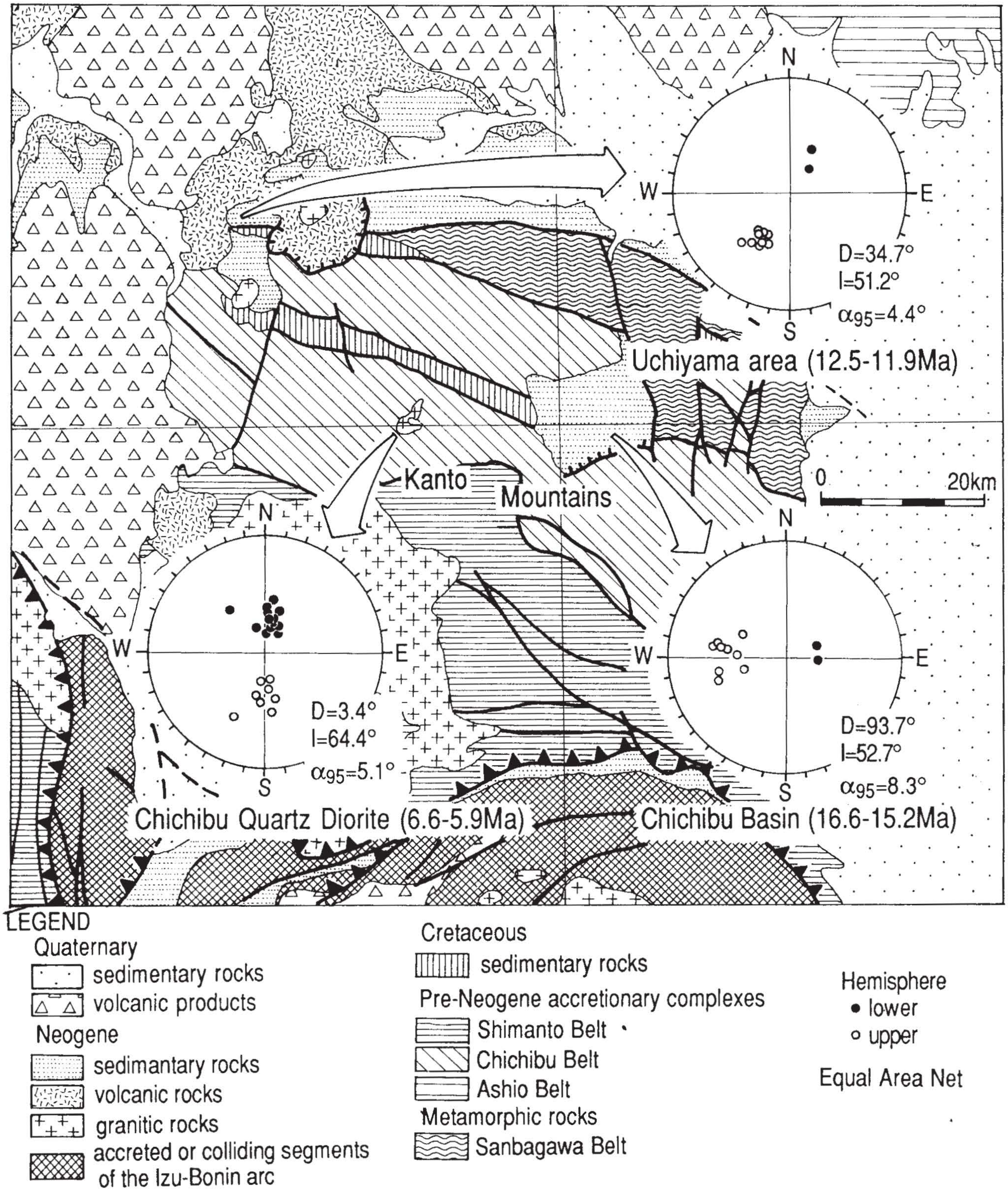

Fig.3. Paleomagnetic results of the east-wing of the Kanto Syntaxis (Kanto Mountains). Paleomagnetic directions of the Chichibu Basin, Uchiyama area and the Chichibu Quartz Diorite are after Hyodo and Niitsuma (1986), Takahashi and Watanabe (1993) and Takahashi and Nomura (1989), respectively. As the zonal distribution of the pre-Neogene geologic terranes is not disturbed, each paleomagnetic direction represents the tectonic rotation of the Kanto Mountains after the time of rock formation.

normal ones. The paleomagnetic declination shows no significant deflection from the north. While the paleomagnetic directions of the Chichibu Quartz Diorite are *in situ* directions being intrusive rocks, a lack of deflected directions

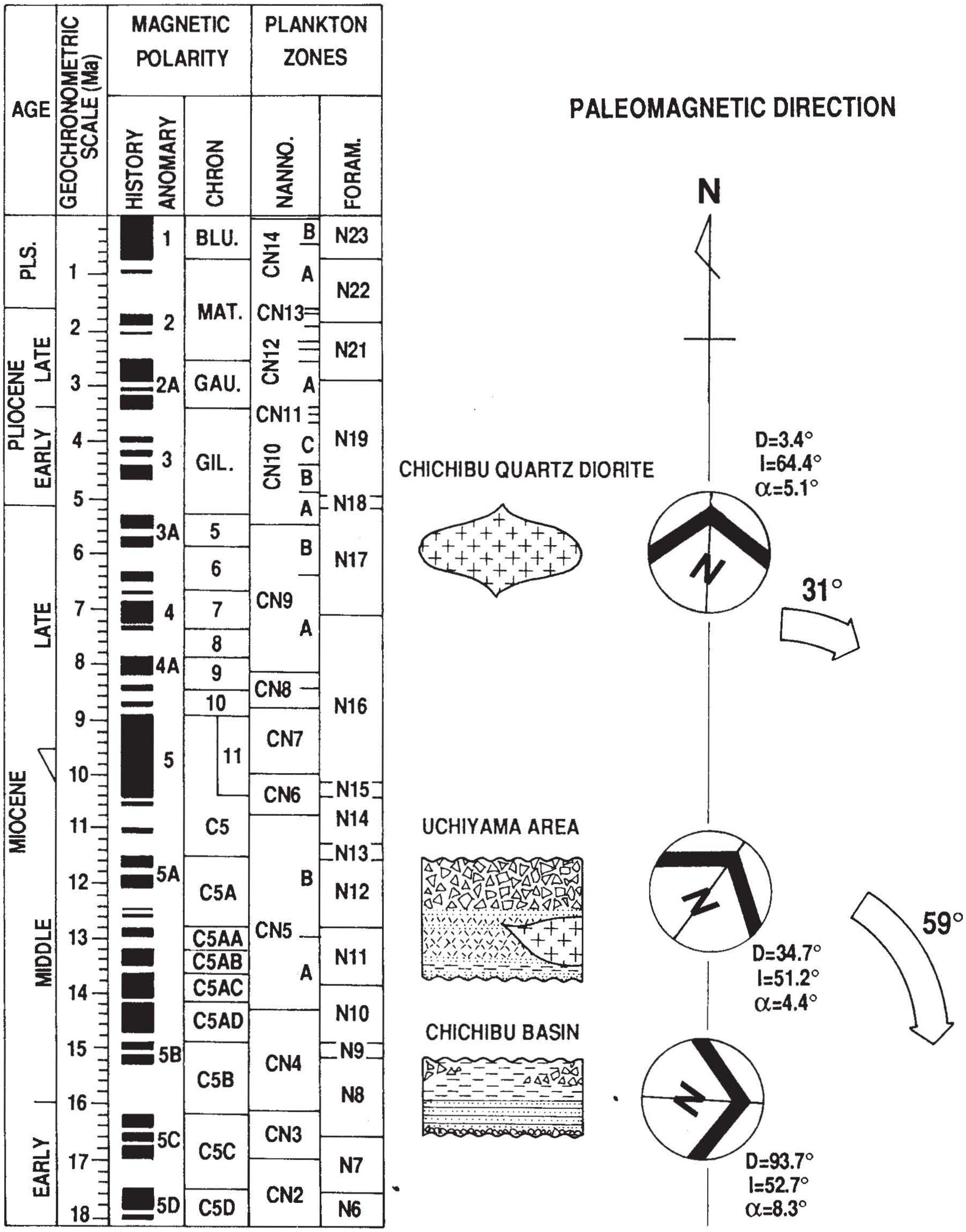

Fig.4. The relations between paleomagnetic declination and the geologic age. The magneto-biostratigraphic time scale is after Berggren *et al.* (1985).

strongly suggests that the rotation of the Kanto Mountains after intrusion of this diorite is negligible. The radiometric ages of this diorite (6.6±0.3 Ma, 5.9±0.4 Ma: Ueno and Shibata, 1986) may represent the most recent timing of the stop of rotation.

Southwest Japan

Kawai *et al.* (1961) first pointed out the tectonic bending of the Japanese Islands based on paleomagnetic data. They found that paleomagnetic declinations in Northeast Japan greatly differ from those in Southwest Japan in pre-

Tertiary ages. Since 1980, extensive paleomagnetic investigations have been carried out, focusing on the rotational movement of the Japanese Islands (Otofuji and Matsuda, 1983, 1984, 1987; Hayashida and Ito, 1984; Otofuji *et al.*, 1985a, b, c; Hayashida, 1986). Much paleomagnetic data show that Southwest Japan has undergone a clockwise rotation, which is thought to have been associated with the breakup of the continental crust and subsequent back-arc spreading of the Japan Sea. Based on a data set obtained from Southwest Japan since 1982, Otofuji *et al.* (1985a) estimated the amount of clockwise rotation relative to stable Eurasia as 47° and gave the date of this rotation by using best-fitting curves for the rotation deduced from declination versus age data; the climax of rotation was around 15 Ma (Figure 5). These data sets were obtained from a sufficiently wide area in Southwest Japan, which implies that Southwest Japan rotated as a coherent block. Coherent motion is also supported by the undisturbed zonal structure of pre-Neogene geologic terranes (Figure1). Recently, Otofuji *et al.* (1991) measured paleomagnetism as well as K-Ar ages of Miocene volcanic rocks in Southwest Japan to elucidate the duration of the rotation. Their data show that more than 80% (39°) of the overall rotation (47°) of Southwest Japan occurred between 16.3 and 14.5 Ma, which implies a rapid rotation of Southwest Japan (20°/m yr.).

Northeast Japan

Few paleomagnetic studies on the late Tertiary rocks in Northeast Japan were performed, e.g., Otofuji *et al.* (1985c); Tosha and Hamano (1986, 1988); Nishitani and Tanoue (1988) and Yamazaki (1989). Otofuji *et al.* (1985c) collected samples from a wide area of Northeast Japan, and concluded that Northeast Japan had rotated counter-clockwise through 47° around a vertical axis. Tosha and Hamano (1986, 1988) made a paleomagnetic study of Tertiary volcanic and sedimentary rocks distributed along the Japan Sea side. They found that the counter-clockwise rotation of Northeast Japan occurred between about 22 and 15 Ma. Based on their paleomagnetic results, it can be concluded that Northeast Japan was situated along the eastern margin of the Asian continent from Early Cretaceous till Early Miocene. The amount of the rotation is estimated to be roughly 20° which is smaller than that estimated by Otofuji *et al.* (1985c). Nishitani and Tanoue (1988) also determined the paleomagnetism of Northeast Japan in order to reconstruct the paleo-position of the Japanese Islands. Their paleomagnetic analysis suggested that the northwestern part of Northeast Japan was part of the Asian continent until the Middle Miocene, and that it suffered a counter-clockwise rotation to the present location during the Late Miocene. Recently, Yamazaki (1989) made a paleomagnetic study of the sedimentary rocks along the Pacific side. He showed that the rotation of Northeast Japan occurred earlier than 16 Ma, which suggests that the counter-clockwise rotation of Northeast Japan was prior to the clockwise rotation of Southwest Japan.

Nohi Area

While recent paleomagnetic studies have revealed the clockwise rotation of Southwest Japan (47°) as mentioned above, some paleomagnetic data obtained from the Nohi area, located in the eastern part of Southwest Japan, suggest a much smaller rotation. Thus the Nohi area comprises a part of the west-wing of the Kanto Syntaxis (Figure 1), that the variance in paleomagnetic directions relative to those of adjacent areas may represent a bending motion of the Kanto Syntaxis. Itoh (1988) studied the Late Cretaceous and Miocene rocks in the Nohi area. The obtained reliable paleomagnetic declinations in the Nohi area were much smaller than the easterly deflected ones in the most of Southwest Japan from Late Cretaceous to Early Miocene. The smaller deflection angle suggests a differential rotation of the west-wing of the Kanto Syntaxis. Based on geologic features as well as on paleomagnetic data, it can be concluded that the northward bending of the pre-Neogene zonal structure might be due to left-lateral plastic deformation during clockwise rotation of Southwest Japan.

COLLISION TECTONICS IN CENTRAL JAPAN

Collision between the Izu-Bonin arc and the Japanese Islands is in progress at the South Fossa Magna region in association with the northwestward migrating, subducting Philippine Sea Plate (Figures 1 and 2). The South Fossa Magna is characterized by very thick and intensively deformed sediments and is thought to have experienced collisions of not less than two allochthonous blocks with central Japan (Niitsuma and Matsuda, 1985; Amano *et al.*, 1986, Niitsuma, 1989; Amano, 1991). The pre-Neogene rocks form a cusp-shaped distribution at the South Fossa Magna where the Izu-Bonin arc joins it. The formation of the Kanto Syntaxis may be considered as the result of the collision between the Izu-Bonin arc and central Japan.

The tectonics in the South Fossa Magna are related to the Eurasian, Philippine Sea and Pacific Plates. The Pacific Plate subducts beneath both the Eurasian and Philippine Sea Plates. While the Philippine Sea Plate has a subduction boundary with the Eurasian Plate, its northern tip collides with central Japan on the Eurasian Plate. The subduction boundary between the Eurasian and Philippine Sea Plates can be traced onshore to the southern Fossa Magna where the nature of the boundary changes to subducting-collisional. The collision of the Izu-Bonin arc with central Japan may be attributed to the buoyancy of the active island arc.

Recently, four exotic segments have been identified in the South Fossa Magna: the Kushigatayama, Misaka, Tanzawa and Izu Blocks mainly consisting of altered volcanic rocks (Amano, 1991). Very thick piles of coarse-grained sediments overlying mudstones are also recognized along the northern collision boundaries of both the Tanzawa and Izu Blocks. The timing of the collision and the accretion of the Izu-Bonin arc onto central Japan was recorded in these sedimentary sequences (Figures 6 and 7). The immature, thickly piled coarse clastic detritus in the trough fills is most likely to result of the intense tectonic movement, as also the abrupt uplifting of the hinterland caused by the collision of the Izu-Bonin arc. Based on the bio-and lithostratigraphy of the conglomerate-dominated

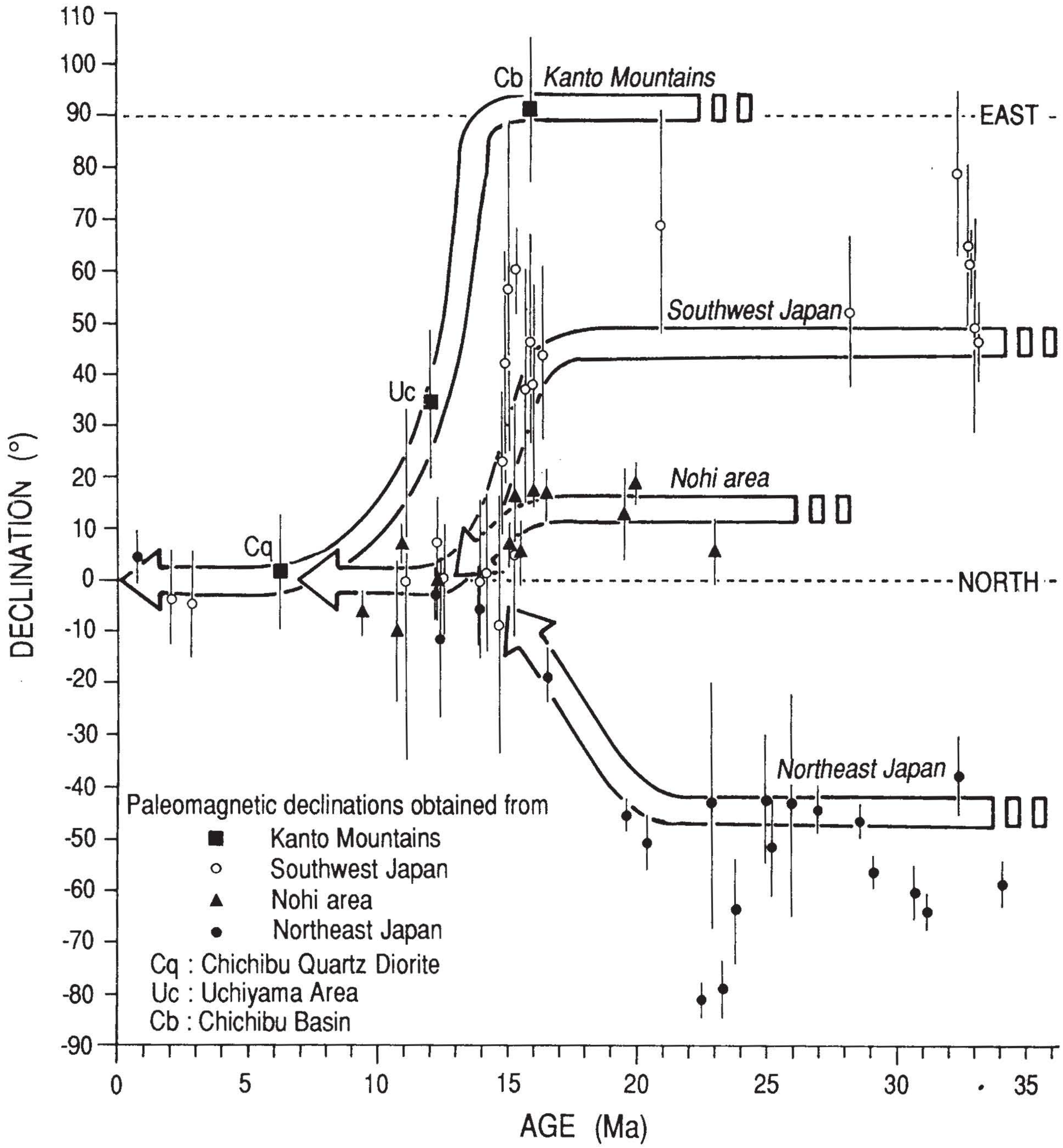

Fig. 5. Declination versus age for the Kanto Mountains (Hyodo and Niitsuma, 1986; Takahashi and Nomura, 1989; Takahashi and Watanabe, 1993), Southwest Japan (Otofuji *et al.*,1985a), Nohi area (Itoh, 1988) and Northeast Japan (Otofuji *et al.*,1985c; Nishitani and Tanoue, 1988).

horizons, Amano (1991) estimated the time of the collision of the Kushigatayama, Misaka, Tanzawa and Izu Blocks at 12 Ma, 9-7 Ma, 5-3 Ma and 1 Ma, respectively. These collisions would be expected to cause strong deformations in and around the colliding blocks.

RECONSTRUCTION OF THE JAPANESE ISLANDS

In conclusion, idealized reconstructions of the Japanese Islands are shown in Figures 8 through 13 mainly based on the paleomagnetic data. The location of the volcanic front (Kano *et al.* 1991) as well as the stress field (Otsuki, 1989, 1990b; Yamamoto, 1991) are also shown. The reconstructed plate boundaries, as well as the offshore area, are partly modified from Otsuki (1990a). These figures indicate well the relations between the clockwise rotation of Southwest Japan, the counter-clockwise rotation of North-east Japan, the collision of the Izu-Bonin arc and the lateral bending of central Japan (formation of the Kanto Syn-taxis).

(1) 22-18Ma

The southwest and northeast Japan arcs were located along the eastern margin of the Asian continent before about 18Ma (Figure 8). It is clear that the pre-Neogene

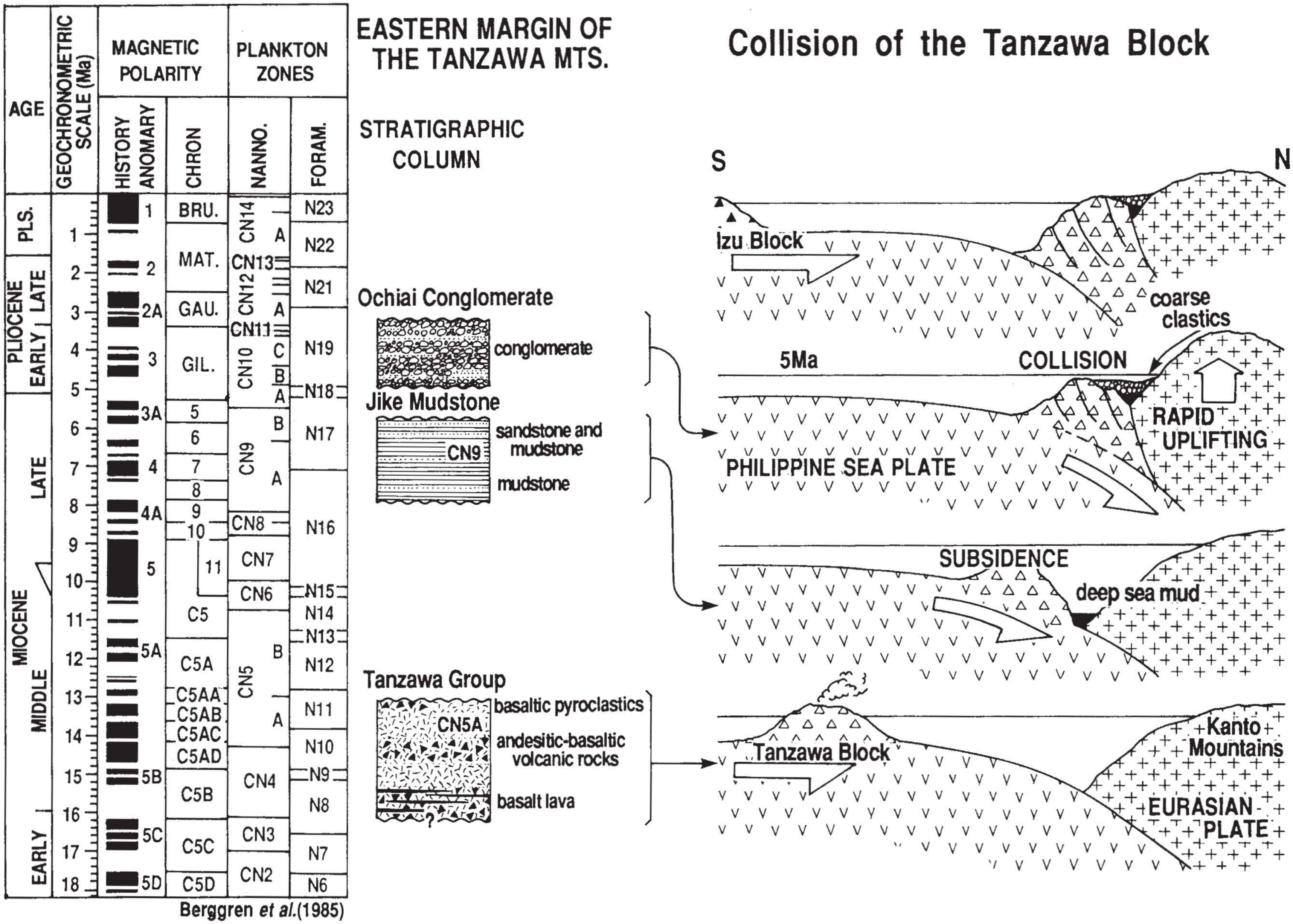

Fig. 6. Schematic diagram showing four stages during the Miocene and Pliocene collisional history of the Tanzawa Block with central Japan. The Jike Mudstone deposited in the deep trough between the Kanto Mountains and the Tanzawa Block, and overlying coarse clastics (Ochiai Conglomerate) abruptly filled up the trough, which may be associated with the collision and accretion of the Tanzawa Block.

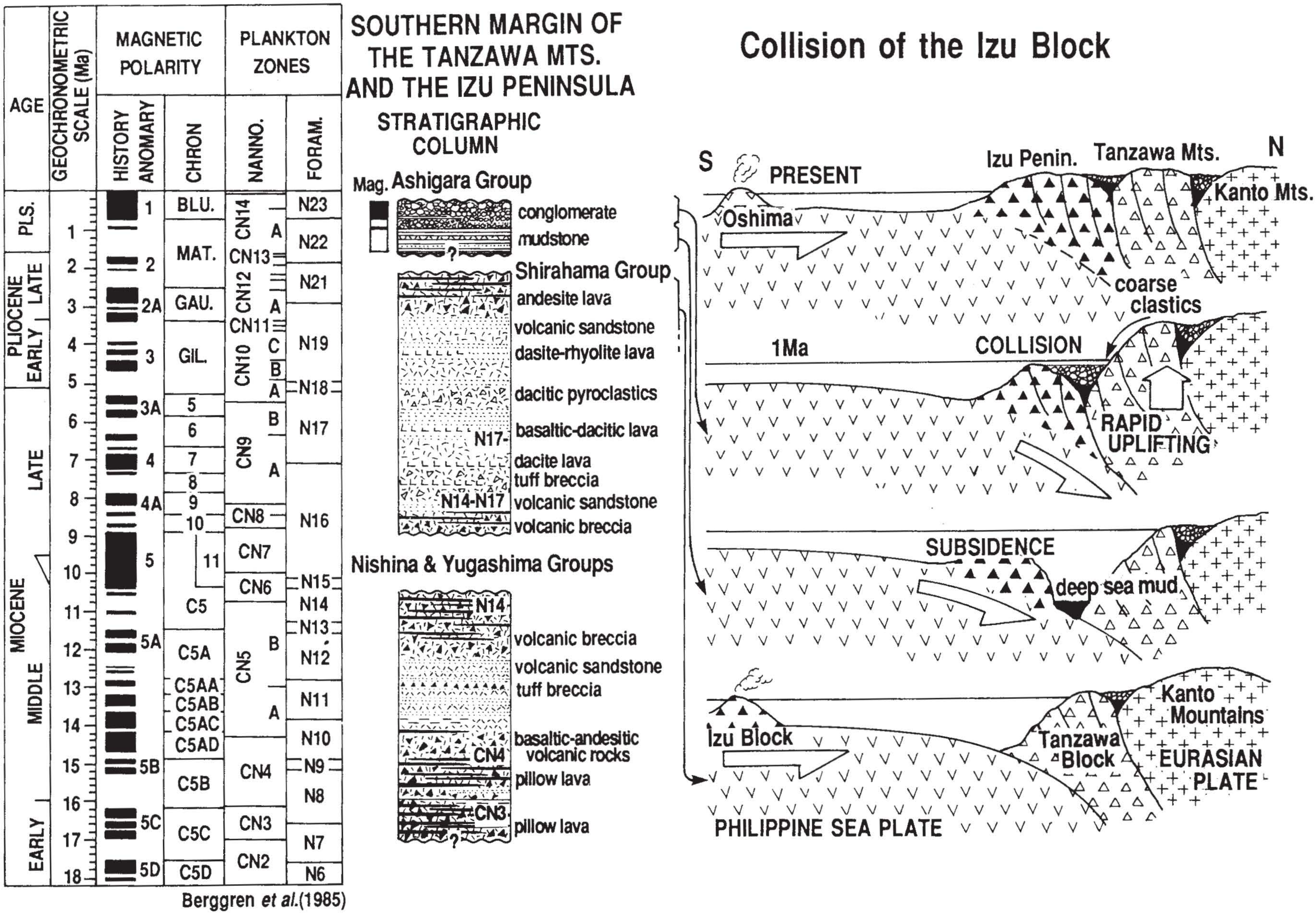

Fig. 7. Schematic diagram of the collision tectonics of the Izu Block with the Tanzawa Mountains (Block). The Ashigara Group, distributed between the Tanzawa and Izu Blocks, is characterized by the coarse trough-filling clastics overlying deep sea sediments, which probably reflects the same collisional history of the Izu Block as that of the Tanzawa Block.

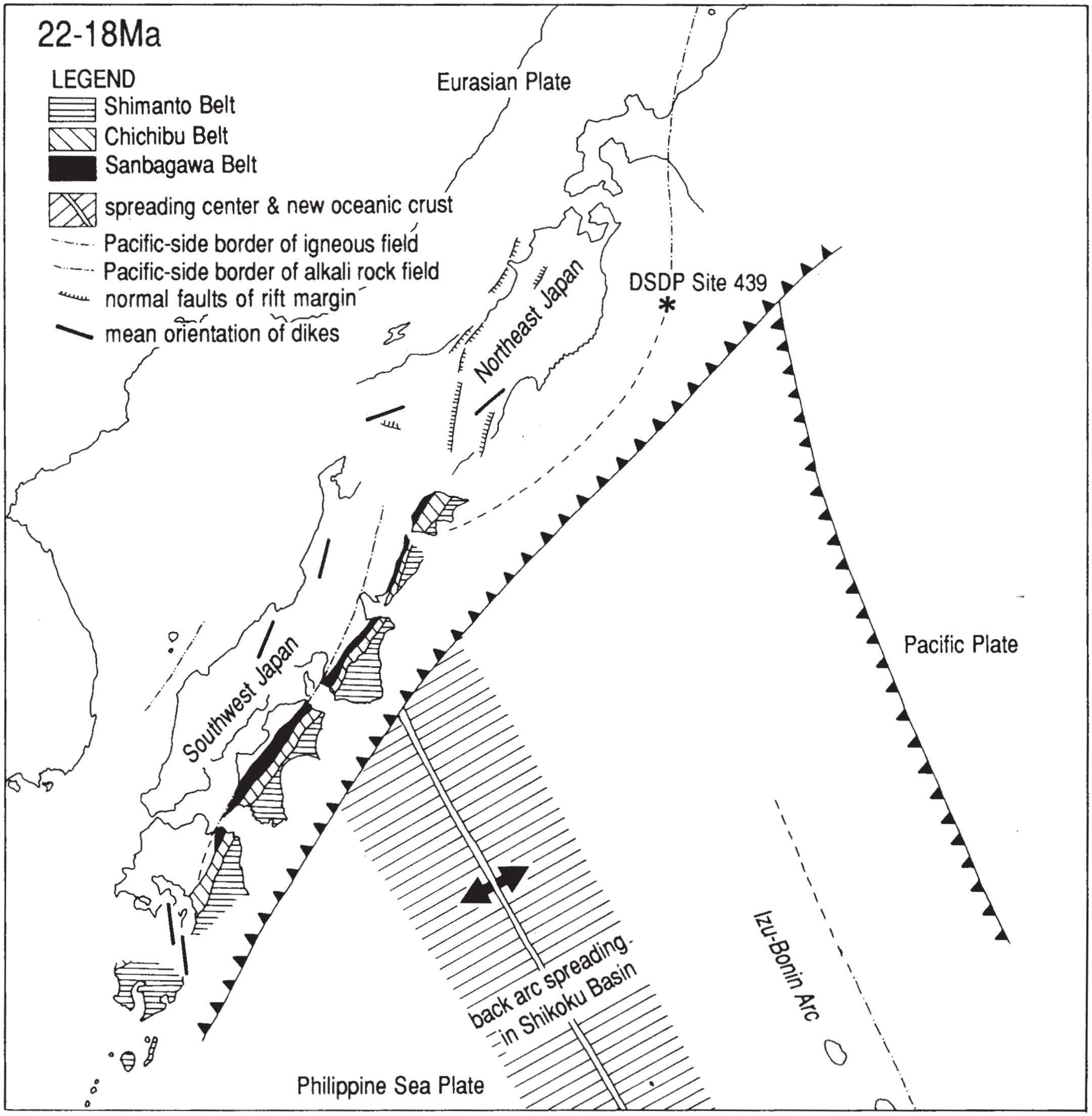

Fig.8. Paleogeographic map of the Japanese Islands in the Early Miocene time. The zonal structure of the pre-Neogene terranes was almost in linear trend before Japan Sea opening.

zonal distribution had almost a linear trend in this period as reconstructed from the paleomagnetic data. Back-arc spreading in the Shikoku Basin started at 25 Ma, and its active spreading center and the newly formed oceanic lithosphere on both sides also subducted beneath the Japanese Islands.

(2) 18-15Ma

This period is characterized by southeastward migration together with rotation of the Japanese Islands (Figure 9). Most of the clockwise rotation of Southwest Japan took place between 16.3 and 14.5 Ma (Otofuji *et al.*, 1991; Hayashida *et al.*, 1991), which clearly suggests a rapid rotation. Though the paleomagnetic declinations of Northeast Japan also turn to the north direction between 20 and 15 Ma, the exact time and the rotation velocity are still unknown, owing to the lack of paleomagnetic data. The clockwise rotation of the Kanto Mountains probably began about 15 Ma, while the west-wing of the Kanto Syntaxis

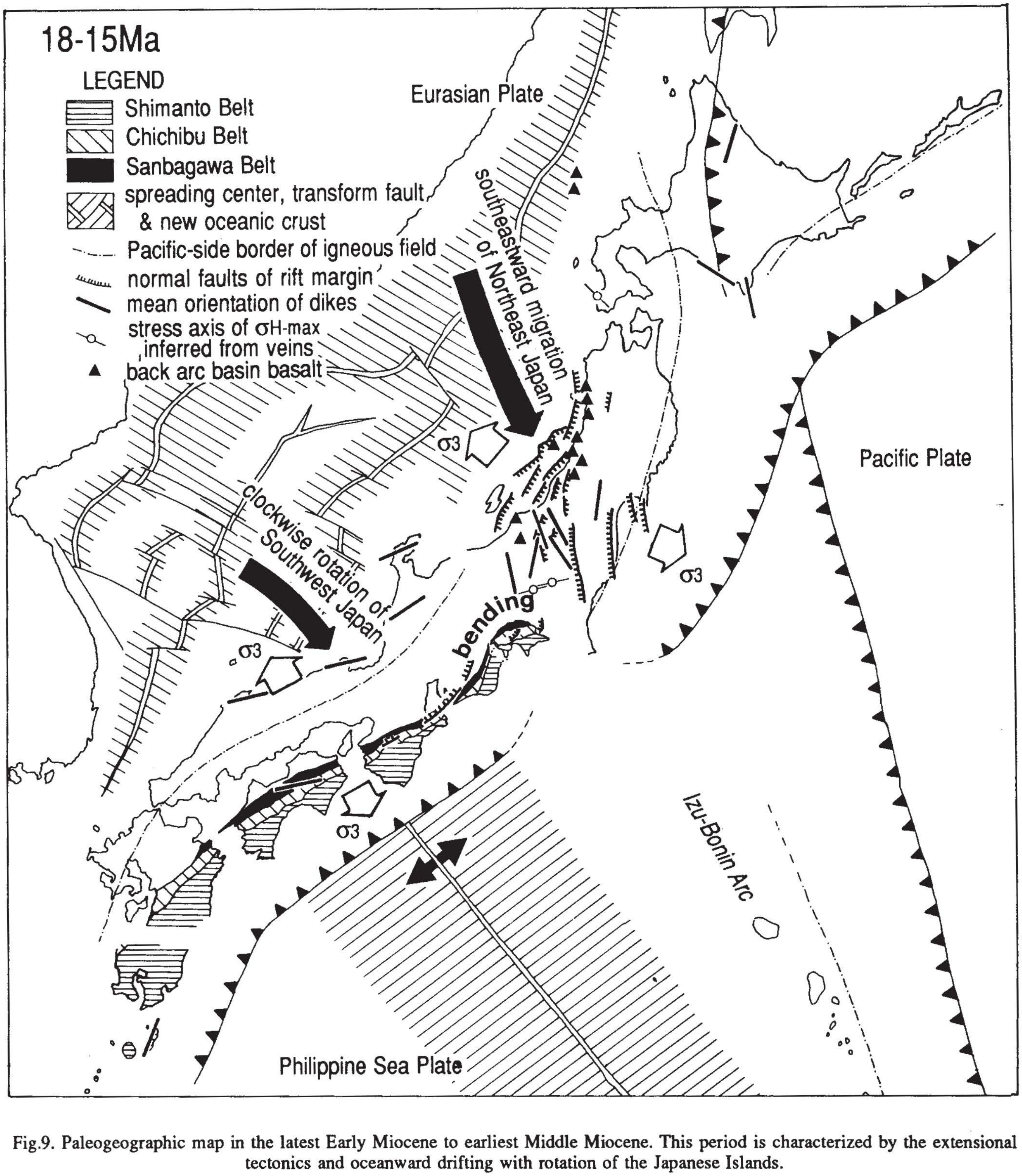

Fig.9. Paleogeographic map in the latest Early Miocene to earliest Middle Miocene. This period is characterized by the extensional tectonics and oceanward drifting with rotation of the Japanese Islands.

(Nohi area) rotated only 13-17° during this stage. The differential rotation within the Japanese Islands produced the bending of central Japan, which strongly suggests that the collision of the Izu-Bonin arc with central Japan already commenced in this stage.

A number of half-grabens were formed especially on the Japan Sea side of Northeast Japan (Yamaji, 1989, 1990), which signifies that Northeast Japan was under extensional tectonics (Yamaji and Sato, 1989). The regional stress field for this interval, deduced from the orientation of parallel feeder dyke swarms and veins (Otsuki, 1990b; Yamamoto, 1991), indicates σ_3 directions almost perpendicular to the axis of the arcs. Yamaji (1990) estimated this extensional deformation interval as 18 to 15 Ma, based on stratigraphic constraints. He also calculated the total subsidence of the inner-arc regions of Northeast Japan at about 2-3 km, of which most was attained within one million years from 16 to 15 Ma. The formation of many half grabens and the abrupt subsidence may represent a stretching and rifting of the lithosphere of Northeast Japan (Takeshita and Yamaji, 1990). On the contrary, few half grabens are recognized in Southwest Japan. Rapid rotation without intra-arc extensional deformation might cause some subsidence of Southwest Japan.

(3)15-12Ma

The clockwise rotation of Southwest Japan ceased about 14 Ma and the rotational motion of Northeast Japan probably ended, while the Kanto Mountains rotated as much as several tens of degrees during this period (Figure 10). Northeast Japan subsided gently and the intra-arc deformation was small. On the other hand, the transgression was immediately followed by a regression in Southwest Japan at the end of the rotation (15-14 Ma). At the same time, the volcanic front shifted toward the fore-arc side and compressional deformation perpendicular to the arc axis occurred concurrently on the back-arc side (Kano *et al.*, 1991). Compressional deformation took place in central Japan (Oishi and Takahashi,1989), while Northeast Japan subsided gently under an intermediate stress field, which may be in accord with a thermal subsidence model (Yamaji and Sato,1989).

(4) 12-7Ma

The intra-arc deformation was localized in central Japan since about 14 Ma. The present Backbone Ranges uplifted initially after the latest Middle Miocene in Northeast Japan (Sato and Amano, 1991). Despite the limited fracture data indicating the nature of the stress field, the direction of horizontal maximum stress shows the same orientation as in the previous stage. The Kanto Mountains rotated about 35° during this interval, resulting in sharp bent structure of the Kanto Syntaxis. The additional rotation of the Kanto Mountains during this stage was probably due to the collision of the Kushigatayama and Misaka Blocks.

(5)7-3Ma

The intermediate stress field deduced from veins, minor faults, and dykes (Amano, 1980; Sato *et al.*, 1982; Otsuki, 1990b) continued since 14 Ma. Many caldera structures related to felsic subaerial volcanism were formed during this period in Northeast Japan (Figure 12). The fractures reflecting the stress field consist of normal faults and strike-slip faults, showing NE-SW trending compressional stress. The coexistence of these two different types of faults suggests that the horizontal compressional stress was nearly equal to the vertical stress. The Kanto Mountains, (east-wing of the Kanto Syntaxis), did not rotate after the intrusion of the Chichibu Quartz Diorite (6.6-5.9 Ma). This means that the cuspate structure of the Kanto Syntaxis was formed before about 6 Ma.

(6)3Ma-Present

This period is characterized by compressional tectonics, as shown in Figure 13. A large number of reversed faults trending parallel to the arc axis were formed in Northeast Japan. The reconstructed stress field from these reversed faults suggests that the maximum and minimum principal stresses are oriented horizontally normally and vertically to the Japan trench. The σ_1 direction in Northeast Japan is almost parallel to the present motion of the Pacific Plate relative to the Eurasian Plate, which implies that the present tectonism of Northeast Japan is related to the converging plates. Southwest Japan also has been under a compressional tectonic regime, while strike-slip faults are dominant. The stress field in Southwest Japan is also well explained by the plate motion. The stress field in central Japan is a mixture of E-W trending stress of Northeast Japan and NW-SE trend of Southwest Japan.

ACKNOWLEDGEMENTS

Thanks are due to Dr. Y. Watanabe of the Geological Survey of Japan for reading the manuscript and offering valuable suggestions.

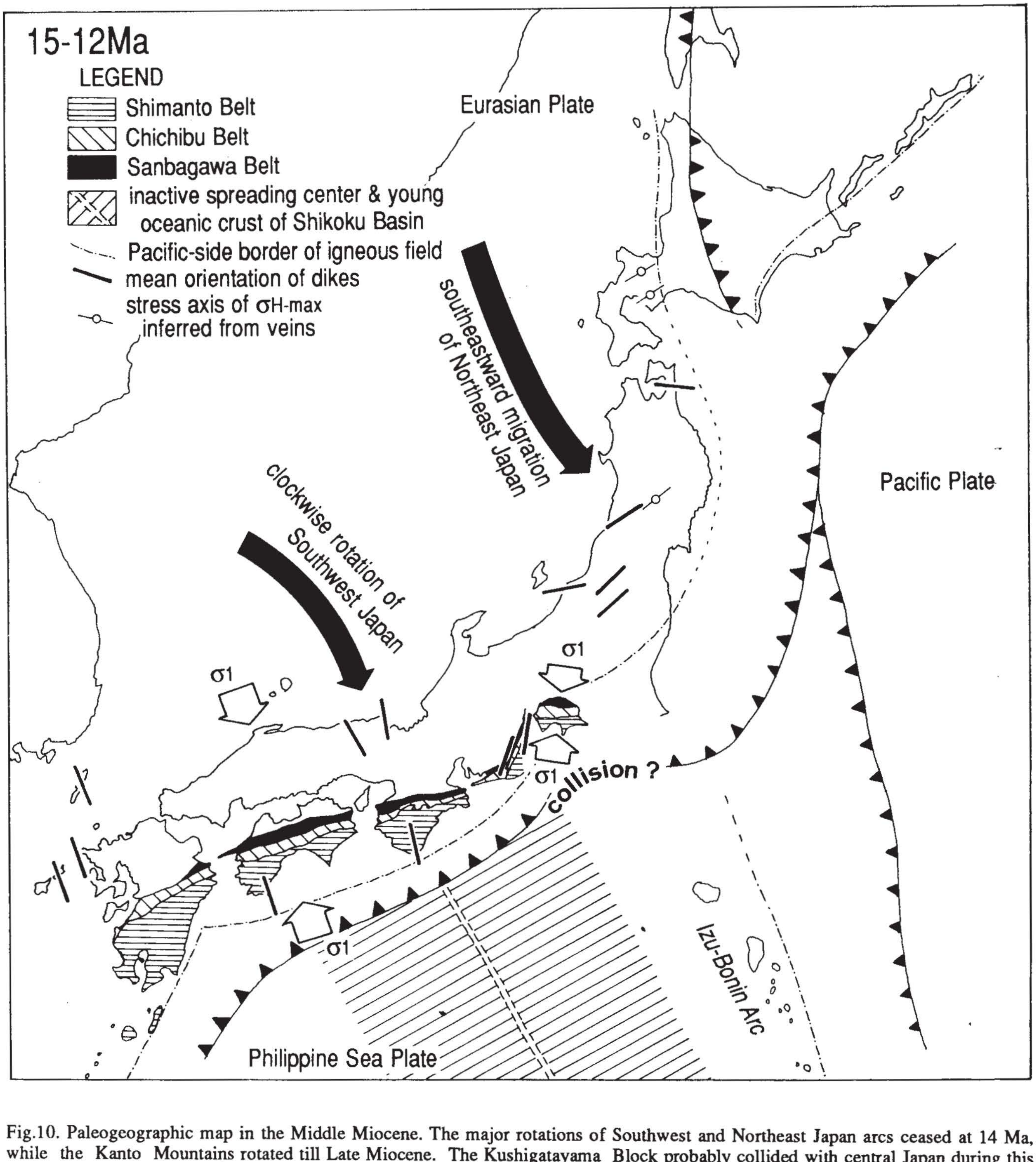

Fig.10. Paleogeographic map in the Middle Miocene. The major rotations of Southwest and Northeast Japan arcs ceased at 14 Ma, while the Kanto Mountains rotated till Late Miocene. The Kushigatayama Block probably collided with central Japan during this stage (Koyama, 1991).

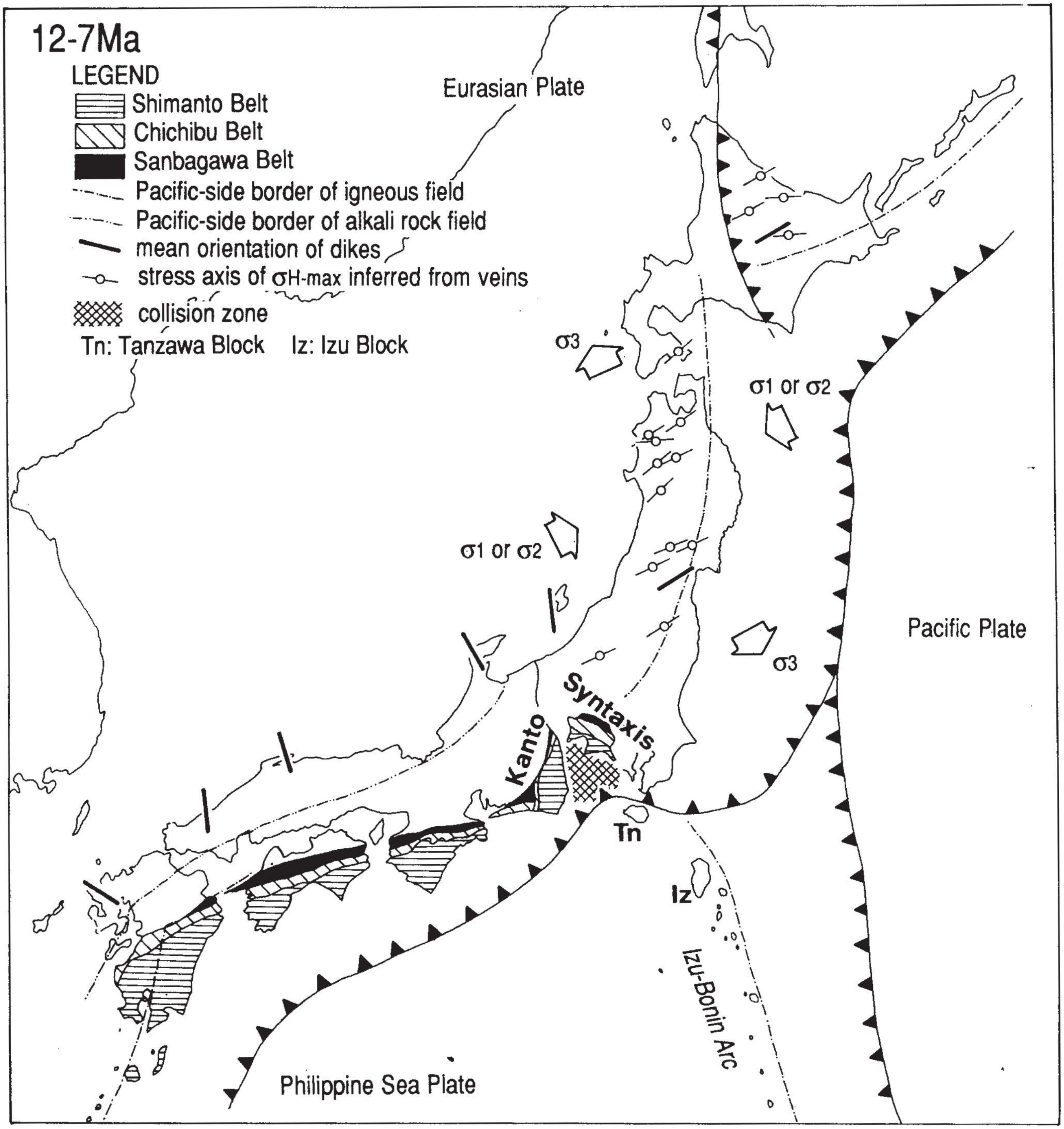

Fig. 11. Paleogeographic map in the late Middle Miocene to early Late Miocene. Major tectonic deformation did not occur during this interval except for central Japan where compressional deformation continued in association with the collision of the Izu-Bonin arc.

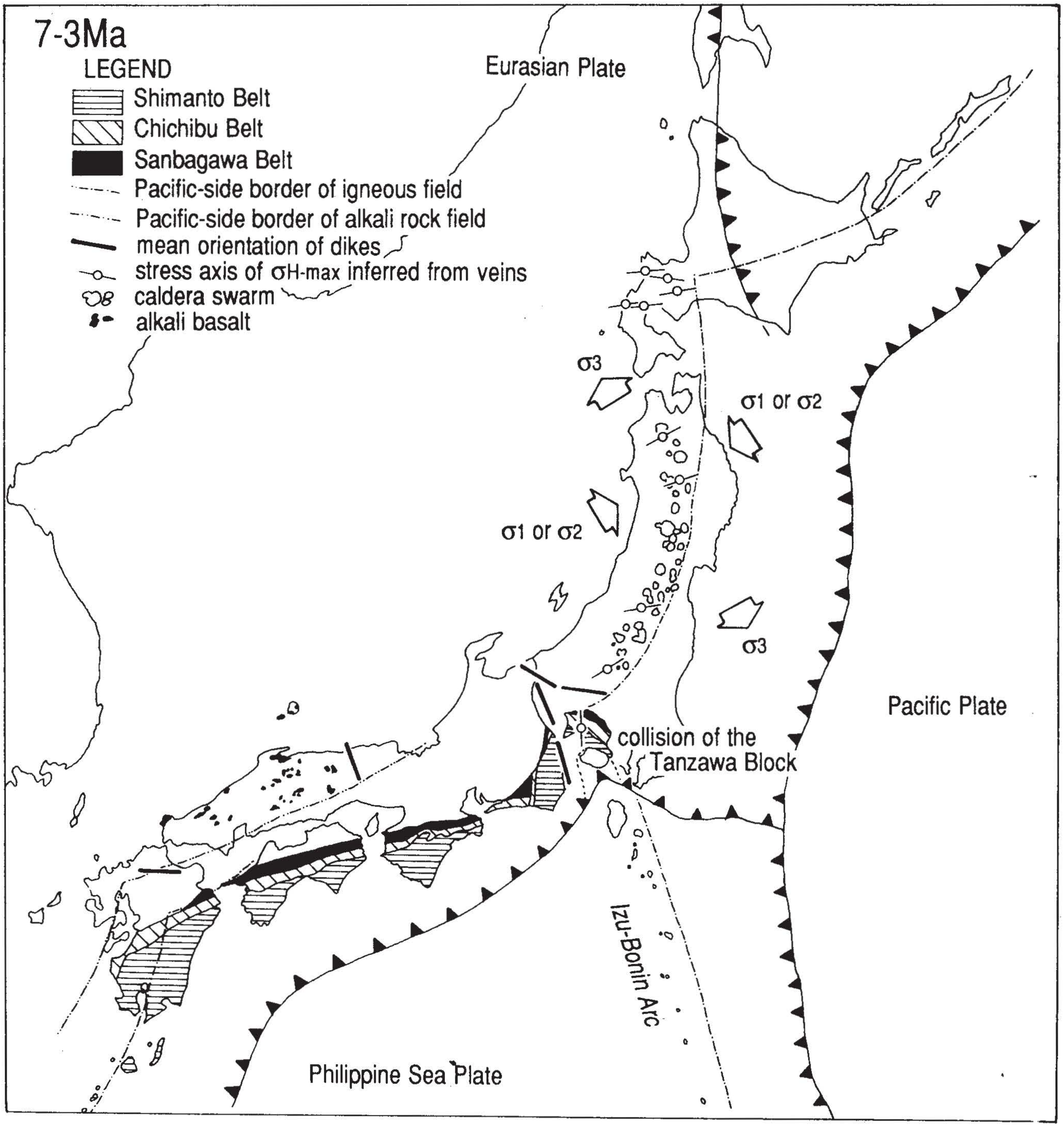

Fig. 12. Paleogeographic map in the late Late Miocene to Early Pliocene. Many calderas were formed under extensional stress field in Northeast Japan. The Tanzawa Block collided and accreted with the Kanto Mountains during this stage, despite the rotation of the Kanto Mountains was negligibly small.

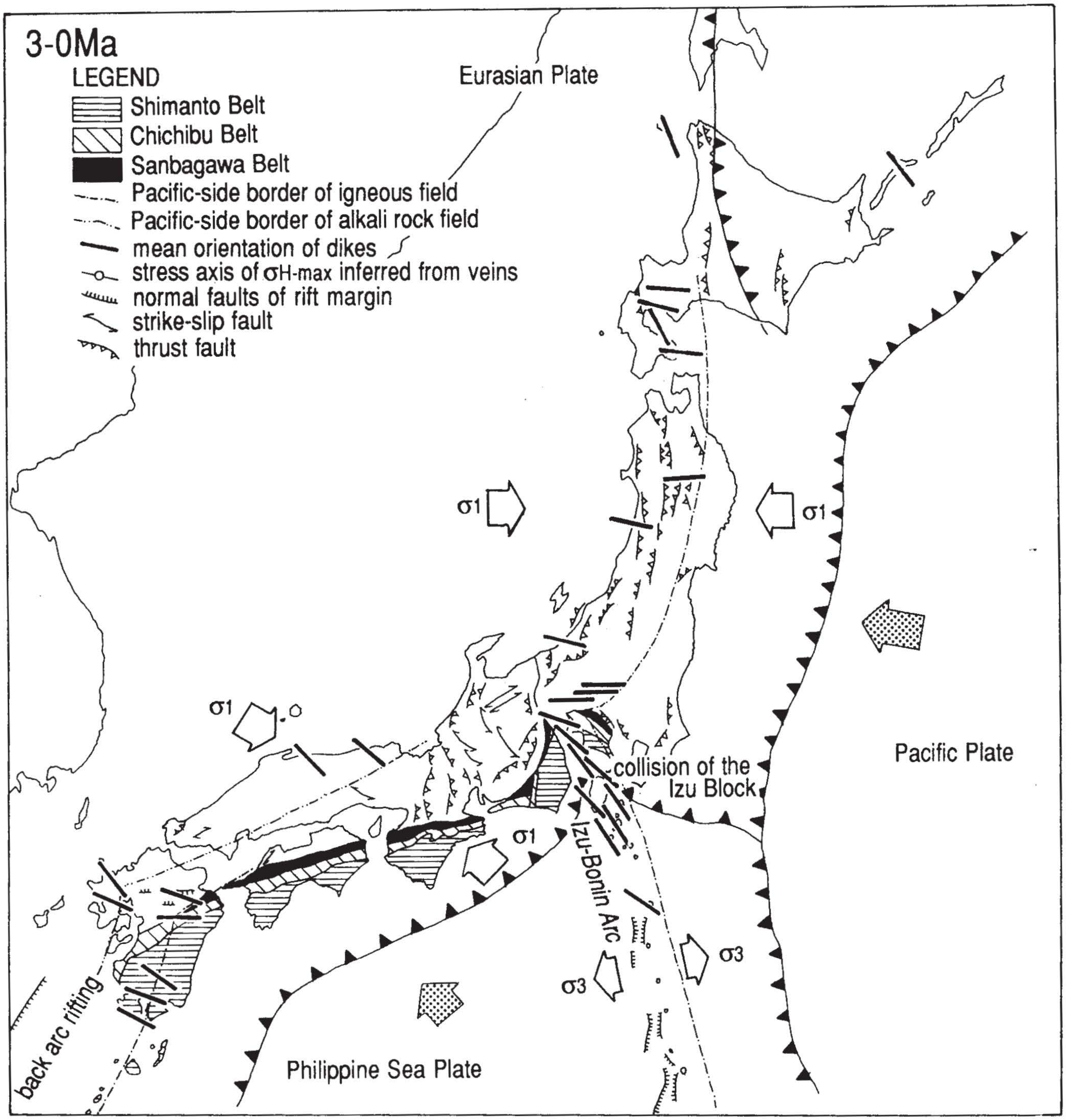

Fig.13. Paleogeographic map in the Late Pliocene to Pleistocene. The Japanese Islands have been under the compressional tectonic regime since the Late Pliocene related to the change in Pacific Plate motion (Sato and Amano, 1991).

BIBLIOGRAPHY

AMANO, K., 1980. The South Fossa Magna region as a multiple collision zone. *Earth Monthly, 8,* 581-586.

AMANO, K., 1991. Multiple collision tectonics of the South Fossa Magna in central Japan. *Modern Geol., 15,* 315-329.

AMANO, K., H. TAKAHASHI, T. TACHIKAWA, K. YOKOYAMA, C. YOKOTA and J. KIKUCHI, 1986. Geology of Ashigara Group-Collision tectonics of Izu micro - continent with Eurasian plate-. *Kitamura Commem. Essays Geol.,* 7-29.

BERGGREN, W. A., D. V. KENT, J. J. FLYNN and J. A. VAN COUVERRING, 1985. Cenozoic geochronology. *Geol. Soc. Am. Bull., 96*, 1407-1418.

BLOW, W. H., 1969. Late Middle Miocene to Recent planktonic foraminiferal biostratigraphy. Proc. 1st Int. Conf. Planktonic Microfossils, Geneva, 1967, 1, 119-422.

GEOLOGICAL SURVEY OF JAPAN, 1992. Geological map of Japan, 1:1,000,000 (3rd ed.).

HALE, C. J., M. FUULER, and R. C. BAILEY, 1978. On the application of microwave heating to lunar paleointensity determination. Proc. 9th Lunar and Planet. Sci. Conf., 3, 3165-3179.

HAYASHIDA, A., 1986. Timing of rotational motion of Southwest Japan inferred from paleomagnetism of the Setouchi Miocene Series. *J. Geomag. Geoelectr., 38*, 295-310.

HAYASHIDA, A., A. FUKUI and M. TORII, 1991. Paleomagnetism of the Early Miocene Kani Group in Southwest Japan and its implication for the opening of the Japan Sea. *Geophys. Res. Lett., 18*, 1095-1098.

HAYASHIDA, A. and Y. ITO, 1984. Paleoposition of Southwest Japan at 16Ma: Implication from paleomagnetism of Miocene Ichishi Group. *Earth Planet. Sci. Lett, 68*, 335-342.

HYODO, H. and N. NIITSUMA, 1986. Tectonic rotation of the Kanto Mountains, related with the opening of the Japan Sea and collision of the Tanzawa Block since middle Miocene. *J. Geomag. Geoelectr., 38*, 335-348.

ITOH, Y., 1986. Differential rotation of northeastern part of Southwest Japan: paleomagnetism of early to late Miocene rocks from Yatsuo area in Chubu District. *J. Geomag. Geoelectr., 38*, 325-334.

ITOH, Y., 1988. Differential rotation of the eastern part of Southwest Japan inferred from paleomagnetism of Cretaceous and Neogene rocks, *J. Geophys. Res., 93*, 3401-3411.

KANO, K., H. KATO, Y. YANAGISAWA and F. YOSHIDA, 1991. Stratigraphy and geologic history of the Cenozoic of Japan. *Rep. Geol. Surv. Japan, 274*, 1-114.

KAWAI, N., H. ITO and S. KUME, 1961. Deformation of the Japanese Islands as inferred from rock magnetism. *Geophys. J. Res. Astr. Soc., 6*, 124-130.

KOBAYASHI, T., 1941. The Sakawa orogenic cycle and its bearing on the origin of the Japanese Islands. *J. Fac. Sci. Tokyo Imp. Univ., 2, 5*, 219-578.

KOYAMA, A., 1991. Collision of the Kushigatayama Block with the Honshu arc during the Middle Miocene. *Modern Geol., 15*, 331-345.

MATSUDA, T., 1978. Collision of the Izu-Bonin arc with central Honshu: Cenozoic tectonics of the Fossa Magna, Japan. *J. Phys. Earth, 26, Supple.*, 409-421.

MATSUDA, T., 1984. Northward-convex structure in South Fossa Magna and collision of Izu Block. *Quat. Res., 23*, 151-154.

MINSTER, J. B. and T. H. JORDAN, 1978. Present-day plate motions. *J. Geophys. Res., 83*, 5331-5354.

MINSTER, J. B. and T. H. JORDAN, 1979. Rotation vectors for the Philippine and Rivera Plates. *EOS, 60*, 958.

NIITSUMA, N., 1982. Touchstone of the plate tectonics -South Fossa Magna, central Japan. *Chikyu Monthly, 4*, 326-333.

NIITSUMA, N., 1989. Collision tectonics in the South Fossa Magna, central Japan. *Modern Geol., 14*, 3-18.

NIITSUMA, N. and T. MATSUDA, 1985. Collision in the South Fossa Magna area, central Japan. *Recent Prog. Natural Sci. Japan, 10*, 41-50.

NISHITANI, T. and S. TANOUE, 1988. Paleomagnetic study for the Oga Peninsula in Northeast Japan. *Rep. Res. Inst. Nat. Resource Min. Coll., Akita Univ., 53*, 69-75.

NOMURA, S. and M. EBIHARA, 1988. K-Ar ages and paleomagnetism of Cenozoic volcanic rocks in the west part of Gunma Prefecture, central Japan. *Sci. Rep. Fac. General Studies, Gunma Univ., 22*, 65-78.

NOMURA, S. and T. KOSAKA, 1987. Geologic development of Neogene System in the southwest part of Gunma Prefecture, central Japan. *Sci. Rep. Fac. General Studies, Gunma Univ., 21*, 51-68.

OISHI, M. and M. TAKAHASHI, 1990. Miocene formations in the Takasaki district, central Japan-with special reference to the developmental process of the Niwaya Unconformity-. *Cont. Inst. Geol. Paleont. Tohoku Univ., 92*, 1-17.

OTOFUJI, Y., A. HAYASHIDA and M. TORII, 1985a. When was the Japan Sea opened?: Paleomagnetic evidence from Southwest Japan. Formation of Active Ocean Margins, 551-566.

OTOFUJI, Y., T. ITAYA and T. MATSUDA, 1991. Rapid rotation of Southwest Japan-paleomagnetism and K-Ar ages of Miocene volcanic rocks of Southwest Japan. *Geophys. J. Int., 105*, 397-405.

OTOFUJI, Y. and T. MATSUDA, 1983. Paleomagnetic evidence for the clockwise rotation of Southwest Japan. *Earth Planet. Sci. Lett., 62*, 349-359.

OTOFUJI, Y. and T. MATSUDA, 1984. Timing of rotational motion of Southwest Japan inferred from paleomagnetism. *Earth Planet. Sci. Lett., 70*, 373-382.

OTOFUJI, Y. and T. MATSUDA, 1987. Amount of clockwise rotation of Southwest Japan-fan shape opening of the southwestern part of the Japan Sea. *Earth Planet. Sci. Lett.*, *85*, 289-301.

OTOFUJI, Y., T. MATSUDA and S. NOHDA, 1985b. Opening mode of the Japan Sea inferred from the paleomagnetism of the Japan Arc. *Nature*, *317*, 603-604.

OTOFUJI, Y., T. MATSUDA and S. NOHDA, 1985c. Paleomagnetic evidence for the Miocene counter-clockwise rotation of Northeast Japan-rifting process of the Japan Arc. *Earth Planet. Sci. Lett.*, *75*, 265-277.

OTSUKI, K., 1989. Reconstruction of Neogene stress fields of Northeast Honshu Arc from metalliferous veins. *Geol. Soc. Japan. Mem.*, *32*, 281-304.

OTSUKI, K., 1990a. Westward migration of the Izu-Bonin trench, northward motion the Philippine Sea Plate, and their relationships to the Cenozoic tectonics of Japanese island arcs. *Tectonophys.*, *180*, 351-367.

OTSUKI, K., 1990b. Neogene tectonic stress fields of northeast Honshu arc and implications for plate boundary conditions. *Tectonophys.*, *181*, 151-164.

SATO, H. and K. AMANO, 1991. Relationship between tectonics, volcanism, sedimentation and basin development, Late Cenozoic, central Japan. *Sediment. Geol.*, *74*, 323-343.

SATO, H., K. OTSUKI and K. AMANO, 1982. Neogene tectonic stress field of Northeast Honshu Arc. *Cicr. Res. Assoc. Struct. Geol.*, 27, 55-79.

TAKAHASHI, M., 1992. Geologic setting of the Miocene Chichibu Basin in the Neogene tectonics of central Japan. *Bull. Saitama Mus. Nat. Hist.*, *10*, 29-45.

TAKAHASHI, M., H. NAGAHAMA and Y. TANAKA, 1989. Age of the lower part of Neogene sedimentary rocks in the Chichibu Basin, as dated by calcareous nannofossils. *Fossils*, *46*, 1-9.

TAKAHASHI, M. and S. NOMURA, 1989. Paleomagnetism of the Chichibu Quartz Diorite -Constraints on the time of lateral bending of the Kanto Syntaxis. *J. Geomag. Geoelectr.*, *41*, 479-489.

TAKAHASHI, M. and Y. WATANABE, 1993. Paleomagnetism of the Miocene igneous rocks in the Uchiyama area, central Japan. *J. Geomag. Geoelectr.*, *45*, 89-101.

TAKESHITA, T. and A. YAMAJI, 1990. Acceleration of continental rifting due to a thermomechanical instability. *Tectonophys.*, *181*, 307-320.

TATEIWA, I., 1976. The Koreo-Japanese Geotectonic Zone. 654pp., Univ. Tokyo Press, Tokyo.

TOSHA, T. and Y. HAMANO, 1986. Paleomagnetic study on the dike swarm in the Oga Peninsula, Northeast Honshu Island. *J. Geomag. Geoelectr.*, *38*, 349-360.

TOSHA, T. and Y. HAMANO, 1988. Paleomagnetism of Tertiary rocks from the Oga Peninsula and the rotation of Northeast Japan. *Tectonics*, *7*, 653-662.

UENO, H. and K. SHIBATA, 1986. Radiometric ages of quartz diorite bodies related to the Chichibu pyrometasomatic deposits and their relevance to the metallogenic epoch. *J. Japan Assoc. Min. Petr. Econ. Geol.*, *81*, 77-82.

YAMAJI, A., 1989. Geology of Atsumi area and Early Miocene rifting in the Uetsu district, northeast Japan. *Geol. Soc. Japan Mem.*, *32*, 305-320.

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

YAMAJI, A. and H. SATO, 1989. Miocene subsidence of the Northeast Honshu Arc and its mechanism. *Geol. Soc. Japan Mem.*, 32, 339-349.

YAMAMOTO, T.,1991. Late Cenozoic dike swarms and tectonic stress field in Japan. *Bull. Geol. Surv. Japan*, *42*, 131-148.

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. *J. Geomag. Geoelectr.*, *41*, 533-584.

Masaki Takahashi
Fuel Resources Department, Geological Survey of Japan
1-1-3 Higashi, Tsukuba, Ibaraki 305, Japan